

Influence of Fly Ash on the Strength Properties of GGBS-Based Geopolymer Concrete

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Abstract - This study examines the effective utilisation of ground granulated blast furnace slag (GGBS) in the development of sustainable fly-ash-based geopolymer concrete (GPC). GGBS was used to replace fly ash by mass at 0%, 5%, 10%, 15% and 20%, and the resulting mixes were evaluated for workability and mechanical performance, including compressive strength, split tensile strength and flexural strength. Sodium hydroxide and sodium silicate solutions served as the alkaline activators, and specimens were cured under ambient conditions. The results show that the geopolymer concrete activated with a 10 M sodium hydroxide solution achieved the highest strength among the mixes tested, and that mechanical performance improved as the proportion of GGBS increased. The findings confirm that industrial by-products such as fly ash and GGBS can be combined to produce a mechanically sound and more sustainable alternative to ordinary Portland cement concrete.

Key Words: Fly ash, GGBS, geopolymer concrete, compressive strength, split tensile strength, flexural strength.

1. INTRODUCTION

Ordinary Portland cement (OPC) concrete remains the most widely used construction material worldwide, but cement manufacturing is a major contributor to global carbon dioxide emissions. Geopolymer concrete (GPC) has emerged as a promising alternative, offering comparable strength and durability while avoiding many of the environmental drawbacks associated with OPC. Geopolymer binders were first termed by Davidovits, who described them as inorganic aluminosilicate materials formed through the reaction of a source material with an alkaline solution, without the use of ordinary cement. In geopolymerisation, silicate and aluminate species in the source material dissolve in an alkaline medium and repolymerise into a three-dimensional network, a process that requires an activator solution rather than simple hydration.

To make construction more sustainable, industrial by-products such as fly ash, GGBS, red mud and metakaolin are increasingly used as cementitious or pozzolanic materials. Fly ash, a by-product of thermal power generation, typically requires elevated-temperature curing to achieve adequate geopolymerisation, which limits its practicality for ambient-cured applications. GGBS, a by-product of the steel industry generated during the quenching of molten iron slag, releases sufficient heat of reaction to support geopolymerisation at ambient temperature, and its inclusion alongside fly ash can

therefore improve early-age strength development without the need for oven curing. The relative proportions of fly ash and GGBS, together with the concentration and ratio of the alkaline activators, govern the fresh and hardened properties of the resulting geopolymer concrete.

1.1 Advantages of Geopolymer Concrete

- Lower creep compared with OPC concrete.
- Utilisation of industrial by-products such as fly ash and silica fume, reducing disposal-related environmental impact.
- Improved resistance to sulphate attack relative to OPC concrete.
- Lower drying shrinkage than OPC concrete.
- Cost-effectiveness for comparable performance levels.
- Reduced pore diameter (up to about 55% lower than OPC concrete), leading to lower permeability.
- Better resistance to acid attack and fire compared with OPC concrete.
- Reduced land-filling costs associated with disposal of fly ash and silica fume.

1.2 Limitations of Geopolymer Concrete

- Limited commercial availability and production infrastructure compared with conventional concrete.
- Higher initial cost owing to specialised raw materials and chemical activators.
- Variability in performance depending on the quality and consistency of the industrial by-products used.
- More demanding handling and mixing procedures because of the alkaline activators involved.
- Comparatively limited standardisation, with building codes not yet fully accommodating geopolymer concrete in many regions.
- Curing requirements, particularly for fly-ash-rich mixes, that can add to construction time.
- Slower adoption owing to limited familiarity among construction professionals and suppliers.

1.3 Objectives

- To characterise the morphology and chemical composition of fly ash and GGBS.
- To determine the optimum proportion of fly ash and GGBS for geopolymer concrete.
- To evaluate the fresh properties of fly-ash- and GGBS-based geopolymer concrete.
- To evaluate the mechanical properties of fly-ash- and GGBS-based geopolymer concrete.

2. LITERATURE REVIEW

Nath and Sarker [A] investigated geopolymer concrete in which GGBS replaced class-F fly ash at 10%, 20% and 30% levels, using 14 M sodium hydroxide and sodium silicate solutions at ratios of 1.5, 2.0 and 2.5. Eight mixes of geopolymer mortar and concrete were ambient-cured for 3, 7, 28 and 56 days, and the study concluded that GGBS could be used to replace fly ash by up to 30% without compromising performance.

Rao and Rao [1] developed geopolymer concrete using fly ash and GGBS as binder materials activated with 8 M sodium hydroxide and sodium silicate at a ratio of 2.5, examining FA-GGBS combinations of 70:30, 60:40 and 50:50 at binder-to-liquid ratios of 0.45, 0.50, 0.55 and 0.60 under both ambient and heat-cured conditions for 7 and 28 days. The results showed that 50% GGBS replacement gave the highest compressive strength at an alkaline-to-binder ratio of 0.5, consistently across the three binder contents examined (360, 420 and 450 kg/m³).

Parveen [4] studied fly-ash-based geopolymer concrete incorporating 10% alcofine, activated with 8 M, 12 M and 16 M sodium hydroxide and sodium silicate solutions at a ratio of 2.5, together with a sulphonate-based superplasticiser. The highest compressive, split tensile and flexural strengths were obtained at 16 M NaOH concentration; the study also found that increasing NaOH molarity improved mechanical strength but reduced workability, and recommended further durability testing.

Bellum and Karthikeyan [2] examined the influence of activator solution on the microstructural and mechanical properties of geopolymer concrete and found that a 70:30 fly-ash-to-GGBS mix achieved the highest 28-day compressive strength under ambient curing, while oven-cured specimens showed 4-15% lower strength than ambient-cured specimens across all hardened-property tests.

Reddy and Venkatesh [B] investigated the influence of red mud on fly-ash-based geopolymer concrete, replacing fly ash with red mud at 5%, 10%, 15% and 20% and using 8 M sodium hydroxide with sodium silicate-to-hydroxide ratios between 2.0 and 2.5, across eleven mixes including an OPC control, ambient-cured for 7, 14, 21 and 28 days. A 10% red-mud replacement combined with a 2.5 activator ratio produced the highest 28-day compressive strength among the mixes studied.

Taken together, the literature indicates that both the proportion of GGBS relative to fly ash and the concentration and ratio of the alkaline activator strongly influence the workability and strength development of geopolymer concrete, with ambient-cured, GGBS-modified fly ash mixes offering a practical route to sustainable, cement-free concrete.

[A], [B]: Full bibliographic details for these two studies (Nath and Sarker; Reddy and Venkatesh) were not present in the source project report and could not be verified against the numbered reference list below. Please supply the complete citations before submission.

3. MATERIALS AND METHODOLOGY

3.1 Fly Ash

The fly ash used in this study was sourced from the Raichur Thermal Power Station, Raichur district, Karnataka, and had a measured specific gravity of 1.70 (Table 1).

3.2 GGBS

GGBS was obtained from JSW and stored in air-tight bags prior to use, with a measured specific gravity of 2.80 (Table 1). Composition data indicated the presence of SiO₂, CaO, MgO and MnO.

Table -1: Specific gravity of fly ash and GGBS

Parameter	FA-1	FA-2	FA-3	GGBS-1	GGBS-2	GGBS-3
Empty bottle W1 (g)	621	621	621	30	30	30
Bottle+water W2 (g)	1160	1160	1160	84	84	84
Bottle+kerosene W3 (g)	2024	1198	2010	75	75	75
Bottle+binder W4 (g)	1675	1675	1675	43	40	44

Specific gravity of fly ash = 1.70; specific gravity of GGBS = 2.80.

3.3 Coarse Aggregate

Naturally occurring crushed/uncrushed stone was used as coarse aggregate. Material free from disintegrated particles, alkali contamination, flaky and elongated pieces was selected, in accordance with standard practice. The measured physical properties are given in Table 2.

Table -2: Physical properties of coarse aggregate

Property	Value
Water content	0.36%
Bulk density	1395 kg/m ³
Specific gravity	2.73
Fineness modulus	1.73
Flakiness index	16.48%
Elongation index	13.60%

3.4 Fine Aggregate

Clean, dry river sand passed through a 2.36 mm sieve to remove pebbles was used as fine aggregate. The saturated-surface-dry specific gravity of 2.67 corresponds to Zone II as per IS 383. Physical properties and sieve analysis results are given in Tables 3 and 4.

Table -3: Physical properties of fine aggregate

Property	Value
Water content	0.52%
Bulk density	1533 kg/m ³
Specific gravity	2.67

Table -4: Sieve analysis of fine aggregate

IS sieve (mm)	Wt. Ret. (g)	% Ret.	Cum. % Ret.	% Passing
4.75	0	0.0	0.0	100.0
2.36	22	2.2	2.2	97.8
1.18	224	22.9	24.6	75.4
0.600	318	31.8	56.4	43.6
0.300	312	31.2	87.6	12.4
0.150	75	7.5	95.1	4.9
Pan	19	1.9	97.0	3.0

Fineness modulus = 337.10 / 100 = 3.37.

3.5 Alkaline Activator Solution

The alkaline activator was a mixture of sodium hydroxide (NaOH, 98% purity pellets) and sodium silicate (Na₂SiO₃) solutions. The required molarity of NaOH solution was prepared by dissolving NaOH pellets in potable water and allowing the solution to stand at room temperature for 24 h before use. For an 8 M solution, 320 g of NaOH pellets (atomic weight 40) was dissolved in 1 L of water. Sodium silicate solution was then added in an amount 2.5 times the

mass of the NaOH solution to form the combined alkaline activator. Following Davidovits' recommendation, the sodium silicate and sodium hydroxide solutions were combined at least one day before mixing with the solid constituents to reduce bleeding and segregation in the fresh concrete.

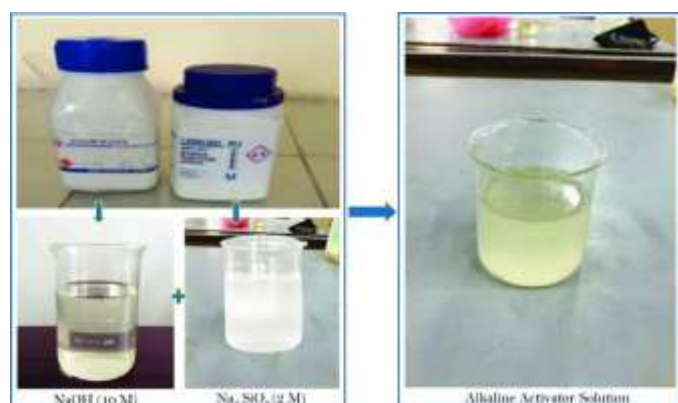


Fig -1: Preparation of the sodium hydroxide-sodium silicate alkaline activator solution

3.6 Research Methodology

The overall experimental methodology, from material collection through to mechanical testing, followed the sequence summarised below: collection of materials (fine/coarse aggregate and water; fly ash and GGBS; sodium silicate, sodium hydroxide and pellets) → combination of materials → assessment of fresh properties → mix design → casting of cubes with replacement of cement by mineral admixture (GGBS) → demoulding → testing and results (Fig. 2).

3.7 Mix Proportions

Five geopolymer concrete mixes were prepared with GGBS replacing fly ash by mass at 0%, 5%, 10%, 15% and 20% (designated FA100, FA95GB5, FA90GB10, FA85GB15 and FA80GB20). The mix proportions per cubic metre are given in Table 5.

Table -5: Mix proportions per cubic metre of geopolymer concrete

Mix ID	FA (kg)	GGBS (kg)	F.Agg (kg)	C.Agg (kg)	Activator (kg)
FA100	400	0	810	990	200
FA95GB5	380	20	810	990	200
FA90GB10	360	40	810	990	200
FA85GB15	340	60	810	990	200
FA80GB20	320	80	810	990	200

3.8 Mixing, Casting and Curing

Fresh geopolymer concrete was dark in colour and cohesive. Prolonged mixing of mixes with high water content led to bleeding and segregation, which in turn reduced hardened compressive strength; combining the sodium silicate and sodium hydroxide solutions one day in advance, as noted above, eliminated this effect. Dry materials were mixed for approximately three minutes, after which the liquid activator was added and wet mixing continued for a further four minutes. Cast-iron moulds were lightly oiled before casting, and the concrete was compacted using a table vibrator and finished with a trowel. Specimens were demoulded after 24 h and left to cure under ambient laboratory conditions until the day of testing. Representative stages of specimen casting and curing are shown in Fig. 7.

3.9 Test Methods

3.9.1 Compressive strength: Compressive strength was determined as the ratio of applied load to cross-sectional area at failure ($\sigma = F/A$), where σ is the stress (N/mm²), F is the applied load (N) and A is the cross-sectional area (mm²).

3.9.2 Split tensile strength: The indirect (splitting) tensile strength was determined on 100 mm diameter × 200 mm height cylinders in accordance with IS 5816:1999, using $f = 2P / (\pi d L)$, where P is the applied load (N), d is the specimen diameter (mm) and L is the specimen length (mm).

3.9.3 Flexural strength: Flexural strength (modulus of rupture) was determined using $f_b = 3Pl / (b d^2)$, where P is the peak load, l is the span length, and b and d are the width and depth of the specimen respectively, calculated to the nearest 0.05 MPa. Flexural strength is of particular relevance to pavement applications, where slabs must resist tensile stresses arising from wheel loading and from volume changes due to temperature and moisture variation.

4. RESULTS AND DISCUSSION

Note on activator molarity: the source project report states different NaOH molarities in different subsections below (10 M for workability and compressive strength; 8 M in the first sentence of 5.3 before switching to 10 M in the same paragraph; 12 M for flexural strength), without describing a multi-molarity test matrix elsewhere in the methodology. This inconsistency is reproduced faithfully from the source and should be checked against the original raw data / lab register before submission, since it is unclear which molarity actually corresponds to the tabulated results.

4.1 Workability

The slump of the 10 M geopolymer concrete mixes increased progressively as GGBS content increased from 0% to 20%, with measured slump values of 80, 95, 105, 110 and 120 mm for FA100 through FA80GB20 respectively (Table 6, Fig. 3), indicating improved workability with increasing GGBS content.

Table -6: Slump values of geopolymer concrete mixes

Mix	Slump (mm)
FA100	80
FA95GB5	95
FA90GB10	105
FA85GB15	110
FA80GB20	120

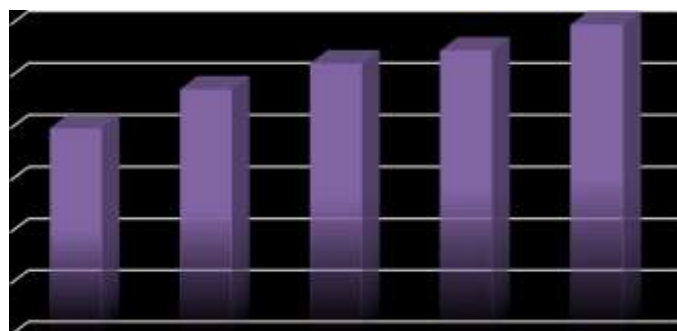


Fig -3: Slump values of geopolymer concrete mixes

4.2 Compressive Strength

The 7- and 28-day compressive strengths of the ambient-cured 10 M geopolymer concrete mixes are given in Table 7 and Fig. 4. Compressive strength increased with increasing GGBS content across the range examined. The 7-day compressive

strengths ranged from 26.80 to 38.90 MPa, and the corresponding 28-day strengths ranged from 42.41 to 54.65 MPa, across the FA100 to FA80GB20 mixes, with the target strength achieved even in the FA100 (0% GGBS) mix.

Table -7: Compressive strength of geopolymer concrete at 7 and 28 days

Mix	7 days (MPa)	28 days (MPa)
FA100	26.8	42.41
FA95GB5	29.2	46.65
FA90GB10	30.4	49.95
FA85GB15	34.8	51.25
FA80GB20	38.9	54.65

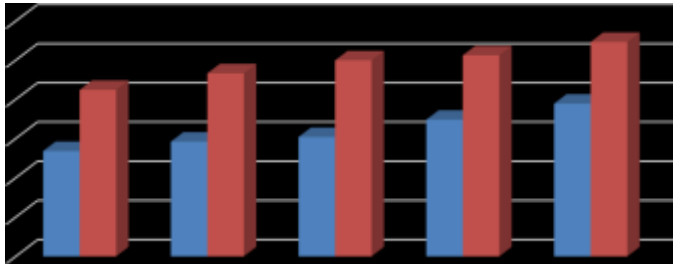


Fig -4: Compressive strength of geopolymer concrete at 7 and 28 days

4.3 Split Tensile Strength

The 28-day split tensile strength of the geopolymer concrete mixes followed a trend similar to that of compressive strength across the replacement levels examined (Table 8, Fig. 5). At 28 days, split tensile strengths of 4.40 to 5.31 MPa were recorded across the FA100 to FA80GB20 mixes.

Table -8: Split tensile strength of geopolymer concrete at 28 days

Mix	28 days (MPa)
FA100	4.4
FA95GB5	4.62
FA90GB10	4.81
FA85GB15	5.1
FA80GB20	5.31



Fig -5: Split tensile strength of geopolymer concrete at 28 days

4.4 Flexural Strength

The 28-day flexural strength results, summarised in Table 9 and Fig. 6, follow a trend similar to the compressive and split tensile strength results across all mixes examined. At 28 days, flexural strengths of 4.62 to 5.90 MPa were recorded across the FA100 to FA80GB20 mixes.

Table -9: Flexural strength of geopolymer concrete at 28 days

Mix	28 days (MPa)
FA100	4.62
FA95GB5	4.82
FA90GB10	4.96
FA85GB15	5.25
FA80GB20	5.9

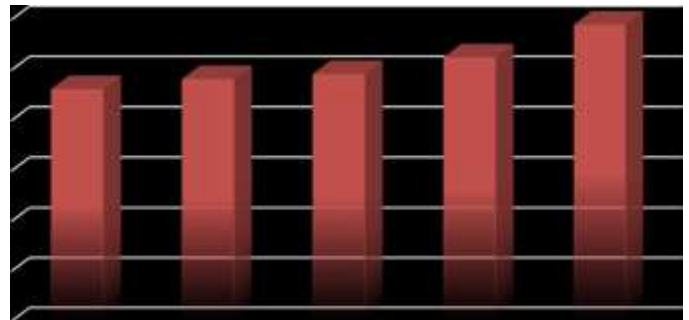


Fig -6: Flexural strength of geopolymer concrete at 28 days

4.5 Specimen Preparation and Testing

Representative photographs of specimen casting, curing and mechanical testing carried out during the experimental programme are shown in Figs. 7 and 8.



Fig -7: Preparation, casting and curing of geopolymer concrete specimens — material batching, mould preparation and cube casting



Fig -8: Specimen finishing and mechanical testing of geopolymer concrete — demoulding, weighing and compression/flexural testing

5. CONCLUSIONS

- An optimum binder combination for cement replacement was identified in terms of the fly ash-GGBS ratio, sodium hydroxide-to-sodium silicate ratio and aggregate-to-binder ratio.
- XRD analysis of both fly ash and GGBS confirmed quartz (a member of the silica group) as the major crystalline phase in both precursor materials.
- Compressive, split tensile and flexural strength of the geopolymer concrete increased as the proportion of GGBS increased relative to fly ash, up to the 20% replacement level examined.
- The strength and microstructural data generated in this study can support the design and development of geopolymer concrete with improved mechanical performance.
- Utilising industrial by-products such as fly ash and GGBS in geopolymer concrete can help reduce the environmental burden associated with their disposal.

Note: the second conclusion above refers to XRD analysis, but no XRD methodology, results, or figures appear elsewhere in the source project report. This claim could not be cross-verified against a corresponding results section and should be checked against the student's raw data before submission.

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