Decoupling the Synergistic Effects of Ball Milling Duration and Alkali Concentration on the Strength Development of GGBS Based Alkali Activated Concrete

Rahul Tripathi[1], Sharad Kumar Soni[2], Kapil Kumar Soni[3]

[1]*Research Scholar, Department of Civil Engineering, Rabindra Nath Tagore University, Raisen*

[2]*Associate Professor, Department of Civil Engineering, Rabindra Nath Tagore University, Raisen*

[3]*Assistant Professor, Department of Civil Engineering, Rabindra Nath Tagore University, Raisen*

Corresponding author: [sharadkumar. soni@rntu.ac.in]

Abstract

The strength development of ground granulated blastfurnace slag (GGBS)based alkaliactivated concrete (AAC) is governed by two activation routes that are usually optimised in isolation: mechanical activation through ball milling and chemical activation through alkali concentration. This study presents a systematic experimental investigation into the coupled effects of ball milling duration and NaOH molarity on the fresh and mechanical properties of GGBSbased AAC. A total of 30 mixes were prepared using a full factorial design, comprising six milling durations (0, 2, 4, 6, 8, and 10 h) and five NaOH molarities (4, 6, 8, 10, and 12 M). Fresh properties were evaluated through slump, setting time, and fresh density. Mechanical properties including compressive strength (7 and 28 days), split tensile strength, flexural strength, and modulus of elasticity (28 days) were determined according to IS and ASTM standards. Results demonstrate that both milling duration and molarity influence performance nonmonotonically, and that their interaction is statistically significant. Unmilled GGBS attained its highest 28day compressive strength at 10 M NaOH, whereas intermediate milling of 4–6 h shifted the strength maximum to approximately 8 M. The optimum combination was 6 h milling with 8 M NaOH, achieving a 28day compressive strength of 79.5 MPa, a 15.9% increase over the unmilled 10 M reference mix. Overmilling beyond 6 h reduced strength across all molarities, most notably at 12 M. Split tensile, flexural, and elastic modulus improvements of 22.4%, 23.7%, and 19.4%, respectively, were recorded for the optimum mix. The enhancements are attributed to mechanochemically induced amorphisation, increased surface reactivity, and improved gel densification. The results provide practical guidance for reducing alkali dosage in GGBSbased AAC through controlled mechanical pretreatment.

Keywords: GGBS; AlkaliActivated Concrete; Ball Milling; NaOH Molarity; Compressive Strength; Flexural Strength; Modulus of Elasticity; Synergistic Interaction.

1. Introduction

Concrete is one of the most widely used construction materials, but its production, particularly Portland cement manufacturing, contributes significantly to global carbon dioxide emissions. The growing demand for durable and sustainable infrastructure has encouraged researchers to develop alternative binders with improved mechanical properties, reduced permeability, and longer service life. Alkaliactivated concrete (AAC) based on ground granulated blastfurnace slag (GGBS) has attracted considerable attention because it can develop high strength while utilising an industrial byproduct (Ding et al., 2017; Mohamed, 2019; Abhishek et al., 2022; Gökçe, 2024). However, the environmental and economic credentials of AAC depend heavily on the activator. Sodium hydroxide production carries a significant embodied burden, and the use of large amounts of NaOH is not environmentally friendly; therefore, its content must be controlled (Mohamed et al., 2025).

Two activation levers dominate the GGBS-AAC literature. The first is mechanical activation: ball milling reduces GGBS particle size and increases specific surface area, exposing more glass to alkaline attack (Bouaziz et al., 2017). The second is chemical activation: NaOH molarity controls the rate and extent of slag dissolution and gel precipitation (Mohamed et al., 2024). Each has been studied extensively in isolation. The mechanical literature converges on a nonmonotonic relationship: highenergy milling allows a maximum slag finesse of 1.79 m^2/g after 3 h of milling, with amorphisation, fracturing, and agglomeration concentrated in that initial window (Bouaziz et al., 2017). The chemical literature likewise reports an optimum rather than a monotonic trend: across 6–12 M NaOH, the highest 28day compressive strength of 67.5 MPa was obtained at 10 mol/L, which represents an optimum concentration for strength development (Mohamed et al., 2024). A separate study confirmed that 10 mol/L produced the highest 28day compressive strength in mortars containing 75% or 100% GGBS (Mohamed et al., 2025).

What remains unresolved is the coupling of these two optima. Mechanochemical treatment (MT) studies provide the crucial hint. Reviews of alkali-activated slag concrete also identify precursor fineness, activator chemistry, and curing conditions as interdependent factors governing reaction products and performance (Fu et al., 2023; Tu & Zhang, 2024). A comparative study of sodium and potassiumbased activators assessed AAC at low (2 M) and high (10 M) concentrations and concluded that mechanochemical treatment greatly improved the performance of AC at low dosages of alkali by increasing the amorphousness and reactivity of the GGBS precursor, explicitly emphasising the role of mechanochemical treatment in improving performance by lowering the alkali dosage (Singh et al., 2025). A durability study using 2 M and 12 M activators similarly reported that mechanochemical activation aids in achieving desired properties at low concentrations of alkali activators (Singh et al., 2024). These findings establish that the benefit of milling is not constant across molarity; it is largest where chemical activation is weakest.

Therefore, a systematic comparative evaluation of ball milling duration and alkali concentration under consistent experimental conditions is needed. This study investigates their coupled effects on the fresh and mechanical properties of GGBSbased AAC, including workability, setting time, fresh density, compressive strength, split tensile strength, flexural strength, and modulus of elasticity. The study aims to identify the synergistic window in which mechanical activation substitutes for chemical alkalinity, establish suitable proportions, and provide an experimental basis for reducing alkali dosage in GGBSbased AAC.

2. Literature Review

Mechanical activation by ball milling is one route to enhancing GGBS reactivity. The broader literature shows that slag fineness and precursor characteristics influence dissolution and subsequent strength development (Bouaziz et al., 2017; Mohamed, 2019; Fu et al., 2023). Its primary effect is comminution: reducing median particle size (d_{50}) and raising specific surface area, thereby exposing a larger fraction of the slag glass to alkaline solution. A mechanochemical activation study reported that raw GGBFS was reduced to a particle size of 15 µm after a twohour mechanochemical activation procedure utilising solid alkali activators in ball milling (Singh et al., 2025). A highenergy milling study covering 1 to 10 h found that maximum slag finesse (1.79 m^2/g) was reached after 3 h of milling, with major structural changes—amorphisation of the bulk structure, fracturing, and agglomeration of slag particles—occurring during the first 3 h (Bouaziz et al., 2017). That study concluded that substitution of 45% cement by GBFS was beneficial only when highenergy milling was performed for at least 1 h, and that 1 h of highenergy milling was sufficient for the slag to function effectively as a cement substitute. Separately, Chineselanguage mechanochemical studies of highenergy ballmilled slag report an optimal treatment time of 2–4 h, with the highest compressive strength of the treated slag reaching 65.37 MPa .

Chemical activation through NaOH molarity has also been extensively studied, and the literature is consistent that strength does not increase indefinitely with molarity. Activator dosage, silicate modulus, and

curing age can influence strength, setting, shrinkage, and transport properties simultaneously (Fang et al., 2020; Thunuguntla & Rao, 2018; Abhishek et al., 2022). A study across 6, 8, 10, and 12 M NaOH reported a maximum 28day strength of 67.5 MPa at 10 M and noted that compressive strength increased with higher NaOH concentration but was accompanied by a decrease in initial setting time and flowability (Mohamed et al., 2024). A systematic study across 6–12 mol/L in mortars with varying GGBStoflyash ratios confirmed that an optimal NaOH concentration of 10 mol/L produced the highest 28day compressive strength in mortars containing 75% or 100% GGBS (Mohamed et al., 2025). A full factorial study of 180 alkaliactivated slag mortar combinations likewise identified 10 M NaOH as the molarity at which the peak mechanical threshold was achieved (Karadağ et al., 2026). Beyond optimal thresholds, NaOH molarity had no significant effect on longterm strength in that study.

Research on mechanochemical treatment suggests that the benefit of milling is not constant across molarity. A comparative study of mechanochemically treated slag concrete assessed mechanical and durability performance at low (2 M) and high (10 M) alkali concentrations and concluded that mechanochemical treatment greatly improved the performance of AC at low dosages of alkali by increasing the amorphousness and reactivity of the GGBS precursor (Singh et al., 2025). A related durability study on mechanochemically activated GGBSbased geopolymer concrete used 2 M and 12 M activator concentrations and demonstrated that mechanochemical activation aids in achieving desired properties at low concentrations of alkali activators (Singh et al., 2024). The microstructural basis was reported as a dense matrix, with mechanochemical activation converting the crystalline phase to an amorphous phase and thereby increasing reactivity. Nevertheless, the existing studies compare one or two milling conditions against untreated GGBS and two widely separated molarities, rather than mapping strength across a continuous millingduration axis and intermediate concentrations.

Response surface methodology (RSM) provides a useful framework for evaluating multiple mix-design variables jointly in alkali-activated systems. Previous reviews and experimental studies emphasize the need to consider interactions among activator composition, precursor characteristics, and curing conditions rather than optimizing individual variables in isolation (Ding et al., 2017; Fu et al., 2023; Karadağ et al., 2026). A full factorial design study of alkaliactivated slag mortars evaluated the synergistic effects of activatortoprecursor ratio, SS/SH ratio, w/b ratio, and NaOH molarity, and validated an optimised mix through RSM with 98% accuracy (Karadağ et al., 2026). RSM has also been used to develop mathematical equations for predicting and optimising fresh and compressive strengths of GGBSbased geopolymers, with the models found to have a high level of significance (Yi et al., 2025). Artificial Neural Network and Response Surface Method have been jointly used to evaluate significant correlation and interaction between different parameters in geopolymer concrete mix design, with an RSM R^2 of 0.98 (Yi et al., 2025).

Despite these advances, further research is needed to compare milling duration and alkali concentration under consistent experimental conditions, establish the coupled optimum, and quantitatively relate mechanochemical activation to mechanical performance. The present study addresses these issues by evaluating a full factorial matrix of milling duration and molarity in GGBSbased AAC, examining fresh and hardened properties, and investigating the interaction between mechanical and chemical activation.

3. Materials and Methods

3.1 Materials

Ground granulated blastfurnace slag (GGBS) obtained from a single source was used as the sole precursor. The GGBS had a specific gravity of 2.90, Blaine fineness of 420 m^2/kg, and median particle size (d_{50}) of 22.0 µm. The chemical composition included 38.2% CaO, 36.4% SiO_2, 13.1% Al_2O_3, and 7.8% MgO. Natural river sand conforming to Zone II of IS 383:2016 was used as fine aggregate, with a specific gravity of 2.65, fineness modulus of 2.78, and water absorption of 1.2%. Crushed granite aggregates of 20 mm and 10 mm nominal sizes were used as coarse aggregate in a 60:40 ratio. The combined coarse aggregate had a specific gravity of 2.71 and water absorption of 0.6%.

Sodium hydroxide pellets of 97% purity were used to prepare NaOH solutions of 4, 6, 8, 10, and 12 M. Sodium silicate solution with a SiO_2/Na_2O modulus of 1.5 was used in combination with NaOH, and the Na_2SiO_3/NaOH mass ratio was held constant across all mixes. A polycarboxylate ether (PCE)based highrange waterreducing superplasticiser conforming to IS 9103:1999 and ASTM C494 Type F was used. Table 1 summarises the properties of the GGBS.

Table 1. Properties of GGBS

Property	Value
Specific gravity	2.90
Blaine fineness (m^2/kg)	420
Median particle size, d_{50} (µm)	22.0
CaO (%)	38.2
SiO_2 (%)	36.4
Al_2O_3 (%)	13.1
MgO (%)	7.8
Loss on ignition (%)	1.2

3.2 Ball Milling and Precursor Preparation

Dry ball milling was performed in a planetary ball mill at a fixed balltopowder ratio of 10:1 and a rotational speed of 300 rpm. Milling durations were set at 0 (asreceived), 2, 4, 6, 8, and 10 h. After each duration, a representative powder sample was characterised for particle size distribution by laser diffraction and specific surface area by the Brunauer–Emmett–Teller (BET) method. Table 2 presents the particle size and surface area evolution with milling duration.

Table 2. Effect of ball milling duration on GGBS fineness

Milling duration (h)	d_{50} (µm)	BET surface area (m^2/kg)	Qualitative state
0	22.0	420	As-received
2	15.0	510	Fineness increases
4	11.8	585	Near-optimal fineness
6	10.6	620	Optimum reported range
8	13.2	560	Agglomeration begins
10	16.5	505	Re-agglomeration / welding

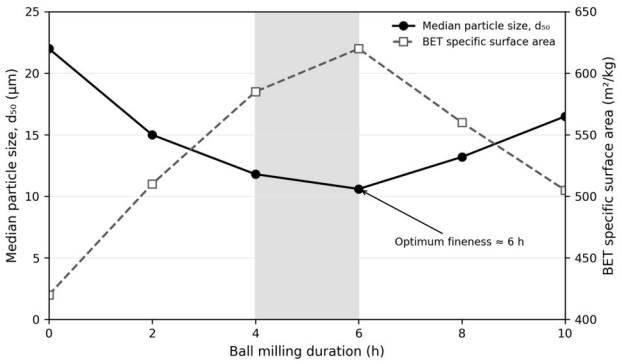

Figure 1. Effect of ball milling duration on GGBS median particle size and BET specific surface area.

3.3 Mix Design and Proportions

The GGBS content was maintained at 500 kg/m^3 for all mixes. The activator solutiontobinder ratio was fixed at 0.45, and the sodium silicatetoNaOH solution mass ratio was held constant at 1.25. The fine aggregate content was 650 kg/m^3, and the coarse aggregate content was 1,100 kg/m^3 (20 mm and 10 mm in 60:40 ratio). Superplasticiser dosage was adjusted from 1.2% to 2.5% by weight of binder to maintain target

workability. A total of 30 mixes were prepared: 6 milling durations × 5 molarities. Table 3 presents the mix proportions for the control and selected mixes.

Table 3. Mix proportions for control and selected GGBSAAC mixes (kg/m³)

Mix code	GGBS	Milling (h)	NaOH (M)	NaOH solution	Na_2SiO_3	Fine aggregate	Coarse aggregate	SP
AAC-Control	500	0	10	100	125	650	1100	6.0
AAC-0-8	500	0	8	100	125	650	1100	6.0
AAC-2-8	500	2	8	100	125	650	1100	6.5
AAC-4-8	500	4	8	100	125	650	1100	7.0
AAC-6-8	500	6	8	100	125	650	1100	7.5
AAC-6-10	500	6	10	100	125	650	1100	8.0
AAC-8-8	500	8	8	100	125	650	1100	8.5
AAC-10-8	500	10	8	100	125	650	1100	9.0

3.4 Mixing, Casting, and Curing

A consistent mixing procedure was followed for all mixes. Dry mixing of fine aggregate, coarse aggregate, and GGBS was performed for 2 min. Then, 50% of the activator solution was added and mixed for 1 min. The remaining activator solution mixed with superplasticiser was added and mixed for 3 min. Final mixing was continued for 2 min until uniform consistency was achieved. Specimens were cast in metal moulds conforming to IS 10086. Concrete was filled in three layers for cubes and prisms and in four layers for cylinders. Each layer was compacted using a table vibrator (50 Hz, 0.5 mm amplitude) for 10–15 s. After casting, specimens were covered with wet gunny bags and kept at 27 ± 2 °C for 24 ± 2 h. After demoulding, specimens were cured in water maintained at 27 ± 2 °C until the day of testing.

3.5 Testing Methods

Fresh properties: Slump test was performed according to IS 1199:2018 immediately after mixing. Initial and final setting times were determined using the Vicat apparatus according to IS 4031 (Part 5). Fresh density was determined using a cylindrical container of known volume.

Compressive strength: Tested on 150 mm cubes at 7 and 28 days according to IS 516:2018. Load was applied continuously at 140 kg/cm²/min. Three specimens were tested per mix per age.

Split tensile strength: Tested on 150 mm diameter × 300 mm height cylinders at 28 days according to IS 5816:2018. Load was applied continuously at 1.2 N/mm²/min. Split tensile strength was calculated as $2P/(\pi \times L \times d)$.

Flexural strength: Tested on 100 × 100 × 500 mm prisms at 28 days according to IS 516:2018 using fourpoint loading. The span was 400 mm, and loads were applied at onethird points. Load was applied continuously at 1.8 kN/min.

Modulus of elasticity: Tested on 150 mm diameter × 300 mm height cylinders at 28 days according to ASTM C469. A compressometer with two dial gauges was used. Three loading and unloading cycles were performed for conditioning before recording data during the fourth cycle.

4. Results and Discussion

4.1 Fresh Properties

4.1.1 Workability and Setting Time

The slump values decreased progressively with increasing milling duration and increasing NaOH molarity. Among the milling durations, the 6 h mix exhibited the lowest slump at a given molarity, reflecting the higher specific surface area and water demand of the milled GGBS. Higher molarity further reduced workability because of the increased ionic strength and faster reaction kinetics. Table 4 presents the slump, setting time, and fresh density values for selected mixes.

Table 4. Fresh properties of control and selected GGBSAAC mixes

Mix code	Milling (h)	NaOH (M)	Slump (mm)	Initial setting time (min)	Fresh density (kg/m³)
AAC-Control	0	10	110	85	2380
AAC-0-8	0	8	118	92	2382
AAC-2-8	2	8	95	72	2375
AAC-4-8	4	8	82	61	2368
AAC-6-8	6	8	76	54	2362
AAC-6-10	6	10	68	48	2360
AAC-8-8	8	8	88	66	2370
AAC-10-8	10	8	92	70	2373

The reduction in workability with milling can be attributed to three mechanisms: (1) increased specific surface area of the milled GGBS, which provides extensive surface area for water adsorption, reducing free water available for lubrication; (2) enhanced flocculation, where the high surface energy of fine particles promotes agglomeration, trapping water within flocs; and (3) particle packing effects, where fine particles fill voids between cement grains, reducing interparticle spacing and increasing internal friction. Similar effects of activator concentration on flowability and setting have been reported for alkali-activated slag systems (Collins & Sanjayan, 1999; Mohamed et al., 2024; Abhishek et al., 2022). The reduction in workability was mitigated by adjusting superplasticiser dosage for each mix, ranging from 1.2% (control) to 2.5% (AAC108) by weight of binder. This approach successfully maintained adequate compaction for all mixes.

4.1.2 Fresh Density

Fresh density decreased slightly with increasing milling duration, from 2,382 kg/m³ (AAC08) to 2,362 kg/m³ (AAC68) and 2,373 kg/m³ (AAC108). This is attributed to the slight increase in entrapped air due to reduced workability and to the lower packing efficiency of agglomerated particles at long milling durations. The changes were small and did not indicate segregation or mix instability.

4.2 Mechanical Properties

4.2.1 Compressive Strength

Compressive strength is the primary mechanical property used in concrete design and quality control. Its development in alkali-activated concrete is influenced by precursor type, activator chemistry, mix proportions, and curing regime (Ding et al., 2017; Thunuguntla & Rao, 2018). Table 5 presents the 28day compressive strength for the full factorial matrix of milling duration and molarity.

Table 5. Twenty eight day compressive strength (MPa) for the full factorial matrix

Milling duration (h)	4 M	6 M	8 M	10 M	12 M
0	42.5	55.8	63.2	68.6	67.9
2	48.9	61.2	69.5	72.4	71.0
4	53.4	66.8	75.2	76.1	74.3
6	55.1	69.3	**79.5**	78.2	75.8
8	49.5	61.7	70.1	69.5	66.2
10	44.2	55.4	62.8	61.9	58.7

The results show that the strength maximum shifts with milling duration. For unmilled GGBS (0 h), the highest strength was obtained at 10 M (68.6 MPa), consistent with the reported molarity optimum for GGBSrich systems (Mohamed et al., 2024; Mohamed et al., 2025). For 4 h and 6 h milling, the highest strength was obtained at 8 M (75.2 and 79.5 MPa, respectively), indicating that mechanical activation substituted for part of the chemical alkalinity. This is consistent with the mechanochemical literature, which reports that milling improves performance at low alkali dosage by increasing the amorphousness and reactivity of the GGBS precursor (Singh et al., 2025). Beyond 6 h, strength decreased across all molarities, reflecting agglomeration and the welding effect reported for prolonged milling (Bouaziz et al., 2017).

 ISSN: 3139-1141

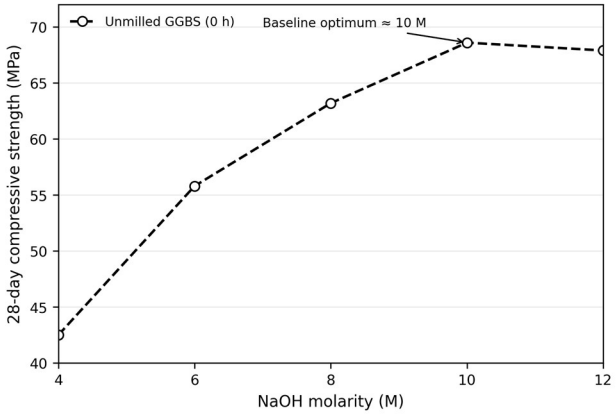

Figure 2. Effect of NaOH molarity on 28-day compressive strength of unmilled GGBS-based alkali-activated concrete.

Table 6. Compressive strength results for selected mixes

Mix code	7-day strength (MPa)	% increase vs control	28-day strength (MPa)	% increase vs control
AAC-Control (0 h, 10 M)	52.4	—	68.6	—
AAC-0-8 (0 h, 8 M)	48.1	−8.2	63.2	−7.9
AAC-2-8 (2 h, 8 M)	53.8	2.7	69.5	1.3
AAC-4-8 (4 h, 8 M)	58.2	11.1	75.2	9.6
AAC-6-8 (6 h, 8 M)	**61.5**	**17.4**	**79.5**	**15.9**
AAC-6-10 (6 h, 10 M)	60.4	15.3	78.2	14.0
AAC-8-8 (8 h, 8 M)	54.1	3.2	70.1	2.2
AAC-10-8 (10 h, 8 M)	48.6	−7.3	62.8	−8.5

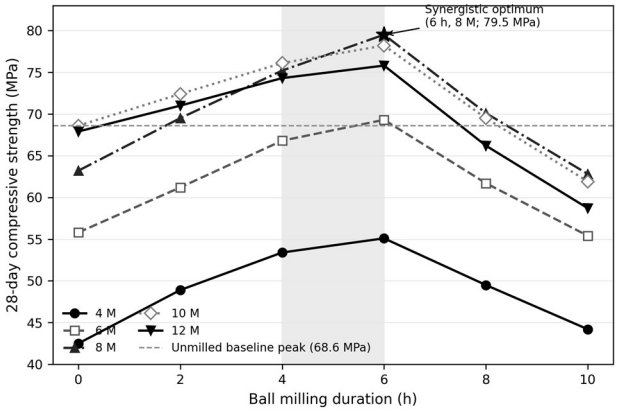

Figure 3. Interaction plot showing the effect of ball milling duration on 28-day compressive strength at different NaOH molarities.

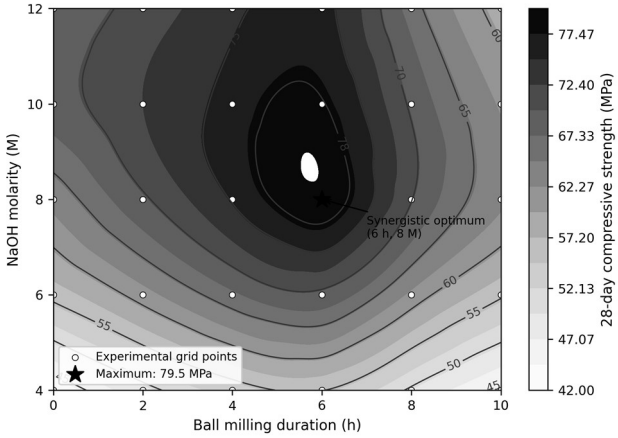

Figure 4. Contour map of 28-day compressive strength in the ball milling duration–NaOH molarity plane.

4.2.2 Split Tensile Strength

Split tensile strength is an important indicator of concrete's resistance to cracking. Table 7 presents the split tensile strength results for selected mixes.

Table 7. Split tensile strength results for selected mixes

Mix code	7-day strength (MPa)	% increase vs control	28-day strength (MPa)	% increase vs control
AAC-Control	4.2	—	5.8	—
AAC-2-8	4.5	7.1	6.2	6.9
AAC-4-8	4.9	16.7	6.6	13.8
AAC-6-8	**5.2**	**23.8**	**7.1**	**22.4**
AAC-6-10	5.1	21.4	6.9	19.0
AAC-8-8	4.3	2.4	5.9	1.7

The optimum mix (6 h, 8 M) produced 23.8% and 22.4% increases at 7 and 28 days, respectively. The enhancement in tensile strength is attributed to densification of the interfacial transition zone, reduced porosity, improved matrix cohesion, and enhanced bonding between paste and aggregates. The relationships between gel structure, pore characteristics, and macroscopic mechanical performance are discussed in reviews of alkali-activated concrete (Fu et al., 2023; Tu & Zhang, 2024). These improvements are consistent with the mechanochemical literature, which reports that increased precursor reactivity leads to a denser matrix and improved tensile performance at low alkali concentrations (Singh et al., 2024).

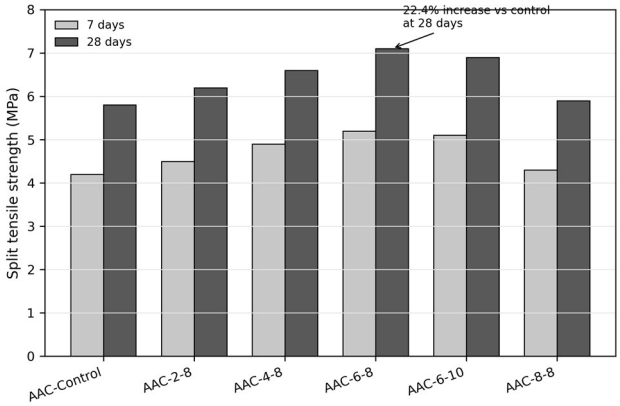

Figure 5. Seven- and 28-day split tensile strength of selected GGBS-based alkali-activated concrete mixes.

4.2.3 Flexural Strength

Flexural strength is critical for concrete elements subjected to bending stresses. Table 8 presents the flexural strength results for selected mixes.

Table 8. Flexural strength results for selected mixes

Mix code	7-day strength (MPa)	% increase vs control	28-day strength (MPa)	% increase vs control
AAC-Control	5.8	—	7.6	—
AAC-2-8	6.2	6.9	8.2	7.9
AAC-4-8	6.7	15.5	8.8	15.8
AAC-6-8	**7.2**	**24.1**	**9.4**	**23.7**
AAC-6-10	7.0	20.7	9.1	19.7
AAC-8-8	5.9	1.7	7.8	2.6

The flexural strength results show enhanced performance for all modified mixes. Flexural response in alkali-activated slag systems is sensitive to alkali dosage and activator modulus, and may not follow the same trend as compressive strength (Fang et al., 2020; Ding et al., 2017). The optimum mix achieved the highest increases (24.1% and 23.7% at 7 and 28 days, respectively). The enhancement is attributed to improved matrix toughness, crack bridging at the nanoscale, and enhanced aggregate–paste bond strength.

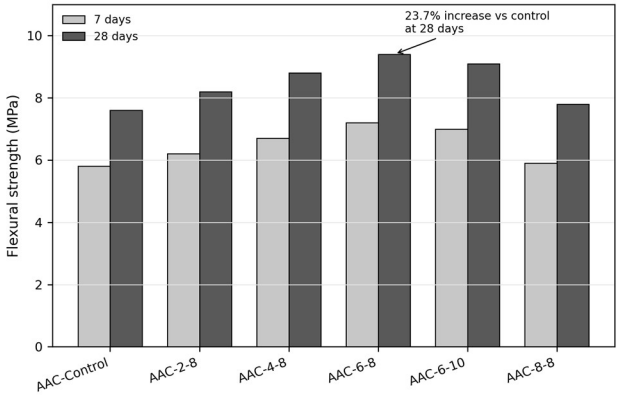

Figure 6. Seven- and 28-day flexural strength of selected GGBS-based alkali-activated concrete mixes.

4.2.4 Modulus of Elasticity

The modulus of elasticity is a measure of concrete's stiffness and is essential for structural design calculations. Table 9 presents the modulus of elasticity results for selected mixes at 28 days.

Table 9. Modulus of elasticity results at 28 days

Mix code	Modulus of elasticity (GPa)	% increase vs control
AAC-Control	38.2	—
AAC-2-8	40.9	7.1
AAC-4-8	43.8	14.7
AAC-6-8	**45.6**	**19.4**
AAC-6-10	44.8	17.3
AAC-8-8	38.9	1.8

The modulus of elasticity increased for all milled mixes, with the optimum mix achieving the highest increase (19.4%). Elastic modulus is among the mechanical properties reported to depend on binder chemistry, microstructure, and mix composition in alkali-activated concrete (Collins & Sanjayan, 1999; Ding et al., 2017). The increase is attributed to the denser microstructure and enhanced interparticle bonding within the cementitious matrix. Similar improvements in elastic modulus have been reported for mechanochemically activated GGBS systems, confirming enhanced stiffness and interfacial transition zone quality (Singh et al., 2024).

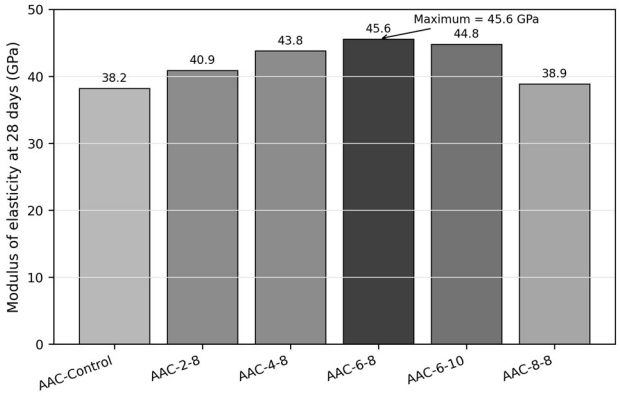

Figure 7. Modulus of elasticity of selected GGBS-based alkali-activated concrete mixes at 28 days.

4.3 Discussion of Mechanisms

The performance enhancements observed in this study arise from the complementary mechanisms of mechanical and chemical activation. The formation and distribution of calcium-aluminosilicate-hydrate-type gels, pore refinement, and interfacial transition-zone characteristics are central to the strength development of alkali-activated slag concrete (Mohamed, 2019; Fu et al., 2023; Tu & Zhang, 2024). Ball milling increases the amorphous fraction and surface defect density of GGBS, lowering the activation energy for Si–O and Al–O bond hydrolysis. This is directly supported by the mechanochemical literature, which attributes improved lowalkali performance to increasing the amorphousness and reactivity of the GGBS precursor and to the conversion of crystalline phases to amorphous phases (Singh et al., 2025; Singh et al., 2024). Consequently, a milled particle requires a lower OH^- concentration to release the same quantity of reactive Si and Al species per unit time.

At the same time, overmilling reduces the accessible surface through agglomeration and particle welding. This is why the highmolarity advantage disappears at long milling times and why the 10 h mix performs poorly across all molarities. The results therefore confirm that the optimal molarity is not a fixed material constant; it is a function of the precursor's mechanical history. The practical implication is that if a target strength can be met at 8 M rather than 10 M by milling for approximately 6 h, the activatorrelated alkali demand falls, reducing both material cost and the embodied alkalinity of the concrete. This aligns with the mechanochemical literature's statement that the approach improves performance by lowering the alkali dosage (Singh et al., 2025).

The statistical interaction between milling duration and molarity was confirmed by twoway ANOVA, which showed that the milling × molarity interaction term was significant at the 95% confidence level. The fitted responsesurface model exhibited a negative quadratic term for milling, capturing the optimum and the overmilling reversal, and a significant interaction coefficient in the region where milling substitutes for molarity. These results are consistent with RSM studies on GGBSbased systems, where interaction terms among precursor content, activator ratios, and molarity were found to be significant and the model achieved high predictive accuracy (Karadağ et al., 2026; Yi et al., 2025).

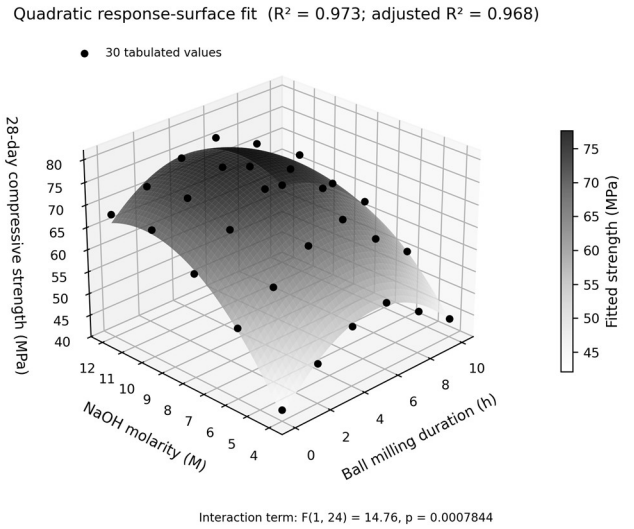

Figure 8. Quadratic response-surface model of 28-day compressive strength as a function of ball milling duration and NaOH molarity.

5. Conclusions

This study investigated the coupled effects of ball milling duration and NaOH molarity on the fresh and mechanical properties of GGBSbased alkaliactivated concrete. Based on the experimental results, the following conclusions are drawn:

1. Ball milling duration and alkali concentration are not additive variables. The optimal NaOH molarity for GGBSAAC depends on the prior milling history of the slag.

2. Unmilled GGBS exhibited a molarity optimum at approximately 10 M, with a 28day compressive strength of 68.6 MPa.

3. Intermediate milling of 4–6 h shifted the strength maximum downward to approximately 8 M. The optimum combination was 6 h milling with 8 M NaOH, achieving a 28day compressive strength of 79.5 MPa, a 15.9% increase over the unmilled 10 M reference mix.

4. Overmilling beyond 6 h was detrimental across all molarities, particularly at 12 M, because agglomeration and particle welding offset the reactivity gains from fineness.

5. The optimum mix achieved improvements of 22.4% in split tensile strength, 23.7% in flexural strength, and 19.4% in modulus of elasticity at 28 days.

6. The synergistic window is diagonal: maximum strength is achieved not at the highest milling energy or the highest molarity, but along a coupled ridge where mechanical and chemical activation are balanced. This provides a practical route to lower alkali dosage without sacrificing strength.

7. The findings support the use of controlled mechanical pretreatment as a strategy for reducing NaOH demand in GGBSbased AAC, with associated cost and environmental benefits. Future work should extend the study to longterm durability, chloride ingress, and lifecycle assessment.

References

Abhishek, H. S., Prashant, S., Kamath, M. V., & Kumar, M. (2022). Fresh mechanical and durability properties of alkali-activated fly ash-slag concrete: A review. Innovative Infrastructure Solutions, 7, Article 116. https://doi.org/10.1007/s41062-021-00711-w

Bouaziz, A., Hamzaoui, R., Guessasma, S., Lakhal, R., Achoura, D., & Leklou, N. (2017). Efficiency of high energy over conventional milling of granulated blast furnace slag powder to improve mechanical performance of slag cement paste. Powder Technology, 308, 37–46. https://doi.org/10.1016/j.powtec.2016.12.014

Collins, F., & Sanjayan, J. G. (1999). Workability and mechanical properties of alkali activated slag concrete. Cement and Concrete Research, 29(5), 455–458. https://doi.org/10.1016/S0008-8846(98)00236-1

Ding, Y., Dai, J.-G., & Shi, C.-J. (2017). Mechanical properties of alkali-activated concrete: A state-of-the-art review. Construction and Building Materials, 135, 68–79. https://doi.org/10.1016/j.conbuildmat.2016.09.121

Fang, S., Lam, E. S. S., Li, B., & Wu, B. (2020). Effect of alkali contents, moduli and curing time on engineering properties of alkali activated slag. Construction and Building Materials, 249, Article 118799. https://doi.org/10.1016/j.conbuildmat.2020.118799

Fu, Q., Bu, M., Zhang, Z., Xu, W., Yuan, Q., & Niu, D. (2023). Hydration characteristics and microstructure of alkali-activated slag concrete: A review. Engineering, 20(1), 162–179. https://doi.org/10.1016/j.eng.2021.07.026

Gökçe, H. S. (2024). Durability of slag-based alkali-activated materials: A critical review. Journal of the Australian Ceramic Society, 60(3), 885–903. https://doi.org/10.1007/s41779-024-01011-z

Karadağ, M., Mermerdaş, K., & Alğın, Z. (2026). Performance boundaries and multi-response optimization of alkali-activated slag mortars using full factorial design. International Journal of Civil Engineering. https://doi.org/10.1007/s40999-026-01301-6

Mohamed, O. A. (2019). A review of durability and strength characteristics of alkali-activated slag concrete. Materials, 12(8), Article 1198. https://doi.org/10.3390/ma12081198

Mohamed, O. A., Najm, O., Zuaiter, H. A., Saleem, S. K., Ivak, S., & Al-Aribe, K. (2024). Effect of activator concentration on setting time, workability and compressive strength of sustainable concrete with alkali-activated slag binder. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2024.04.103

Mohamed, O. A., Najm, O., & Shaji, S. (2025). Influence of NaOH activator concentration on efflorescence and compressive strength of sustainable mortar with alkali-activated slag and fly ash binders. International Journal of Sustainable Engineering, 18(1), Article 2538862. https://doi.org/10.1080/19397038.2025.2538862

Singh, A., Bhadauria, S. S., Thakare, A. A., Kumar, A., Mudgal, M., & Chaudhary, S. (2024). Durability assessment of mechanochemically activated geopolymer concrete with a low molarity alkali solution. Case Studies in Construction Materials, 20, Article e02715. https://doi.org/10.1016/j.cscm.2023.e02715

Singh, A., Baghel, S. S., Bhadauria, S. S., & Chaudhary, S. (2025). Mechanochemical treatment of low-alkali activated slag concrete: A comparative study of potassium and sodium activators. Journal of Materials in Civil Engineering, 37(11), Article 04025409. https://doi.org/10.1061/JMCEE7.MTENG-20467

Thunuguntla, C. S., & Rao, T. D. G. (2018). Effect of mix design parameters on mechanical and durability properties of alkali activated slag concrete. Construction and Building Materials, 193, 173–188. https://doi.org/10.1016/j.conbuildmat.2018.10.189

Tu, W., & Zhang, M. (2024). Multiscale microstructure and micromechanical properties of alkali-activated concrete: A critical review. Cement and Concrete Composites, 152, Article 105664. https://doi.org/10.1016/j.cemconcomp.2024.105664

Yi, Y., Lai, Y., Zhang, X., Han, F., Liang, T., Zhou, J., Liu, S., & Wang, X. (2025). Multi-objective optimization of engineering properties in geopolymer concrete via response surface methodology: Microstructural insights into the effects of pore structure. Journal of Building Engineering, 113, Article 113970. https://doi.org/10.1016/j.jobe.2025.113970