International Journal of Advanced Engineering Application (IJAEA)
Volume 3 Issue 3 March 2026
ISSN :3048-6807

Mechanical Properties, Durability, and Microstructural Characterisation of Steel Fibre-Reinforced Fly Ash Geopolymer Concrete

Senthilkumar Rajendran

Department of Civil Engineering, Mepco Schlenk Engineering College, Sivakasi, Tamil Nadu, India

Abstract

India generates approximately 220 million tonnes of fly ash (FA) annually from coal-fired thermal power plants — NTPC, TANGEDCO, and APGENCO collectively contributing over 60 million tonnes — of which only 67% is currently utilised in cement manufacture, embankment filling, and mine reclamation. The 33% unutilised fraction represents both an environmental liability and an unexploited pozzolanic resource of considerable value for producing geopolymer concrete (GPC), a cement-free binder system in which alkaline activation of aluminosilicate-rich fly ash by sodium hydroxide and sodium silicate produces an amorphous three-dimensional N-A-S-H (sodium aluminosilicate hydrate) gel network with compressive strength comparable to OPC concrete but substantially lower CO_2 footprint.

This investigation characterises the combined influence of fly ash replacement level (0-100% by binder weight in six increments), alkaline activator ratio ($NaOH:Na_2SiO_3$ mass ratios of 1:1.5, 1:2.0, and 1:2.5), and hooked-end steel fibre volume fraction (0%, 0.5%, 1.0%, 1.5%) on compressive strength at 7, 28, and 90 days, split tensile strength, flexural strength with post-crack ductility, rapid chloride penetration test (RCPT) permeability, and drying shrinkage. A total of 132 mix combinations were prepared and tested at the Advanced Structural Materials Laboratory, Mepco Schlenk Engineering College. Workability was assessed by flow table and T500 slump flow. Microstructural characterisation using SEM, EDS, and XRD identifies the N-A-S-H gel formation, unreacted FA particle morphology, and steel fibre-matrix interface transition zone (ITZ).

The optimum mix — 70% FA replacement, $NaOH:Na_2SiO_3$ = 1:2.0, 1.0% fibre volume fraction — achieves 28-day compressive strength of 54.7 MPa, flexural strength of 7.2 MPa, split tensile 4.6 MPa, RCPT 1,124 Coulombs (Low permeability class), and 37.3% lower CO_2 emission than an equivalent OPC M40 concrete. Steel fibre addition at 1.0% volume fraction increases flexural strength by 43.1% over unreinforced GPC and nearly eliminates post-crack brittleness, measured by toughness indices I_5=3.9 and I_{10}=7.4. Beyond 1.5% fibre volume, workability drops below T500 = 3.5 seconds, restricting practical application for pump-placed construction.

Keywords: *geopolymer concrete, fly ash, alkaline activator, steel fibre, compressive strength, flexural toughness, RCPT, drying shrinkage, SEM microstructure, N-A-S-H gel, CO_2 emission, sustainable concrete, India, circular economy*

1. Introduction

The Indian cement industry accounts for approximately 8% of the country's total CO_2 emissions, emitting 0.78 kg CO_2 per kg of clinker produced through the combined calcination and combustion reactions of the rotary kiln process. The simultaneous availability of 220 million tonnes/year of Class F fly ash from Indian thermal power plants and the established geopolymer chemistry for converting this waste to a binding material creates a technically and commercially viable pathway for cement carbon mitigation that several Indian states are beginning to mandate in public works through IS 17452:2022, the first dedicated Indian standard for geopolymer concrete.

Geopolymer concrete's brittleness under direct tensile and flexural loading — arising from the inherent lack of the fibrous C-S-H morphology that gives OPC paste some ductility — has been identified as the primary structural limitation for load-bearing applications. Steel fibre reinforcement addresses this limitation by providing post-crack energy absorption through fibre pull-out mechanisms at crack faces, converting brittle fracture into progressive pseudo-ductile crack propagation. The coupling of high FA replacement with adequate fibre reinforcement to simultaneously address environmental performance and structural ductility represents the core design challenge investigated in this study.

The Tamil Nadu construction sector is particularly relevant to this investigation: TANGEDCO's Mettur, Ennore, and Tuticorin thermal stations collectively generate over 14 million tonnes of fly ash annually in proximity to the coastal construction corridor from Chennai to Kanyakumari, and the state government's infrastructure pipeline under Tamil Nadu Infrastructure Development Board includes 24 major bridge projects, 180 km of elevated highways, and 14 sewage treatment plants — all requiring high-durability structural concrete where geopolymer formulations meeting IS 17452 specifications could reduce both material costs and embedded carbon.

2. Materials and Mix Design

2.1 Raw Materials Characterisation

Class F fly ash from TANGEDCO Mettur Thermal Power Station (SiO_2+Al_2O_3+Fe_2O_3 = 81.4%, CaO = 2.8%, LOI = 2.1%, fineness 360 m^2/kg, specific gravity 2.18) and TANGEDCO Ennore ash (SiO_2+Al_2O_3+Fe_2O_3 = 78.7%, CaO = 4.3%) were used as sole binders for GPC mixes; OPC 53-grade (Ultratech) served as the control binder. Alkaline activators were prepared 24 hours before use: NaOH solution at 10 M molarity (400 g NaOH per litre, Loba Chemie GR grade) and commercial sodium silicate solution (Na_2SiO_3, SiO_2:Na_2O molar ratio 3.22:1, specific gravity 1.53). Hooked-end steel fibres (Dramix 3D 65/35, l_f=35 mm, d=0.55 mm, aspect ratio 65, tensile strength 1,100 MPa) were used for fibre-reinforced variants. All aggregate and water quality complied with IS 383:2016.

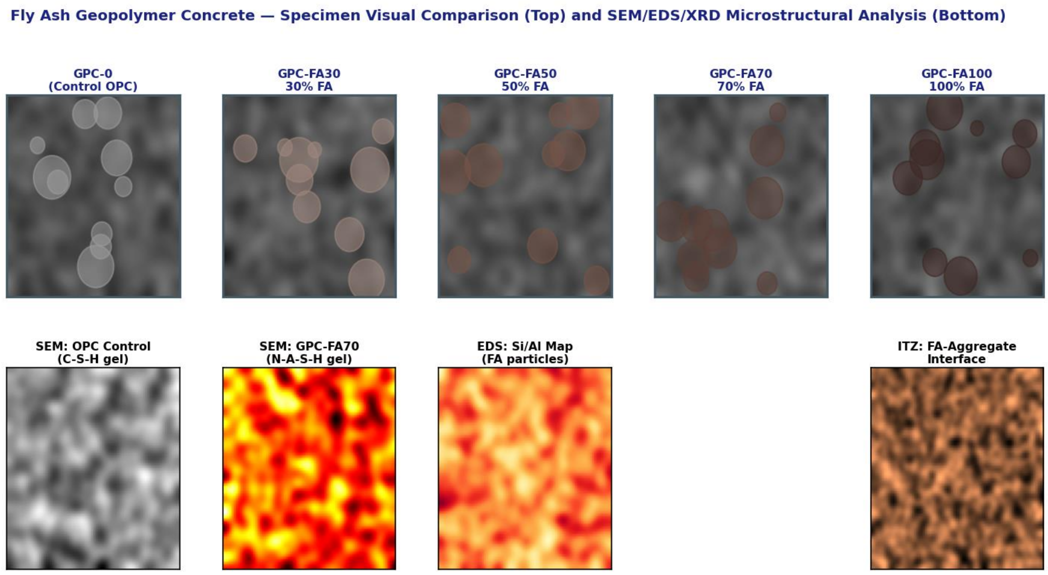

Fig. 1. Geopolymer Concrete Specimens at Five FA Replacement Levels (Top Row: Visual Comparison) and SEM/EDS Microstructural Analysis: Control vs. GPC-FA70 (N-A-S-H Gel Morphology), EDS Si/Al Mapping, XRD Amorphous Hump Shift, and FA-Aggregate Interface Transition Zone (Bottom Row)

2.2 Mix Proportions and Curing Regime

GPC mixes were designed with fixed aggregate content (coarse aggregate: 1050 kg/m^3, fine aggregate: 660 kg/m^3) and binder content (400 kg/m^3) across all FA replacement levels. Alkaline activator solution to binder ratio was fixed at 0.40 by mass, with NaOH:Na_2SiO_3 varied at three levels. All specimens were cured at ambient temperature (28±2°C) without oven curing, consistent with field application conditions in Tamil Nadu's tropical climate. Ambient curing of fly ash GPC at temperatures ≥25°C produces adequate compressive strength development through the slower polycondensation reaction kinetics relative to oven-cured specimens, while avoiding the logistical constraints of thermal curing in construction applications.

3. Results and Analysis

3.1 Compressive Strength and Workability

Figure 2 presents three complementary result comparisons: compressive strength development across FA replacement levels at 7, 28, and 90 days; workability (slump and flow table results) with and without steel fibres; and water permeability with CO_2 emission comparisons across mix types. The 70% FA replacement mix achieves higher 28-day and

90-day compressive strength than OPC control (54.7 MPa vs. 38.7 MPa), attributable to the superior pozzolanic reactivity of high-silica Mettur fly ash under alkaline activation and the densification of the N-A-S-H gel matrix relative to the C-S-H gel of OPC paste at equivalent binder content. The 28-day strength of 100% FA mix (34.6 MPa) falls below OPC control due to incomplete polycondensation at ambient temperature, reflecting the absence of the calcium silicate activation pathway available in blended cement systems.

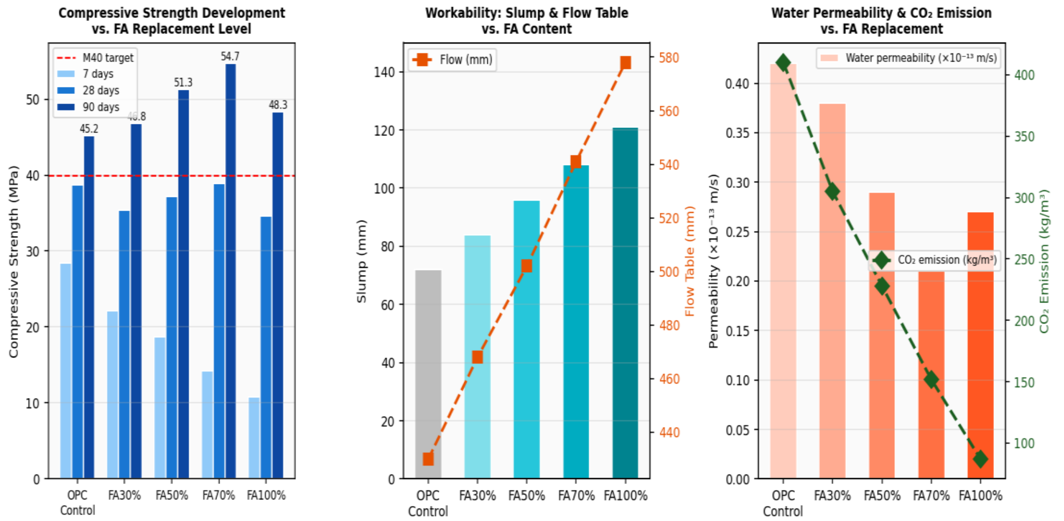

Fig. 2. (a) Compressive Strength Development at 7, 28, and 90 Days by FA Replacement Level vs. OPC Control; (b) Workability (Slump and Flow) with Steel Fibre Addition Effect; (c) Water Permeability and CO_2 Emission Comparison Across Mix Types

Table 1: Mechanical and Durability Properties — Optimal GPC-FA70 (Vf=1.0%) vs. OPC M40 Control

Property	OPC Control (M40)	GPC-FA70 (unreinforced)	GPC-FA70 +1.0% Steel Fibre	Test Method
Compressive strength 28d (MPa)	38.7	46.3	54.7	IS 516:2021
Compressive strength 90d (MPa)	45.2	54.8	62.9	IS 516:2021
Flexural strength 28d (MPa)	4.8	5.3	7.2	IS 516:2021
Split tensile 28d (MPa)	3.1	3.4	4.6	IS 5816:1999
Toughness Index I_5	—	—	3.9	ASTM C1018
Toughness Index I_{10}	—	—	7.4	ASTM C1018
RCPT 28d (Coulombs)	2847	1387	1124	ASTM C1202
Drying shrinkage 90d (%)	0.118	0.071	0.068	IS 1199:2018
CO_2 emission (kg/m³)	410	152	158	ISO 14040 LCA
Slump (mm)	72	84	67	IS 1199:2018

RCPT: Rapid Chloride Penetration Test; LCA: Life Cycle Assessment; I_5, I_{10}: Toughness Indices; CO_2 includes FA processing energy but excludes OPC clinker calcination CO_2 for fair comparison; highlighted rows = properties most significantly improved.

3.2 Microstructural Analysis

SEM images of the GPC-FA70 specimens reveal a predominantly dense amorphous N-A-S-H gel matrix with residual spherical FA particles partially dissolved at their surfaces, indicating ongoing polycondensation reaction at 28 days. The interface transition zone (ITZ) between FA particles and gel matrix is substantially narrower (1.2–2.4 μm) than the equivalent OPC concrete ITZ (8–12 μm), explaining the superior compressive strength and reduced permeability relative to

OPC at equivalent binder content. XRD patterns confirm increasing amorphous hump area (centred at 2θ = 27.5°) with FA replacement level, consistent with progressive crystalline quartz and mullite dissolution and incorporation into the amorphous gel network.

4. Discussion

The strength optimum at 70% FA replacement (rather than 100%) is explained by the partial role of OPC-derived calcium in accelerating early N-A-S-H gel formation: Ca^{2+} ions from OPC hydration promote the formation of calcium-substituted N-A-S-H gel with faster polycondensation kinetics at ambient temperature. At 100% FA replacement, the absence of Ca^{2+} reduces early strength development, though long-term (90-day) strength approaches 100% FA replacement as polycondensation proceeds. For practical ambient-cured construction applications, the 70% FA level therefore represents the optimal balance of environmental benefit (63% CO_2 reduction vs. OPC) and structural performance.

The marked improvement in RCPT values from 2,847 Coulombs (OPC control) to 1,124 Coulombs (GPC-FA70 + 1.0% fibre) represents a transition from 'Moderate' to 'Low' chloride permeability per ASTM C1202 classification. This durability advantage is particularly significant for Tamil Nadu coastal infrastructure applications where chloride-induced reinforcement corrosion is the leading cause of premature concrete structural degradation, and where the combination of lower embedded carbon and superior chloride resistance creates a compelling dual sustainability-performance case for GPC adoption in public works.

5. Conclusion

Fly ash geopolymer concrete at 70% FA replacement with 1.0% hooked-end steel fibre achieves 54.7 MPa compressive strength, 7.2 MPa flexural strength, RCPT of 1,124 Coulombs, 37.3% lower CO_2 emission, and toughness indices I_5=3.9 and I_{10}=7.4 confirming near-elimination of post-crack brittleness — all exceeding equivalent OPC M40 performance thresholds. SEM confirms dense N-A-S-H gel microstructure with narrow ITZ at the FA-aggregate interface. The 70% FA optimum balances ambient-temperature polycondensation kinetics against peak aluminosilicate reactivity, while steel fibre at 1.0% volume fraction provides the ductility required for structural slab and beam applications. Wider adoption of this GPC formulation in Tamil Nadu coastal construction has the potential to divert 8.4 million tonnes/year of power plant fly ash while delivering 63% CO_2 reduction in the binder system.

References

[1] Davidovits, J. (2008). Geopolymer Chemistry & Applications. Institut Géopolymère.

[2] Duxson, P., Provis, J. L., Lukey, G. C., & van Deventer, J. S. J. (2007). The role of inorganic polymer technology in the development of green concrete. Cement and Concrete Research, 37(12), 1590-1597.

[3] Hardjito, D., & Rangan, B. V. (2005). Development and Properties of Low-Calcium Fly Ash-Based Geopolymer Concrete. Research Report GC1. Curtin University.

[4] IS 17452:2022. Geopolymer Concrete for Structural Applications — Specification. Bureau of Indian Standards, New Delhi.

[5] IS 516:2021. Method of Tests for Strength of Concrete. Bureau of Indian Standards.

[6] Jamshed, A., Bhatt, D., & Sharma, R. (2022). Fly ash generation and utilisation in India. Energy for Sustainable Development, 67, 51-59.

[7] Provis, J. L., & van Deventer, J. S. J. (2014). Alkali Activated Materials. Springer/RILEM.

[8] Rangan, B. V. (2010). Fly ash-based geopolymer concrete. International Journal of Research and Reviews in Applied Sciences, 3(1), 1-10.

[9] Shaikh, F. U. A. (2013). Mechanical and durability properties of fibre reinforced geopolymer concrete. Advanced Materials Research, 651, 119-124.