



Solidification of (Pb–Zn) mine tailings by fly ash-based geopolymer I: influence of alkali reagents ratio and curing condition on compressive strength

Alsény Bah^{1,2} · Daolun Feng³ · Emmanuel Adu Gyamfi Kedjanyi¹ · Ziyi Shen¹ · Alhassane Bah⁴ · Feihu Li¹

Received: 14 February 2021 / Accepted: 28 October 2021 / Published online: 15 November 2021
© Springer Japan KK, part of Springer Nature 2021

Abstract

Fly ash-based geopolymer is a crucial application for tackling climate change, limiting the production of greenhouse emissions. The main aim of this study was to determine the effect of the fundamental parameters on compressive strength to ensure a feasible and effective solidification of mine tailings. Three sodium hydroxide (NaOH) molarities (5, 8, and 10 M) and sodium silicate (Na₂SiO₃) were combined to form the alkaline solution. Four fly ash (FA) proportions (28%, 44%, 54, and 61%) of the dry mix and mine tailings (MT) were utilized as raw materials. This study demonstrated that both 25 °C and 65 °C have a considerable effect on the mechanical properties of geopolymers. The UCS value increased with an increase in NaOH molarity. In addition, the highest Unconfined Compressive Strength (UCS) value was achieved (36.04 MPa) at 10 M. Furthermore, the results also showed that UCS values kept decreasing with the increase of SiO₂/Al₂O₃ and Na₂O/SiO₂ ratios. The optimal UCS values found were in the range of 0.28–0.38 liquid/solid ratio. It has been concluded that the previously mentioned parameters have a strong influence on the mechanical strength of fly ash-based geopolymer with the new proposed FA proportion.

Keywords Geopolymer · Solidification · Mine tailings · Alkaline solution · Compressive strength

Introduction

Mine tailings (MT) dumping has become a critical problem throughout the mining sector. In modern practice, the mine tailings or waste produced is gathered and transferred in paste or slurry form or discarded in huge tailings ponds that are expensive and utilize vast land areas. The dumping of mining waste in ponds can also provoke safety and environmental issues, such as surface water pollution [1–4].

However, the physical stabilization of large quantities of mineralogical waste, especially tailings and fly ash, has become an economic, political, and social necessity. Here is a requirement for an affordable technology that can deal with large volumes of waste materials, including polluted topsoil, fly ash (FA), landfill leachate, and heavy-metal mine tailings [5]. Moreover, van Jaarsveld et al. [6] and other researchers such as Davidovits et al. [7] have shown that geopolymerization implies a heterogeneous method of chemical reactions between solid aluminosilicate oxides and alkali metal silicate solutions under strongly alkaline conditions and mild temperatures, resulting in amorphous semi-crystalline polymeric structures consisting of Si–O–Al, and Si–O–Si bonds [8] tends to satisfy the above criteria and can enable a practical approach to the processing and use of waste materials historically unused. Furthermore, geopolymer not only achieves efficiency compared to OPC (Ordinary Portland Cement) in several applications, but it also provides extra benefits, including the rapid growth of compressive strength, high acidic resistance, exemplary composite compliance, immobilization of harmful and dangerous substances, as well as a significant decrease of the production of greenhouse

✉ Feihu Li
fhli@nuist.edu.cn

¹ School of Environmental Science and Engineering, Nanjing University of Information Science and Technology, 219 Ningliu Road, Nanjing 210044, China

² Merchant Marine College, Shanghai Maritime University, Shanghai 201306, China

³ College of Ocean Science and Engineering, Shanghai Maritime University, Shanghai 201306, China

⁴ School of Electrical Engineering, Kunming University of Science and Technology, Kunming 650093, China

emissions [9–11]. Additionally, whenever alkali-activated geopolymers are employed as binder materials for the Solidification/Stabilization of hazardous waste, the polycondensation stages in the geopolymerisation reactions are said to promote the immobilization and trapping of hazardous species through diverse chemical and physical processes [12, 13]. In addition to that, it's been discovered that geopolymer matrices containing alkali-activated precursor material and sodium silicate can provide significant compressive strength ranging from 2 to 60 MPa while completely immobilizing heavy metals like Cr, Cd, and Pb [13]. Glukhovskiy discovered an alkali-activated process throughout the late 1950s and 1960s that contains calcium silicate hydrate (C–S–H) and aluminosilicate processes [14]. Geopolymer is essentially a synthesized alkali aluminosilicate component formed by a solid aluminosilicate process with a high concentration alkaline hydroxide and silicate solution [15]. While MT is abundant in silica and alumina, they could be a prospective source of material for geopolymer development [4]. Besides, FA and MT have been known as sources of alumina and silica, which are responsible for geopolymerization. Some residue materials, including MT, blast furnace slag, and MT, produce adequate reactionary alumina and silica quantities, which are utilized as sources of in situ geopolymerization processes [16].

An application of sodium hydroxide (NaOH) with sodium silicate solution (Na_2SiO_3) results in increased geopolymerization rates for the alkaline reagents solution associated with hydroxide only [17]. Furthermore, Xu and Van Deventer [18] have shown that specific raw materials from aluminosilicate minerals are being utilized to manufacture geopolymers, requiring extra silica (Si) for the geopolymerization operation. The dissolution of aluminosilicate demands alkali hydroxide, whereas the NaOH solution reacts as a binder [14].

Recently, several researchers have investigated geopolymerization processes for the consolidation of MT [19–22]. MT was utilized as raw materials, and alkaline reagents were applied to cause geopolymerization reactions; the MT was then condensed after curing. For example, copper mine tailings-based bricks have been formulated by geopolymerization at varying alkaline reagents concentrations, water, pressure formation, and temperature curing. The compressive strength of the bricks at the optimum synthesis phase was 33.7 MPa [23]. Jiao X et al. [24] produced geopolymer-based vanadium MT after reheating the MT combined with sodium hydroxide (NaOH). The maximum compressive strength obtained was 55.7 MPa. Kuranchie et al. [25] have researched the impact of curing conditions (time and temperature) and alkaline reagents concentration on iron MT-based bricks production by geopolymerisation. A 50.53 MPa has been gained as compressive strength for the bricks under an optimum synthesis regime. These experiments provide

another solution to the consolidation of mining waste through building bricks, in which the remaining reagents and toxic metals may be controlled following geopolymerisation reactions [26].

The curing condition of geopolymer is useful in assessing the presence of water throughout FA-based geopolymer strengthening [27]. Since water is indeed a crucial component throughout alkaline-activating processes, the curing of the humidity system specifically affects the structural and mechanical properties of alkaline-activating of FA-based geopolymer and concrete [28, 29]. Furthermore, in FA-based geopolymers, the curing temperature has been a reaction catalyst [17]. Additionally, curing conditions, including temperature and time, are important factors influencing the mechanical properties of geopolymers. [13, 30]. Furthermore, with Na, Si, and Al as major components, geopolymerization interactions proceed more efficiently. Dissolution of particles in an alkaline solution is more efficient with increasing time (28 and 91 days). That also accounts for the enhanced compressive strength of geopolymers over time. [13, 31].

The enhancement of mechanical characteristics of a fly ash-based geopolymer is a significant issue, as its key applications are in the construction domain as cement material and concrete. The fly ash-based geopolymer compressive strength depends on different factors, such as alkaline solutions reagents, $\text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{Na}_2\text{O}/\text{SiO}_2$, and liquid/solid ratios and curing conditions (temperature and duration). To figure out their effect on the mechanical strength of the geopolymers, the influence of these parameters on UCS was investigated. To achieve that, in this study, we proposed a new FA proportion (28%, 44%, 54, and 61%) of the dry mix, which resulted in optimum compressive strength, and we found that with this FA proportion, more mining waste can be reused to reduce the waste stream.

Materials and methods

Materials

Two raw materials (FA and MT) were utilized in this investigation from different places. Fly Ash (FA) class F is mainly characterized by some significant oxides (SiO_2 (40.15%), Al_2O_3 (35.50%), CaO (8.33%), and Fe_2O_3 (7.57%)). It was provided in powder by Jiangsu Nanre Power Generation Co., Ltd. (Nanjing, China). Mine Tailings (MT) characterized in major oxide by SiO_2 (18.83%), Fe_2O_3 (6.20%), CaO (29.49%), LOI (28.86%) from Nanjing Yinmao Lead–Zinc Mining Industry Co., Ltd. (Nanjing, China). The complete chemical composition of FA and MT is shown in Table 1 based on the fused X-ray fluorescence (XRF) result. The alkali reagents were NaOH, Na_2SiO_3 , and deionized water.

Table 1 Chemical composition of FA and MT

| Element (wt %) | | | Element (ppm) | | |
|--------------------------------|-------|-------|----------------------|-------|-------|
| Chemical composition | FA | MT | Chemical composition | FA | MT |
| SiO ₂ | 40.15 | 18.83 | As | 21.3 | 151.9 |
| Al ₂ O ₃ | 35.50 | 1.61 | Mo | 14.4 | 0.7 |
| Fe ₂ O ₃ | 7.57 | 6.20 | Pb | 101.4 | 622.4 |
| MnO ₂ | 0.11 | 9.12 | Rb | 47.2 | 10.6 |
| CaO | 8.33 | 29.49 | Th | 32.3 | 11.5 |
| MgO | 1.21 | 2.83 | U | 12.5 | 7.5 |
| K ₂ O | 1.48 | 0.15 | Y | 64.5 | 63.6 |
| Na ₂ O | 1.10 | 0.12 | Zr | 433.8 | 28.7 |
| P ₂ O ₅ | 0.37 | 0.03 | Ga | 67.4 | 26.6 |
| TiO ₂ | 1.51 | 0.06 | Cu | 75.1 | 52.9 |
| SO ₃ | 0.70 | 2.30 | Co | 25.4 | 1.4 |
| LOI | 1.64 | 28.96 | Ni | 45.5 | 10.1 |
| – | – | – | Cr | 61.7 | 24.3 |
| – | – | – | V | 182.1 | 97 |

Table 2 Activator utilized

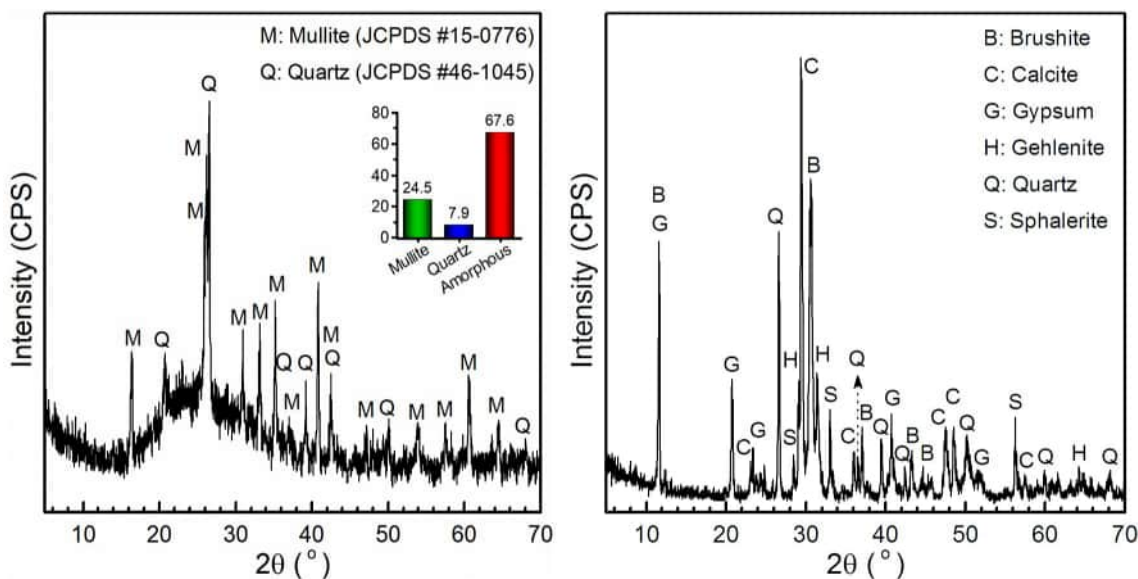
| | SiO ₂ (%) | Na ₂ O (%) | H ₂ O (%) |
|-----------------|----------------------|-----------------------|----------------------|
| Sodium silicate | 13.36 | 29.84 | 56.8 |

NaOH 96% pellets supplied by Shanghai Macklin Biochemical Co., Ltd. Ganjiashan Yourui Refractories Co. delivered the sodium silicate (Table 2), Ltd. Figure 2 illustrates the particle size distribution of the mine tailing, roughly 42.50% of the particles were lower than 60 μm, the particles from

5.56 to 9.41 wt % were larger than 60 to 200 μm, and therefore the second larger particle size distribution size is 13,02 wt % held by further than 200 μm. Figure 1a reveals the chemical composition of fly ash performed by X-Ray diffractometer (XRD XRD-6100 diffractometer (Shimadzu, Japan with 20–60 kV and 2–80 mA). The existence of crystalline quartz (7.9%) and mullite (24.5%) is apparent. Figure 1b depicts the mineralogical investigation of MT analyzed by XRD, showing that the main minerals in MT are mostly crystalline materials typically consisting of quartz, brushite, calcite, gypsum, gehlenite, and sphalerite (Fig. 2). Figure 3 displays the microstructure of FA and MT analyzed by Scanning electron microscope (SEM) FEI INSPEC-S50/ Thermo-Fisher Noran 6. The crystals of the MT are irregular in shape, while the FA particles are round spheres. Many of the large particles of the MT are constructed by fine particles. The FA comprises some cracked spheres inside with thicker particles (cenospheres).

Alkaline solution preparation

Sodium hydroxide and sodium silicate were selected as alkali reagents to form the alkaline solution. Sodium-based solutions were selected owing to their cost accessibility compared to potassium-based solutions. Besides, many studies, such as Palomo et al. [17], have used the same alkali reagents in geopolymerization and yielded a satisfying result. The solubility of Al³⁺ and Si⁴⁺ in NaOH is also greater than in the KOH solution with an identical concentration [32]. The sodium hydroxide 96% NaOH pellets were used to prepare the sodium hydroxide solution by dissolving the NaOH flakes into deionized water. Different

**Fig. 1** XRD patterns of **a** Fly ash (FA) and **b** mine tailings

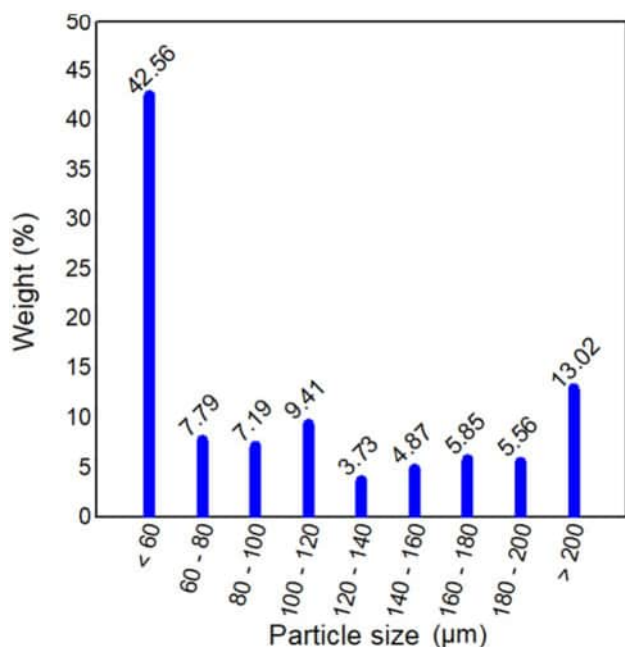


Fig. 2 Particle Size Distribution of the Mine Tailings

masses of NaOH solids were used based on the molarity. For instance, a NaOH solution with 5 M consisted of $5 \times 40 = 200$ g of NaOH solids in flakes per liter of the solution, whereas 40 represents the molecular weight of NaOH. For one recipe, 10.8 g of the NaOH flake was weighted and added to 54 ml tap water, and stirred for 5 min with a magnetic stirrer to form a transparent soln. enough time (24 h) was provided for it to cool down. Similarly, for 8 M and 10 M, 320 g and 400 g of NaOH solids were weighted, respectively. A similar procedure was followed to prepare the NaOH solution for one recipe based on the molarity.

Commonly, the Na_2SiO_3 solution is combined with NaOH to improve compressive strength [33]. Due to the high viscosity of sodium silicate, geopolymer gels may be formed, and a compact final fly ash-based geopolymer microstructure is obtained [32]. The sodium silicate (Na-Silicate) solution was utilized, which is described in Table 2 and consists of a 0.46 molar ratio of silica to sodium oxide.

The alkaline solution was prepared by mixing the NaOH solution with the Na-silicate solution together for 15 min before adding it to the solid mixture. Three alkaline solutions were designed depending on the molarity of NaOH (5 M, 8 M, and 10 M), named A5, A8, and A10, respectively. The volume of the alkaline solution prepared depends on the number of geopolymer recipes for each NaOH molarity. The ratio of NaOH solution to Na_2SiO_3 for all the specimens was 0.43, 0.69, and 0.86. A combination of sodium silicate and sodium hydroxide solutions is still the most reported and efficient alkaline activator [34]. Moreover, a blend of the above two alkaline solutions provides the geopolymer product with higher mechanical characteristics than any of them alone [35, 36].

Geopolymer synthesis

Twelve geopolymer matrices were formulated with different FA proportions (28%, 44%, 54%, and 61%) of the dry mix. MT was ground, sieved, and maintained constant for all mixtures. The following FA/MT ratios were applied: 0.38; 0.7; 1.15 and 1.54 (Table 3). Geopolymers were formulated by manually mixing dry materials (FA and MT) in a plastic beaker for at least five minutes and then gradually adding alkaline solutions and extra water until a coherent mixture was gained. Four different alkaline solution/FA ratios were selected: 0.6; 0.8; 1.2 and 2.4 (Table 4). The geopolymer mixture (paste) was then cast into (20 × 20 × 20) mm cubed molds (Fig. 4a) and cured

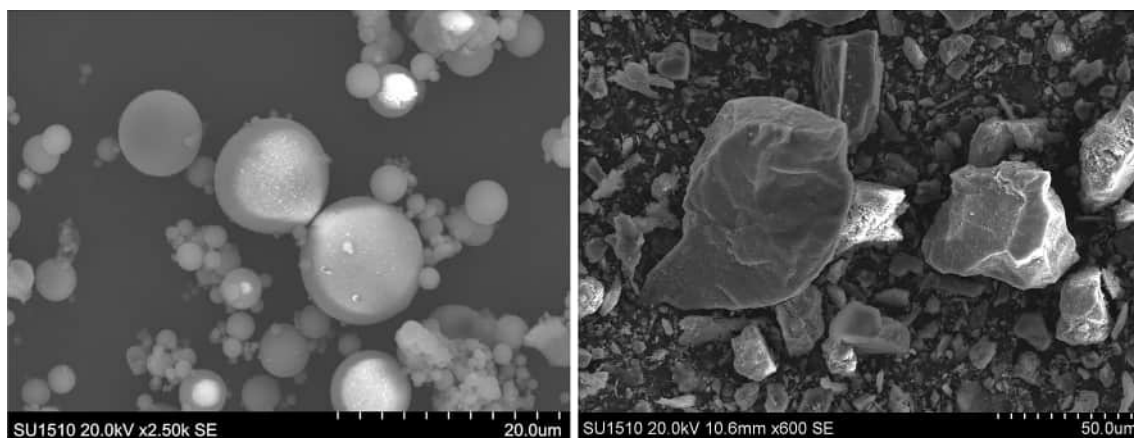


Fig. 3 SEM images of **a** fly ash, **b** mine tailing, respectively

Table 3 Different ratios of alkali reagents

| Specimens label | FA% | SiO ₂ /Al ₂ O ₃ ratio | Na ₂ O/ Al ₂ O ₃ ratio | Na ₂ O/SiO ₂ ratio | L/S ratio | FA/MT ratio | S/L ratio |
|-----------------|-----|--|---|--|-----------|-------------|-----------|
| FMA5-01 | 61 | 1.53 | 0.36 | 0.23 | 0.30 | 1.54 | 3.23 |
| FMA5-02 | 54 | 1.66 | 0.46 | 0.28 | 0.34 | 1.15 | 2.96 |
| FMA5-03 | 44 | 1.91 | 0.66 | 0.35 | 0.38 | 0.77 | 2.65 |
| FMA5-04 | 28 | 2.60 | 1.22 | 0.47 | 0.44 | 0.38 | 2.29 |
| FMA8-01 | 61 | 1.53 | 0.46 | 0.30 | 0.30 | 1.54 | 3.31 |
| FMA8-02 | 54 | 1.66 | 0.59 | 0.36 | 0.33 | 1.15 | 3.04 |
| FMA8-03 | 44 | 1.91 | 0.86 | 0.45 | 0.37 | 0.77 | 2.74 |
| FMA8-04 | 28 | 2.60 | 1.59 | 0.61 | 0.42 | 0.38 | 2.39 |
| FMA10-01 | 61 | 1.53 | 0.53 | 0.34 | 0.29 | 1.54 | 3.36 |
| FMA10-02 | 54 | 1.66 | 0.68 | 0.41 | 0.32 | 1.15 | 3.10 |
| FMA10-03 | 44 | 1.91 | 0.99 | 0.52 | 0.36 | 0.77 | 2.80 |
| FMA10-04 | 28 | 2.60 | 1.84 | 0.71 | 0.41 | 0.38 | 2.45 |

Table 4 Mixture Design

| NaOH Molarity (M) | Alkaline/FA ratio | NaOH/Na ₂ SiO ₃ ratio | Mine tailings (g) | Fly Ash (g) | Na ₂ SiO ₃ (g) | NaOH solution | |
|-------------------|-------------------|---|-------------------|-------------|--------------------------------------|---------------|------------|
| | | | | | | Flakes (g) | Water (ml) |
| 5 | 0.6 | 0.43 | 97.5 | 150 | 25 | 10.8 | 54 |
| | 0.8 | | | | | | |
| | 1.2 | | | | | | |
| | 2.4 | | | | | | |
| 8 | 0.6 | 0.69 | 97.5 | 150 | 25 | 17.2 | 54 |
| | 0.8 | | | | | | |
| | 1.2 | | | | | | |
| | 2.4 | | | | | | |
| 10 | 0.6 | 0.86 | 97.5 | 150 | 25 | 17.2 | 54 |
| | 0.8 | | | | | | |
| | 1.2 | | | | | | |
| | 2.4 | | | | | | |

under different temperatures. Twelve geopolymer cubes were produced for each geopolymer matrix for analysis purposes (Fig. 4b). The average of 3 cubes was calculated to represent the compressive strength value of each geopolymer specimen for each curing time. The geopolymer specimens were labeled based on the FA content (28%; 44%; 54% and 61% by mass) and NaOH molarity as follows: for 5 M NaOH, FMA5-1; FMA5-2; FMA5-3; FMA5-4; for 8 M FMA8-1; FMA8-2 FMA8-3 FMA8-4 and for 10 M FMA10-1 FMA10-2 FMA10-3 and FMA10-4.

Both specimens were treated at two varying temperatures in the oven for 24 h, respectively, at 25 °C and 65 °C to investigate the role of the curing temperature in the solidification of mine tailings fly ash-based geopolymer. After demoulding, the geopolymer specimens were placed in the oven for 24 h under different curing temperatures (25 °C and 65 °C) and then returned under

ambient temperature (laboratory condition 8 °C ± 2 °C) for further curing.

The total number of specimens cast was 144 cubic. There were 12 × 4 = 48 cubic specimens cast for each NaOH molarity. The compressive strength tests on these specimens were performed at 7, 14, and 28 days respectively, and for each NaOH concentration, three specimens were repeatedly analyzed at each age. The UCS tests aimed to seek out the perfect geopolymer specimen in terms of NaOH molarity, which provides the greatest compressive strength.

The compressive strength tests were carried out utilizing a universal testing machine, with a loading rate of 5 MPa/s in compliance with the ASTM C109M-2008 standard. Both triplicate measurements and average values were collected and used as data.



Fig. 4 a Geopolymers molding process and b produced geopolymers cubes

Analysis of results

Unconfined compressive strength (UCS)

The outcomes of the unconfined compression analysis are depicted in Figs. 5, 6, 7, 8, 9, 10, 11. These graphs display the influence of curing temperature, NaOH concentration, $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio, fly ash content, and curing period on the mechanical strength of fly ash-based geopolymer.

Figure 5 displays the influence of curing temperatures on mechanical strength after 7 days of curing at 25 °C at 65 °C with different NaOH molarity. From this figure, it is evident that both 25 °C and 65 °C have a considerable effect on the mechanical properties of geopolymers. Higher temperatures result in higher UCS.

Figure 6a–c display the influence of the $\text{NaOH}/\text{Na}_2\text{SiO}_3$ ratio, NaOH at 25 °C and 65 °C on UCS with various fly ash contents after 7 days of curing. Figure 6a depicts that the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio is one of the great precursors that leads to a higher UCS or better mechanical strength. The higher the $\text{NaOH}/\text{Na}_2\text{SiO}_3$ ratio, the better the UCS is. Figure 6b, c show the same result. It can be observed from both of

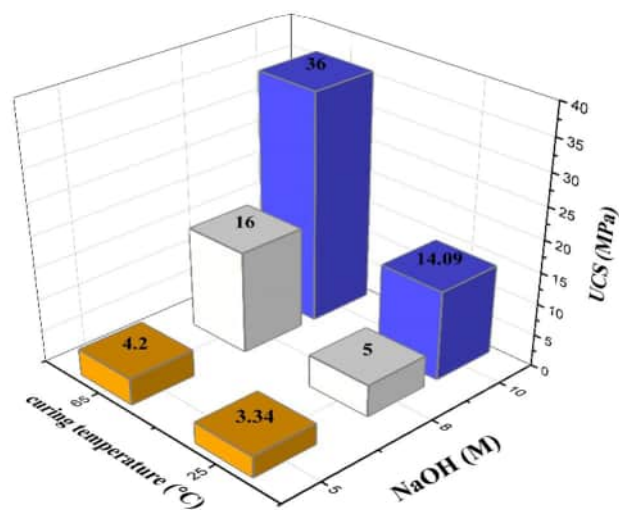


Fig. 5 Influence of curing temperature on UCS after 7 days

them that NaOH concentration has a significant influence on UCS. The UCS value increased with an increase in NaOH concentration.

Figure 7a–c display the effect of the curing period on the mechanical strength or durability of geopolymers. The samples were tested with various FA proportions (28%, 44%, 54%, and 61%) at 10 M NaOH concentration and cured for three periods of time (7, 14, and 28 days). The UCS of specimens cured under 25 °C increases with time Fig. 7a compared with those cured under 65 °C Fig. 7b which slightly decreased the UCS over time. Besides, all of the UCS results of geopolymers with different NaOH concentrations increased with time Fig. 7c.

Four (FA) contents (28%, 44%, 54, and 61%) of the dry mix were utilized to assess the role of FA in the geopolymerization of mine tailings. To achieve this investigation, some geopolymer specimens were tested at various NaOH molarities (Fig. 8a), FA/MT ratios (Fig. 8b) and curing temperatures (Fig. 8c). This finding shows that 61% of FA presents the highest UCS value. Using a 1.54 FA/MT ratio at 10 M NaOH under 25 °C results in a higher UCS.

Figure 9a, b depict the influence of the $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{Na}_2\text{O}/\text{SiO}_2$ ratios on the UCS of geopolymers treated (Fig. 9a) at 65 °C with three different $\text{NaOH}/\text{Na}_2\text{SiO}_3$ ratios (0.43, 0.69 and 0.86) after a 7-day curing period and (Fig. 9b) at 25 °C with three different NaOH concentrations (5, 8 and 10 M) after 28 days of curing. From both Fig. 9a, b, it is evident that the UCS values kept decreasing with the increase of the $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{Na}_2\text{O}/\text{SiO}_2$ ratios.

The influence of the liquid/solid ratios of the 12 geopolymers cured at 25 °C and 65 °C over 24 h in the oven on UCS is depicted in Fig. 11a, b. The UCS values were found in the range of a 0.28–0.38 liquid/solid ratio, and as the liquid/solid ratio increases, the UCS will decrease.

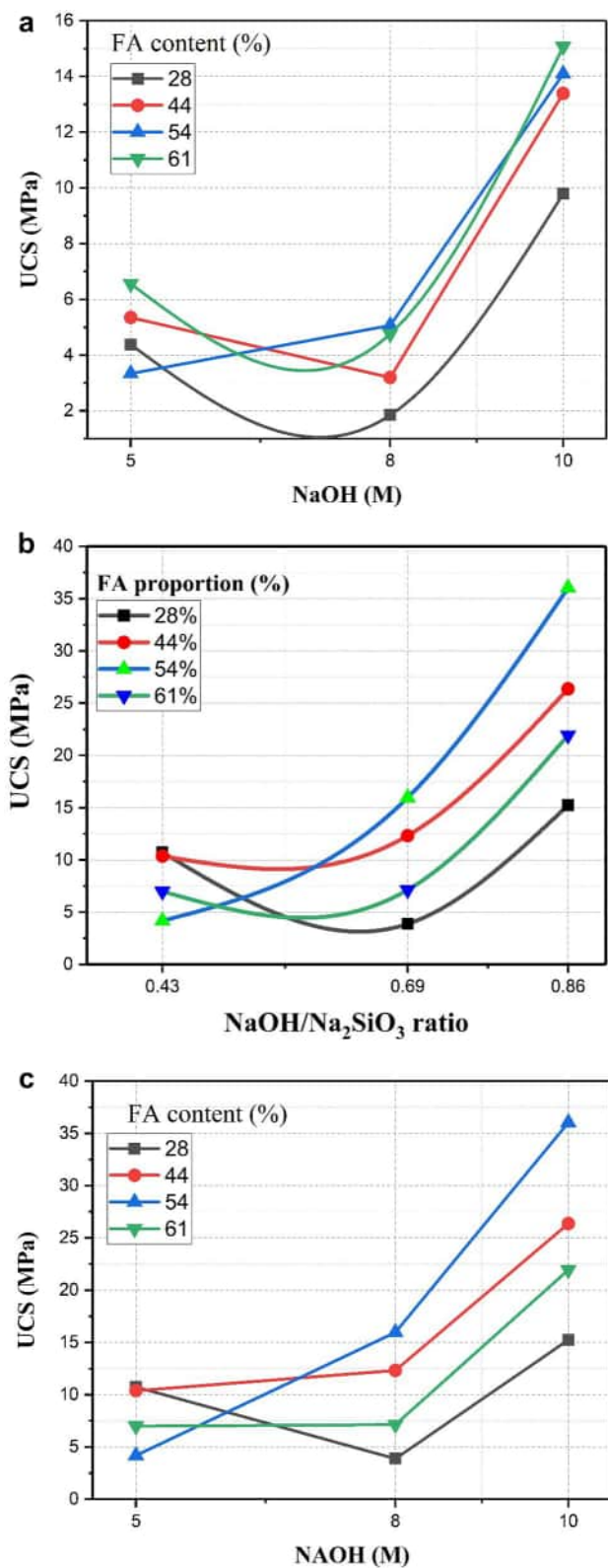


Fig. 6 a NaOH at 25 °C, b influence of Na₂SiO₃/NaOH and c NaOH at 65 °C on UCS with various fly ash contents after 7 days of curing

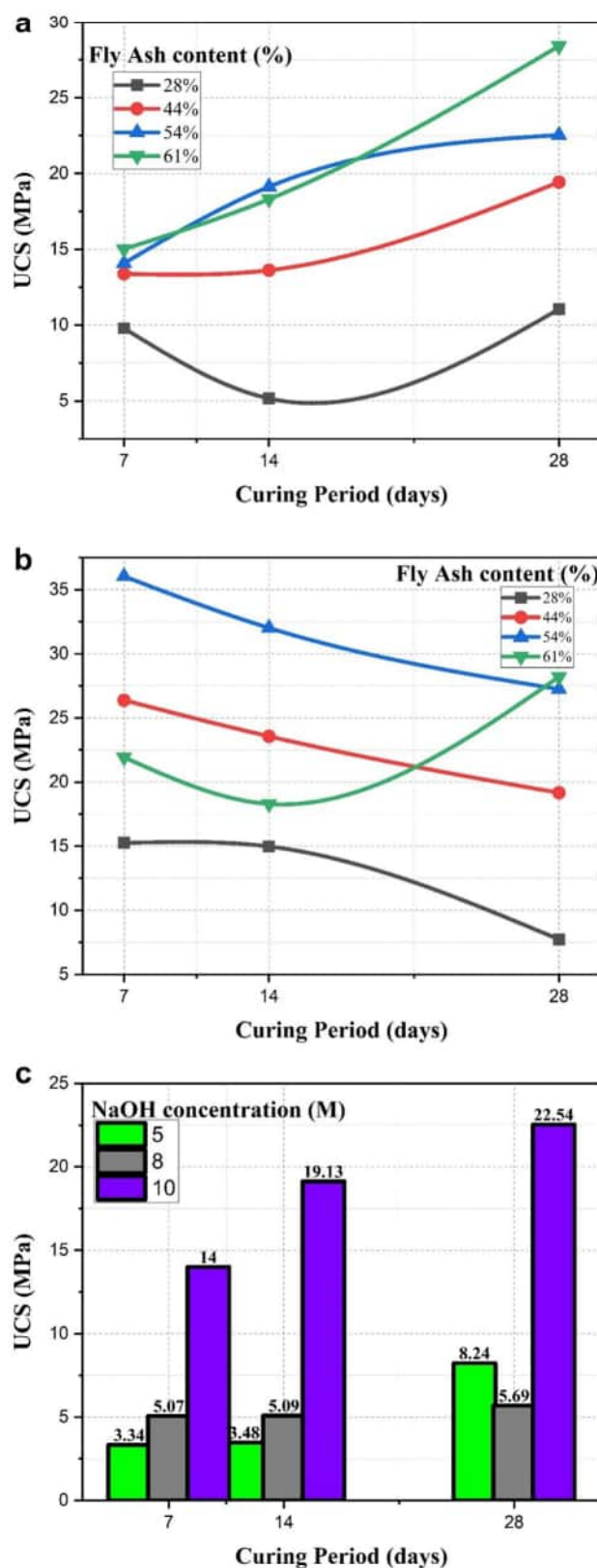


Fig. 7 Influence of curing time on UCS. a At 25 °C, b At 65 °C and c with 5 M, 8 M and 10 M NaOH with various FA contents

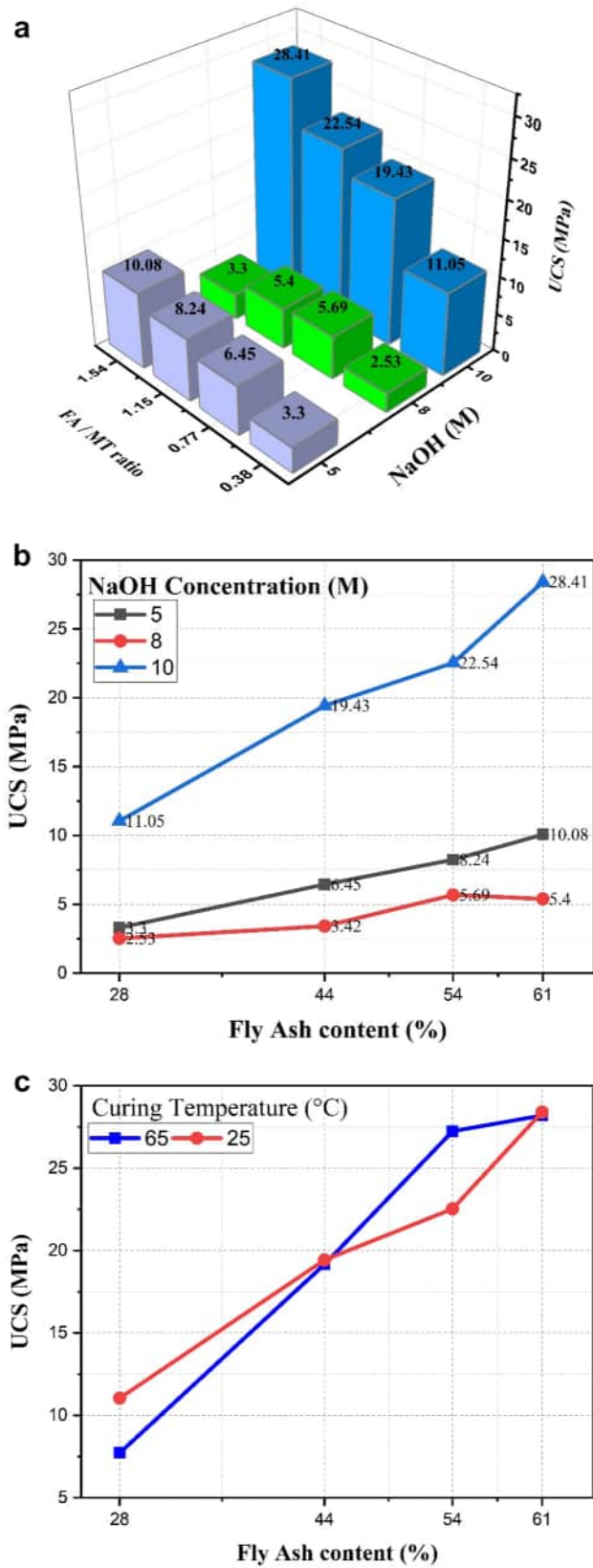


Fig. 8 Effect of FA on UCS. With **a** NaOH molarity, **b** FA/MT ratio and cured under different temperature **c**

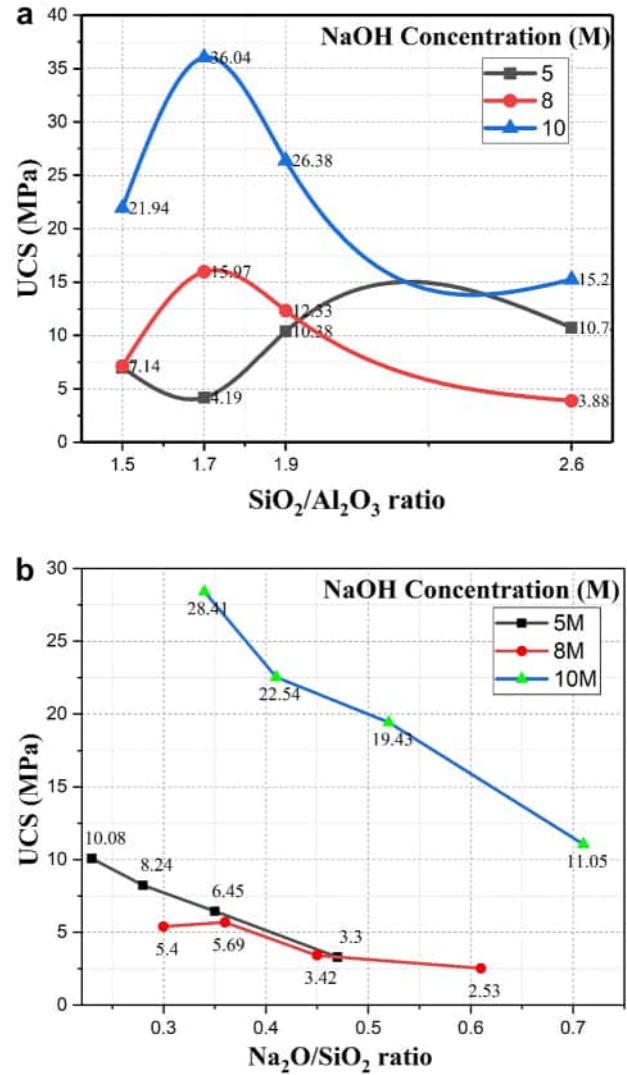


Fig. 9 Influence of SiO₂/Al₂O₃ and Na₂O/SiO₂ ratio on UCS of geopolymers cured **a** at 65 °C with three different NaOH/Na₂SiO₃ ratio after 7 days of curing period and **b** at 25 °C with three different NaOH concentration (5, 8 and 10 M) after 28 days of curing

Discussion

Influence of curing temperature on UCS

The effect of curing temperature on UCS was assessed. As obviously seen in Fig. 5, the specimens treated at 65 °C in the oven for 24 h generated the highest UCS (36 MPa) at 10 M NaOH after 7 days of curing compared to 25 °C, which produced an optimum of 14.09 MPa. Figure 5 illustrates that for the NaOH concentrations tested (5, 8, and 10 M), the geopolymers treated under 65 °C were found to be optimal compared to those cured at 25 °C with the same NaOH molarity, FA/MT ratio, and FA content. The UCS value also increased once the curing temperature was elevated. This

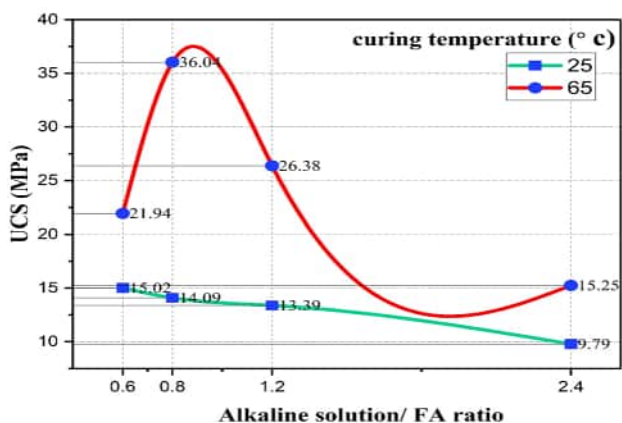


Fig. 10 Influence of alkaline solution/FA ratio on UCS with different curing temperature at 10 M NaOH after 7 days with 54% of FA

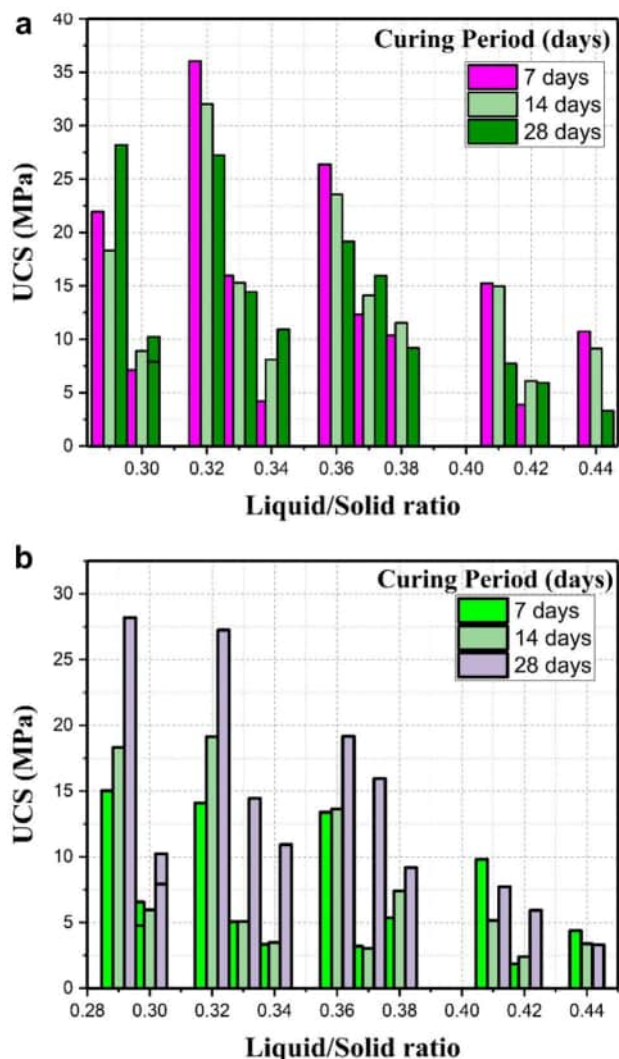


Fig. 11 Influence of liquid/solid ratio of geopolymers on UCS cured a 65 °C and b 25 °C

result is in agreement with Provis, and van Deventer’s [37, 38] findings, which confirmed that the mechanism of geopolymerization could be strongly encouraged if the binder is treated at a temperature between 60 and 90 °C for 8–24 h. In addition, many researchers have already experienced a similar influence from curing temperatures, such as Bakria et al. [29, 38]. Therefore, curing at too extreme temperatures or for a significantly prolonged period may undermine the microstructure and cause increased shrinkage and fracturing, resulting in reduced strength [16, 39].

Influence of NaOH molarity and NaOH/Na₂SiO₃ on UCS

Three NaOH molarities were chosen to prepare the alkaline solution to investigate the effect of NaOH and the NaOH/Na₂SiO₃ ratio in the geopolymerization of mine tailings fly ash-based geopolymer. In geopolymerization, alkaline solution plays two essential functions: the breakdown of silica and alumina and the charge-balancing of alumina particles through the supply of metal cations [4, 40].

This study demonstrated that raising NaOH molarity results in higher UCS values which, has been corroborated by many researchers, including Zhang et al. [4, 41–43]. In addition, another study revealed that compressive strength was enhanced from 5 to 10 M NaOH. However, a slight reduction in strength occurred once the NaOH molarity increased to 10–15 M [44], which is following this study. This rise in UCS with greater molarity of NaOH can be explained for many reasons. Firstly, throughout geopolymerization, the form and concentration of the alkaline solution can affect the liberation of Si⁴⁺ and Al³⁺ through fly ash. A highly concentrated alkaline solution is usually advantageous for achieving higher UCS, but an optimum NaOH molarity is also required [32, 45].

On the other hand, this rise in UCS is also largely due to the silica and alumina dissolution significantly. Thus, the inclusion of a tremendous amount of silica and alumina constituents in geopolymerization [4]. Furthermore, this may be due to the rise of Na ions throughout the process, which was necessary for geopolymerization because Na ions were utilized to regulate the charges and developed the aluminosilicate structures as a binder throughout the combination [46]. Therefore, a large quantity of NaOH will extend the processing time by restricting calcium leaching and allowing standard geopolymerization to monitor the processing of the geopolymer mix [47].

The effect of the NaOH/Na₂SiO₃ ratio on UCS after 7 days of curing with four different fly ash proportions (28%, 44%, 54%, and 61%) at three NaOH molarities (5, 8, and 10 M) was evaluated. From this research, it has been concluded that the higher the NaOH/Na₂SiO₃ ratio is, the higher the UCS will be. Figure 6a illustrates that the highest

UCS value was achieved (36 MPa) with the highest NaOH/Na₂SiO₃ ratio (0.86) of geopolymers at 65 °C. Similar results have been gained with the highest UCS value in the range of 60–70 MPa at NaOH 10 M with a NaOH/Na₂SiO₃ molar ratio of 1.0, curing for 48 h at 65 °C [32, 48]. In this study, the same result can be found by increasing the NaOH/Na₂SiO₃ ratio. In addition, a similar effect from the alkaline ratio was also revealed by many studies, including K. Parthiban and K. Saravana Raja Mohan [49].

Influence of the SiO₂/Al₂O₃ and Na₂O/SiO₂ ratios on UCS

This research, along with that of others such as A. B. Malkawi et al. [50], has demonstrated that the increase in the Na₂O/SiO₂ ratio adversely affects the UCS due to the surplus of the Na cations released by NaOH, which has interacted with atmospheric carbon dioxides that may disrupt the polymerization processes [51].

The SiO₂/Al₂O₃ ratio is among the key factors influencing geopolymerization. Some research suggested that to achieve a geopolymer with optimum UCS, the SiO₂/Al₂O₃ ratio should generally be within 1–3. The particular value is based on the source material utilized [4, 52–55], according to this finding (Fig. 9a). In addition, 21.94, 36.04, and 26.38 MPa were the maximum UCS values of 1.5, 1.7, and 1.9 SiO₂/Al₂O₃ ratio, respectively (Fig. 9a), which is also in agreement with Zhang et al. [4, 56], findings. An increase in the SiO₂/Al₂O₃ ratio leads to a decreased UCS. It might be attributed to the high content of SiO₂ in mine tailings and fly ash.

This study has demonstrated that the mechanical strength of UCS increases as the Na₂O/SiO₂ ratio decreases (Fig. 9b and Table 3). Similarly, Malkawi et al. [50, 57, 58] have proven the same result. This might be due to the influence of the NaOH/Na₂SiO₃ ratio.

Influence of Fly Ash content, FA/MT, and alkaline solution/FA ratios on UCS

This study, along with the research of Abdullah et al. [46, 59], indicated that the UCS value incrementally increases when fly ash content and the concentration of alkaline solution rises (Fig. 8a). That is because of the increase of OH or sodium oxide substance concentration in the geopolymerization process. There are reactions among fly ash and alkali and condensation between both. The resulting Si⁴⁺ and Al³⁺ a particle, accompanied by certain complex crystallization, oligomerization, and polymerization, results in a new aluminosilicate-based polymer with a new amorphous three-dimensional network structure [32]. Furthermore, the quantity of liberated Si⁴⁺ and Al³⁺ is affected by the concentration of the NaOH solution. A highly concentrated NaOH

solution (10 M) is advantageous for decomposing aluminosilicate in fly ash and releasing Si⁴⁺ and Al³⁺ [32].

That rise of UCS with FA content could be understood by the blended SiO₂/Al₂O₃ ratio and the discrepancy among the MT and FA constituent's reactivity. Table 3 demonstrates that when the FA/MT ratio increase, the SiO₂/Al₂O₃ ratio conversely decreases. The effect of four Alkaline solution/FA ratios (0.6 0.8 1.2 and 2.4) on UCS with different curing temperatures at 10 M NaOH were studied and shown in Fig. 10. It has been found that a greater alkaline solution/FA ratio results in a better mechanical strength. The optimum UCS value was achieved at a 0.8 Alkaline solution/FA ratio with 36.04 (MPa). However, a significant decrease in UCS was observed from a 1.2 alkaline solution/FA ratio to 2.4. Leong et al. [60] achieved a similar result, where the UCS was enhanced substantially once the alkaline solution/FA ratio rose from 0.3 to 0.4 but mildly lowered when the alkaline solution/FA ratio increased above 0.4.

Influence of curing period on UCS

In this investigation, the role of the curing period was revealed as a critical factor in the solidification and stabilization of the mine tailings fly ash-based geopolymer. The UCS values of geopolymers cured under 25 °C (Fig. 7a) kept increasing over time, which is in agreement with the findings of Zhuang et al. [32], who claimed that longer curing time in the range of 6 h to 28 days enhanced the process of geopolymerization, leading to increased compressive strength. This was in contrast with those cured at 65 °C (Fig. 7b), which slightly decreased over time; this is in concordance with Palomo [17] results which confirmed that an extended curing period at elevated temperatures disintegrates the granular structure of the geopolymer, leading to dehydration and increased shrinking, and ultimately reduces the compressive strength. Nevertheless, this decrease might be attributed to room temperature (8 °C ± 2 °C), where the geopolymer specimens were kept after being cured in the oven at 65 °C for 24 h. This investigation was carried out during winter when the temperature was below 10 °C. That is why the optimum UCS value was achieved in 7 days (36 MPa). Nevertheless, further research is needed to demonstrate that paradox.

Influence of the liquid/solid ratio on UCS

The cumulative weight of the liquid part was the amount of the weight of water throughout the sodium silicate solution, the mass of water in the sodium hydroxide solution, and the mass of additional water, if any, applied to the blend. The weight of the solid part was the total amount of the fly ash mass, mine tailings mass, the mass of the sodium hydroxide solids, and the mass of the solids in the silicate sodium solution.

In Table 2 and Fig. 11(a–b), it can be deduced that the liquid/solid ratio (L/S) has a high effect on UCS. It diminishes with the increase of the L/S ratio. However, when the liquid part is too high, it can negatively affect the mechanical strength. By inversely computing this ratio to the solid/liquid ratio (S/L) in Table 2, it can be seen that the UCS is significantly enhanced with the increase of the S/L ratio. The chosen S/L ratios were in the range of 2.3–3.3, which is in accordance with the most appropriate ratio preferred for fly ash geopolymerization, around 3.0, as shown in the documentation [61]. This augmentation in UCS with the enhancement of the S/L ratio was reported by other researchers such as Yahya et al. [62]. It can be attributed to the extra water.

Conclusion

Based on the previously mentioned results, we conclude that the alkaline reagents ratios and curing conditions are great contributors to the mechanical strength, making fly ash-based geopolymer a suitable application in construction materials to tackle climate change. A good compressive strength can be achieved at a 25 °C curing temperature over time. Nevertheless, this research suggests avoiding performing geopolymer tests during winter when the temperature is below 10 °C, especially when testing high temperatures. Otherwise, one should find an alternative to keep the geopolymer specimens under room condition at 25 °C or above. In terms of an alkaline solution, the compressive strength is influenced by NaOH, particularly at 10 M. The NaOH/Na₂SiO₃ and Solid/Liquid ratios were found to contribute to the mechanical strength increasingly. We also suggest using this proposed fly ash proportion (28%, 44%, 54 and 61%) of the dry mix in manufacturing geopolymer, which has been demonstrated in this study to help achieve high compressive strength and allow the use of much mining waste that remains challenging for industries. Furthermore, because of the high compressive strength achieved in this study, which is acknowledged as a critical factor in achieving effective immobilization of heavy metals, we recommend using this proposed mixture to immobilize heavy metals in mine tailings such as Cu, Pb, Zn.

Acknowledgements We acknowledged and grateful to the Postgraduate Research & Practice Innovation Program of Jiangsu Province (SJCX17-0261), NSFC (51002080, 41501197), SPITP (201610300273), Top-notch Academic Programs Project of Jiangsu Higher Education Institutions (PPZY2015C222), and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD) for their support.

Author contributions AB conceptualization, methodology, software, formal analysis, investigation, visualization, writing—original draft. FD writing—review and editing, supervision. EAGK investigation,

software. ZS software, formal analysis. AB review and editing. FL supervision, project administration, validation, resources, writing—review and editing.

Declarations

Conflict of interest The authors declare no conflict of interest.

References

- Skousen JG, Sexstone A, Ziemkiewicz PF (2015) Acid mine drainage control and treatment. In: Barnhisel RI, Darmody RG, Daniels WL (eds) Reclamation of Drastically Disturbed Lands. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, pp 131–168
- Morin KA, Hutt NM (2001) Environmental geochemistry of mine-site drainage: practical theory and case studies Environ Geochemistry Minesite Drain. Surrey, British Columbia
- R. R. Zeng X, Wu J (1998) Seismic stability of coal-waste tailings dams. Geotechnical earthquake engineering and soil dynamics III. In: Proceedings of a specialty conference. Asce, 950–61
- Zhang L, Ahmari S, Zhang J (2011) Synthesis and characterization of fly ash modified mine tailings-based geopolymers. Constr Build Mater 25(9):3773–3781. <https://doi.org/10.1016/j.conbuildmat.2011.04.005>
- Van Jaarsveld JGS, Van Deventer JSJ, Schwartzman A (1999) The potential use of geopolymeric materials to immobilize toxic metals: part II. Material and leaching characteristics. Miner Eng 12(1):75–91. [https://doi.org/10.1016/s0892-6875\(98\)00121-6](https://doi.org/10.1016/s0892-6875(98)00121-6)
- Van Deventer JSJ, Lorenzen L, Van Jaarsveld JGS (1998) Factors affecting the immobilisation of metals in geopolymerised fly ash Res Report. Dep Chem Eng Univ Stellenbosch, South Africa, pp 283–291
- Davidovits J (1994) Properties of Geopolymer Cements. In: Proceedings First International Conference on Alkaline, Cem. Concr, pp 131–49
- Dimas D, Giannopoulou I, Paniais D (2009) Polymerization in sodium silicate solutions: a fundamental process in geopolymerization technology. J Mater Sci 44(14):3719–3730. <https://doi.org/10.1007/s10853-009-3497-5>
- Drechsler GAM (2005) Innovative material technologies: bringing resources sustainability to construction and mining industries. In: 48th Inst. Quarr. Conf. Adelaide SA, Aust
- Jakubick AT, McKenna G, Robertson AM (2003) Stabilisation of tailings deposits: international experience. Min. Environ. Con. III, pp 9
- Neupane K (2016) Fly ash and GGBFS based powder-activated geopolymer binders: a viable sustainable alternative of portland cement in concrete industry. Mech Mater 103:110–122. <https://doi.org/10.1016/j.mechmat.2016.09.012>
- Ferone C, Roviello G, Colangelo F, Cioffi R, Tarallo O (2013) Novel hybrid organic-geopolymer materials. Appl Clay Sci 73(1):42–50. <https://doi.org/10.1016/j.clay.2012.11.001>
- Singh R, Budarayavalasa S (2021) Solidification and stabilization of hazardous wastes using geopolymers as sustainable binders. J Mater Cycles Waste Manag 23(5):1699–1725. <https://doi.org/10.1007/s10163-021-01245-0>
- Komnitsas D, Zaharaki K (2007) Geopolymerisation: a review and prospect for the mineral industry. Miner Eng 20:1261–1277
- Van Deventer JSJ, Provis JL, Duxson P, Lukey GC (2006) Technological, environmental and commercial drivers for the use of geopolymers in a sustainable materials industry. 2006 TMS Fall

- Extraction Processing Division Sohn International Symposium, 3:241–252
16. Van Jaarsveld JGS, Van Deventer JSJ, Lukey GC (2002) The effect of composition and temperature on the properties of fly ash- and kaolinite-based geopolymers. *Chem Eng J* 89(1–3):63–73. [https://doi.org/10.1016/S1385-8947\(02\)00025-6](https://doi.org/10.1016/S1385-8947(02)00025-6)
 17. Palomo A, Grutzeck MW, Blanco MT (1999) Alkali-activated fly ashes: a cement for the future. *Cem Concr Res* 29(8):1323–1329. [https://doi.org/10.1016/S0008-8846\(98\)00243-9](https://doi.org/10.1016/S0008-8846(98)00243-9)
 18. Xu H, Van Deventer JSJ (2000) The geopolymerisation of aluminosilicate minerals. *Int J Miner Process* 59(3):247–266. [https://doi.org/10.1016/S0301-7516\(99\)00074-5](https://doi.org/10.1016/S0301-7516(99)00074-5)
 19. Wan Q, Rao F, Song S, Zhang Y (2019) Immobilization forms of ZnO in the solidification/stabilization (S/S) of a zinc mine tailing through geopolymerization. *J Mater Res Technol* 8(6):5728–5735. <https://doi.org/10.1016/j.jmrt.2019.09.040>
 20. Van Jaarsveld JGS, Lukey GC, Van Deventer JSJ, Graham A (2000) The stabilisation of mine tailings by reactive geopolymerisation. *Australas Inst Min Metall Publ Ser* 5(5):363–372
 21. Niu H et al (2020) Recycling mica and carbonate-rich mine tailings in alkali-activated composites: a synergy with metakaolin. *Miner Eng* 157:106535. <https://doi.org/10.1016/j.mineng.2020.106535>
 22. Xia M et al (2019) Solidification/stabilization of lead-zinc smelting slag in composite based geopolymer. *J Clean Prod* 209:1206–1215. <https://doi.org/10.1016/j.jclepro.2018.10.265>
 23. Ahmari S, Zhang L (2012) Production of eco-friendly bricks from copper mine tailings through geopolymerization. *Constr Build Mater* 29:323–331. <https://doi.org/10.1016/j.conbuildmat.2011.10.048>
 24. Jiao X, Zhang Y, Chen T, Bao S, Liu T, Huang J (2011) Geopolymerisation of a silica-rich tailing. *Miner Eng* 24(15):1710–1712. <https://doi.org/10.1016/j.mineng.2011.09.008>
 25. Kuranchie FA, Shukla SK, Habibi D (2016) Utilisation of iron ore mine tailings for the production of geopolymer bricks. *Int J Mining Reclam Environ* 30(2):92–114. <https://doi.org/10.1080/17480930.2014.993834>
 26. Lee S, van Riessen A, Chon CM, Kang NH, Jou HT, Kim YJ (2016) Impact of activator type on the immobilisation of lead in fly ash-based geopolymer. *J Hazard Mater* 305:59–66. <https://doi.org/10.1016/j.jhazmat.2015.11.023>
 27. Kovalchuk G, Fernández-Jiménez A, Palomo A (2007) Alkali-activated fly ash: effect of thermal curing conditions on mechanical and microstructural development—Part II. *Fuel* 86(3):315–322. <https://doi.org/10.1016/j.fuel.2006.07.010>
 28. Criado M, Fernández-Jiménez A, Palomo A (2010) Alkali activation of fly ash. Part III: effect of curing conditions on reaction and its graphical description. *Fuel* 89(11):3185–3192. <https://doi.org/10.1016/j.fuel.2010.03.051>
 29. Mustafa Al Bakria AM, Kamarudin H, Bin Hussain M, Khairul Nizar I, Zarina Y, Rafiza AR (2011) The effect of curing temperature on physical and chemical properties of geopolymers. *Phys Procedia* 22(2010):286–291. <https://doi.org/10.1016/j.phpro.2011.11.045>
 30. Arioz E, Arioz Ö, Koçkar ÖM (2013) The effect of curing conditions on the properties of geopolymer samples. *Int J Chem Eng Appl* 4(6):423–426. <https://doi.org/10.7763/ijcea.2013.v4.339>
 31. Arnold MC, de Vargas AS, Bianchini L (2017) Study of electric-arc furnace dust (EAFD) in fly ash and rice husk ash-based geopolymers. *Adv Powder Technol* 28(9):2023–2034. <https://doi.org/10.1016/j.apt.2017.05.007>
 32. Zhuang XY et al (2016) Fly ash-based geopolymer: Clean production, properties and applications. *J Clean Prod* 125:253–267. <https://doi.org/10.1016/j.jclepro.2016.03.019>
 33. Criado M, Palomo A, Fernández-Jiménez A (2005) Alkali activation of fly ashes. Part I: effect of curing conditions on the carbonation of the reaction products. *Fuel* 84(16):2048–2054. <https://doi.org/10.1016/j.fuel.2005.03.030>
 34. Tho-In T, Sata V, Chindaprasirt P, Jaturapitakkul C (2012) Previous high-calcium fly ash geopolymer concrete. *Constr Build Mater* 30:366–371. <https://doi.org/10.1016/j.conbuildmat.2011.12.028>
 35. Naghizadeh SOEA (2017) Pozzolanic materials and waste products for formulation of geopolymer cements in developing countries: a review. *Concr. Beton J. Concr Soc South Afr* 151(November):22–31
 36. Naghizadeh A, Ekolu SO (2019) Method for comprehensive mix design of fly ash geopolymer mortars. *Constr Build Mater* 202:704–717. <https://doi.org/10.1016/j.conbuildmat.2018.12.185>
 37. Bernal SA et al (2014) Alkali activated materials, vol 13. Springer, Dordrecht
 38. Vora PR, Dave UV (2013) Parametric studies on compressive strength of geopolymer concrete. *Procedia Eng* 51:210–219. <https://doi.org/10.1016/j.proeng.2013.01.030>
 39. Tao Z, Pan Z (2019) Geopolymer concrete at ambient and elevated temperatures recent developments and challenges. *NED Univ J Res* 2:113–128. <https://doi.org/10.35453/nedjr-stmech-2019-0007>
 40. Steveson M, Sagoe-Crentsil K (2005) Relationships between composition, structure and strength of inorganic polymers: PPPart 2 Fly ash-derived inorganic polymers. *J Mater Sci* 40(16):4247–4259. <https://doi.org/10.1007/s10853-005-2794-x>
 41. Hardjito D, Wallah SE, Sumajouw DMJ, Rangan BV (2004) On the development of fly ash-based geopolymer concrete. *ACI Mater J* 101(6):467–472. <https://doi.org/10.14359/13485>
 42. Hou Y, Wang D, Zhou W, Lu H, Wang L (2009) Effect of activator and curing mode on fly ash-based geopolymers. *J Wuhan Univ Technol Mater Sci Ed* 24(5):711–715. <https://doi.org/10.1007/s11595-009-5711-3>
 43. Guo X, Shi H, Dick WA (2010) Compressive strength and microstructural characteristics of class C fly ash geopolymer. *Cem Concr Compos* 32(2):142–147. <https://doi.org/10.1016/j.cemconcomp.2009.11.003>
 44. Chindaprasirt P, Jaturapitakkul C, Chalee W, Rattanasak U (2009) Comparative study on the characteristics of fly ash and bottom ash geopolymers. *Waste Manag* 29(2):539–543. <https://doi.org/10.1016/j.wasman.2008.06.023>
 45. De Vargas AS, Dal Molin DCC, Vilela ACF, Da Silva FJ, Pavão B, Veit H (2011) The effects of Na₂O/SiO₂ molar ratio, curing temperature and age on compressive strength, morphology and microstructure of alkali-activated fly ash-based geopolymers. *Cem Concr Compos* 33(6):653–660. <https://doi.org/10.1016/j.cemconcomp.2011.03.006>
 46. Abdullah MMA, Kamarudin H, Mohammed H, Khairul Nizar I, Rafiza AR, Zarina Y (2011) The relationship of NaOH molarity, Na₂SiO₃/NaOH ratio, fly ash/alkaline activator ratio, and curing temperature to the strength of fly ash-based geopolymer. *Adv Mater Res* 328–330:1475–1482
 47. Chindaprasirt P, De Silva P, Hanjitsuwan S (2014) Effect of high-speed mixing on properties of high calcium fly ash geopolymer paste. *Arab J Sci Eng* 39(8):6001–6007. <https://doi.org/10.1007/s13369-014-1217-1>
 48. Rattanasak U, Chindaprasirt P (2009) Influence of NaOH solution on the synthesis of fly ash geopolymer. *Miner Eng* 22(12):1073–1078. <https://doi.org/10.1016/j.mineng.2009.03.022>
 49. Parthiban K, Saravana Raja Mohan K (2014) Effect of sodium hydroxide concentration and alkaline ratio on the compressive strength of slag based geopolymer concrete. *Int J ChemTech Res* 6(4):2446–2450
 50. Malkawi AB, Nuruddin MF, Fauzi A, Almatarneh H, Mohammed BS (2016) Effects of alkaline solution on properties of the HCFA geopolymer mortars. *Procedia Eng* 148(July):710–717. <https://doi.org/10.1016/j.proeng.2016.06.581>

51. Mustafa Al Bakri AM, Kamarudin H, Bnhussain M, Rafiza AR, Zarina Y (2012) Effect of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratios and NaOH molarities on compressive strength of fly-ash-based geopolymer. *ACI Mater J* 109(5):503–508. <https://doi.org/10.14359/51684080>
52. Davidovits J (1991) Geopolymers—inorganic polymeric new materials. *J Therm Anal* 37(8):1633–1656. <https://doi.org/10.1007/BF01912193>
53. Xu H, Van Deventer JSJ (2003) Effect of source materials on geopolymerization. *Ind Eng Chem Res* 42(8):1698–1706. <https://doi.org/10.1021/ie0206958>
54. Cheng TW, Chiu JP (2003) Fire-resistant geopolymer produce by granulated blast furnace slag. *Miner Eng* 16(3):205–210. [https://doi.org/10.1016/S0892-6875\(03\)00008-6](https://doi.org/10.1016/S0892-6875(03)00008-6)
55. Zheng L, Wang W, Shi Y (2010) The effects of alkaline dosage and Si/Al ratio on the immobilization of heavy metals in municipal solid waste incineration fly ash-based geopolymer. *Chemosphere* 79(6):665–671. <https://doi.org/10.1016/j.chemosphere.2010.02.018>
56. De Silva P, Sagoe-Crenstil K, Sirivivatnanon V (2007) Kinetics of geopolymerization: role of Al_2O_3 and SiO_2 . *Cem Concr Res* 37(4):512–518. <https://doi.org/10.1016/j.cemconres.2007.01.003>
57. Mustafa Al Bakri AM, Kamarudin H, Omar AK, Norazian MN, Ruzaidi CM, Rafiza AR (2011) The effect of alkaline activator ratio on the compressive strength of fly ash-based geopolymers. *Aust J Basic Appl Sci* 5(9):1916–1922
58. Kirschner AV, Harmuth H (2004) Investigation of geopolymer binders with respect to their application for building materials. *Ceram Silikaty* 48(3):117–120
59. Scholar RS, Babu KG (2008) Durability study of low calcium fly ash. 3rd ACF international conference-ACF/VCA, pp 1153–1159
60. Leong HY, Ong DEL, Sanjayan JG, Nazari A (2016) The effect of different Na_2O and K_2O ratios of alkali activator on compressive strength of fly ash based-geopolymer. *Constr Build Mater* 106:500–511. <https://doi.org/10.1016/j.conbuildmat.2015.12.141>
61. Nikoloutsopoulos N, Sotiropoulou A, Kakali G, Tsivilis S (2018) The effect of Solid/Liquid ratio on setting time, workability and compressive strength of fly ash based geopolymers. *Mater Today Proc* 5(4):27441–27445. <https://doi.org/10.1016/j.matpr.2018.09.062>
62. Yahya Z, Abdullah MMAB, Hussin K, Ismail KN, Razak RA, Sandu AV (2015) Effect of solids-to-liquids, Na_2SiO_3 -to- NaOH and curing temperature on the palm oil boiler ash (Si + Ca) geopolymerisation system. *Materials (Basel)* 8(5):2227–2242. <https://doi.org/10.3390/ma8052227>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.