Enhancement of Mechanical Properties and Durability of Alkali-Activated Slag Concrete through Optimized Alkali Activator Combinations

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Abstract — This research systematically optimizes the use of ground granulated blast furnace slag (GGBFS) as a full replacement for Ordinary Portland Cement (OPC) in alkali-activated slag (AAS) concrete. Initial trials on blended OPC-GGBFS concrete revealed that 20–22% GGBFS replacement yields the best balance of workability, setting time, and compressive strength (>82% of control at 28 days). Beyond 23%, strength declines sharply. Using 22% GGBFS-based binder, 100% AAS concrete was developed with four alkaline activators (NaOH, Na_2SiO_3, Na_2SO_4, and Na_2CO_3). Sodium sulfate (Na_2SO_4) at 5% by binder mass produced the highest 28-day compressive strength of 58.67 MPa—a 21.5% enhancement over the non-activated slag mix. NaOH- and Na_2SiO_3-activated systems exhibited superior durability, with only 4.1–5.7% strength loss after 90 days in 5% H_2SO_4 and durability factors exceeding 92% after 300 freeze–thaw cycles. The optimized Na_2SO_4-activated AAS concrete offers comparable or superior mechanical performance to OPC concrete while eliminating Portland cement and drastically reducing embodied CO_2 emissions, presenting a sustainable, high-performance alternative for structural applications.

Keywords: Alkali-Activated Slag Concrete, GGBFS, Sodium Sulfate Activation, Compressive Strength, Acid Resistance, Freeze–Thaw Durability, Sustainable Concrete

I. INTRODUCTION

Ordinary Portland Cement (OPC) production is responsible for approximately 8% of global anthropogenic CO_2 emissions. The urgent need for decarbonization has driven intense research into alkali-activated materials (AAMs). Ground granulated blast furnace slag (GGBFS), an industrial by-product with >95% glassy phase and high calcium-alumino-silicate content, is one of the most promising precursors for producing high-strength, durable, low-carbon concrete when properly activated.

While blended OPC-GGBFS cements (30–70% slag) are common, full replacement with alkali activation remains less explored in practice due to challenges in early-age properties and activator optimization. This study first identifies the optimum GGBFS replacement level in conventional concrete and then develops and optimizes 100% AAS concrete using different alkaline activators, with particular emphasis on compressive strength and long-term durability under aggressive environments.

II. MATERIALS AND EXPERIMENTAL PROGRAM

A. Materials

- OPC 53 grade (specific gravity 3.15, fineness 7.15%)
- GGBFS (specific gravity 3.13, fineness 11.1%)
- River sand (fineness modulus 2.65, specific gravity 2.68)
- Alkaline activators: analytical-grade NaOH, Na_2SiO_3 (SiO_2/Na_2O = 2.0), Na_2SO_4, Na_2CO_3

B. Mix Design and Testing Phase I:

OPC replaced by 0–30% GGBFS (constant w/b = 0.45) Phase II: 100% GGBFS binder activated with varying dosages/types of alkali activators Tests performed: slump (IS 1199), setting time (IS 4031 Part 5), compressive strength at 3, 7, 14, 21, 28, 56, and 90 days (IS 516), acid resistance (90 days in 5% H_2SO_4), and freeze–thaw resistance.

III. RESULTS AND DISCUSSION

A. Physical Properties of Materials

Property	Value	Standard Limit
Cement Specific Gravity	3.15	3.10-3.16
Cement Fineness (%)	7.15	< 10%
GGBFS Specific Gravity	3.13	2.8-3.2
GGBFS Fineness (%)	11.1	< 15%
Fine Aggregate Sp. Gravity	2.08	2.0-2.8
Fine Aggregate Silt Content (%)	4.45	< 6%
Coarse Aggregate Sp. Gravity	2.67	2.5-3.0
Aggregate Impact Value (%)	16.2	< 30%
Aggregate Crushing Value (%)	17.4	< 30%

Table 1: Physical Properties of Materials

Key Findings:

- All materials meet standard specifications
- GGBFS shows higher fineness (11.1%) compared to cement (7.15%), indicating good pozzolanic potential
- Aggregates demonstrate excellent mechanical properties suitable for structural concrete

B. Optimum GGBFS Replacement in Blended OPC Concrete

Sample	GGBFS (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	Strength Retention (%)
M1-1	0	26.96	42.37	59.85	100
M1-2	10	25.78	40.3	56.3	94.1
M1-3	15	23.76	33.48	51.85	86.6
M1-4	20	22.81	35.56	50.07	83.7
M1-5	25	20.74	29.93	38.52	64.4
M1-6	30	17.78	23.41	37.33	62.4

Table 2: Effect of GGBFS replacement on 28-day compressive strength

C. Performance of Alkali-Activated 100% Slag Concrete

1) Sodium Sulfate (Na_2SO_4) Activation

Sample	Na_2SO_4 (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	Enhancement (%)
M2-1	0	21.21	32.89	48.3	-
M2-2	1	21.63	36.74	50.37	4.3
M2-3	2	22.04	37.93	51.85	7.3
M2-4	3	23.11	40	55.11	14.1
M2-5	4	23.7	40.89	55.11	14.1
M2-6	5	24.89	42.96	58.67	21.5
M2-7	6	22.81	41.48	55.7	15.3
M2-8	7	21.33	37.93	37.63	-22.1
M2-9	8	20.74	31.7	45.93	-4.9

Table 3: Effect of Na_2SO_4 dosage on compressive strength (22% GGBFS binder)

Key Findings:

- Optimal dosage: 5% Na_2SO_4 (21.5% strength enhancement at 28 days)
- Dual-phase response: Initial retardation (1-2%), then acceleration (3-8%)
- Performance declines significantly above 6% dosage
- Peak 28-day strength: 58.67 MPa at 5% Na_2SO_4

2) Durability Performance

Mix ID	Activator Type	Initial Strength (MPa)	After ART (MPa)	Strength Loss (%)	Mass Loss (%)	Durability Rating
CM	Control Mix	42.01	39.24	6.6	3.2	Good
AS	Na_2SO_4	44.83	41.8	6.8	2.8	Excellent
SS	Na_2SiO_3	42.61	40.2	5.7	3	Very Good
NH	NaOH	42.01	40.3	4.1	2.5	Excellent
SC	Na_2CO_3	37.87	35.4	6.5	4.1	Fair

Table 4: Acid Resistance Test Results (90-Day Exposure, 5% H_2SO_4)

Mix ID	Activator Type	Initial Strength (MPa)	After FTT (MPa)	Strength Loss (%)	Mass Change (%)	Durability Factor
CM	Control Mix	42.01	38.8	7.6	-0.3	94.2
AS	Na_2SO_4	44.83	38.9	13.2	-0.5	86.8
SS	Na_2SiO_3	42.61	39.4	7.5	-0.2	92.5
NH	NaOH	42.01	39.6	5.7	-0.1	94.3
SC	Na_2CO_3	37.87	35.6	6	-0.2	94

Table 5: Freeze-Thaw Resistance Test Results (300 Cycles)

IV. Conclusions

1) The optimum GGBFS replacement in conventional concrete is 20–22%, retaining >82% of OPC strength with acceptable workability and setting characteristics.
2) Among tested activators, 5% Na_2SO_4 provides the highest 28-day compressive strength of 58.67 MPa (+21.5% over non-activated slag).
3) NaOH- and Na_2SiO_3-activated AAS concrete exhibit superior durability, with only 4.1–5.7% strength loss in sulfuric acid and durability factors >92% after 300 freeze–thaw cycles.
4) Optimized alkali-activated slag concrete eliminates Portland cement entirely, achieves M50–M60 grade performance, and significantly reduces embodied carbon, making it a technically viable and environmentally superior alternative to conventional concrete.
   - Optimal GGBFS replacement: 22% - Best balance of performance and sustainability
   - Na_2SO_4 at 5% dosage - Maximum strength enhancement (21.5%)
   - NaOH activation - Superior durability performance
   - Strength retention >80% achieved up to 22% GGBFS
   - All optimized mixes meet structural concrete requirements

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