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Experimental Study on Fly Ash-GGBS Based Geopolymer Concrete

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ABSTRACT: This study focuses on the development of M25 grade geopolymer concrete as a sustainable alternative to conventional Ordinary Portland Cement (OPC) concrete and compares it to an M25 conventional concrete. The increasing environmental concerns associated with cement production, particularly high carbon dioxide emissions and energy consumption, have led to the exploration of eco-friendly construction materials. In this research, industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS) are utilized as primary binder materials, activated by alkaline solutions of sodium hydroxide and sodium silicate. The experimental program involves the preparation of different mix proportions by varying the ratio of fly ash and GGBS to evaluate their effect on workability and compressive strength. Cube specimens are cast, cured under oven-dry conditions, and tested at 3 days under 90-degree temperature to assess strength development. The results indicate that geopolymer concrete exhibits excellent early high strength and improved durability compared to conventional concrete.

I. INTRODUCTION

The rapid growth of infrastructure and urbanization has resulted in an enormous demand for concrete, making Ordinary Portland Cement (OPC) the most extensively used construction material worldwide. However, the manufacture of OPC is associated with severe environmental consequences due to its high energy requirement and large carbon footprint. Approximately 0.8–1.0 tons of carbon dioxide is emitted for every tons of cement produced, and the cement industry alone contributes nearly 7–8% of global anthropogenic CO_2 emissions. The calcination of limestone and the combustion of fossil fuels during clinker production further intensify environmental degradation and resource depletion. Consequently, the development of sustainable and low-carbon alternatives to conventional cementitious materials has become a major research focus in the field of construction materials.

Among the available alternatives, geopolymer concrete has emerged as a promising next-generation binder system because of its ability to utilize industrial aluminosilicate wastes and significantly reduce greenhouse gas emissions. Geopolymer concrete is synthesized by the alkali activation of silica- and alumina-rich precursor materials such as fly ash and Ground Granulated Blast Furnace Slag (GGBS). In the presence of alkaline activators, typically sodium hydroxide and sodium silicate, these materials undergo dissolution, reorientation, and polycondensation reactions to form a three-dimensional aluminosilicate network. Unlike OPC systems, which rely on hydration reactions, geopolymerization produces a stable polymeric binder characterized by superior mechanical strength, low permeability, and excellent durability.

Fly ash-based geopolymer systems are known for their long-term strength and chemical resistance, whereas the incorporation of GGBS accelerates the reaction kinetics and promotes early-age strength development under ambient curing conditions.

Recent investigations have demonstrated that geopolymer concrete can reduce the carbon footprint of construction by approximately 40–80% in comparison with OPC-based concrete, while maintaining or even exceeding the required structural performance. In addition, the absence of prolonged water curing and the potential for rapid setting make geopolymer concrete particularly suitable for precast members, pavement construction, emergency repair works, and other applications requiring high early strength. Nevertheless, the performance of geopolymer concrete is strongly influenced by several parameters, including the fly ash-to-GGBS ratio, alkaline activator concentration, sodium silicate-to-sodium

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hydroxide ratio, and curing conditions. Therefore, optimization of these parameters is to achieve the desired workability, strength, and durability characteristics.

The present study aims to develop an M25 grade geopolymer concrete using fly ash and GGBS as binder materials activated with sodium hydroxide and sodium silicate solutions. Emphasis is placed on evaluating the influence of binder proportion and alkaline activation on the fresh and hardened properties of the concrete. The study further compares the performance of the developed geopolymer mix with conventional OPC concrete in terms of compressive strength, durability, and sustainability, thereby assessing its suitability for long-term structural applications and environmentally responsible construction practices.

II. LITERATURE REVIEW

Recent studies highlight the growing importance of sustainable alternatives to conventional concrete. **Girish Chandra Gandhi (2025)** explored M40 concrete incorporating GGBS, fly ash, and carbon nanotubes, demonstrating improved mechanical strength and durability while reducing environmental impact. Similarly, **Chenggong Zhao et al. (2025)** developed high-strength geopolymer concrete capable of curing at ambient temperature, identifying optimal mix parameters and emphasizing enhanced microstructure and durability.Research by **Pruthviraj & Anadinni (2022)** showed that increasing molarity improves geopolymer concrete strength, though careful handling is required due to heat generation during alkaline activation. In addition, **Patel & Pandya (2022)** reported that geopolymer concrete offers higher compressive strength but at a relatively higher initial cost compared to conventional concrete.

Earlier studies also emphasized durability and material performance. **Wazien & Mustafa (2019)** highlighted the suitability of geopolymers in repair works due to superior bonding and resistance properties. **Nath & Sarker (2014)** observed that increasing the slag content enhances strength but reduces workability, while curing conditions significantly influence the development of strength.The fundamental concept of geopolymers was introduced by **Davidovits (2014)**, who described them as eco-friendly inorganic binders with low CO_2 emissions and high durability. Supporting this, **Nath & Kumar (2013)** and **Aleem & Arumairaj (2012)** investigated mix proportions and material interactions, identifying optimum aggregate ratios and activator contents for improved strength.

Further contributions by **Thockchom et al. (2011)** and **Bhikshma et al. (2011)** demonstrated that additives like silica fume enhance strength and sulphate resistance, while also explaining the chemical structure of geopolymerization. Finally, **Lloyd & Rangan (2010)** provided a comprehensive overview of geopolymer concrete, establishing it as a viable, low-carbon alternative to traditional Portland cement concrete.

III. MATERIALS

Fly Ash

Fly ash used in this project was obtained from NTPC Mouda and belongs to the Class F category. It is a fine, powdery material rich in silica and alumina, exhibiting strong pozzolanic properties. The specific gravity of fly ash is 2, and it significantly contributes to improving the workability, durability, and long-term strength of concrete.

GGBS (Ground Granulated Blast Furnace Slag)

GGBS is a by-product of the iron manufacturing industry and appears as a fine, off-white powder with high glass content. It contains calcium silicates and aluminosilicates, which contribute to its cementitious properties when activated. The fineness of GGBS used was greater than 320 m^2/kg, satisfying IS 16714-2018 requirements. The material contributes to higher long-term strength and better microstructural properties of geopolymer concrete.

Fine Aggregate

Fine aggregate used in this study was natural river sand obtained from the Bhandara River. It falls under Zone II as per IS 383-1970 and has a fineness modulus of 3.086. The sand is clean, hard, and free from impurities, ensuring good bonding with the binder materials. It has a specific gravity of 2.621and water absorption of about 1.8%. Fine aggregate plays a crucial role in enhancing the workability, surface finish, and overall strength of concrete.

Coarse Aggregate

Coarse aggregate used was sourced from Panchgav, Nagpur, consisting of crushed stone with particle sizes 20mm and 10mm. It has a fineness modulus of 8.62, specific gravity of 3.06, and water absorption of 1.56%. The aggregates are strong, durable, and free from deleterious materials, which ensures good compressive strength and structural stability.

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Sodium Hydroxide (NaOH)

Sodium hydroxide in the form of flakes with about 99% purity was used as an alkaline activator. It was dissolved in water to prepare a 12-molar solution, which is essential for initiating the geopolymerization process. NaOH helps in dissolving silica and alumina present in fly ash and GGBS, leading to the formation of a strong geopolymer binder.

Sodium Silicate (Na_2SiO_3)

Sodium silicate, also known as water glass, was used along with sodium hydroxide as part of the alkaline activator solution. It provides soluble silica, which enhances the polymerization process and improves the bonding, strength, and setting characteristics of geopolymer concrete. The combination of sodium silicate and sodium hydroxide plays a critical role in achieving desired mechanical properties.

Alkaline Activator Solution

The alkaline activator solution was prepared by mixing sodium hydroxide and sodium silicate in a ratio of 1:2.5 by weight. This solution is responsible for initiating the geopolymerization reaction by dissolving aluminosilicate materials and forming a strong binding matrix. The concentration of NaOH was maintained at 12M to ensure effective reaction and strength development.

IV. METHODOLOGY

The methodology adopted for the preparation of geopolymer concrete involved a systematic experimental procedure including material selection, mix design, preparation of alkaline activator, mixing, casting, and curing of specimens. Initially, suitable materials such as fly ash, GGBS, fine aggregate, coarse aggregate, and alkaline activators (sodium hydroxide and sodium silicate) were selected based on their physical and chemical properties. The mix design was carried out for M25 grade geopolymer concrete by maintaining a binder content of 400 kg/m³ and an activator-to-binder ratio of 0.35. The alkaline activator solution was prepared by mixing sodium hydroxide and sodium silicate in a ratio of 1:2.5, with sodium hydroxide solution having a concentration of 12M. The solution was prepared 24 hours prior to mixing to allow proper dissolution and stabilization.The mixing process was carried out in two stages to ensure uniformity. In the first stage, dry materials such as fly ash, GGBS, and aggregates were thoroughly mixed for about 3 minutes. In the second stage, the prepared alkaline activator solution was gradually added to the dry mix and mixed continuously for 5–8 minutes until a homogeneous and workable concrete mix was obtained. The fresh geopolymer concrete was then tested for workability using a slump cone test, where a slump value of approximately 120 mm was achieved, indicating good workability.

For casting, cube moulds of size 150 mm × 150 mm × 150 mm were cleaned, oiled, and filled with concrete in three layers. Each layer was compacted using 25 strokes of a tamping rod, followed by vibration to remove entrapped air and ensure proper compaction. After casting, the specimens were left undisturbed at room temperature for 24 hours for initial setting. The specimens were then demolded carefully and subjected to heat curing in an oven at a temperature of 90°C for 72 hours to accelerate the geopolymerization process and achieve early strength gain. This systematic methodology ensured the development of geopolymer concrete with desired strength, durability, and performance characteristics.

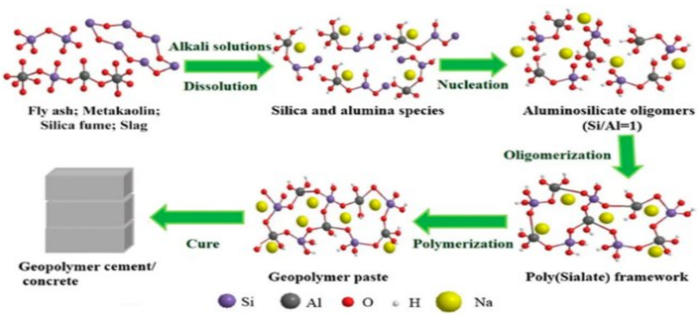

Fig 1 Geopolymerization Reaction (Source: https://www.researchgate.net/publication/352158993_Pathways_to_Commercialisation_for_Brown_Coal_Fly_Ash-Based_Geopolymer_Concrete_in_Australia)

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Mix Design Steps

1. Stipulation of proportioning
i) Grade Designation – M25
ii) Characteristics Compressive Strength = 25 MPa
iii) Binder = 100% Fly ash
iv) Activator/Binder ratio = 0.35
v) Sodium Silicate/ Sodium Hydroxide = 2.5
vi) Workability = 120 mm (slump)
vii) Exposure Condition = Moderate
2. Target Mean Strength
Fck= Fck + t x s
=25 + 1.65 x 4
= 31.6 N/mm2
4. Selection of Binder Content
Typical binder content = 350-450 kg/m3
Adopt 400 kg/m3
5. Calculation of alkaline activator content
Activator = 0.35 x 400
= 140 kg/m3
Total = 140 kg/m3
6. Split of activator
Sodium silicate / sodium hydroxide = 2.5
Na_2SiO_3 + NaOH = 140
3.5 NaOH = 140
NaOH = 40 kg
Na_2SiO_3 = 100 kg
7. Selection of Aggregate
As per IS 10262
Coarse aggregate = 65%
Fine aggregate = 35%
Approximate density of GPC = 2400 kg/m3
Total aggregate = 2400- (Binder + Activator)
= 2400 – (400 + 140)
= 1860 kg
Fine aggregate = 0.35 x 1860
= 651 kg
Coarse aggregate = 0.65 x 1860
= 1209 kg
8. Selection of water content
Typical additional water = 5 – 10%
Assume = 8% to ensure workability
0.08 x 400
= 32 kg
9. Mix proportion for M25 grade
1. Fly Ash = 400 kg/m3
2. NaOH = 40 kg/m3
3. Na_2SiO_3 = 100 kg/m3
4. Fine Aggregate = 650 kg/m3
5. Coarse Aggregate = 1210 kg/m3
6. water = 30 kg/m3
10. Design Mix Ratio for M25 geopolymer concrete
Mix proportion
1: 1.63: 3.02
Alkaline activator = 0.35, and Sodium silicate/ sodium hydroxide = 2.5

Table-1: Different Fly Ash and GGBS Proportions

Mix Type	Cement %	Fly Ash %	GGBS %
Mix 1 (Conventional)	100	0	0
Mix 2	0	100	0
Mix 3	0	0	100
Mix 4	0	50	50
Mix 5	0	70	30
Mix 6	0	30	70
Mix 7	0	90	10
Mix 8	0	80	20

V. EXPERIMENTAL PROGRAM

Geopolymer Concrete

Geopolymer concrete is produced by activating aluminosilicate materials, such as fly ash and Ground Granulated Blast Furnace Slag (GGBS), using a strong alkaline solution. Unlike conventional concrete, it does not rely on hydration but on a geopolymerization process, resulting in faster strength gain, reduced shrinkage, and improved durability. Due to these advantages, geopolymer concrete is considered a sustainable alternative to Portland cement concrete, particularly suitable for structural and prestressed applications.

Preparation of Alkaline Activator

The alkaline activator solution was prepared by dissolving sodium hydroxide flakes in water and allowing it to cool for 24 hours. After cooling, it was mixed with sodium silicate in the required proportion. This solution was prepared one day prior to casting to ensure proper reaction and stability.

Fig 2 Alkaline Activator Solution

Fig 3 Concrete Cube Casting

Preparation of Concrete

Concrete mixing was carried out in two stages. Initially, dry materials (fly ash/GGBS and aggregates) were mixed for 3-5 minutes. Then, the alkaline activator solution was added gradually and mixed for 5–8 minutes until a uniform and workable mix was obtained. Cube specimens of size 150 mm × 150 mm × 150 mm were cast for compressive strength testing. For each mix, three specimens were prepared.

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Fig 4 Heat Curing in Oven (90°C)

VI. RESULT AND DISCUSSION

Conventional Concrete (M25 Grade)

Cube specimens were cast using conventional concrete. The concrete was placed in moulds and properly compacted to eliminate voids. After 24 hours, specimens were demoulded and subjected to water curing for 28 days. The top surface was finished smoothly to ensure uniform load distribution. Compressive strength was determined by using a Compression Testing Machine (CTM).

Geopolymer Concrete (M25 Grade)

Similar cube specimens were prepared for geopolymer concrete. After casting and compaction, the specimens were demoulded after 24 hours and subjected to heat curing at 90°C. The surfaces were finished smoothly before testing. Compressive strength was measured using a CTM.

Table 2 Compressive Strength of Heat-Cured GPC (90°C)

Mix Type	Cube 1 Strength (N/mm²)	Cube 2 Strength (N/mm²)	Cube 3 Strength (N/mm²)	Avg. Strength (N/mm²)
Mix 1 (Conventional)	26.25	27.65	26.49	26.50
Mix 2	26.74	25.96	26.65	26.45
Mix 3	99.83	93.34	81.36	91.51
Mix 4	63.23	63.46	59.27	61.36
Mix 5	37.75	49.64	45.46	44.28
Mix 6	42.77	38.77	36.66	39.40
Mix 7	16.80	17.00	17.56	17.12
Mix 8	38.18	39.58	38.50	38.75

Analysis of Results

The compressive strength results clearly indicate that the performance of geopolymer concrete varies significantly with the proportion of Fly Ash and GGBS. Among all mixes, Mix 3 achieved the highest average compressive strength of 91.51 N/mm², while Mix 7 recorded the lowest strength of 17.12 N/mm².

Mixes containing higher proportions of GGBS generally exhibited superior strength compared to those with higher fly ash content. Moderate combinations, such as Mix 4, also showed good performance, indicating a balanced interaction between the materials.

Effect of GGBS Content

An increase in GGBS content significantly enhances compressive strength due to its high calcium content, which promotes faster geopolymerization and results in a denser microstructure.

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Effect of Fly Ash Content

Fly ashes improve workability and provide good consistency; however, it contributes to the lower early strength due to its slower reaction rate compared to GGBS.

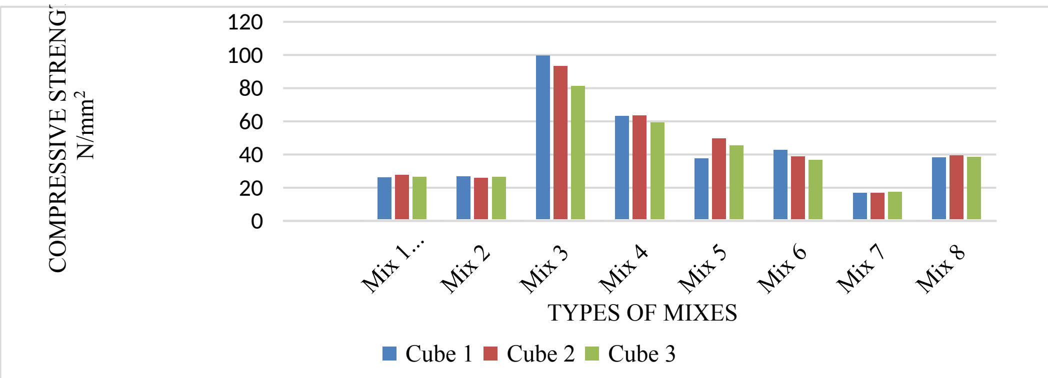

Fig 5 Compressive Strength of Various Mixes

Effect of Heat Curing

Heating at 90°C for 72 hours accelerates the geopolymerization process, leading to rapid strength development and improved overall performance.

Comparison with Conventional Concrete Geopolymer concrete mixes, particularly those with higher GGBS content, exhibited significantly higher compressive strength compared to conventional concrete. This demonstrates that geopolymer concrete can be considered a strong and sustainable alternative to traditional Portland cement concrete.

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