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Experimental Investigation on the Strength Characteristics of Alkali-Activated Slag Concrete

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Abstract

The construction sector is increasingly adopting alternative cementitious materials to reduce the environmental impact associated with Portland cement production. Alkali-activated slag concrete (AASC) is a promising low-carbon material in which industrial by-products are chemically activated to develop a cementitious binder. In the present study, the strength behaviour of alkali-activated slag concrete was investigated with emphasis on compressive strength, split tensile strength, and beam load–deflection response. Ground granulated blast furnace slag (GGBS), silica fume, and gypsum were used in the binder system, while sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were used as alkaline activators. Concrete mixes corresponding to 18 M and 19 M activator concentrations were investigated, and the 19 M mix was selected as the optimum mix based on the reported test results. Specimens were evaluated at 3, 7, and 28 days. The average 28-day compressive strength of the selected alkali-activated mix was 39.64 N/mm², compared with 30.66 N/mm² for conventional concrete. The corresponding average split tensile strengths were 2.85 and 2.17 N/mm², respectively. Beam testing at 28 days also indicated a higher load-carrying capacity and lower deflection for the alkali-activated beam within the reported test range. The results demonstrate the potential of GGBS-based alkali-activated concrete as a sustainable alternative to conventional concrete.

Keywords: Alkali-Activated Slag Concrete, Ground Granulated Blast Furnace Slag, Silica Fume, Gypsum, Sodium Hydroxide, Sodium Silicate, Compressive Strength, Split Tensile Strength

1. Introduction

Ground granulated blast furnace slag (GGBS) is an industrial by-product generated during iron production and is widely used as a supplementary cementitious material. Partial replacement of Portland cement with GGBS can improve durability, workability, resistance to chemical attack, and long-term strength while reducing the cement-related carbon footprint [1–8]. However, the performance of GGBS-containing systems depends strongly on mixture proportions, curing conditions, activator compatibility, and the reactivity of the slag. Delayed early-age strength, setting behaviour, workability, and variability in material quality remain important considerations for wider field implementation [9–12].

Research on alkali-activated and geopolymer concretes has demonstrated that industrial by-products can be transformed into high-performance binders through alkaline activation. Singh et al. [13] investigated GGBFS-based geopolymer concrete activated with sodium hydroxide and sodium metasilicate and reported that appropriate alkali activation can produce high strength under ambient curing. Behfarnia and Shahbaz [14] examined the residual tensile strength and physical characteristics of alkali-activated slag concrete after exposure to elevated temperatures and reported favourable residual performance compared with conventional concrete. Pandit et al. [15] reviewed the durability of fly ash- and GGBFS-based alkali-activated concrete under environmental exposures and highlighted its potential as a sustainable alternative to Portland cement concrete.

Deng et al. [16] evaluated the effects of water-to-binder ratio, alkali dosage, and lightweight aggregate size on alkali-activated concrete and showed that these parameters substantially influence workability and mechanical performance. Amer et al. [17] investigated the bond behaviour between alkali-activated slag concrete and steel reinforcement at ambient and elevated temperatures and reported that the material can retain significant bond strength at high temperatures. Nedunuri and Muhammad [18] developed slag–fly ash binders activated with sodium silicate and examined workability, rheological behaviour, and compressive strength for pumping applications.

Studies on ambient-cured geopolymer concrete have also indicated that useful strength can be obtained without energy-intensive heat curing. Kumar et al. [19] reported satisfactory mechanical behaviour under ambient curing, while Nuruddin et al. [20] examined different curing regimes and found that external exposure could enhance strength development. Wallah and Rangan [21] demonstrated that low-calcium fly ash-based geopolymer concrete can develop substantial long-term strength under both heat-cured and ambient conditions. Vijai et al. [22] investigated fly ash–GGBS combinations and identified an optimum mixture that balanced strength and workability under ambient curing.

Further investigations have focused on improving the performance and practicality of alkali-activated systems. Nath and Sarker [23] studied the influence of GGBFS on setting, workability, and early strength of fly ash geopolymer concrete. Hammad et al. [24] reported that fibre incorporation can improve the mechanical and durability characteristics of GGBS-based alkali-activated concrete. Mijarsh et al. [25] applied the Taguchi method to optimize geopolymer mortar containing treated palm oil fuel ash, demonstrating the usefulness of statistical optimization for complex binder systems. Dave and Bhogayata [26] combined Taguchi optimization with Indian Standard mix-design guidance to develop a systematic approach to geopolymer concrete proportioning.

Hadi et al. [27] optimized GGBFS-based geopolymer concrete and reported a high 7-day compressive strength, although the short setting time presented a workability challenge. Xie et al. [28] studied the combined use of GGBS and fly ash with recycled aggregate and reported improved durability characteristics associated with a denser matrix and stronger interfacial transition zone. Jayarajan and Arivalagan [29] investigated fly ash–GGBS geopolymer concrete activated using sodium hydroxide and sodium silicate and reported that desirable mechanical properties can be achieved under ambient curing.

The Bureau of Indian Standards specification IS 12089:1987 provides requirements for granulated slag used in the manufacture of Portland slag cement and specifies relevant quality characteristics of the material [30]. Although previous studies have established the potential of alkali-activated materials, continued experimental evaluation is useful for understanding strength development and structural response for specific combinations of GGBS, silica fume, gypsum, and alkaline activators. Accordingly, the present investigation compares conventional concrete with an alkali-activated slag-based concrete using compressive strength, split tensile strength, and beam load–deflection tests.

2. Materials and Methodology

2.1 Materials

The experimental programme used ground granulated blast furnace slag (GGBS), silica fume, gypsum, sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), and aggregate materials. The constituent materials were procured and subjected to preliminary checks to establish their suitability for concrete production. The available manuscript identifies GGBS, silica fume, and gypsum as the binder constituents and sodium hydroxide and sodium silicate as the alkaline activators.

2.2 Preparation of Alkaline Solutions

Alkaline activator solutions were prepared using sodium hydroxide and sodium silicate. Two activator concentrations, 18 M and 19 M, were considered during the experimental programme. The 19 M formulation was subsequently selected for the reported alkali-activated concrete specimens on the basis of the strength results.

2.3 Mix Preparation and Specimen Casting

The dry binder constituents were thoroughly blended before the alkaline solutions were introduced gradually. The resulting mixture was combined with the aggregate system to obtain a uniform concrete mix. Fresh concrete was placed in moulds and compacted to minimize entrapped air. Cubes, cylinders, and beams were prepared for the respective mechanical and structural tests.

2.4 Curing and Testing

The cast specimens were cured under the conditions adopted in the experimental programme. Strength tests were conducted at 3, 7, and 28 days. Compressive strength was determined using 150 mm × 150 mm × 150 mm cube specimens. Split tensile strength was evaluated using cylindrical specimens, with the manuscript reporting 150 mm × 300 mm cylinders for the alkali-activated concrete. Beam specimens were tested at 28 days to obtain load–deflection data.

2.5 Experimental Programme

The study consisted of a conventional concrete series and an alkali-activated slag concrete series. Nine cube specimens were reported for each series for compressive strength evaluation, and nine cylindrical specimens were reported for each series for split tensile strength evaluation. The optimum alkali concentration was identified as 19 M from the reported results, and the corresponding mixture was used for the beam investigation.

3. Results and Discussion

3.1 Compressive Strength

Compressive strength was determined using 150 mm × 150 mm × 150 mm cube specimens at 3, 7, and 28 days. The average values obtained for conventional concrete were 10.93, 18.94, and 30.66 N/mm², respectively. The selected 19 M alkali-activated slag concrete produced average strengths of 36.53, 37.26, and 39.64 N/mm² at the same ages. Thus, the alkali-activated mixture developed substantially higher early-age and 28-day compressive strength than the conventional concrete used for comparison.

Table 1. Compressive Strength of Conventional Concrete

Sample	3 Days (N/mm²)	7 Days (N/mm²)	28 Days (N/mm²)
1	10.26	18.23	30.26
2	11.01	18.68	30.71
3	11.52	19.91	31.03
Average	10.93	18.94	30.66

Table 2. Compressive Strength of Alkali-Activated Slag Concrete (19 M)

Sample	3 Days (N/mm²)	7 Days (N/mm²)	28 Days (N/mm²)
1	36.63	37.20	39.56
2	36.72	37.50	39.89
3	36.24	37.10	39.47
Average	36.53	37.26	39.64

Table 3. Comparison of Compressive Strength

Concrete Type	3 Days (N/mm²)	7 Days (N/mm²)	28 Days (N/mm²)
Conventional	10.93	18.94	30.66
Alkali-activated slag	36.53	37.26	39.64

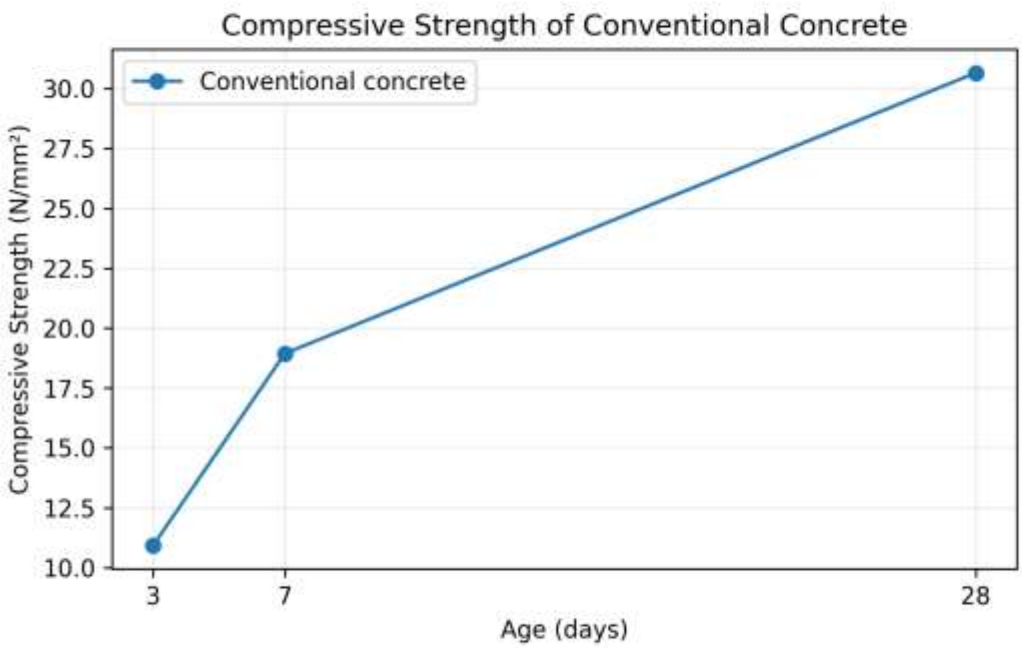

Figure 1. Compressive Strength of Conventional Concrete

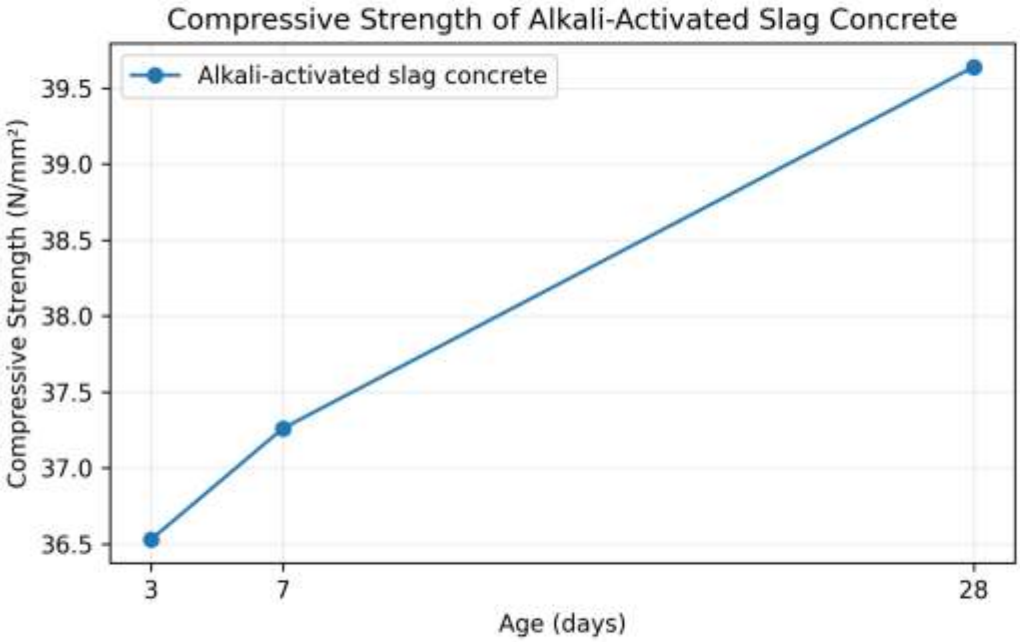

Figure 2. Compressive Strength of Alkali-Activated Slag Concrete

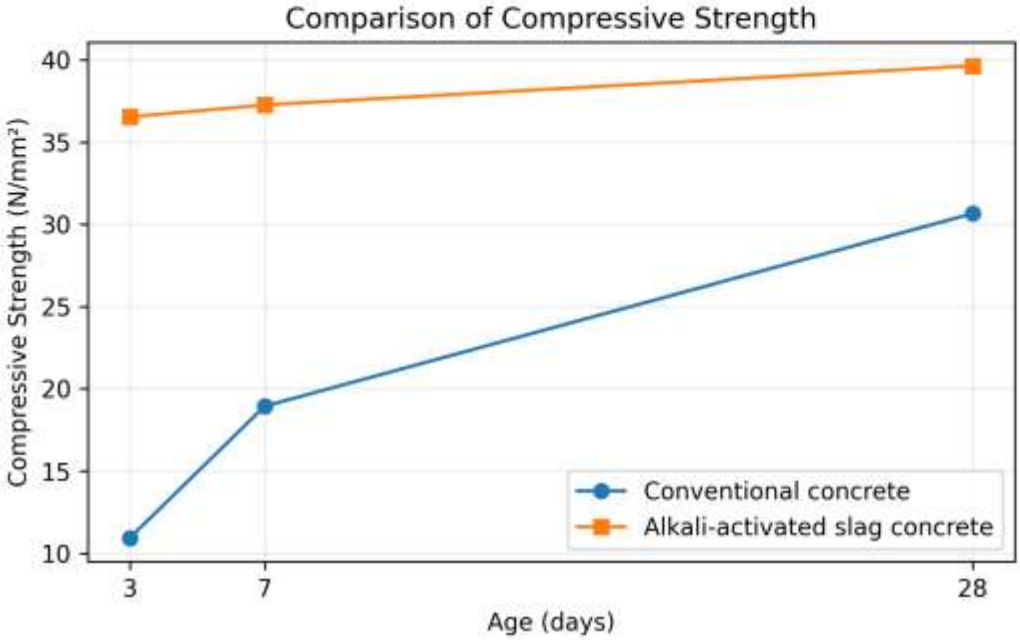

Figure 3. Comparison of Compressive Strength

The results show a rapid increase in compressive strength of the conventional concrete from 3 to 28 days. The alkali-activated mixture, however, exhibited high strength at 3 days and continued to gain strength up to 28 days. The 28-day average strength of 39.64 N/mm² was 8.98 N/mm² greater than that of the conventional concrete.

3.2 Split Tensile Strength

Split tensile strength was evaluated at 3, 7, and 28 days. For conventional concrete, the average strengths were 0.84, 1.73, and 2.17 N/mm², respectively. The 19 M alkali-activated slag concrete yielded average values of 2.11, 2.22, and 2.85 N/mm². The results indicate that the alkali-activated mixture provided higher tensile resistance at all investigated ages.

Table 4. Split Tensile Strength of Conventional Concrete

Sample	3 Days (N/mm²)	7 Days (N/mm²)	28 Days (N/mm²)
1	0.72	1.41	2.10
2	0.89	1.80	2.17
3	0.91	2.00	2.26
Average	0.84	1.73	2.17

Table 5. Split Tensile Strength of Alkali-Activated Slag Concrete (19 M)

Sample	3 Days (N/mm²)	7 Days (N/mm²)	28 Days (N/mm²)
1	2.02	2.10	2.78
2	2.10	2.15	2.82
3	2.23	2.42	2.95
Average	2.11	2.22	2.85

Table 6. Comparison of Split Tensile Strength

Concrete Type	3 Days (N/mm²)	7 Days (N/mm²)	28 Days (N/mm²)
Conventional	0.84	1.73	2.17
Alkali-activated slag	2.11	2.22	2.85

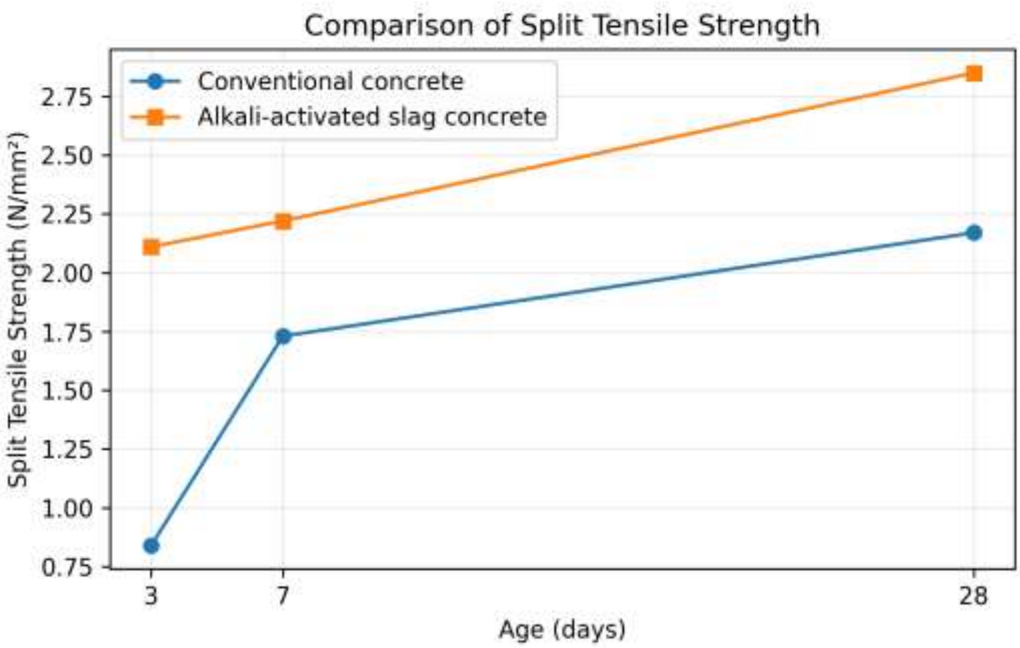

Figure 4. Comparison of Split Tensile Strength

At 28 days, the average split tensile strength of the alkali-activated concrete was 2.85 N/mm² compared with 2.17 N/mm² for conventional concrete. This corresponds to an increase of approximately 31.34% based on the reported averages.

3.3 Beam Load–Deflection Behaviour

Beam specimens were tested after 28 days to assess structural response. The conventional beam reached a reported maximum load of 130 kN at a deflection of 2.14 mm before the recorded data terminated. The alkali-activated beam reached 165 kN at a deflection of 1.71 mm. The load–deflection data therefore indicate greater load-carrying capacity and lower recorded deflection for the alkali-activated beam within the reported test range.

Table 7. Load–Deflection Data for Conventional Concrete Beam at 28 Days

Load (kN)	Deflection (mm)
5	0.04
10	0.05
15	0.08
20	0.09
25	0.10
30	0.16
35	0.22
40	0.29
45	0.34
50	0.40
55	0.45
60	0.51
65	0.54
70	0.57
75	0.65
80	0.73
85	0.78
90	0.84
95	0.93
100	1.04
105	1.19
110	1.25
115	1.39
120	1.48
125	1.57
130	2.14

Table 8. Load–Deflection Data for Alkali-Activated Slag Concrete Beam at 28 Days

Load (kN)	Deflection (mm)
5	0.03
10	0.06
15	0.07
20	0.08

25	0.09
30	0.12
35	0.16
40	0.19
45	0.21
50	0.24
55	0.29
60	0.34
65	0.39
70	0.41
75	0.45
80	0.49
85	0.52
90	0.59
95	0.62
100	0.68
105	0.74
110	0.83
115	0.91
120	0.95
125	1.01
130	1.19
135	1.25
140	1.30
145	1.42
150	1.56
155	1.59
160	1.67
165	1.71

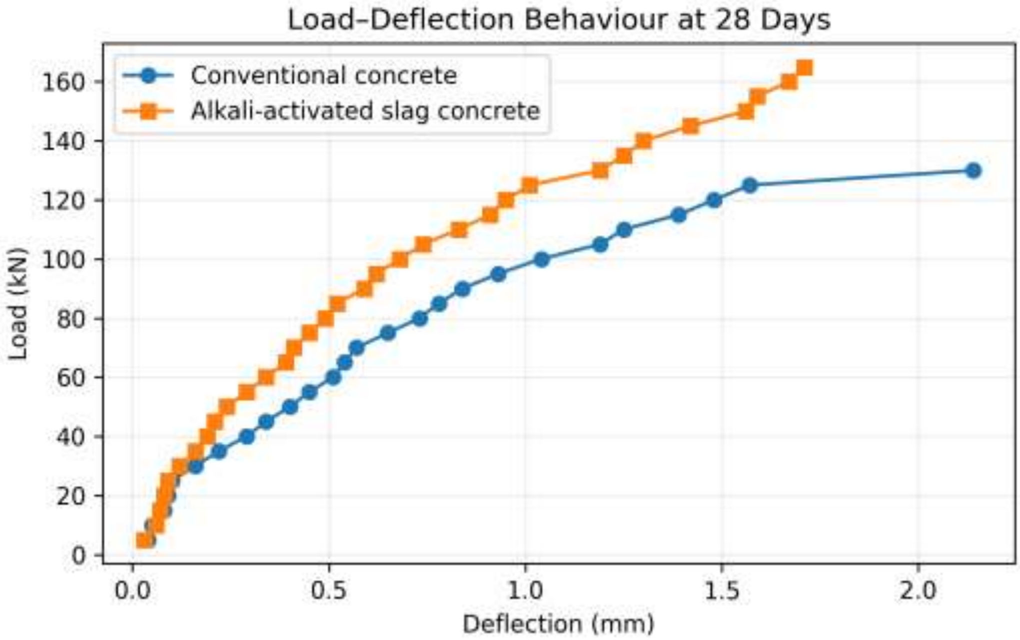

Figure 5. Comparison of Load–Deflection Behaviour at 28 Days

The beam results show a comparatively stiffer response for the alkali-activated specimen over much of the tested load range. The reported peak load increased from 130 kN for the conventional beam to 165 kN for the alkali-activated beam, while the corresponding recorded deflection decreased from 2.14 mm to 1.71 mm.

4. Conclusions

- Alkali-activated slag concrete based on GGBS, silica fume, gypsum, sodium hydroxide, and sodium silicate demonstrated higher mechanical strength than the conventional concrete used in this investigation.
- The 19 M alkali concentration was selected as the optimum formulation based on the reported experimental results and was used for the subsequent alkali-activated concrete evaluation.
- The average 28-day compressive strength increased from 30.66 N/mm² for conventional concrete to 39.64 N/mm² for the alkali-activated mixture, representing an increase of approximately 29.29%.
- The average 28-day split tensile strength increased from 2.17 N/mm² to 2.85 N/mm², corresponding to an increase of approximately 31.34%.
- The 28-day beam test data showed a reported maximum load of 165 kN for the alkali-activated beam compared with 130 kN for the conventional beam.
- The alkali-activated beam exhibited a recorded deflection of 1.71 mm at 165 kN, whereas the conventional beam reached 2.14 mm at the reported maximum load of 130 kN.
- Overall, the experimental results support the potential of alkali-activated slag concrete as a sustainable alternative to conventional concrete for applications in which the investigated strength characteristics are relevant.

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