

2025

NaOH Molarity Effect on Mechanical and Hydrochloric Acid Resistance of Geopolymer Mortar Based on Slag

Mahmoud Ziada

Department of Civil Engineering, Istanbul Aydin University, Istanbul, Türkiye,
mahmoudm.s.ziada@aydin.edu.tr

Zahraa Mohammed Kamil Al-Mayali

Department of Civil Engineering, Istanbul Aydin University, Istanbul, Türkiye,
zmohammedalmayali@stu.aydin.edu.tr

Follow this and additional works at: <https://commons.yildiz.edu.tr/jscmt>



Part of the [Biomaterials Commons](#), [Chemical Engineering Commons](#), [Civil and Environmental Engineering Commons](#), [Engineering Science and Materials Commons](#), [Materials Science and Engineering Commons](#), [Mechanical Engineering Commons](#), and the [Molecular, Cellular, and Tissue Engineering Commons](#)

Recommended Citation

Ziada, Mahmoud and Al-Mayali, Zahraa Mohammed Kamil (2025) "NaOH Molarity Effect on Mechanical and Hydrochloric Acid Resistance of Geopolymer Mortar Based on Slag," *Journal of Sustainable Construction Materials and Technologies*: Vol. 10: Iss. 2, Article 8.

<https://doi.org/10.29187/2458-973X.1184>

Available at: <https://commons.yildiz.edu.tr/jscmt/vol10/iss2/8>

This Research Article is brought to you for free and open access by YTU Press. It has been accepted for inclusion in Journal of Sustainable Construction Materials and Technologies by an authorized editor of YTU Press.



RESEARCH ARTICLE

NaOH Molarity Effect on Mechanical and Hydrochloric Acid Resistance of Geopolymer Mortar Based on Slag

Mahmoud Ziada[✉]*, Zahraa Mohammed Kamil Al-Mayali[✉]

Department of Civil Engineering, Istanbul Aydin University, Istanbul, Türkiye

ABSTRACT

The present research investigates the influence of different sodium hydroxide (NaOH) molarities on the mechanical characteristics and hydrochloric acid (HCl) resistance of geopolymer grouts manufactured from ground granulated blast-furnace slag (GGBS). Geopolymer mortars have attracted interest as sustainable substitutes for traditional cementitious materials due to their advantageous environmental effects and enhanced durability features. This study involved the fabrication of geopolymer mortar specimens by altering the NaOH molarity (M) from 6 M to 14 M. The mechanical and physical qualities were assessed using compressive strength, capillary water absorption, flexural strength, slump flow, and ultrasonic pulse velocity (UPV) tests. Subsequently, the geopolymer mortar specimens with various molarities were exposed to 5% HCl to evaluate the HCl resistance of these specimens by subjecting the specimens to a 5% HCl solution for 28 days. Compressive strength, microstructural analysis, flexural strength, UPV, and mass changes tests were also conducted after 14 and 28 days of exposure to HCl. The results indicate that the molarity of NaOH substantially affects both mechanical strength and resistance to acid degradation. After 28 days of HCl exposure, an increase of 59.63% was observed in the compressive strength of the 10 M containing sample compared to the 6 M containing sample, while this increase decreased to 43.84% in the 14 M sample. This work highlights the essential significance of NaOH molarity in optimizing geopolymer formulations for use in harsh settings, providing insights into the equilibrium between strength enhancement and durability.

Keywords: Molarity, Hydrochloric acid, Geopolymer, GGBS, Mechanical properties

1. Introduction

Ordinary Portland cement (OPC) is the primary raw material in concrete and building materials. However, the manufacturing of Portland cement inflicts significant damage on the environment. A considerable amount of carbon dioxide is produced by burning fossil fuels and cement production [1], which react and progressively become detrimental to all living organisms. Consequently, the quantity of cement in concrete should be diminished or substituted with various alternatives such as fly ash, GGBS, and nano-silica to mitigate pollution. Cement production

sectors lack sustainability due to their dependence on non-renewable raw materials. Joseph Davidovits initially proposed the notion of a geopolymer in 1978 [2], and it represents a distinctive substance. The main properties of geopolymers, including their setting time and strength, are greatly influenced by alumina-silica proportions in the mixture design [3]. Geopolymer composites have a wide range of uses in the membrane materials, coatings, metallurgy, remediation, and transportation industries [4–6]. A prior study [7] found that at a pressure of 70 MPa, geopolymers demonstrated a reduction in emissions of greenhouse gases of 166.36 kg CO₂/m³, accounting

Received 18 March 2025; revised 28 April 2025; accepted 12 May 2025.
Available online 30 June 2025

* Corresponding author.

E-mail addresses: mahmoudm.s.ziada@aydin.edu.tr (M. Ziada), zmohammedalmayali@stu.aydin.edu.tr (Z. M. K. Al-Mayali).

<https://doi.org/10.29187/2458-973X.1184>

2458-973X/© 2025 Published by Yıldız Technical University Press, İstanbul, Türkiye. This is an open access article under the CC BY-NC 4.0 Licence (<https://creativecommons.org/licenses/by-nc/4.0/>).

for approximately 62.73% of carbon emissions. Consequently, carbon dioxide emissions from geopolymer production are decreased relative to those of Portland cement while preserving comparable compressive strength. In addition, geopolymers based on GGBS and other binders have emerged as competitive and sustainable substitutes for traditional Portland cement in the construction materials sector [8]. Such options can reduce environmental effects while concurrently improving mechanical qualities. It is worth noting that geopolymer has a propensity for brittleness, with a fracture energy of about 40% of that of OPC [9].

A prior study [10] analyzes the molarity of sodium hydroxide, varying from 2 M to 16 M. They observed that the mechanical properties of geopolymer specimens are enhanced by elevated NaOH molarity. Also, they found that nano-silica degradation is distinctly evident in active specimens with varying concentrations of NaOH solution. In the presence of low molar pH solutions, geopolymer samples exhibit superior early strength compared to cementitious composites, and this is crucial when utilizing them as they regulate the interval between adhesion and strength development [11]. The literature discusses the impact of NaOH molarity, the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio, the molar ratios of $\text{SiO}_2/\text{Na}_2\text{O}$ in the activating solution, and the $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ ratio in the overall activated mixture. There exists variability and contradiction in the findings documented in the literature [12–17]. A study established that a mass ratio of Na_2SiO_3 to NaOH of 2.5 in the activating solution is optimal for generating stable fly ash-based geopolymers [18]. The ideal $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio for fly ash-based geopolymer is anticipated to be between 0.67 and 1.0, with NaOH concentrations varying from 10 M to 20 M [19]. A study on fly ash-based geopolymers established that the greatest strength was attained with a $\text{Na}_2\text{SiO}_3/\text{NaOH}$ mass ratio 2.0 [20]. The optimal strength in fly ash-based geopolymers has been achieved with a $\text{SiO}_2/\text{Na}_2\text{O}$ oxide ratio of 0.69 in the activation solution [21]. The amount of NaOH needed in the activation solution is contingent upon the specific type of fly ash utilized [22]. Another study [23] investigated the feasibility of creating sustainable self-consolidating concrete using a geopolymer binder and repurposed aggregates. The research examined the impact of four concentrations of NaOH (8, 10, 12, and 14 M) on the fresh characteristics of self-consolidating concrete. Eight concrete mixtures based on GGBS were evaluated, four utilizing natural aggregate and four employing recycled aggregate. The results show that recycled aggregate and NaOH molarity affect the fresh properties, but it is possible

to develop self-consolidating concrete that meets the EFNARC limits [24].

It has been essential to investigate the effects of durability, such as the effects of acid on geopolymers. The swift advancement of global industrialization has resulted in significant environmental contamination and deterioration, eliciting widespread social concern, particularly over the issue of acid rain [25, 26]. The acid rain environment pertains to precipitation, such as rain and snow, with pH values below 5.6, resulting in a mildly acidic or acidic situation [27]. In a rainy climate, all geotechnical engineering materials are influenced by exterior stresses and chemical erosion during their service life [28]. Acidic conditions will deteriorate geotechnical engineering materials' physical and mechanical qualities [29]. A prior work [30] examined the compressive strength and electrochemical impedance spectroscopy of red coal metakaolin geopolymer immersed in a high-concentration HCl solution (pH value 2). They found that the geopolymer's compressive strength initially increased and then declined with prolonged immersion in an HCl solution. Also, they found that at an immersion duration of 14 days, the compressive strength peaked at 39.3 MPa [30].

Previous research has mainly focused on improving the mechanical properties of geopolymer concrete by using various industrial by-products and alkali activators. Arunachalam et al. [31] investigated the application of copper slag as a substitute for fine aggregate in geopolymer concrete and evaluated its mechanical and microstructural characteristics under ambient curing conditions. Their findings indicated that the complete replacement of fine aggregate with copper slag and elevated NaOH molarity markedly improved strength and matrix density. Aziz et al. [32] investigated the influence of NaOH concentration and CaO–Si constituents on the mechanical properties of GGBFS-based geopolymers. Their findings indicated that a 10 M NaOH solution yielded excellent compressive strength, corroborated by the development of calcium silicate hydrate and calcium carbonate phases inside the microstructure. Hanjitsuwan et al. [33] investigated the effects of different NaOH concentrations on the physical and electrical characteristics of high-calcium fly ash geopolymer pastes. Elevated NaOH concentrations improved compressive strength and conductivity by promoting geopolymerization and the dissolution of reactive species from the fly ash. Verma and Dev [34] examined the impact of NaOH molarity and alkaline ratio on the mechanical characteristics of fly ash–slag-based geopolymer concrete. Their findings indicated that a 14 M NaOH solution and a $\text{Na}_2\text{SiO}_3/\text{NaOH}$

Table 1. Chemical proportions of GGBS (%).

Materials	Loss of Ignition	Na ₂ O	Fe ₂ O ₃	MgO	Al ₂ O ₃	CaO	SiO ₂
GGBS	0.03	0.79	1.1	5.87	12.83	35.58	40.55

ratio of 2.5 produced maximum strength, especially under oven-curing conditions. Younis [23] examined the influence of different NaOH molarities on the fresh characteristics of self-compacting slag-based geopolymer concrete using recycled aggregate. The research established that NaOH concentration and aggregate type affect workability, yet self-compacting concrete that complies with EFNARC criteria can still be effectively produced. Although previous studies have examined the impact of alkaline activators on geopolymer systems, the precise function of NaOH in augmenting molarity to improve the chemical durability of slag-based geopolymers is still inadequately comprehended. Notably, there is a significant deficiency of research examining the impact of NaOH concentration fluctuations on the resistance of slag-based geopolymers to acidic environments, particularly hydrochloric acid, which has received less attention than sulfuric acid.

Numerous studies have examined the influence of NaOH molarity on the mechanical and microstructural characteristics of geopolymer systems, predominantly concentrating on fly ash matrices, frequently under heat curing conditions. Furthermore, whereas durability factors like sulfuric acid resistance have been examined, the effect of NaOH molarity on the HCl resistance of slag-based geopolymers is yet inadequately investigated. This study seeks to fill this gap by analyzing the impact of different NaOH molarities on the compressive strength and HCl resistance of slag-based geopolymers cured at ambient conditions. In addition, this work explicitly examines NaOH content's effect on the HCl resistance of slag-based geopolymers during ambient curing, a topic seldom explored in prior research. Incorporating strength assessments, mass loss evaluations, and microstructural research offers an extensive perspective on acid durability associated with activator concentration. This research examines GGBS-based geopolymer grout specimens activated with varying molarities of NaOH and subjected to a 5% HCl solution for 28 days to reduce this gap. This study introduces a fresh methodology by investigating the impact of different NaOH molarities on the mortar's resistance to acid assault. This subject has not been thoroughly explored in previous studies. Compressive strength tests, water absorption assessments, and scanning electron microscopy (SEM) evaluated the physical, mechanical, and microstructural characteristics. The results provide novel insights into the reactions of

Table 2. The chemical proportions of Na₂SiO₃ (%).

Na ₂ O	Density (g/ml) 20 °C	Heavy metals	SiO ₂	Fe
9.6	1.36	≤ 0.005	26.5	≤ 0.005

Table 3. The chemical proportions of NaOH (%).

SO ₄ (%)	Fe (%)	Cl (%)	NaOH	Al (%)	Na ₂ CO ₃
≤ 0.01	≤ 0.002	≤ 0.01	99	≤ 0.002	0.4

GGBS-based geopolymer grouts under acidic settings, with implications for enhancing their durability in severe chemical environments.

2. Materials and approaches

2.1. Used materials

In this study, GGBS was used as a binder, and the chemical composition of the binder is illustrated in Table 1. NaOH and Na₂SiO₃ were utilized as catalysts in the geopolymer formulations, and the mechanical characteristics of the activators appear in Table 2 and Table 3. HCl was used as an acidic medium to study the acid resistance. The images of GGBS, sand, and NaOH solutions used in geopolymer mortar are shown in Fig. 1.

2.2. Mix ratios and production of geopolymer samples

To generate 6, 8, 10, 12, and 14 M NaOH solutions, 0.12, 0.16, 0.20, 0.24, and 0.28 kg of NaOH were added to a 500 ml volumetric flask, which was then filled with distilled water to the 500 ml mark. Before preparing the GGBS-based geopolymer mortar in this investigation, NaOH solutions of 6, 8, 10, 12, and 14 M were made and allowed to cool for 24 hours at 20 °C. Subsequently, the NaOH solution was combined with the Na₂SiO₃ solution. This study fixed the Na₂SiO₃ solution to NaOH solution ratio to 2. Subsequently, the sand was combined with the GGBS to produce a dry mixture, to which the activator solution was incorporated. The mixture was blended using a mixing apparatus illustrated in Fig. 2(a) for two minutes until it achieved homogeneity. The mixes were subsequently positioned in pre-lubricated molds measuring 50×50×50 mm and 40×40×160 mm, as shown in Fig. 2(b). Subsequently, the molds were agitated on the shaking table to remove the entrapped



Fig. 1. The constituents that compose geopolymer mortars: (a) GGBS, (b) sand, and (c) NaOH solutions.

air. Finally, the samples were demolded and maintained at 20 ± 2 °C for 28 days. Also, the mixture amounts used in this study are given in Table 4.

2.3. Performed tests

This study evaluated the compressive strength, flexural strength, slump, water absorption, mass change, and UPV tests on geopolymer specimens to

determine the effect of molarity values on the HCl resistance of GGBS-based geopolymer mortar. In all tests performed in this study, three samples from each series were used, and as a result, the averages and error bars of the samples were provided. In addition, SEM analysis was conducted to examine the microstructural features of the samples. A slump flow value test was performed for each mixture made from different molarities (6, 8, 10, 12, 14 M) to determine the consistency of the mix. The mixture was placed in two layers in a conical mold on the surface of the device, and each layer was pounded with a copper-coated wooden hammer. After placement, the table was dropped 25 times by rotating the arm apparatus. Subsequently, the mold was lifted vertically, and then the diffusion diameters were measured in two different directions, and their average was taken. The test for compressive strength was conducted on materials sized $50 \times 50 \times 50$ mm, while the test for flexural strength was executed on samples sized $40 \times 40 \times 160$ mm before immersing in HCl solution. The HCl was diluted to 5%, as illustrated in Fig. 3, and the samples were immersed in it for 28 days at a temperature of 20 °C, as shown in Fig. 4.

The compressive strength test was repeated on the samples exposed to the acid after 14 and 28 days, according to ASTM C109 [35]. Similarly, the flexural strength test was executed on the geopolymer samples before and after being placed in the acid at 14 and 28 days, according to ASTM C348 [36]. In addition, the UPV device shown in Fig. 5(a) was used to conduct the UPV experiment on cubic specimens before and after being placed in the acid at 3, 7, 14, and 28 days according to ASTM C597-16 [37] as shown in Fig. 5(b).

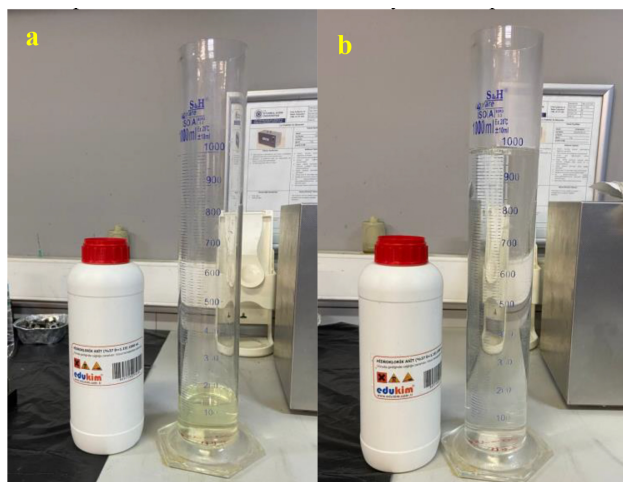
An experiment on capillary absorption of water was carried out on GGBS-based geopolymer specimens using ASTM C1585 [38]. GGBS-based geopolymer sam-



Fig. 2. Geopolymer mortar: (a) during the mixing process and (b) after pouring into the molds.

Table 4. Geopolymer mortar mix design (kg/m³).

Series	Sand	GGBS	Na ₂ SiO ₃	NaOH Solution	Solid NaOH	Water (from NaOH solution)
6 M	1302.5	603	261.3	130.7	17	113.7
8 M	1302.5	603	261.3	130.7	22.2	108.5
10 M	1302.5	603	261.3	130.7	27.4	103.3
12 M	1302.5	603	261.3	130.7	32.7	98
14 M	1302.5	603	261.3	130.7	37.9	92.8

**Fig. 3.** Preparation process of 5% HCl solution: (a) before adding water, and (b) after adding water to HCl.

ples of 40×40×160 mm were dried in an oven at 105 °C for 24 h. Then, the dry weight (Wd) of the specimens was weighed before and after applying vaseline, except for the surface in contact with water and the opposing surface, followed by the dry specimens being immersed in water to a depth of 5 mm, as shown in Fig. 6(a). Then, the specimens were taken from the water as shown in Fig. 6(b), and their wet weight (Ww) was taken after 30 min, 1, 2, 3, 6, 9, 24, 48, and 72 h. Then, the results were analyzed and discussed.

3. Results

3.1. Slump flow values

Notwithstanding their intrinsic limitations, single-point workability assessments are used for quality control and concrete standards. Creating stable mixes with reduced slump has resulted in adopting the flow examination [39]. The slump flow examination is the most commonly employed approach and evaluates exceptional workability. This is used to assess the horizontal deformation of concrete in the absence of obstructions [40]. The slump cone is placed on a non-porous surface and is full of newly mixed concrete in layers, each layer being compacted. After filling the slump cone, it is raised vertically to a considerable

height, allowing the concrete to flow. The diameter of the concrete is ascertained by averaging measurements taken from two perpendicular orientations of the concrete's flow. An increased slump flow signifies an improved ability of the concrete to fill the formwork. Fig. 7 presents the average flow values of the geopolymer mixtures with different molarities. The peak flow of 148.385 mm was achieved for the 6 M contained geopolymer samples. Then, increasing the molarity decreased the flow radius of the fresh mixtures. The flow decreases were 4.15%, 7.39%, 8.07%, and 8.72% for 8 M, 10 M, 12 M, and 14 M, respectively, compared with the 6 M sample.

3.2. UPV findings

UPV test was carried out on geopolymer specimens with 6, 8, 10, 12, and 14 M. The UPV test was conducted to assess the influence of different NaOH molarities on the samples and to ascertain the cohesiveness of GGBS-based geopolymer mortar after 28 days. Fig. 8 illustrates the results of the UPV test conducted on the specimens. The sample matrix, possessing an elevated void count, necessitates a prolonged duration, but the penetration rate diminishes. The vacancy ratio significantly affects the mechanical characteristics of GGBS-based geopolymer samples. Thus, this study determined the highest UPV value achieved at a 10 molarity for GGBS-based geopolymer samples. The UPV values increased by 11.77% compared to 6 molarity and increased by 4.53%, 4.25%, and 3.57% at 7, 14, and 28 days, respectively, compared to 6 molarity of GGBS-based geopolymer samples. The volume of voids in the geopolymer structure and the UPV values demonstrate an inverse correlation [41].

Additionally, this study found that the GGBS-based geopolymer samples exposed to HCl became more compact after 14 days. This can be attributed to the formed product filling the pores. Park et al. [42] consistently reported that the tiny ettringite crystals at the optimal gypsum dose filled the pores.

3.3. Compressive strength

The compressive strength experiment was conducted for geopolymer samples. Three samples for

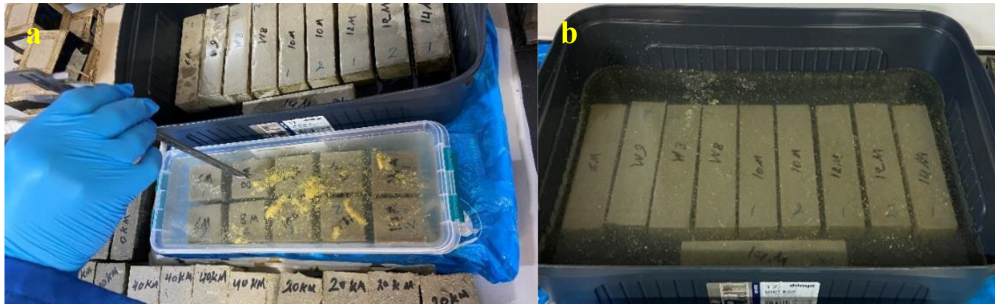


Fig. 4. (a) Cubic and (b) prismatic geopolymer samples placed in HCl solution.



Fig. 5. (a) UPV device and (b) UPV experiment conducted on a cubic sample.



Fig. 6. Water absorption experiment: (a) before and (b) after extracting the samples from the container.

each molarity were used in the test before and after 14 and 28 days of exposure to HCl. This experiment examined the mechanical features of geopolymer specimens of different molarities. The mean outcomes of the collected data were then computed. Fig. 9 depicts the compressive strength outcomes of geopolymer specimens of different molarities before and after 14 and 28 days of exposure to acid. This work concluded that the compressive strength at 10 M is greater compared to 6 M, 8 M, and 14 M samples. Thus, the enhancement in compressive strength values of 8, 10, 12, and 14 M samples compared to 6 M was 26.08, 37.48, 28.83, and 25.02%, respectively. After 14 days of HCl exposure, the increases in the compressive strength outcomes of 8, 10, 12, and 14 M samples compared with 6 M were 24.69, 56.91, 26.01, and 17%, respectively. Also, after 28 days of HCl exposure, the increases in compressive strength results of 8, 10, 12, and 14 M samples compared with 6 M were 29.4, 59.63, 47.61, and 43.84%, respectively. Thus, 10 M, geopolymerization is more pronounced compared to 6 M, leading to the formation of Si-Al gel

due to additional N-A-S-H gel paste crystalline phases, which improve strength properties [43].

Following acid exposure, the compressive strength of the 10 M increased by 91.36% after 14 days relative to its initial strength before acid exposure. The initial rise in compressive strength of slag-based geopolymer mortar after 14 days of HCl exposure, followed by a drop after 28 days, indicates a complex interaction of chemical reactions. The initial increase in strength may arise from various potential mechanisms. Initially, the acid may induce the creation of a silica-rich gel via the dissolving of calcium-based phases, with the liberated silica subsequently settling inside the pore structure, resulting in a denser matrix. Secondly, pore filling and densification may transpire as dissolved constituents re-precipitate within the voids [44]. A third approach is leaching less stable elements and re-precipitating more stable compounds that temporarily augment strength. The development of a dense, silica-rich surface layer from the initial reaction may lead to a perceived enhancement in strength at the 14-day interval. The following

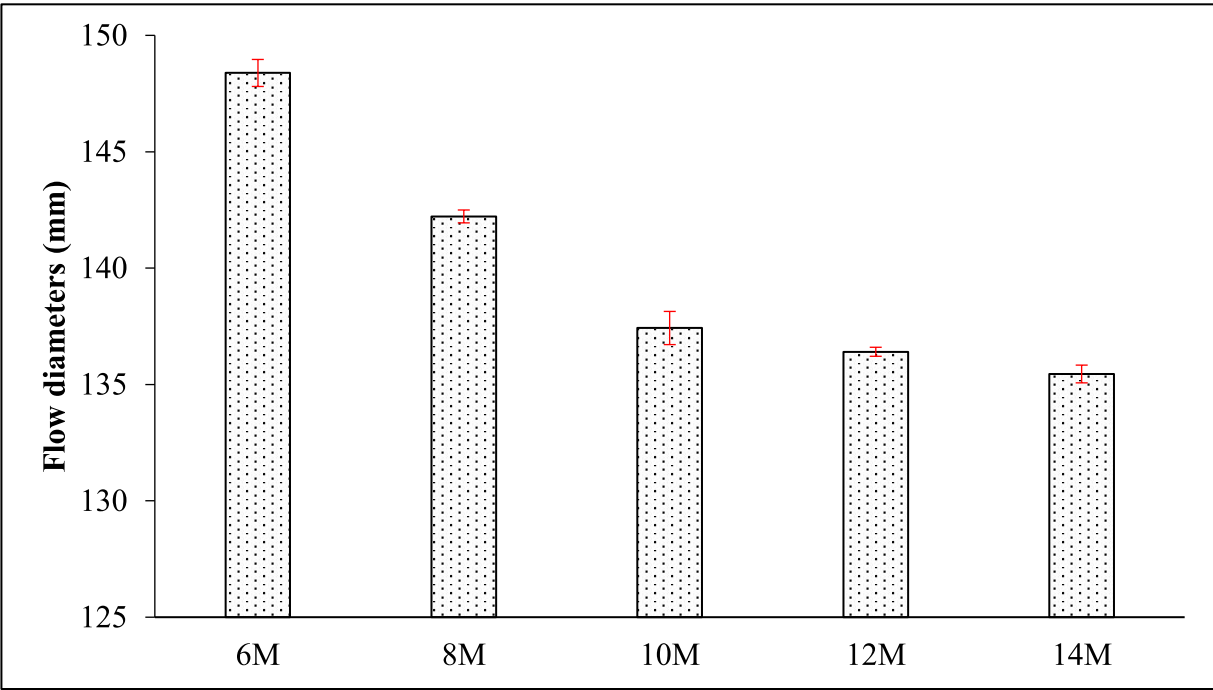


Fig. 7. Average flow diameters of geopolymer mortar mixtures with different molarities.

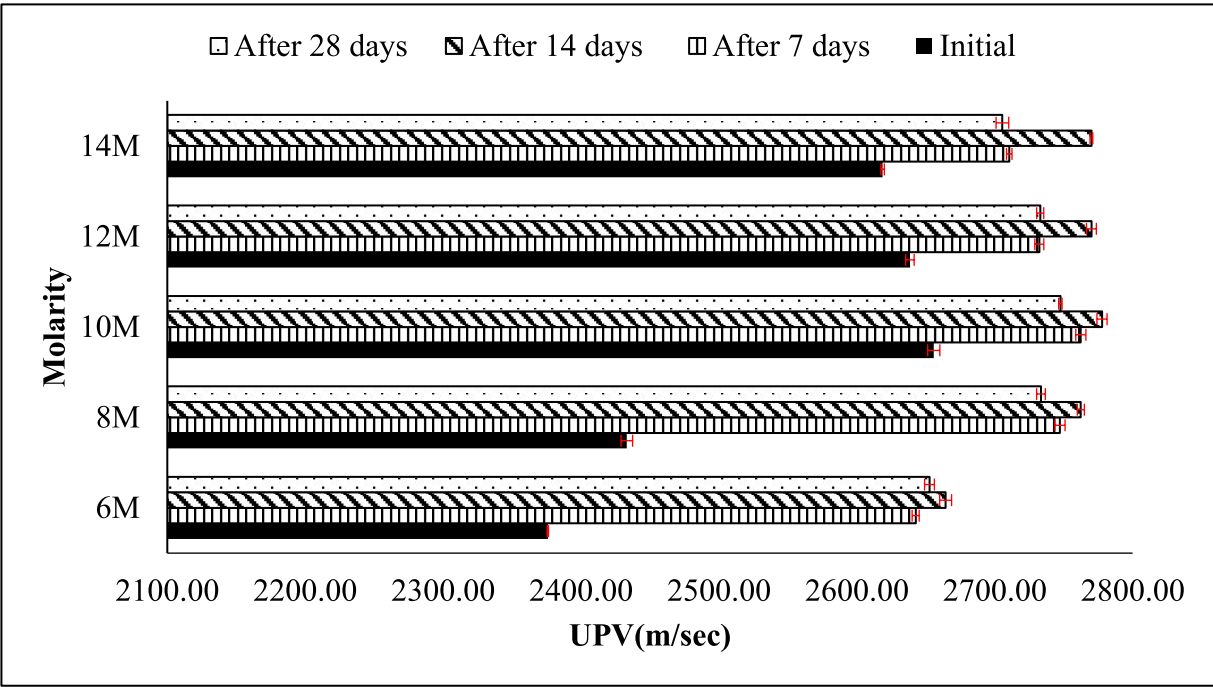


Fig. 8. UPV values of geopolymer samples with different molarities before and after exposure to HCl for 14 and 28 days.

reduction in compressive strength after 28 days suggests that these initial advantageous effects are temporary. Extended contact with HCl likely results in the ongoing dissolving and degradation of the geopolymer matrix, negating any initial densification or fortification. This indicates that the initial

beneficial effects are probably superficial or pertain to the creation of metastable phases. Aygörmez and Canpolat [45] attributed the reason for the higher stability of geopolymers to the presence of the Al-Si-O bridge, which is resistant to acid effects. Subsequently, at 28 days, the compressive strength of the

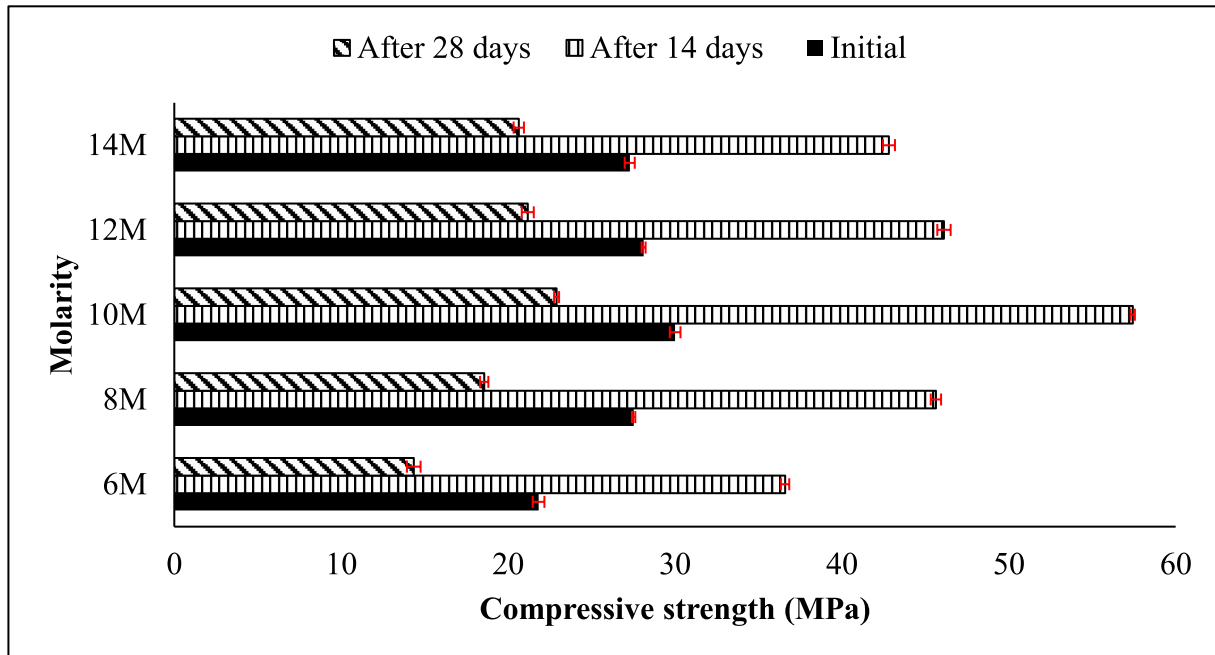


Fig. 9. Compressive strength values of geopolymer samples with different molarities before and after exposure to HCl for 14 and 28 days.

10 M specimen diminished by 23.67% compared to its initial strength at 28 days before acid exposure. The acid exposure of geopolymer composites serves as an expedited durability assessment for determining long-term degradation in a condensed timeframe. In cement, concrete, and geopolymer, HCl is thought to induce microstructural degradation of geopolymer specimens [46, 47].

3.4. Flexural strength

A flexural strength test was performed on geopolymer samples. This experiment examined the mechanical characteristics of geopolymer specimens with varying molarity. The median outcomes of the acquired data were computed. Fig. 10 presents the flexural strength outcomes of geopolymer specimens with varying molarity before and after 14 and 28 days of acid exposure. This study determined that the flexural strength at 10 M exceeds that of the 6 M, 8 M, 12 M, and 14 M specimens. Thus, the increases in flexural strength of the 8 M, 12 M, and 14 M samples before acid, compared to the 6 M sample, were 9.46, 20.16, 4.36, and 1.91%, respectively. The increases of the flexural strength values of 8 M, 10 M, 12 M, and 14 M geopolymer samples compared with 6 M were 5.35, 26.52, 7.53, and 3.71%, respectively, after 14 days of HCl exposure. Also, the increases in flexural strength results of 8 M, 10 M, 12 M, and 14 M geopolymer samples in comparison with 6 M were 13.94, 39.44, 20.33, and 16.37%, respectively,

after 28 days of HCl exposure. Additionally, when compared to the compressive strength of 10 M samples not exposed to HCl solution, the compressive strength of 10M samples exposed to HCl solution for 14 days increased by 12.11%, and the compressive strength of specimens subjected to HCl solution for 28 days increased by 0.87%. Hence, the compressive strength of the geopolymer samples exposed to HCl increased after 14 days, and this increase decreased significantly after 28 days. The flexural strength of slag-based geopolymer mortar first enhances after 14 days of HCl exposure due to silica gel formation, pore densification, and developing a protective silica-rich layer [44]. This enhancement is transient. Prolonged acid exposure for 28 days deteriorates the geopolymer matrix, diminishing its flexural strength. This suggests that initial improvements are superficial or pertain to unstable stages. Chen and Jiang [48] noted that the extent of ettringite production in a sodium sulfate solution occurs in three distinct phases: penetration, strength enhancement, and formation of the macro cracks.

3.5. Mass changes

The mass change test was conducted for the samples immersed in 5% hydrochloric acid. Fig. 11 shows mass change increases of the geopolymer samples with different molarities exposed to HCl for 7, 14, and 28 days. Fig. 11 illustrates that the lowest mass change was obtained from 10 M geopolymer samples.

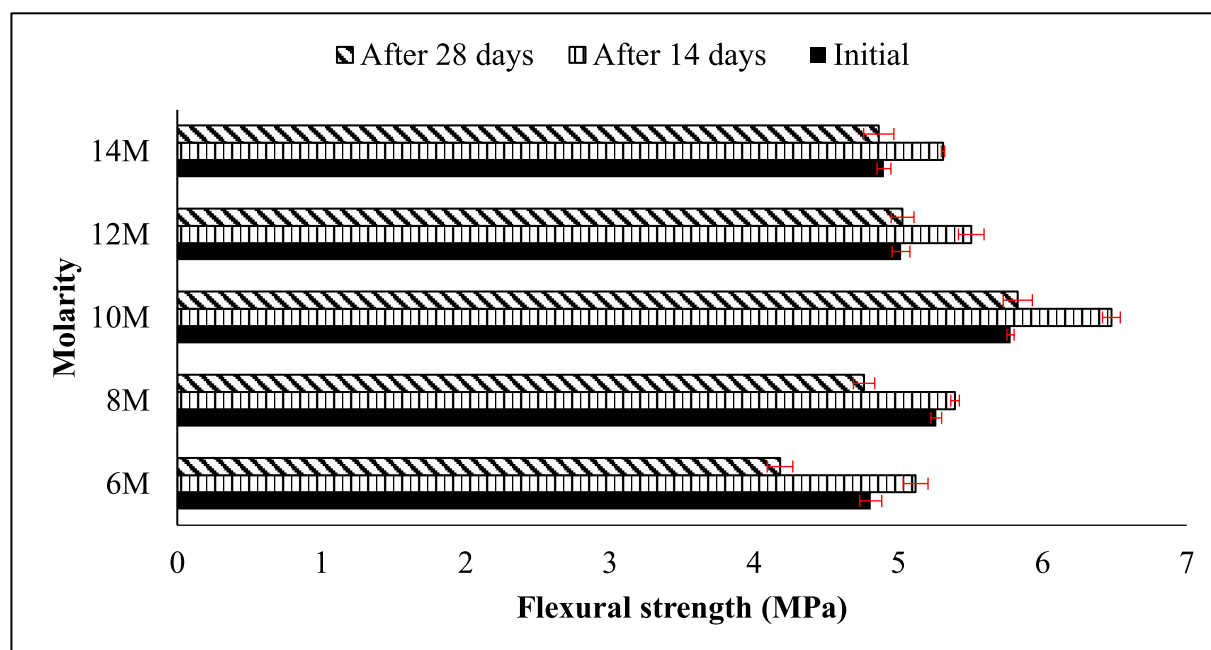


Fig. 10. Flexural strength values of geopolymer samples with different molarities before and after exposure to HCl for 14 and 28 days.

This shows that the 10 M sample is more compact than the other, which is compatible with the strength results. The increases in the mass change values of 10 M geopolymer samples after 7, 14, and 28 days of HCl exposure, compared to 10 M geopolymer samples before HCl exposure, were 2.27%, 2.50%, and 3.82%, respectively. Also, these increases were increased to 2.72%, 3.38%, and 4.39% for 6 M samples and 2.33%, 2.87%, and 4.09% for 14 M samples after 7, 14, and 28 days of HCl exposure, respectively. The low weight change at 10 M of GGBS-based geopolymer samples is attributed to the chemical reaction that produces a strong network of strong chemical bonds between aluminates and silicates, which enhances the cohesion of the materials and increases their resistance to harsh conditions [45].

3.6. Water absorption

Water absorption and capillary absorption of water tests were conducted to assess the porosity of geopolymer mortar samples. The void ratio and water absorption percentages are given in Fig. 12. As Fig. 12 shows, it was found that the 10 M sample had the lowest void ratio and, therefore, the lowest water absorption percentage compared to the other samples. The void ratios of the samples decreased as they increased from 6 M to 10 M, but after 12 M, the void ratios increased again. From here, it can be concluded that the most significant M sample was the 10 compact sample. Fig. 13 shows the capillary

absorption curves of geopolymer specimens with different molarities. Similar findings were found in the water absorption test, where 10 M had the lowest water absorption amount among all series. For a more effective comparison, capillary water absorption coefficients were calculated as given in Fig. 14. The void quantities of the samples decreased as the molarity climbed from 6 M to 10 M, but rose again after reaching 12 M. This may be due to the products formed by HCl and the calcium content of GGBS-based geopolymer samples. Increasing these products can fill the pores, but will subsequently cause the structure of the samples to deteriorate. Prior research [49] indicated that the development of secondary ettringite may result in the swelling and cracking of concrete under certain circumstances. Consistent with the strength results, the samples' strength diminished as water's absorption and porosity augmented [50]. The study's results demonstrated that samples exhibiting high porosity and water absorption yielded reduced compressive strength. The study's results demonstrated that samples exhibiting high porosity and water absorption yielded reduced compressive strength.

3.7. Microstructural analysis

The 10 M sample with the highest strength was selected for SEM analysis. SEM analyses of this sample before, 14 days, and 28 days after acid exposure are given in Fig. 15. The sample showed no significant deterioration in the microstructure when exposed to

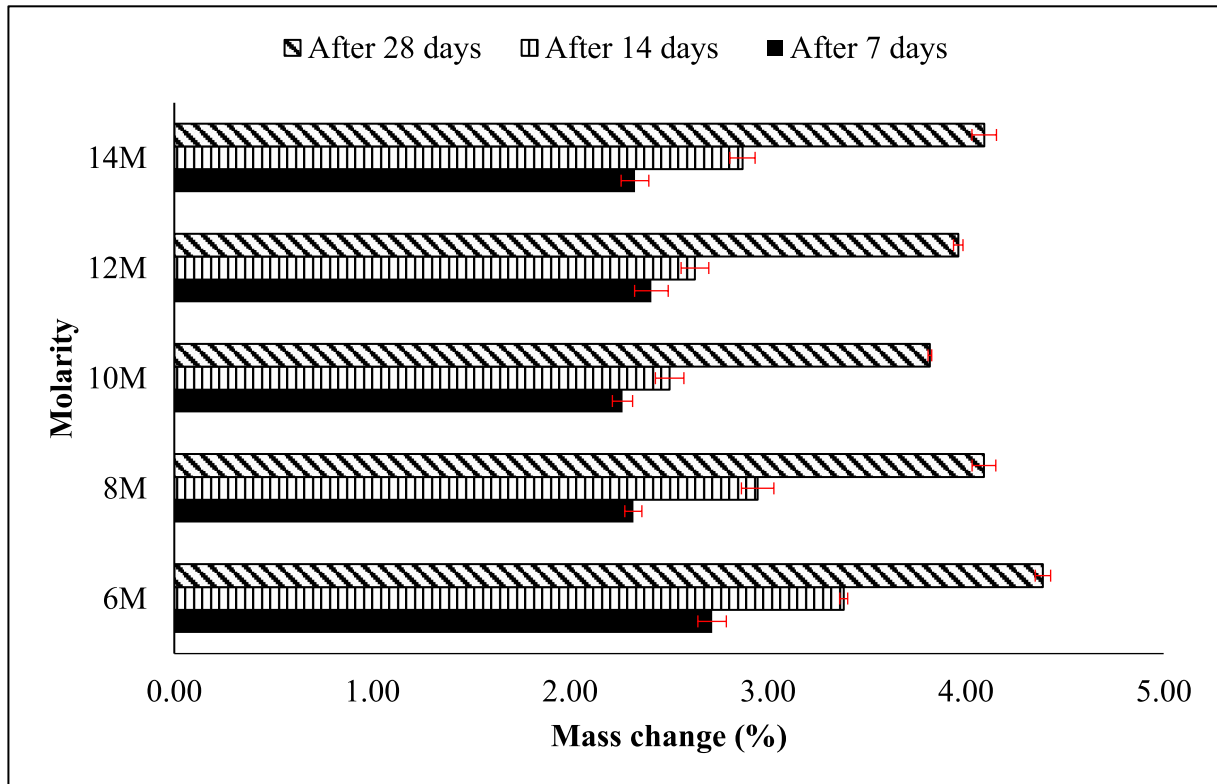


Fig. 11. The mass changes and increases of the geopolymer specimens with different molarities subjected to HCl for 7, 14, and 28 days.

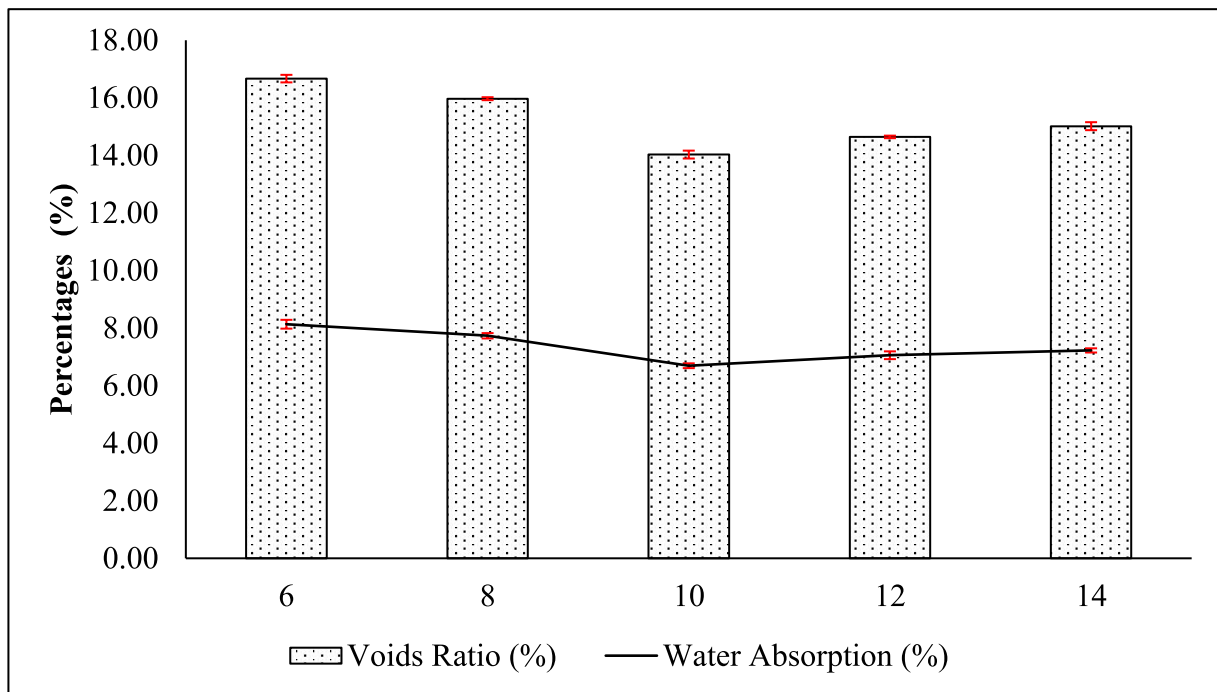


Fig. 12. Void ratio and water absorption percentages of geopolymer mortar specimens based on GGBS.

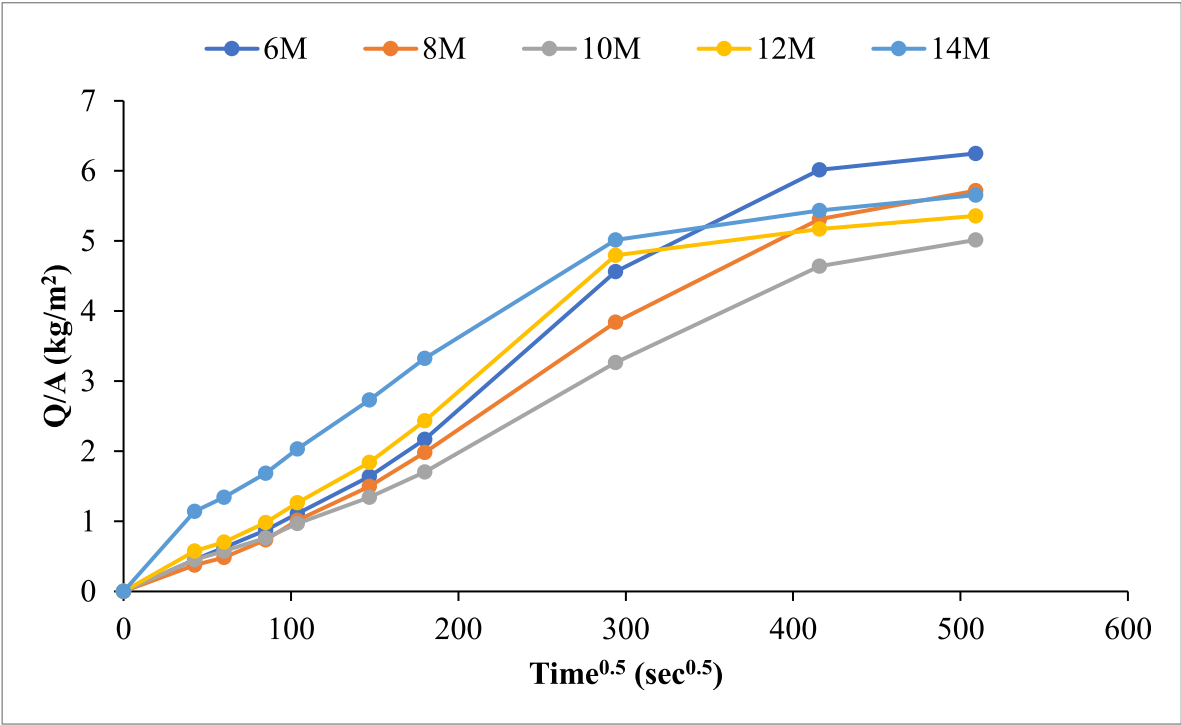


Fig. 13. A mount of absorbed water per square meter of GGBS-based geopolymer specimens with varying molarities of sodium hydroxide.

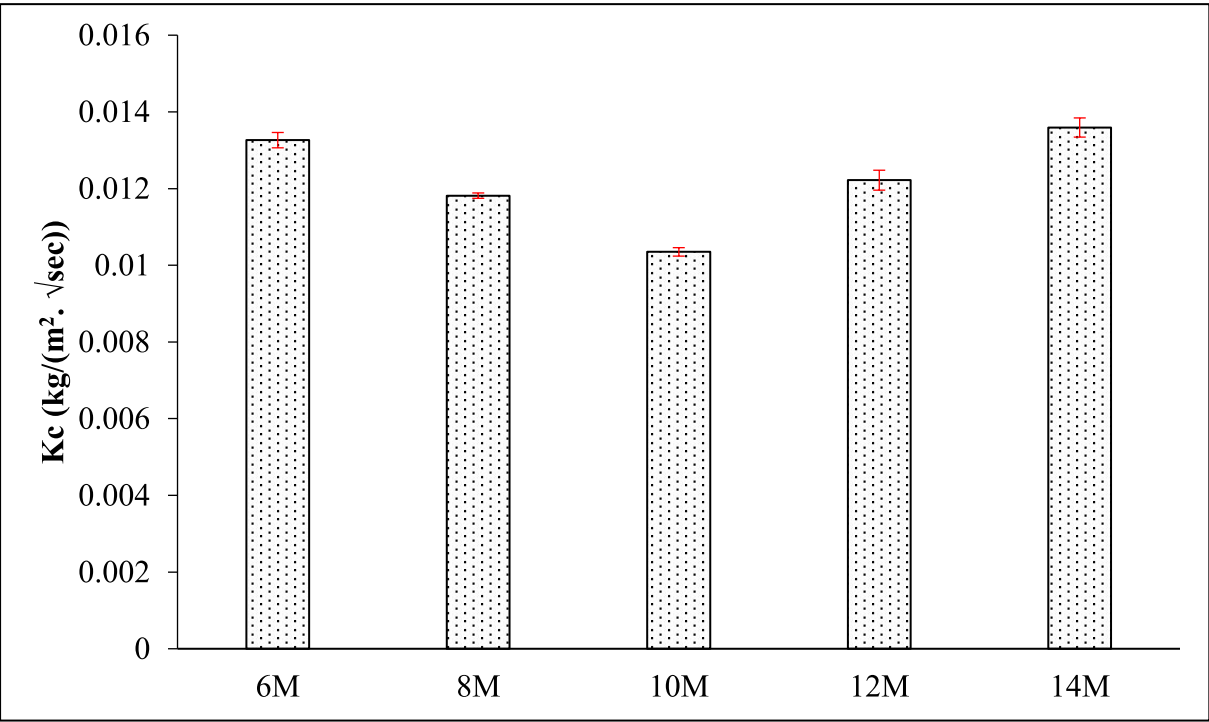


Fig. 14. Capillary water absorption factor (K_c) of geopolymer mortar based on GGBS.

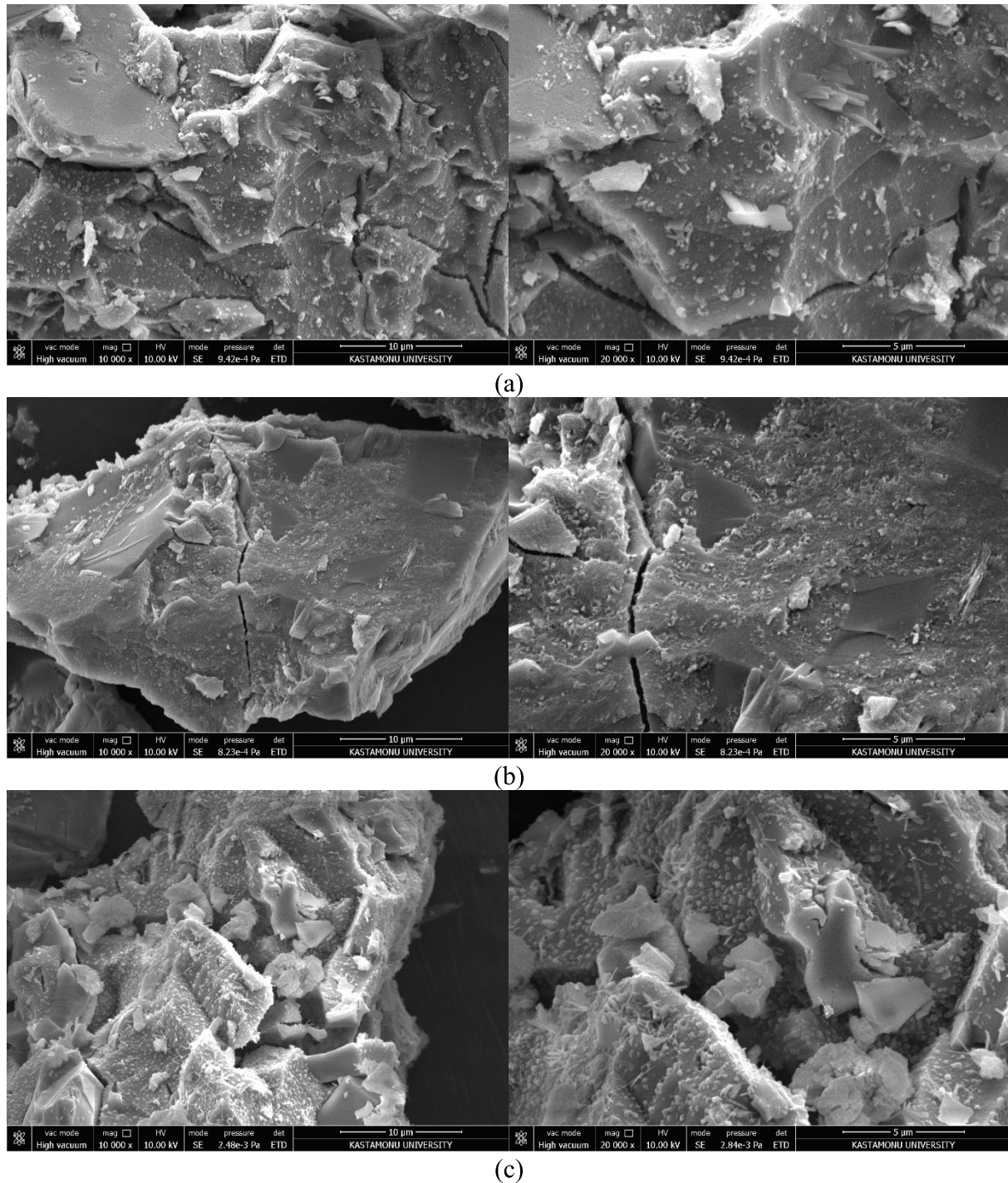


Fig. 15. 10k and 20k x magnification SEM of 10 M sample, a) before exposure to hydrochloric acid, b) after 14 days of exposure to hydrochloric acid, and (c) after 28 days of exposure to hydrochloric acid.

HCl after 14 days. Instead, products formed on the structure of the 10 M sample were exposed to HCl for 14 days, as shown in Fig. 15(b). The geopolymer samples demonstrated a decrease in strength when subjected to hydrochloric acid, attributable to the acid's degradation of the Si-O-Al present in the gel.

These connections amalgamate within the gel to fortify the connections constituting the matrix [51–53].

Additionally, swelling products were formed when the 10 M sample was exposed to HCl for 28 days. As seen in Fig. 15(c), the abundant presence of these products caused the sample to swell and its strength

to decrease. New crystals were discovered inside the microscopic structures of the specimens associated with the gypsum's crystal structure [54, 55]. Gypsum's crystal structure constituted the pale stratum in the specimen post-acid treatment, and the extent of deterioration within the specimen is ascribed to the emergence of an alternative phase of gypsum; therefore, the calcium concentration inside the samples is influenced. Gypsum crystals accelerated fracture creation and reduced strength [56].

4. Conclusion

This research determined that a 10 M NaOH molarity is ideal for GGBS-based geopolymer mortar, yielding the most favorable balance of workability, mechanical strength, and acid resistance. The slump flow test indicated that 6 M samples exhibited the most significant flow, but each molar increase resulted in diminished flow values. Elevated molarity (up to 10 M) led to reduced porosity, augmented compressive strength, and enhanced UPV values, signifying improved matrix cohesiveness. Specimens treated with 10 M NaOH demonstrated the greatest compressive strength at all curing intervals, especially after 28 days, and exhibited remarkable resistance to hydrochloric acid immersion with negligible weight alteration. These findings underscore the significance of NaOH molarity in enhancing the performance of geopolymer concrete, particularly for applications necessitating durability and mechanical strength.

This study examines the effect of NaOH concentration on the strength and HCl resistance of slag-based geopolymers under ambient curing, identifying 10 M as the most optimal molarity. The results indicate enhanced durability at this molarity. Nevertheless, this study did not include Energy Dispersive X-ray Spectroscopy (EDS) and Fourier-Transform Infrared Spectroscopy (FTIR) analyses, which could have offered more information on the geopolymer's elemental composition and molecular bonding. Later research could benefit from using these analyses to build on the findings given. In addition, the study was confined to one acid and slag type, underscoring the necessity for additional research under varied conditions.

Acknowledgement

The authors of this study express their gratitude to the staff of the Civil Engineering Laboratory at Istanbul Aydin University.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

All graphs and data obtained or generated during the investigation appear in the published article.

Funding Statement

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Author Contribution

Mahmoud Ziada: Writing review & editing, Validation, Supervision, Resources, Project administration, Conceptualization, Supervision, Data curation. Zahraa Mohammed Kamil Al-Mayali: Writing review & editing, Writing original draft, Validation, Resources, Methodology, Investigation, Formal analysis.

Ethics

There are no ethical issues with the publication of this manuscript.

References

1. Hanle LJ, Jayaraman KR, Smith JS. CO₂ emissions profile of the US cement industry. Washington DC: Environmental Protection Agency. 2004;10.
2. Davidovits J. Geopolymers: Inorganic polymeric new materials. *Journal of Thermal Analysis and Calorimetry*. 1991;37(8):1633–56.
3. Rowles M, O'Connor B. Chemical optimisation of the compressive strength of aluminosilicate geopolymers synthesised by sodium silicate activation of metakaolin. *Journal of Materials Chemistry*. 2003;13(5):1161–5.
4. He J, Jie Y, Zhang J, Yu Y, Zhang G. Synthesis and characterization of red mud and rice husk ash-based geopolymer composites. *Cement and Concrete Composites*. 2013;37:108–18. doi:10.1016/j.cemconcomp.2012.11.010.
5. Zhang J, He Y, Wang Y, Mao J, Cui XC. Synthesis of a self-supporting faujasite zeolite membrane using geopolymer gel for separation of alcohol/water mixture. *Materials Letters*. 2014;116:167–70. doi:10.1016/j.matlet.2013.11.008.
6. Zhang HY, Kodur V, Qi SL, Wu B. Characterizing the bond strength of geopolymers at ambient and elevated temperatures. *Cement and Concrete Composites*. 2015;58:40–9. doi:10.1016/j.cemconcomp.2015.01.006.

7. Shi X, Zhang C, Liang Y, Luo J, Wang X, Feng Y, Li Y, Wang Q, Abomohra AE. Life cycle assessment and impact correlation analysis of fly ash geopolymer concrete. *In Materials*. 2021;14(23). doi:10.3390/ma14237375.
8. Ziada M. The effect of nano-TiO₂ and Nano-Al₂O₃ on mechanical, microstructure properties and high-temperature resistance of geopolymer mortars. *Arabian Journal for Science and Engineering*. 2024. doi:10.1007/s13369-024-09570-w.
9. Pan Z, Sanjayan JG, Rangan BV. Fracture properties of geopolymer paste and concrete. *Magazine of Concrete Research*. 2011;63(10):763–71. doi:10.1680/macr.2011.63.10.
10. Huseien GF, Ismail M, Khalid NHA, Hussin MW, Mirza J. Compressive strength and microstructure of assorted wastes incorporated geopolymer mortars: Effect of solution molarity. *Alexandria Engineering Journal*. 57(4):3375–86. doi:10.1016/j.aej.2018.07.011.
11. Sheethal MKT, Wp PK, Mt PK. Development of high strength geopolymer concrete using low molarity NaOH. *Int J Eng Res Technol*. 2015;4:194–200.
12. Rovnanik P. Effect of curing temperature on the development of hard structure of metakaolin-based geopolymer. *Construction and Building Materials*. 2010;24(7):1176–83. doi:10.1016/j.conbuildmat.2009.12.023.
13. Gao K, Lin KL, Wang D, Hwang CL, Shiu HS, Chang YM, Cheng TW. Effects SiO₂/Na₂O molar ratio on mechanical properties and the microstructure of nano-SiO₂ metakaolin-based geopolymers. *Construction and Building Materials*. 2014;53:503–10. doi:10.1016/j.conbuildmat.2013.12.003.
14. Cheng TW, Chiu JP. Fire-resistant geopolymer produced by granulated blast furnace slag. *Minerals Engineering*. 2003;16(3):205–10. doi:10.1016/S0892-6875(03)00008-6.
15. Chithiraputhiran S, Neithalath N. Isothermal reaction kinetics and temperature dependence of alkali activation of slag, fly ash and their blends. *Construction and Building Materials*. 2013;45:233–42. doi:10.1016/j.conbuildmat.2013.03.061.
16. Rattanasak U, Chindaprasit P, Suwanvitaya P. Development of high volume rice husk ash alumino silicate composites. *International Journal of Minerals, Metallurgy, and Materials*. 2010;17:654–9. doi:10.1007/s12613010-0370-0.
17. Hwang CL, Huynh TP. Effect of alkali-activator and rice husk ash content on strength development of fly ash and residual rice husk ash-based geopolymers. *Construction and Building Materials*. 2015;101:1–9. doi:10.1016/j.conbuildmat.2015.10.025.
18. Hardjito D, Rangan BV. Development and properties of low-calcium fly ash-based geopolymer concrete. 2005.
19. Chindaprasit P, Silva PD, Sagoe-Crentsil K, Hanjitsuwan S. Effect of SiO₂ and Al₂O₃ on the setting and hardening of high calcium fly ash-based geopolymer systems. *Journal of Materials Science*. 2012;47:4876–83. doi:10.1007/s10853-012-6353-y.
20. Leong HY, Ong DEL, Sanjayan JG, Nazari A. The effect of different Na₂O and K₂O ratios of alkali activator on compressive strength of fly ash based-geopolymer. *Construction and Building Materials*. 2016;106:500–11. doi:10.1016/j.conbuildmat.2015.12.141.
21. Criado M, Fernández-Jiménez A, De La Torre AG, Aranda MAG, Palomo A. An XRD study of the effect of the SiO₂/Na₂O ratio on the alkali activation of fly ash. *Cement and Concrete Research*. 2007;37(5):671–9. doi:10.1016/j.cemconres.2007.01.013.
22. Álvarez-Ayuso E, Querol X, Plana F, Alastuey A, Moreno N, Izquierdo M, Font O, Moreno T, Díez S, Vázquez E. Environmental, physical and structural characterisation of geopolymer matrixes synthesised from coal (co-) combustion fly ashes. *Journal of Hazardous Materials*. 2008;154(1–3):175–83. doi:10.1016/j.jhazmat.2007.10.008.
23. Younis KH. Influence of sodium hydroxide (NaOH) molarity on fresh properties of self-compacting slag-based geopolymer concrete containing recycled aggregate. *Materials Today: Proceedings*. 2022;56:1733–7. doi:10.1016/j.matpr.2021.10.411.
24. EFNARC. The European guidelines for self-compacting concrete specification, production and use “the european guidelines for self compacting concrete”. 2005.
25. Chen R, Yang K, Qiu X, Zeng X, Wang P, Xu J, Chen J. Degradation mechanism of CA mortar in CRTS I slab ballastless railway track in the Southwest acid rain region of China—materials analysis. *Construction and Building Materials*. 2017;149:921–33. doi:10.1016/j.conbuildmat.2017.04.017.
26. Cao C, Zheng SS, Hu WB. A survey on concrete structure properties under acid rain erosion. *Material Reports*. 2019;33(11):1869–74. doi:10.11896/cldb.17110051.
27. Shi Z, Zhang J, Xiao Z, Lu T, Ren X, Wei H. Effects of acid rain on plant growth: A meta-analysis. *Journal of Environmental Management*. 2021;297:113213. doi:10.1016/j.jenvman.2021.113213.
28. Ranjan P, Parvathi G, Sarathi R, Robinson RG, Harid N, Griffiths H. Influence of water, acid rain and bentonite on ionization characteristics of sand under lightning impulse voltage. *IEEE Transactions on Dielectrics and Electrical Insulation*. 2021;28(3):897–905. doi:10.1109/TDEI.2021.009501.
29. Chang J, Yang HP, Xiao J, Xu YF. Soil-water chemical tests and action mechanism of acid rain infiltration into expansive soil. *Chin. J Geotech Eng*. 2022;44:1483–92.
30. Liu J, Chen W, Xie G, Xie X, Ning Q, Bai X. Strength characteristics and electrochemical impedance spectroscopy study of red mud-coal metakaolin geopolymer in a hydrochloric acid environment. *International Journal of Electrochemical Science*. 2023;18(7):100182. doi:10.1016/j.ijoes.2023.100182.
31. Arunachalam N, Maheswaran J, Chellapandian M, Ozbakkaloglu T. Effective utilization of copper slag for the production of geopolymer concrete with different NaOH molarity under ambient curing conditions. *In Sustainability*. 2022;14(23). doi:10.3390/su142316300.
32. Hakem Aziz I, Mustafa Al Bakri Abdullah M, Arif Anuar Mohd Salleh M, Victor Sandu V. The incorporation of sodium hydroxide (NaOH) concentration and CaO-Si components on ground granulated blast furnace slag geopolymers. *IOP Conference Series: Materials Science and Engineering*. 2020;864(1):12005. doi:10.1088/1757-899X/864/1/012005.12005.
33. Hanjitsuwan S, Hunpratub S, Thongbai P, Maensiri S, Sata V, Chindaprasit P. Effects of NaOH concentrations on physical and electrical properties of high calcium fly ash geopolymer paste. *Cement and Concrete Composites*. 2014;45:9–14. doi:10.1016/j.cemconcomp.2013.09.012.
34. Verma M, Dev N. Sodium hydroxide effect on the mechanical properties of flyash-slag based geopolymer concrete. *Structural Concrete*. 2021;22(S1):E368–79. doi:10.1002/suco.202000068.
35. ASTM C109/C109M. Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or [50 mm] cube specimens). 2021.
36. ASTM C 348-21. Standard test method for flexural strength of hydraulic-cement mortars. Norma ASTM Internacional. 2021.
37. ASTM C597. Standard test method for pulse velocity through concrete. 2016.
38. ASTM C 1585-13. Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes. 1585-13. doi:10.1520/C1585-13.
39. Domone P. The slump flow test for high-workability concrete. *Cement and Concrete Research*. 1998;28(2):177–82. doi:10.1016/S0008-8846(97)00224-X.

40. Jithendra C, Elavenil S. Influences of parameters on slump flow and compressive strength properties of aluminosilicate based flowable geopolymer concrete using taguchi method. *Silicon*. 2020;12(3):595–602. doi:10.1007/s12633-01900166-w.
41. Aksogan O. Durability of concrete made with natural granular granite, silica sand and powders of waste marble and basalt as fine aggregate. *Journal of Building Engineering*. 2018;19. doi:10.1016/j.jobbe.2018.04.022.
42. Park H, Jeong Y, Jun Y, Jeong JH, Oh JE. Strength enhancement and pore-size refinement in clinker-free CaO-activated GGBFS systems through substitution with gypsum. *Cement and Concrete Composites*. 2016;68:57–65. doi:10.1016/j.cemconcomp.2016.02.008.
43. Amarender R, Rayana H. Study on the molarity effect of sodium hydroxide on geopolymer concrete incorporating nanosilica. *Journal of Physics: Conference Series*. 2024;2779(1):12040. doi:10.1088/1742-6596/2779/1/012040.
44. Sturm P, Gluth GJG, Jäger C, Brouwers HJH, Kühne HC. Sulfuric acid resistance of one-part alkali-activated mortars. *Cement and Concrete Research*. 2018;109:54–63. doi:10.1016/j.cemconres.2018.04.009.
45. Aygörmmez Y, Canpolat O. Long-term sulfuric and hydrochloric acid resistance of silica fume and colemanite waste reinforced metakaolin-based geopolymers. *Revista de La Construcción*. 2021;20(2):291–307. doi:10.7764/RDL.C.20.2.291.
46. Vafaei M, Allahverdi A, Dong P, Bassim N, Mahinroosta M. Resistance of red clay brick waste/phosphorus slag-based geopolymer mortar to acid solutions of mild concentration. *Journal of Building Engineering*. 2021;34:102066. doi:10.1016/j.jobbe.2020.102066.
47. Kwasny J, Aiken TA, Soutsos MN, McIntosh JA, Cleland DJ. Sulfate and acid resistance of lithomarge-based geopolymer mortars. *Construction and Building Materials*. 2018;166:537–53. doi:10.1016/j.conbuildmat.2018.01.129.
48. Chen J, Jiang M. Long-term evolution of delayed ettringite and gypsum in Portland cement mortars under sulfate erosion. *Construction and Building Materials*. 2009;23(2):812–6. doi:10.1016/j.conbuildmat.2008.03.002.
49. Sharifi Y, Visrudi HN. Hydrochloric acid resistance of mortars incorporating waste glass powder as cementitious materials. *Structural Concrete*. 2024;25(1):303–19. doi:10.1002/suco.202300303.
50. Thokchom S, Ghosh P, Ghosh S. Resistance of fly ash based geopolymer mortars in sulfuric acid. *ARPN J. Eng Appl Sci*. 2009;4(1):65–70.
51. Chang JJ, Yeih W, Hung CC. Effects of gypsum and phosphoric acid on the properties of sodium silicate-based alkaliactivated slag pastes. *Cement and Concrete Composites*. 2005;27(1):85–91. doi:10.1016/j.cemconcomp.2003.12.001.
52. Nematollahi B, Qiu J, Yang EH, Sanjayan J. Microscale investigation of fiber-matrix interface properties of strain-hardening geopolymer composite. *Ceramics International*. 2017;43(17):15616–25. doi:10.1016/j.ceramint.2017.08.118.
53. Williams RP, van Riessen A. Development of alkali activated borosilicate inorganic polymers (AABSIP). *Journal of the European Ceramic Society*. 2011;31(8):1513–6. doi:10.1016/j.jeurceramsoc.2011.02.021.
54. Sata V, Sathonsaowaphak A, Chindaprasirt P. Resistance of lignite bottom ash geopolymer mortar to sulfate and sulfuric acid attack. *Cement and Concrete Composites*. 2012;34(5):700–8. doi:10.1016/j.cemconcomp.2012.01.010.
55. Song XJ, Marosszeki M, Brungs M, Munn R. Durability of fly ash based geopolymer concrete against sulphuric acid attack. *International Conference on Durability of Building Materials and Components*. 2005;10.
56. Aygörmmez Y, Canpolat O, Al-mashhadani MM. Assessment of geopolymer composites durability at one year age. *Journal of Building Engineering*. 2020;32:101453. doi:10.1016/j.jobbe.2020.101453.