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# Optimizing Characteristics of Ferro-Geopolymer Composites for Structural Applications

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**_Abstract_**

*This study focuses on developing an optimal mix for geopolymer mortar (GPM) using varying molarities of NaOH solution and different binder-to-aggregate ratios. The primary objective was to determine the mix that yields the highest compressive strength. GPM cubes were prepared and subjected to two curing methods – oven curing and steam curing. Compressive strength tests were conducted at 3, 7, and 28 days. The results show that the compressive strength of GPM cubes increases with NaOH molarity up to 14M, with a significant decline observed at 16M. A binder-to-aggregate ratio of 2.5 was identified as the most effective, providing maximum strength, especially when combined with 14M NaOH. Oven-cured specimens consistently displayed higher compressive strength compared to steam-cured ones, due to enhanced polymerization at elevated temperatures. The findings suggest that a 14M NaOH solution with a 2.5 binder-to-aggregate ratio, combined with oven curing, produces the most robust geopolymer matrix. This optimized mix has potential applications in the development of ferro-geopolymer composite elements for sustainable and durable construction materials.*

**Keywords:** Geopolymer mortar, compressive strength, NaOH molarity, binder-to-aggregate ratio, oven curing, steam curing, ferro-geopolymer

## INTRODUCTION

Cement concrete has been extensively utilized as a construction material since the 19th-century advent of Portland cement. It is an “artificial stone” created by combining cement, sand, aggregates, and water in precise proportions. Like natural stone, cement concrete exhibits high compressive strength but low tensile strength. To address this limitation, reinforcements were added, leading to the development of reinforced cement concrete (RCC). Notably, French engineer Joseph-Louis Lambot pioneered its use by constructing a boat using cement, sand, steel, wire mesh, and water. This invention, later termed ferrocement, represents one of the earliest applications of RCC [1–3].

Ferrocement is a composite material consisting of cement mortar reinforced with fibers, enhancing its overall performance beyond that of its individual components. The term “ferrocement” denotes a combination of cement (mortar) and ferrous materials (steel fibers). According to the ACI Committee 549, ferrocement is defined as a type of thin-walled reinforced concrete construction, where hydraulic cement is typically reinforced with multiple layers of fine mesh. These meshes, made from metal or other suitable materials, are characterized by their small diameters (Figure 1) [4–6].

While cement is a crucial binding agent in construction, its production has significant

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environmental consequences. The cement industry is a major contributor to carbon dioxide ($CO_2$) emissions. The key raw material, limestone (calcium carbonate), is heated with shale at around 1400°C to produce cement, a process that releases substantial amounts of $CO_2$ and other greenhouse gases, contributing to global warming. Cement production is responsible for approximately 5% of global $CO_2$ emissions. The burning of fossil fuels contributes 40% of these emissions, calcination accounts for 50%, and the remaining 10% comes from activities like transportation and electricity usage. It is estimated that producing 1 ton of cement results in an equivalent release of $CO_2$ into the atmosphere. India, second only to China in cement production, faces growing pressure to adopt sustainable construction practices [7–10].

**Figure 1.** Lambot’s ferrocement boat.

India’s reliance on coal-powered thermal plants for more than 65% of its electricity has resulted in large quantities of fly ash, a by-product that poses environmental disposal challenges. Initially, fly ash was partially incorporated into cement to reduce $CO_2$ emissions, but further reductions can be achieved by fully replacing cement with fly ash or similar industrial by-products. Geopolymer concrete (GPC), which uses fly ash or similar materials instead of cement, offers a sustainable alternative [11–13].

## OBJECTIVES

The primary objectives of this study are to develop an optimal mix design for geopolymer mortar (GPM) by evaluating the effects of varying sodium hydroxide (NaOH) molarity and binder-to-aggregate ratios on compressive strength. It aims to analyze the influence of different curing methods, specifically oven and steam curing, on the strength development of GPM cubes at 3, 7, and 28 days. The study seeks to determine the best combination of NaOH molarity and binder-to-aggregate ratio for achieving maximum compressive strength. Additionally, the study applies the optimal GPM mix in the development of ferro-geopolymer composite elements for enhanced structural performance [14].

## MATERIAL

The materials utilized for casting the ferro-geopolymer specimens include fly ash, an alkaline activator solution (comprising NaOH and sodium silicate ($Na_2SiO_3$)), fine aggregate, and a superplasticizer. These materials were sourced, and preliminary tests were conducted as necessary [15].

### Fly Ash

Fly ash was obtained from the Mandeep district in Madhya Pradesh. It was classified as Class F according to ASTM C618-08a standards.

### Activator Solution

In conventional cement concrete, strength develops through a hydration reaction, while in GPC, strength is derived from a polymerization reaction. To achieve the required strength, GPC must be activated using a highly reactive alkaline activator solution. This solution consists of NaOH pellets with a purity of 99% and $Na_2SiO_3$ solution, which contains 8% $Na_2O$, 28% $SiO_2$, and the remainder as water by mass. The pellets are dissolved in water to produce the NaOH solution, a process that generates significant heat due to its exothermic nature. The concentration of NaOH in the solution varies based on the molarity; for instance, a 14 M NaOH solution contains 560 grams of NaOH dissolved in one liter of solution, considering the molecular weight of NaOH is 40. The alkaline activator is prepared by combining one part of the NaOH solution with 2.5 parts of the $Na_2SiO_3$ solution by mass. After mixing, the activator solution is allowed to cool for 24 hours to reach room temperature before casting. NaOH is generally preferred over potassium hydroxide due to its lower cost and greater reactivity. Standard NaOH pellets are commercially available [16–20].

### Fine Aggregate

Manufactured sand was utilized as the fine aggregate for preparing the mortar. A sieve analysis was performed in accordance with IS 383-1970 standards. For the preparation of mortar cubes and test specimens, M-sand that passed through a 2 mm sieve and was retained on a 90-micron sieve was employed [21].

### Superplasticizer

Due to the stiff nature of the mix, ensuring workability is a significant concern when preparing geopolymer mixtures. Conplast SP 430 was selected as the superplasticizer. According to the mix design procedure, the superplasticizer content should not exceed 2% of the binder weight [22].

### Water

For the preparation of the alkaline solution and the mixing of GPM, potable water that meets drinking water standards available in the laboratory was used.

## RESULTS AND DISCUSSION

The optimal mix for GPM was determined by evaluating the compressive strength of the mortar cubes. The findings are presented in Table 1. Subsequent sections will discuss the influence of various factors, including curing methods, the molarity of NaOH, and the binder-to-aggregate ratio, on the compressive strength of the GPM cubes [23, 24].

The compressive strength of GPM cubes was evaluated for different molarities of NaOH solution (8M, 12M, 14M, and 16M) and binder-to-aggregate ratios, using both oven curing and steam curing methods over 3, 7, and 28 days. The results reveal several key trends related to curing methods, molarity, and binder-to-aggregate ratio, each influencing the compressive strength in distinct ways [25].

## EFFECT OF CURING METHOD

Across all tested molarities and binder-to-aggregate ratios, GPM cubes cured using the oven method consistently showed higher compressive strength compared to those cured with steam. This trend is attributed to the enhanced polymerization reaction in oven curing due to elevated temperatures, which promotes greater bonding and the formation of denser geopolymer matrices. For instance, at 14M NaOH and a binder-to-aggregate ratio of 2.5, the compressive strength at 28 days reached 38.5 MPa for oven-cured specimens, while steam-cured samples achieved a slightly lower strength of 36.6 MPa. The difference is particularly notable in early age strength development, where oven-cured cubes tend to exhibit more rapid strength gains [25].

**Table 1.** Results of compressive strength tests for geopolymer mortar (GPM) cubes.

| **Molarity of NaOH Solution** | **Binder to Aggregate Ratio** | **Compressive Strength (MPa)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | ***Oven Cured*** | | | ***Steam Cured*** | | |
| | | *3 Days* | *7 Days* | *28 Days* | *3 Days* | *7 Days* | *28 Days* |
| 8 | 0.33 | 1.6 | 2.2 | 2.9 | 1.5 | 2.1 | 2.7 |
| | 0.5 | 2.4 | 3.9 | 5.2 | 2.2 | 3.7 | 5.0 |
| | 1 | 4.2 | 6.0 | 8.5 | 3.9 | 5.8 | 8.2 |
| | 2 | 11.9 | 14.4 | 19.1 | 11.0 | 13.7 | 18.2 |
| | 2.5 | 17.5 | 20.2 | 24.9 | 16.1 | 19.4 | 23.7 |
| | 3 | 9.3 | 11.6 | 14.5 | 8.7 | 11.0 | 13.7 |
| 12 | 0.33 | 2.3 | 3.9 | 5.1 | 2.2 | 3.7 | 4.9 |
| | 0.5 | 3.8 | 5.6 | 7.1 | 3.5 | 5.4 | 6.8 |
| | 1 | 5.2 | 8.2 | 10.8 | 4.8 | 7.9 | 10.3 |
| | 2 | 15.9 | 18.1 | 22.4 | 14.7 | 17.3 | 21.4 |
| | 2.5 | 22.1 | 25.8 | 29.4 | 20.4 | 24.5 | 27.9 |
| | 3 | 12.9 | 15.3 | 18.1 | 11.9 | 14.6 | 17.2 |
| 14 | 0.33 | 3.2 | 6.7 | 7.9 | 3.0 | 6.4 | 7.6 |
| | 0.5 | 5.4 | 10.3 | 12.6 | 5.1 | 9.9 | 12.0 |
| | 1 | 7.4 | 14.2 | 16.4 | 6.8 | 13.6 | 15.6 |
| | 2 | 20.5 | 24.8 | 29.4 | 19.0 | 23.7 | 28.0 |
| | 2.5 | 24.8 | 31.3 | 38.5 | 23.2 | 29.9 | 36.6 |
| | 3 | 18.6 | 23.0 | 27.3 | 17.1 | 22.0 | 26.0 |
| 16 | 0.33 | 2.8 | 5.2 | 5.9 | 2.6 | 5.1 | 5.6 |
| | 0.5 | 4.5 | 7.0 | 8.0 | 4.2 | 6.7 | 7.7 |
| | 1 | 6.8 | 10.4 | 11.6 | 6.2 | 9.9 | 11.0 |
| | 2 | 17.6 | 21.4 | 24.4 | 16.4 | 20.4 | 23.2 |
| | 2.5 | 23.1 | 26.7 | 30.0 | 21.5 | 25.5 | 28.6 |
| | 3 | 14.3 | 16.8 | 18.8 | 13.3 | 16.0 | 17.9 |

### Influence of NaOH Molarity

The molarity of the NaOH solution significantly affects the compressive strength of GPM cubes. Among the tested molarities, 14 M NaOH solution delivered the best performance across most binder-to-aggregate ratios, particularly at a ratio of 2.5. For example, with a 14 M solution and a binder-to-aggregate ratio of 2.5, the compressive strength reached 38.5 MPa for oven-cured specimens and 36.6 MPa for steam-cured specimens at 28 days. The results indicate that the optimal NaOH molarity enhances the dissolution of fly ash and promotes geopolymerization. However, increasing the molarity beyond 14 M, such as 16 M, did not further enhance strength, suggesting that excess NaOH might leave unreacted alkaline solution, which could fill voids but does not contribute to the binding phase [26].

### Effect of Binder-to-Aggregate Ratio on Compressive Strength

- The binder-to-aggregate ratio plays a crucial role in determining the compressive strength of the GPM cubes. Across all NaOH molarities, the 2.5 binder-to-aggregate ratio consistently provides the highest compressive strength. For example, with 14M NaOH solution, the 2.5 ratio yielded 38.5 MPa (oven-cured) and 36.6 MPa (steam-cured) at 28 days [27].

- Ratios below 2.5, such as 0.33 and 0.50, exhibit significantly lower compressive strength, with the 0.33 ratio recording values as low as 2.9 MPa (oven-cured) and 2.7 MPa (steam-cured) at 28 days for 8M NaOH. These low ratios are likely insufficient to facilitate complete geopolymerization, resulting in weaker bonds between particles [28].
- Ratios above 2.5, such as 3.0, showed a decline in compressive strength, possibly due to the presence of excess alkaline activators that fill voids but do not contribute to bonding, leading to reduced strength. For example, with 14M NaOH and a 3.0 ratio, the compressive strength at 28 days decreased to 27.3 MPa (oven-cured) and 26.0 MPa (steam-cured) (Figure 2) [29].

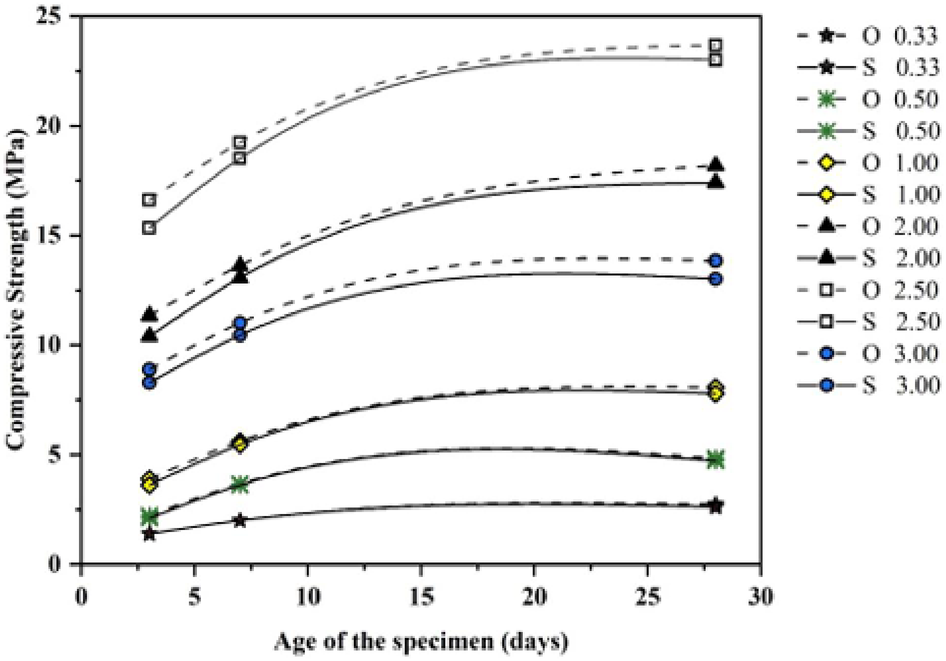

**Figure 2.** Plot showing the relationship between compressive strength and the age of specimens for GPM cubes prepared with an 8M NaOH solution.

## CONCLUSIONS

- The study established that curing method significantly affects the compressive strength of GPM, with oven curing outperforming steam curing due to enhanced polymerization at higher temperatures.
- The optimal NaOH molarity for achieving maximum compressive strength was determined to be 14M.
- A binder to aggregate ratio of 2.5 was identified as the most effective for maximizing the compressive strength of GPM, indicating the critical role of mix proportions.
- Results indicate that careful selection of curing conditions and mix ratios is essential for developing high-strength GPMs.
- The findings support the potential of GPMs as sustainable alternatives in construction applications.

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