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EFFECT OF GEOPOLYMER BINDER INDEX ON COMPRESSIVE STRENGTH OF FLY ASH, GGBS BASED GEOPOLYMER CONCRETE

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Abstract. The abstract outlines a study aimed at investigating the effect of various factors on the compressive strength of Geopolymer Concrete (GPC). Specifically, the research focuses on the influence of Class F Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), and the molarity of the alkaline activator. Here's a breakdown of the key components:
The study utilizes **Sodium Silicate (Na_2SiO_3)** and **Sodium Hydroxide (NaOH)** as alkaline activators, with varying molarities (8, 10, and 12). The mix proportions of **Fly Ash to GGBS** are varied, including ratios like 80:20, 70:30, down to 20:80.
Alkaline liquid content to Fly Ash ratio is fixed at 0.36. The **fine aggregate to total aggregate ratio** is 32%.
The ratio of **sodium silicate to sodium hydroxide solution** is kept constant at 2.5. Three identical concrete specimens are cast for each variation and tested for compressive strength at **7 days and 28 days** under ambient curing conditions.
The study introduces a **Binder Index**, a new parameter, to quantify the combined effects of Fly Ash, GGBS, and the molarity of the alkaline activator on the compressive strength of the Geopolymer Concrete. The primary objective is to analyze how the combination of Fly Ash and GGBS at different proportions, along with the alkaline activator's molarity, affects the compressive strength of Geopolymer Concrete under ambient temperature curing.
The findings from this study can provide valuable insights into the optimization of Geopolymer Concrete mix designs for sustainable construction practices, focusing on factors like material combinations and activator concentrations.

Key words*: Geopolymer Concrete (GPC), Fly ash(FA), Ground Granulated Blast Furnace Slag(GGBS), Compressive Strength(f_{ck}), Binder Index(B_i), Ambient temperature.*

Introduction

The production of Portland cement is energy-intensive and contributes significantly to CO2 emissions, which are a major driver of climate change and global warming. These environmental concerns are primarily due to the release of greenhouse gases, especially carbon dioxide (CO2), through human activities. The cement industry is responsible for a significant portion of these emissions, as producing one ton of Portland cement results in approximately one ton of CO2 being released into the atmosphere [1]. Despite this, Portland cement remains the primary binder in concrete construction, prompting ongoing efforts to find more environmentally friendly alternatives. Various supplementary cementing materials, such as fly ash, silica fume, ground granulated blast furnace slag (GGBS), rice-husk ash, and metakaolin, are being explored to reduce Portland cement use and mitigate global warming. One promising alternative is the use of alkali-activated binders, made from industrial by-products containing silicate materials. In 1978, Davidovits proposed the creation of binders through a polymeric reaction between alkaline liquids and the silicon and aluminum present in geological or by-product materials like fly ash and GGBS. These binders, termed **Geopolymers**, have become a focal point in sustainable construction research [2]. Fly ash and GGBS are among the most commonly used industrial by-products in geopolymer formulations [3-4]. Numerous studies have explored geopolymer pastes and concrete materials, leading to the current research, which aims to examine the effects of GGBS-to-fly ash ratios and molarity on the compressive strength of geopolymer concrete. To quantify these effects, a new parameter called **Binder Index** is introduced, which helps measure the impact of GGBS, fly ash, and molarity on the compressive strength of geopolymer concrete developed at ambient temperature.

2. Experimental Investigation

The experimental program focused on determining the compressive strength of geopolymer concrete by casting and testing 100 mm-sized cubes. Seven different fly ash-to-GGBS proportions were considered: 80:20, 70:30, 60:40, 50:50, 40:60, 30:70, and 20:80. The alkaline liquid content to fly ash ratio was maintained at 0.36, while the fine aggregate to total aggregate ratio was kept at 32%. Sodium hydroxide solutions with molarities of 8, 10, and 12 were used in all experiments. Three identical specimens were cast for each variation and tested for compressive strength after 7 and 28 days of ambient curing.

2.1 Materials

Fly ash used in the study was sourced from the Kothagudem Thermal Power Station, Bhadradri Kothagudem District, Telangana, India. GGBS was obtained from Blue Way Exports, Vijayawada, Andhra Pradesh, India. The specific gravities of fly ash and GGBS were 2.17 and 2.90, respectively. The chemical compositions of fly ash and GGBS are provided in Table 1. Natural river sand, conforming to grading zone II of IS 383:1970, was used as fine aggregate. The specific gravity and fineness modulus of the sand were 2.32 and 2.81, respectively. Coarse aggregates with a maximum size of 12 mm, sourced locally, were employed. Sodium hydroxide solutions with molarities of 8, 10, and 12 were prepared from NaOH pellets, as detailed in Table 2. The NaOH solution was mixed with sodium silicate (Na_2SiO_3) solution, with the ratio of sodium silicate to sodium hydroxide maintained at 2.5 [5, 6, 7]. The mixture was allowed to rest at room temperature for 24 hours before casting. To achieve the desired workability, the superplasticizer Conplast SP-430 was used.

Table 1. Chemical Composition of Fly Ash and GGBS percentage by mass.

Material	SiO_2	Al_2O_3	Fe_2O_3	SO_3	CaO	MgO	Na_2O	LOI
Fly ash	60.12	26.63	4.22	0.32	4.1	1.21	0.2	0.85
GGBS	34.16	20.1	0.81	0.88	32.8	7.69	nd	.

Table 2. Materials used for NaOH solution preparation.

	8 moles/L	10 moles/L	12 moles/L
Sodium hydroxide pellets , (grams)	262	314	361
Potable Water (grams)	738	686	639

2.2 Mix proportions: The unit weight of Geopolymer concrete is taken as 2400 Kg/m^3.The Geopolymer Concrete mix proportions are shown in table 3.

Table 3. Geopolymer Concrete mix proportions.

FA:GGBS	GeopolymerConcrete mix proportions (Kg/m^3)							
	Coarse Aggregate	Fine Aggregate	Fly ash (FA)	GGBS	NaOH Solution	Sodium Silicate	Super Plasticizer (2% of the Binder)	Extra water (7.5% of the Binder)
80:20	1100	517.45	460.16	115.04	59.10	148.25	11.50	43.15
70:30	1100	517.45	402.64	172.56	59.10	148.25	11.50	43.15
60:40	1100	517.45	345.12	230.08	59.10	148.25	11.50	43.15
50:50	1100	517.45	287.6	287.6	59.10	148.25	11.50	43.15

40:60	1100	517.45	230.08	345.12	59.10	148.25	11.50	43.15
30:70	1100	517.45	172.56	402.64	59.10	148.25	11.50	43.15
20:80	1100	517.45	115.04	460.16	59.10	148.25	11.50	43.15

2.3 Casting of Geopolymer Concrete specimens: The solid ingredients of the Geopolymer concrete, including aggregates, fly ash, and GGBS, were dry mixed for approximately three minutes to ensure uniform distribution. The liquid components—alkaline solution, water, and superplasticizer—were pre-mixed separately before being added to the dry ingredients. The wet mixing continued for an additional four minutes. The resulting fresh Geopolymer concrete was dark in color and had a shiny appearance, with a highly cohesive texture. Workability was measured using the conventional slump test.

To compact the fresh concrete into cube molds, the mixture was placed in three equal layers, each layer compacted for ten seconds using a vibration table. After 24 hours, the specimens were demolded and left for ambient curing.

For compressive strength testing, the Geopolymer concrete specimens were tested using a Universal Testing Machine with a capacity of 1000 kN. The load was gradually increased at a constant rate until failure occurred, with the maximum loads recorded for each specimen in accordance with IS 516-1956 [8]. Three identical **specimens were cast for each variation and tested after 7 and 28 days of ambient curing. The results are provided in Table 4. The Binder Index (Bi) was used to evaluate the combined effect of GGBS, fly ash, and the molarity of the alkaline activator on the compressive strength of the geopolymer concrete [9, 10, 11].**

Binder Index = Molarity x [GGBS / (GGBS + Fly Ash)]......eq (1)

Table 4. Compressive Strength values for Geopolymer concrete

FA:GGBS	Compressive Strength (Mpa)								
	8 moles/L			10 moles/L			12 moles/L		
	7D	28D	7D/28D	7D	28D	7D/28D	7D	28D	7D/28D
80:20	15.6	22.6	0.70	20.4	35.6	0.58	27.5	39	0.71
70:30	20.1	26.6	0.77	29	41	0.71	35	54	0.65
60:40	24	42.5	0.56	33	48.5	0.68	40	59.5	0.67
50:50	31.92	49	0.65	40	58	0.69	45	65	0.69
40:60	42	55.2	0.76	44.9	62.5	0.72	51.2	76	0.67
30:70	46.9	59	0.78	52	68	0.76	55	81	0.68
20:80	58	68.9	0.85	62	74	0.84	66.5	86	0.77

Table 5. Binder index Vs Compressive Strength of GPC

Binder Index = [GGBS / (GGBS + Fly Ash)]	Compressive Strength (Mpa)		Ratio of 7 day strength to 28 day strength of GPC
	7 days	28 days	7D/28D
	7D	28D	
1.6	15.5	22	0.70
2	20.4	35	0.58
2.4	27.5	39	0.71
2.4	20	26	0.77

3	29	41	0.71
3.6	35	54	0.65
3.2	24	42.5	0.56
4	33	48.5	0.68
4.8	40	59.5	0.67
4	32	49	0.65
5	40	58	0.69
6	45	65	0.69
4.8	42	55.2	0.76
6	44.9	62.5	0.72
7.2	51.2	76	0.67
5.6	46	59	0.78
7	52	68	0.76
8.4	55	81	0.68
6.4	58	68	0.85
8	62	74	0.84
9.6	66.5	86	0.77

The variation of Compressive strength with GGBS to fly ash ratio are shown in fig 1, fig 2 and fig 3. The variation of Compressive strength with Binder index is shown in fig 4.

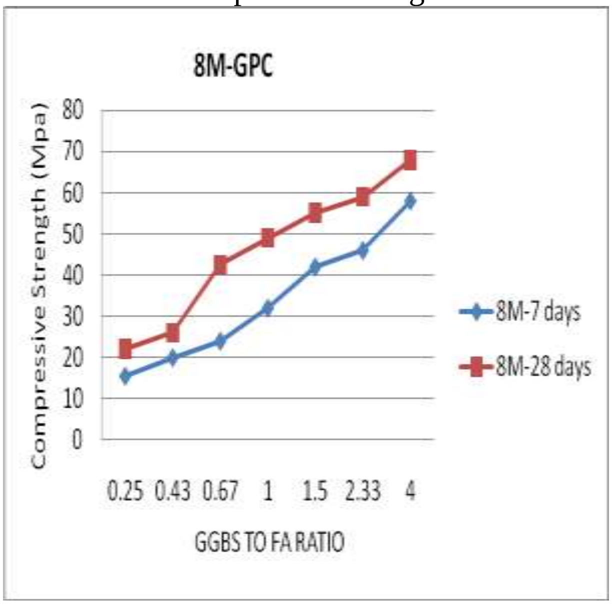

Fig 1. GGBS to fly ash ratio Vs Compressive Strength of GPC, 8 moles/L.

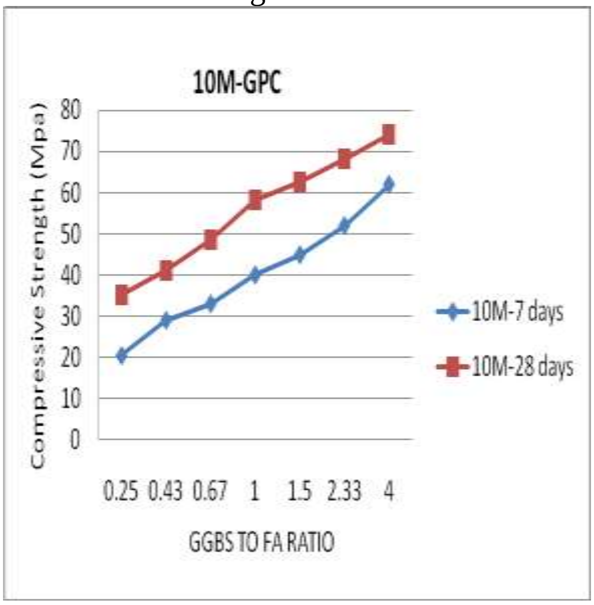

Fig 2. GGBS to fly ash ratio Vs Compressive Strength of GPC, 10 moles/L.

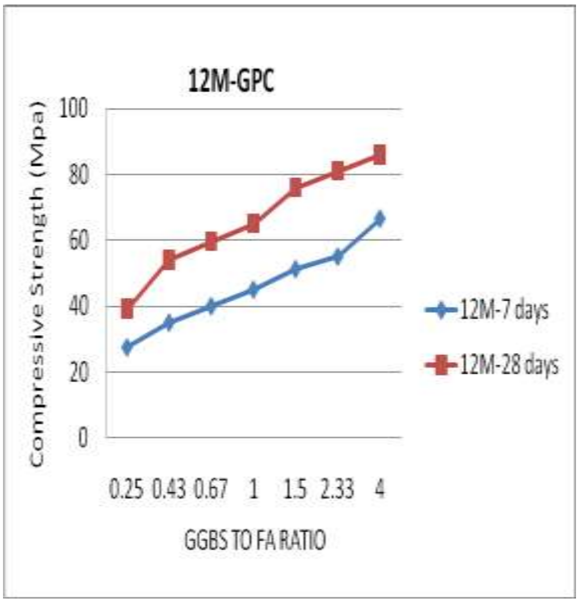

Fig 3. GGBS to fly ash ratio Vs Compressive Strength of GPC, 12 moles/L.

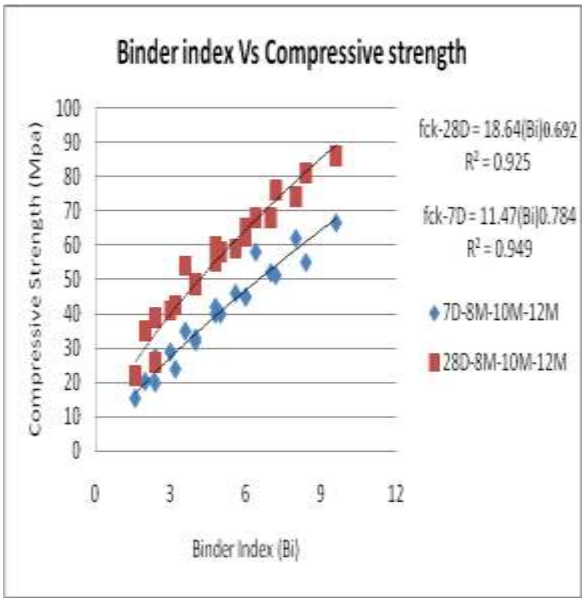

Fig 4. Binder index Vs Compressive Strength of GPC.

From above figures it is observed that the Compressive strength of Geopolymer concrete has increased with increase in GGBS to Fly ash ratio , molarity of alkaline activaort and Binder index.

3.1 Effect of Molarity of alkaline activator on Compressive strength of Geopolymer concrete

The influence of the molarity of the alkaline activator on the compressive strength of Geopolymer concrete, for various GGBS to fly ash ratios, is illustrated in Figures 1, 2, and 3. Generally, as the molarity of the alkaline activator increased, the compressive strength of the Geopolymer concrete also showed an increase.

3.2 Effect of Binder index on Compressive strength of Geopolymer concrete.

The Compressive strength of Geopolymer concrete increased with the increase in binder index values. The variation of Compressive strength along with the binder index is shown in fig 4. The binder index has been used to study the combined effects of GGBS to fly ash proportion, molarity of alkaline activator on Compressive strength of Geopolymer concrete. The following best fit equations give the relation between the compressive strength at 7 days and 28 days of air curing with binder index along with the correlation coefficient (R^2).

f_{ck}-7day=11.47($\mathbf{B_i}$)$^{0.784}$, $R^2 = 0.949$…. eq (2)
f_{ck}-28day=18.64($\mathbf{B_i}$)$^{0.692}$, $R^2 = 0.925$ …. eq (3)
Where $\mathbf{B_i}$ is binder index.

a. **Overview of Compressive Strength and Binder Index Relation**
   The compressive strength of geopolymer concrete increases with an increase in the binder index. This trend suggests that a higher binder index leads to a denser and more robust geopolymer matrix.
b. **Variables Considered**
   Binder Index: Represents the combined influence of the GGBS to fly ash ratio and the molarity of the alkaline activator.
   Compressive Strength: Measured at 7 and 28 days under air-curing conditions.
c. **Graphical Representation**
   The relationship between compressive strength and binder index is depicted in **Fig. 4** (as mentioned). This visualization demonstrates how different binder index values influence the material's mechanical properties.

d. **Best Fit Equations**

Mathematical models have been developed to describe the relationship between the binder index and compressive strength. These equations provide predictions for 7-day and 28-day compressive strength values and are accompanied by a high correlation coefficient (R^2), indicating a strong relationship.

Example format of equations (replace placeholders with actual values):

e. f_{ck}-7day=11.47($\mathbf{B_i}$)$^{0.784}$, $R^2 = 0.949$…. eq (2)

f. f_{ck}-28day=18.64($\mathbf{B_i}$)$^{0.692}$, $R^2 = 0.925$ …. eq (3)

g. Where $\mathbf{B_i}$ is binder index.

h. **Correlation Coefficient (R^2):**

Indicates the accuracy of the best-fit equations in predicting the compressive strength values based on binder index.

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5. Conclusions

Based on the analysis of experimental results, the following conclusions were drawn regarding the compressive strength behavior of geopolymer concrete:

1. **Effect of GGBS Proportion**
   a. The compressive strength (both 7-day and 28-day) increases with an increase in the proportion of GGBS in the binder mix.
2. **Effect of GGBS to Fly Ash Ratio**
   a. Higher GGBS-to-fly ash ratios result in increased compressive strength at both 7 and 28 days.
3. **Effect of Alkaline Activator Molarity**
   a. Increasing the molarity of the alkaline activator solution enhances the compressive strength at both 7-day and 28-day curing periods.
4. **Effect of Binder Index**
   a. The compressive strength increases with an increase in the binder index, reflecting the combined influence of GGBS, fly ash, and alkaline activator molarity.
5. **Fly Ash and GGBS Combination**
   a. A combination of fly ash and GGBS can be effectively used to produce geopolymer concrete, eliminating the need for heat curing. This makes the process energy-efficient and suitable for ambient curing conditions.
6. **Binder Index as a Predictor**
   a. The proposed binder index, which accounts for GGBS proportion, fly ash content, and alkaline activator molarity, is a reliable parameter for predicting the compressive strength of geopolymer concrete.
7. **Non-Linear Relationship**
   a. The relationship between the binder index and compressive strength is non-linear, suggesting that the strength gain is influenced by complex interactions among the binder components.

6. References

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