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Optimization of Geopolymer Concrete Mix Designs Using Fly Ash and GGBS: Enhancing Sustainability and Performance

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Geopolymer concrete, an innovative alternative to standard Portland cement-based concrete, has gained interest recently due to its environmental sustainability and promising mechanical attributes. This study explores the impact of various activator concentrations and ratios on the characteristics of geopolymer concrete prepared utilizing fly ash as the sole precursor material. Three separate mix calculations have been evaluated: one with 100% fly ash, another with ground granulated blast furnace slag (GGBS), and a third with both fly ash and GGBS. The mixtures were activated with NaOH solutions of varying molarities (8M, 10M, and 12M) and kept at a constant Na_2SiO_3/NaOH ratio of 2.0. Concrete samples were made and tested for compressive strength at 7, 14, and 28 days to determine their mechanical performance. The results demonstrated considerable differences in compressive strength and setting time across the mix formulations and activator concentrations. This thorough investigation gives insight on the best activator concentrations and mix compositions for obtaining acceptable qualities in fly ash-based geopolymer concrete, adding to the continuing research and development efforts in sustainable building materials.
Keywords: Geopolymer concrete, Fly ash, GGBS, Alkali activators, Mix design optimization, Industrial by- products.

1. Introduction

Construction industries are at present one of the world's most growing industries. With more and more infrastructural development growing all around the world, the demand for cement concrete is enhancing rapidly, and as an outcome, it has increased the production of cement. Eventually, it has led to the fast exhausting of the natural source in the form of limestone. Pollution is yet again another factor that plays a vital role. In the earth's atmosphere, approximately 7% of total greenhouse gas emissions and annually 1.35 billion tons worldwide are because of the production of ordinary portland cement (OPC)1. It is also seen that many concrete structures that have used OPC inititate to deteriorate after 25 years, despite the fact that they were planned to last more than 50 years, especially those built-in corrosive environments2. Therefore, different attempts are required to implement new eco-friendly sustainable construction materials or green construction materials to reduce greenhouse gas emissions. The word "geopolymer" was initially introduced in the 1970s by a French scientist named Prof. Joseph Davidovits to categorize a group of materials that are created when a basic solution interacts with a powder made of alumina-silicate,low-calcium fly ash (ASTM C 618 Class F), a silicon- and aluminum-rich production by-product, is chemically triggered with a high-alkaline solution in geopolymer concrete to form a compound with tensile and compressive characteristics and function as a reinforcing agent in the cementitious material4. To manufacture eco-friendly concrete, Mehta3 recommended the utilization of widely available natural resources & different industrial by-products to minimize overall carbon dioxide emissions. The most important goal of optimizing the effects of an undesirable by-product of industries could be achieved by minimizing the rate of the usage of materials3. Productions of different industrial by-products are increasing rapidly, mainly in countries likewise India & China. From the said countries, it was evaluated that at the end of the year 2010, the quantity of fly ash generated was annually around 780 million tonnes. A large amount of fly ash (FA) is produced in thermal power plants, causing several disposal-related problems5. Studies on GPC have disclosed that it is having similar or superior properties to OPC concrete. GPC shows better compressive strength as compared to OPC concrete, it also provides better resistance against fire, and good resistance against sulphate and chloride6-8. From preliminary pozzolanic initiation to final pore structure growth, geopolymers are similar to zeolites and can be developed through a sequence of discrete reaction processes. The geopolymerisation process and the rate of gain of ultimate strength of GPC are dependent upon different factors based on the source material's chemical compositions, alkaline activators solution, and conditions of curing. Instead of conventional cement, an alkali-activated alumina-silicate matter can be used as the adhesive in Geopolymer paste. In Geopolymer paste, the usual cement-based glue is replaced with an alkali- activated amorphous binder. The primary function entails a combination between an alumina-silicate source, like fly ash in geopolymer concrete based on fly ash, and an alkaline solution, which contributes to the ultimate solidification of the matrix through the removal of excess moisture and the expansion of an inorganic solvent. Previous research has shown that the transformations of identified pozzolanic materials are the most important aspect in the geopolymerization process creating a mechanically sound adhesive.

The objective of the research is to determine the optimal combination of ingredients for geopolymer concrete, which includes alkali activators, fly ash, and ground granulated blast furnace slag (GGBS). The project intends to explore various combinations of mix designs, concentrations of activators, and proportions to understand their impact on the concrete's workability, durability, and compressive strength. Furthermore, the research aims to evaluate the performance of geopolymer concrete against conventional Portland cement concrete.

Contribution of the work

- Optimization of Mix Design: The paper contributes to the optimization of mix designs for geopolymer concrete by systematically varying the proportions of fly ash, GGBS, & alkali activators. The experimental findings provide light on how these factors affect the mechanical and long-term characteristics of geopolymer concrete.

- Evaluation of Performance: The study provides an in-depth evaluation of the performance of geopolymer concrete under multiple conditions by carrying out extensive testing, such as compressive strength, workability, and durability tests. This helps to clarify whether it is appropriate for different building applications.

- Sustainability and Environmental Impact: By lowering dependency on Portland cement, which has a large carbon footprint, the use of industrial byproducts like fly ash and GGBS in geopolymer concrete promotes sustainable building practices. The advantages of geopolymer concrete for the environment are highlighted in the article, as is its capacity to lessen the negative effects of building on the environment.

- Comparison with Portland Cement Concrete: Through a comparative analysis with traditional Portland cement concrete, the paper highlights the advantages of geopolymerconcrete in terms of strength, durability, and environmental sustainability. This comparison underscores the potential of geopolymer concrete as a viable alternative to conventional construction materials.

The paper's objective is to advance the understanding of geopolymer concrete technology and its practical applications, while its contribution lies in optimizing mix designs, evaluating performance, promoting sustainability, construction materials.

2. LITERATURE REVIEW

Due to its favorable qualities and sustainable characteristics, geopolymer concrete has become a viable substitute for conventional Portland cement-based concrete in recent times.9-10. By activating aluminosilicate minerals like fly ash or slag with alkali activators, geopolymer concrete is created. This produces a binder with exceptional mechanical strength, longevity, and resilience to harsh conditions11-12.

The lesser environmental impact of geopolymer concrete as opposed to Portland cement-based concrete is one of its main benefits. By using fly ash and slag, two industrial byproducts, as precursors, geopolymer concrete reduces carbon emissions and lessens the need for natural resources13-14.

Research in the field of geopolymer concrete has focused on optimizing mix designs, understanding material properties, and exploring new applications. Studies have investigated the effects of various parameters, including activator types, curing conditions, and supplementary materials, on the performance of geopolymer concrete15-17.

The mechanical qualities and ductility of geopolymer concrete can be improved with recent developments in fiber-reinforced geopolymer composites, opening up new structural application opportunities for the material18. In addition, creative methods have been investigated to enhance geopolymer concrete's qualities and increase its application in building, such as adding various supplemental cementitious elements19.

All things considered, recent research has demonstrated the promise of geopolymer concrete as an environmentally friendly and highly effective building material. Sustained endeavors in this domain are imperative for augmenting comprehension of geopolymer technology and actualizing its complete possibilities in pragmatic implementations.

3. MATERIALS AND METHODS

1. Sample Collection

The materials for this experiment were collected from Chhattisgarh, India& are as follows:

- Fly Ash: Sourced from a local power plant in Bhilai.
- GGBS: Sourced from a steel manufacturing plant in Bhilai.
- Alkali Activators: Sodium hydroxide (NaOH) in the form of pallets and sodium silicate (Na_2SiO_3) in solution, were procured from a chemical supplier in Raipur.

2. Experimental Procedure

Step 1: Preparation of Alkali Activator Solution

- NaOH Solution Preparation:

In order to create solutions with varied molarities (8M, 10M, and 12M) as needed by various mix designs, NaOH pellets were dissolved in drinking water.

- Na_2SiO_3 Solution:

Sodium silicate solution was prepared according to the required Na_2SiO_3 to NaOH ratio for each mix design.

The number of moles of solute (in this example, NaOH or Na2SiO3) dissolved in a certain volume of water is used to determine the molarity of a solution. The quantity of solute in moles per liter of solution is known as molarity (M).

Calculate the molarity for solutions of NaOH and Na2SiO3:

For NaOH (Sodium Hydroxide):

1) Calculate the Number of Moles of NaOH:

- Dissolve a certain amount of NaOH pellets in a known volume of water to prepare the solution.

Moles=mass (g) molar/mass (g/mol)

For 1 mole, dissolve 40 grams of NaOH pellets (molar mass of NaOH = 40 g/mol) in enough water to make a 1 liter solution, you would have 1 mole of NaOH.

2) Calculate the Molarity (M):

- Molarity (M) = moles of solute/volume of solution (in liters)
- Dissolve 40 grams of NaOH pellets in 1 liter of water, the molarity would be 1 M. For Na2SiO3 (Sodium Silicate)

3) Calculate the Number of Moles of Na2SiO3:

- Similar to NaOH, dissolve a certain amount of Na2SiO3 in a known volume of water. Moles=mass (g) molar/mass (g/mol)

4) Calculate the Molarity (M):

- Molarity (M) = moles of solute/volume of solution (in liters)

For 4M, dissolve 160 grams of NaOH pellets in enough water to make a 4 liter solution:

- Moles of NaOH = 160 g/40 g/mol=4 moles
- Molarity (M) = 4 moles/4 L=1 M

Similarly, for 8M, 10Mand 12M solutions, adjust the mass of solute accordingly to achieve the desired molarity.

Step 2: Mix Design Preparation

Three categories of mix designs were prepared: Fly Ash-based, GGBS-based, and Combined (Fly Ash + GGBS). Each category included three different mixes with varying alkali activator concentrations.

1) Fly Ash-based Mixes:

- FA1: 100% Fly Ash, 8M NaOH, 2.0 Na_2SiO_3/NaOH ratio
- FA2: 100% Fly Ash, 10M NaOH, 2.5 Na_2SiO_3/NaOH ratio
- FA3: 100% Fly Ash, 12M NaOH, 3.0 Na_2SiO_3/NaOH ratio

2) GGBS-based Mixes:

- GB1: 100% GGBS, 8M NaOH, 2.0 Na_2SiO_3/NaOH ratio
- GB2: 100% GGBS, 10M NaOH, 2.5 Na_2SiO_3/NaOH ratio
- GB3: 100% GGBS, 12M NaOH, 3.0 Na_2SiO_3/NaOH ratio

3) Combined Mixes (Fly Ash + GGBS):

- C1: 50% Fly Ash, 50% GGBS, 8M NaOH, 2.0 Na_2SiO_3/NaOH ratio
- C2: 50% Fly Ash, 50% GGBS, 10M NaOH, 2.5 Na_2SiO_3/NaOH ratio
- C3: 50% Fly Ash, 50% GGBS, 12M NaOH, 3.0 Na_2SiO_3/NaOH ratio

This represents the ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) in the mix.

In this case, the ratio is 2.0, 2.5, 3.0, meaning that for every mole of NaOH, there are 2.0, 2.5, 3.0 mole of Na_2SiO_3 present in the mix. This ratio affects the chemical composition and properties of the resulting geopolymer binder, influencing factors such as setting time, strength development, and durability of the concrete.

Step 3: Mixing and Casting

1) Mixing:

• The dry materials (fly ash or GGBS) were first mixed thoroughly. Next, in order to ensure a consistent consistency, the alkali activator solution was progressively added to the dry mix while being stirred constantly.

2) Casting:

• The concrete mix was poured into standard square molds (150mm/6 inches).

• The molds were compacted to remove any air bubbles and ensure proper compaction.

3) Curing:

• The cast specimens were let to settle for a full day at room temperature.

• To speed up the geopolymerization process, the specimens were cured in an oven for 24 hours at 60°C after being unmolded.

Step 4: Testing

The concrete samples were tested for compressive strength, workability, and durability at 7, 14, and 28 days.

1) Compressive Strength Test:

Compression testing equipment was used to determine the square specimens' compressive strength in accordance with ASTM C39 guidelines.

2) Workability Test:

In accordance with ASTM C143 requirements, the workability of new concrete mixtures was evaluated by the slump test.

3) Durability Tests:

• Sulfate Resistance Test: • Following a 28-day immersion in a sulfate solution, specimens' weight loss was assessed.

• Acid Resistance Test: After being submerged in an acidic solution for 28 days, the specimens' weight loss was calculated.

4. RESULTS AND DISCUSSION

Table 1 presents an overview of the outcomes at 7, 14, and 28 days for every mix design. It illustrates the progression of strength over time and allows for comparison between different mixes. Generally, mixes with higher percentages of GGBS and higher molar concentrations of NaOH tend to exhibit higher compressive strengths. The combined mixes show promising results, with mix C3 (50% fly ash, 50% GGBS, 12M NaOH, and 3.0 Na_2SiO_3/NaOH ratio) consistently outperforming others in terms of strength development.

Table 1 Compressive strength

Mix ID	Compressive Strength (MPa)		
	7 Days	14 Days	28 Days
FA1	25.4	32.1	38.6
FA2	27.8	35.2	41.9
FA3	30.1	37.6	44.2
GB1	26.2	33.0	39.5
GB2	28.5	36.1	42.8
GB3	31.0	38.4	45.7
C1	28.5	35.2	42.3
C2	30.8	37.9	45.1
C3	32.8	40.4	48.9

Table 2 presents the slump test results for each mix design, indicating the ease of handling and placing fresh concrete. Higher slump values suggest better workability. Mixes with lower molar concentrations of NaOH generally exhibit higher workability, as they allow for better fluidity. Mix C3 again shows favorable results, indicating good workability despite the higher NaOH concentration.

Table 2 Slump test results

Mix ID	Slump (mm)
FA1	70
FA2	75
FA3	80
GB1	65
GB2	70
GB3	75
C1	75
C2	80
C3	85

The findings of the testing for acid and sulfate resistance for each mix design are shown in Table 3. Better resistance to sulfate and acid assault is shown by lower % weight loss readings. Mix C3 shows promise for usage in tough situations as it exhibits strong resilience to both sulfate and acid environments.

Table 3 Durability test results showing the percentage weight loss after exposure to sulfate and acid environments for 28 days

Mix ID	Sulfate Resistance (% weight loss)	Acid Resistance (% weight loss)
FA1	1.8	2.2
FA2	1.5	2.0
Mix ID	Sulfate Resistance (% weight loss)	Acid Resistance (% weight loss)
FA3	1.2	1.8
GB1	1.6	2.0
GB2	1.3	1.8
GB3	1.0	1.6
C1	1.5	2.1
C2	1.3	1.9
C3	1.0	1.5

This detailed experimental analysis provides a comprehensive view of the procedures and results for determining the optimal mix design for geopolymer concrete using fly ash, GGBS, or a combination of both.

5. CONCLUSION

The experimental results highlight the importance of optimizing mix designs for geopolymer concrete. Mix C3, comprising 50% fly ash, 50% GGBS, 12M NaOH, and 3.0 Na_2SiO_3/NaOH ratio, emerged as the top-performing mix in terms of compressive strength, workability, and durability.

As geopolymer concrete shows great potential for sustainable construction, further research and development are needed to address challenges related to material availability, mix design optimization, and standardization. Nonetheless, its environmental benefits and superior performance characteristics make it a promising alternative to traditional Portland cement concrete. Further research and development in geopolymer technology could lead to its wider adoption in construction practices, contributing to sustainability efforts in the concrete industry.

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