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Performance-Driven Mix Design of Sustainable Fly Ash-Based Geopolymer Concrete

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Abstract
Geopolymer is a new development in the world of concrete in which cement is totally replaced by pozzoloanic materials like fly ash and activated by highly alkaline solutions to act as a binder in the concrete mix. For the selection of suitable ingredients of geopolymer concrete to achieve desire strength at required workability, an experimental investigation has been carried out for the gradation of geopolymer concrete and a mix design procedure is proposed on the basis of quantity and fineness of fly ash, quantity of water, grading of fine aggregate, fine to total aggregate ratio. Sodium silicate solution with Na2O = 16.37 %, SiO2 = 34.35 % and H2O = 49.28 % and sodium hydroxide solution having 13M , 10M 15M concentration were obtained throughout the experiment. Water-to-geopolymer binder ratio of 0.40, alkaline solution-to-fly ash ratio of 0.35 and sodium silicate-to-sodium hydroxide ratio of 2.0 by mass were fixed on the basis of workability and cube compressive strength. Workability of geopolymer concrete was measured by flow table apparatus and cubes of 150 mm .side were cast and tested for compressive strength after specified period of oven heating. The temperature of oven heating was maintained at 60 °C for 24 h duration and tested 7 days after heating. It is observed that the results of workability and compressive strength are well match with the required degree of workability and compressive strength. So, proposed method is used to design normal and standard geopolymer concrete.

Keyword: Geopolymer concrete, Mix design, Fly ash, alkaline solution, Compressive strength.

INTRODUCTION
Concrete is widely used in construction due to its cost-effectiveness, good mechanical properties, and ease of handling. The primary binding component in conventional concrete is Portland cement, whose production is on the rise to meet growing construction demands. However, this results in increased carbon dioxide (CO_2) emissions—about one ton of CO_2 is released for every ton of cement produced. Globally, cement manufacturing contributes roughly 1.35 billion tons of CO_2 annually, representing 7% of total greenhouse gas emissions. Moreover, cement production consumes significant natural resources.
To address this environmental concern, efforts have been made to partially or completely replace cement with supplementary cementitious materials like fly ash, blast furnace slag, and rice husk ash.
Fly ash is a by-product of coal combustion in thermal power plants. Globally, around 780 million tons of fly ash are generated each year, but only 17–20% is effectively used. In India, more than 220 million tons are produced annually, yet only 35–50% is utilized, primarily in cement production, concrete admixtures, and soil stabilization. The remaining is dumped, occupying large tracts of land.
To make better use of fly ash, Davidovits proposed chemically activating pozzolanic materials like fly ash

using alkaline solutions at elevated temperatures. This process forms a three-dimensional aluminosilicate network, resulting in geopolymer concrete, which is a sustainable alternative to traditional cement-based concrete.

Unlike cement concrete, geopolymer concrete requires a different mix design approach due to the unique chemical nature of fly ash and absence of hydration reactions. The present study proposes a new mix design method based on:

- Fly ash quantity and fineness,
- Required water content for workability,
- Fine aggregate grading,
- A solution-to-fly ash ratio of 0.35,
- Water-to-binder ratio of 0.40, and
- Sodium silicate-to-sodium hydroxide ratio of 2.0.

Cubes were heat-cured at 60 °C for 24 hours and tested at 7, 14, and 28 days.

I. EXPERIMENTAL WORK.

II- A MATERIALS

In the suggested mix design approach, low-calcium fly ash, sourced from a thermal power plant, was utilized as the primary binder material. To activate the fly ash, laboratory-grade sodium hydroxide flakes with 97.8% purity and sodium silicate solution containing 50.72% solids were employed as alkaline activators. River sand, readily available locally, was used as the fine aggregate, while the coarse aggregates consisted of crushed basalt stones in 12.5 mm and 20 mm sizes, also sourced locally.

II-B PARAMETERS CONSIDERED FOR GEOPOLYMER CONCRETE MIX DESIGN

To formulate an effective mix design for fly ash-based geopolymer concrete, extensive investigations were carried out. The parameters selected were primarily based on their influence on workability and compressive strength:

1. FLY ASH

The amount and fineness of fly ash are crucial in the geopolymerization process. A higher quantity and finer particles of fly ash improve both strength and workability, especially under heat curing. Therefore, the proposed mix design method places strong emphasis on these two aspects, choosing fly ash quantity based on its fineness and the target compressive strength of the concrete.

2. ALKALINE ACTIVATORS

Sodium-based activators are used, specifically a combination of sodium hydroxide and sodium silicate, since using either alone proves insufficient. Increasing the concentration of these solutions enhances compressive strength, although a higher sodium hydroxide molarity (M) can also make the mix more brittle and costly. Additionally, more water may be required for workability, which dilutes the solution's effectiveness. To balance these factors, sodium hydroxide concentration is fixed at 13 M, and sodium silicate composition includes 16.37% Na_2O, 34.35% SiO_2, and 49.72% H_2O. A 2:1 mass ratio of sodium silicate to sodium hydroxide is maintained to ensure early setting and reliable strength results.

3. WATER

In geopolymer concrete, water's role is limited to enhancing workability in the plastic state, as it is expelled during polymerization and does not contribute to strength. The amount of water needed increases with the fineness of fly ash. Thus, the water quantity is carefully selected based on the required workability, fly ash fineness, and the grading of fine aggregate.

4. AGGREGATE

Aggregates fill 70–85% of the concrete volume and must be properly graded to minimize voids. Both fine and coarse aggregates are proportioned to achieve maximum packing density. The grading of fine aggregates significantly influences workability, and so an appropriate fine-to-total aggregate ratio is chosen based on sand grading for optimal results.

5. DEGREE OF HEATING

Curing temperature and duration are vital for the activation of geopolymer concrete. In this study, cube samples were demolded after 24 hours and placed in an oven at 60 °C for 24 hours. After curing, they were allowed to cool gradually to room temperature before testing. Tests conducted after a 7-day period revealed that both longer heating durations and longer rest periods after curing improve compressive strength. Hence, this curing condition was adopted as standard for mix design.

6. WATER TO GEOPOLYMER BINDER RATIO

This is the ratio of total water (including water in alkaline solutions and any additional water) to total binder content (fly ash, sodium hydroxide, and sodium silicate). While Rangan suggested a solid-based ratio, this study used a simpler binder-based ratio. It was found that strength decreases as this ratio increases, similar to the behavior in cement concrete. A ratio of 0.35 resulted in a stiff mix, while 0.40 led to slight segregation but acceptable performance. Therefore, 0.40 was selected as the optimal ratio, balancing both workability and strength.

7. SOLUTION TO FLY ASH RATIO

This ratio refers to the mass of alkaline solution (soium silicate + sodium hydroxide) relative to fly ash. While strength improves as this ratio increases, the gain becomes marginal beyond 0.35. Additionally, higher ratios increase mix viscosity and cost. Therefore, a solution-to-fly ash ratio of 0.35 was chosen for the final mix design to ensure a good balance of strength, flow, and economy.

Mix Design Steps for Geopolymer Concrete

1. DETERMINING FLY ASH QUANTITY (F)

The quantity of fly ash is determined based on the required target strength and its fineness, assuming a solution-to-fly ash ratio of 0.35 by mass.

2. CALCULATION OF THE ALKALINE ACTIVATORS

Once the amount of fly ash is known, the total quantity of alkaline solution (sodium hydroxide + sodium silicate) is determined using the same 0.35 solution-to-fly ash ratio. The two activators are then split using a 1:1 mass ratio.

3. DETERMINING SOLID CONTENT IN ALKALINE SOLUTION

The solid content in both sodium silicate and sodium hydroxide is calculated based on their respective percentages of solid matter, which is essential for accurate binder content calculation.

4. WATER QUANTITY SELECTION

The total water needed is estimated based on the desired workability, the fineness of fly ash, and the grading of fine aggregate. This includes the water already present in the alkaline solutions.

5. WATER CONTENT CORRECTION

Since aggregate grading significantly affects water demand, especially with finer particles, corrections are applied based on IS 10262 guidelines. This helps ensure the mix remains workable under varying grading conditions.

6. ADDITIONAL WATER REQUIREMENT

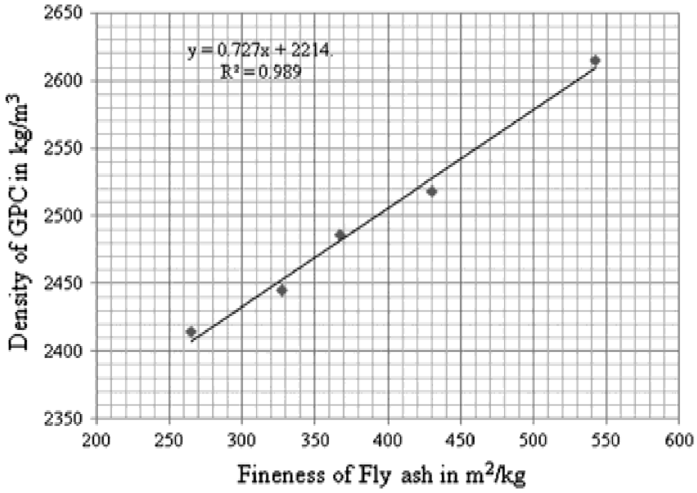
Sometimes, the water content in the alkaline activators is insufficient for workability. The extra water needed is calculated as:
Additional quantity of water; if required
= Total quantity of water - Water present in alkaline solutions.

7. FINE AND COARSE AGGREGATE CONTENT

Aggregate Contents is obtained using following relations:
Total quantity of aggregate = Wet Density of Geopolymer concrete – {Quantity of Geopolymer Binder + Additional water; if any}
Sand content = {Fine-to-total aggregate content in %] x {Total quantity of aggregate}
Coarse aggregate content ={Total quantity of aggregate} –{ Sand content }

8. ADJUSTMENT FOR FIELD CONDITION.

The mix proportions assume saturated surface dry aggregates. Adjustments are made if aggregates are either moist or dry, to correct both water and aggregate content accordingly.



Relation between fineness of fly ash and density of geopolymer concrete

III RESULT AND DISCUSSION

The freshly prepared fly ash-based geopolymer concrete exhibited a viscous and cohesive texture, dark coloration, and a slightly glassy appearance. After thorough mixing, its workability was assessed using the flow table test, following the guidelines of IS 5512-1983 and IS 1727-1967.
Due to the viscous nature of the mix and the release of water during the polymerization process, conventional methods like the slump cone test and compaction factor test were found to be unsuitable. The slump test resulted in prolonged subsidence, while in the compaction factor test, the mix failed to flow properly. Thus, the flow table test was deemed more appropriate for evaluating the workability of geopolymer concrete.
After determining workability, concrete cubes of 150 mm were cast in three layers and compacted, following practices similar to those used in conventional concrete. The cubes were demoulded after 24 hours, and their mass density was calculated using the average weight of three specimens. The measured average mass density was 2,601.48 kg/m³, which is 3.33% higher than the design value.
The specimens were then thermally cured in an oven at 60°C for 24 hours. To prevent thermal shock, the cubes were allowed to cool gradually inside the oven to room temperature. After a 7-day test period,

compressive strength was measured. The M20-grade geopolymer concrete achieved a compressive strength of 27.22 MPa, which is 2.69% below the target value of 28.25 MPa, but well within the ±15% tolerance permitted by IS 456:2000. Overall, the mix design approach demonstrated cost-effectiveness and satisfactory performance.

CONCLUSION

This study presents a **methodical approach** for designing fly ash-based geopolymer concrete of ordinary and standard grades, considering key factors such as:

- Quantity and fineness of fly ash,
- Water content,
- Fine aggregate grading,
  while maintaining:
- a water-to-geopolymer binder ratio of 0.40,
- a solution-to-fly ash ratio of 0.35,
- a sodium silicate-to-sodium hydroxide ratio of 2, and
- 13 M concentration of sodium hydroxide.

Thermal curing was carried out at 60°C for 24 hours, and performance was evaluated after 7 days.
Experimental results for M20 to M40 grade geopolymer concrete mixes using the proposed method demonstrated adequate workability and strength, validating the effectiveness of the procedure. These design guidelines thus provide a reliable and economical foundation for producing Ordinary and Standard Grade geopolymer concrete in line with the specifications of IS 456:2000.

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