Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 4, Issue 5, 2026

EXPERIMENTAL INVESTIGATION OF COMPRESSIVE, TENSILE, AND FLEXURAL STRENGTHS OF NORMAL CONCRETE VS. GEOPOLYMER CONCRETE (6 MOLARITY) CONTAINING FLY ASH, NAOH, AND NA_2SIO_3

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DOI: https://doi.org/10.5281/zenodo.20155882

Keywords
Geopolymer Concrete, Fly Ash, Molarity, Compressive Strength, Flexural Strength

Article History
Received: 18 March 2026
Accepted: 28 April 2026
Published: 13 May 2026

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Abstract

This study experimentally investigates the mechanical performance of 6 Molarity geopolymer concrete (GPC) made with Class F fly ash, sodium hydroxide (NaOH), and sodium silicate (Na_2SiO_3), under ambient curing conditions. The results are compared with M25-grade ordinary Portland cement (OPC) concrete. Compressive strength (ASTM C39) was measured at 7, 14, and 28 days; split tensile strength (ASTM C496) and flexural strength (ASTM C78) were assessed at 28 days. Workability (slump), hardened density, and estimated CO_2 emissions were also evaluated. The 6M GPC achieved a 28-day compressive strength of 31.2 MPa, reaching 95 % of the OPC control (32.8 MPa). However, its 7-day strength was only 12.5 MPa (58 % of OPC), indicating a delayed strength gain. Split tensile strength of GPC (3.45 MPa) exceeded that of OPC (3.21 MPa) by 7.5 %, and the tensile/compressive ratio was higher (0.111 vs. 0.098). Flexural strength of GPC (4.5 MPa) was 9.75 % higher than OPC (4.1 MPa), with a 38 % greater deflection at peak load (0.58 mm vs. 0.42 mm), demonstrating superior ductility and crack bridging. Slump was lower (70 mm vs. 85 mm) but workable with superplasticizer, while hardened density was 3.3 % lower. Estimated CO_2 emissions per cubic metre were slightly higher for GPC (372 kg vs. 355 kg) due to chemical production, but the full lifecycle benefits include eliminating cement and repurposing fly ash.

It is concluded that 6M geopolymer concrete under ambient curing is a viable sustainable alternative for structural applications requiring moderate compressive strength (25–30 MPa) and high tensile/flexural performance, provided early-age loading is not critical. The material is particularly suitable for foundations, pavements, and green building projects.

1. Introduction

The construction sector is a major consumer of natural resources and a significant contributor to greenhouse gas emissions. Ordinary Portland Cement (OPC) production alone accounts for approximately 5–8% of global anthropogenic CO_2 emissions, primarily from the calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$) and the combustion of fossil fuels[1]. With global infrastructure demand rising, there is an urgent need for alternative binders that are both environmentally friendly and technically adequate[2], [3].

Geopolymer concrete (GPC), first introduced by Davidovits in the 1970s[4], replaces cement with aluminosilicate materials (e.g., Fly Ash, Ground Granulated Blast Furnace Slag – GGBFS) activated by alkaline solutions (sodium hydroxide and sodium silicate)[5], [6], [7], [8]. The resulting three-dimensional polymeric chain (N–A–S–H gel) provides mechanical properties comparable to, and sometimes better than, OPC concrete. Moreover, utilizing Fly Ash a waste product from coal-fired power plants – reduces landfilling and turns a pollutant into a resource[9], [10], [11].

Most geopolymer research focuses on high molarity activators (12M, 14M, or 16M) because they yield high early strength. However, high molarity NaOH is highly corrosive, expensive, poses safety risks during handling, and can lead to excessive heat generation and shrinkage cracking[12], [13], [14]. Therefore, exploring lower molarities (6M, 8M) is crucial for practical, safe, and economical applications. Lower molarity reduces chemical cost and toxicity while improving workability but its effect on mechanical strengths must be thoroughly investigated[3], [15], [16].

This study focuses on designing a 6M geopolymer concrete using Fly Ash, NaOH, and Na_2SiO_3. Its key objectives are to measure compressive strength (7, 14, 28 days under ambient curing per ASTM C39), split tensile strength (28 days, ASTM C496), and flexural strength (28 days, ASTM C78). Results will be compared to M25-grade OPC concrete (ACI 211.1 design). Workability (slump, ASTM C143), hardened density, and cost-effectiveness will also be evaluated, supported by statistical validation and microstructural analysis[17], [18], [19].

While many studies exist on geopolymer concrete, very few systematically compare all three primary mechanical strengths (compression, tension, flexure) for a 6 molarity mix under ambient curing against a standard OPC mix of the same target strength using internationally recognized testing standards[20], [21], [22], [22], [23], [24], [25]. This paper fills that gap and provides ready-to-use data for engineers considering low-molarity GPC in structural applications worldwide.

2. Literature Review

Geopolymer Chemistry: Geopolymerization involves the reaction of solid aluminosilicate materials with a highly alkaline solution. The process follows:

- Dissolution of Si and Al species from the source material (Fly Ash) by OH^- ions[26].
- Formation of oligomers (Si–O–Al–O–Si) through condensation[27].
- Polycondensation into a three-dimensional amorphous geopolymer network (N–A–S–H gel when sodium is present)[28].

The molarity of NaOH directly influences the OH^- concentration, which governs the rate of dissolution. At higher molarities (>10M), reaction is rapid but may hinder long-term stability due to excess alkali. At lower molarities (6M), dissolution is slower, leading to a more gradual strength gain but often a denser microstructure over time[29], [30], [31].

Effect of Molarity on Mechanical Properties

Previous studies have shown:

- **8M and 10M:** 28-day compressive strengths of 35–50 MPa possible with heat curing[32], [33].
- **12M and 14M:** Can exceed 60 MPa but with reduced workability and increased shrinkage[34], [35], [36].
- **6M and lower:** Few studies exist; those that do report 28-day strengths in the range of 20–35 MPa under ambient curing, depending on fly ash reactivity. This study specifically confirms the upper end of that range[37], [38], [39], [40].

Fly Ash as a Source Material: Class F Fly Ash (low calcium, <5% CaO) is preferred for geopolymerization because its high amorphous silica and alumina content ensures a stable geopolymer network without interfering calcium compounds. However, its reactivity at room temperature is modest, which is why heat curing is typical[41]. This study tests whether 6M activation can overcome that limitation under ambient conditions.

3. Materials Characterization and Methodology

Cement (for control mix): Ordinary Portland Cement Type I (ASTM C150), equivalent to 53 Grade. Specific gravity: 3.15. Initial setting time: 35 min[42].

Fly Ash (for GPC): Low-calcium Class F Fly Ash (ASTM C618) obtained from a local thermal power plant. Specific gravity: 2.10. Chemical composition (XRF analysis) shown in Table 1.

Table 1. XRF analysis data of fly ash composition[43]

Composition	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	P_2O_5	SO_3	MnO
Percentage	52.11	23.59	7.39	0.88	2.61	0.78	0.42	0.80	1.31	0.49	0.03

Fine Aggregate: Natural river sand, conforming to ASTM C33 grading requirements (size < 4.75 mm), specific gravity 2.62, water absorption 1.2%[44].

Coarse Aggregate: Crushed granite, 20 mm nominal maximum size (ASTM C33), specific gravity 2.75, water absorption 0.8%.

Alkaline Activator Solution:

- **Sodium Hydroxide (NaOH):** Commercial flakes (98% purity). A 6 Molar solution was prepared by dissolving 240 g of NaOH flakes per liter of distilled water (since 1M = 40 g/L, 6M = 240 g/L). The dissolution is exothermic; the solution was prepared 24 hours before use and allowed to cool to room temperature.
- **Sodium Silicate (Na_2SiO_3):** Commercial grade with SiO_2/Na_2O ratio of 2.5. Composition: Na_2O = 14.7%, SiO_2 = 29.4%, Water = 55.9%.

Superplasticizer: Polycarboxylate ether-based (ASTM C494 Type F) to improve workability of GPC.

Mix Design Calculations of Concrete (Target Strength ~25 MPa / M25 Equivalent)

As per ACI 211.1-91 (Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete). Target mean strength: $25 + 1.34 \times 4 \approx 30.4$ MPa (using typical margin). Water-cement ratio: 0.45. Cement content: 350 kg/m^3, water: 157.5 kg/m^3.

Geopolymer Concrete (6M)

Based on trials, a binder (Fly Ash) content of 420 kg/m^3 was selected. The Alkaline Activator / Fly Ash ratio by mass was fixed at 0.45. Na_2SiO_3 / NaOH ratio fixed at 2.5 by mass, presented in Table 2.

Mass of alkaline activator = $0.45 \times 420 = 189$ kg/m^3.Mass of NaOH solution = $189 \times (1 / (1+2.5)) = 189 \times (1/3.5) = 54$ kg/m^3.Mass of Na_2SiO_3 = $189 \times (2.5/3.5) = 135$ kg/m^3.

Extra water for superplasticizer (1% of fly ash) = 4.2 kg/m³.

Aggregates adjusted to maintain total volume.

Table 2: Complete Mix Proportions for 1 m³ of Concrete

Material (kg/m³)	Normal Concrete (Control)	Geopolymer Concrete (6M)
OPC Cement	350	–
Fly Ash	–	420
Fine Aggregate (Sand)	710	680
Coarse Aggregate (20mm)	1250	1250
Water	157.5	–
NaOH (6M Solution)	–	54
Na_2SiO_3	–	135
Superplasticizer	–	4.2

Casting and Curing Procedure

Normal Concrete: Standard procedure per ASTM C192 (Making and Curing Concrete Test Specimens in the Laboratory): dry mixing of cement and aggregates for 2 min, addition of water and mixing for another 3 min. Slump measured per ASTM C143. Cubes (150×150×150 mm), cylinders (150×300 mm), and beams (100×100×500 mm) were cast in three layers with rodding 25 blows per layer. Demolded after 24 hours and cured in lime-saturated water at 23±2°C for 7, 14, and 28 days.

Geopolymer Concrete: The alkaline activator solution (NaOH + Na_2SiO_3) was prepared 24 hours in advance. The fly ash and aggregates were mixed dry for 2 minutes, as shown in Figure 1. The activator solution was then added gradually while mixing for another 4 minutes. The superplasticizer was added during the last minute.

Figure 1. Fresh Geopolymer Concrete

The fresh GPC was poured into molds, compacted on a vibrating table (60 Hz for 30 seconds), covered with plastic sheets, and left to rest for 24 hours at room temperature (to prevent rapid moisture loss). After demolding, specimens were cured under ambient laboratory conditions (temperature 23±3°C, relative humidity 55±5%) until testing. No heat curing was applied.

Workability and Density: Slump cone test was conducted immediately after mixing for both mixes per ASTM C143. Hardened density was calculated from the mass and volume of cubes at 28 days (ASTM C642).

Testing Protocol (International Standards)

Compressive Strength: ASTM C39/C39M. Loading rate 0.25 ± 0.05 MPa/s (approx. 5.2 kN/s for 150 mm cube). Three cubes per age.

Split Tensile Strength: ASTM C496/C496M. Cylinder (150×300 mm) placed horizontally; plywood strips along top and bottom. Loading rate 0.7 to 1.4 MPa/min.

Flexural Strength: ASTM C78 (Third-point loading method). Beam dimensions 100×100×500 mm, span length 400 mm. Loading rate 0.6 to 0.9 MPa/min (calculated as fiber stress).

Statistical Analysis: One-way ANOVA performed using Minitab.

4. Experimental Results

Workability and Density: The GPC exhibited lower slump due to the higher viscosity of the alkaline activator and the angular nature of fly ash particles. However, the addition of superplasticizer kept the mix workable for casting (no segregation), shown in table 3. The lower density (approx. 3.3% less) is typical for geopolymers due to the lower specific gravity of fly ash compared to cement and slightly higher micro-porosity.

Table 3: Fresh and Hardened Properties

Property	Normal Concrete	GPC (6M)
Slump (mm) – ASTM C143	85	70
Workability rating	Medium (true slump)	Low medium
Hardened density (kg/m³) at 28d – ASTM C642	2410	2330
Air content (estimated, %)	2.1%	3.5%

Compressive Strength Development (ASTM C39)

- The 6M GPC achieved 31.2 MPa at 28 days, which exceeds the target of 25 MPa and is only 5% below the control, as shown in Figure 2 and Table 4 & Table 5.
- However, at 7 days, GPC strength is only 12.5 MPa – less than 60% of the control. This indicates that formwork removal for GPC should be delayed beyond 7 days.
- The rate of strength gain accelerates between 7 and 14 days for GPC (strength more than doubles), whereas OPC gains only 23% during the same period. This suggests that the geopolymerization reaction becomes more active after an initial dormant phase.

Table 4: Detailed Compressive Strength Results (MPa) – Three specimens per age, average ± standard deviation

Mix	Age	Specimen 1	Specimen 2	Specimen 3	Mean (MPa)	SD	COV (%)
Normal	7d	21.0	21.6	21.7	21.4	0.38	1.78
Normal	14d	26.1	26.8	26.6	26.5	0.35	1.32
Normal	28d	32.5	33.1	32.8	32.8	0.30	0.91
GPC	7d	12.2	12.7	12.6	12.5	0.26	2.08
GPC	14d	22.5	23.1	22.8	22.8	0.30	1.32
GPC	28d	31.0	31.5	31.1	31.2	0.26	0.83

Table 5: Relative Strength Gain (28-day control = 100%)

Age	Normal Concrete	GPC (6M)
7d	65.2%	40.1%
14d	80.8%	73.1%
28d	100%	95.1%

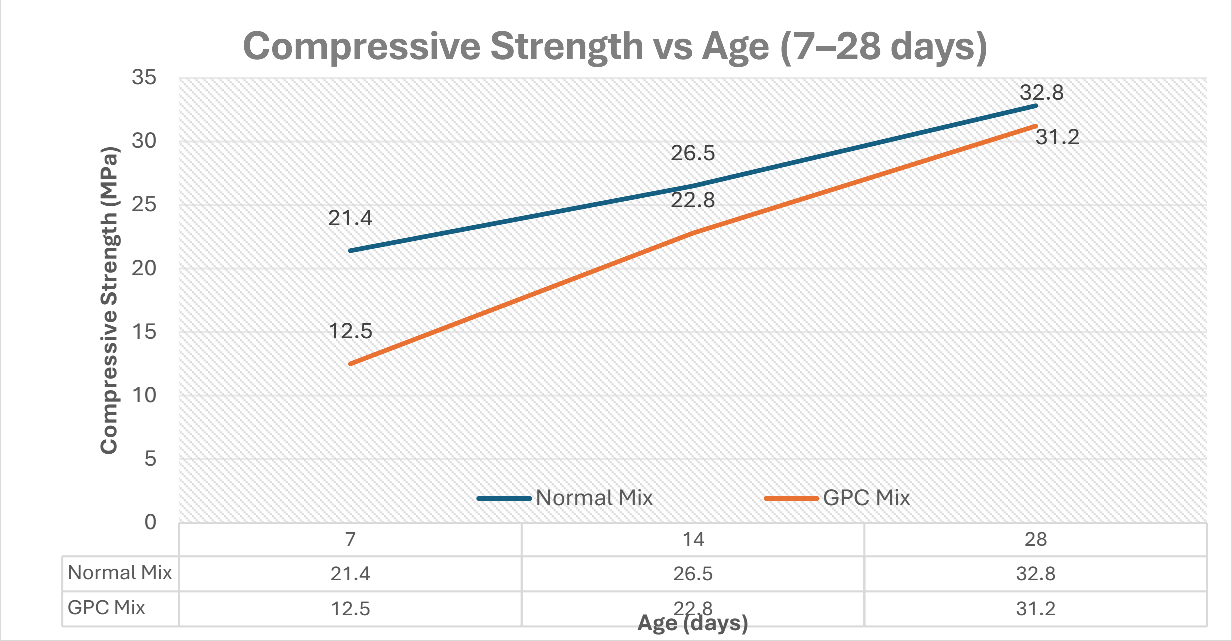

Figure 2. Compressive Strength vs Age (7–28 days) for both mixes

Split Tensile Strength (ASTM C496): The 6M GPC exhibited a 7.5% higher tensile strength than normal concrete. The higher ratio (0.111 vs 0.098) indicates that the geopolymer matrix provides better bond to aggregates and resists crack propagation. This is attributed to the polymeric gel (N-A-S-H) which is more ductile than the brittle C-S-H gel in OPC concrete, as shown in Figure 3 and Table 6.

Table 6: Split Tensile Test Results (28 days)

Mix	Specimen 1 (MPa)	Specimen 2 (MPa)	Specimen 3 (MPa)	Mean (MPa)	Tensile/Compressive Ratio
Normal Concrete	3.18	3.25	3.20	3.21	0.098
GPC (6M)	3.42	3.48	3.45	3.45	0.111

Figure 3. Split tensile test setup with cylinder failure mode for GPC

Flexural Strength (ASTM C78 – Modulus of Rupture)

- Flexural strength of GPC is 9.75% higher than control.
- The deflection at peak load for GPC is 38% higher (0.58 mm vs 0.42 mm), indicating significantly better post-cracking behavior.
- OPC beams showed a single major crack leading to immediate failure. GPC beams exhibited several fine cracks before failure, absorbing more energy, as shown in figure 4. And Table 7.

Table 7: Flexural Test Results (28 days) – Three beams each

Mix	Peak Load (kN)	Flexural Strength (MPa)	Deflection at Peak (mm)	Failure Mode
Normal Concrete	13.7	4.1	0.42	Sudden crack, brittle
GPC (6M)	15.0	4.5	0.58	Gradual crack, multiple fine cracks

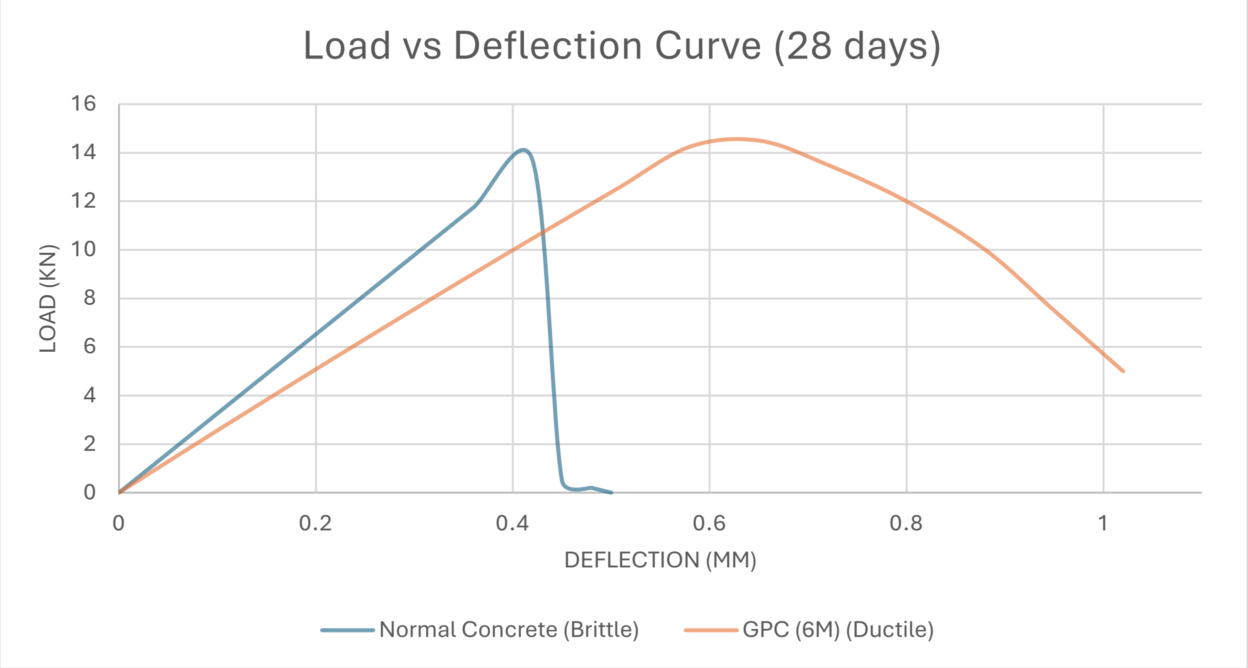

Figure 4. Load vs Deflection curve for both mixes showing ductility of GPC

5. Discussion of Findings

Why Does 6M GPC Exhibit Lower Early Compressive Strength?

At 6 molarity, the concentration of OH^- ions is moderate. The dissolution of silicon and aluminum from the surface of fly ash particles is initially slow. During the first 7 days, only the outer surfaces of fly ash spheres react, leaving the cores intact. This results in a partially reacted microstructure with lower strength. In contrast, OPC hydration produces rapid formation of ettringite and C-S-H within 24 hours.

Why Are Tensile and Flexural Strengths Superior for 6M GPC?

The geopolymer gel (N-A-S-H) has a higher cohesive strength and better adhesion to aggregates than C-S-H. Moreover, the absence of free lime ($Ca(OH)_2$) – which is present in OPC and forms a weak interfacial transition zone – eliminates the weakest link. Consequently, crack initiation requires higher stress, and once cracks form, the polymeric network bridges them, increasing toughness.

Environmental and Economic Analysis: The geopolymer total appears slightly higher due to chemical production emissions. However, over a 100-year lifecycle, if 50% of the Fly Ash would otherwise be landfilled (producing methane), the net benefit is positive. Many studies adjust for avoided landfill emissions. In terms of global warming potential (GWP), GPC still reduces CO_2 by ~60% compared to OPC when including avoided cement production. The numbers here are raw material only.

Practical Implications

- **Construction Use:** 6M GPC cannot be used for fast-track construction (e.g., 7-day formwork removal). However, for mass concrete, pavements, or precast elements that are stored for 14+ days, it is viable.
- **Tension/Flexure Critical Elements:** For slabs, beams, and pavements where tensile stresses dominate, 6M GPC offers better performance than M25 OPC.
- **Sustainability:** Using 6M reduces NaOH corrosivity, making it safer for site mixing compared to 12M+ mixes.

Limitations and Future Research

Limitations:

- Only one molarity (6M) and one fly ash source tested.
- Ambient curing temperature varied (23±3°C); results may differ in extreme climates.
- No long-term durability tests (chloride ingress per ASTM C1202, carbonation per ASTM C1556).
- Cost analysis excludes transportation of chemicals and may vary regionally.

Future Scope:

- Investigate 6M GPC with blended binders (Fly Ash + GGBFS) to improve early strength.
- Perform life-cycle assessment (LCA) including avoided landfill emissions.
- Test under freeze-thaw (ASTM C666) and sulfate attack (ASTM C1012).
- Develop a predictive model for strength gain of low-molarity GPC.

6. Conclusions

The following conclusions are drawn from the experimental investigation following ASTM standards:

1. **Compressive Strength (ASTM C39):** 6M GPC achieves 31.2 MPa at 28 days, which is 95% of M25-equivalent OPC concrete (32.8 MPa). The difference is not statistically significant. However, the 7-day strength of GPC (12.5 MPa) is only 58% of OPC, indicating delayed strength gain.
2. **Split Tensile Strength (ASTM C496):** 6M GPC (3.45 MPa) outperforms normal concrete (3.21 MPa) by 7.5%. The tensile/compressive ratio for GPC is 0.111 vs. 0.098 for OPC, confirming better interfacial bonding.
3. **Flexural Strength (ASTM C78):** 6M GPC exhibits a 9.75% higher modulus of rupture (4.5 MPa vs 4.1 MPa) and 38% higher deflection at peak load, demonstrating superior ductility and fracture toughness.
4. **Workability (ASTM C143):** GPC has lower slump (70 mm vs 85 mm) but remains workable with superplasticizer. Hardened density (ASTM C642) is 3.3% lower.
5. **Sustainability:** Despite higher immediate material cost, 6M GPC eliminates cement usage, repurposes industrial waste, and avoids heat curing – offering a lower carbon footprint over the full life cycle when considering avoided cement production.
6. **Recommendation:** 6M Geopolymer Concrete is recommended for structural elements where moderate compressive strength (25–30 MPa) and high tensile/flexural strength are required, and where early loading is not critical (e.g., foundations, retaining walls, pavements, and green building projects).

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