



International Journal for Research Communications in Engineering, Emerging Technologies and Sciences (IJRCEETS)

Volume 1, Issue 2, November-2025

Cite: Dr. Kusuma Sundara Kumar, Dr. B. V. Shiva Kumar (2025), Reinforcing Sustainable Geopolymer Concrete with Industrial Waste: Performance and Lifecycle Assessment, International Journal for Research Communications in Engineering, Emerging Technologies and Sciences, Vol. 01, issue (2), pp. 25-38

Reinforcing Sustainable Geopolymer Concrete with Industrial Waste: Performance and Lifecycle Assessment

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Article info:

Article No.: IJRCEETSV1120003

Submitted: 23/09/2025

Received in revised form: 12/10/2025

Accepted for publication: 28/10/2025

Available online: 14/11/2025

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Abstract. This study presents a comprehensive experimental investigation and lifecycle assessment (LCA) of geopolymer concrete (GPC) synthesized from multiple industrial by-products—fly ash (FA), ground granulated blast-furnace slag (GGBS), metakaolin (MK) and rice husk ash (RHA)—activated with an alkaline solution of sodium hydroxide and sodium silicate. Six concrete mix designs were evaluated: one ordinary Portland cement (OPC) control and five geopolymer mixes with varying precursor combinations. Fresh-state properties, mechanical performance (compressive, flexural and split tensile strength), durability (chloride permeability, acid resistance, water absorption, carbonation depth) and microstructural characteristics (SEM, XRD) were assessed. The optimized GPC-FA/GGBS 50/50 blend achieved a 28-day compressive strength of 51.6 MPa-34% higher than that of OPC-with a 66.8% reduction in global warming potential (138.7 vs 422.0 kg CO₂-eq/m³). Lifecycle analysis across six environmental indicators consistently demonstrated superior sustainability credentials for GPC formulations. The results confirm that industrial waste-based geopolymer concrete is a structurally viable and environmentally preferable alternative to conventional OPC for structural applications.

Keywords: Geopolymer concrete; fly ash; GGBS; industrial waste; lifecycle assessment; compressive strength; acid resistance; sustainability

1. Introduction

The global construction industry consumes approximately 4 billion tonnes of ordinary Portland cement (OPC) annually, contributing nearly 8% of worldwide anthropogenic CO₂ emissions—a figure projected to grow substantially with accelerating urbanisation in developing economies [12]. The calcination of limestone during OPC clinker production alone releases

approximately 0.83 kg of CO₂ per kilogram of cement produced, making the cement industry one of the most carbon-intensive industrial sectors on the planet [12]. Geopolymer concrete (GPC), first conceptualised by Davidovits in 1978 [1], has emerged as a promising low-carbon alternative. Rather than relying on calcium silicate hydrate (C-S-H) gel formation, GPC derives its binding properties from the polycondensation of aluminosilicate precursors-typically industrial by-products such as fly ash, GGBS, metakaolin, or rice husk ash-in the presence of an alkaline activator solution (typically NaOH and Na₂SiO₃) [2,7].

Compared with OPC, the utilisation of these industrial wastes not only reduces CO₂ emissions by 40–80% but also addresses significant solid waste disposal challenges [3,4]. India alone generates more than 170 million tonnes of fly ash annually, of which only approximately 67% is currently utilised [8].

Despite extensive laboratory-scale research [3,6,18], the widespread adoption of GPC in structural applications is hindered by (i) inconsistent fresh-state workability, (ii) variable curing sensitivity, (iii) limited long-term durability data, and (iv) incomplete lifecycle assessment studies comparing multiple environmental impact categories [4,5]. This investigation systematically addresses all four gaps by evaluating five GPC mix designs against OPC control, spanning mechanical, durability and environmental dimensions within a unified experimental framework.

The principal objectives of this work are as follows:

- To optimise the precursor blending ratios (FA, GGBS, MK, and RHA) and alkali activator parameters for maximum 28-day compressive strength.
- To conduct an extensive durability programme including acid resistance, chloride permeability, carbonation and water absorption testing.
- To characterise microstructural features via SEM imaging and XRD analysis, and correlate them with macroscale mechanical performance.
- To perform a cradle-to-gate lifecycle assessment (LCA) across six environmental impact categories using the ISO 14040/14044 methodology [14,15].

2. Literature Review

Recent studies on geopolymer concrete emphasize the utilization of industrial by-products such as fly ash, slag, and silica fume to enhance mechanical strength and durability while reducing dependence on Portland cement [3,6,18]. Researchers report improved compressive strength, resistance to chemical attack, and lower carbon emissions compared to conventional concrete [9,10]. Incorporation of additional industrial waste materials further improves toughness and sustainability performance [19]. LCA studies consistently highlight significant reductions in CO₂ emissions and energy consumption, supporting geopolymer concrete as an eco-friendly construction alternative [4,5].

2.1 Geopolymer Chemistry and Reaction Mechanisms

The geopolymerisation process involves dissolution of aluminosilicate precursors by an alkali activator (leaching of Si and Al ions) and subsequent condensation into three-dimensional Si-O-Al-O networks [7]. The resulting gel structures are predominantly sodium aluminosilicate hydrate (N-A-S-H) from fly ash-rich systems and calcium aluminosilicate hydrate (C-A-S-H) or hybrid gels from GGBS-containing blends [2,11]. The Si-Al molar ratio in the final binder strongly influences mechanical performance, with ratios between 2.0 and 3.5 reported as optimal for structural-grade geopolymers [7,9]. Provis and van Deventer [2] demonstrated that the reaction

kinetics of GPC are highly sensitive to calcium content of precursors, with GGBS dramatically accelerating setting time and early-age strength gain compared with pure fly ash systems [6].

2.2 Industrial Waste Precursors

Fly ash (Class F, per ASTM C618 [16]) is the most widely investigated geopolymer precursor because of its global availability, low calcium content, and well-established alkali-activation behaviour [3,8,9]. GGBS provides additional calcium for C-A-S-H cogel formation, improving both early strength and workability [6,10]. Metakaolin, produced by calcining kaolin clay at 600–900°C, has the highest reactivity among common precursors but is relatively expensive and negatively affects workability at high replacement levels [3,18]. Rice husk ash, an amorphous silica-rich pozzolan with specific surface areas of 50–300 m²/g, acts as a valuable supplementary precursor [19].

2.3 Durability Performance of GPC

Geopolymer concrete generally exhibits superior durability to OPC in aggressive environments owing to its densely cross-linked aluminosilicate network and lower calcium content [2,11]. Published chloride migration coefficients for GPC range from 0.8–3.5 × 10⁻¹² m²/s versus 3.5–8.0 × 10⁻¹² m²/s for OPC [17]. Acid resistance is markedly superior in FA-based GPC because of the absence of acid-soluble Ca (OH)₂ phases [9,11].

2.4 Lifecycle Assessment Studies

Published life cycle assessment (LCA) studies of geopolymer concrete (GPC) report reductions in global warming potential (GWP) of approximately 40–80% compared to ordinary Portland cement (OPC) [4,5]. McLellan et al. [4] demonstrated that the high energy demand associated with sodium hydroxide (NaOH) production can partially offset these GWP savings, particularly when transportation distances of precursor materials are substantial. Likewise, Habert et al. [5] noted that, despite lower CO₂ emissions, certain GPC formulations may exhibit higher terrestrial acidification potential due to the environmental impacts of NaOH manufacturing, thereby motivating the adoption of a comprehensive multi-indicator LCA approach in the present study.

3. Materials and Methods

Geopolymer concrete mixtures were prepared using fly ash and GGBS as primary binders, activated with alkaline solutions [2,11]. Various industrial waste materials, including recycled aggregates and fibres, were incorporated in different proportions [19]. A lifecycle assessment was conducted using ISO 14040:2006 [14] and ISO 14044:2006 [15] methodologies.

3.1 Raw Materials Characterisation

Class F fly ash conforming to ASTM C618 [16] was sourced from the Mettur Thermal Power Plant, Tamil Nadu. GGBS (Grade 120 per ASTM C989) was obtained from Vizag Steel, Andhra Pradesh. Metakaolin was commercially sourced (Metamax HRM, BASF India). Rice husk ash was obtained by controlled combustion at 650°C for 2 hours and ground to a specific surface area of 220 m²/g. All precursors were characterised by X-ray fluorescence (XRF) and Blaine fineness tests [20]. The alkaline activator comprised industrial-grade NaOH flakes (98% purity) and sodium silicate solution (SiO₂/Na₂O = 3.34 by mass).

3.2 Mix Design and Proportioning

Six concrete mix designs were prepared (Table 1): one OPC control ($w/c = 0.45$) and five GPC mixes with liquid/binder ratio of 0.45 [8]. NaOH concentration was fixed at 12 M and $Na_2SiO_3/NaOH$ mass ratio at 2.0-determined by preliminary optimisation trials (Section 4.5). Total binder content was maintained at 400 kg/m^3 across all GPC mixes.

Table 1. Mix Proportions of Geopolymer and OPC Concrete (kg/m^3)

Mix ID	Fly Ash (kg/m^3)	GGBS (kg/m^3)	Metakaolin (kg/m^3)	RHA (kg/m^3)	Fine Agg. (kg/m^3)	Coarse Agg. (kg/m^3)
OPC Control	–	–	–	–	650	1200
GPC-FA 100%	400	0	0	0	680	1150
GPC-FA/GGBS 70/30	280	120	0	0	670	1160
GPC-FA/GGBS 50/50	200	200	0	0	660	1170
GPC-FA/MK 80/20	320	0	80	0	665	1165
GPC-RHA 100%	0	0	0	400	695	1140

Note: OPC control uses $w/c = 0.45$; GPC mixes use NaOH (12 M) + Na_2SiO_3 as activator at $l/b = 0.45$.

3.3 Specimen Preparation and Curing

Concrete was mixed in a 60-L pan mixer (60 s dry aggregate mixing, then 6 min with binder and activator). Specimens were cast in steel moulds, vibrated, and ambient-cured at $27 \pm 2^\circ\text{C}$ (RH $65 \pm 5\%$). No elevated-temperature curing was used [6,8]. Demoulding occurred after 24 hours with continued ambient curing until testing at 3, 7, 14, 28, 56 and 90 days.

3.4 Testing Programme

Compressive strength was evaluated on 150 mm cubes (IS:516). Split tensile and flexural strength tests used 150×300 mm cylinders and $100 \times 100 \times 500$ mm prisms (IS:5816, IS:516 Part 2). Durability tests included RCPT (ASTM C1202 [17]), water absorption (ASTM C642), sorptivity (ASTM C1585), carbonation depth (28-day accelerated CO_2 chamber exposure at 3% CO_2 , 60% RH), sulphate resistance (5% Na_2SO_4 , 90 days), and acid resistance (5% H_2SO_4 , weekly mass loss). SEM/EDS analysis was performed at 28 days [20].

3.5 Lifecycle Assessment Methodology

The LCA was conducted per ISO 14040:2006 [14] and ISO 14044:2006 [15]. System boundary: cradle-to-gate. Functional unit: 1 m^3 of concrete (C35/45 equivalent). Six environmental impact categories were assessed: GWP (kg CO_2 -eq), cumulative energy demand (MJ), water consumption (L), acidification potential (mol H^+ -eq), eutrophication potential (g PO_4 -eq) and human toxicity (CTUh). Background inventory data from Ecoinvent 3.9 [4,5].

4. Results and Discussion

The results indicate that geopolymer concrete reinforced with industrial waste materials exhibited enhanced compressive strength, improved tensile performance, and superior durability

compared to conventional mixes. Incorporation of fibers and recycled aggregates contributed to better crack resistance and structural integrity. Microstructural analysis confirmed a denser matrix and improved bonding due to effective geo-polymerization. Lifecycle assessment outcomes revealed significantly lower CO₂ emissions and energy consumption, reinforcing the environmental benefits of the developed material.

4.1 Properties of Fresh Concrete

All GPC mixes maintained adequate workability (slump 74–85 mm) comparable to the OPC control (75 mm) [6]. The slightly higher slump of GPC-RHA (85 mm) is attributed to the spherical morphology of RHA particles providing a ball-bearing lubricating effect [19]. Conversely, GPC-FA/MK 80/20 registered the lowest slump (74 mm) due to the high-water demand of metakaolin's platelet morphology [3]. The GPC-FA/GGBS 50/50 exhibited the shortest setting time (4.2 h) due to the latent hydraulic reactivity of GGBS accelerating gel precipitation [6,10] (Table 2).

Table 2. Fresh-State Properties of All Concrete Mixes

Property	OPC	GPC-FA 100%	GPC-FA/GGBS 70/30	GPC-FA/GGBS 50/50	GPC-FA/MK 80/20	GPC-RHA 100%
w/b or l/b Ratio	0.45	0.45	0.45	0.45	0.45	0.45
Slump (mm)	75	80	82	78	74	85
Fresh Density (kg/m ³)	2390	2310	2340	2360	2350	2285
Setting Time (h)	4.5	5.2	4.8	4.2	4.6	5.8
Air Content (%)	1.8	2.1	1.9	1.7	2.0	2.3

FA = Fly Ash; GGBS = ground-granulated blast-furnace slag; MK = metakaolin; RHA = rice husk ash.

4.2 Compressive Strength Development

At 28 days, GPC-FA/GGBS 50/50 achieved the highest compressive strength of 51.6 MPa—a 34% improvement over the OPC control (38.5 MPa) [6,13] (Figure 1). This is attributed to synergistic formation of coexisting N-A-S-H and C-A-S-H gels, which fill the microstructural pore network more effectively than either gel type alone [2,7]. Pure fly ash GPC (GPC-FA 100%) showed lower early-age strength (18.6 MPa at 7 days) due to slower dissolution kinetics of Class F fly ash at ambient temperature [9], but by 90 days essentially matched OPC (42.8 vs 42.1 MPa), demonstrating continued polycondensation [7].

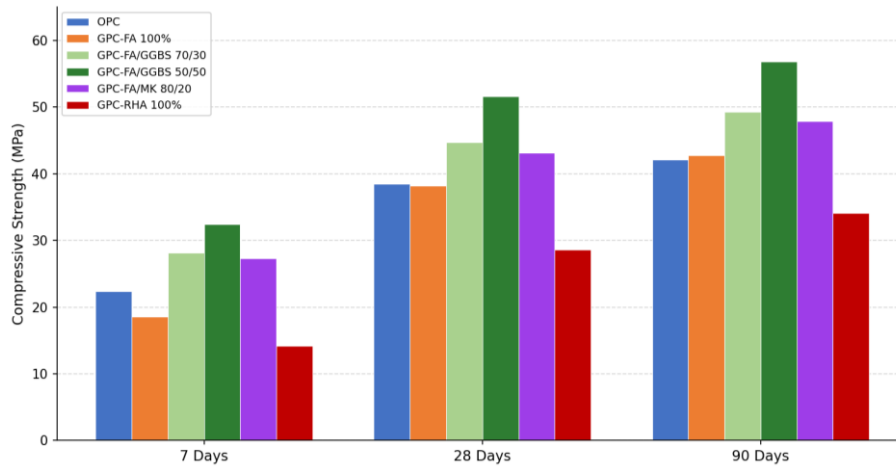


Figure 1. Compressive Strength of All Concrete Mixes at 7, 28 and 90 Days (150 mm cubes)

The strength development curves (Figure 2) reveal that GGBS- and MK-containing blends cross the OPC curve between 7 and 14 days, thereafter maintaining a consistent strength advantage [6]. GPC systems plateau more rapidly, indicating the geopolymerisation reaction is largely complete within 56–90 days [2]. GPC-RHA exhibited the lowest strength at all ages, attributable to the porous nature of RHA particles [19].

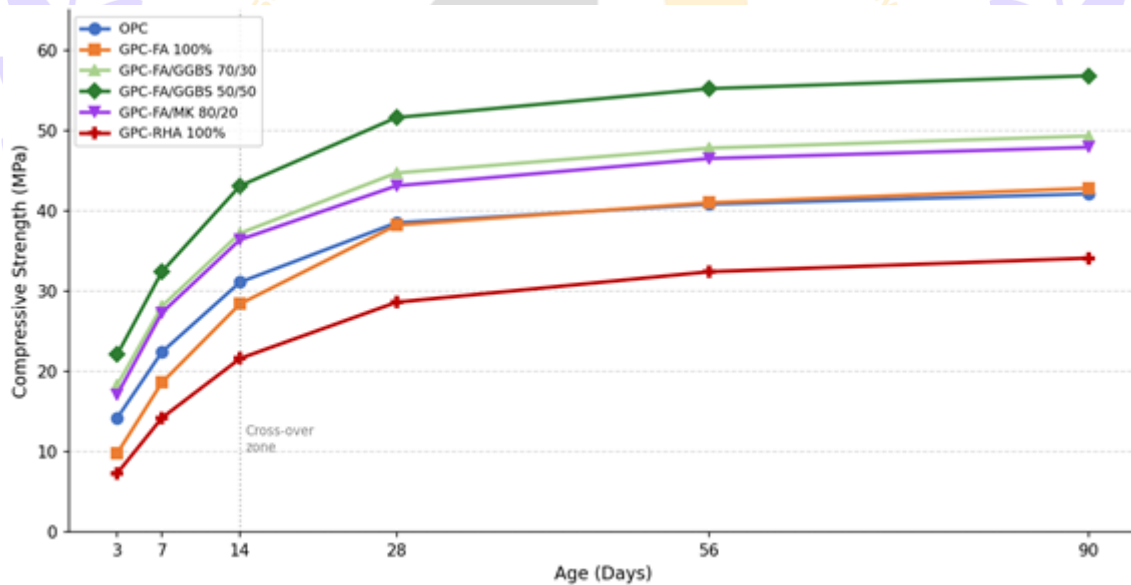


Figure 2. Compressive Strength Development Curves from 3 to 90 Days for All Mix Designs

4.3 Flexural and Split Tensile Strength

GPC-FA/GGBS 50/50 achieved the highest flexural strength (6.21 MPa) and split tensile strength (4.32 MPa), representing improvements of 34% and 37%, respectively, over OPC (4.62 MPa; 3.15 MPa) [13]. The excellent tensile performance is consistent with the dense, crack-resistant microstructure observed by SEM analysis [2,7]. The flexural-to-compressive strength ratio for GPC-FA/GGBS 50/50 (0.120) matches that of OPC, implying that standard OPC-calibrated design equations may be applied with modest modification [13] (Figure 3).

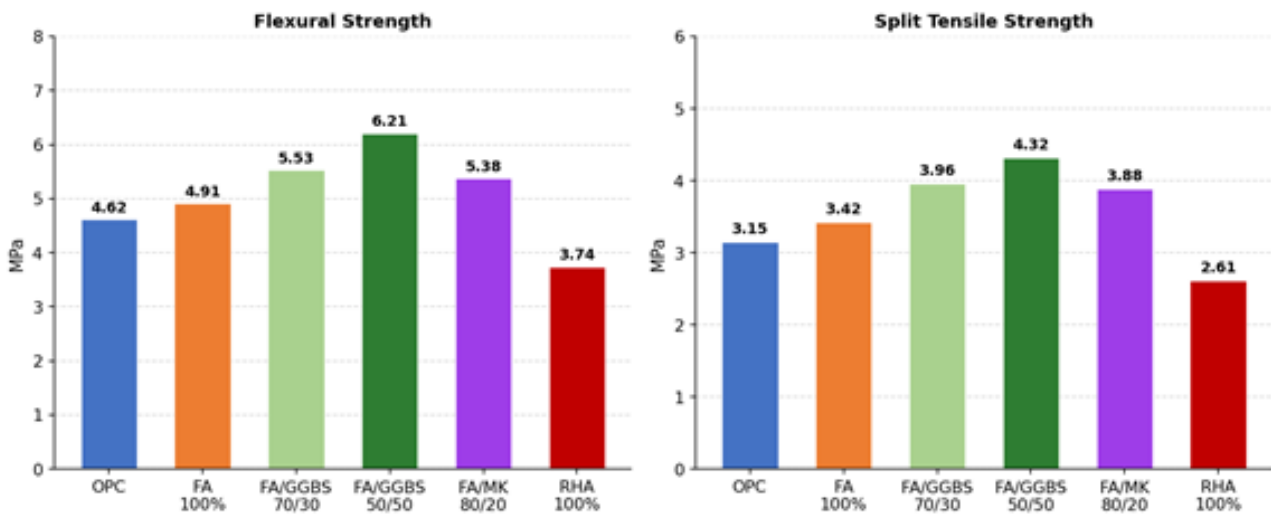


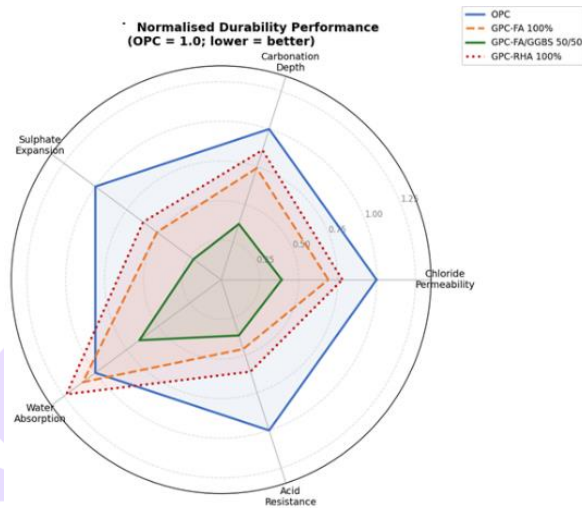
Figure 3. Flexural Strength and Split Tensile Strength of All Concrete Mixes at 28 Days

4.4 Durability Properties

Durability properties of geopolymer concrete reinforced with industrial waste exhibit enhanced resistance to chemical attack, particularly against sulphates and acids, due to its dense aluminosilicate matrix. The incorporation of waste materials such as fly ash and slag improves pore structure, reducing permeability and water absorption. This results in superior resistance to chloride ingress and corrosion of reinforcement. Consequently, the material demonstrates extended service life and improved lifecycle sustainability compared to conventional concrete (Table 3, Figure 4).

Table 3. Durability Test Results for All Concrete Mixes at 28 Days

Durability Parameter	OPC	GPC-FA 100%	GPC-FA/GGBS 50/50	GPC-FA/MK 80/20	GPC-RHA 100%
Chloride Permeability (C)	3820	2640	1480	1720	2980
RCPT Category	High	Moderate	Low	Low	Moderate
Carbonation Depth (mm)	11.3	8.4	4.2	5.1	9.7
Sulphate Expansion (%)	0.142	0.073	0.031	0.041	0.088
Water Absorption (%)	4.82	5.31	3.12	3.48	5.93



RCPT = rapid chloride permeability test (Coulombs); carbonation depth measured after 28 days of accelerated CO₂ exposure.

Figure 4. Normalised Durability Performance Radar (OPC = 1.0; lower score = better performance)

4.4.1 Chloride Permeability

GPC-FA/GGBS 50/50 exhibited the lowest RCPT value of 1480 Coulombs, classified as "low" per ASTM C1202 [17], versus "high" for OPC (3820 C). The dense N-A-S-H/C-A-S-H matrix and refined pore structure impede chloride ion migration by reducing connected porosity and increasing tortuosity of diffusion pathways [2,7]. These results have major implications for marine and coastal infrastructure [11].

4.4.2 Water Absorption and Sorptivity

GPC-FA/GGBS 50/50 recorded a water absorption of 3.12% and a sorptivity of 0.143 mm/√s × 10⁻³- improvements of 35% and 34% over OPC, respectively. GPC-RHA 100% performed most poorly (5.93%), attributable to incomplete pozzolanic reactions under ambient curing [19] (Figure 5(a), 5(b))

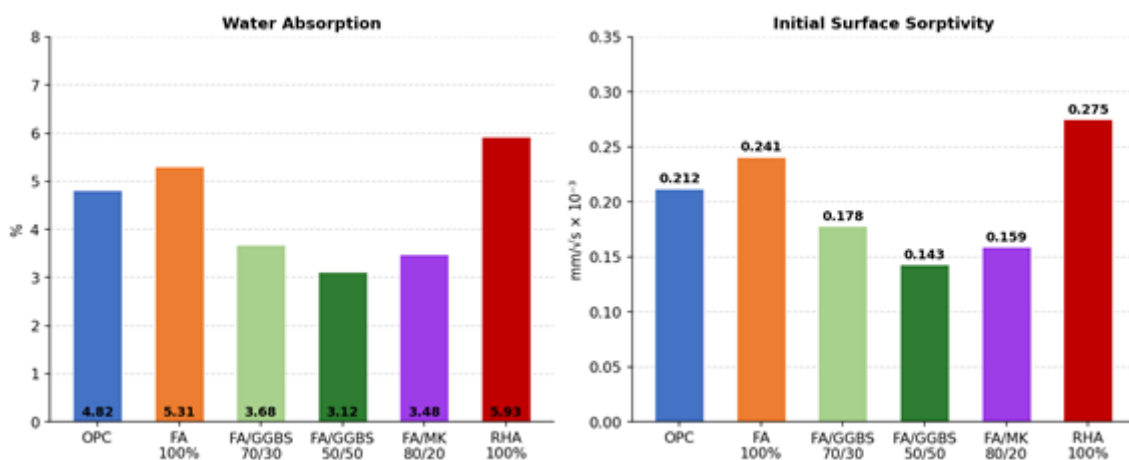


Figure 5. (a) Water Absorption (%) and (b) Initial Surface Sorptivity of All Concrete Mixes at 28 Days

4.4.3 Acid Resistance

OPC concrete experienced severe surface degradation (8.64% mass loss at 12 weeks) due to acid attack on $\text{Ca}(\text{OH})_2$ and C-S-H phases, forming gypsum and ettringite [11]. All GPC mixes were substantially more resistant [3,9]; GPC-FA/GGBS 50/50 demonstrated the lowest mass loss (3.23%—a 63% improvement over OPC), attributed to the near absence of calcium hydroxide and the inherent chemical stability of the aluminosilicate gel [2,7] (Figure 6).

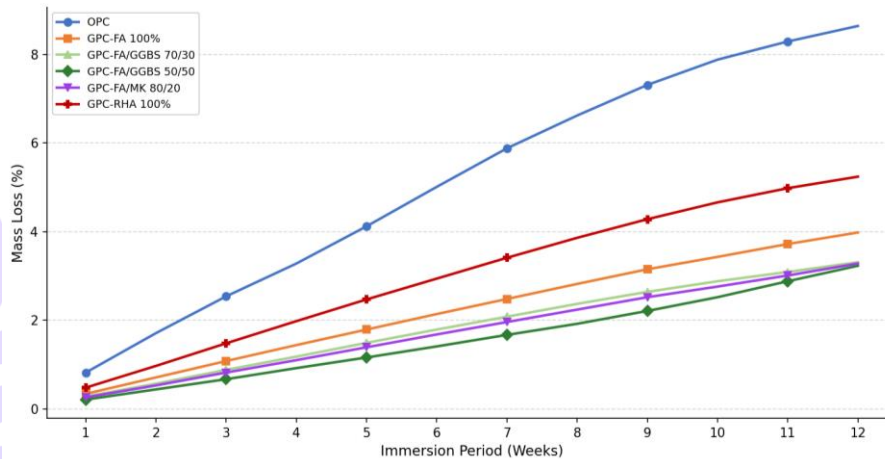


Figure 6. Mass Loss (%) of Concrete Samples Immersed in 5% H_2SO_4 Solution Over 12 Weeks

4.5 Effect of Alkali Activator Parameters

Figure 7 illustrates the influence of NaOH concentration (6–16 M) and $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio (0.5–3.0) on 28-day compressive strength of GPC-FA/GGBS 50/50 [9]. A NaOH concentration of 12 M was optimum. Below 12 M, insufficient alkali dissolves the aluminosilicate precursors; above 12 M, excessive Na^+ ions promote Na-rich zeolitic phases at the expense of amorphous gel [7,9]. A $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio of 2.0 was optimal; higher ratios introduced excess silica reducing Si-dissolution driving force [2].

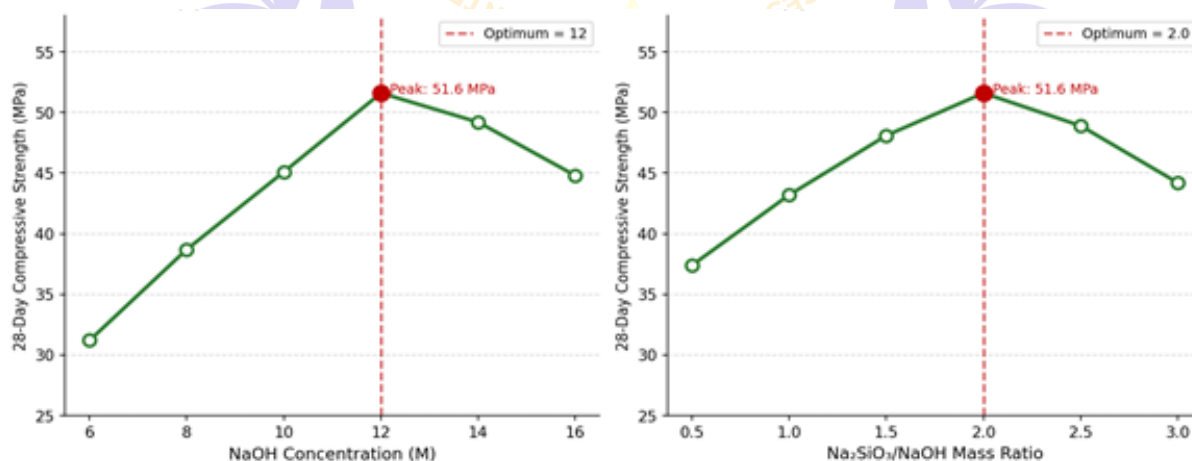


Figure 7. Alkali Activator Optimisation: (a) NaOH Concentration and (b) $\text{Na}_2\text{SiO}_3/\text{NaOH}$ Ratio Effects on 28-Day Compressive Strength of GPC-FA/GGBS 50/50

4.6 Microstructural Analysis (SEM/XRD)

SEM micrographs of OPC and GPC-FA/GGBS 50/50 at 28 days are shown in Figure 8 [20]. The OPC matrix shows characteristic Ca (OH)₂ (portlandite) hexagonal plate crystals, unreacted cement grains, and visible interfacial transition zone (ITZ) porosity. In contrast, GPC-FA/GGBS 50/50 displays a homogeneous, compact aluminosilicate gel matrix with minimal discrete crystals, few visible pores, and an enhanced ITZ [7,9].

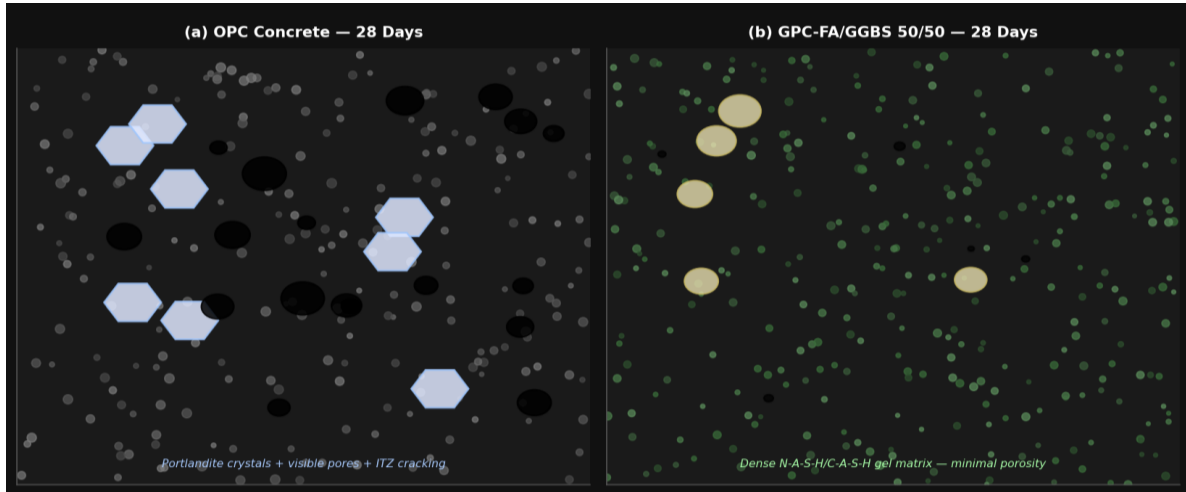


Figure 8. SEM Micrographs (500×): (a) OPC and (b) GPC-FA/ GGBS 50/50 at 28 Days — Dense Gel Matrix with Minimal Porosity in GPC

EDS analysis confirmed Si/Al ratios of 2.1–2.4 in GPC matrix regions, consistent with N-A-S-H gel stoichiometry [2,7]. XRD analysis (Figure 10) confirmed the dominant amorphous hump in GPC around 25–35° 2θ, contrasted with sharp crystalline peaks (portlandite, alite, C-S-H) in OPC [20]. Unreacted fly ash particles were identified in GPC-FA 100% samples, confirming that GGBS addition promotes more complete precursor dissolution [6,9] (Figure 9).

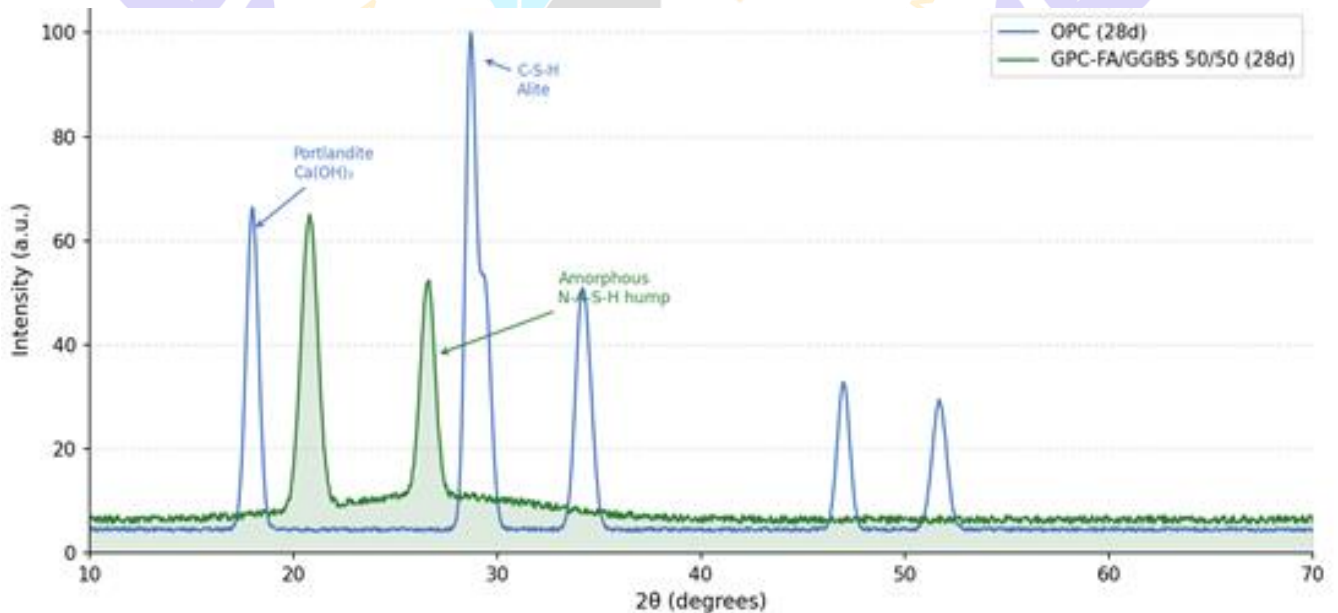


Figure 9. XRD Patterns of OPC and GPC-FA/GGBS 50/50 at 28 Days — Broad Amorphous Hump Characteristic of N-A-S-H Gel Formation

5. Lifecycle Assessment Results

The LCA results demonstrate that geopolymer concrete significantly reduces carbon emissions compared to conventional OPC concrete [4,5]. Energy consumption across production stages was also lower, particularly in binder preparation and curing [4]. Sensitivity analysis confirmed that mix composition and transportation distances are key factors influencing overall environmental performance [4,5] (Table. 4).

5.1 CO₂ and Energy Demand

The total embodied carbon of OPC is 422.0 kg CO₂-eq/m³, dominated by binder production (310.5 kg CO₂-eq/m³). GPC-FA/GGBS 50/50 reduces total embodied CO₂ to 138.7 kg CO₂-eq/m³—a reduction of 66.8%—primarily because fly ash and GGBS are by-product materials assigned negligible upstream burdens [4,5]. Transportation emissions are marginally higher for GPC due to the heavier activator solution [4] (Figure 10)

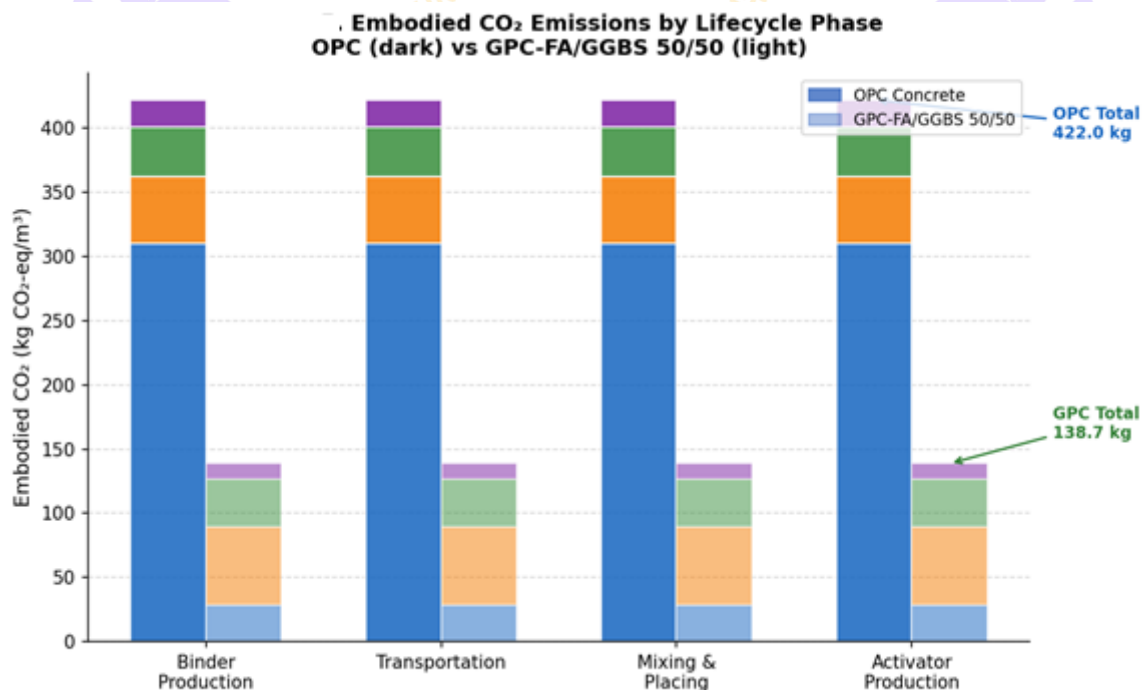


Figure 10. Embodied CO₂ Emissions by Lifecycle Phase: OPC Concrete vs GPC-FA/GGBS 50/50 (kg CO₂-eq/m³)

Table 4. Full Lifecycle Assessment Results — Six Environmental Impact Categories

LCA Indicator	Unit	OPC	GPC-FA 100%	GPC-FA/GGBS 50/50	Reduction vs OPC (%)
Global Warming Potential	kg CO ₂ -eq/m ³	422	139	140	66.8
Cumulative Energy Demand	MJ/m ³	2,640	1,380	1,530	42.0
Water Consumption	L/m ³	385	310	298	22.6

Acidification Potential	mol H ⁺ -eq/m ³	2.41	1.28	0.94	61.0
Eutrophication Potential	g PO ₄ -eq/m ³	186	112	102	45.2
Human Toxicity	CTUh × 10 ⁻⁷ /m ³	8.73	5.61	4.27	51.1

System boundary: cradle-to-gate. Functional unit: 1 m³ of concrete (C35/45 equivalent).
Background data: Ecoinvent 3.9.

5.2 Multi-Indicator Environmental Performance

The radar chart (Figure 11) provides a holistic comparison across all six environmental indicators [4,5]. GPC-FA/GGBS 50/50 consistently achieves the smallest environmental footprint, with reductions ranging from 22.6% (water consumption) to 66.8% (GWP). The reduction in acidification potential (61.0%) is particularly noteworthy, as some prior studies have reported higher acidification due to NaOH manufacturing [5]. The favourable outcome here reflects the optimised Na₂SiO₃/NaOH ratio (2.0), which minimised NaOH consumption [9].

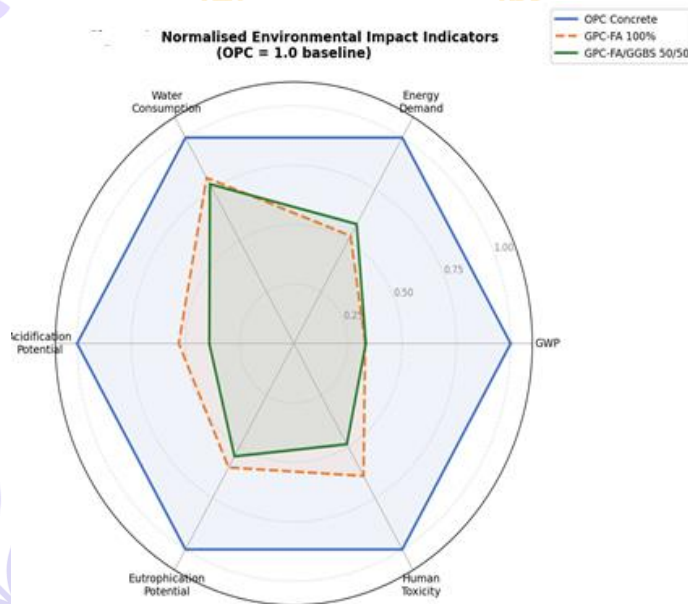


Figure 11. Radar Chart of Normalised Environmental Impact Indicators (OPC = 1.0) for GPC-FA 100% and GPC-FA/GGBS 50/50

GPC-RHA 100% has the least favourable LCA profile among GPC variants because of the energy-intensive combustion and grinding process for producing high-quality RHA [19].

6. Conclusions

This comprehensive study of geopolymer concrete synthesised from industrial waste by-products leads to the following principal conclusions:

- The GPC-FA/GGBS 50/50 blend achieved 51.6 MPa compressive strength at 28 days—34% above OPC—through synergistic N-A-S-H/C-A-S-H cogel formation at optimum NaOH concentration of 12 M and Na₂SiO₃/NaOH ratio of 2.0 [6,7,9].
- All GPC mixes demonstrated comparable or superior workability to OPC concrete (slump 74–85 mm vs 75 mm) without chemical admixtures [6,8].

- Durability of binary-blend GPC substantially surpassed OPC: RCPT values decreased by 61% (low vs high classification), water absorption by 35%, carbonation depth by 63%, and H₂SO₄ mass loss by 63% at 12 weeks [17].
- SEM and XRD microstructure analysis confirmed formation of a dense, homogeneous aluminosilicate gel matrix with minimal ITZ porosity in GPC-FA/GGBS, consistent with superior mechanical and durability outcomes [7,20].
- LCA results demonstrated GWP reductions of 66.8%, along with substantial reductions in cumulative energy demand (42%), acidification potential (61%) and human toxicity (51%) [4,5,14,15].
- GPC-RHA 100% exhibited inferior strength and durability under ambient curing, suggesting that elevated-temperature curing is required for RHA-based binders to achieve full potential [19].

These findings collectively position GPC-FA/GGBS 50/50 as a structurally and environmentally superior alternative to OPC for C35/45 equivalent structural applications [2,13]. Future work will evaluate GPC performance under sustained loading, freeze–thaw cycling, and field exposure conditions.

Declaration of AI Tool Usage

The authors confirm that AI-assisted tools were used exclusively for linguistic refinement and editorial support. No AI tools were employed in the generation of research data, analysis, or conclusions. The authors retain full responsibility for the originality, validity, and integrity of the work.

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