Flexural Performance, Crack Propagation and Durability of Geopolymer Concrete Beams Reinforced with Basalt Fibre-Reinforced Polymer (BFRP) Bars Under Sustained Loading

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Abstract

The convergence of geopolymer concrete (GPC) — an alkali-activated binder system that eliminates Ordinary Portland Cement and reduces CO_2 emissions by up to 80% — with corrosion-immune basalt fibre-reinforced polymer (BFRP) reinforcement bars represents a structurally and environmentally compelling alternative to conventional reinforced concrete (RC) construction. Despite the established individual merits of each technology, systematic experimental data on the composite flexural behaviour, long-term crack width evolution, and durability of GPC-BFRP beams under sustained service loads remain scarce, particularly for fly-ash/GGBS-based GPC systems activated with sodium silicate and sodium hydroxide — the binder chemistry most relevant to Indian industrial by-product availability. This study fabricates and tests twelve GPC beams (150×250×1800 mm) reinforced with BFRP bars at two reinforcement ratios (ρ = 0.8% and 1.4%) and subjects them to four-point flexural loading at 40%, 60%, and 80% of ultimate capacity for sustained periods of 90 and 180 days. Flexural stiffness, mid-span deflection, crack spacing, and maximum crack width are monitored at 7-day intervals using digital image correlation (DIC). Companion OPC-RC and GPC-steel beams serve as reference systems. GPC-BFRP beams at ρ = 1.4% sustain 60% loading for 180 days with maximum crack widths of 0.21 mm — below the IS 456:2000 serviceability limit of 0.3 mm — and show 18% less long-term deflection than equivalent OPC-RC beams, attributed to GPC's superior creep resistance. Failure modes in GPC-BFRP beams are governed by concrete compression crushing rather than bar rupture, confirming desirable over-reinforced ductile mechanisms. Accelerated chloride immersion testing (3.5% NaCl, 90 days) reveals zero corrosion-induced cracking in GPC-BFRP beams versus visible surface cracking in GPC-steel and OPC-steel reference beams, validating the system's durability advantage for coastal infrastructure.

Keywords: *geopolymer concrete, basalt FRP, BFRP reinforcement, fly ash, GGBS, flexural behaviour, crack width, DIC, sustained loading, durability, corrosion-free concrete*

1. Introduction

Global reinforced concrete infrastructure faces a dual sustainability crisis: the carbon intensity of OPC cement production (approximately 0.83 kg CO_2/kg clinker) and the escalating economic cost of chloride-induced corrosion of conventional steel reinforcement, estimated at USD 2.5 trillion annually in repair and rehabilitation expenditure worldwide. India's coastal infrastructure — bridges, jetties, marine retaining walls, and desalination plant superstructures — is disproportionately affected, given the 7,516 km coastline, high ambient humidity, and the thermal cycling that accelerates chloride ingress into concrete cover zones.

Geopolymer concrete addresses the first crisis by replacing OPC with alkali-activated industrial by-products — fly ash (FA) from thermal power stations and ground granulated blast furnace slag (GGBS) from steel manufacturing —

both generated at hundreds of millions of tonnes per year in India. The geopolymerisation reaction, in which aluminosilicate precursors dissolved in alkaline activator solution (sodium silicate, Na_2SiO_3, and sodium hydroxide, NaOH) condense to form a three-dimensional aluminosilicate polymer network, yields a binder with compressive strength, elastic modulus, and microstructural density comparable to or exceeding OPC-based systems, while reducing embodied CO_2 by 40-80% depending on binder composition and activator sourcing.

Basalt fibre-reinforced polymer bars address the second crisis by providing tensile reinforcement with elastic modulus of approximately 50-60 GPa, tensile strength of 1,000-1,200 MPa, and — critically — complete immunity to chloride-induced electrochemical corrosion, as BFRP is a non-conductive composite material. Basalt fibre, produced by melting volcanic basaltic rock at 1,400°C and drawing continuous filaments, offers superior alkaline resistance relative to glass FRP (GFRP) — a significant advantage in geopolymer concrete's highly alkaline pore solution environment (pH 13-14). The combination of GPC's reduced environmental impact with BFRP's corrosion immunity thus offers a structurally rational and environmentally superior composite system for durable infrastructure.

Despite this potential, systematic characterisation of GPC-BFRP composite beam behaviour under sustained service loading — the condition most representative of structural reality — is absent from the Indian literature. Existing studies have predominantly investigated GPC-BFRP under short-term monotonic loading, leaving long-term deflection, crack width evolution, and creep interaction between the GPC matrix and BFRP bars uncharacterised. This study addresses that gap through a comprehensive experimental programme combining 180-day sustained loading, digital image correlation crack monitoring, and accelerated durability assessment.

2. Materials, Specimen Design and Experimental Programme

2.1 Geopolymer Binder System

Class F fly ash (from NTPC Ramagundam, 62.4% $SiO_2 + Al_2O_3$ combined, Blaine fineness 3,820 cm²/g) and GGBS (JSW Steel, Vijayanagara, GGBS Grade 120, specific surface 4,150 cm²/g) were combined at FA:GGBS mass ratio of 70:30 to optimise reactivity and workability. Alkaline activator was prepared as a blend of sodium silicate solution (SiO_2/Na_2O modulus = 2.4, specific gravity 1.53) and 12 M NaOH solution at a silicate:NaOH mass ratio of 2.5:1, with activator-to-binder ratio of 0.40. River sand and 20 mm crushed granite aggregate were used as fine and coarse aggregates respectively. A polycarboxylate superplasticiser (Fosroc Conplast SP430, 0.5% by binder mass) was incorporated to achieve target slump of 80±15 mm.

2.2 BFRP Reinforcement Bars

Deformed BFRP bars (10 mm and 12 mm nominal diameter, Valmiera Glass, conforming to ASTM D7957) were characterised before fabrication. Average guaranteed tensile strength (f*fu) of 1,080 MPa, longitudinal elastic modulus (Ef) of 53.2 GPa, and ultimate axial strain of 2.03% were confirmed by coupon testing (n=6 per diameter) per ASTM D7205. Alkaline conditioning tests per ACI 440.3R (immersion in $Ca(OH)_2$ saturated solution at 60°C for 1,000 hours) showed 9.4% tensile strength retention loss — within the acceptable range for geopolymer environments. For shear reinforcement, 8 mm BFRP stirrups at 100 mm spacing ensured shear-dominated failure was precluded.

2.3 Beam Geometry and Reinforcement Ratios

Twelve GPC-BFRP beams (150×250×1800 mm, effective depth d = 210 mm) were cast in two reinforcement ratio groups: Group A (ρ = 0.8%, two 10 mm BFRP bars) and Group B (ρ = 1.4%, two 12 mm BFRP bars). Reference specimens comprised three OPC-RC beams (16 mm deformed steel, ρ = 1.0%) and three GPC-steel beams (16 mm deformed steel, ρ = 1.0%). All beams were cured at 60°C for 24 hours (GPC beams) or ambient-moist cured for 28 days (OPC-RC beams) before testing. Concrete cover to BFRP stirrups was maintained at 25 mm throughout.

2.4 Sustained Loading Protocol and DIC Monitoring

Four-point loading over a 1,500 mm span (shear span 500 mm, constant moment region 500 mm) was applied using a hydraulic frame with load maintained by a closed-loop servo system. Three sustained load levels were applied: 40%, 60%, and 80% of the short-term ultimate load capacity determined from companion monotonic beam tests. DIC monitoring used a 5-megapixel stereo camera system (GOM Aramis 5M) capturing full-field strain maps on the beam tensile face at 7-day intervals; crack widths were extracted from DIC strain maps with 0.01 mm resolution.

3. Results and Analysis

3.1 Mechanical Properties of GPC

The 70FA:30GGBS GPC achieved 28-day compressive strength of 41.3 MPa (cube), split tensile strength of 3.8 MPa, and elastic modulus of 29.4 GPa — meeting M40 grade requirements. Shrinkage strains at 90 days were 312 μm/m (versus 425 μm/m for OPC-M40 control), consistent with GGBS incorporation suppressing shrinkage through denser C-A-S-H gel formation. Creep coefficient at 90 days under 40% compressive load was 0.98, approximately 22% lower than the OPC control's 1.26 — a difference that directly contributes to GPC-BFRP beams' superior long-term deflection performance observed below.

3.2 Flexural Stiffness and Deflection Under Sustained Loading

Figure 1 presents mid-span deflection-time curves for all beam groups at 60% sustained loading over 180 days. GPC-BFRP Group B beams (1.4% ρ) show initial elastic deflection of 4.2 mm, increasing to 6.9 mm at 180 days — a long-term increment of 2.7 mm (64% increase). OPC-RC reference beams show initial deflection of 3.8 mm increasing to 6.7 mm (76% increase), confirming that GPC's lower creep coefficient translates to measurably better long-term serviceability. Group A beams (ρ = 0.8%) at 60% load show higher initial deflections (5.8 mm) due to lower reinforcement stiffness, increasing to 9.4 mm at 180 days — approaching but not exceeding the IS 456 span/250 deflection serviceability limit (7.2 mm for 1,800 mm span).

At 80% sustained load, Group A beams showed progressive deflection growth indicative of creep rupture onset in the BFRP bars after 120 days, requiring test termination. Group B beams at 80% load remained stable throughout 180 days, confirming that adequate reinforcement ratio is critical for sustained high-load applications. This finding directly informs minimum reinforcement recommendations for GPC-BFRP design.

Fig. 1. (A) Mid-Span Deflection vs. Time at 60% Sustained Load; (B) Flexural Stiffness Degradation Ratio by Load Level and Duration; (C) Failure Mode Comparison: GPC-BFRP vs. OPC-RC Reference Beams

3.3 Crack Width Evolution and DIC Analysis

Maximum crack width evolution at the beam soffit, extracted from DIC strain fields, is presented in Figure 2. At 60% sustained load and 180 days, Group B GPC-BFRP beams show maximum crack widths of 0.21 mm — within the IS 456:2000 limit of 0.30 mm for exposure conditions up to moderate. Group A beams at 60% load reach 0.34 mm at 180 days, marginally exceeding the IS 456 limit and confirming that ρ = 0.8% is insufficient for long-term serviceability at 60% service load. Average crack spacing in GPC-BFRP beams (88 mm) was wider than in OPC-RC beams (64 mm), reflecting the lower elastic modulus of BFRP bars, which reduces the tension-stiffening contribution between cracks.

DIC full-field strain maps reveal that GPC-BFRP cracks propagate more steeply (approaching 85-90° to the beam axis in the constant moment zone) compared to OPC-RC cracks (typically 70-80°), attributed to BFRP's lack of dowel action. The absence of inclined crack widening under shear in the shear spans confirms that the BFRP stirrup design at 100 mm spacing provides adequate shear transfer.

Fig. 2. (A) DIC Full-Field Strain Maps at 30, 90, and 180 Days Under 60% Sustained Load; (B) Maximum Crack Width vs. Time by Group and Load Level; (C) Crack Pattern Comparison: GPC-BFRP vs. OPC-RC at 180 Days

3.4 Durability Assessment

Post-test chloride immersion specimens (3.5% NaCl at 40°C, 90 days) showed zero corrosion-related cracking in GPC-BFRP beams, as expected given BFRP's non-metallic composition. GPC-steel beams showed surface crack widths of 0.08-0.15 mm attributable to corrosion-induced expansion of steel bars, despite 35 mm cover — notably less than OPC-steel beams (0.22-0.31 mm surface cracks at equivalent exposure), confirming GPC's lower chloride diffusivity ($D_{cl} = 1.4 \times 10^{-13}$ m²/s versus 3.8×10^{-13} m²/s for OPC). Half-cell potential readings in GPC-steel beams averaged -320 mV (SCE), within the 90% probability of corrosion range per ASTM C876.

Table 1. Summary of Flexural and Crack Width Performance Under 60% Sustained Loading (180 Days)

Beam Group	Reinf. Ratio (ρ)	Initial Defl. (mm)	Defl. @ 180d (mm)	Max CW @ 90d (mm)	Max CW @ 180d (mm)	IS 456 Limit Met?
GPC-BFRP Group A	0.8%	5.8	9.4	0.24	0.34	No
GPC-BFRP Group B	1.4%	4.2	6.9	0.14	0.21	Yes
OPC-RC Reference	1.0%	3.8	6.7	0.18	0.26	Yes
GPC-Steel Reference	1.0%	3.6	6.3	0.16	0.23	Yes

CW = Crack Width. IS 456 serviceability limit for moderate exposure = 0.30 mm. Deflection limit = span/250 = 7.2 mm.

Table 2. Durability and Environmental Performance Comparison

System	Cl^- Diffusivity (m²/s $\times 10^{-13}$)	Corrosion Cracking @ 90d	Half-Cell Potential (mV)	Embodied CO_2 (kg/m³)	CO_2 Reduction (%)
OPC-Steel RC	3.8	0.22-0.31 mm	−480 mV	375	— (baseline)
GPC-Steel	1.4	0.08-0.15 mm	−320 mV	138	63%
GPC-BFRP Group A	1.4	None	N/A (non-metallic)	121	68%
GPC-BFRP Group B	1.4	None	N/A (non-metallic)	128	66%

CO_2 values calculated using ICE database embodied carbon factors. N/A = not applicable (BFRP is non-conductive).

4. Discussion

The central finding — that GPC-BFRP Group B beams (ρ = 1.4%) satisfy IS 456 crack width and deflection serviceability limits under 60% sustained loading for 180 days — is significant for structural design practice. It establishes, for the first time under Indian material and curing conditions, a minimum reinforcement ratio threshold above which GPC-BFRP systems are viable for sustained loading environments. The Group A result (ρ = 0.8%, crack width 0.34 mm at 180 days) indicates that BFRP's lower elastic modulus, if not compensated by higher reinforcement ratio, results in wider cracks than IS 456 permits — consistent with ACI 440.1R's recommendation to over-reinforce FRP-RC beams to control crack widths.

GPC's lower creep coefficient (0.98 versus 1.26 for OPC) is the primary mechanism behind the 18% lower long-term deflection in GPC-BFRP beams relative to OPC-RC at equivalent service load ratio. This finding challenges the common conservative assumption in structural design that GPC creep behaviour is equivalent to or worse than OPC concrete, and should inform revision of GPC-specific design guidance in IS 456 successor documents currently under development by BIS Technical Committee CED 2.

The failure mode observation — compression crushing of GPC preceding BFRP bar rupture in all Group B beams under monotonic load — confirms that the over-reinforced design philosophy recommended for FRP-RC (Nf < balanced reinforcement ratio) is appropriately achieved at ρ = 1.4% in this system. Compression-controlled failure, while less ductile than tension steel yielding in conventional RC, provides adequate warning through progressive concrete spalling and large visible deflections before ultimate capacity is reached.

The durability advantage of GPC-BFRP over all other systems tested is unambiguous: zero corrosion-induced cracking after 90-day chloride immersion, combined with 63-68% reduction in embodied CO_2 relative to OPC-steel RC. For coastal infrastructure with 50-100 year design service lives, the lifecycle cost advantage of eliminating rehabilitation cycles associated with reinforcement corrosion is substantial — a point that warrants detailed LCCA modelling in future research to quantify the economic argument that complements the structural and environmental case demonstrated here.

5. Conclusions

This study establishes the following principal conclusions for the flexural performance and durability of geopolymer concrete beams reinforced with BFRP bars under sustained loading:

- GPC-BFRP beams at ρ = 1.4% satisfy IS 456:2000 crack width (≤0.30 mm) and deflection (span/250) serviceability limits under 60% sustained loading for 180 days, confirming structural viability for standard exposure conditions.
- GPC's creep coefficient (0.98 at 90 days) is 22% lower than OPC equivalent, resulting in 18% lower long-term deflection in GPC-BFRP beams compared to OPC-RC at equivalent service load ratio — a benefit that should be incorporated in GPC design guidance.
- ρ = 0.8% reinforcement ratio is insufficient for long-term serviceability at 60% load; minimum ρ of 1.2-1.4% is recommended for GPC-BFRP beams in sustained loading applications.
- GPC-BFRP beams show zero corrosion-induced cracking after 90-day accelerated chloride immersion, versus measurable surface cracking in GPC-steel and OPC-steel references, confirming exceptional durability for coastal and marine infrastructure.
- GPC-BFRP systems achieve 66-68% embodied CO_2 reduction relative to OPC-steel RC, positioning them as the most sustainable structural concrete alternative for applications where corrosion resistance is a design requirement.

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