EFFECT OF ALKALI ACTIVATOR TYPE AND HYDROXIDE-TO-SILICATE RATIO ON THE FRESH AND MECHANICAL PROPERTIES OF GROUND GRANULATED BLAST FURNACE SLAG-BASED GEOPOLYMER PASTES

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ABSTRACT

This study investigated the effects of different alkali activator combinations and hydroxide-to-silicate (H/S) ratios on the fresh and hardened properties of ground granulated blast furnace slag (GGBFS)-based geopolymer pastes. Four alkali activator systems, namely sodium silicate–sodium hydroxide (NaS–NaH), sodium silicate–potassium hydroxide (NaS–KH), potassium silicate–sodium hydroxide (KS–NaH), and potassium silicate–potassium hydroxide (KS–KH), were prepared using sodium silicate (Na_2SiO_3), potassium silicate (K_2SiO_3), sodium hydroxide (NaOH), and potassium hydroxide (KOH) solutions. The activator-to-binder ratio was maintained constant at 0.50 for all mixtures, while the hydroxide-to-silicate (H/S) ratio was varied at 0.55, 0.65, 0.75, and 0.85. The prepared geopolymer paste specimens were cured at room temperature (25 ± 2 °C) for 28 days. The fresh properties of the geopolymer pastes were evaluated through the flow spread test, whereas the hardened properties were assessed by compressive strength, flexural strength, and water absorption tests. The experimental results demonstrated that both the H/S ratio and the alkali activator composition had a significant influence on the fresh and hardened properties of the geopolymer pastes. Increasing the H/S ratio from 0.55 to 0.85 improved the workability of all mixtures but generally resulted in reductions in compressive and flexural strengths and an increase in water absorption. Among the investigated activator systems, the sodium silicate–potassium hydroxide (NaS–KH) combination more effectively promoted the geopolymerization reaction, resulting in superior mechanical performance compared with the other activator systems. The highest compressive and flexural strengths were obtained for the NaS–KH mixture with an H/S ratio of 0.55, reaching 118.98 MPa and 5.87 MPa, respectively. The findings indicate that the combined optimization of alkali activator composition and the hydroxide-to-silicate ratio plays a critical role in achieving a balanced combination of workability, mechanical performance, and durability-related properties in GGBFS-based geopolymer pastes.

Keywords: Geopolymer paste, Hydroxide-to-silicate ratio, Mechanical properties, Potassium, Sodium.

INTRODUCTION

The development of low-carbon binding materials has become an important research direction in construction materials engineering. One approach to reducing the dependence on ordinary Portland cement is the utilization of industrial by-products as reactive binder constituents (Pala and Gülmez, 2025). Among these materials, ground granulated blast furnace slag (GGBFS) is particularly suitable for alkaline activation because of its reactive glassy structure and its considerable calcium and silicate contents (Wang et al. 2025). Converting GGBFS into a binding material also provides an opportunity to

utilize an industrial by-product in value-added construction applications rather than relying exclusively on conventional cementitious resources.

The hardening mechanism of alkali-activated GGBFS differs substantially from the hydration process of Portland cement (Jiang et al. 2022). When GGBFS comes into contact with a highly alkaline solution, its glassy structure is attacked and reactive species are released into the liquid phase. These dissolved species subsequently participate in precipitation and polymerization reactions, producing reaction products that connect the initially separate slag particles and form a hardened matrix (Chami et al. 2024). The characteristics of this matrix depend strongly on the chemical environment established during activation (Genua et al. 2025; Jiang et al. 2024). Therefore, the selection and proportioning of the alkaline components represent key factors in controlling the engineering properties of slag-based binders.

Activator solutions generally contain a hydroxide component together with a soluble silicate source (Skane et al. 2025). These two constituents perform different but complementary functions during activation. Hydroxide solutions establish the alkaline conditions required to promote dissolution of the precursor, whereas silicate solutions introduce additional soluble silica into the reaction medium (Tamada et al. 2012; Khalifa et al. 2020). Consequently, changing the balance between hydroxide and silicate modifies not only the alkalinity of the activating solution but also its silica availability and rheological characteristics. Such changes may influence precursor dissolution, reaction rate, formation of binding products, pore development, and ultimately the fresh and hardened behavior of the resulting material (Li, 2026).

Another important consideration is the alkali cation associated with the hydroxide and silicate components. Sodium-based activators, particularly sodium hydroxide and sodium silicate, have been widely adopted in alkali-activated binder research (Guo et al. 2023). However, potassium hydroxide and potassium silicate can also effectively provide the alkaline conditions required for slag activation. Sodium and potassium ions differ in ionic size and chemical interactions within the reaction medium, and these differences may affect the mobility of dissolved species, solution characteristics, reaction kinetics, and development of the hardened structure (Zhang et al. 2026). Thus, activator systems containing different combinations of sodium- and potassium-based components cannot necessarily be expected to exhibit identical fresh or mechanical behavior.

The hydroxide-to-silicate (H/S) ratio is particularly relevant when different alkali cations are considered simultaneously. Increasing the H/S ratio alters activator alkalinity and soluble silicate availability, thereby influencing slag dissolution and reaction kinetics (Nazerian et al. 2026). Conversely, a lower H/S ratio increases the proportion of silicate solution available in the activator. The resulting balance can create competing effects on workability and strength development. Improved fresh-state workability does not necessarily correspond to enhanced mechanical performance or a denser hardened microstructure. Similarly, the activator composition that provides high strength at one H/S ratio may respond differently when the ratio is altered. Therefore, the H/S ratio should be evaluated together with activator chemistry rather than treated as an independent mixture parameter.

Most previous investigations of alkali-activated slag systems have primarily employed sodium hydroxide and sodium silicate, while potassium-containing and mixed Na/K activation routes have received comparatively less attention (Firdous and Stephan, 2019; Dai et al. 2022). Furthermore, studies directly comparing sodium silicate and potassium silicate in combination with both NaOH and KOH over the same range of H/S ratios are relatively limited. Such a comparison is important for distinguishing the influence of the silicate source from that of the hydroxide cation and for determining how these factors interact with changes in activator proportions. Examining these variables within a common experimental framework may therefore provide a clearer understanding of the sensitivity of GGBFS-based pastes to activator composition.

Based on this consideration, the present study comparatively evaluates four alkaline activation systems for GGBFS-based geopolymer pastes: sodium silicate–sodium hydroxide (NaS–NaH), sodium silicate–potassium hydroxide (NaS–KH), potassium silicate–sodium hydroxide (KS–NaH), and potassium silicate–potassium hydroxide (KS–KH). Four H/S ratios of 0.55, 0.65, 0.75, and 0.85 were investigated while the activator-to-binder ratio was fixed at 0.50. Flow spread was measured to characterize fresh-state behavior, whereas compressive strength, flexural strength, and water absorption were determined to assess hardened performance. By evaluating these properties together, the study seeks to establish how variations in H/S ratio interact with sodium- and potassium-based activator combinations and to

determine the activation conditions that provide a suitable compromise between workability, mechanical resistance, and water absorption.

MATERIALS AND METHODS

Materials

Ground granulated blast furnace slag (GGBFS), obtained from Karabük Iron and Steel Works (Türkiye), was employed as the sole aluminosilicate source in the geopolymer paste mixtures (Figure 1). The relatively high CaO content of GGBFS favors the formation of calcium-rich binding phases during alkaline activation, thereby facilitating strength development under ambient curing conditions. The material had a blaine fineness of 4180 cm²/g, and its particle size was predominantly within the range of 20–30 µm. The physical characteristics and oxide composition of the GGBFS are summarized in Tables 1 and 2, respectively.

Table 1. Some physical characteristics of ground granulated blast furnace slag

		Sieve Diameter (mm)	Passing Through Sieve (%)
Blaine Fineness (cm^2/gr)	4180	0.025	75
Loss on Ignition (%)	0.13	0.040	88
		0.063	96
Specific Gravity	2.79	0.090	99
		0.125	100

Table 2. Chemical characteristics of ground granulated blast furnace slag.

SiO_2 (%)	40.27
Al_2O_3 (%)	13.18
Fe_2O_3 (%)	0.75
CaO (%)	28.07
MgO (%)	7.45
SO_3 (%)	1.64
Na_2O (%)	0.61
K_2O (%)	1.04
TiO_2 (%)	1.46
MnO (%)	2.35
SrO (%)	0.07



Figure 1. Physical appearance of ground granulated blast furnace slag

Sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium silicate (Na_2SiO_3), and potassium silicate (K_2SiO_3) were employed as alkaline activators (Figure 2). NaOH and KOH, supplied in solid form with 99% purity, were separately dissolved in water to obtain 12 M hydroxide solutions. This concentration was selected to provide a sufficiently alkaline environment for the activation of GGBFS and was kept constant throughout the experimental program. The silicate activators were used in their commercially supplied liquid form. The chemical compositions and physical characteristics of the alkaline activators are summarized in Table 3.

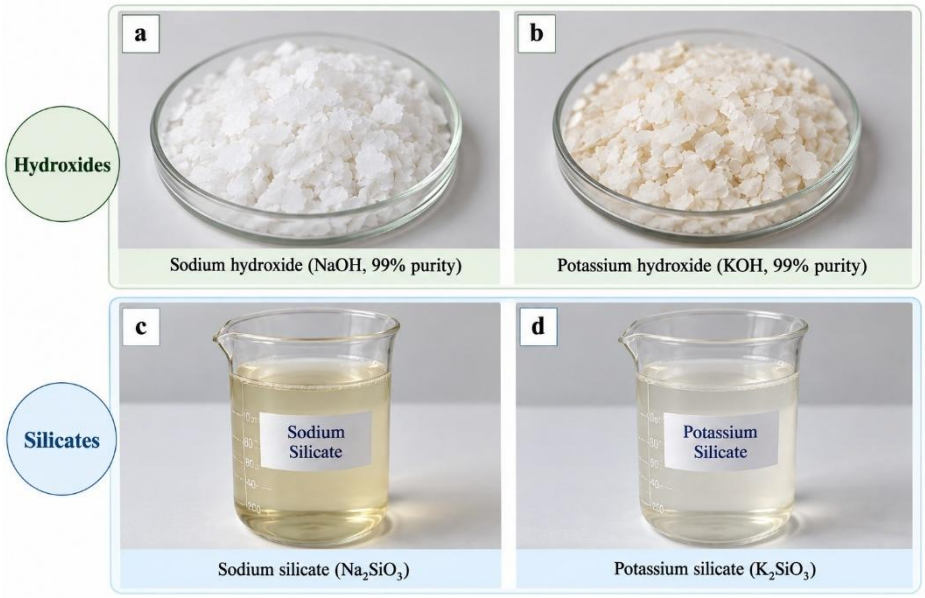


Figure 2. Alkaline activators used in this study: (a) NaOH, (b) KOH, (c) Na_2SiO_3, and (d) K_2SiO_3

Table 3. Chemical and physical properties of the alkaline activators

Alkaline Activator	H_2O (%)	SiO_2 (%)	Na_2O (%)	K_2O (%)	Density (g/cm³)
Na_2SiO_3	53.1	32.2	14.7	–	1.32
K_2SiO_3	60.3	27.0	–	12.8	1.34
NaOH	21.9	–	75.2	–	1.28
KOH	12.9	–	–	87.1	1.28

Mix Proportions

Sixteen GGBFS-based geopolymer paste mixtures were formulated by combining four alkaline activator systems with four different hydroxide-to-silicate (H/S) ratios. The investigated activator systems were sodium silicate–sodium hydroxide (NaS–NaH), sodium silicate–potassium hydroxide (NaS–KH), potassium silicate–sodium hydroxide (KS–NaH), and potassium silicate–potassium hydroxide (KS–KH). The activator-to-binder (A/B) ratio was maintained at 0.50 by mass for all mixtures, whereas the H/S ratio was varied as 0.55, 0.65, 0.75, and 0.85. Here, H/S represents the mass ratio of the hydroxide solution to the silicate solution. For each mixture, the total amount of alkaline activator was kept constant, while the amounts of hydroxide and silicate solutions were adjusted according to the selected H/S ratio. The quantities of materials required for the preparation of the geopolymer paste mixtures are presented in Table 4.

Table 4. Mix proportions of GGBFS-based geopolymer pastes

Mixture ID	H/S Ratio	GGBFS (g)	Na_2SiO_3 (g)	K_2SiO_3 (g)	NaOH (g)	KOH (g)
NaS–NaH	0.55	2640	851.6	–	468.4	–
NaS–KH		2640	851.6	–	–	468.4
KS–NaH		2640	–	851.6	468.4	–
KS–KH		2640	–	851.6	–	468.4
NaS–NaH	0.65	2640	800.0	–	520.0	–
NaS–KH		2640	800.0	–	–	520.0
KS–NaH		2640	–	800.0	520.0	–
KS–KH		2640	–	800.0	–	520.0
NaS–NaH	0.75	2640	754.3	–	565.7	–
NaS–KH		2640	754.3	–	–	565.7
KS–NaH		2640	–	754.3	565.7	–
KS–KH		2640	–	754.3	–	565.7
NaS–NaH	0.85	2640	713.5	–	606.5	–
NaS–KH		2640	713.5	–	–	606.5
KS–NaH		2640	–	713.5	606.5	–
KS–KH		2640	–	713.5	–	606.5

The geopolymer pastes were produced using a laboratory mixer. For each mixture, the required amounts of hydroxide and silicate solutions were determined according to the designated H/S ratio and combined with GGBFS. The constituents were mixed until a uniform paste with no visible segregation was obtained. Following mixing, the fresh paste was immediately placed into the molds and compacted to minimize entrapped air and ensure proper filling. The molded specimens were subsequently stored under ambient laboratory conditions (25 ± 2 °C) for 28 days prior to testing. The overall sequence of paste preparation and specimen production is illustrated in Figure 3.

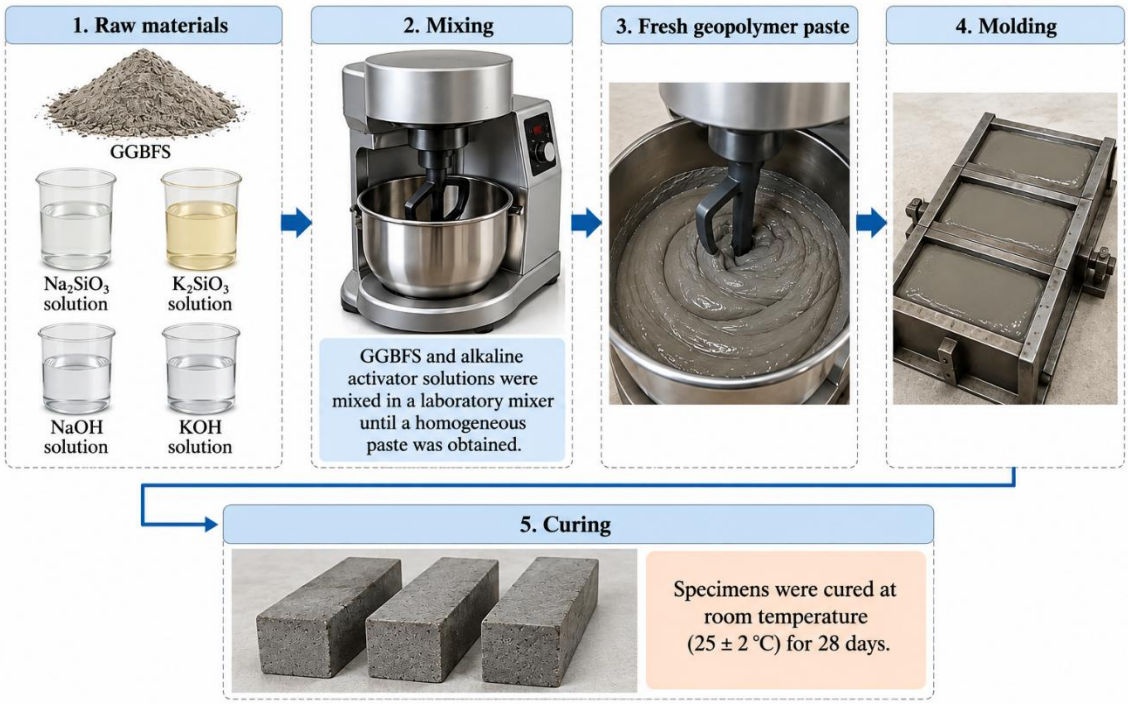


Figure 3. Schematic illustration of the preparation process for GGBFS-based geopolymer pastes

Test Procedures

The workability of fresh GGBFS-based geopolymer pastes was evaluated using the mini-slump method proposed by Kantro (1980). Following paste preparation, the mini-slump cone was filled and subsequently lifted vertically, allowing the material to spread freely on a level surface. The spread diameter was measured in two perpendicular directions, and their mean value was reported as the mini-slump flow. The same procedure was applied to all mixtures to evaluate changes in workability associated with the activator system and H/S ratio.

The flexural strength of the geopolymer pastes was determined after 28 days of ambient curing in accordance with TS EN 196-1. Prismatic specimens measuring 40×40×160 mm were subjected to three-point bending, and the maximum load reached at failure was recorded to determine the flexural strength. The specimens split into two halves during the flexural test were subsequently used to determine the compressive strength. Following the flexural test, compressive strength tests were conducted on the 40×40 mm sections of the fractured specimens in accordance with TS EN 196-1. The specimens were loaded until failure, and the compressive strength was calculated from the maximum applied load and the loaded area. In addition, the 28-day water absorption of the mixtures was determined on prismatic specimens measuring 40×40×160 mm in accordance with ASTM C642. The absorption values were calculated based on the mass difference between the dry and water-saturated specimens.

RESULTS AND DISCUSSION

Fresh-State Properties

Figure 4 presents the spread diameter results of GGBFS-based geopolymer pastes prepared with different alkaline activator combinations and hydroxide-to-silicate ratios. The spread diameters varied between 8.00 and 12.60 cm, depending on the activator composition and H/S ratio. Increasing the H/S ratio from 0.55 to 0.85 improved workability in all mixtures, with increases of 18.75%, 11.50%, 10.53%, and 9.57% for NaS–NaH, NaS–KH, KS–NaH, and KS–KH, respectively. Since the total activator content was kept constant, increasing the H/S ratio reduced the proportion of silicate solution in the mixtures. This reduction may decrease the concentration of soluble silicate species and suppress the rapid development of aluminosilicate gel structures during the early stages of activation. Previous studies have reported that increasing silicate content promotes gel polycondensation and structural buildup, thereby increasing mixture viscosity and reducing flowability (Provis and Van Deventer, 2009; Tekle et al. 2021; Moolchandani, 2025). Accordingly, the higher spread diameters observed at elevated H/S ratios can be associated with reduced silicate-induced particle interactions and improved mobility of the fresh paste.

The type of alkaline activator also significantly influenced workability. At H/S = 0.55, replacing NaH with KH in NaS-based mixtures increased the spread diameter by 25.00%, while replacing NaS with KS in NaH-based mixtures produced an increase of 18.75%. At an H/S ratio of 0.85, the KS–KH mixture exhibited the highest spread diameter of 12.60 cm, whereas the NaS–NaH mixture showed the lowest value of 9.50 cm. This trend was consistently observed across all investigated H/S ratios. This difference may be attributed to the distinct physicochemical behavior of Na^+ and K^+ ions during alkaline activation. Owing to its smaller ionic radius and higher charge density, Na^+ can influence the dissolution and early reaction kinetics of aluminosilicate species differently from K^+ (Siciliano et al. 2025). The accelerated early-stage structural development in sodium-based systems may contribute to reduced paste flowability. Moreover, previous research has reported differences in the viscosity and reaction behavior of sodium- and potassium-silicate solutions (Mundra et al. 2023). The higher water content of the K_2SiO_3 solution (60.3%) compared with Na_2SiO_3 (53.1%) may further contribute to the improved workability of KS-containing mixtures (Table 3). Consequently, the combination of potassium silicate and potassium hydroxide appears to provide more favorable fresh-state characteristics, whereas the NaS–NaH system exhibits the lowest spread diameters throughout the investigated H/S range.

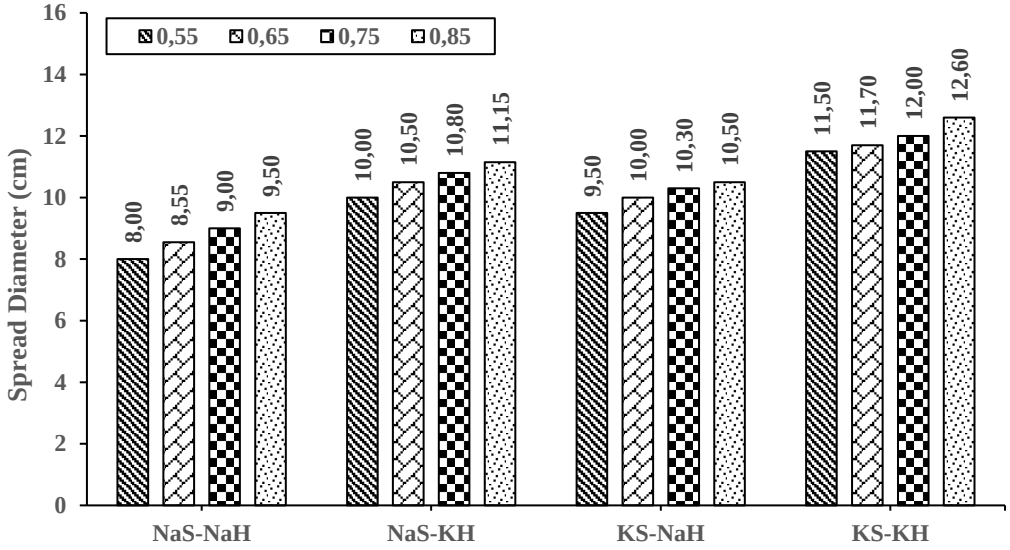


Figure 4. Spread diameter of GGBFS-based geopolymer pastes

Hardened-State Properties

Figures 5 and 6 illustrate the compressive and flexural strengths of GGBFS-based geopolymer pastes prepared with different alkaline activator combinations and hydroxide-to-silicate ratios. Both mechanical properties were strongly influenced by activator composition and H/S ratio.

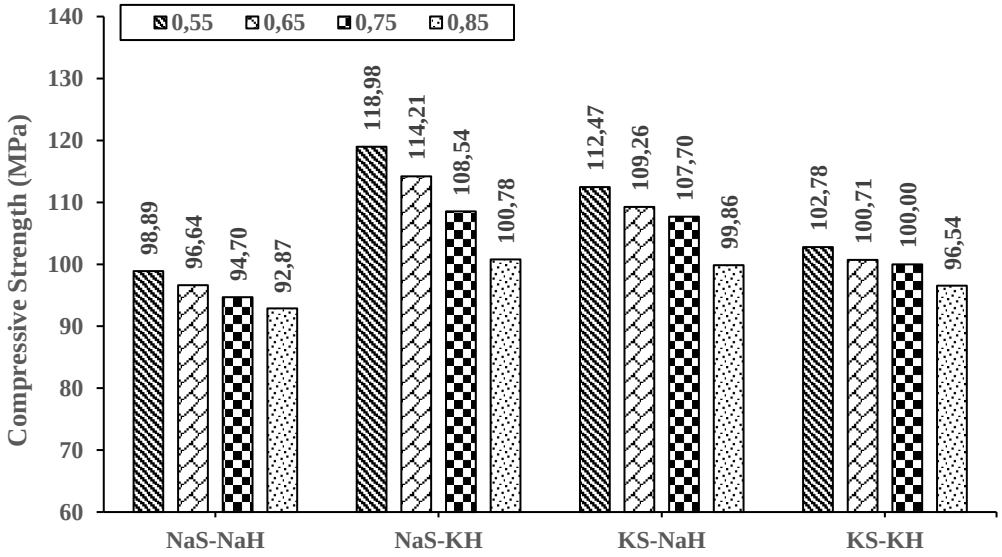


Figure 5. Compressive strength results for different alkaline activator combinations and H/S ratios

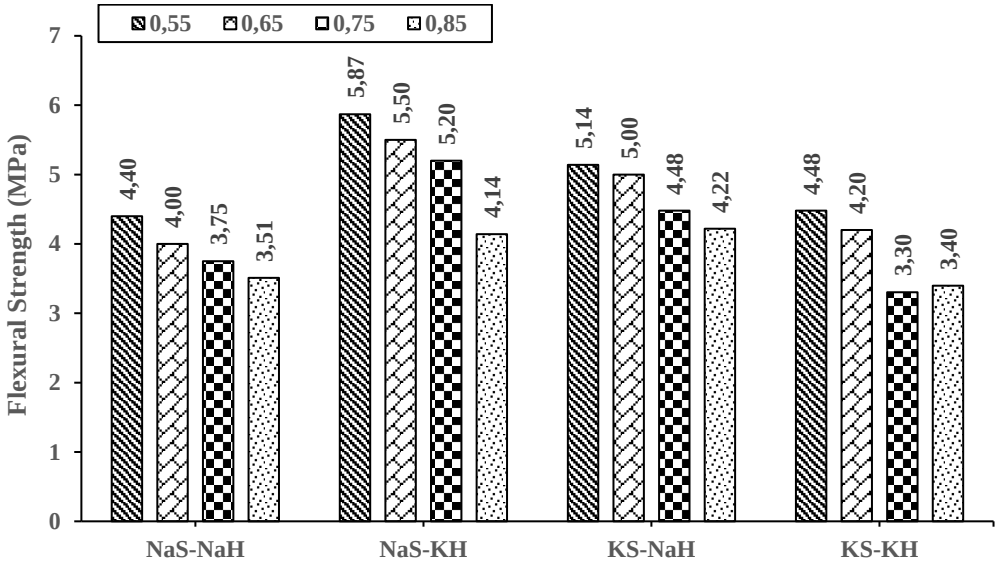


Figure 6. Flexural strength results for different alkaline activators and H/S ratios

Increasing the H/S ratio from 0.55 to 0.85 consistently reduced compressive strength across all activator systems. The corresponding reductions were 6.09%, 15.30%, 11.21%, and 6.07% for NaS–NaH, NaS–KH, KS–NaH, and KS–KH, respectively. The highest compressive strength of 118.98 MPa was achieved by the NaS–KH mixture at H/S = 0.55, whereas the lowest value of 92.87 MPa was recorded for NaS–NaH at H/S = 0.85. At H/S=0.55, replacing NaH with KH in sodium silicate-based mixtures increased compressive strength by 20.32%, demonstrating the beneficial effect of combining sodium silicate with potassium hydroxide. At the same ratio, the NaS–KH mixture also exhibited 5.79% higher compressive strength than KS–NaH and 15.76% higher strength than KS–KH.

As illustrated in Figure 6, the NaS–KH mixture exhibited the highest flexural strength of 5.87 MPa at H/S=0.55, exceeding the corresponding NaS–NaH, KS–NaH, and KS–KH mixtures by 33.41%, 14.20%, and 31.03%, respectively. This superior performance may be attributed to the formation of a more cohesive and interconnected hybrid aluminosilicate gel network in the NaS–KH system, which may enhance matrix integrity and restrict microcrack propagation under flexural loading. Nader et al. (2026) and Marjanović et al. (2015) reported that hybrid aluminosilicate gel structures can enhance matrix integrity and refine pore structure, thereby improving mechanical performance. However, increasing the H/S ratio from 0.55 to 0.85 resulted in flexural strength reductions ranging from 17.90% to 29.47% across all activator combinations. The reduced silicate availability at higher H/S ratios may limit gel connectivity and increase the susceptibility of the matrix to crack initiation (Priyadarshini et al. 2026). In contrast, the KS–KH mixtures exhibited a non-monotonic response, with flexural strength decreasing from 4.48 to 3.30 MPa up to H/S=0.75, followed by a slight recovery to 3.40 MPa at H/S=0.85. The comparatively lower flexural performance of potassium silicate-based mixtures may be related to differences in gel structure and continuity, as discussed in previous studies (Xu and Van Deventer, 2000; Wong et al. 2021).

The reduction in mechanical strength with increasing H/S ratio may be associated with the decreasing availability of soluble silicate species as the proportion of silicate solution decreases. An adequate supply of soluble silica is essential for the development of calcium-rich aluminosilicate binding gels, particularly C-A-S-H and related hybrid gel structures, which contribute to matrix densification and mechanical strength (Liu et al. 2025). Consequently, reducing the silicate content may limit gel connectivity and produce a less compact binding matrix. The superior compressive and flexural strengths of NaS–KH mixtures may be attributed to the favorable interaction between sodium silicate and potassium hydroxide, promoting a balanced dissolution and gel formation process. As discussed in previous studies, differences in Na^+ and K^+ ionic characteristics can influence reaction kinetics and the organization of binding products (Siciliano et al. 2025).

The water absorption results (Figure 7) reveal significant differences in water absorption characteristics among the alkaline activator systems. NaS–KH maintained the lowest water absorption values throughout the investigated H/S range (9.27%–9.71%), whereas the highest value of 11.54% was observed for NaS–NaH at an H/S ratio of 0.85. The lower water absorption of NaS–KH mixtures may

indicate a denser matrix with fewer interconnected pores, thereby limiting water penetration. Moreover, the relatively small increase in water absorption observed in the NaS–KH system demonstrates that these favorable pore characteristics are largely maintained despite variations in the H/S ratio. Notably, the NaS–KH mixture at H/S = 0.55 exhibited the lowest water absorption alongside the highest compressive strength, demonstrating an inverse relationship between these properties. Previous studies have demonstrated that changes in the pore structure of alkali-activated slag binders are influenced by the chemical composition of alkaline activators, which affects the formation and characteristics of binding gels (Cen et al. 2024). As the H/S ratio increased from 0.55 to 0.85, water absorption showed a relative increase of 4.75% to 13.94% across all activator combinations.

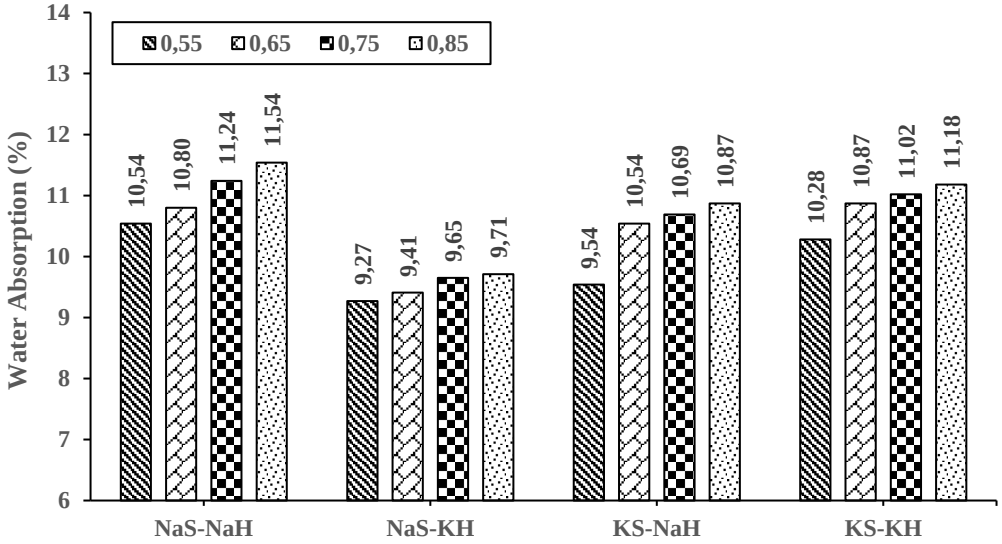


Figure 7. Water absorption of geopolymer pastes

CONCLUSIONS

This study investigated the combined effects of alkaline activator composition and H/S ratio on the fresh-state properties, mechanical performance, and water absorption of GGBFS-based geopolymer pastes. The findings demonstrate that activator selection and solution proportions must be considered together to achieve a suitable balance between workability, strength, and resistance to water absorption. The main conclusions are summarized as follows:

- The superior flowability of KS–KH mixtures highlights the potential of potassium-based activators to improve fresh-state workability. Increasing the H/S ratio from 0.55 to 0.85 enhanced the flow diameter by 9.57–18.75% across all mixtures, indicating that higher hydroxide proportions generally improve the workability of GGBFS-based geopolymer pastes.

- The NaS–KH mixtures generally exhibited superior mechanical performance, highlighting the important role of activator chemistry in the strength development of GGBFS-based geopolymer matrices. However, increasing the H/S ratio from 0.55 to 0.85 reduced compressive strength by 6.07–15.30% across the investigated mixtures, demonstrating the adverse effect of higher hydroxide proportions on mechanical performance.

- Mixed sodium–potassium activator systems generally exhibited favorable mechanical performance compared with the investigated single-alkali systems, highlighting the potential benefits of combining different alkali activators.

- Among the investigated mixtures, the NaS–KH system consistently exhibited the lowest water absorption values, ranging from 9.27% to 9.71% across the investigated H/S ratios. Increasing the H/S ratio from 0.55 to 0.85 increased water absorption by 4.75–13.94% across all mixtures. These findings suggest a potentially more favorable pore structure in the NaS–KH system, although further microstructural investigations are required to confirm this interpretation.

- Overall, an H/S ratio of 0.55 provided the most favorable mechanical strength and water absorption performance within the investigated range, whereas higher H/S ratios improved flowability.

These findings highlight the importance of balancing fresh-state workability and hardened-state performance when selecting the activator composition for GGBFS-based geopolymer pastes.

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