EFFECT OF BINDER INDEX ON SPLIT TENSILE STRENGTH OF FLY ASH, GGBS BASED GEOPOLYMER CONCRETE.

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This article explores the impact of Class F Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), and the molarity of the alkaline activator on the split tensile strength of geopolymer concrete (GPC). Sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions were used as activators with molarities of 8, 10, and 12. The proportions of Fly Ash to GGBS were varied across the following ratios: 80:20, 70:30, 60:40, 50:50, 40:60, 30:70, and 20:80. The alkaline liquid-to-fly ash ratio was maintained at 0.36, and the fine aggregate-to-total aggregate ratio was fixed at 32%. The sodium silicate-to-sodium hydroxide ratio was set at 2.5.
Three identical specimens for each mix variation were cast and tested after 7 and 28 days of ambient curing. To evaluate the combined influence of Fly Ash, GGBS, and molarity on the split tensile strength of geopolymer concrete under ambient conditions, a parameter called the *Binder Index* was introduced. The study provides insights into the relationship between mix proportions, curing conditions, and the resulting mechanical performance of geopolymer concrete.
Key words: Geopolymer Concrete (GPC), Fly ash (FA), Ground Granulated Blast Furnace Slag(GGBS), Split Tensile Strength(f_{ct}), Binder Index(B_i), Ambient temperature.

1.Introduction Concrete is one of the most widely used construction materials in the world. A key component of conventional concrete is Portland cement, whose production not only depletes natural resources but also significantly contributes to environmental pollution. It is estimated that 5–6% of the global carbon dioxide (CO_2) emissions generated by human activities result from cement production【1】.

Geopolymer concrete has emerged as a sustainable and environmentally friendly alternative to Portland cement concrete. Geopolymers, a novel class of binders introduced by Joseph Davidovits in the 1970s【2】, have garnered increasing attention, particularly fly ash-based geopolymers, since the 1990s. Geopolymer concrete is formed through the polymerization process, utilizing fly ash and ground granulated blast furnace slag (GGBS) as binders, activated by an alkaline solution. This alkaline solution typically consists of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH).

Numerous studies have explored the properties of geopolymer pastes and geopolymer concrete materials【3–4】. Building upon this foundation, the present research focuses on investigating the effect of fly ash, GGBS, and the molarity of the alkaline activator on the split tensile strength of geopolymer concrete under ambient curing conditions.

To evaluate the combined influence of these factors, a novel parameter called the *Binder Index* (Bi) is introduced. This parameter quantifies the effects of the binders and alkaline activator on the split tensile strength of geopolymer concrete, offering a more comprehensive understanding of its behavior and performance in ambient environments.

2. Experimental investigation

The experimental program aimed to determine the **split tensile strength** of geopolymer concrete (GPC) using cylindrical specimens of 100 mm diameter and 200 mm height. The experimental procedure included the following steps:

1. **Material Proportions**
    - Seven different Fly Ash-to-GGBS proportions were used: **80:20, 70:30, 60:40, 50:50, 40:60, 30:70, and 20:80**.
    - The **alkaline liquid-to-fly ash ratio** was maintained at **0.36**.

  - The **fine aggregate-to-total aggregate ratio** was fixed at **32%**【5】.
2. **Alkaline Activator**
   - Sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions were used as alkaline activators.
   - Three levels of **alkaline molarity** were tested: **8M, 10M, and 12M**.
3. **Specimen Preparation**
   - Three identical specimens were cast for each combination of fly ash-to-GGBS ratio and molarity of alkaline activator.
4. **Curing and Testing**
   - The specimens were cured under **ambient conditions** for **7 days and 28 days** before testing.
   - The split tensile strength of the specimens was measured following standard testing procedures.

This experimental program provided a systematic approach to investigate the effects of binder composition and alkaline activator molarity on the split tensile strength of geopolymer concrete under ambient curing conditions.

2.1 Materials The materials used for this experimental investigation were sourced and prepared as follows:

Binders

1. **Fly Ash**
   - Source: Kothagudem Thermal Power Station, Bhadradri Kothagudem District, Telangana, India.
   - Specific Gravity: **2.17**.
   - Chemical composition: Detailed in **Table 1**.
2. **Ground Granulated Blast Furnace Slag (GGBS)**
   - Source: Blue Way Exports Supplier, Vijayawada, Andhra Pradesh, India.
   - Specific Gravity: **2.90**.
   - Chemical composition: Detailed in **Table 1**.

Aggregates

1. **Fine Aggregate**
   - Type: Natural river sand conforming to **grading zone II** of IS 383:1970.
   - Specific Gravity: **2.32**.
   - Fineness Modulus: **2.81**.
2. **Coarse Aggregate**
   - Maximum size: **12 mm**.
   - Source: Locally available.

Alkaline Activators

1. **Sodium Hydroxide (NaOH)**
   - Molarities: **8M, 10M, and 12M**.
   - Sodium hydroxide pellets used for solution preparation are detailed in **Table 2**.
2. **Sodium Silicate (Na_2SiO_3)**
   - Mixed with NaOH solution in a **2.5:1 ratio** (by weight).
   - The prepared mixture was stored for **24 hours** at room temperature before casting.

Superplasticizer

- Type: **Conplast SP-430** (polycarboxylate ether-based superplasticizer).
- Purpose: To enhance workability and ensure proper flowability of the geopolymer concrete mix.

This selection of materials ensured compliance with standards and provided a reliable basis for studying the split tensile strength of geopolymer concrete under varying binder compositions and molarity levels.

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 2400Kg/m^3.The Geopolymer Concrete mix proportions are shown in table 3.

Table 3. Geopolymer Concrete mix proportions.

FA:GGBS	Geopolymer Concrete mix proportions (Kg/m^3)						
	Coarse Aggregate	Fine Aggregate	Fly ash	GGBS	NaOH Solutio	Sodium Silicate	SP
80:20	1100	517.45	460.1	115.04	59.10	148.25	11.50
70:30	1100	517.45	402.6	172.56	59.10	148.25	11.50
60:40	1100	517.45	345.1	230.08	59.10	148.25	11.50
50:50	1100	517.45	287.6	287.6	59.10	148.25	11.50
40:60	1100	517.45	230.0	345.12	59.10	148.25	11.50
30:70	1100	517.45	172.5	402.64	59.10	148.25	11.50
20:80	1100	517.45	115.0	460.16	59.10	148.25	11.50

2.3 Casting of Geopolymer Concrete specimens

The procedure for preparing and testing geopolymer concrete specimens for split tensile strength was as follows:

Mixing Process

Dry Mixing : The solid constituents, including **aggregates**, **fly ash**, and **GGBS**, were mixed thoroughly in a dry state for approximately **three minutes**.

Preparation of Liquid Mix : The liquid components, consisting of the **alkaline solution**, **added water**, and **superplasticizer**, were pre-mixed separately before being combined with the dry mix. The wet mixing process continued for another **four minutes** until a uniform, cohesive mixture was achieved.

Appearance and Workability : The fresh geopolymer concrete appeared **dark in color** with a **shiny surface** and exhibited a cohesive texture. The workability of the fresh mix was assessed using the **conventional slump test**.

Specimen Preparation : Casting and Compaction

The fresh geopolymer concrete was poured into cylindrical molds (100 mm diameter and 200 mm height) in **three equal layers**. Compaction was achieved using a **vibration table** for **ten seconds**.

Demolding and Curing : Specimens were demolded after **24 hours** and subjected to **ambient curing**.

Testing Procedure : The split tensile strength tests were performed using a **universal testing machine** with a capacity of **1000 KN**. The load was applied at a constant rate until specimen failure, and the maximum load was recorded as per **IS 516-1956**【7】.

Specimen Details : Total Cylinders Cast: 126 .

Fly Ash to GGBS Proportions: 80:20, 70:30, 60:40, 50:50, 40:60, 30:70, and 20:80. **Molarities**: 8M, 10M, and 12M.

Testing Ages: 7 days and 28 days of ambient curing.

Results and Binder Index (Bi) : Test results, summarized in **Table 4**, include split tensile strength values for different proportions and molarities. The **Binder Index (Bi)** was introduced to evaluate

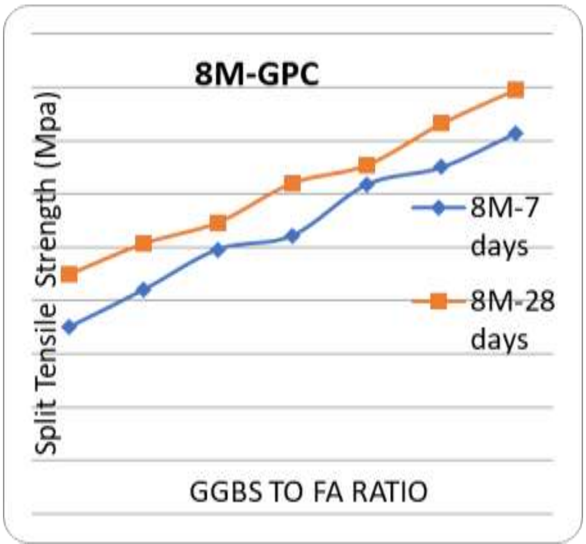
the combined effects of **GGBS**, **fly ash**, and the molarity of the alkaline activator on the split tensile strength【8–10】.
This rigorous experimental approach ensures reliable and repeatable results, providing critical insights into the behaviour of geopolymer concrete under ambient curing conditions.

3. 0 Results and Discussions

Table 4. Split Tensile Strength values for Geopolymer Concrete

FA:GGBS	[GGBS / (GGBS + Fly ash)]	Split Tensile Strength (Mpa)					
		8 moles/L		10 moles/L		12 moles/L	
		7D	28D	7D	28D	7D	28D
80:20	0.2	1.75	2.24	2.07	2.48	2.48	3.03
70:30	0.3	2.10	2.53	2.45	3.22	2.93	3.50
60:40	0.4	2.48	2.73	2.87	3.50	3.25	3.86
50:50	0.5	2.61	3.10	3.18	3.98	3.66	4.24
40:60	0.6	3.09	3.27	3.50	4.14	3.89	4.78
30:70	0.7	3.25	3.66	3.79	4.46	4.14	5.00
20:80	0.8	3.57	3.98	3.98	4.78	4.52	5.13

The effect of GGBS to Fly ash ratio on Split tensile Strength of Geopolymer concrete is shown in fig 1, fig 2. & fig 3.



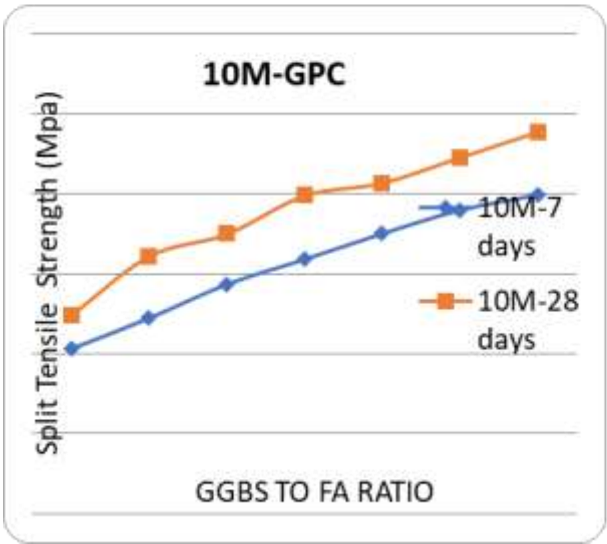
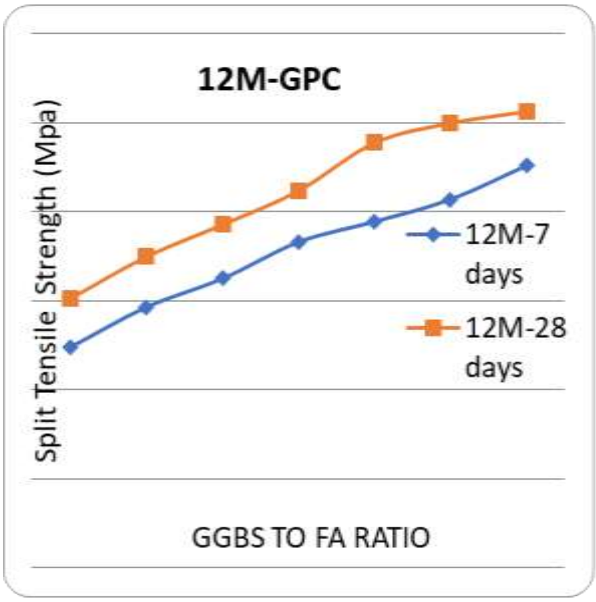


Fig 1.GGBS to Fly ash ratio Vs Split Tensile Strength of GPC

Fig 2.GGBS to Fly ash ratio Vs SplitTensile strength of GPC



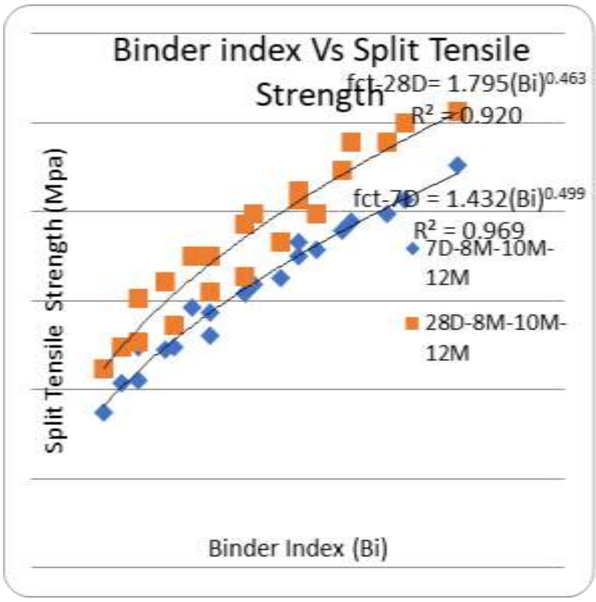


Fig 3. GGBS to Fly ash ratio Vs Split Tensile Strength Fig 4. Binder index Vs Split Tensile Strength of GPC

3.1 Effect of GGBS to Fly ash ratio on Split Tensile strength of Geopolymer concrete(GPC).

The influence of the **GGBS-to-Fly Ash ratio** on the split tensile strength of geopolymer concrete (GPC) was investigated for 7-day and 28-day ambient curing conditions at different molarity levels of the alkaline activator.

Observations

- **Figures 1 to 3** illustrate the variation in split tensile strength for each molarity (8M, 10M, and 12M).
- A consistent increase in the **split tensile strength** was observed with an increase in the GGBS-to-Fly Ash ratio across all curing durations.

Trend Analysis

- **GGBS Contribution**:
  - GGBS contributes to enhanced reactivity and denser microstructure due to its higher calcium content.
  - The polymerization process benefits from the faster setting and strength development attributed to GGBS.
- **Fly Ash Contribution**:
  - While fly ash provides long-term strength and workability, higher proportions of GGBS promote early strength gain due to its superior chemical reactivity.

This trend indicates that **higher GGBS content** in the binder significantly improves the split tensile strength of GPC under ambient curing conditions. This finding underscores the importance of optimizing the binder composition to achieve desired mechanical properties in geopolymer concrete.

3.2 Effect of molarity of alkaline activator on Split tensile strength of Geopolymer concrete (GPC)

The impact of the **molarity of the alkaline activator** on the split tensile strength of geopolymer concrete (GPC) was analyzed for various GGBS-to-Fly Ash proportions and curing durations (7 days and 28 days).

Observations

- **Figures 1 to 3** depict the variation in split tensile strength with molarity levels (**8M, 10M, and 12M**) for different GGBS-to-Fly Ash ratios.
- A clear increase in split tensile strength was observed with the increase in **molarity of the alkaline activator** for all binder compositions and curing periods.

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Trend Analysis

- **Higher Molarity Contribution**:
    - Increasing the molarity enhances the concentration of hydroxide ions, accelerating the dissolution of aluminosilicate materials in Fly Ash and GGBS.
    - This results in a more efficient polymerization process, forming a denser and stronger geopolymeric matrix.
- **Combined Effect with GGBS**:
    - For a fixed GGBS-to-Fly Ash ratio, higher molarity leads to greater early-age and long-term strength due to improved geopolymer gel formation and microstructural development.

This trend highlights that **higher molarity alkaline solutions** significantly contribute to the development of split tensile strength in GPC, particularly when paired with optimal GGBS proportions, under ambient curing conditions.

3.3 Effect of Binder index on Split Tensile strength of Geopolymer concrete (GPC)

The **Binder Index (Bi)** is introduced as a parameter to quantify the combined influence of **Fly Ash**, **GGBS**, and the **molarity of the alkaline activator** on the split tensile strength of geopolymer concrete (GPC).

Binder Index Definition

The Binder Index is calculated using the following equation:

Binder Index (Bi)=Molarity×[GGBSGGBS+Fly Ash](1)\text{Binder Index (Bi)} = \text{Molarity} \times \left[\frac{\text{GGBS}}{\text{GGBS} + \text{Fly Ash}}\right] \tag{1}Binder Index (Bi)=Molarity×[GGBS+Fly AshGGBS](1)

Observations

- The variation of split tensile strength with Binder Index is shown in **Figure 4** and the corresponding data is provided in **Table 5**.
    - **Trend**: An increase in Binder Index correlates with an increase in the split tensile strength of GPC for both **7 days** and **28 days** of ambient curing.

Best Fit Equations

The relationship between the split tensile strength and Binder Index is expressed through the following equations:

1. **For 7-Day Split Tensile Strength**:

fct-7D=1.795(Bi)0.463,R2=0.920(2)f_{\text{ct-7D}} = 1.795 (\text{Bi})^{0.463}, \quad R^2 = 0.920 \tag{2}fct-7D=1.795(Bi)0.463,R2=0.920(2), Where fct-7Df_{\text{ct-7D}}fct-7D is the split tensile strength after 7 days of curing.

2. **For 28-Day Split Tensile Strength**:

fct-28D=1.432(Bi)0.499,R2=0.969(3)f_{\text{ct-28D}} = 1.432 (\text{Bi})^{0.499}, \quad R^2 = 0.969 \tag{3}fct-28D=1.432(Bi)0.499,R2=0.969(3), Where fct-28Df_{\text{ct-28D}}fct-28D is the split tensile strength after 28 days of curing.

Significance of Binder Index

- **Combined Influence**:
    - The Binder Index effectively integrates the contributions of GGBS content, Fly Ash content, and alkaline activator molarity into a single parameter.
    - The high **correlation coefficients** (R2=0.920R^2 = 0.920R2=0.920 and R2=0.969R^2 = 0.969R2=0.969) indicate that the equations provide an accurate prediction of split tensile strength based on the Binder Index.
- **Practical Implications**:
    - The Binder Index offers a reliable tool for optimizing binder proportions and activator molarity to achieve desired tensile strength in geopolymer concrete.
    - This parameter simplifies the study of multiple variables and their interactions in geopolymer concrete performance.

4.0 Conclusions

The following conclusions can be made from the analysis of test results.
Based on the analysis of test results, the following conclusions are drawn:

1. **Effect of GGBS Content**
   - The **split tensile strength** of geopolymer concrete (GPC) increased with the increase in the **GGBS-to-Fly Ash ratio**, highlighting the beneficial role of GGBS in enhancing strength through improved reactivity and microstructural densification.
2. **Effect of Molarity of Alkaline Activator**
   - An increase in the **molarity** of the alkaline activator resulted in a significant improvement in the split tensile strength of GPC for both **7 days** and **28 days** of ambient curing.
3. **Combined Influence via Binder Index**
   - The **Binder Index (Bi)** was introduced to quantify the combined effects of **Fly Ash**, **GGBS**, and the **molarity** of the alkaline activator on the split tensile strength of GPC.
   - The Binder Index provided a reliable and predictive relationship for split tensile strength through best-fit equations, as evidenced by high correlation coefficients (R2>0.92R^2 > 0.92R2>0.92).
4. **Strength Development**
   - Both **7-day** and **28-day** split tensile strengths showed non-linear growth with an increase in the Binder Index, indicating the synergistic effects of binder proportions and activator molarity on the geopolymerization process.
5. **Ambient Curing Performance**
   - Geopolymer concrete achieved significant tensile strength under **ambient curing conditions**, making it a viable alternative to heat-cured systems and reducing energy demands in practical applications.
6. **Sustainability**
   - The use of **Fly Ash** and **GGBS** in GPC provides an eco-friendly alternative to conventional Portland cement, effectively reducing **CO_2 emissions** and conserving natural resources.
7. **Practical Utility**
   - The study demonstrates that the Binder Index is a practical tool for mix design and performance prediction, offering valuable insights into optimizing material proportions for enhanced tensile strength.

These findings reinforce the potential of geopolymer concrete as a sustainable, high-performance construction material.

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