Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

Influence of Alkaline to Fly Ash Ratio on Performance Characteristics of Geopolymer Concrete

A Comprehensive Review of Mechanical Properties, Workability & Durability

Prof. Magar K.A(1), Shelke Aditya Babasaheb (2), Mhaske Siddhant Machindra(3), Alkute Sagar Navnath(4), Bhorse Om Sanjay(5)

(1)Prof, Department of Civil Engineering, Sau. Sundarbai Manik Adsul Polytechnic, Chas, Ahilyanagar, Maharashtra, India

(2,3,4,5) Students, Department of Civil Engineering, Sau. Sundarbai Manik Adsul Polytechnic, Chas, Ahilyanagar, Maharashtra, India

1. EXECUTIVE SUMMARY

Geopolymer concrete (GPC) has emerged as a compelling low-carbon alternative to Ordinary Portland Cement (OPC) concrete, leveraging industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS) as primary binders. Among the key mix design variables, the alkaline activator to fly ash (A/FA) ratio exerts a dominant influence on the engineering performance of geopolymer concrete.

This report synthesizes findings from experimental research to critically evaluate how varying the A/FA ratio affects compressive strength, workability (slump), split tensile strength, flexural strength, and long-term durability. The investigation covers A/FA ratios ranging from 0.35 to 0.65 across different curing regimes, binder compositions, and grades of concrete.

Key findings indicate that an optimum A/FA ratio of 0.40–0.45 produces the highest compressive strengths under ambient curing, while ratios below 0.35 cause workability issues and ratios above 0.55 lead to significant strength reduction due to excess free alkaline solution diluting the gel matrix. These insights provide actionable guidance for engineers designing sustainable concrete mixes.

2. INTRODUCTION

2.1 Background

Portland cement concrete is the most widely consumed construction material globally, with over 4 billion tonnes of cement produced annually. Its manufacture, however, accounts for approximately5–8% of global CO_2 emissions - a figure that has intensified calls for sustainable alternatives. Geopolymer concrete, first theorised by Davidovits in 1978, offers a pathway to near-zero-emission binders by replacing cement entirely with aluminosilicate-rich industrial by-products.

Fly ash - a fine residue collected from coal combustion power plants - is particularly attractive as a geopolymer precursor because of its abundant supply, cost-effectiveness, and high silicon (Si) and aluminium (Al) content. When activated with an alkaline solution, fly ash undergoes a polycondensation reaction to form a three-dimensional alumino-silicate polymer network that binds aggregates into a durable matrix.

2.2 Role of the Alkaline Activator

The alkaline activator, typically a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), or a single geo-activator solution, is critical to the geopolymerisation process. It dissolves the Si-Al species from the fly ash surface and provides the ionic environment necessary for polycondensation. The ratio of alkaline liquid to fly ash binder (A/FA) therefore controls both the rheological and mechanical properties of the resulting concrete.

An insufficient A/FA ratio limits dissolution of precursor particles, yielding incomplete polymerisation and low strengths. Conversely, an excessive ratio introduces surplus liquid, which dilutes the gel, increases porosity, and compromises mechanical performance. Identifying the optimum A/FA ratio for a given binder composition and curing condition is thus a central challenge in GPC mix design.

2.3 Scope of this Report

This report covers the following performance parameters as functions of A/FA ratio:

- Compressive strength at 7 and 28 days
- Workability (slump value)
- Split tensile strength
- Flexural strength
- Water absorption and durability
- Cost implications relative to OPC concrete

The analysis draws primarily on the experimental study by G. Mallikarjuna Rao et al. (2020), supplemented by corroborating literature from Nath & Sarker (2014), Deb et al. (2014), Hardjito et al. (2004), and other peer-reviewed sources.

3. MATERIALS AND MIX DESIGN

3.1 Source Materials

Class F fly ash (low-calcium, SiO_2 = 60.11%, Al_2O_3 = 26.53%) obtained from coal-fired thermal power plants was used as the primary aluminosilicate precursor. GGBS (CaO = 32.6%, SiO_2 = 34.06%) was incorporated in select mixes to accelerate setting and enhance early strength. Table 1 presents the chemical compositions.

Oxide Composition	Fly Ash (%)	GGBS (%)	Role in Geopolymerisation
SiO_2	60.11	34.06	Primary network former
Al_2O_3	26.53	20.00	Framework charge balancer
CaO	4.00	32.60	C-S-H & C-A-S-H gel former
Fe_2O_3	4.25	0.80	Minor contributor
MgO	1.25	7.89	Minor contributor

Table 1: Chemical composition of fly ash and GGBS by mass (%)

3.2 Alkaline Activator Details

A single geo-activator solution ($SiO_2:Na_2O$ modulus Ms = 2.92, containing 28.98% SiO_2 and 9.92% Na_2O by weight) was used as the sole alkaline activator in the primary study. This eliminates the hazards of handling high-molarity NaOH while providing an appropriate activator chemistry. The A/FA ratio was varied systematically by adjusting the quantity of geo-activator relative to the binder content.

In comparative literature studies, activators comprising NaOH (8–16 M) combined with Na_2SiO_3 at a Na_2SiO_3/NaOH mass ratio of 2.5 were also investigated, as these are the most commonly reported systems in geopolymer research.

3.3 Mix Design Summary

Four grades of concrete (M20, M30, M40, M50) were designed with equivalent mix proportions for both OPC and GPC systems. In GPC mixes, cement was fully replaced by fly ash and GGBS at varying ratios, and water was replaced by geo-activator. Table 2 summarises the key mix parameters.

ID	Grade (MPa)	FA:GGBS	A/Binder	Binder (kg/m³)	Fine Agg. (kg/m³)	Coarse Agg. Mix (kg/m³)
Mix A	20	100:0	0.50	396	608	1216
Mix B	30	90:10	0.43	438	660	1104
Mix C	40	70:30	0.40	350	896	1140
Mix D	50	50:50	0.36	427	466	1504

Table 2: Geopolymer concrete mix proportions for different grades

4. EFFECT ON COMPRESSIVE STRENGTH

4.1 General Trend

Compressive strength is the most critical mechanical property of concrete and the primary design parameter. Among all mix variables, the A/FA ratio has the most pronounced effect on GPC strength because it directly governs the degree of geopolymerisation and the density of the resulting gel matrix.

Research consistently reports an inverse relationship between the A/FA ratio and compressive strength beyond a critical optimum value. As the ratio increases from a low value, strength initially rises due to improved dissolution of Si-Al species; past the optimum, further increases in liquid content dilute the gel network, increase porosity, and reduce strength.

4.2 Experimental Results (7-Day and 28-Day Strengths)

Table 3 presents the compressive strength results for both OPC and GPC systems at 7 and 28 days curing under ambient (outdoor) conditions. The data highlights the pivotal role of GGBS addition and A/FA ratio on strength development.

Mix	A/FA Ratio	FA:GGBS	OPC 7d (MPa)	OPC 28d (MPa)	GPC 7d (MPa)	GPC 28d (MPa)
Mix A	0.50	100:0	14.70	22.41	5.50	20.02
Mix B	0.43	90:10	20.78	35.62	28.22	31.59
Mix C	0.40	70:30	38.54	47.50	41.50	44.73
Mix D	0.36	50:50	41.39	57.39	55.20	57.20

Table 3: Compressive strength of OPC and GPC at 7 and 28 days (MPa)

4.3 Key Observations

- Mix A (A/FA = 0.50, 100% fly ash): GPC 7-day strength was only 5.50 MPa—approximately 37% of OPC— due to slow polymerisation with pure fly ash and high liquid content. By 28 days, strength reached 20.02 MPa, still marginally below the OPC equivalent.
- Mix B (A/FA = 0.43, FA:GGBS = 90:10): Introduction of 10% GGBS dramatically boosted 7- day GPC strength to 28.22

MPa (vs. 20.78 MPa OPC), demonstrating that even small GGBS additions accelerate the formation of C-A-S-H gel.

- Mix C (A/FA = 0.40, FA:GGBS = 70:30): GPC achieved 41.50 MPa at 7 days, exceeding the OPC value of 38.54 MPa. The 28-day strength of 44.73 MPa closely matched the OPC value (47.50 MPa).
- Mix D (A/FA = 0.36, FA:GGBS = 50:50): GPC reached 57.20 MPa at 28 days, essentially

equivalent to OPC (57.39 MPa). The lower A/FA ratio combined with higher GGBS resulted in near-complete polymerisation and maximum gel density.

4.4 Effect of A/FA Ratio— Mechanistic Explanation

The geopolymerisation reaction proceeds in three stages: (1) dissolution of Si and Al species from fly ash by alkaline solution, (2) formation of oligomeric species in solution (gel precursors), and (3) polycondensation of these species into a three-dimensional aluminosilicate network. The A/FA ratio influences all three stages.

At low A/FA ratios (<0.35), insufficient alkaline liquid means incomplete dissolution of the fly ash surface, leaving unreacted cores that serve as micro-defects. At high A/FA ratios (>0.55), excess activator solution acts as a diluent, increasing the water/gel ratio and creating a more porous microstructure analogous to the effect of a high water/cement ratio in OPC concrete. The optimum A/FA ratio typically 0.40–0.45 for ambient-cured fly ash/GGBS blends balances complete

dissolution against microstructural density.

5. EFFECT ON WORKABILITY

5.1 Slump Behaviour

Workability, measured as slump by the standard slump cone test, is a critical fresh-state property that governs placement and compaction. In geopolymer concrete, the A/FA ratio is the primary determinant of workability its role being analogous to the water/cement ratio in OPC systems.

Increasing the A/FA ratio consistently increases slump values across all mix compositions. This is because additional alkaline liquid reduces inter-particle friction and lowers the viscosity of the fresh paste. Table 4 summarises representative slump values for different A/FA ratios reported in literature.

A/FA Ratio	FA:GGBS	Slump (mm)	Workability Class
0.35	100:0	20–35	Very low (S1)
0.40	70:30	45–65	Low (S2)
0.45	70:30	75–95	Medium (S3)
0.50	100:0	100–125	Medium-High (S3/S4)
0.55	50:50	130–160	High (S4)

Table 4: Representative slump values vs. A/FA ratio (literature compilation)

5.2 GGBS Effect on Workability

Increasing GGBS content in the binder reduces workability for a given A/FA ratio, because GGBS particles are finer than fly ash (Blaine fineness: GGBS ~400–450 m^2/kg vs. fly ash ~300–350 m^2/kg), increasing the surface area requiring wetting. Furthermore, the rapid reaction of GGBS with activator accelerates stiffening, reducing the available working time. Superplasticizer addition (0.5–1.0% by binder mass) is typically required for A/FA$\leq$ 0.40 with GGBS contents$\geq$ 30%.

The fly ash spherical morphology, conversely, provides a ball-bearing effect that enhances workability. Mixes with high fly ash content ($FA \geq 70\%$) and $A/FA \geq 0.45$ generally achieve adequate workability without admixtures.

6. EFFECT ON TENSILE AND FLEXURAL STRENGTH

6.1 Split Tensile Strength

Split tensile strength (fct) is approximately 8–12% of compressive strength in OPC concrete. Geopolymer concrete exhibits a similar ratio, though the exact proportion depends on the A/FA ratio and binder composition. As A/FA decreases toward the optimum, the tensile-to-compressive strength ratio tends to improve, indicating a denser and more homogeneous gel matrix with fewer micro- cracks.

Table 5 presents representative split tensile strength values compiled from experimental investigations at 28 days curing.

A/FA Ratio	Grade (MPa)	GPC Compressive (MPa)	GPC Tensile (MPa)	fct/fc (%)	OPC Tensile (MPa)
0.50	M20	20.02	1.85	9.24	2.10
0.43	M30	31.59	2.95	9.34	3.20
0.40	M40	44.73	4.40	9.83	4.30
0.36	M50	57.20	6.10	10.66	5.80

Table 5: Split tensile strength of GPC vs. A/FA ratio at 28 days

6.2 Flexural Strength

Flexural strength (modulus of rupture) follows a trend similar to compressive and tensile strengths—decreasing as A/FA ratio increases beyond the optimum. Research by Hardjito et al. (2004) reported that geopolymer concrete with A/FA ratios of 0.35–0.40 achieved flexural strengths of 8–12 MPa, comparable to equivalent-grade OPC concrete. At A/FA = 0.55, flexural strength dropped by approximately 20–25% relative to the optimum.

The relationship between flexural strength (fr) and compressive strength (fc) for GPC follows: $fr \approx 0.69\sqrt{fc}$ (MPa), compared with the ACI 318 expression $fr \approx 0.62\sqrt{fc}$ for OPC concrete - indicating that GPC exhibits slightly higher flexural-to-compressive strength ratios, particularly at lower A/FA ratios.

7. DURABILITY CHARACTERISTICS

7.1 Water Absorption

Water absorption is a key indicator of concrete permeability and durability. Lower A/FA ratios produce denser microstructures with reduced capillary porosity, resulting in lower water absorption values. Experimental data indicate that GPC with A/FA = 0.36–0.40 exhibits water absorption of 1.5–2.5%,

compared with 3.5–5.0% for A/FA = 0.50–0.55 – a reduction of 40–50%, attributable to the denser aluminosilicate gel matrix formed at lower liquid contents.

7.2 Acid Resistance

Geopolymer concrete demonstrates significantly superior resistance to acid attack compared to OPC concrete, as the aluminosilicate network is inherently more stable than the calcium silicate hydrate (C-S-H) in OPC under acidic conditions.

The A/FA ratio modulates this resistance: lower ratios produce a more completely cross-linked polymer network with fewer unreacted fly ash particles, reducing the number of vulnerable interfaces.

Studies exposing GPC specimens to 5% H_2SO_4 and 5% HCl solutions for 90 days reported mass loss of only 1.2–2.8% for A/FA = 0.40, compared with 8–15% for OPC concrete of equivalent compressive strength.

7.3 Chloride Ion Penetration

The RCPT (Rapid Chloride Permeability Test) results show that GPC with A/FA = 0.40–0.45 falls in the 'very low' permeability category (<1000 Coulombs), compared with 'low to moderate' permeability (1000–4000 Coulombs) for typical OPC concrete. Increasing A/FA to 0.55 raises RCPT values to 1200–1800 Coulombs due to increased porosity, though still comparable to or better than OPC.

7.4 Dry Density

The dry density of GPC mixes ranged from 2400 to 2500 kg/m³ - essentially equivalent to OPC concrete (2350–2450 kg/m³). Denser mixes with lower A/FA ratios and higher GGBS contents tended toward the upper end of this range, consistent with their lower porosity and higher compressive strengths.

8. COST ANALYSIS

8.1 Material Costs

The economic viability of geopolymer concrete depends on the relative costs of its constituent materials versus OPC concrete. Table 6 lists the unit material costs used in the analysis (based on Indian market prices circa 2020).

Material	Unit	Rate(₹)	Notes
OPC Cement	50 kg bag	330	₹6,600/MT
Fly Ash	Metric tonne (MT)	800	Industrial by-product
GGBS	kg	1.50	₹1,500/MT
Geo-Activator (Na_2SiO_3)	kg	16	Single-solution activator
Fine Aggregate	MT	1,000	River sand
Coarse Aggregate	MT	700	20mm max size
Superplasticizer	kg	250	Conplast SP430

Table 6: Unit material costs for cost comparison (Indian market, 2020)

8.2 Cost Comparison per m³

Table 7 compares the production cost per m³ of OPC and GPC concrete for each grade. The geo- activator constitutes the dominant cost component in GPC (approximately 60–70% of total material cost), while in OPC, cement accounts for 55–65%.

Grade	A/FA	OPC Cost (₹/m³)	GPC Cost (₹/m³)	Saving(₹)	Saving (%)
M20	0.50	4,073	4,944	**−871**	**−17.6%**
M30	0.43	4,324	4,854	**−530**	**−10.9%**
M40	0.40	5,494	4,988	**+506**	**+9.2%**
M50	0.36	5,618	4,758	**+860**	**+15.3%**

Table 7: Cost comparison of OPC vs. GPC per m³ (negative = GPC more expensive)

8.3 Economic Interpretation

The cost analysis reveals a grade-dependent economic pattern. For lower-grade concrete (M20–M30), the high geo-activator requirement at larger A/FA ratios (0.43–0.50) makes GPC 11–18% more expensive than equivalent OPC concrete. This is primarily because the activator accounts for a disproportionately large share of the binder system cost.

However, for high-grade concrete (M40–M50), the scenario reverses: GPC offers savings of 9–15% over OPC. This is because high-grade OPC concretes require large cement contents (350–430 kg/m³

at ₹6,600/MT), while GPC leverages fly ash (₹800/MT) and GGBS (₹1,500/MT)— industrial by- products at a fraction of cement's cost— with activator quantities kept low by the reduced A/FA ratios (0.36–0.40).

From a cost-performance perspective, the optimum A/FA ratio for economic efficiency lies at 0.36–0.40, where GPC not only matches OPC strength but delivers meaningful cost savings for structural grades.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary of Findings

This report has examined the influence of the alkaline to fly ash (A/FA) ratio on compressive strength, workability, tensile strength, flexural strength, durability, and cost of geopolymer concrete. The principal conclusions are:

- The A/FA ratio is the single most influential parameter in GPC mix design, exerting effects analogous to the water/cement ratio in OPC concrete.
  - An optimum A/FA ratio of 0.40–0.45 maximises compressive strength under ambient curing conditions for fly ash/GGBS blended binders.
  - Pure fly ash GPC (100% FA, A/FA = 0.50) achieves only ~25% of its 28-day strength at 7 days; GGBS additions of even 10% dramatically accelerate early strength gain.
  - At A/FA = 0.36 with 50% GGBS, GPC achieves compressive strength (57.2 MPa)
  - essentially equivalent to M50 OPC concrete (57.4 MPa) under ambient curing - without any heat treatment.
  - Workability increases proportionally with A/FA ratio; values below 0.40 require superplasticizer addition for adequate fresh concrete placement.
  - GPC demonstrates superior durability versus OPC— including lower water absorption (by 40–50%), better acid resistance, and very low chloride permeability— particularly at low A/FA ratios.
  - Economically, GPC is less cost-effective than OPC for grades M20–M30, but delivers savings of 9–15% for high-grade M40–M50 concrete.

9.2 Design Recommendations

Based on the synthesis of findings, the following guidelines are recommended for practitioners designing fly ash/GGBS geopolymer concrete:

- For structural concrete (M30 and above), use an A/FA ratio of 0.40–0.45 with a FA:GGBS ratio of 70:30 to 50:50 for optimum strength, workability, and cost balance.

- For high-performance concrete (M50+), reduce A/FA to 0.35–0.38 and increase GGBS to 40–50%; supplement with superplasticizer at 0.5–1.0% binder content.
- For ambient-cured, in-situ applications, rely on the exothermic GGBS reaction to provide sufficient activation energy—oven curing is neither required nor practical.
- Evaluate the geo-activator (single-solution) approach for large-scale projects, as it simplifies mix preparation and reduces the hazards associated with high-molarity NaOH handling.
- For projects where carbon footprint reduction is a key objective, all GPC grades offer significant embodied carbon savings (estimated 60–80% CO_2 reduction vs. OPC),

regardless of grade.

9.3 Future Research Directions

Several areas warrant further investigation to advance the practical deployment of geopolymer concrete:

- Long-term durability studies (>5 years) of ambient-cured GPC under realistic field exposure conditions
- Shrinkage and creep behaviour as functions of A/FA ratio and binder composition
- Standardisation of geo-activator silica modulus specifications for different binder types
- Life-cycle cost analysis incorporating CO_2 pricing and fly ash transport logistics
- Structural performance of GPC reinforced elements under seismic and fatigue loading

10. REFERENCES

[1] G. Mallikarjuna Rao, Y. Anil Kumar, Dr. Jagadish Vengala, Dr. M. Venu - "Performance of Fly Ash and GGBS Based Geopolymer Concrete Using Single Alkaline Activator Solution and Its Cost Analysis," IOP Conf. Ser.: Mater. Sci. Eng. 998, 012051, 2020.

[2] Davidovits, J. - "Synthetic mineral polymer compound of silico aluminate family and preparation process," US Patent 4,472,199, 1978.

[3] Nath, P. & Sarker, P.K. - "Effect of GGBS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition," Construction and Building Materials, 66:163–171, 2014.

[4] Deb, P.S., Nath, P., Sarker, P.K. - "The effects of GGBS blending with fly ash and activator content on workability and strength properties of geopolymer concrete cured at ambient temperature," Materials & Design, 62:32–39, 2014.

[5] Hardjito, D., Wallah, S.E., Sumajouw, D.M.J., Rangan, B.V.— "On the Development of Fly Ash-Based Geopolymer Concrete," ACI Materials Journal, 101(6):467–472, 2004.

[6] Wang, S.D., Pu, X.C., Scrivener, K.L., Pratt, P.L. - "Alkali-activated slag cement and concrete: a review of properties and problems," Advanced Cement Research, 7(27):93–102, 1995.

[7] Pinto, A. - "Alkali-activated metakaolin based binder," PhD Thesis, University of Minho, 2004.

[8] Mallikarjuna Rao, G., Gunneswara Rao, T.D. - "Final Setting Time and Compressive Strength of Fly Ash and GGBS-Based Geopolymer Paste and Mortar," Arabian Journal for Science and Engineering, 40:3067–3074, 2015.

[9] Thaarrini, J., Dhivya, S. - "Comparative Study on the Production Cost of Geopolymer and Conventional Concretes," International Journal of Civil Engineering Research, 7(2):117–124, 2016.

[10] Palomo, A., Grutzek, M.W., Blanco, M.T. - "Alkali-activated fly ashes: a cement for the future," Cement and Concrete Research, 29(8):1323–1329, 1999.