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EFFECT OF BINDER INDEX AND ALKALINE CONCENTRATION ON SPLIT TENSILE STRENGTH DEVELOPMENT OF AMBIENT-CURED GEOPOLYMER CONCRETE

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ABSTRACT

This study investigates the influence of the geopolymer binder index on the split tensile strength of geopolymer concrete (GPC) produced with varying proportions of Ground Granulated Blast Furnace Slag (GGBS) and fly ash. Experimental variables included GGBS:Fly Ash ratios (20:80, 40:60, 50:50, 60:40, 80:20), sodium hydroxide molarity levels (8M, 10M, 12M), and curing periods (7 and 28 days), while maintaining a constant alkaline-to-binder ratio of 0.38. The binder index, representing the combined reactivity of GGBS and fly ash, was correlated with tensile strength performance. Results showed that higher GGBS content significantly enhanced tensile strength due to increased calcium–alumino–silicate–hydrate (C–A–S–H) gel formation. At 28 days, 8M GPC improved from 2.35 MPa at a 20:80 ratio to 3.94 MPa at 80:20, while 12M GPC at 80:20 achieved a maximum of 4.22 MPa. Increased NaOH molarity accelerated early-age strength development, with 7-day strengths reaching up to 3.37 MPa for 12M

mixes. A strong positive correlation was observed between binder index and tensile strength, confirming its value as a performance predictor. The findings highlight that optimizing GGBS content and activator molarity is critical for achieving superior tensile performance in GPC.

Keywords: Geopolymer concrete, Binder index, Split tensile strength, GGBS, Fly ash, Sodium hydroxide molarity

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1. Introduction

Geopolymer concrete (GPC) has gained significant attention as a sustainable alternative to ordinary Portland cement (OPC) concrete due to its reduced greenhouse gas emissions, utilization of industrial by-products, and superior mechanical and durability performance [1, 2]. Unlike OPC, which derives its binding properties from the hydration of clinker phases, GPC forms through the alkaline activation of aluminosilicate precursors, resulting in a three-dimensional polymeric gel network [3].

Common precursors include low-calcium Class F fly ash and calcium-rich ground granulated blast furnace slag (GGBS). When used in combination, these materials provide complementary benefits: fly ash contributes to long-term strength through the gradual formation of sodium–alumino–silicate–hydrate (N–A–S–H) gels, while GGBS enhances early-age strength due to the formation of calcium–alumino–silicate–hydrate (C–A–S–H) gels [4, 5]. Several studies have reported that increasing the GGBS proportion accelerates geopolymerization, resulting in denser microstructures and improved compressive and tensile strength [6, 7].

While compressive strength has been the primary focus of most GPC research, tensile properties—especially split tensile strength—are critical for assessing cracking resistance and post-cracking performance [8]. In recent years, the binder index has emerged as a quantitative parameter that represents the combined reactivity of GGBS and fly ash in a given mix [9]. Higher binder index values indicate greater potential for gel formation and improved

mechanical performance. However, although some studies have linked binder index to compressive strength, its influence on split tensile strength, particularly under varying sodium hydroxide (NaOH) molarity levels and curing ages, remains insufficiently explored.

Therefore, the present study aims to investigate the effect of binder index on the split tensile strength of geopolymer concrete incorporating different GGBS:Fly Ash ratios, NaOH molarity levels (8M, 10M, 12M), and curing periods (7 and 28 days). The objectives are to:

1. Evaluate the influence of GGBS content on split tensile strength at varying molarity levels.
2. Determine the correlation between binder index and tensile performance at different curing ages.
3. Assess the role of NaOH molarity in early-age tensile strength development.

The outcomes of this study are expected to contribute to the optimization of GPC mix designs for improved tensile performance and durability while maintaining sustainability benefits.

2.0 Materials and Methods

2.1 Materials

The primary aluminosilicate precursors used in this study were low-calcium Class F fly ash and ground granulated blast furnace slag (GGBS). The fly ash was obtained from a thermal power plant and conformed to ASTM C618 requirements, while the GGBS was sourced from a local steel manufacturing plant and met ASTM C989 specifications. The chemical compositions of both materials were determined by X-ray fluorescence (XRF) analysis, indicating that GGBS contained higher calcium oxide (CaO) content, which is favorable for early C–A–S–H gel formation.

The alkaline activator solution comprised sodium hydroxide (NaOH) pellets and sodium silicate (Na_2SiO_3) solution. NaOH solutions of three molarity levels—8M, 10M, and 12M—were prepared by dissolving pellets in potable water at least 24 hours before use to minimize heat generation during dissolution. The sodium silicate solution had a silica modulus ($\text{SiO}_2/\text{Na}_2\text{O}$) of approximately 2.5. The mass ratio of sodium silicate to sodium hydroxide was fixed at 2.5 for all mixes, while the alkaline-to-binder (A/B) ratio was maintained at 0.38.

Locally sourced river sand with a fineness modulus of 2.65 was used as fine aggregate, and crushed granite with a maximum nominal size of 20 mm served as coarse aggregate.

Aggregates met the grading requirements of IS: 383–2016. Potable water was used for mixing and curing.

Table 1. 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

Table 12. Chemical Composition of Fly ash and GGBS Percentage by mass

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	CaO	MgO	Na ₂ O	Ti	K ₂ O	LOI
Fly ash	58.5	22.3	8.2	1.6	1.08	1.05	0.12	1.52	5.13	0.3
GGBS	35.25	20.12	0.85	0.82	32.9	7.82	-	-	-	-

2.2 Mix Proportions

The mix design considered key variables, including the SS/SH ratio, the composition of the alkaline activator, and the replacement level of FA with GGBS. Details of these proportions are shown in Table 1 & 3, and the molar ratios of key chemical components are listed in Table 2.

Concrete mixtures were proportioned to achieve a target density of approximately 2400 kg/m³, following established procedures for GGBS-based GPC mix design. Five binder ratios of FA to GGBS were investigated: 20:80, 40:60, 50:50, 60:40, and 80:20 by mass, designated as:

- **Mix A:** 20% FA, 80% GGBS
- **Mix B:** 40% FA, 60% GGBS
- **Mix C:** 50% FA, 50% GGBS
- **Mix D:** 60% FA, 40% GGBS
- **Mix E:** 80% FA, 20% GGBS

For each mix, NaOH molarity levels of 8M, 10M, and 12M were used, with a fixed SS/SH ratio of 2.5. To improve workability, 2% superplasticizer (by binder mass) and an additional 7.5% water were added.

Table 3. Geopolymer Concrete mix proportions.

FA: GGBS	Molarity (M)	Coarse Aggregate	Fine Aggregate	Fly Ash	GGBS	NaOH Solution	Super Plasticizer (2% of the Binder)	Extra Water (7.5% of the Binder)
80:20	8,10&12	1174	503.15	419	104.8	199.05	10.47	39.28
60:40	8,10&12	1174	503.15	314.3	209.5	199.05	10.47	39.28
50:50	8,10&12	1174	503.15	261.9	261.9	199.05	10.47	39.28
40:60	8,10&12	1174	503.15	209.5	314.3	199.05	10.47	39.28
20:80	8,10&12	1174	503.15	104.8	419	199.05	10.47	39.28

2.3 Casting and Testing of Geopolymer Concrete Specimens

The solid constituents of the geopolymer concrete, namely aggregates, fly ash (FA), and ground granulated blast furnace slag (GGBS), were dry-mixed in a laboratory pan mixer for approximately 3 minutes. The liquid components — alkaline activator solution ($\text{Na}_2\text{SiO}_3 + \text{NaOH}$), added water, and superplasticizer — were premixed and then gradually incorporated into the solids. Wet mixing continued for about 4 minutes until a uniform, cohesive mix was obtained. The fresh geopolymer concrete appeared dark in color, with a shiny surface and high cohesiveness. Workability was assessed using the conventional slump test.

Concrete was placed into 100 mm × 200 mm cylindrical moulds in three equal layers, each compacted on a vibrating table for 10 seconds. Specimens were demoulded after 24 hours and subjected to ambient curing ($27 \pm 2^\circ\text{C}$, $\text{RH} > 60\%$).

Split tensile strength tests were conducted on a Universal Testing Machine (UTM) with a 1000 KN capacity, following IS: 5816–1999 and IS: 516–1959 procedures. The load was applied at a constant rate until specimen failure, and the maximum load was recorded. For each mix variation, three identical specimens were tested after 7 and 28 days of curing. In total, 126 cylinders were cast and tested, covering five FA-to-GGBS ratios (20:80, 40:60, 50:50, 60:40, 80:20) and three molarities of NaOH (8M, 10M, 12M).

To study the combined influence of GGBS content, FA content, and alkaline activator molarity, the Binder Index (Bi) [10]

$$Bi = \text{Molarity} \times \frac{\text{GGBS}}{\text{GGBS} + \text{FA}}$$

3.0 Results & Discussion

Table 4. 7 & 28-Day Split Tensile Strength vs. Binder Index (8M, 10M, 12M; A/B = 0.38)

Alk/Binder Ratio = 0.38						7 Days	28 Days	
Sl. No	Mix Designation	NaOH molarity	GGBS: Fly ash	GGBS/Fly ash	Geopolymer Binder Index	Split Tensile Strength (MPa)	Split Tensile Strength (MPa)	7D/28D strength ratio
1	8A	8	20:80	0.25	1.6	1.9	2.35	0.8
2	8B	8	40:60	0.67	3.2	2.38	2.72	0.86
3	8C	8	50:50	1	4	2.79	2.97	0.92
4	8D	8	60:40	1.5	4.8	2.86	3.28	0.85
5	8E	8	80:20	4	6.4	3.24	3.44	0.92
6	10A	10	20:80	0.25	2	2.15	2.5	0.84
7	10B	10	40:60	0.67	4	2.7	3.06	0.86
8	10C	10	50:50	1	5	2.86	3.28	0.85
9	10D	10	60:40	1.5	6	3.18	3.75	0.83
10	10E	10	80:20	4	8	3.81	3.91	0.96
11	12A	12	20:80	0.25	2.4	2.41	2.97	0.8
12	12B	12	40:60	0.67	4.8	2.95	3.28	0.88
13	12C	12	50:50	1	6	3.11	3.41	0.89
14	12D	12	60:40	1.5	7.2	3.33	3.97	0.82
15	12E	12	80:20	4	9.6	3.97	4.22	0.92

Effect of Binder Index and Alkaline Concentration on Split Tensile Strength Development of Ambient-Cured Geopolymer Concrete

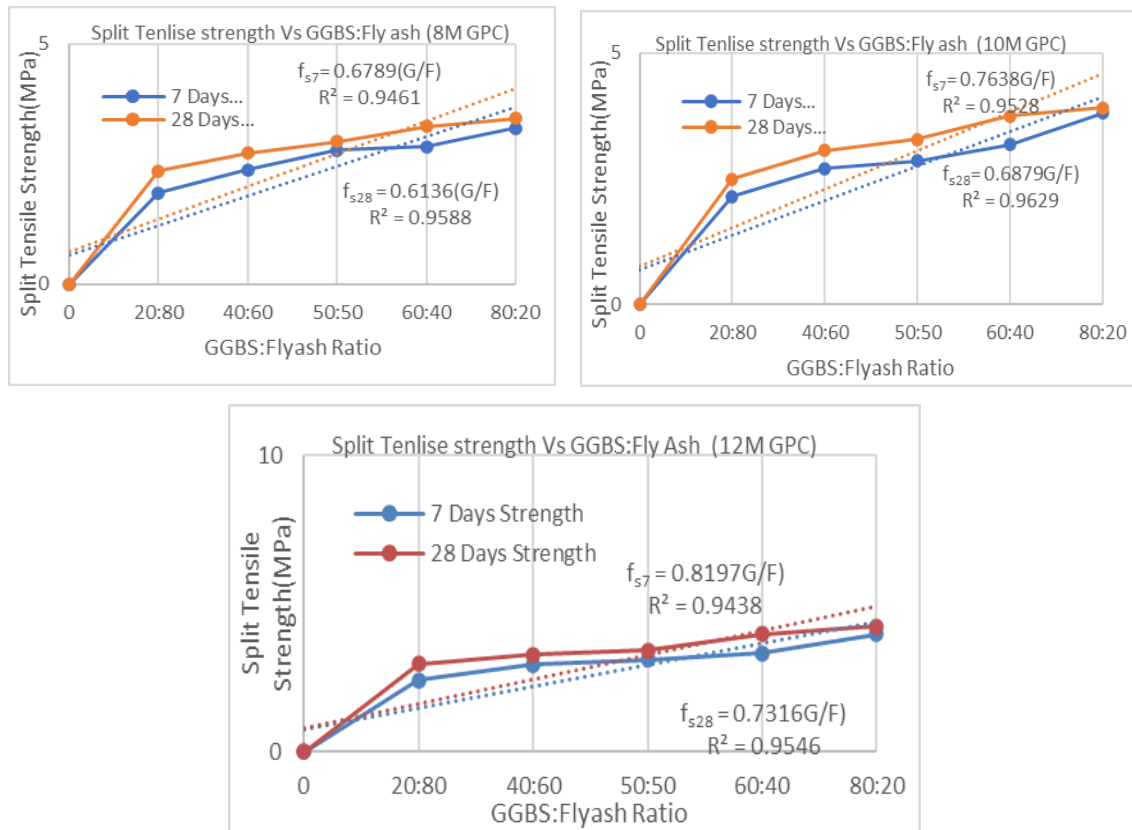


Figure 1. Split tensile strength vs. GGBS:FA ratio for 8M, 10M & 12M of GPC (7 & 28 days)

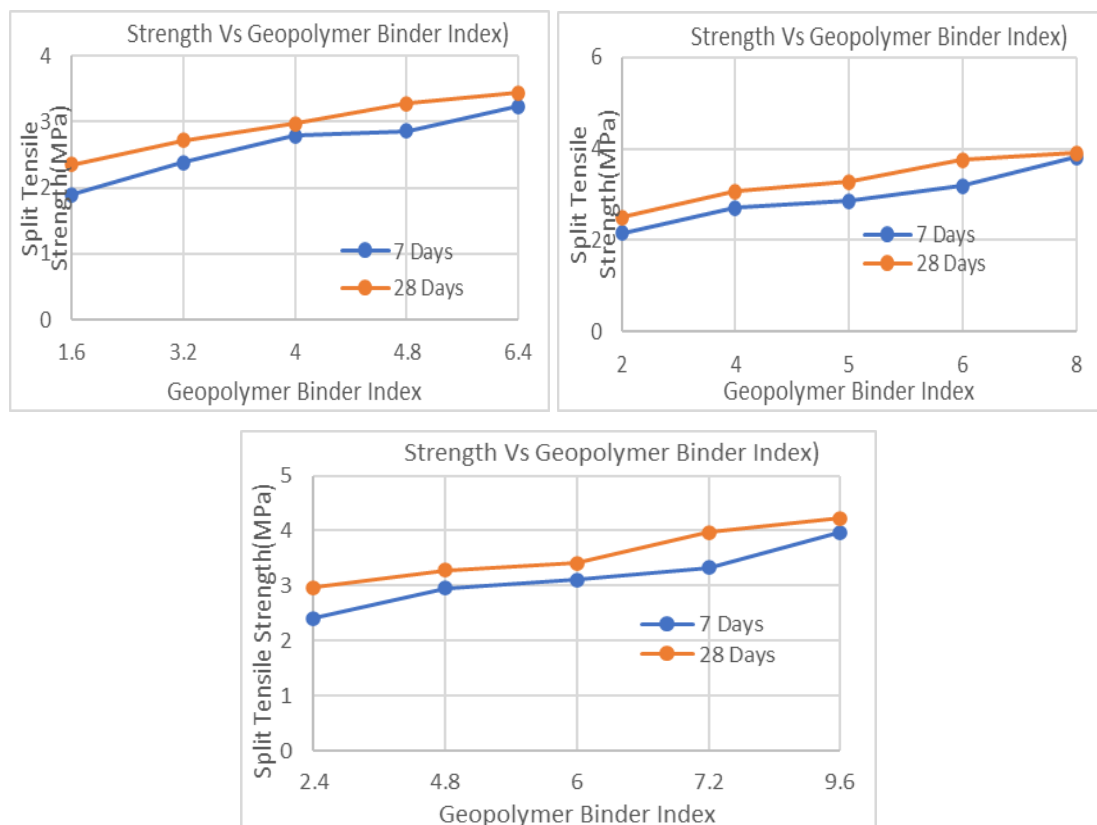


Figure 2. Split tensile strength vs. binder index for 8M, 10M & 12M GPC (7 & 28 days)

3.1 Effect of Binder Composition (GGBS:Fly Ash Ratio)

The variation in split tensile strength of geopolymer concrete (GPC) for different GGBS:Fly Ash ratios at 7 and 28 days under ambient curing conditions is presented in Table 4 and Figure 1. All mixes were prepared with a constant alkaline-to-binder ratio of 0.38, and tested for three sodium hydroxide molarity levels (8M, 10M, and 12M).

The results indicate a consistent increase in split tensile strength with higher GGBS content, regardless of molarity and curing age. For example, in 8M GPC at 28 days, tensile strength increased from 2.35 MPa for a 20:80 GGBS:FA mix to 3.44 MPa for an 80:20 mix. Similar trends were observed for 10M and 12M GPC, with the highest 28-day tensile strength of 4.22 MPa recorded for an 80:20 mix at 12M. This enhancement is attributed to the higher calcium oxide (CaO) content in GGBS, which promotes the formation of calcium–alumino–silicate–hydrate (C–A–S–H) gels, resulting in a denser matrix and improved interfacial bonding.

3.2 Effect of Alkaline Activator Concentration (NaOH Molarity)

Across all binder compositions, increasing NaOH molarity significantly improved both early-age and long-term tensile strength. For example, at a 60:40 GGBS:FA ratio, the 28-day tensile strength rose from 3.28 MPa (8M) to 3.97 MPa (12M).

Higher molarity also accelerated early strength development. At the same 60:40 ratio, the 7-day strength for 12M GPC was 3.37 MPa, representing ~85% of the corresponding 28-day strength. This trend reflects the faster dissolution of aluminosilicate precursors and more rapid geopolymer gel formation at higher alkalinity.

3.3 Effect of Binder Index (Bi)

The relationship between the geopolymer binder index (Bi) and split tensile strength is illustrated in Figure 2. The binder index reflects both the proportion of GGBS in the mix and the concentration of the alkaline activator. Results indicate a strong positive correlation between Bi and tensile strength at both 7 and 28 days.

For instance, in 8M GPC, the 28-day strength increased from 2.35 MPa at Bi = 1.6 to 3.44 MPa at Bi = 6.4. A higher binder index enhances the reactive binder fraction, improves dissolution of aluminosilicates, and accelerates geopolymerization, resulting in a denser and more cohesive matrix.

3.4 Strength Development Ratio (7-day / 28-day)

The strength ratios for all mixes ranged from 0.80 to 0.96, indicating steady and continuous tensile strength gain over time. The highest ratios were associated with mixes containing higher GGBS content and elevated NaOH molarity, demonstrating the combined

importance of binder composition and activator concentration for achieving balanced early-age and long-term performance.

Overall, the results confirm that a combination of high GGBS content ($\geq 60\%$) and elevated NaOH molarity ($\geq 12\text{M}$), with a constant alkaline-to-binder ratio of 0.38, maximizes tensile strength in ambient-cured GPC. This approach ensures rapid early-age strength gain while maintaining high long-term performance.

4.0 Conclusions

The experimental investigation into the split tensile strength behavior of geopolymer concrete (GPC) incorporating varying proportions of GGBS and fly ash, activated with different sodium hydroxide molarities, has led to the following key conclusions:

1. **Influence of GGBS Content:** The split tensile strength of GPC increased consistently with higher GGBS content for all NaOH molarity levels and curing ages. The highest strength value of **4.22 MPa** was recorded for the mix containing **80% GGBS and 20% FA** activated with **12M NaOH** at 28 days. This performance is attributed to the higher calcium oxide (CaO) content in GGBS, which promotes the formation of C–A–S–H gels and enhances matrix densification.
2. **Effect of NaOH Molarity:** Increasing the NaOH molarity from 8M to 12M resulted in substantial improvements in both early-age (7-day) and long-term (28-day) tensile strength. This enhancement can be linked to the accelerated dissolution of reactive aluminosilicate phases and the faster rate of geopolymerization at higher alkalinity levels.
3. **Relationship with Binder Index:** A strong positive correlation was observed between the **geopolymer binder index (Bi)** and the split tensile strength at both testing ages. Mixes with higher binder indices exhibited a denser and more cohesive microstructure, primarily due to greater C–A–S–H gel development, which improved tensile load-bearing capacity.
4. **Strength Development Trend:** The ratio of 7-day to 28-day split tensile strength ranged between **0.80 and 0.96**, indicating steady strength gain over time. Mixes with higher molarity activators achieved superior early-age performance, demonstrating their suitability for applications requiring early loading capacity.

5. **Recommended Mix Parameters:** Based on the study results, a GPC mix incorporating $\geq 60\%$ GGBS, activated with **12M NaOH**, and designed with an **alkaline-to-binder ratio of 0.38** is recommended for achieving superior split tensile strength under ambient curing conditions.

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