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Fresh and Mechanical Properties of Fly Ash-GGBS Based Geopolymer Concrete: Effect of NaOH Molarity, Slag Content and Curing Condition

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Abstract: ***The manufacture of ordinary Portland cement (OPC) releases ~1 ton of CO_2 per ton of cement produced, which is encouraging the construction industry to seek low-carbon binders. One of the most promising options is geopolymer concrete where industrial by-products are used as a complete replacement of cement. The present paper deals with an experimental investigation on M30 grade geopolymer concrete using low calcium (Class F) fly ash and ground granulated blast furnace slag (GGBS) as source material and sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions as alkaline activators. In this experimental program we investigated two series of mixes. The first series of binders consisted of 100 % fly ash and the NaOH concentration ranged from 8 M to 16 M. In second series, fly ash was replaced by GGBS 10-50% by mass and NaOH concentration was maintained constant 12M . All the mixtures were cured at room temperature and in oven at 60^oC for 24 h. The ratio of Na_2SiO_3/NaOH was 2.0. The test results showed that the compressive strength of fly-ash-only concrete increased continuously with the increase of NaOH molarity, increasing by about 62% from 8 M to 16 M, and that oven curing improved the strength at each molarity. The addition of GGBS gave a much greater improvement, the 28-day ambient cured strength almost doubling from about 30 N/mm^2 (fly ash alone, 12 M) to 61.42 N/mm^2 at 30 % GGBS, which was the optimum replacement level. Above 30% GGBS the strength dropped back (due to rapid early stiffening). Most importantly, the combined mixes achieved nearly the same 28-day strength under the ambient curing as under the oven curing, which implies that the combination of fly ash-GGBS does not require any heat curing. The split tensile strength ranged from 7-8% of the compressive strength, and the split tensile and flexural strengths were linearly correlated to the compressive strength (R^2 ~ 0.95 and 0.93). The results indicate that fly ash-GGBS geopolymer concrete is a viable ambient-curing and eco-friendly alternative for OPC concrete for structural-grade applications.***

Keywords: Geopolymer concrete; fly ash; GGBS; NaOH molarity; ambient curing; compressive strength; sustainable construction.

I. INTRODUCTION

Ordinary Portland cement (OPC) is the principal cementing agent in concrete, the world's most widely used building material. OPC manufacturing is unfortunately energy intensive and carbon intensive. The production of one tonne of cement emits nearly one tonne of CO_2 into the atmosphere and the cement industry is one of the major industrial contributors to greenhouse gas emissions [1, 2]. At the same time, coal-fired power stations and the iron-making industry generate large volumes of by-products - fly ash and ground granulated blast furnace slag (GGBS) - which are still largely dumped in landfills or ash ponds. India produces over 100 million tonnes of fly ash annually, of which only a small percentage is used productively. Disposal of ash occupies tens of thousands of acres of land and poses threat to soil, ground water and human health [3, 4].

Geopolymer concrete is a solution to both problems at the same time. A geopolymer is an inorganic alumino-silicate binder, synthesized by activation of silica- and alumina-rich source materials with a strong alkaline solution. This concept was elaborated by Davidovits in the late 1970s [5, 6]. Geopolymerisation is a process where silicate and aluminate species dissolve from the source material and then re-condense to form a three dimensional Si-O-Al-O network. The hardened product binds aggregates in the same way as hydrated cement does, but without any Portland cement, so it can reduce binder-related CO_2 emissions by up to 80% [2, 7]. The geopolymer concretes are also reported to develop high early strength, low creep and shrinkage and good resistance to sulphates, acids, fire and elevated temperatures [8-11].

The most common source material for geopolymers is low-calcium (Class F) fly ash, which is abundant, low-cost and contains high amounts of reactive alumino-silicate glass [12, 13]. However, the main drawback of fly-ash-only geopolymer concrete is that it gains strength slowly at room temperature and usually requires heat curing at about 60-90 °C to perform well [13, 14]. Such dependence upon ovens limits the material to precasting plants and precludes its use in ordinary field work. A practical way round the problem is to mix the fly ash with a calcium rich material such as GGBS. The calcium in the slag reacts with the alkaline solution to form calcium-silicate-hydrate (C-S-H) and calcium-alumino-silicate-hydrate (C-A-S-H) gels together with the sodium-alumino-silicate (N-A-S-H) geopolymer gel, and this additional reaction happens at room temperature, providing early strength without external heat [15-17].

Some researchers have studied this system in parts. The strength of fly-ash geopolymer concrete was influenced by NaOH concentration, silicate-to-hydroxide ratio, curing time and curing temperature as found by Hardjito et al. [13, 14]. Madheswaran et al. [18] and Tank et al. [19] have verified that in general, higher NaOH molarity results in better strength, but too high concentrations can be counterproductive. Nath and Sarker [16], Hariharan et al. [20], Abhilash et al. [21], Guru Jawahar and Mounika [22] and Shah [23] showed the increasing strength and the possibility of ambient curing with the addition of GGBS to fly ash. Pandey et al. [24] and Sunarsih et al. [25] also showed similar benefits with improved durability-related transport properties. However, recent reviews indicate that the guidance on mix design of geopolymer concrete is still dispersed and systematic data connecting molarity, slag content and curing condition for a particular design grade are still limited [26].

The present study was designed to overcome this limitation by means of a single coherent test programme. Initially, an M30 grade geopolymer concrete was prepared using 100% fly ash and the concentration of NaOH was varied over five levels (8, 10, 12, 14 and 16 M) to establish the effect of activator strength. The workability, compressive strength, split tensile strength and flexural strength of the blended mixes were then tested with partial replacement of fly ash with GGBS at five levels (10-50% by mass) at 12 M concentration. Each mix was cured under ambient conditions and in an oven at 60 °C for 24 h, to allow the two regimes to be directly compared. Finally, simple linear relationships were obtained between the compressive strength and the tensile and flexural strength for the purpose of preliminary design. The specific objectives were: (i) to design an M30 grade fly ash geopolymer concrete; (ii) to quantify the effect of NaOH molarity on its strength; (iii) to determine the optimum GGBS replacement level at 12 M; and (iv) to establish whether the blend system can attain its design strength under ambient curing alone.

II. MATERIALS AND EXPERIMENTAL METHODS

A. *Materials*

Fly ash of Class F variety with low-calcium content was collected from the electrostatic precipitators of a coal-fired thermal power station that met the IS 3812 (Part 1) [27] and ASTM C618 [28] and stored in moisture-proof containers. The total SiO_2 + Al_2O_3 + Fe_2O_3 content was above 70% and the CaO content was only 1.92%. The SiO_2/Al_2O_3 ratio of about 1.67 is within the range considered favorable for geopolymerisation [12]. A slag grinding plant supplied GGBS conforming to IS 12089 [29] containing about 32% CaO and finer than the fly ash (420 m2/kg against 330 m^2/kg). Table 1 lists the physical and chemical properties of two binders.

Table 1. Physical and chemical properties of fly ash and GGBS (fly ash value / *GGBS value)

Oxide / property	Fly ash	Oxide / property	GGBS
SiO_2 (%)	53.20	MgO (%)	0.88 / 8.15*
Al_2O_3 (%)	31.85	SO^3 (%)	0.48 / 0.18*
Fe_2O_3 (%)	5.64	Fineness (m^2/kg)	330 / 420*
CaO (%)	1.92 / 32.10*	Specific gravity	2.20 / 2.91*
SiO_2/Al_2O_3	1.67 / 1.66*	Colour	Grey / off-white*

Locally available river sand falling in Zone II of IS 383 [30], with a specific gravity of 2.58, a fineness modulus of 2.52 and water absorption of 1.10%, served as the fine aggregate. Crushed granite of 20 mm and 10 mm nominal sizes from a single quarry was used as the coarse aggregate (specific gravities of 2.87 and 2.85, water absorption of 1.05% and 1.58%, aggregate impact values of 12.10% and 13.45%, respectively). All aggregates were used in a saturated surface-dry condition. The alkaline activator combined laboratory-grade NaOH flakes (98.5% purity) with a commercial sodium silicate solution (14.7% Na_2O, 29.4% SiO_2, 55.9% water;

specific gravity 1.27). Potable water free of harmful salts was used to prepare the NaOH solutions, and a fixed extra dose of 25 kg/m³ of water was added to every mix to maintain cohesion and workability, since no chemical superplasticiser was used.

B. Mix design

The mixes were designed for a target mean compressive strength of 38.25 N/mm² at 28 days, corresponding to M30 grade as per IS 456 [31]. Because no Indian code yet covers geopolymer mix design, the proportioning followed the method developed by Rangan and co-workers [32, 33], refined here through a series of laboratory trial batches. The unit weight of the concrete was taken as 2350 kg/m³, of which 70% (1645 kg/m³) was aggregate, split as 40% 20-mm coarse aggregate, 30% 10-mm coarse aggregate and 30% fine aggregate. The binder content was 450 kg/m³ with an alkaline-liquid-to-binder ratio of 0.50, giving 225 kg/m³ of activator. The Na_2SiO_3/NaOH mass ratio was fixed at 2.0 (150 kg/m³ silicate solution and 75 kg/m³ hydroxide solution), a value the trial mixes showed gave the best balance of workability and strength and which also agrees with the literature [13, 19]. For the blended mixes the 450 kg/m³ of binder was simply divided between fly ash and GGBS in the required ratio. The complete proportions are given in Table 2.

Table 2. Mix proportions for all binder systems (per m³ of concrete)

Material (kg/m³)	100FA	90FA10GS	80FA20GS	70FA30GS	60FA40GS	50FA50GS
Fly ash	450	405	360	315	270	225
GGBS	0	45	90	135	180	225
20 mm aggregate	658	658	658	658	658	658
10 mm aggregate	494	494	494	494	494	494
Fine aggregate	493	493	493	493	493	493
Na_2SiO_3 solution	150	150	150	150	150	150
NaOH solution	75	75	75	75	75	75
Extra water	25	25	25	25	25	25

C. Preparation of the alkaline activator

Five NaOH concentrations were prepared - 8, 10, 12, 14 and 16 M - by dissolving 320, 400, 480, 560 and 640 g of flakes per litre of solution, respectively (molar mass of NaOH = 40 g/mol). The flakes were added slowly to the measured water, never the reverse, and because the dissolution is strongly exothermic the solutions were prepared at least 24 hours before casting so that they cooled and stabilised fully [14]. The NaOH and sodium silicate solutions were combined at the fixed mass ratio of 2.0 about 15 minutes before batching and kept stirred until use; blending the two solutions too far in advance caused the activator to stiffen and set.

D. Mixing, casting and curing

All concrete was produced in a tilting drum mixer using a fixed sequence: the saturated surface-dry aggregates were blended dry for two minutes; the binder was added and dry-mixed for a further three minutes; and the activator plus the extra water were then added slowly and wet-mixed for four to five minutes. The slump of each fresh blended mix was measured immediately after mixing as per IS 1199 [34]. Specimens were compacted in layers by rodding followed by table vibration in accordance with IS 516 [35], taking care to avoid over-vibration. Two curing regimes were applied to every mix: (i) ambient curing, in which the specimens were left in the open laboratory air (about 25-42 °C) without any applied moisture; and (ii) oven curing, in which the specimens were held at 60 °C for 24 hours immediately after casting and then cooled slowly to room temperature. The 60 °C level was selected from trial batches as the temperature that accelerated the reaction without causing the surface cracking observed at higher temperatures [10, 17].

E. Test programme

Ten distinct mixes were studied: fly-ash-only concrete at the five NaOH molarities, tested for compressive strength, and five fly ash-GGBS blends at 12 M (10-50% GGBS, designated 90FA10GS through 50FA50GS), tested for slump, compressive strength, split tensile strength and flexural strength. For each mix and curing condition, three 150 mm cubes were tested in compression at 7 and 28 days (IS 516 [35]), three 150 × 300 mm cylinders were tested in splitting tension at 28 days (IS 5816 [36]), and three 100 × 100 × 500 mm prisms were tested in third-point bending over a 400 mm span at 28 days (IS 516 [35]).

The split tensile strength was computed as $f_{sp} = 2P/(\pi DL)$ and the modulus of rupture as $f_r = PL/(bd^2)$. Each reported value is the mean of three specimens. Table 3 summarises the variables and tests.

Table 3. Experimental variables and mix designations (*All = slump, compressive at 7 & 28 d, split tensile and flexural at 28 d)

Mix ID	Binder	NaOH	Curing	Tests
100FA (8-16M)	100% fly ash	8-16 M	Ambient & 60 °C	Compressive (7, 28 d)
90FA10GS	90% FA + 10% GGBS	12 M	Ambient & 60 °C	All*
80FA20GS	80% FA + 20% GGBS	12 M	Ambient & 60 °C	All*
70FA30GS	70% FA + 30% GGBS	12 M	Ambient & 60 °C	All*
60FA40GS	60% FA + 40% GGBS	12 M	Ambient & 60 °C	All*
50FA50GS	50% FA + 50% GGBS	12 M	Ambient & 60 °C	All*

III. RESULTS AND DISCUSSION

A. *Workability*

Table 4 and Figure 1 show the slump values of the five blended mixes. The slump fell steadily from 147 mm for 90FA10GS to 90 mm for 50FA50GS as the GGBS content rose. Two mechanisms explain this trend. First, the spherical, glassy fly ash particles act like miniature ball bearings and lubricate the mix, whereas the angular slag particles increase internal friction and demand more liquid for the same flow. Second, the calcium-rich slag begins to react with the activator almost immediately, stiffening the paste earlier [15, 16]. Comparable reductions in workability with increasing slag content have been reported for similar fly ash-slag systems [25]. Even at 50% GGBS, however, the mix remained placeable and could be compacted without difficulty.

Table 4. Slump of fly ash-GGBS geopolymer concrete (12 M NaOH)

No.	Mix	Slump (mm)	Workability class
1	90FA10GS	147	Very good / high
2	80FA20GS	135	Good
3	70FA30GS	116	Good / medium
4	60FA40GS	105	Medium
5	50FA50GS	90	Medium / low

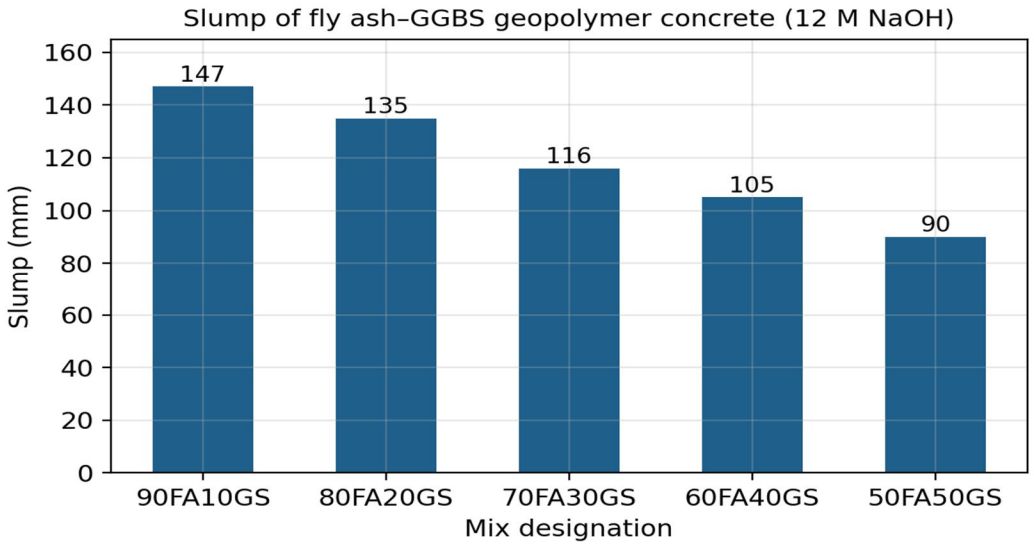

Figure 1. Effect of GGBS content on the slump of fresh geopolymer concrete

B. Compressive strength of 100% fly ash geopolymer concrete

Table 5 presents the compressive strength of the fly-ash-only mixes, and Figure 2 plots the trends. The strength rose consistently with NaOH molarity at every age and under both curing regimes. Under ambient curing the 28-day strength climbed from 22.33 N/mm² at 8 M to 36.18 N/mm² at 16 M - a gain of about 62% - while the oven-cured values rose from 25.09 to 39.93 N/mm² (about 59%).

Table 5. Compressive strength (N/mm²) of 100% fly ash geopolymer concrete

Molarity	7-day, ambient	28-day, ambient	7-day, 60 °C	28-day, 60 °C
8 M	11.43	22.33	16.62	25.09
10 M	13.04	27.25	17.12	28.23
12 M	15.15	30.23	20.53	32.90
14 M	17.26	33.20	23.94	38.08
16 M	19.36	36.18	25.49	39.93

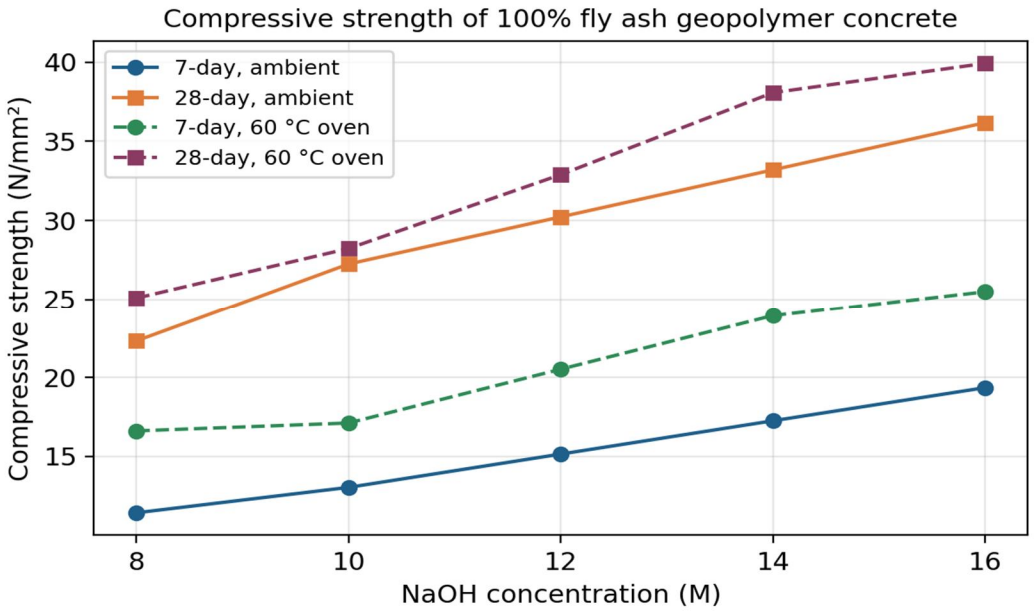

Figure 2. Effect of NaOH molarity and curing condition on the compressive strength of 100% fly ash geopolymer concrete

The mechanism behind the molarity effect is straightforward. A more concentrated NaOH solution supplies more hydroxide ions, which dissolve the glassy silica and alumina of the fly ash more effectively. The larger pool of dissolved silicate and aluminate species then condenses into more N-A-S-H gel, the load-bearing phase of a low-calcium geopolymer [5, 12, 37]. Because the fly ash used here contains less than 2% CaO, essentially all the strength comes from this polymerisation route rather than from C-S-H formation. The observed gains agree well with earlier findings by Hardjito and Rangan [13] and Madheswaran et al. [18]. It should be noted that the molarity benefit cannot continue indefinitely: at very high concentrations the unreacted excess sodium can remain in the pore solution and the gain in strength flattens or even reverses [19]. Within the 8-16 M window of this study, however, the response stayed positive throughout. Curing temperature had a clear additional effect. Oven curing at 60 °C raised the 28-day strength at every molarity, by roughly 10-12%, and the benefit was much larger at 7 days, particularly at lower molarities. For the ambient-cured cubes the 7-day strength was only about 50-54% of the 28-day value, whereas for the oven-cured cubes it reached 64-66%. Mild heating accelerates both the dissolution of fly ash particles and the condensation of the gel, so a large share of the final strength develops within the first few days [10, 38]. This pronounced temperature sensitivity of the low-calcium system is exactly the practical limitation that motivated the addition of GGBS in the second test series. It is also evident that the fly-ash-only mix at 12 M reached only 30.23 N/mm² under ambient curing - short of the 38.25 N/mm² target mean strength - confirming that 100% fly ash binders struggle to achieve M30 without heat.

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C. Compressive strength of fly ash-GGBS geopolymer concrete

Table 6 and Figures 3 and 4 present the compressive strength of the blended mixes at 12 M. Adding GGBS transformed the performance of the concrete. Whereas the fly-ash-only mix at the same molarity reached about 30 N/mm² at 28 days under ambient curing, the blended mixes reached 41-61 N/mm². Strength rose with GGBS content up to 30% replacement and then fell back at higher slag levels: the 70FA30GS mix gave the highest 28-day strength under both regimes (61.42 N/mm² ambient and 61.99 N/mm² oven), while the 40% and 50% mixes settled in the 50-57 N/mm² range.

Table 6. Compressive strength (N/mm²) of fly ash-GGBS geopolymer concrete (12 M)

Mix	7-day, ambient	28-day, ambient	7-day, 60 °C	28-day, 60 °C
90FA10GS	17.49	41.48	37.40	42.27
80FA20GS	28.84	54.80	44.34	61.57
70FA30GS	46.98	61.42	53.58	61.99
60FA40GS	40.35	52.06	52.53	54.80
50FA50GS	42.44	50.88	50.62	56.86

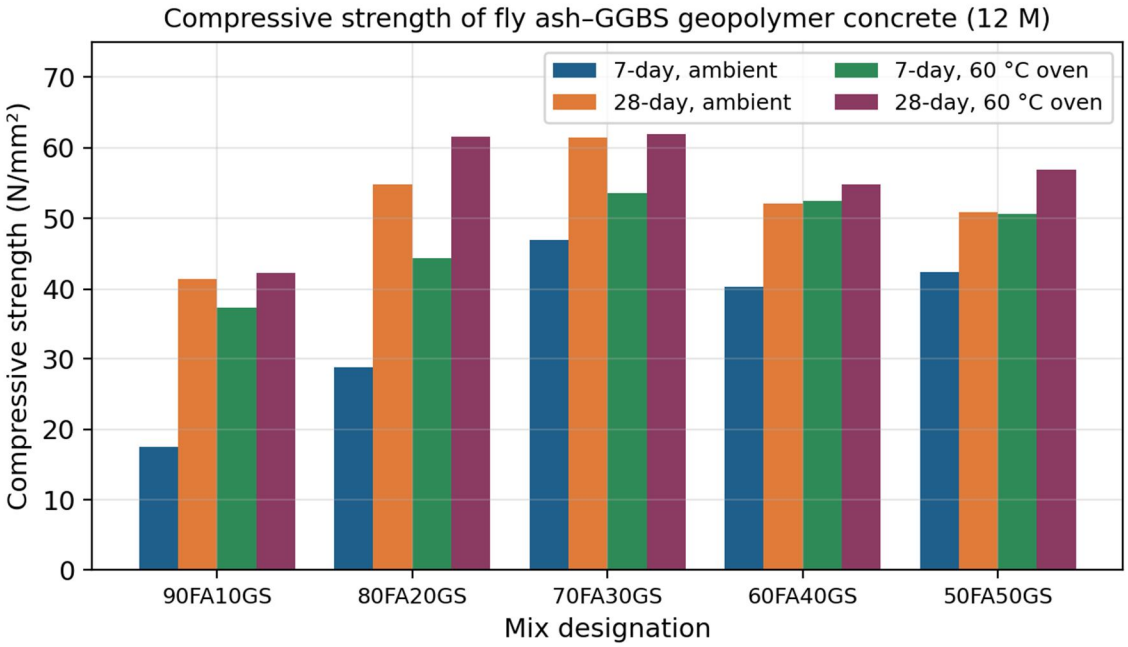

Figure 3. Compressive strength of fly ash-GGBS geopolymer concrete at 7 and 28 days under both curing regimes (12 M)

The improvement stems from a dual gel mechanism. When GGBS enters the binder, its calcium and silica react with the alkaline solution to form C-S-H and C-A-S-H gels, in parallel with the N-A-S-H geopolymer gel still being produced by the fly ash. The two gel families coexist, interlock and fill the pore space, creating a denser and stronger matrix than either reaction can achieve alone [15, 37, 39]. Crucially, the calcium-driven reaction proceeds at room temperature, which is why even the ambient-cured blended cubes reached high strengths with no oven at all.

The fall in strength beyond 30% GGBS is attributed to the increasingly rapid early stiffening of the high-calcium mixes. When the paste sets too quickly, there is less time for a uniform, well-connected gel network to develop, and pockets of unreacted material can become trapped; the reduced workability of the slag-rich mixes (Section 3.1) compounds the problem by making full compaction harder. Optimum slag contents in the region of 30% have likewise been reported in other fly ash-GGBS geopolymer studies [16, 24, 40], so the 70:30 proportion identified here is consistent with the wider literature.

The effect of curing temperature on the blended mixes differed sharply from its effect on the fly-ash-only mixes. Heat still accelerated early strength strongly - the 7-day strength of the 90FA10GS mix more than doubled from 17.49 N/mm² (ambient) to 37.40 N/mm² (oven) - but by 28 days the two curing regimes had nearly converged for most mixes; for 90FA10GS the difference was only about 2%, and for 70FA30GS it was under 1%. In effect, the slag supplies its own internal activation through its heat-releasing calcium reaction, so the ambient-cured concrete simply catches up over time [15, 16]. From a practical standpoint this is the most significant result of the study: fly ash-GGBS geopolymer concrete can develop strengths well above the M30 requirement under ordinary site-style ambient curing, removing the dependence on heat curing that has confined fly-ash geopolymers to precast plants [17, 26].

D. Split tensile strength

Table 7 and Figure 4(a) give the 28-day split tensile strengths of the blended mixes. The values ranged from 2.99 to 4.79 N/mm². As with compression, the 70FA30GS mix performed best under ambient curing (4.79 N/mm²) and the 90FA10GS mix was weakest. Oven curing gave slightly higher tensile strengths for most mixes, the largest gains appearing at 20% and 40% slag, while for 70FA30GS the ambient and oven values were essentially identical.

Table 7. 28-day split tensile strength (STT, N/mm²) and corresponding compressive strength (fc, N/mm²) of fly ash-GGBS mixes (12 M); ratios given as ambient / oven

Mix	STT ambient	STT 60 °C	fc ambient	fc 60 °C	STT/fc (%)
90FA10GS	2.99	3.13	41.48	42.27	7.2 / 7.4
80FA20GS	3.89	4.62	54.80	61.57	7.1 / 7.5
70FA30GS	4.79	4.71	61.42	61.99	7.8 / 7.6
60FA40GS	3.75	4.33	52.06	54.80	7.2 / 7.9
50FA50GS	4.02	4.26	50.88	56.86	7.9 / 7.5

Expressed as a fraction of the matching compressive strength, the split tensile strength remained within a narrow band of about 7-8% for every mix and curing condition. This consistency shows that the tensile capacity scales in step with the compressive capacity, behavior that is typical of both cementitious and geopolymeric materials and similar to conventional concrete [37, 40]. The improvement in tensile strength up to 30% GGBS mirrors the compressive trend and supports the picture of a denser, better-bonded combined gel at the optimum slag content.

E. Flexural strength

Table 8 shows the 28-day flexural strengths (modulus of rupture) and Figure 4(b) shows them graphically. The values ranged from 4.15 to 6.53. The oven cured 80FA20GS mix had the highest result (6.53 N/mm^2) and the 70FA30GS was close behind (6.20 N/mm^2). The lowest values were achieved with the 90FA10GS mix. Oven curing improved the flexural strength of all mixes, the 80FA20GS and 50FA50GS showing the greatest improvement, contrary to the 28-day compressive results.

Table 8. 28-day flexural strength (N/mm²) of fly ash-GGBS geopolymer concrete (12 M)

No.	Mix	Flexural strength, ambient	Flexural strength, 60 °C oven
1	90FA10GS	4.15	4.31
2	80FA20GS	5.70	6.53
3	70FA30GS	5.90	6.20
4	60FA40GS	5.26	5.64
5	50FA50GS	4.78	5.86

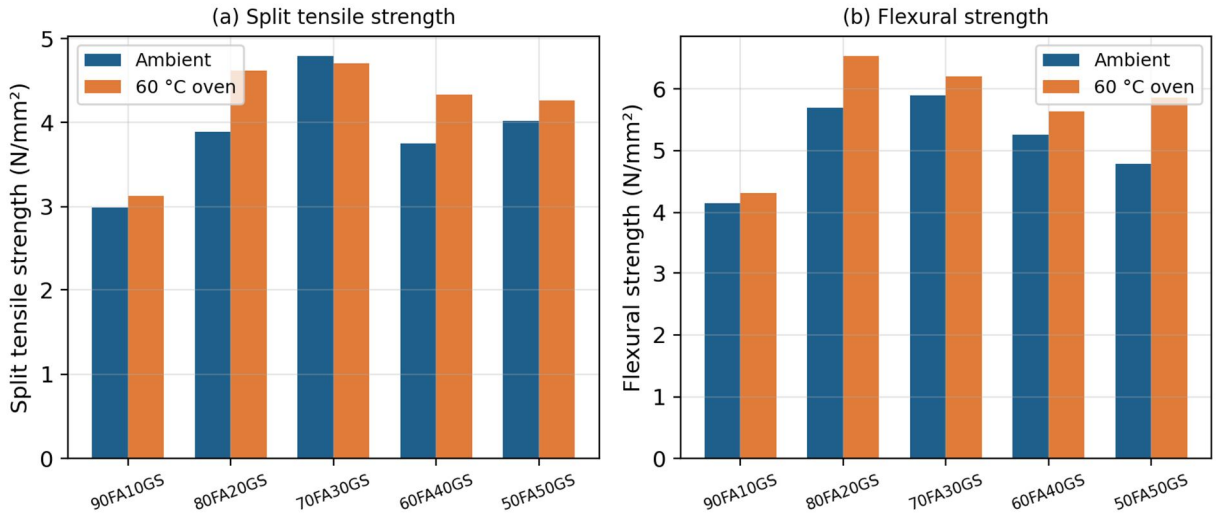

Figure 4. 28-day (a) split tensile and (b) flexural strength of fly ash-GGBS geopolymer concrete (12 M)

Flexural strength depends on the ability of the matrix to resist tension at the bottom fibre of the bent prism, and is therefore very sensitive to how well the gel bonds the aggregate. The 20-30% GGBS mixes performed best, again pointing to an optimum slag window where the combined C-S-H/N-A-S-H gel is densest [39]. The clearer benefit of oven curing in flexure than in 28-day compression suggests that the extra heat chiefly refines the gel-aggregate interface, which matters proportionally more in bending than in direct compression [10]. The flexural strengths recorded here exceed the values normally expected of plain OPC concrete of comparable grade, which is encouraging for structural use.

F. Relationships between strengths

Figure 5 plots the 28-day split tensile and flexural strengths of all ten blended-mix data points (five mixes × two curing conditions) against their compressive strengths, together with least-squares straight lines. Both properties rise linearly with compressive strength. The fitted relationships are:

$$f_{sp} = 0.082\, f_c - 0.37 \quad (R^2 = 0.95) \qquad (1)$$

$$f_r = 0.104\, f_c - 0.14 \quad (R^2 = 0.93) \qquad (2)$$

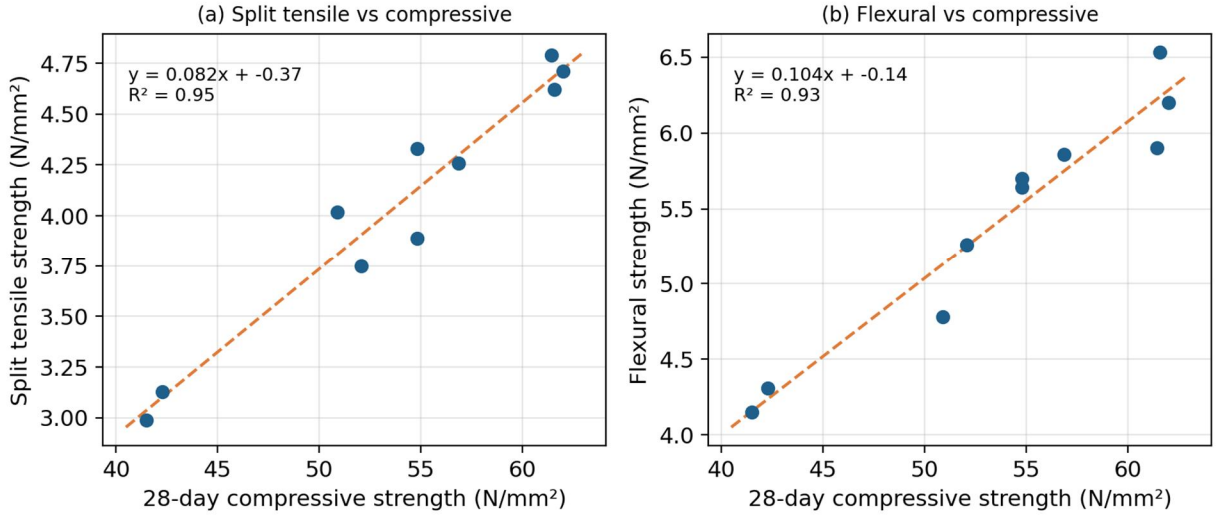

Figure 5. Relationship of (a) split tensile and (b) flexural strength with 28-day compressive strength for fly ash-GGBS geopolymer concrete (12 M)

where all strengths are in N/mm². The split tensile strength tracks at roughly 7-8% of the compressive strength and the flexural strength at a slightly higher fraction, matching the usual ordering of these properties in concrete. The high coefficients of determination mean the expressions are useful for preliminary design, allowing the tensile and flexural capacities of these mixes to be estimated from the much more routinely measured compressive strength [13, 26]. The residual scatter reflects the influence of gel chemistry and curing condition, which act on the secondary strengths somewhat independently of compression.

IV. CONCLUSIONS

An M30-grade geopolymer concrete was developed using fly ash and GGBS as the complete binder, and its fresh and mechanical properties were studied as functions of NaOH molarity (8-16 M), GGBS replacement level (10-50%) and curing condition (ambient versus 60 °C oven). The following conclusions are drawn:

1) The compressive strength of 100% fly ash geopolymer concrete increased steadily with NaOH concentration. The 28-day ambient-cured strength rose from 22.33 N/mm² at 8 M to 36.18 N/mm² at 16 M (about 62%), and the oven-cured strength from 25.09 to 39.93 N/mm², because a stronger alkaline solution dissolves more reactive silica and alumina from the ash.

2) Oven curing at 60 °C benefited the fly-ash-only mixes at every molarity, especially at early age: 7-day strengths reached 64-66% of the 28-day value under heat against only 50-54% under ambient conditions. Fly-ash-only concrete therefore remains dependent on heat curing, and at 12 M it could not reach the M30 target mean strength under ambient curing alone.

3) Partially replacing fly ash with GGBS raised the 28-day ambient strength dramatically, from about 30 N/mm² to as much as 61.42 N/mm². Strength peaked at 30% replacement (mix 70FA30GS) and declined at higher slag levels because rapid early stiffening hindered gel development and compaction. A 70:30 fly ash to GGBS ratio at 12 M is therefore the recommended optimum.

4) For the blended mixes, heat curing mainly accelerated early strength; the 28-day strengths under ambient and oven curing were nearly equal (within about 2% for the best mixes). Fly ash-GGBS geopolymer concrete can thus achieve well above M30 strength under ordinary ambient curing, removing the principal practical barrier to site use of geopolymer concrete.

5) Split tensile strength ranged from 2.99 to 4.79 N/mm² and stayed within 7-8% of the corresponding compressive strength for all mixes and both curing regimes. Flexural strength ranged from 4.15 to 6.53 N/mm², with the 20-30% GGBS mixes performing best.

6) Both secondary strengths correlated linearly with compressive strength ($f_{sp} = 0.082f_c - 0.37$, $R^2 = 0.95$; $f_r = 0.104f_c - 0.14$, $R^2 = 0.93$), providing simple tools for preliminary design.

7) Workability fell as GGBS content rose, with slump dropping from 147 mm at 10% slag to 90 mm at 50% slag, owing to the angular shape and early reactivity of the slag particles; all mixes nonetheless remained placeable.

Overall, the study demonstrates that two industrial by-products - fly ash and GGBS - can together fully replace Portland cement in a structural-grade concrete that cures at ambient temperature, offering a practical route to lower-carbon construction while diverting waste from landfills. Future work should extend the programme to long-term durability (chloride and sulphate exposure, carbonation), elevated-temperature performance, microstructural characterisation (SEM/XRD) and full-scale structural elements.

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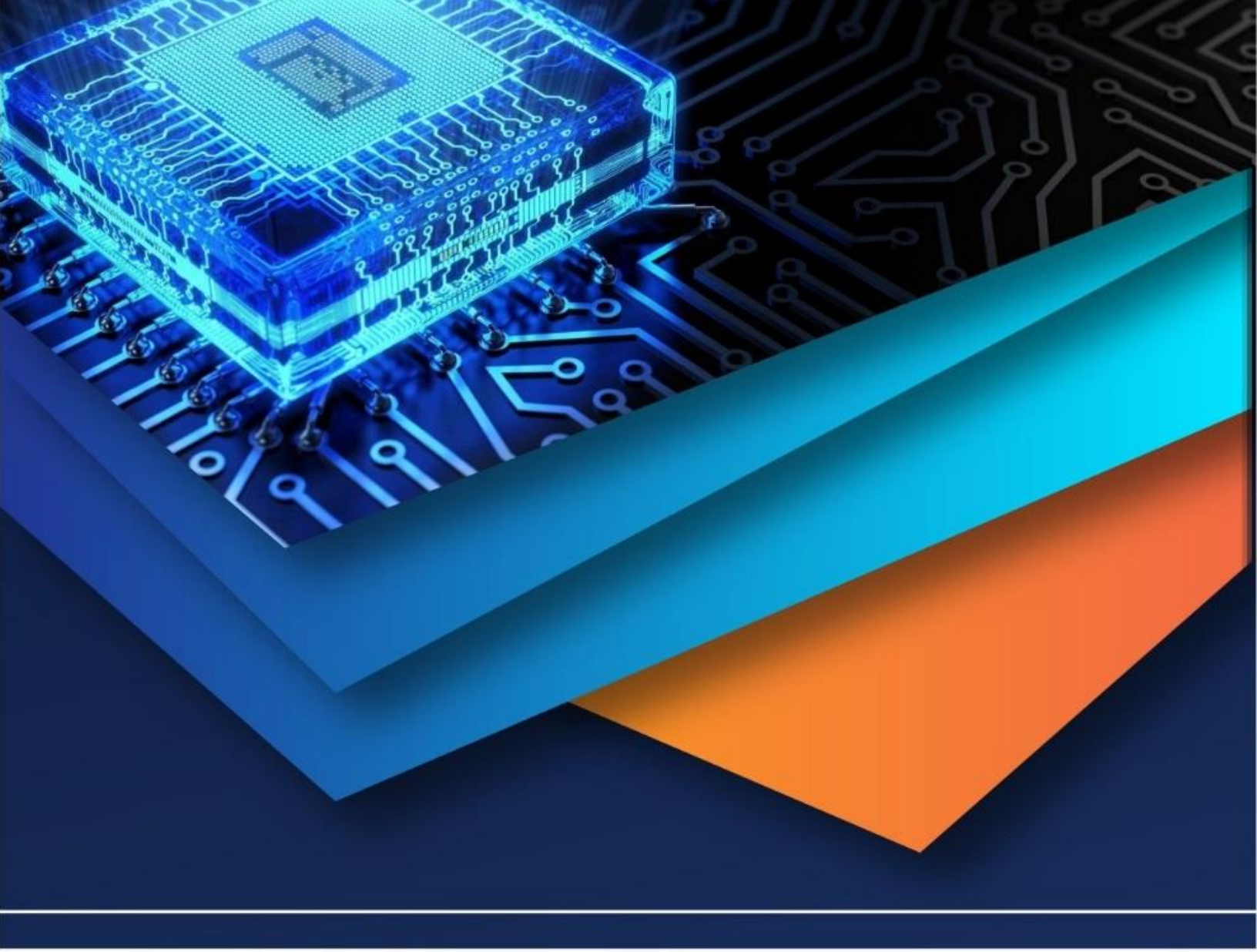

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