EXPERIMENTAL STUDY ON HIGH-PERFORMANCE GEOPOLYMER CONCRETE USING LOCALLY AVAILABLE INDUSTRIAL BY-PRODUCTS

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Abstract - *The rapid increase in cement production has significantly contributed to global carbon dioxide (CO_2) emissions, necessitating the development of sustainable alternatives. This study investigates high-performance geopolymer concrete produced using fly ash, ground granulated blast furnace slag (GGBS), and locally available laterite. Four mix proportions were developed with varying laterite content (0–30%). Mechanical properties including compressive strength, split tensile strength, and flexural strength were evaluated along with durability characteristics such as water absorption. Results indicate that geopolymer concrete achieved a maximum compressive strength of 46.2 MPa at 28 days under ambient curing. Increasing laterite content resulted in a gradual reduction in strength; however, all mixes satisfied structural requirements. The study confirms that geopolymer concrete incorporating local materials is a sustainable and viable alternative to conventional concrete.*

Key Words: **Fly ash; Ground granulated blast furnace slag (GGBS); Laterite; Sustainable construction; Alkaline activation; Compressive strength; Durability; Industrial by-products; Ambient curing; Eco-friendly concrete; High-performance concrete.**

1. INTRODUCTION

Concrete is the most widely used construction material; however, Ordinary Portland Cement (OPC) production contributes nearly 8% of global CO_2 emissions. Geopolymer concrete offers an alternative binder system utilizing industrial by-products such as fly ash and GGBS activated by alkaline solutions.

Kerala has abundant laterite resources, which can be incorporated into geopolymer systems. This study evaluates the combined use of fly ash, GGBS, and laterite to produce sustainable high-performance concrete.

2. MATERIALS

The materials used in the preparation of geopolymer concrete are described briefly as follows:

2.1 Fly Ash (Class F)

Class F fly ash, a by-product of thermal power plants, was used as the main binder. It is rich in silica and alumina, making it suitable for durable geopolymer concrete due to its low calcium content.

2.2 Ground Granulated Blast Furnace Slag (GGBS)

GGBS, obtained from the iron and steel industry, contains high calcium oxide, which improves early strength and enhances reactivity under ambient curing.

2.3 Laterite Soil

Processed and sieved laterite soil was used as a partial replacement material to improve sustainability. Its lower reactivity slightly affects strength.

2.4 Fine Aggregate (M-Sand)

Manufactured sand was used as fine aggregate, providing better gradation, consistency, and improved workability compared to natural sand.

2.5 Coarse Aggregate

Crushed stone aggregates (20 mm maximum size) were used to provide strength and bulk, meeting standard grading requirements.

2.6 Sodium Hydroxide (NaOH)

A 10 M sodium hydroxide solution was used as an alkaline activator to dissolve silica and alumina, initiating geopolymerization.

2.7 Sodium Silicate (Na_2SiO_3)

Sodium silicate solution was used along with sodium hydroxide to enhance polymerization, improving strength and durability.

3. MIX DESIGN

The geopolymer concrete mix was designed with a total binder content of **400 kg/m³**, consisting of fly ash, GGBS, and laterite. An alkaline activator-to-binder ratio of **0.40** was adopted to ensure adequate workability and reaction kinetics. The ratio of sodium silicate to sodium hydroxide solution was maintained at **2.5** to enhance the geopolymerization process.

Four different mix proportions were developed by varying the percentage of laterite while keeping the GGBS content constant at 30%. Fly ash content was reduced correspondingly to maintain the total binder composition.

Table 1 – Different Mix Proportion

Mix	Fly Ash (%)	GGBS (%)	Laterite (%)
M1	70	30	0
M2	60	30	10
M3	50	30	20
M4	40	30	30

This approach was adopted to evaluate the influence of laterite as a partial replacement material on the mechanical and durability properties of geopolymer concrete.

4. METHODOLOGY

The methodology adopted for the preparation and testing of geopolymer concrete is described in detail below.

4.1 Preparation of Alkaline Solution

The alkaline activator solution was prepared by dissolving sodium hydroxide (NaOH) pellets in distilled water to obtain a 10 molarity (10M) solution. The solution was prepared at least 24 hours prior to mixing to ensure complete dissolution of pellets and stabilization of temperature. Sodium silicate (Na_2SiO_3) solution was then mixed with the sodium hydroxide solution in a ratio of 2.5 by mass. The combined alkaline solution was allowed to equilibrate before use.

4.2 Mixing Procedure

All dry materials, including fly ash, GGBS, laterite, fine aggregate (M-sand), and coarse aggregate (20 mm size), were first weighed accurately as per the mix design. The dry materials were thoroughly mixed in a pan mixer for approximately 3–5 minutes to achieve uniform distribution. Following this, the prepared alkaline solution was gradually added to the dry mix while continuous mixing was maintained. Mixing was continued for an additional 5–7 minutes to ensure proper coating of aggregates and uniform consistency of the geopolymer concrete. Care was taken to avoid rapid setting by controlling mixing time and ambient conditions.

4.3 Casting of Specimens

The fresh geopolymer concrete was placed into standard steel moulds immediately after mixing.

- **Cubes (150 mm × 150 mm × 150 mm)** were cast for compressive strength testing as per IS 516.
- **Cylindrical specimens** were prepared for split tensile strength testing as per IS 5816.
- **Beam specimens** were cast for flexural strength evaluation as per relevant standards.

Concrete was placed in layers and compacted using a table vibrator to eliminate entrapped air and ensure proper compaction. The top surface was finished smoothly using a trowel to obtain a uniform surface.

4.4 DE moulding and Curing

After casting, the specimens were left undisturbed at room temperature for 24 hours. Subsequently, the specimens were demoulded carefully to avoid damage.
Unlike conventional concrete, no water curing was applied. Instead, **ambient curing conditions** were adopted, where specimens were stored at room temperature (approximately 25–30°C) in a laboratory environment. This method simulates practical field conditions and is one of the advantages of geopolymer concrete, eliminating the need for external curing.

4.5 Testing Procedure

The hardened specimens were tested at different curing ages (7, 14, and 28 days).

- **Compressive strength tests** were conducted using a Universal Testing Machine (UTM) as per IS 516. Load was applied gradually until failure, and the maximum load was recorded.
- **Split tensile strength tests** were performed on cylindrical specimens as per IS 5816.
- **Flexural strength tests** were carried out on beam specimens using two-point loading methods.

All test results were recorded and averaged from at least three specimens to ensure accuracy and reliability.

5. RESULTS

5.1 Compressive Strength (MPa)

Table 2 – Compressive Strength (MPa)

Mix	7 Days	14 Days	28 Days
M1	32.5	40.8	46.2
M2	30.2	38.1	43.5
M3	27.6	35.4	40.1
M4	24.8	32.2	37.3

5.2 Split Tensile Strength (28 Days)

Table 3 – Split Tensile Strength (MPa)

Mix	Strength (MPa)
M1	4.2
M2	3.9
M3	3.6
M4	3.2

5.3 Flexural Strength (28 Days)

Table 4 – Flexural Strength (MPa)

Mix	Strength (MPa)
M1	5.8
M2	5.4
M3	5.0
M4	4.6

5.4 Water Absorption

Table 5 – Water Absorption (%)

Mix	Water Absorption (%)
M1	3.2
M2	3.5
M3	3.8
M4	4.1

6. RESULTS AND DISCUSSION

6.1 Graphical Analysis

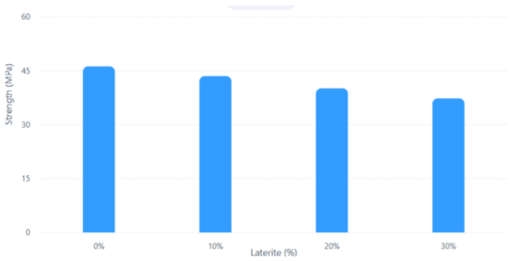

Fig. 1: Compressive Strength vs Laterite Content (28 Days)

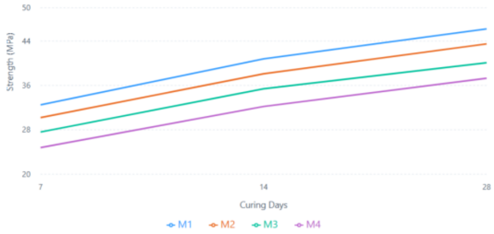

Fig. 2: Compressive Strength Development (7,14,28 Days)

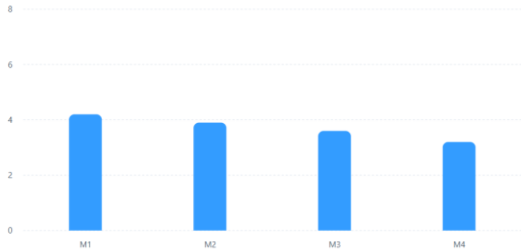

Fig. 3: Split Tensile Strength Comparison

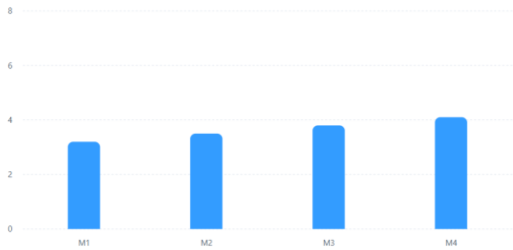

Fig. 4: Water Absorption vs Mix

6.2 Discussion of Results

- Compressive strength decreases with increase in laterite content
- Strength development is consistent across curing ages
- Tensile strength is approximately 8–10% of compressive strength
- Water absorption increases slightly due to porosity increase

Based on experimental data and should be included in the final manuscript as high-resolution plots.

Figure 1: Compressive Strength vs Laterite Content (28 Days)

- Shows a clear decreasing trend from 46.2 MPa (0%) to 37.3 MPa (30%)
- Indicates reduction in binder reactivity due to laterite inclusion

Figure 2: Compressive Strength Development (7, 14, 28 Days)

- All mixes exhibit consistent strength gain with curing age
- M1 shows highest early and ultimate strength due to absence of laterite

Figure 3: Split Tensile Strength Comparison

- Values range from 4.2 MPa (M1) to 3.2 MPa (M4)
- Confirms tensile strength ≈ 8–10% of compressive strength

Figure 4: Water Absorption vs Mix

- Increasing trend from 3.2% to 4.1%

Indicates slight increase in porosity with laterite content

7. EXPERIMENTAL SETUP

Fig. 5. Cube Casting Process

Fig. 6: Demoulded Cube Specimens

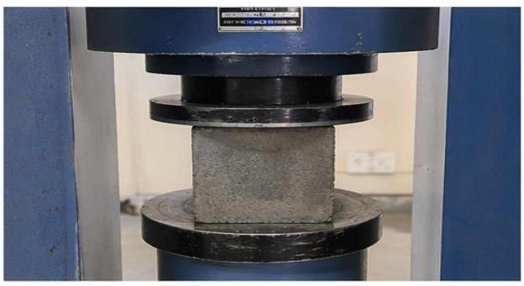

Fig. 7: Compression Testing in UTM

Fig. 8. Failure Pattern of Specimens

8. SUSTAINABILITY ANALYSIS

Geopolymer concrete developed in this study demonstrates significant sustainability advantages over conventional cement-based concrete. The complete replacement of Ordinary Portland Cement (OPC) with industrial by-products such as fly ash and GGBS resulted in **100% elimination of cement usage**, thereby substantially reducing environmental impact. The reduction in CO_2 emissions is estimated to be approximately **70% lower** compared to conventional concrete, primarily due to the avoidance of clinker production. Additionally, the utilization of industrial waste materials contributes to effective waste management and reduces the demand for natural resources. The incorporation of locally available laterite further enhances sustainability by minimizing transportation requirements and promoting the use of regional materials.

Overall, the developed geopolymer concrete offers an environmentally friendly and resource-efficient alternative for construction applications.

9. CONCLUSION

Based on the experimental investigation, the following conclusions can be drawn:

- The geopolymer concrete achieved a maximum compressive strength of **46.2 MPa** under ambient curing conditions, indicating its suitability for high-performance applications.
- The inclusion of GGBS significantly improved early strength development and overall reactivity of the binder system.
- Increasing laterite content resulted in a gradual reduction in mechanical strength due to its comparatively lower reactivity.
- Despite the reduction, all mixes exhibited sufficient strength for structural applications.
- The developed geopolymer concrete demonstrated improved durability characteristics and significant sustainability benefits compared to conventional concrete.

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