Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 4, Issue 4, 2026

EFFECT OF SODIUM HYDROXIDE (NAOH) MOLARITY ON WORKABILITY AND 28 DAY COMPRESSIVE STRENGTH OF SILICA FUME AND COAL FLY ASH BASED GEOPOLYMER CONCRETE

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DOI: https://doi.org/10.5281/zenodo.19448461

Keywords
geopolymer concrete; coal fly ash; silica fume; sodium hydroxide molarity; Na_2SiO_3/NaOH ratio; slump; compressive strength.

Article History
Received: 11 February 2026
Accepted: 21 March 2026
Published: 06 April 2026

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Abstract

The production of ordinary Portland cement (OPC) is one of the main causes linked with carbon dioxide (CO_2) emissions which results in climate instability and environmental degradation, motivating exploration of industrial by products as sustainable supplementary Cementous materials (SCMs). This research focuses on experimental assessment of the geopolymer concrete (GPC) produced with silica fume and coal fly ash with alkaline solutions of NaOH and Na_2SiO_3. This study evaluates the effect of sodium hydroxide (NaOH) molarity and AA/B on the workability and 28 day compressive strength of geopolymer concrete made with silica fume and coal fly ash. Eighteen mix designs were prepared with three different NaOH molarities (10M, 12M, and 14M), Na_2SiO_3/NaOH ratios (1.5, 2.0, and 2.5), and alkaline activator-to-binder ratios (0.50 and 0.67). Three standard 100 mm cubes were cast for each mix, producing a total of 54 specimens. All specimens were heat cured at 90°C and then stored under ambient laboratory conditions until testing at 28 days. Workability was measured by slump, and compressive strength was determined by dividing the maximum failure load by cross sectional area of the cube. The results revealed GPC workability decreased with higher NaOH molarities, slump values averaged of 84.17 mm at 10M, 69.00 mm at 12M, and 54.00 mm at 14M. The 28 day compressive strength followed non trend, it increased from 21.92 MPa at 10M to 24.41 MPa at 12M before declining slightly to 23.63 MPa at 14M series. The highest strength mix was GPC-14, which combined 12M NaOH, Na_2SiO_3/NaOH = 2.0, and an activator-to-binder ratio of 0.50 and achieved 32.62 MPa. Finally, the identifies optimum mix demonstrates high potential for environment friendly construction. By substituting OPC with industrial by products this research contributes to the mitigation of global CO_2 emissions and offers a sustainable solution for the modern construction industry.

1. INTRODUCTION

The construction industry remains dependent on concrete globally, and the traditional process of manufacturing results in significant environmental challenges. OPC production alone accounts for around 8% of CO_2 emissions [1]. The reduction in utilization of ordinary Portland cement remains a major sustainability driver in concrete research, and life cycle assessment data has shown that GPC produced from fly ash and silica fume can offer a lower impact alternative to traditional binders [2].

The chemical basis of geopolymerization was established by Davidovits, who described geopolymers as inorganic polymeric binders formed through alkaline activation of aluminosilicate source materials [3], [4]. The engineering feasibility of low-calcium fly ash based geopolymer concrete was later demonstrated experimentally by Hardjito, Wallah, Sumajouw, and Rangan [5], [6].

In the Pakistani and broader Sindh context, researchers have studied the use of supplementary cementitious materials and silica rich industrial by products as viable routes for performance improvement and lower embodied carbon in concrete [7], [8]. Keerio e al. further found that locally developed metakaolin, coal bottom ash, and waste glass can effectively be used into concrete and mortar formulations [9]. Research by Bheel et al. on alternative ash based binders further supports the regional feasibility of optimized low-carbon cementitious systems in Pakistani construction sector [10], [11].

Fly ash based geopolymer concrete develops strength through alkaline activation rather than conventional hydration. The process depends on dissolution of reactive aluminosilicate phases, followed by polycondensation and formation of a rigid three-dimensional binder network [3], [4]. In fly ash concrete systems, this reaction pathway is highly sensitive to activator composition, curing temperature, and mixture design [5], [6].

The concentration of NaOH is one of the most influential variables in geopolymerization process because it governs both dissolution intensity and reaction kinetics. Experimental studies on fly ash based geopolymer concrete have indicated that molarity changes and influences both workability and compressive strength, and that an optimum concentration range is usually observed rather than unlimited gains with increasing alkalinity [12], [13]. Studies on geopolymer mortars and self compacting concrete systems confirms the same practical sensitivity of fresh and hardened properties to activator concentration, highlighting the precise balance required between these [14], [15].

Silica fume is commonly mixed with fly ash based alkali activated systems to provide additional reactive silica and to improve particle packing through its characteristic micro filler effect [16], [17]. Direct fly ash and silica fume blends have resulted in improved matrix densification when the precursor blend and activator chemistry are compatible [18]. Studies using silica fume derived activator solutions and optimized geopolymer binders likewise indicate that silica availability interacts strongly with silicate dosage, molarity, and liquid content [19], [20]. Recent optimization studies on silica fume modified geopolymer mortars and self compacting geopolymer concrete (SCGC) have further reinforced that conclusion [21], [22], [23].

Despite these advancements and progress, direct experimental comparison of both workability and 28 day compressive strength for fly ash and silica fume geopolymer concrete prepared specifically with 10M, 12M, and 14M NaOH under a 90°C heat curing regime remains limited. Following it, this study therefore focuses on slump and 28 day compressive strength to determine how NaOH molarity, Na_2SiO_3/NaOH ratio and activator to binder ratio, affect or influence fresh state and hardened performance of geopolymer concrete. This was achieved through an 18 mix (GPC-1 to GPC-18) experimental matrix involving the testing of 54 geopolymer concrete cubes.

2. Materials and methods

2.1 Materials

The binder system consisted of coal fly ash and silica fume. Coal fly ash was treated as a low calcium precursor consistent with Class F/Type F practice in fly ash based geopolymer concrete, whereas silica fume was treated as a high reactivity supplementary silica source. The alkaline activator comprised sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). To increase workability Sika ViscoCrete high performance superplasticizer was used.

The experimental phase was structured around a full factorial design which involved three NaOH molarity levels (10M, 12M, and 14M), three Na_2SiO_3/NaOH ratios (1.5, 2.0, and 2.5), and two alkaline activator to binder ratios (0.50 and 0.67). To ensure statical reliability, Three 100 mm cube specimens were cast for each of the 18 mix designs, giving a total of 54 concrete cubes. The mix design (Table 1) was used to integrate mix specific NaOH solid dosage, water content, sodium silicate dosage, and the measured response of each mix.

Table 1 GPC Mix Design

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			03163323103 24MS-CET-17			AFTER MIXING DRY MATERIAL, MIX IT WITH STEP 3					
				STEP 01 (24 Hours Early)		STEP 02 AFTER 24 HOURS				STEP 03 MIX NA2SIO3 IN STEP 1	
Mix ID	No of Cubes	NaOH (M)	SS/SH Ratio	NaOH Solid (kg/m3)	Water (kg/m3)	Silica Fume	Coal Fly Ash	Fine Aggregate	Coarse Aggregate	NaOH Solution (kg/m3)	Na2SiO3 (kg/m3)
GPC 1	3	10	1.5	128.1	192	600	600	2400	3600	320.1	480
GPC 2	3	12	1.5	153.6	166.5	600	600	2400	3600	320.1	480
GPC 3	3	14	1.5	179.1	140.7	600	600	2400	3600	319.8	480
GPC 4	3	10	2	106.8	159.9	600	600	2400	3600	266.7	533.4
GPC 5	3	12	2	128.1	138.6	600	600	2400	3600	266.7	533.4
GPC 6	3	14	2	149.4	117.3	600	600	2400	3600	266.7	533.4
GPC 7	3	10	2.5	91.5	137.1	600	600	2400	3600	228.6	571.5
GPC 8	3	12	2.5	109.8	118.8	600	600	2400	3600	228.6	571.5
GPC 9	3	14	2.5	128.1	100.5	600	600	2400	3600	228.6	571.5
GPC 10	3	10	1.5	96	144	600	600	2400	3600	240	360
GPC 11	3	12	1.5	115.2	124.8	600	600	2400	3600	240	360
GPC 12	3	14	1.5	134.4	105.6	600	600	2400	3600	240	360
GPC 13	3	10	2	80.1	120	600	600	2400	3600	200.1	399.9
GPC 14	3	12	2	96	104.1	600	600	2400	3600	200.1	399.9
GPC 15	3	14	2	111.9	87.9	600	600	2400	3600	199.8	399.9
GPC 16	3	10	2.5	68.7	102.9	600	600	2400	3600	171.6	428.7
GPC 17	3	12	2.5	82.2	89.1	600	600	2400	3600	171.3	428.7
GPC 18	3	14	2.5	96	75.3	600	600	2400	3600	171.3	428.7

2.2 Specimen preparation and curing

To ensure chemical stability, the alkaline activator solution Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3) were mixed as per the design sheet 24 hours prior to casting of cubes. The dry constituents including, silica fume (passed via #325 sieve), coal fly ash (passed via #325 sieve), fine aggregate (Hill Sand obtained from Bohlari passed via 4.75 mm), and coarse aggregate (Locally available crushed stone passed via 12.7 mm and reserved on 4.75 mm) were then dry mixed until the precursor and aggregate phases were uniformly achieved. After dry mixing the already prepared alkaline activator solution was then introduced to dry material gradually, followed by the superplasticizer for enhancing workability, and mixing continued until a homogenous and cohesive geopolymer concrete was obtained.

Fresh concrete was cast into steel cube molds measuring 100 mm × 100 mm × 100 mm. Each mould was filled in layers and compacted to minimize entrapped air. The molded cubes were then heat cured at 90°C for 24 hours, demolded after cooling, and then stored under ambient laboratory conditions until the 28 day test age (Figure 1).

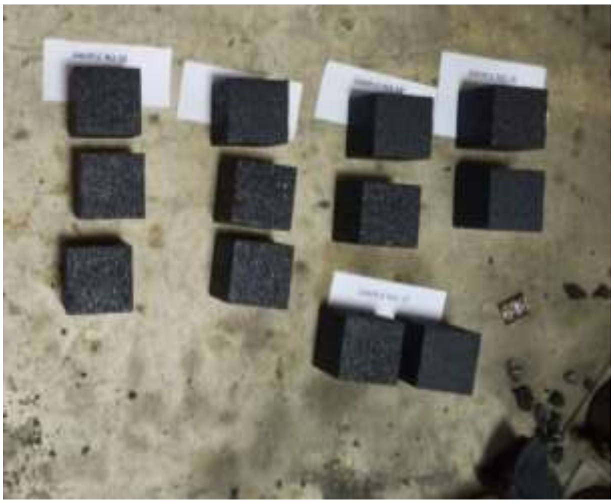
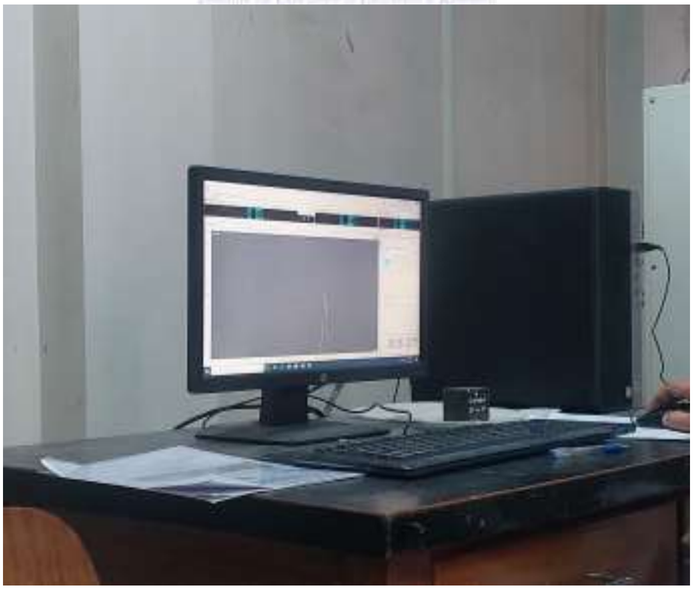


Figure 1 GPC Cubes

2.3 Test methods and data reduction

The workability of fresh geopolymer concrete was evaluated by the slump test in accordance with ASTM C143/C143M. To minimize the effects of ambient temperature and early stage geopolymerization on consistency, the slump was carried out immediately after completion of mixing cycle.

The compressive strength of geopolymer concrete was determined at 28 days using 100 mm cube specimens in accordance with BS EN 12390-3. A constant lading rate was applied using calibrated Universal Testing Machine (UTM) until specimen failure occurred. The compressive strength (f_c) was calculated by dividing the maximum failure load by the cross sectional area of the loaded face, with results reported in Megapascals (MPa) (Figure 2).



$f_c = P/A$

Figure 2 Testing of GPC Cubes

3. Results and discussion

3.1 Workability response

The slump results showed a systematic decline with increasing NaOH molarity. When the 18 mixes were categorized by molarity, the average slump decreased from 84.17 mm at 10M to 69.00 mm at 12M and finally to 54.00 mm at 14M. Relative to the 10M baseline, the 12M and 14M series demonstrated slump / workability reductions of 18.0% and 35.8%, respectively. This trend is attributed to dynamic viscosity of the alkaline activators at higher molarities, which increases the interna friction of the fresh geopolymer concrete and resist flow during the slump test.

This organized decline in workability was consistently observed within matched mix families. For instance, $Na_2SiO_3/NaOH$ = 1.5 and AA/B = 0.67, slump decreased from 91 mm in GPC-1 to 75 mm in GPC-2 and 60 mm in GPC-3. At $Na_2SiO_3/NaOH$ = 2.0 and AA/B = 0.50, the corresponding slump values were 83 mm, 68 mm, and 53 mm for GPC-13, GPC-14, and GPC-15, respectively. These observations confirm that the workability reduction is systematic response to increase in molarity rather than an incidental experimental variation (Figure)

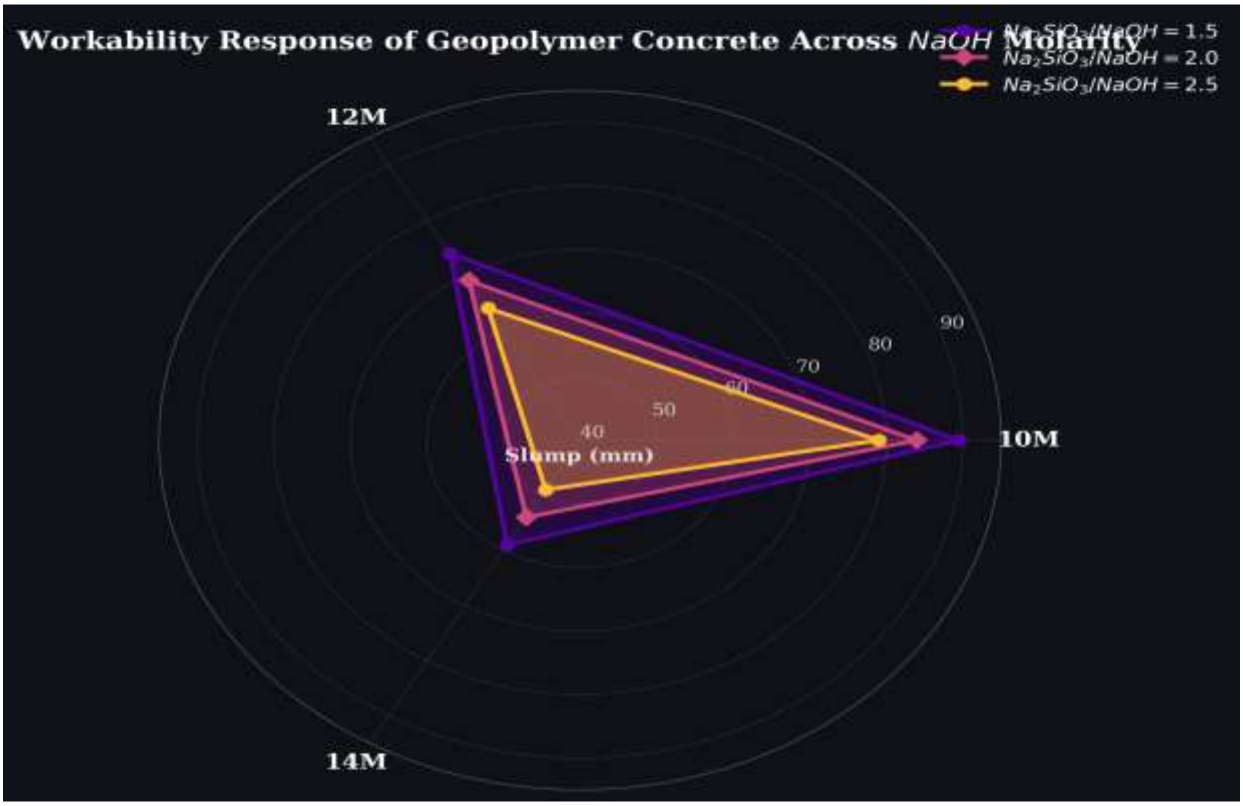


Figure 3 Workability Response

This fresh state behaviour is consistent with established literature indicating that increasing NaOH concentration increase activator viscosity and increases the cohesiveness of fly ash based geopolymer mixtures [13], [14]. Similar trends and observations have also been discussed for self compacting geopolymer concrete and related alkali activated systems sensitive to NaOH molarity [15]. In silica fume modified binders, the ultrafine silica fraction can intensify the reduction in workability by increasing surface area and liquid demand [16], [17].

3.2 28 day compressive strength response

The 28 day compressive strength results showed a non-linear relationship with NaOH molarity. Averaged across the experimental matrix, the compressive strength increased from 21.92 MPa at 10M to a peak 24.41 MPa at 12M before decreasing slightly to 23.63 MPa at 14M. This transition shows an 11.36% strength enhancement from 10M to 12M, whereas the 14M average remained 3.20% below the 12M average peak. Resultantly, 12M was identified a the practical optimum molarity for maximized mechanical performance.

Table 2 Compressive Strength Response

NaOH Molarity	Avg. Strength (MPa)	% Change (from 10M)	Trend Status
10M	21.92	–	Baseline
12M	24.41	+11.36%	**Optimum**
14M	23.63	+7.80%	Decline

The same trend was further preserved in the matched combination sets. At $Na_2SiO_3/NaOH$ = 1.5 and AA/B = 0.67, the average strength increased from 18.89 MPa (GPC-1) to 20.52 MPa (GPC-2) and then declined to 19.72 MPa (GPC-3). At $Na_2SiO_3/NaOH$ = 2.0 and AA/B = 0.50, strength rose from 26.82 MPa (GPC-13) to a peak 32.62 MPa (GPC-14) before decreasing slightly to 31.71 MPa in GPC-15. Resultantly, GPC-14 was therefore identified as the optimal mix design within experiment, achieving the highest overall mechanical performance (Table 3).

Table 3 Compressive Strength Trend

Mix ID	Molarity	Na2SiO3/NaOH	AA/B	Strength (MPa)	Status
GPC1	10M	1.5	0.67	18.89	Baseline
GPC2	12M	1.5	0.67	20.52	Local Peak
GPC3	14M	1.5	0.67	19.72	Decline
GPC13	10M	2.0	0.50	26.82	Baseline
GPC14	**12M**	**2.0**	**0.50**	**32.62**	**GLOBAL PEAK**
GPC15	14M	2.0	0.50	31.71	Decline

The strength increase observed from 10M to 12M indicates that the increase in alkalinity improved precursor dissolution and promoted the development of robust aluminosilicate geopolymer gel. The slight decline at 14M suggests that beyond an optimum concentration threshold, further NaOH additions does not necessarily improve hardened performance in proportion to the extra alkalinity [12], [13]. This behavior aligns with the broader fly ash geopolymer literature, which identifies a balanced activator concentration rather than the maximum molarity as the critical condition for optimizing machinal properties [6], [15].

3.3 Interaction of molarity with $Na_2SiO_3/NaOH$ ratio and activator dosage

Molarity was the central variable in this paper, but it did not act independently of the other mixture parameters. When the results were grouped by $Na_2SiO_3/NaOH$ ratio, the average 28-day compressive strengths were 20.22 MPa at a ratio of 1.5, 25.68 MPa at a ratio of 2.0, and 24.05 MPa at a ratio of 2.5. The ratio of 2.0 therefore produced the strongest overall response within the present matrix. This outcome is consistent with studies showing that silica availability and silicate dosage must be balanced with NaOH concentration to maximize geopolymerization efficiency [19], [21]. Related investigations using silica-fume-derived activators and optimized binder systems also indicate that excessive or insufficient silicate dosage can both reduce performance relative to an intermediate optimum [20], [23].

Activator dosage also exerted a strong influence. Averaged across the full matrix, the AA/B = 0.50 series produced 26.89 MPa, whereas the AA/B = 0.67 series produced 19.74 MPa. The lower activator dosage therefore produced a 36.2% increase in average 28-day compressive strength, while the difference in average slump between the two dosage levels was comparatively small. This supports the interpretation that liquid dosage must remain compatible with binder reactivity rather than being increased indiscriminately for flow [20], [21], [14].

The role of silica fume should, however, be interpreted carefully. The present study investigated a fly ash–silica fume geopolymer system, but it did not include a fly ash-only control series. Accordingly, the paper does not claim to isolate the independent contribution of silica fume experimentally. Instead, it shows that the tested fly ash–silica fume system performed best at 12M when paired with a Na_2SiO_3/NaOH ratio of 2.0 and an AA/B ratio of 0.50. That interpretation is consistent with the reported densification and microfiller benefits of silica fume in related geopolymer systems [16], [18], [12].

4. Conclusions

Based on the experimental investigation of 54 geopolymer concrete specimens across 18 unique mix designs, the following conclusions are drawn.

1. NaOH molarity established a unique trade-off between fresh state consistency and 28 day mechanical performance of the geopolymer concrete made via silica fume and coal fly ash.
2. The average slump reduced significantly as alkalinity increased, falling from 84.17 mm at 10M to 69.00 mm at 12M, and finally to 54.00 mm at 14M. This 35.8% total decrease in slump is attributed to the increased dynamic viscosity of the high molarity activator (Figure 4).
3. The 28 day compressive strength reflected a non linear trend, increasing from 21.92 MPa (10M) to a peak 24.41 MPa(12M) before a nominal decline 23.63 MPa (14M). Resultantly, 12M is identified a the practical (Figure 4).

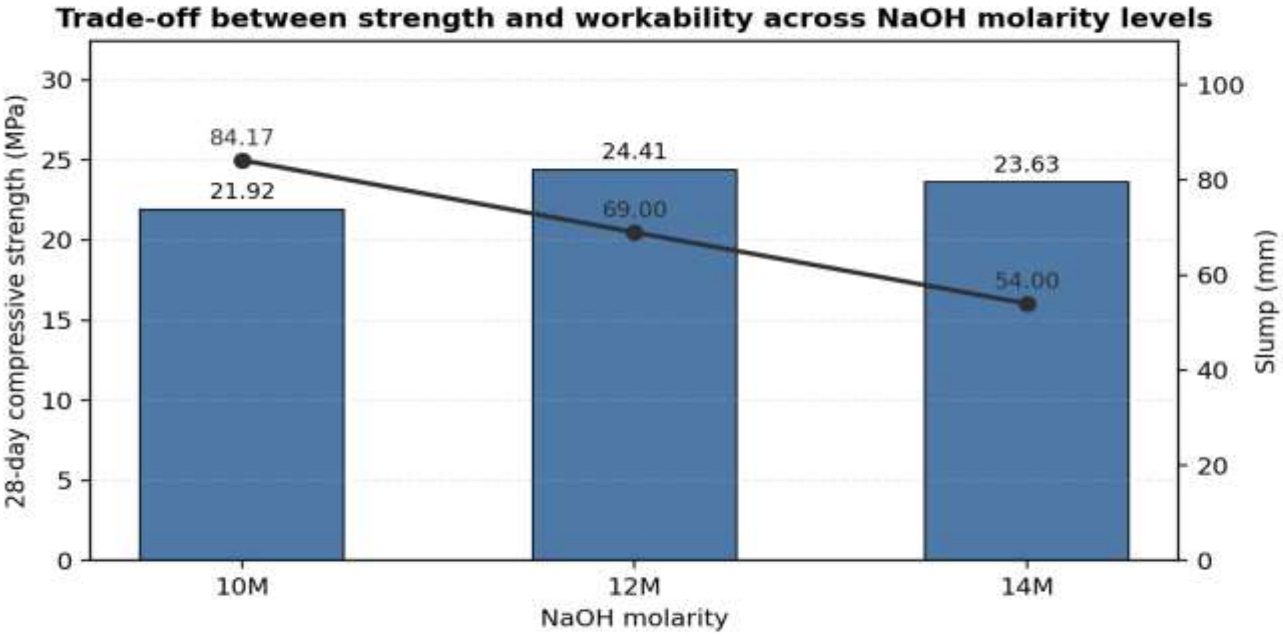


Figure 4 Trade-off between grouped average 28-day compressive strength and grouped average slump across the three NaOH molarity levels

5. Recommendations for Future Work

1. Future research should evaluate the resistance of this specific fly ash and silica fume blend to aggressive environmental conditions, including sulfate attack, acid resistance, and chloride ion penetration, specifically considering high silica fume content.
2. To better understand the strength trend, advanced characterization techniques such as X-ray Diffraction (XRD) should be used to examine the interfacial transition zone (ITZ) and the density of geopolymer gel.
3. Different curing regimes including water, heat, and ambient may be formulated to investigate the potential curing condition to reduce the energy footprint.

References

[1] S. Barbhuiya, B. B. Das, D. Adak, et al., "Low carbon concrete: advancements, challenges and future directions in sustainable construction," Discov. Concr. Cem., vol. 1, no. 3, 2025, doi: 10.1007/s44416-025-00002-y.

[2] R. Bajpai, K. Choudhary, A. Srivastava, K. S. Sangwan, and M. Singh, "Environmental impact assessment of fly ash and silica fume based geopolymer concrete," J. Clean. Prod., vol. 254, art. no. 120147, 2020, doi: 10.1016/j.jclepro.2020.120147.

[3] J. Davidovits, "Geopolymers and geopolymeric materials," *J. Therm. Anal.*, vol. 35, no. 2, pp. 429–441, Mar. 1989, doi: 10.1007/BF01904446.

[4] J. Davidovits, "Geopolymers," *J. Therm. Anal.*, vol. 37, no. 8, pp. 1633–1656, Aug. 1991, doi: 10.1007/BF01912193.

[5] D. Hardjito, S. E. Wallah, D. M. J. Sumajouw, and B. V. Rangan, "On the development of fly ash-based geopolymer concrete," ACI Mater. J., vol. 101, no. 6, pp. 467–472, 2004, doi: 10.14359/13485.

[6] D. Hardjito, S. E. Wallah, D. M. J. Sumajouw, and B. V. Rangan, "Fly ash-based geopolymer concrete," Aust. J. Struct. Eng., vol. 6, no. 1, pp. 77–86, 2005, doi: 10.1080/13287982.2005.11464946.

[7] M. A. Keerio, S. A. Abbasi, A. Kumar, N. Bheel, K. ur Rehman, and M. Tashfeen, "Effect of silica fume as cementitious material and waste glass as fine aggregate replacement constituent on selected properties of concrete," Silicon, vol. 14, pp. 165–176, 2022, doi: 10.1007/s12633-020-00806-6.

[8] M. A. Keerio, A. Saand, R. Chaudhry, N. Bheel, N. ul Karim Bhatti, and S. Soohu, "The effect of local metakaolin developed from natural material Soorh on selected properties of concrete/mortar," Silicon, vol. 14, pp. 1807–1816, 2022, doi: 10.1007/s12633-021-00993-w.

[9] M. A. Keerio, A. Saand, A. Kumar, N. Bheel, and K. Ali, "Effect of local metakaolin developed from natural material Soorh and coal bottom ash on fresh, hardened properties and embodied carbon of self-compacting concrete," Environ. Sci. Pollut. Res., vol. 28, no. 42, pp. 60000–60018, 2021, doi: 10.1007/s11356-021-14960-w.

[10] A. Kumar, N. Bheel, I. Ahmed, S. H. Rizvi, R. Kumar, and A. A. Jhatial, "Effect of silica fume and fly ash as cementitious material on hardened properties and embodied carbon of roller compacted concrete," Environ. Sci. Pollut. Res., vol. 29, pp. 1210–1222, 2022, doi: 10.1007/s11356-021-15734-0.

[11] N. Bheel, M. Alwetaishi, I. A. Jae, A. Syamsir, A. S. Alraeeini, S. A. Waheeb, L. Alkhattabi, and O. Benjeddou, "Enhancing performance and sustainability of GGBFS-based self-compacting geopolymer concrete blended with coal bottom ash and metakaolin by using RSM modelling," Sci. Rep., vol. 14, art. no. 19754, 2024, doi: 10.1038/s41598-024-70800-0.

[12] I. Pane et al., "Compressive strength of fly ash-based geopolymer concrete with a variable of sodium hydroxide (NaOH) solution molarity," MATEC Web Conf., vol. 147, art. no. 01004, 2018, doi: 10.1051/matecconf/201814701004.

[13] F. H. A. Zaidi et al., "Effect of different NaOH molarity towards fly ash based geopolymer for underwater concreting," AIP Conf. Proc., vol. 2267, art. no. 020035, 2020, doi: 10.1063/5.0024742.

[14] P. Pradhan, S. Panda, S. K. Parhi, and S. K. Panigrahi, "Effect of critical parameters on the fresh properties of self-compacting geopolymer concrete," Mater. Today Proc., vol. 62, pp. 6325–6335, 2022, doi: 10.1016/j.matpr.2022.02.506.

[15] N. L. N. Kiran Kumar and I. V. Ramana Reddy, "A study on the effect of NaOH molarity on fly ash based self-compacting geopolymer concrete," Mater. Today Proc., 2023, doi: 10.1016/j.matpr.2023.03.144.

[16] S. K. Das et al., "Fresh, strength and microstructure properties of geopolymer concrete incorporating lime and silica fume as replacement of fly ash," J. Build. Eng., vol. 32, art. no. 101780, 2020, doi: 10.1016/j.jobe.2020.101780.

[17] E. Yavuz, N. I. Kul Gul, and N. U. Kockal, "Characterization of class C and F fly ashes based geopolymers incorporating silica fume," Ceram. Int., vol. 48, no. 21, pp. 32213–32225, 2022, doi: 10.1016/j.ceramint.2022.07.163.

[18] P. Cong and L. Mei, "Using silica fume for improvement of fly ash/slag based geopolymer activated with calcium carbide residue and gypsum," Constr. Build. Mater., vol. 275, art. no. 122171, 2021, doi: 10.1016/j.conbuildmat.2020.122171.

[19] Y. Cheng et al., "Study on the effectiveness of silica fume-derived activator as a substitute for water glass in fly ash-based geopolymer," J. Build. Eng., vol. 51, art. no. 104228, 2022, doi: 10.1016/j.jobe.2022.104228.

[20] B. O. Adeleke, J. M. Kinuthia, J. Oti, and M. Ebailila, “Physico-mechanical evaluation of geopolymer concrete activated by sodium hydroxide and silica fume-synthesised sodium silicate solution,” Materials, vol. 16, no. 6, art. no. 2400, 2023, doi: 10.3390/ma16062400.

[21] S. Arslan, A. Oz, A. Benli, B. Bayrak, G. Kaplan, and A. C. Aydin, “Sustainable use of silica fume and metakaolin in slag/fly ash-based self-compacting geopolymer composites: Fresh, physico-mechanical and durability properties,” Sustainable Chem. Pharm., vol. 39, art. no. 101512, 2024, doi: 10.1016/j.scp.2024.101512.

[22] Z. Ergeshov et al., “Influence of silica fume on the mechanical and microstructural properties and life cycle assessment of fly ash-based geopolymer mortar,” Arab. J. Sci. Eng., 2025, doi: 10.1007/s13369-025-10142-9.

[23] H. Altawil and M. Olgun, “Optimization of mechanical properties of geopolymer mortar based on Class C fly ash and silica fume: A Taguchi method approach,” Case Stud. Constr. Mater., vol. 22, art. no. e04332, 2025, doi: 10.1016/j.cscm.2025.e04332.