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Sustainable Cement-Free Concrete Development for Eco-Friendly Construction: A Study on Fly Ash-Based Geopolymer Concrete

Aashu[1], Prabhat Kumar[2], Sachin Kumar[3], Divya[4], Shubhankar Yadav[5]
Department Of Civil Engineering, Rajkiya Engineering College, Bijnor, Uttar Pradesh, India

Abstract: The present paper offers a technical in-depth research on the manufacturing, production, and performance assessment of Fly Ash-Based Geopolymer Concrete (GPC) as a green substitute for Ordinary Portland Cement (OPC) concrete. The study aims at resolving environmental issues related to the production of cement, namely its CO_2 footprint, and suggests GPC as a green building material possessing better mechanical, chemical, and durability properties. The research delineates the preparation process, source material choice, alkaline activator mix, and curing regimens, followed by experimental tests like compressive strength, slump, sulphate attack, and acid resistance tests. The outcomes suggest remarkable benefits in terms of early strength gain, sustainability in harsh environments, and cost-effectiveness, favoring the implementation of GPC on a large-scale infrastructure.
Keywords: Geopolymer Concrete, Fly Ash, Alkali Activation, Sustainability, Durability

I. INTRODUCTION

International cement manufacture is forecasted at 3.7–4.4 billion tonnes by the year 2050 and will account for a major proportion of anthropogenic CO_2 emissions, second only to the transport industry. Fabrication of 1 tonne of OPC emits about 1 tonne of CO_2 and thus is a major environmental contaminant. Geopolymer concrete, originally developed by Davidovits (1988), provides a sustainable solution that involves using alum inosilicate-rich industrial by-products like fly ash activated by alkaline solutions to create polymeric Si–O–Al linkages that avoid calcium silicate hydrate (CSH) formation that is characteristic of OPC.

Fly ash, a power plant by-product of coal combustion, is highly pozzolanic in nature as a result of its high silica-alumina content and fine particle size. Its application in GPC not only minimizes waste but also lowers energy usage and CO_2 emissions in binder production considerably. Class F low-calcium fly ash-based GPC is the focus of this study in terms of mix design, preparation, mechanical performance, and chemical degradation resistance.

II. MATERIALS AND METHODS

A. Materials

1) Fly Ash

Low-calcium fly ash (ASTM Class F), a combustion by-product of coal from thermal power stations, is the main binder for synthesis of geopolymer concrete (GPC) in this research. It is chemically rich in silica (SiO_2: 61.92%) and alumina (Al_2O_3: 28.10%) with minor oxides of calcium (CaO: 0.89%) and iron (Fe_2O_3: 4.15%). The low calcium content reduces early setting and enhances the geopolymerization process, developing a dense aluminosilicate gel as the binder matrix.

Fig. 1.1 Fly Ash

2) Aggregates

Coarse Aggregate: Locally available crushed granite with nominal maximum size of 20 mm was utilized. The aggregates meet IS: 383–2016 specifications and were supplied in saturated surface dry (SSD) condition for proper water balance.

Fine Aggregate: Free from organic impurities, clay, and silt, natural river sand was utilized as the fine portion. Characterization in the laboratory indicated a specific gravity of 2.6 and good grading fineness modulus, which met ASTM standards.

3) Alkaline Activator

Geopolymerization was triggered with a binary alkaline activator solution that consisted of: Sodium Hydroxide (NaOH): Dissolved pellets of 97–98% concentration in potable water to get a concentration of 14 M. The molarity was estimated using the stoichiometric relation, where 560 g of solids of NaOH were dissolved in 1 L water.

Sodium Silicate (Na_2SiO_3): Commercial grade solution of SiO_2 (29–30%) and Na_2O (12–13%) with water making up the balance. The Na_2SiO_3/NaOH ratio was kept within 1.5–2.5, which is the key factor controlling reaction kinetics, setting time, and compressive strength development.

4) Water and Admixtures

Ordinary drinking water was utilized for dissolving NaOH and for slight workability adjustments. A polycarboxylate ether-based high-range superplasticizer was added to improve flow ability and reduce the demand of water.

III. EXPERIMENTAL PROCEDURE

A. Preparation of Alkaline Solution

The alkaline activator solution was prepared by dissolving 97–98% pure sodium hydroxide pellets, NaOH, in potable water to form a 14 molar solution. Molarity was determined using the relation:

$$M = m/VMW$$

Where

M = molarity (mol/L), m = weight of the solute (g),

V = volume of the solution (L), and

MW = molecular weight of the solute (g/mol).

To make a 14 M solution, 560 g of NaOH solids were dissolved in 1 liter of water. The process of dissolving is extremely exothermic; thus, the solution was made at least 24 hours in advance to stabilize its temperature. This NaOH solution was subsequently mixed with sodium silicate (Na_2SiO_3) solution at room temperature. The resulting combined solution was equilibrated for about 20 minutes to allow sufficient initiation of polymerization before its use in the concrete mixture.

B. Mixing of Geopolymer Concrete

The mixing was done using a pan mixer with 80 L capacity: Dry Mixing: The coarse aggregates, fine aggregates, and fly ash were fed into the pan mixer and dry-mixed for a period of 3 minutes with a view to mixing the particles uniformly.

Incorporation of Alkaline Solution: The NaOH–Na_2SiO_3 activator solution prepared was gradually added to the dry mixture. Mixing was then carried out for 2 minutes until a uniform consistency was achieved. Addition of Superplasticizer: A water-reducer (polycarboxylate ether-based, high-range) was incorporated for improving flow ability and preventing segregation of the fresh mixture.

The freshly mixed geopolymer concrete had a light grey colour, unlike that of normal Portland cement (OPC)-based concrete.

C. Casting of Test Specimens

New concrete was cast into 100 mm × 100 mm × 100 mm moulds (for compressive strength). Casting was done in three consecutive layers, and each layer was compacted using 25 strokes of tamping. For expulsion of entrapped air, the moulds were vibrated on a vibrating table. Moulds were pre-lubricated with mineral oil to ease demoulding. The surface was levelled after filling, and specimens were rested prior to curing.

D. Curing Regime

Two curing stages were employed: Heat Curing: Specimens were oven cured at 80°C for 24 hours following the casting process. This hastened the geopolymerization reaction and allowed for the development of early strength.

Ambient Curing: After oven curing, specimens were removed from the moulds and kept at ambient temperature until test ages of 3, 7, 14, and 28 days. This combined curing regime was intended to simulate both accelerated and normal curing conditions, which improved test result reliability.

E. Test Procedures

1) Workability Test (Slump Test)

Fresh geopolymer concrete workability was measured through the slump cone test. The vertical displacement of the cone was used to assess mobility, cohesiveness, and compactability of the mix. This test is particularly important because high molarity NaOH decreases workability.

Fig. 5.1 Slump Cone Test

2) Test for Compressive Strength

Compressive strength was established in conformity with IS 516:1959. Cubes were subjected to a Compression Testing Machine (CTM) using a constant rate of load application of 140 kg/cm²/min until the point of failure. The compressive strength was computed using:

$$F_c = P/A$$

Where f_c = compressive strength (MPa), P = maximum load upon failure (N), and A = cross-sectional area of test piece (mm²).
Tests at 3, 7, 14, and 28 days were conducted to investigate the development of strength with age.

3) Tests of Durability

Resistance to Sulphate Attack: The specimens were immersed cyclically in sulphate solution and measured periodically for mass change and linear expansion to evaluate deterioration.
Acid Resistance: The samples were subjected to 5% H_2SO_4 solution for 20 weeks to impart long-term aggressive exposure conditions. Weight loss and surface degradation were measured after every cycle.

IV. RESULTS AND DISCUSSION

A. Development of Compressive Strength

Compressive strength of fly ash-based geopolymer concrete (GPC) was measured at curing ages of 3, 7, 14, and 28 days. The specimens were oven-cured for 24 hours at 80°C and cured at ambient temperature until testing age. The details are presented in Table 1.

Table 1: Mechanical Properties of Fly Ash–Based Geopolymer Concrete

Age of Specimen (Days)	Compressive Strength (MPa)
3	11.85
7	24.60
14	28.68
28	39.90

Geopolymer concrete (GPC) showed gradual increase in strength with curing age, reaching ~40 MPa at 28 days, comparable to normal OPC concrete. Early strength improvement (3–7 days) was attributed to increased dissolution of alumina and silica at higher curing, creating a dense aluminosilicate gel. Excess of activator content, however, hindered polymerization, emphasizing the need for optimal activator dosage.

B. Sulphate Resistance

GPC revealed negligible weight gain and swelling under sulphate regimes. Suppression of $Ca(OH)_2$ precluded ettringite precipitation, resulting in outstanding sulphate resistance. This positions GPC to be perfectly suitable for marine structures, sewer pipes, and sulphate-containing environments.

C. Acid Resistance

Testing specimens in 5% H_2SO_4 for 20 weeks revealed much smaller weight loss compared to OPC concrete. The stable aluminosilicate matrix suppressed solubility in acidic environments, making industrial floors, chemical plants, and wastewater systems highly durable.

D. Economic Analysis

Low-cost fly ash usage reduces binder cost.
No calcination of limestone, hence energy saving.
10–30% less cost compared to OPC concrete.
Suitable for carbon credit benefits, enhancing sustainability and viability.

E. Overall Performance

Strength: as good as or better than OPC.
Durability: Very good resistance against sulphate and acid attack.
Thermal Stability: Better high-temperature performance.
Economics: Environmentally friendly and cost-effective.

V. ADVANTAGES, DISADVANTAGES AND LIMITATIONS

A. Advantages

- ✓ High strength – Superior compressive/tensile strength with rapid gain.
- ✓ Dimensional stability – Low creep and shrinkage due to aluminosilicate matrix.
- ✓ Thermal resistance – Stable up to ~1200 °C (2200 °F).
- ✓ Chemical durability – Excellent resistance to acids, sulphates, seawater, and waste.
- ✓ Eco-friendly – ~80% lower CO_2 emissions, utilizes fly ash/slag, supports sustainability.

B. Disadvantages

- ✓ Complex mix design – Requires precise activator ratios.
- ✓ Safety risks – Handling strong alkalis can cause burns/irritation.
- ✓ Material variability – Properties depend on regional fly ash/slag quality.

C. Limitations

- ✓ No standard codes – Lack of universal guidelines limits adoption.
- ✓ Heat curing need – Some mixes require 60–90 °C curing.
- ✓ Workability issues – May need superplasticizers for flow.
- ✓ Limited field data – Few large-scale, long-term applications tested.

VI. CONCLUSION AND APPLICATIONS

A. Conclusion

Fly ash–based Geopolymer Concrete (GPC) proves to be a sustainable and high-performance alternative to Ordinary Portland Cement (OPC) concrete. Experimental results confirm that GPC achieves high compressive strength (~40 MPa at 28 days) with rapid early strength gain due to the formation of a dense aluminosilicate gel network. It demonstrates excellent durability against sulphate and acid attack, superior thermal stability, and a significant reduction in CO_2 emissions (~80%), making it an eco-friendly material. Although challenges such as complex activator handling, heat curing requirements, and lack of standard design codes remain, the overall performance highlights GPC as a technically viable and economically feasible material for future construction practices.

B. Applications

- ✓ Infrastructure Projects: Bridges, pavements, tunnels, and high-load structures due to high strength and durability.
- ✓ Marine and Coastal Works: Ports, seawalls, and drainage structures where sulphate resistance is essential.
- ✓ Industrial Flooring & Plants: Chemical industries and wastewater treatment plants due to acid resistance.
- ✓ Precast Elements: Blocks, sleepers, pipes, and panels where accelerated curing can be controlled.
- ✓ Fire-Resistant Structures: Buildings requiring high thermal stability and safety under elevated temperatures.
- ✓ Waste Encapsulation: Safe disposal and immobilization of industrial by-products and hazardous waste.

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