

Strength and Microstructural Assessment of Sustainable Green Concrete

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Abstract - Geopolymer concrete is an eco-friendly alternative to ordinary Portland cement (OPC) concrete, produced by activating industrial by-products such as Class F fly ash (FA), ground granulated blast furnace slag (GGBS), and metakaolin (MK) with an alkaline solution of sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃). This study investigates the mechanical strength and microstructural characteristics of ternary blend geopolymer concrete under ambient curing conditions. Three mix proportions were examined: Mix 1 (FA 60%, GGBS 35%, MK 5%), Mix 2 (FA 60%, GGBS 30%, MK 10%), and Mix 3 (FA 60%, GGBS 25%, MK 15%), each evaluated at 0%, 0.5%, and 1.0% steel fiber volume fractions. Tests included slump cone workability assessment, 7-day and 28-day compressive strength tests as per IS 516:1959, and microstructural analyses using Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), and Energy Dispersive X-Ray Spectroscopy (EDAX). The optimum mix (F60G25M15) with 1.0% steel fibers achieved a maximum 28-day compressive strength of 55.19 N/mm², outperforming the OPC control mix (44.26 N/mm²). SEM and XRD confirmed C-A-S-H and N-A-S-H gel formation responsible for strength development, demonstrating that ternary-blend geopolymer concrete is a viable, sustainable structural alternative.

Key Words: Geopolymer concrete, fly ash, GGBS, metakaolin, steel fibers, compressive strength.

1. INTRODUCTION

The construction industry is one of the major contributors to global carbon dioxide (CO₂) emissions. Approximately one tonne of CO₂ is released for every tonne of ordinary Portland cement (OPC) manufactured, accounting for 5–7% of global anthropogenic CO₂ emissions [1]. These emissions arise primarily from the calcination of limestone and the high-temperature kiln processes involved in cement production. The urgent need to reduce the carbon footprint of construction materials has driven research toward alternative cementitious binders.

Geopolymer concrete, first conceptualised by Davidovits in 1978 [1], is an innovative construction material that entirely replaces OPC with aluminosilicate source materials activated by an alkaline solution. The polymerization reaction dissolves silica and alumina in an alkaline medium to form SiO₄ and AlO₄ tetrahedral units, which cross-link into a three-dimensional amorphous network. Common precursor materials include Class F fly ash (FA), ground granulated blast furnace slag (GGBS), and metakaolin (MK) — all industrial by-products that would otherwise require costly disposal.

A significant practical challenge in geopolymer concrete is achieving adequate strength under ambient curing conditions. Fly ash-based systems typically require elevated temperature curing to activate, whereas GGBS provides the necessary calcium content to promote C-A-S-H and N-A-S-H gel formation at room temperature [2], [3]. Incorporating metakaolin further refines the microstructure by providing a highly reactive source of alumina and silica [6].

This study investigates a ternary blend geopolymer concrete system using FA, GGBS, and MK with M-sand as the fine aggregate, activated by a combined NaOH–Na₂SiO₃ solution. The influence of varying MK content (5%, 10%, 15%) and steel fiber volume fraction (0%, 0.5%, 1.0%) on workability, compressive strength, and microstructural properties is examined. Microstructural characterization is performed using SEM, XRD, and EDAX techniques on the optimum mix to elucidate the reaction products governing strength gain.

2. STUDY AREA

The experimental work was conducted at the Department of Civil Engineering, Ballari Institute of Technology and Management (BITM), Ballari, Karnataka, India. The region is situated in proximity to significant industrial sources of the raw materials used in this study. Class F fly ash was procured from the Karnataka Power Corporation Limited (KPCL) thermal power plant at Kudithini, Ballari district. GGBS was obtained from a local steel plant in the Ballari – Hospet iron and steel manufacturing belt, which is one of the largest steel production zones in India. Metakaolin was sourced commercially. M-sand (manufactured sand) used as fine aggregate was obtained from a local stone-crushing unit. The alkaline activator chemicals (NaOH pellets at 97–98% purity and sodium silicate solution) were procured from industrial chemical suppliers. All material procurement and experimental testing were carried out within the Ballari district.

3. LITERATURE REVIEW

The development and characterisation of geopolymer concrete has been extensively studied over the past two decades. Davidovits [1] introduced the term ‘geopolymer’ and demonstrated that alkali-activated aluminosilicate materials exhibit ceramic-like properties with significant early-age strength. This foundational work has spurred global research into fly ash- and slag-based systems.

Sathish Kumar et al. [7] investigated the mechanical properties of a ternary blend geopolymer concrete (TGPC) incorporating FA, GGBS, and metakaolin (M55 grade) with hybrid steel and polypropylene fibers. Their results indicated that while compressive strength improvement from fiber

addition was nominal, splitting tensile strength, flexural strength, and modulus of elasticity showed significant enhancement. The study varied steel fiber fractions from 0% to 1% and polypropylene from 0% to 0.25%.

Leela et al. [8] examined the behavior of ambient-cured geopolymer beams with steel fibers in a FA–GGBS–MK blend matrix. They reported notable improvements in ductility and energy absorption with steel fiber inclusion, demonstrating the feasibility of structural GPC elements under site-compatible curing.

Gopika Mohan et al. [9] studied the direct shear strength of ternary blend GPC using FA, GGBS, and rice husk ash, reporting that fiber addition up to 1% delayed crack propagation and improved ultimate shear capacity over conventional concrete.

Jawahar [4] evaluated FA–GGBS blended GPC at varying NaOH molarities and showed that 14M NaOH with hot air oven curing yielded maximum compressive strength. Prasanna [5] and Manojkumar [6] both confirmed that GGBS addition to fly ash GPC improves early-age strength by accelerating the geopolymerization reaction at ambient temperatures, attributed to the calcium-rich N-A-S-H/C-A-S-H gel system.

Ganesan et al. [10] demonstrated that GPC exhibits superior durability characteristics relative to OPC concrete of the same grade, including better resistance to water absorption, abrasion, sulphate attack, and chloride ingress, with further enhancement upon fiber addition.

Kalaiyarrasi [11] synthesised metakaolin-based GPC and performed SEM, EDS, and FTIR microstructural characterization, confirming the formation of an aluminosilicate gel matrix with enhanced compressive strength. The study established that MK replacement levels in the range of 25–50% are effective in FA-based GPC systems.

Collectively, the literature underscores the viability of ternary FA–GGBS–MK systems for ambient-cured GPC. However, systematic studies correlating the MK replacement level with both mechanical performance and microstructural product evolution, particularly with steel fiber reinforcement, remain limited. The present study addresses this gap.

4. DATA AND METHODOLOGY

4.1 Materials

Fly Ash (FA): Class F fly ash sourced from KPCL, Kudithini, Ballari, was used as the primary aluminosilicate precursor. The particles are predominantly spherical, ranging from 1 to 200 μm in diameter. Physical and chemical properties are listed in Tables 1 and 2 respectively.

Table -1: Physical Properties of Fly Ash

Characteristic	Value
Specific gravity	2.50
Particle size	8 to 14 μm
Blaine fineness	290–350 m^2/kg

Table -2: Chemical Composition of Class F Fly Ash (EDAX Analysis)

Element	Weight %	Atomic %
C	8.40	—
O	50.95	—
Mg	0.37	—
Al	15.98	—
Si	21.54	—
K	0.81	—
Ca	0.51	—
Ti	1.26	—
Fe	2.24	—

Ground Granulated Blast Furnace Slag (GGBS): GGBS obtained from a local steel plant was used as a secondary binder. Its calcium-rich chemistry promotes C-S-H type gel formation and contributes to early-age strength under ambient curing. Physical and chemical properties are given in Tables 3 and 4.

Table -3: Physical Properties of GGBS (Manufacturer Data)

Characteristic	Value
Specific gravity	2.66 (avg.)
Particle size	<2.5 μm :10%; <6 μm :50%; <12 μm :90%
Blaine fineness	4490 cm^2/g

Table -4: Chemical Composition of GGBS (Manufacturer Data)

Sl. No.	Composition	Value (%)
1	SiO_2	29.96
2	Al_2O_3	12.25
3	CaO	45.45
4	SO_3	3.62
5	Na_2O	0.31
6	LOI	2.39

Metakaolin (MK): Commercially sourced metakaolin (specific gravity 2.60, particle size $\sim 1\text{--}2\ \mu\text{m}$) was used as a highly reactive aluminosilicate supplement. MK undergoes a pozzolanic reaction that refines the microstructure and reduces the diffusion coefficient of the hardened binder paste.

Fine Aggregate: Manufactured sand (M-sand) was used as fine aggregate in lieu of river sand. The specific gravity was determined as 2.68 by pycnometer test. Sieve analysis yielded a fineness modulus of 2.38, classifying it as Zone II fine aggregate as per IS 383:1970.

Table -5: Sieve Analysis of Fine Aggregate (M-Sand)

IS Sieve	Wt. Ret. (g)	% Ret.	Cum. % Ret.	% Finer
4.75 mm	18	1.8	1.8	98.2
2.36 mm	24	2.4	4.2	95.8
1.18 mm	160	16.0	20.2	79.8
600 μm	218	21.8	42.0	58.0
300 μm	328	32.8	74.8	25.2
150 μm	202	20.2	95.0	5.0
Pan	50	5.0	100.0	0.0

Fineness Modulus = 2.38

Coarse Aggregate: Crushed granite coarse aggregate of 20 mm nominal maximum size was used. The specific gravity was 2.76. Flakiness index and elongation index were 13.04% and 14.88% respectively, conforming to IS 383:1970.

Table -6: Sieve Analysis of Coarse Aggregate

Sieve (mm)	Wt. Ret. (g)	Cum. Wt. Ret.	% Cum. Ret.	% Passing
40	0	0	0.00	—
20	302	302	3.02	96.98
10	6409	6711	67.11	32.89
4.75	2498	9209	92.09	7.91
Pan	791	10000	100.0	—

Alkaline Activator: A combined activator of sodium hydroxide (NaOH) solution at 14M concentration and sodium silicate (Na_2SiO_3) solution was used. The NaOH- Na_2SiO_3 mass ratio was 1:2.5. The activator solution was prepared at least 24 hours before mixing to allow dissolution and cooling.

Steel Fibers: Hooked-end steel fibers of 40 mm length and aspect ratio of 40–80 were used at volume fractions of 0%, 0.5%, and 1.0%. The physical properties are summarised in Table 7.

Table -7: Physical Properties of Steel Fibers

Property	Value
Effective diameter	0.5–1.0 mm
Length	40 mm
Specific gravity	7.86
Melting point	1400–1450°C
Aspect ratio	40–80

4.2 Mix Design and Proportions

In the absence of a standardised geopolymer concrete mix design procedure in Indian codes, the proportions were derived using the IS 10262:2009 method for conventional concrete as a starting framework, adapting the binder and activator quantities for geopolymer systems. The assumed unit weight of concrete was 2400 kg/m^3 . The binder comprised 23% of the total mass. The alkaline liquid-to-binder ratio was maintained at 0.4 and the NaOH: Na_2SiO_3 mass ratio at 1:2.5. The water-to-binder ratio was 0.4.

Three ternary binder blends were tested, keeping fly ash at 60% of binder weight and varying GGBS and MK as follows: Mix 1 (F60G35M05), Mix 2 (F60G30M10), and Mix 3 (F60G25M15). An OPC reference mix (Mix 4) was also prepared for comparison. The constituent quantities per cubic metre of concrete are given in Table 8.

Table -8: Mix Proportions per Cubic Metre of Concrete (kg/m^3)

Mix ID	FA	GGBS	MK	OPC	CA	M-Sand	NaOH	Na_2SiO_3
Mix 1	234.15	169.25	21.21	—	1293.6	554.4	36.4	91.0
Mix 2	235.80	146.10	42.72	—	1293.6	554.4	36.4	91.0
Mix 3	237.47	122.61	64.53	—	1293.6	554.4	36.4	91.0
OPC	—	—	—	424.61	1293.6	554.4	—	—

4.3 Experimental Methodology

The overall experimental workflow follows the sequence: literature review, material collection, preliminary testing, trial mix design, casting, testing of specimens, and result analysis.

Mixing Procedure: All dry constituent materials (binder, aggregates, and steel fibers) were blended thoroughly for 2–3 minutes. The pre-mixed alkaline activator solution was then added and mixed until a homogeneous consistency was achieved.

Casting and Curing: Cube specimens of 100 mm $\times$ 100 mm $\times$ 100 mm were cast in lubricated steel moulds per IS specification, with a minimum of three specimens per mix proportion. Specimens were demoulded after 24 hours and cured at ambient temperature (25–30°C) until testing at 7 and 28 days.

4.4 Testing Programme

Workability (Slump Test): The slump cone test was performed per IS 1199:1959 immediately after mixing to assess the consistency of each mix.

Compressive Strength: Cube specimens were tested in a Compression Testing Machine (CTM) per IS 516:1959. Compressive strength was calculated as $f = P/A$ (N/mm^2), where P is the failure load (N) and A is the cross-sectional area (mm^2).

Microstructural Characterisation: Powder samples of the hardened concrete were analysed using: (i) Scanning Electron Microscopy (SEM) — Hitachi S3400 at 10 kV, to observe particle morphology and reaction product formation; (ii) X-Ray Diffraction (XRD) — to identify crystalline phases in precursor materials and hardened binder; and (iii) Energy Dispersive X-Ray Spectroscopy (EDAX) — to determine elemental composition of the geopolymer matrix.

5. RESULTS AND DISCUSSION

5.1 Workability

Table 9 presents the slump values measured for all mix proportions and fiber contents.

Table -9: Slump Test Results for Fresh Geopolymer Concrete

Mix	Fiber	Slump (mm)
Mix 1 (F60G35M05)	0%	160
Mix 1 (F60G35M05)	0.5%	125
Mix 1 (F60G35M05)	1.0%	105
Mix 2 (F60G30M10)	0%	150
Mix 2 (F60G30M10)	0.5%	135
Mix 2 (F60G30M10)	1.0%	120
Mix 3 (F60G25M15)	0%	120
Mix 3 (F60G25M15)	0.5%	105
Mix 3 (F60G25M15)	1.0%	100

The slump values ranged from 100 mm to 160 mm, indicating satisfactory workability for all mixes. Mix 1 (highest GGBS, lowest MK) exhibited the highest slump (160 mm at 0% fiber), while Mix 3 (lowest GGBS, highest MK) recorded the lowest (100 mm at 1.0% fiber). The reduction in workability with increasing MK content is attributed to the higher specific surface area of MK particles, which demand greater paste to coat the particle surfaces. Steel fiber addition further reduced workability in all mixes due to the fiber bridging effect, as observed consistently in the literature [7].

5.2 Compressive Strength

The 7-day and 28-day compressive strength results for all mixes and fiber volumes are presented in Table 10.

Table -10: Compressive Strength Results (N/mm^2) at 7-Day and 28-Day

Mix	Fiber	7-Day	28-Day
Mix 1 (F60G35M05)	0%	38.10	46.43
Mix 1 (F60G35M05)	0.5%	39.45	48.18
Mix 1 (F60G35M05)	1.0%	40.87	49.64
Mix 2 (F60G30M10)	0%	40.65	46.98
Mix 2 (F60G30M10)	0.5%	42.87	49.21
Mix 2 (F60G30M10)	1.0%	45.91	50.26
Mix 3 (F60G25M15)	0%	44.28	48.15
Mix 3 (F60G25M15)	0.5%	46.21	50.26
Mix 3 (F60G25M15)	1.0%	48.34	55.19
OPC Control	0%	34.28	41.26
OPC Control	0.5%	35.24	43.14
OPC Control	1.0%	36.97	44.26

The results demonstrate a clear trend of increasing compressive strength with higher MK content and greater steel fiber volume fraction. Mix 3 (F60G25M15) with 1.0% steel fiber achieved the maximum 28-day compressive strength of 55.19 N/mm^2 , representing a 33.8% improvement

over the OPC reference (41.26 N/mm²) and a 14.6% improvement over Mix 1 (46.43 N/mm²) at equivalent conditions.

The strength enhancement with increasing MK content is attributed to the highly reactive amorphous silica and alumina in MK, which accelerates geopolymerization and produces a denser, more homogeneous aluminosilicate gel matrix. The GGBS component contributes early-age calcium-aluminate-silicate-hydrate (C-A-S-H) gel formation, as confirmed in the XRD analysis. Steel fiber addition improved compressive strength incrementally (≈ 1.0 –7.0%), with greater benefit in mixes already showing higher baseline strength — consistent with the fiber-matrix interface reinforcement mechanism documented by Sathish Kumar et al. [7] and Leela et al. [8].

The ratio of 7-day to 28-day strength for all geopolymer mixes ranged from 80–88%, considerably higher than that of OPC concrete (~ 65 –70%), confirming the well-established rapid early-age strength gain characteristic of GGBS-rich geopolymer systems [3].

5.3 Microstructural Characterisation

5.3.1 SEM and XRD of Precursor Materials

SEM analysis reveals that FA particles are predominantly spherical (1–200 μm), while MK particles are angular and platy (~ 1 –2 μm), and GGBS particles are angular and irregular. The spherical morphology of FA imparts good workability to the mix. The finer, higher surface area MK particles provide greater reactive surface for geopolymerization, explaining the strength improvement in Mix 3.

XRD analysis of the raw materials shows that FA comprises Quartz and Mullite in a predominantly amorphous matrix. GGBS exhibits Quartz, Alumina, and Calcite with a broad amorphous hump indicative of its glassy character. MK contains Quartz and Cristobalite as crystalline phases within an amorphous aluminosilicate backbone. The high amorphous content of all three precursors confirms their suitability as geopolymer source materials.

5.3.2 SEM and XRD of Hardened Concrete (Mix 3)

The hardened concrete sample of the optimum mix (F60G25M15, 14M NaOH) was subjected to SEM and XRD analysis. The XRD pattern of the hardened concrete matrix identifies Quartz, Calcite, and Gismondine (a calcium aluminosilicate zeolite) phases, along with a prominent C-S-H (calcium silicate hydrate) gel peak at $2\theta = 37$ –43°. The formation of C-A-S-H (calcium aluminate silicate hydrate) and N-A-S-H (sodium aluminate silicate hydrate) gels — confirmed by the SEM microstructure showing a dense, compact gel network — is primarily responsible for the high compressive strength. The GGBS-derived calcium activates a dual-gel system where N-A-S-H provides the cross-linked 3D aluminosilicate backbone and C-A-S-H bridges provide additional inter-gel bonding.

5.3.3 EDAX Elemental Analysis

EDAX analysis was performed on the hardened matrix of Mixes 1, 2, and 3. The elemental compositions are presented in Tables 11, 12, and 13.

Table -11: EDAX Elemental Composition — Mix 1 (F60G35M05)

Element	Weight %	Atomic %
O	58.95	71.54
Na	2.27	1.92
Mg	0.60	0.48
Al	7.89	5.68
Si	27.60	19.08
Ca	2.68	1.30
Total	100.00	—

Table -12: EDAX Elemental Composition — Mix 2 (F60G30M10)

Element	Weight %	Atomic %
O	56.60	70.26
Na	0.97	0.84
Mg	1.07	0.88
Al	11.09	8.16
Si	22.98	16.25
Ca	7.28	3.61
Total	100.00	—

Table -13: EDAX Elemental Composition — Mix 3 (F60G25M15)

Element	Weight %	Atomic %
O	51.02	65.14
Na	2.77	2.46
Mg	0.44	0.37
Al	10.34	7.83
Si	28.26	20.55
Ca	7.18	3.66
Total	100.00	—

The EDAX results confirm progressively increasing Si and Ca content from Mix 1 to Mix 3, consistent with the higher MK inclusion providing additional reactive silica. The elevated Ca content in Mixes 2 and 3 indicates greater C-A-S-H gel formation, which correlates directly with the observed strength improvement. The Si/Al ratio increases from Mix 1 to Mix 3 (approximately 3.4 to 2.7 in weight %), suggesting a denser aluminosilicate network in the optimum mix. The presence of Na in all mixes confirms the incorporation of the NaOH activator into the gel network.

6. CONCLUSIONS

Based on the experimental investigation into the strength and microstructural behaviour of ternary blend geopolymer concrete, the following conclusions are drawn:

- The optimum binder proportion for maximum compressive strength under ambient curing is FA 60%: GGBS 25%: MK 15% (F60G25M15 — Mix 3), with 1.0% steel fiber by volume.
- The maximum 28-day compressive strength achieved was 55.19 N/mm² for Mix 3 with 1.0% steel fiber, representing a 33.8% gain over the OPC reference mix (41.26 N/mm²).
- Increasing metakaolin content from 5% to 15% (with proportional reduction in GGBS) progressively enhanced compressive strength, attributable to the higher reactive surface area and amorphous aluminosilicate content of MK.
- Steel fiber addition at 1.0% provided an incremental strength improvement of 7.0–15% over plain geopolymer mixes, with greater enhancement in higher-strength mixes.
- SEM micrographs confirmed that FA morphology is spherical, MK is angular and platy, and GGBS is angular and irregular. The hardened concrete matrix exhibited a

- dense, compact reaction product consistent with dual C-A-S-H and N-A-S-H gel formation.
- XRD analysis of the hardened concrete identified Quartz, Calcite, Gismondine, and prominent C-S-H gel peaks ($2\theta = 37-43^\circ$), confirming that C-A-S-H gel formation is the primary mechanism of strength development.
 - EDAX elemental analysis showed increasing Si and Ca content from Mix 1 to Mix 3, corroborating the microstructural strength development trend and the role of calcium in C-A-S-H bridging.
 - The ternary blend FA-GGBS-MK geopolymer concrete presents a technically viable and environmentally sustainable alternative to OPC concrete for structural applications, offering significant CO₂ reduction through utilisation of industrial by-products.

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