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Research Article

Analysis of Fly Ash and GGBS-based Geopolymer Concrete under Different Curing Conditions

Deepmala Pandey[1]*, Rakesh Kumar Pandey[1] and R. K. Mishra[2]
[1]Department of Civil Engineering, MATS UNIVERSITY, Arang, Raipur, CG, India
[2]Department of Civil Engineering, Bhilai Institute of Technology, Kendri, Raipur, CG, India
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*deepmalapandey54@gmail.com

ABSTRACT

This research explores how changes in the amount of activator, curing methods, and the type of starting materials affect the characteristics of geopolymer concrete (GPC). Concrete mixtures were made using various ratios of fly ash, ground granulated blast furnace slag (GGBS), and sodium hydroxide (NaOH) solutions of different concentrations (8, 10, and 12M), and then cured under normal room temperature, heat, and steam conditions. The initial properties of the concrete were measured with a slump test, and the properties that had been fully set, such as the ability to withstand compression, split tensile strength, and bending strength, were tested at 7, 14, and 28 days. The findings indicate that increasing the concentration of NaOH and using steam for curing greatly enhances the strength of GPC, with the best-performing mix of fly ash and GGBS. A cost analysis comparing GPC with standard Portland cement concrete (PCC) indicates that while GPC has higher initial costs, it offers superior durability and environmental benefits.

Keywords: Geopolymer; Concrete; Fly ash; GGBS; Sodium hydroxide.

1. INTRODUCTION

Since cement production has a pronounced environmental impact, the building industry isconstantly exploring eco-friendly alternatives to traditional Portland cement concrete (PCC). Geopolymer concrete (GPC) is a promising solution that uses waste materials from industries such as fly ash (FA) and ground granulated blast furnace slag (GGBS) as key constituents (Ahmed *et al.* 2022). This saves waste and considerably reduces carbon dioxide emissions compared to PCC manufacture (Ahmed et al. 2021).Geopolymer concrete is created by mixing alumino-silicate materials with alkali activators such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) to initiate the polymerization process. These activators aid in the chemical processes that produce a strong, long-lasting binder (Davidovits *et al.* 1989). GPC's efficiency is determined by several factors, including the type and quantity of raw materials employed, the degree of alkali activators, and the curing conditions (Mohammed *et al.* 2021).The purpose of this research is to improve the mix design of geopolymer concrete by examining the impacts of varied mixes of FA and GGBS, as well as altering alkali activator concentrations. The research covers a side-by-side comparison of the new and solid properties of GPC and regular PCC under various curing conditions. In addition, a cost study is performed to determine the economic viability of employing GPC in construction. The main goal of this study is to investigate how varying concentrations of activators, curing methods, and the incorporation of fly ash and GGBS impact the initial and final characteristics of geopolymer concrete. This encompasses assessing workability by conducting slump tests and determining mechanical robustness through tests for compressive, tensile, and flexural strength at different curing stages. The conventional methods have used fly ash, blast furnace slag, and alkaline activator solution prepared using distilled water and cured using ambient and oven curing.

Advancements and research in the field of alkali-activated materials and geopolymers focuses on exploring alternative binders for construction materials, aiming to provide environmentally friendly and sustainable solutions (Lee *et al.* 2024). For modeling the compressive strength of geopolymer mortars the statistical approaches helps in developing a relationship between various parameters and the compressive strength of geopolymer mortar, providing valuable insights into optimizing the properties of these materials (Ahmed *et al.* 2022). The flexural properties of reinforced geopolymer concrete incorporating hazardous heavy metal waste ash and glass powder, the mechanical characteristics and performance of geopolymer concrete with these components offers insights into sustainable and innovative construction techniques (Suresh *et al.* 2022). Comprehensive analysis of the compressive strength of sustainable geopolymer concrete composites highlights current research, breakthroughs, problems, and future directions in the field of sustainable geopolymer concrete (Ahmed *et al.* 2021). The influence of different alkaline activators on the mechanical properties of fly ash-based geopolymer concrete cured at room temperature focuses

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on effects of various activators on the strength and durability of geopolymer concrete, providing valuable insights for enhancing its performance (Ghafoor *et al.* 2021). Alkali-activated materials, such as geopolymer concrete (GPC), align well with sustainable development goals due to their benefits: high strength, utilization of secondary materials, low carbon footprint, reduced greenhouse gas emissions, and good frost resistance (Mohammed *et al.* 2021). By Determination of flexural strength and failure behavior of geopolymer concrete beams reinforced with carbon fiber-reinforced polymer bars provide insights into their structural characteristics and potential applications (Ahmed *et al.* 2020). The technical characteristics of ordinary Portland cement concrete with those of alkali-activated slag concrete and high-strength fly ash-based geopolymer concrete helps in understanding the mechanical and durability properties of these different types of concrete, providing insights into the potential advantages and challenges of using alternative binders in concrete production (Farhan *et al.* 2019). The effects of varying curing conditions on the mechanical properties of geopolymer concrete made with fly ash helps in understanding how different curing techniques influenced the strength and durability of geopolymer concrete (Hassan *et al.* 2019). The fresh and hardened properties of one-part geopolymer binders made from fly ash and cured at room temperature helps understand the influence of slag and alkali activators on the performance of geopolymer binders, thus helping to study about their development and behavior under ambient curing conditions (Oderji *et al.* 2019). The study of influence of reactive alumina, sodium content, and molarity on the alkaline activation of nano clays and GGBS, emphasizes on reactive alumina's role in achieving compressive strength (Ravitheja and Kumar, 2019). In geopolymer concrete, where cement is replaced with fly ash and activated by alkaline solutions, as an eco-friendly alternative to conventional concrete, where 76% aggregate content is analyzed as optimal for workability, with maximum strength achieved at 90°C using 12M NaOH, emphasizing its potential for sustainable construction (Chithambaram *et al.* 2018).

2. MATERIALS AND METHODS

2.1 Materials

The materials for this experiment were collected from Raipur, Chhattisgarh, India:

- Fly Ash: Sourced from a thermal power plant in Raipur, Chhattisgarh, India.
- GGBS: Sourced from a steel plant in Bhilai, Chhattisgarh, India.
- NaOH: Pellets dissolved in water to prepare solutions of 8, 10, and 12M concentrations.
- Na_2SiO_3: Commercially available solution used in combination with NaOH.

2.2 Sample Preparation

Concrete mix samples were prepared at the Bhilai Institute of Technology, Kendri, Raipur, India. The mixes were:

- FA1: 100% Fly Ash, 8M NaOH, 2.0 Na_2SiO_3/NaOH ratio
- FA2: 100% Fly Ash, 10M NaOH, 2.0 Na_2SiO_3/NaOH ratio
- FA3: 100% Fly Ash, 12M NaOH, 2.0 Na_2SiO_3/NaOH ratio
- GGBS1: 100% GGBS, 8M NaOH, 2.0 Na_2SiO_3/NaOH ratio
- GGBS2: 100% GGBS, 10M NaOH, 2.0 Na_2SiO_3/NaOH ratio
- GGBS3: 100% GGBS, 12M NaOH, 2.0 Na_2SiO_3/NaOH ratio
- FA+GGBS: 50% Fly Ash, 50% GGBS, 10M NaOH, 2.0 Na_2SiO_3/NaOH ratio

2.3 Mixing and Casting

The activator solutions were prepared by dissolving NaOH pellets in water to achieve the desired molarity. Na_2SiO_3 was mixed with NaOH solution at a 2.0 ratio. The fly ash and/or GGBS were thoroughly mixed with the activator solution to form a homogenous paste. The paste was then cast into square molds (150mm/6") and vibrated to remove air bubbles as shown in Fig 1.

Fig. 1: Experimental Samples of Geopolymer Concrete

2.4 Curing Conditions

Three different curing conditions were applied:

- Ambient Curing: Samples cured at room temperature (25 °C).
- Oven Curing: Samples cured at 60°C for 24 hours.
- Steam Curing: Samples cured in a steam environment at 80°C for 8 hours.

2.5 Measurement of Fresh Properties

In this experiment, the "True Slump" type of slump test, as per IS: 1199-1959,was used. True slump refers to a uniform downward displacement of the concrete without any lateral or shear movement. This type of slump indicates good workability and cohesiveness of the concrete mix.

To carry out the slump test, new mixtures of geopolymer concrete were made following the set ratios, which included materials like fly ash or GGBS, alkaline catalysts, and aggregates. The inside of the slump cone and the base plate were wetted to avoid the concrete absorbing water from the mixture, and the slump cone was positioned on the base plate. The cone was filled in three layers, each about one-third of the cone's height. Each layer was evenly compacted by pressing it down 25 times with a tamping rod. Once the cone was full, any surplus concrete was removed from the top to ensure a flat and uniform top surface. The slump cone was then lifted steadily straight up, without any sideways or rotational movement, allowing the concrete to naturally slump due to its weight. Right after lifting, a vertical scale was set up next to the slumped concrete to measure the vertical distance from the top of the slump cone to the highest point of the slumped concrete, which indicated the slump value. This value was noted to the nearest 5 mm, along with information about the concrete mix, the environmental conditions, and any variations from the standard process.

2.6 Measurement of Hardened Properties

2.6.1 Compressive Strength

Compressive strength tests were conducted at 7, 14, and 28 days according to standard procedures, by testing the cubical specimens.

2.6.2 Split Tensile Strength

Split tensile strength tests were conducted at28 days to evaluate the tensile properties of the geopolymer concrete and results are presented in Table 2.

2.6.3 Flexural Strength

Flexural strength tests were conducted at28 days to assess the bending strength of the concrete, and presented in Table 3.

2.6.4 Cost Analysis

A cost analysis was conducted comparing GPC with standard PCC. The analysis considered material costs, energy consumption for curing, and labor costs as depicted in Table 4.For material costs, GPC typically uses fly ash and GGBS, both by-products of coal combustion and the steel industry, respectively. These materials are generally available at lower costs, especially in regions with coal-fired power plants and steel manufacturing facilities. NaOH and Na_2SiO_3 were used as activators in GPC. The cost of NaOH varies with concentration, with higher molarity solutions being more expensive. Aggregates used in GPC are similar in cost to those used in PCC. On the other hand, PCC primarily relies on Portland cement as the binding material, which is typically more expensive than fly ash or GGBS. Aggregates and water used in PCC contribute to the overall mix but are generally similar in cost to that of GPC.

Labor costs for both GPC and PCC are relatively similar. However, GPC may require specialized knowledge for mixing and handling the activators, which could slightly increase labor costs depending on the expertise required.

Curing time and costs also differ between GPC and PCC. GPC can be cured through various methods, including ambient curing, oven curing, and steam curing. Ambient curing is cost-effective but results in slower strength gain. Oven curing and steam curing, while providing faster strength gain, require energy input, thus increasing the cost. PCC is typically cured at ambient conditions with additional moisture curing to prevent drying out. While PCC curing times are longer compared to GPC with steam curing, they are less energy-intensive.

In terms of quality, GPC can achieve comparable or superior compressive strengths to PCC, especially with optimized mix designs and curing conditions. GPC is generally more resistant to chemical attacks and has lower permeability, enhancing its durability. The workability of GPC can be tailored using different activator ratios and molarities. PCC, on the other hand, has well-established and reliable compressive strength with predictable strength gain over time. While PCC durability can be enhanced with additives, it is generally less resistant to chemical attacks compared to GPC. PCC's workability is well-known and can be modified with admixtures to suit different construction needs. All these findings are presented in Table 5.

3. RESULTS AND DISCUSSION

3.1 Slump Test (Workability)

An increased slump value signifies better workability, meaning the concrete mix was more liquid and simpler to manage. On the other hand, a decreased slump value indicatesa decreased workability, showing a more rigid mix that needed more work to be placed and compacted.

- FA1 (100% Fly Ash, 8M NaOH, 2.0 Na_2SiO_3/NaOH ratio): Slump = 160 mm
- FA2 (100% Fly Ash, 10M NaOH, 2.0 Na_2SiO_3/NaOH ratio): Slump = 150 mm
- FA3 (100% Fly Ash, 12M NaOH, 2.0 Na_2SiO_3/NaOH ratio): Slump = 140 mm

- GGBS1 (100% GGBS, 8M NaOH, 2.0 Na_2SiO_3/NaOH ratio): Slump = 170 mm
- GGBS2 (100% GGBS, 10M NaOH, 2.0 Na_2SiO_3/NaOH ratio): Slump = 160 mm
- GGBS3 (100% GGBS, 12M NaOH, 2.0 Na_2SiO_3/NaOH ratio): Slump = 150 mm
- FA+GGBS (50% Fly Ash, 50% GGBS, 10M NaOH, 2.0 Na_2SiO_3/NaOH ratio): Slump = 155 mm

The results indicate that increasing the molarity of NaOH slightly reduces the workability of the mixes, likely due to the higher viscosity of more concentrated solutions. Mixes containing GGBS generally exhibited higher workability compared to those with only fly ash.

3.2 Compressive Strength

It is calculated by testing the prepared and cured concrete specimens in a standard compression testing machine. The ability of concrete to withstand compression is a key factor in evaluating its structural integrity. Experiments were carried out at 7, 14, and 28 days.

Table 1. Compressive strength of different concrete mix

Mix ID	Curing Condition	7 days (MPa)	14 days (MPa)	28 days (MPa)
FA1	Ambient	18.5	25.0	31.2
FA1	Oven	22.1	28.4	34.7
FA1	Steam	24.5	30.2	37.5
FA2	Ambient	19.8	26.7	33.5
FA2	Oven	23.4	30.1	36.9
FA2	Steam	25.8	32.5	39.8
FA3	Ambient	21.0	28.1	35.0
FA3	Oven	24.7	31.5	38.4
FA3	Steam	27.2	34.3	41.2
GGBS1	Ambient	20.0	26.5	32.0
GGBS1	Oven	23.2	28.9	34.5
GGBS1	Steam	25.4	30.8	36.7
GGBS2	Ambient	21.5	28.3	34.2
GGBS2	Oven	25.0	31.2	37.1
GGBS2	Steam	27.3	34.0	39.8
GGBS3	Ambient	22.8	29.7	36.0
GGBS3	Oven	26.1	32.5	38.5
GGBS3	Steam	28.5	35.2	41.3
FA+GGBS	Ambient	23.1	30.0	37.1
FA+GGBS	Oven	26.4	33.0	39.0
FA+GGBS	Steam	29.0	35.7	42.5

The information shows that an increased concentration of NaOH and steam curing methods greatly improve the compressive strength of geopolymer concrete. Mixing fly ash with GGBS (FA+GGBS) resulted in the greatest compressive strength values for all curing methods and testing durations.

3.3 Split Tensile Strength

Tensile strength tests were carried out at 28 days to assess the tensile characteristics of the geopolymer concrete, as presented in Table 2.

The split tensile strength results align with the compressive strength findings, showing improved performance with higher NaOH molarity and steam curing.

3.4 Flexural Strength

Flexural strength tests were conducted at 28 days to assess the bending strength of the concrete as depicted in Table 3.

Table 2. Split tensile strength of the geopolymer concrete

Mix ID	Curing Condition	28 days (MPa)
FA1	Ambient	3.2
FA1	Oven	3.7
FA1	Steam	4.0
FA2	Ambient	3.5
FA2	Oven	4.0
FA2	Steam	4.3
FA3	Ambient	3.7
FA3	Oven	4.2
FA3	Steam	4.6
GGBS1	Ambient	3.3
GGBS1	Oven	3.8
GGBS1	Steam	4.1
GGBS2	Ambient	3.6
GGBS2	Oven	4.1
GGBS2	Steam	4.5
GGBS3	Ambient	3.8
GGBS3	Oven	4.3
GGBS3	Steam	4.7
FA+GGBS	Ambient	3.9
FA+GGBS	Oven	4.4
FA+GGBS	Steam	4.8

Table 3. Flexural strength test result

Mix ID	Curing Condition	28 days (MPa)
FA1	Ambient	5.0
FA1	Oven	5.5
FA1	Steam	5.9
FA2	Ambient	5.3
FA2	Oven	5.8
FA2	Steam	6.2
FA3	Ambient	5.5
FA3	Oven	6.0
FA3	Steam	6.4
GGBS1	Ambient	5.1
GGBS1	Oven	5.6
GGBS1	Steam	6.0
GGBS2	Ambient	5.4
GGBS2	Oven	5.9
GGBS2	Steam	6.3
GGBS3	Ambient	5.6
GGBS3	Oven	6.1
GGBS3	Steam	6.5
FA+GGBS	Ambient	5.7
FA+GGBS	Oven	6.2
FA+GGBS	Steam	6.6

The flexural strength results further support the trend observed in compressive and tensile strengths, highlighting the benefits of using higher molarity NaOH and steam curing.

3.5 Cost Analysis

A cost analysis was conducted comparing GPC with standard Portland cement concrete. The analysis considered material costs, energy consumption for curing, and labor costs as depicted in Table 4.

The cost analysis reveals that while GPC is more expensive than PCC primarily due to the cost of activators and curing energy, it offers significant environmental benefits and superior mechanical properties, which can justify the higher initial investment for specific applications.

Table 4. Cost comparison of GPC and PCC

Component	GPC (INR/m³)	PCC (INR/m³)
Raw Materials	3000	2500
Activators	1500	-
Curing Energy	500	200
Labor	1000	1000
Total Cost	6000	3700

Table 5. Cost analysis over time

Cost Component	GPC	PCC
Material Cost	Lower for fly ash and GGBS; higher for activators	Higher for cement
Labor Cost	Additional cost for training	Standard labor costs
Curing Cost	Higher for oven/steam curing, lower for ambient	Lower, primarily ambient curing
Quality	Higher durability, adjustable workability	Reliable strength, adjustable with admixtures
Long-term Performance	Superior resistance to chemical attack, longevity	Reliable with knownperformance metrics

Overall, while GPC may have higher initial costs due to the use of chemical activators and potentially higher curing costs, these can be offset by the lower cost of precursor materials like fly ash and GGBS. Additionally, the superior durability and chemical resistance of GPC can result in lower maintenance costs over the lifespan of the structure. In contrast, PCC has higher material costs due to cement but benefits from well-understood handling and curing processes with predictable performance outcomes. The choice between GPC and PCC will depend on specific project requirements, availability of materials, and long-term performance considerations.

The study revealed that the fresh properties of geopolymer concrete (GPC), assessed through slump tests, showed varying workability based on NaOH molarity and precursor materials. Higher NaOH concentrations generally reduced workability, especially in fly ash-based mixes, while the combination of fly ash and GGBS provided balanced workability. Hardened properties, including compressive, split tensile, and flexural strengths, significantly improved with higher NaOH molarity and steam curing. The FA+GGBS mix consistently exhibited superior performance across all strength tests, suggesting that GGBS enhances long-term strength and durability due to additional hydration products.

In terms of cost analysis, GPC benefits from lower material costs owing to the use of fly ash and GGBS, which are cheaper than Portland cement; however, the cost of chemical activators like NaOH and Na_2SiO_3 adds to the initial expenses. Despite the higher initial costs, GPC offers long-term economic advantages due to its superior durability and lower maintenance requirements compared to Portland cement concrete. The environmental benefits of GPC, such as reduced carbon emissions and utilization of industrial by-products, further enhance its attractiveness as a sustainable construction material.

GPC with optimized mix designs and curing conditions not only meets but often exceeds the performance of traditional PCC, making it a viable and sustainable alternative for the construction industry.

4. CONCLUSION

This research has proven that geopolymer concrete has significant benefits over conventional Portland cement concrete in both performance and environmental sustainability. The findings from the experiments indicate that increasing the concentration of NaOH solutions and using steam curing methods significantly improve the strength of GPC. Among the various mixtures examined, the mix of fly ash and GGBS

(FA+GGBS) consistently achieved the highest strengths in compression, tensile splitting, and bending.This outstanding performance is due to the combined action of the pozzolanic reaction between fly ash and GGBS, which results in the creation of extra hydration products that boost long-term strength and durability. Regarding its initial properties, the FA+GGBS mix offered a good balance of workability, making it ideal for real-world use. The cost comparison showed that while GPC might have higher upfront expenses due to the need for chemical activators, these expenses are compensated by the lower costs of fly ash and GGBS when compared to Portland cement. Moreover, the long-term financial advantages of GPC, such as reduced maintenance and better durability, further support its adoption.

Furthermore, GPC offers significant environmental benefits by reducing carbon emissions and utilizing industrial by-products, aligning with sustainable construction practices. Overall, the findings of this study suggest that GPC, with optimized mix designs and curing conditions, is not only a viable alternative to PCC but also a superior choice for achieving durable, sustainable, and high-performance concrete structures.

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CONFLICT OF INTEREST

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