

ORIGINAL ARTICLE

Lightweight and durable foamed geopolymers aerated using dual-function lime and aluminum powder for sustainable construction

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Abstract

This study examines the production of lightweight foamed geopolymers using aluminum powder as the main foaming agent and lime as both a partial replacement for ground granulated blast-furnace slag (GGBFS) and a secondary contributor to pore formation. While the individual effects of aluminum powder and lime have been reported in the literature, their combined use in GGBFS-based foamed geopolymers has received little attention. In particular, the influence of lime on both matrix development and pore generation remains unclear. Nine mixtures were prepared by varying the lime content between 0 and 20% and the aluminum powder dosage between 3 and 12 g. The results indicate that adding 10% lime produced the most balanced performance. At this level, the pore structure became more uniform, pore coalescence was reduced, and early-age strength improved compared with mixtures without lime. Increasing the lime content to 20% did not generate additional porosity and generally resulted in lower performance. The beneficial effect of 10% lime was also reflected in the durability results. Mixtures containing 10% lime together with moderate aluminum dosages showed lower thermal conductivity and better resistance to freeze–thaw cycles and carbonation. SEM observations confirmed that these mixtures developed a more homogeneous pore network with fewer interconnected voids. The findings suggest that lime can do more than simply replace part of the precursor. When used at an appropriate dosage, it alters the foaming process and helps stabilize the resulting pore structure. This offers a practical route for producing foamed geopolymers with improved mechanical performance, durability, and thermal efficiency.

Keywords Aluminum powder · Lime · Foamed geopolymers · Pore formation · Mechanical properties

1 Introduction

Geopolymers are alkali-activated aluminosilicate binders that have attracted considerable interest as an alternative to ordinary Portland cement (OPC) due to their lower environmental footprint [1]. Depending on the precursor and activator system, they can be produced at relatively low temperatures, often below 100 °C, and in many cases satisfactory performance can be achieved under ambient curing conditions [2]. Although early



developments were largely driven by the need for fire-resistant materials [3], the scope of geopolymer applications has expanded significantly over the past decades. Today, they are being explored for a wide range of applications, including sustainable construction, thermal insulation, and acoustic materials.

For lightweight applications, pore formation is commonly induced using foaming agents such as aluminum (Al) powder, hydrogen peroxide, or organic surfactants, which release gas during the mixing and setting processes. Despite considerable progress in this field, achieving an optimal pore structure remains a major challenge, as reducing density often comes at the expense of mechanical performance.

In addition to reducing the reliance on clinker-based binders, geopolymer systems have demonstrated good long-term mechanical performance, high thermal resistance, and durability in aggressive environments. Another attractive feature is their ability to incorporate a wide range of industrial by-products and waste streams, including fly ash [4], construction and industrial wastes [5], slags [6], and dolomite [7]. This flexibility aligns well with current efforts to promote resource efficiency and circular economy practices within the construction sector. Despite these advantages, the widespread use of geopolymers in the construction industry remains limited. The gap between laboratory-scale research and large-scale implementation is often attributed to a combination of technical challenges, regulatory uncertainty, and market acceptance issues [8]. One way to accelerate their adoption is to target applications where conventional cement-based materials face clear limitations or where geopolymers can provide additional value.

Lightweight foamed materials (FM) represent such an application area. These materials are increasingly used in non-structural elements because of their low density and thermal insulation properties. However, conventional foamed materials are typically produced using large quantities of OPC, with cement contents that can exceed 600 kg/m^3 [9]. Such high binder contents inevitably increase the embodied carbon of the material and diminish many of the environmental benefits associated with lightweight construction. In this regard, foamed geopolymers offer an opportunity to combine reduced environmental impact with the functional advantages required for lightweight building applications. Reducing density through the introduction of air voids can improve thermal insulation and lower material consumption, making these materials attractive for non-structural and energy-efficient building applications. Pore formation is commonly achieved using foaming agents such as aluminum powder, hydrogen peroxide, or various surfactants, all of which generate gas during the fresh stage of the material. However, producing a lightweight geopolymer with a well-controlled pore structure remains a challenge. A reduction in density is often accompanied by a loss of strength, and excessive pore connectivity can adversely affect durability. As a result, the development of foamed geopolymers requires a careful balance between porosity and engineering performance.

The growing demand for energy in the built environment, particularly for heating, ventilation, air conditioning, and cooling (HVAC) systems, continues to place significant strain on global energy resources. It is estimated that HVAC-related operations account for nearly 38% of total building energy use [10], highlighting the importance of improving the energy efficiency of building envelopes. Consequently, considerable attention has been directed toward lightweight construction materials that can reduce heat transfer through building components [11] while also lowering the environmental burden associated with material production [12].

In parallel, there has been growing interest in the use of alternative binders [13] and waste-derived resources [14] to develop more sustainable construction material. A substantial body of research has demonstrated that industrial by-products can be successfully incorporated into cementitious systems [15], reducing carbon emissions without compromising mechanical performance or durability [16]. Against this backdrop, foamed geopolymers have attracted increasing attention. Their low density and inherently low thermal conductivity make them well suited for insulation-oriented applications, while the use of industrial by-products as precursors offers additional environmental benefits. These characteristics position foamed geopolymers as a promising material for energy-efficient and sustainable building construction [17].

The most popular FMs include foamed concrete, glass foam, and porous ceramic. Among these materials, foamed concrete exhibits reasonably low thermal conductivity and an adjustable density. Controlling the

distribution, nature, and size of voids is the essential step in the production of FM. The voids can be introduced either via gas-releasing agents (such as hydrogen peroxide (H_2O_2), fine Al powder, or zinc powder) or by introducing air bubbles via an organic foaming agent [18]. Various foaming techniques, along with the mixture proportions and the curing regimes employed, influence the distributions and sizes of FM, which, in turn, impact the properties of the resulting FM. Among various foaming techniques/materials, Al powder is commonly used and is highly reactive under alkaline conditions [19]. The previous studies conducted on FM have mainly drawn the following conclusions [20]:

- Thermal and mechanical characteristics are primarily influenced by curing conditions, pore distribution, and pore-size distribution.
- Thermal performance depends on insulation characteristics and the density of material components.
- Increasing foaming agents (such as Al powder) increases the growth rate of porosity.

Given their low energy consumption, low thermal conductivity, good thermal stability, and low environmental burden, foamed geopolymers have emerged as promising lightweight porous materials in recent years [21]. Foamed geopolymer eliminates the need for high-temperature processing and produces approximately 80% less CO_2 emissions compared to cement-based foams. This significantly reduces the energy consumption of building materials during production while conserving energy and retaining heat during application. It is an eco-friendly, sustainable material that aligns with the national strategy of "energy saving and emission reduction." They have been evaluated for various uses, including membranes and their supports [22], adsorbents [23], filters [24], catalysts [25], and acoustic [26] and thermal insulators [27]. These applications are not feasible with their traditional dense alternatives.

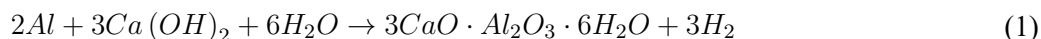
The properties of foamed geopolymers are influenced by several factors, including the type [28] and dosage [29] of the foaming agent, binder composition [30], water content [31], and curing conditions [32]. Previous studies have consistently shown that increasing the amount of foaming agent generally leads to lower density and reduced mechanical strength, while porosity increases. However, when the foaming agent content exceeds a critical level, which varies depending on the mixture design and foaming mechanism, individual pores begin to merge, resulting in pore coalescence [19] and, in extreme cases, structural instability or collapse [33]. Considerable research has focused on the use of metallic powders and hydrogen peroxide as foaming agents in geopolymer systems. While these studies have provided valuable insights into pore formation and material performance, the range of foaming strategies investigated remains relatively limited. Given the diverse applications of geopolymers, there is a clear need to examine alternative foaming approaches. In particular, combining different foaming agents may offer opportunities to better control pore development and exploit potential synergistic effects, leading to improved mechanical, thermal, and durability performance in foamed geopolymer materials.

Although previous studies have examined lime either as a pore-generating additive [34] or as a constituent of geopolymer binder systems [35], its simultaneous use as both a partial binder replacement and a synergistic foaming aid in combination with aluminum powder has not been investigated. Moreover, the influence of such a dual-agent approach on pore structure development, mechanical performance, and durability under different environmental conditions remains largely unexplored. To address this research gap, the present study investigates the interaction between lime and aluminum powder in GGBFS-based foamed geopolymers through a comprehensive experimental program encompassing physical, mechanical, thermal, durability, and microstructural characterization.

2 Materials and methods

In this study, GGBFS and slaked lime acquired from were used as binder materials. Expanded perlite was used as a fine aggregate. The expanded perlite used in this study was obtained from Akper Mining Industry Trade Co. Ltd., Türkiye. In addition to precursor replacement, lime was used as a foaming agent, along with Al powder,

to generate hydrogen bubbles via a reaction among calcium hydroxide, aluminum, and water [36]. Hydrogen bubbles increase the volume of mortar (see Eq. 1).



Additionally, sodium hydroxide (SH) with 97% purity and liquid sodium silicate (SS) were used to prepare the alkaline activation solution. The activator solution was prepared 1 day prior to mixing to allow sufficient time for the chemicals to fully dissolve. A total of 9 different mixes were prepared with varying amounts of slag, lime, and Al powder. The total binder (GGBFS+lime) weight across all mixes was 3000 g. The weights of perlite, SH, and SS were 1100 g, 600 g, and 600 g for all specimens, respectively. The mixture designs are presented in Table 1.

The specimen preparation involved dry mixing of expanded perlite, GGBFS, lime, and Al powder for 2 min. Alkaline activating solution, prepared 1 day in advance, was then gradually introduced, followed by mixing for another 2 min. Mortar mixture was cast into molds and placed in an environmental chamber for 24 ± 2 h at 23 ± 2 °C. Afterward, the samples were demolded and cured in a curing chamber at 30 °C and 90% relative humidity for 28 days.

Physical properties of the specimens, namely moisture uptake, dry and after immersion bulk densities, apparent density, volume of permeable voids, and air content, were measured first. The details of mechanical and durability tests, together with specimen characteristics and the following standards for each test, are given in Table 2. To ensure reproducibility, three specimens ($n=3$) were cast for each mix design and testing day/condition. Therefore, all reported values represent the mean of three specimens/measurements, with standard deviations shown as error bars where applicable.

3 Results and discussion

3.1 Density and porosity

Figure 1 depicts the volume of permeable voids and air content in foamed geopolymers containing different amounts of lime and Al powder. Given that not all air-filled pores are permeable, closed pores trap air and do not contribute to permeability, whereas open or interconnected pores do; therefore, a higher air content typically increases total porosity. However, whether this results in a greater volume of permeable voids depends on the extent of pore connectivity.

In this context, the samples without lime (L0A3, L0A6, and L0A12) exhibited a decrease in both air content and permeable voids as Al content increased, suggesting that higher Al concentrations promote rapid gas release and possible pore coalescence before the geopolymer matrix sets. This results in more closed pores, consistent with the observed divergence between total air content and permeable porosity. In contrast, lime-containing

Table 1 Mixture proportions

Spec	Expanded perlite (g)	Slag (g)	Lime (g)	Lime (%)	Al powder (g)	SH (g)	SS (g)
(1)	(2)	(3)	(4)	(4) × 100/(3+4)	(6)	(7)	(8)
L0A3		3000	0	0	3		
L0A6		3000	0	0	6		
L0A12		3000	0	0	12		
L10A3		2700	300	10	3		
L10A6	1100	2700	300	10	6	600	600
L10A12		2700	300	10	12		
L20A3		2400	600	20	3		
L20A6		2400	600	20	6		
L20A12		2400	600	20	12		

Table 2 Performed experiments, specimen characteristics, and followed standards

Test	Test day/Remarks	Number of specimens	Sample size (mm)	Standard
Air content	90 days	3	40 × 40 × 160	TS 480–11
Volume of permeable voids	90 days	3	40 × 40 × 160	ASTM C457-09
Moisture uptake	90 days	3	40 × 40 × 160	ASTM C642
Apparent density	90 days	3	40 × 40 × 160	ASTM C567
Bulk density	90 days	3	40 × 40 × 160	TS EN 12350-6
Compressive Strength	3, 7, and 28 days	3 specimens per mix design and testing day	40 × 40 × 160	ASTM C109
Flexural Strength	3, 7, and 28 days		40 × 40 × 160	ASTM C78
Thermal Conductivity	90 days	3	200 × 200 × 30	TS EN 12664
High-temperature resistance	28 days A high-temperature furnace with a capacity of 1250 °C was utilized to expose samples to elevated temperatures. Samples were heated to 300 °C, 600 °C, 900 °C, and 1200 °C with rate of heat of 5 °C/min for 1 h, followed by cooling in the furnace for 30 min to avoid any thermal shock. Afterward, mass loss and samples' residual compressive strength was measured	3 specimens per mix design and exposure temperature	40 × 40 × 160	–
FT resistance	28 days The specimens were subjected to 30, 60, and 90 FT cycles. Each cycle consisted of 3 h of freezing (–18 °C) and 3 h of thawing (+4 °C). Afterward, mass loss and samples' residual compressive strength was determined	3 specimens per mix design and FT cycle condition	40 × 40 × 160	ASTM C666
Carbonation depth	The specimens were placed in the laboratory under open-air conditions, with a CO ₂ concentration of approximately ~0.04%, a temperature of 20 ± 2 °C, and a relative humidity of 40–45% for one year	3	40 × 40 × 160	–

mixes (especially at 10%) displayed a stable porosity profile and higher alignment between air and permeable void content. These characteristics indicate improved gas entrapment and slower setting behavior, likely due to lime's lower reactivity relative to GGBFS, which allows for more interconnected and uniformly distributed pores. Although pore formation in composites without lime may seem enough, most lime-free samples tend to have higher density and lower strength than those containing lime, as discussed in later sections.

Figure 1 also shows the apparent and dry bulk densities of foamed geopolymers. The figure shows that, regardless of the amount of lime and Al powder, the dry bulk density is lower than the apparent density. This is because the bulk density accounts for voids and pore spaces, whereas the apparent density does not. Except for samples containing 20% lime, the apparent and dry bulk densities correlate with air content and the volume of permeable voids, as shown in Fig. 1. For samples with 0–10% lime, an increase in Al content resulted in a lower apparent density, mirroring the trend observed in the volume of permeable voids. In contrast, dry bulk density exhibited an opposite trend to air content as the Al powder content increased in samples containing 0–10% lime. The lower densities observed in most samples containing 10–20% lime, compared to those without lime, can be credited to the greater density of GGBFS relative to lime.

Fig. 1 Apparent density, dry bulk density, volume of permeable voids, and air content of foamed geopolymers containing different amounts of lime and Al powder. *The variation among specimens was within approximately $\pm 2\%$

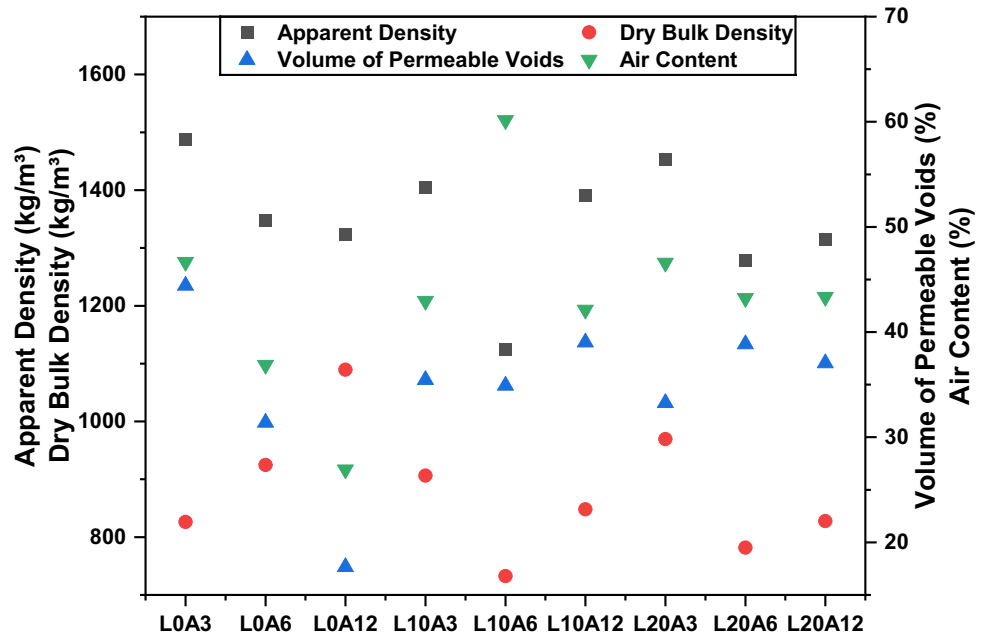


Fig. 2 Moisture uptake and bulk density (after immersion) of foamed geopolymers containing different amounts of lime and Al powder. *The variation among specimens was within approximately $\pm 2\%$

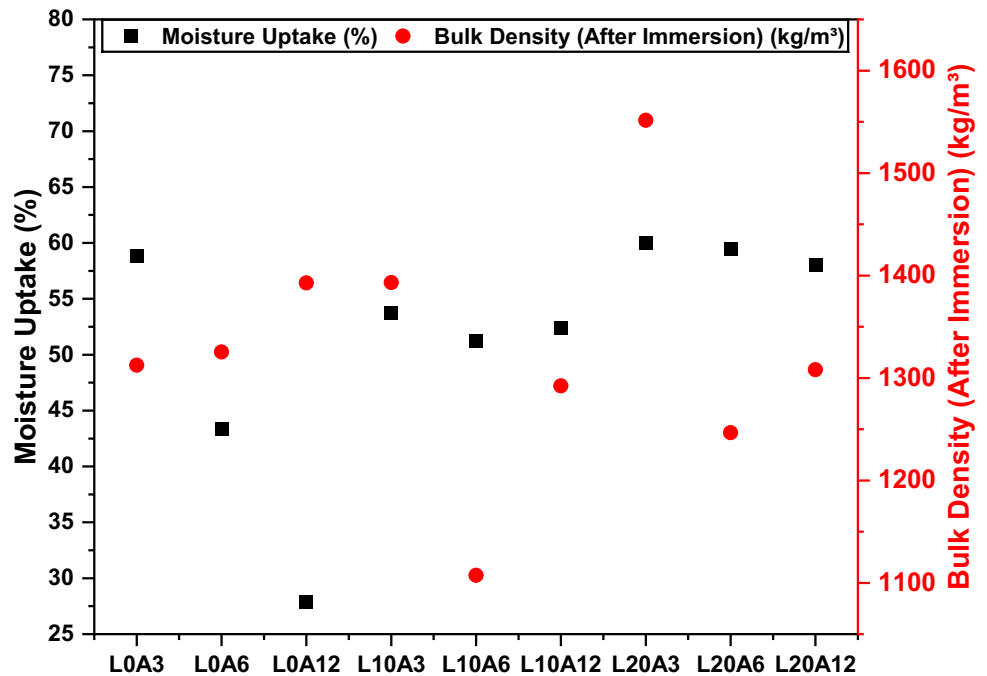


Figure 2 shows the moisture uptake and bulk density (after immersion) of foamed geopolymers containing different amounts of lime and Al powder. These characteristics confirm most of the points discussed for Fig. 1, where samples with a higher volume of permeable voids exhibited higher moisture uptake and bulk density, and vice versa, although slight fluctuations were observed. In other words, most samples with higher air content exhibited lower bulk density after immersion, and vice versa, along with a few fluctuations.

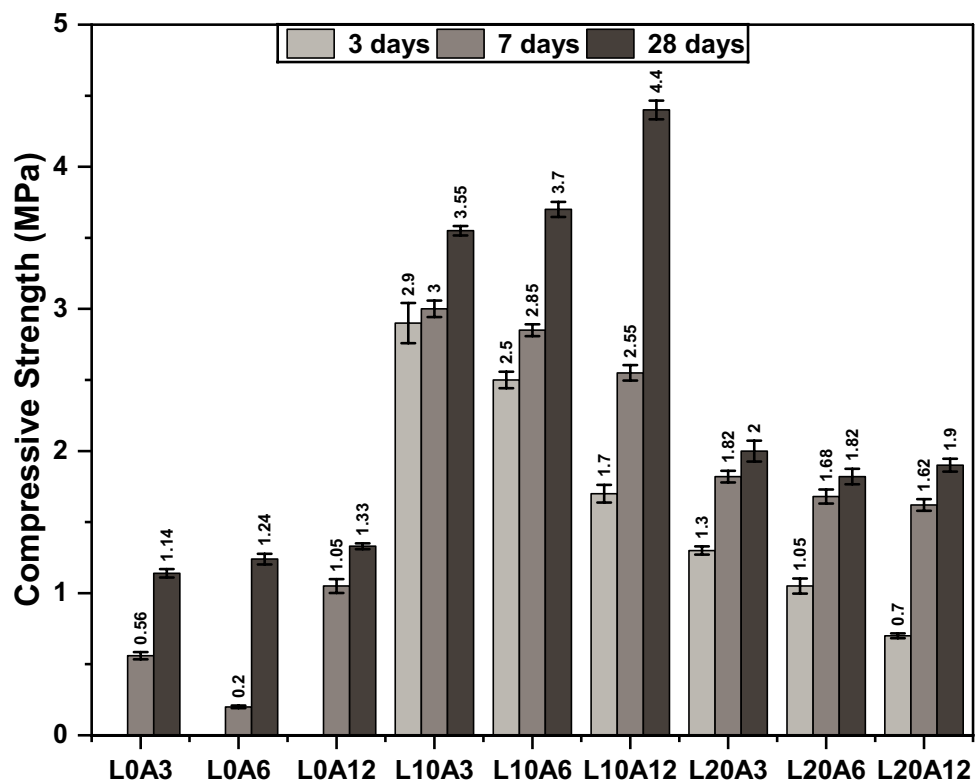
3.2 Compressive strength

Foamed geopolymers' compressive strength containing varying percentages of lime and Al powder is shown in Fig. 3. The figure demonstrates that compressive strength increased with sample age, irrespective of the amounts of lime and Al powder added. The absence of early-age strength in lime-free mixes may be attributed to insufficient calcium availability, which is key to early geopolymerization. This observation is consistent with previous studies reporting that the addition of lime or other calcium-containing precursors enhances geopolymer formation. For example, Diab [37] and Lekshmi and Sudhakumar [38] suggested that calcium present in calcium-rich precursors (such as lime and GGBFS) promote the formation of calcium aluminosilicate hydrate (C–A–S–H) gel, which, upon precipitation, acts as a nucleation site and facilitates rapid geopolymerization within the system. However, higher dosages of lime or other calcium-rich sources may adversely affect the geopolymerization process, as previously reported by Catalfamo et al. [39], who observed that incorporating calcium oxide into fly ash at levels above 3 wt.% can interfere with crystallization during zeolite formation.

In line with these findings, the present study indicates that incorporating 10% lime improves the compressive strength of geopolymers compared to 20%, as supported by the SEM images in Fig. 4. The L10A6 sample shows a relatively uniform pore structure with predominantly isolated and spherical pores, whereas the L20A6 sample exhibits larger, irregular, and more interconnected voids. This difference in pore morphology suggests improved pore stability and distribution at 10% lime. The enhanced performance at 10% lime may be associated with more effective early gel formation, which helps stabilize the pore structure during gas evolution. In contrast, the reduced strength at 20% lime may be linked to excessive calcium content, which could accelerate reaction processes and lead to less controlled pore development. However, this interpretation is inferred from the observed microstructural differences rather than directly measured reaction kinetics; therefore, future work should focus on quantifying reaction kinetics and phase evolution to validate these mechanisms.

Figure 5 illustrates the pore distribution in foamed geopolymers with varying amounts of lime and Al powder. In samples with 20% lime, the pores are concentrated along the edges, whereas in samples without lime, they are

Fig. 3 Compressive strength of foamed geopolymers having several percentages of lime and Al powder (values represent mean $\pm$ standard deviation ($n=3$), with error bars indicating $\pm$ SD)



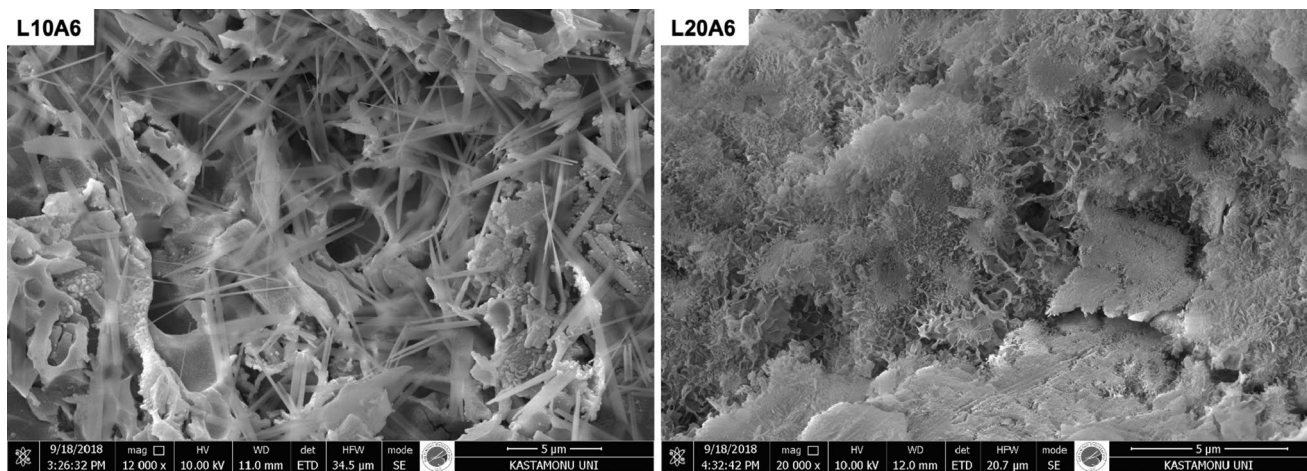


Fig. 4 SEM images of L10A6 and L20A6

predominantly located in the center. In contrast, samples with 10% lime exhibit minimal pore coalescence, with the coalesced pores being uniformly distributed throughout the sample. If a binder sets quickly, it hinders the foaming process and the related gas-induced expansion; therefore, the authors believe that replacing GGBFS with lime slowed the reaction, providing sufficient time for foaming and expansion to occur.

Figure 4 illustrates an increase in 28-day compressive strength with higher Al powder content, which was observed in this study, particularly in samples containing 10% lime. This trend differs from earlier reports [40], which typically show that excess Al powder reduces compressive strength due to increased porosity. A likely explanation for this deviation lies in the interplay between reaction kinetics, binder chemistry, and gas evolution timing. The presence of lime may delay the setting time and stabilize the foam, allowing better entrapment of hydrogen gas released by the Al powder, resulting in a more uniform and optimized pore structure rather than uncontrolled expansion and collapse. Additionally, Al powder may play a dual role by supplying reactive alumina species to the alkaline medium, slightly altering the Si/Al ratio and promoting geopolymer gel formation in ways not accounted for in conventional formulations. The relatively high compressive strength observed in the L10A12 mixture can likely be related to the combined effects of enhanced gel formation, more controlled gas generation, and a reduction in defects within the pore walls and surrounding matrix. These results indicate that the aluminum powder dosage at which strength begins to deteriorate is not fixed, but rather depends on factors such as lime content, binder composition, and curing regime.

3.3 Flexural strength

The flexural strength results of foamed geopolymers containing different lime and aluminum powder contents are presented in Fig. 6. Unlike the typical strength development observed in conventional cementitious materials, several foamed geopolymer mixtures, particularly those incorporating lime, exhibited a slight decrease in flexural strength with age. This behavior is somewhat unexpected, as ordinary cement-based systems generally gain strength over time through continued hydration. In contrast, the hardening of geopolymers is governed by geopolymerization and the progressive development of an aluminosilicate gel network.

In highly porous materials such as foamed geopolymers, long-term mechanical performance is influenced not only by gel formation but also by changes within the pore structure and surrounding matrix. The reduction in flexural strength may be linked to shrinkage-related effects, pore restructuring during maturation, or the formation of microcracks at the pore–matrix interface. These phenomena are likely to have a greater impact on flexural behavior than on compressive strength, as tensile stresses are more sensitive to local defects and discontinuities within the material [41]. Similar observations have been reported in previous studies, which found flexural strength to

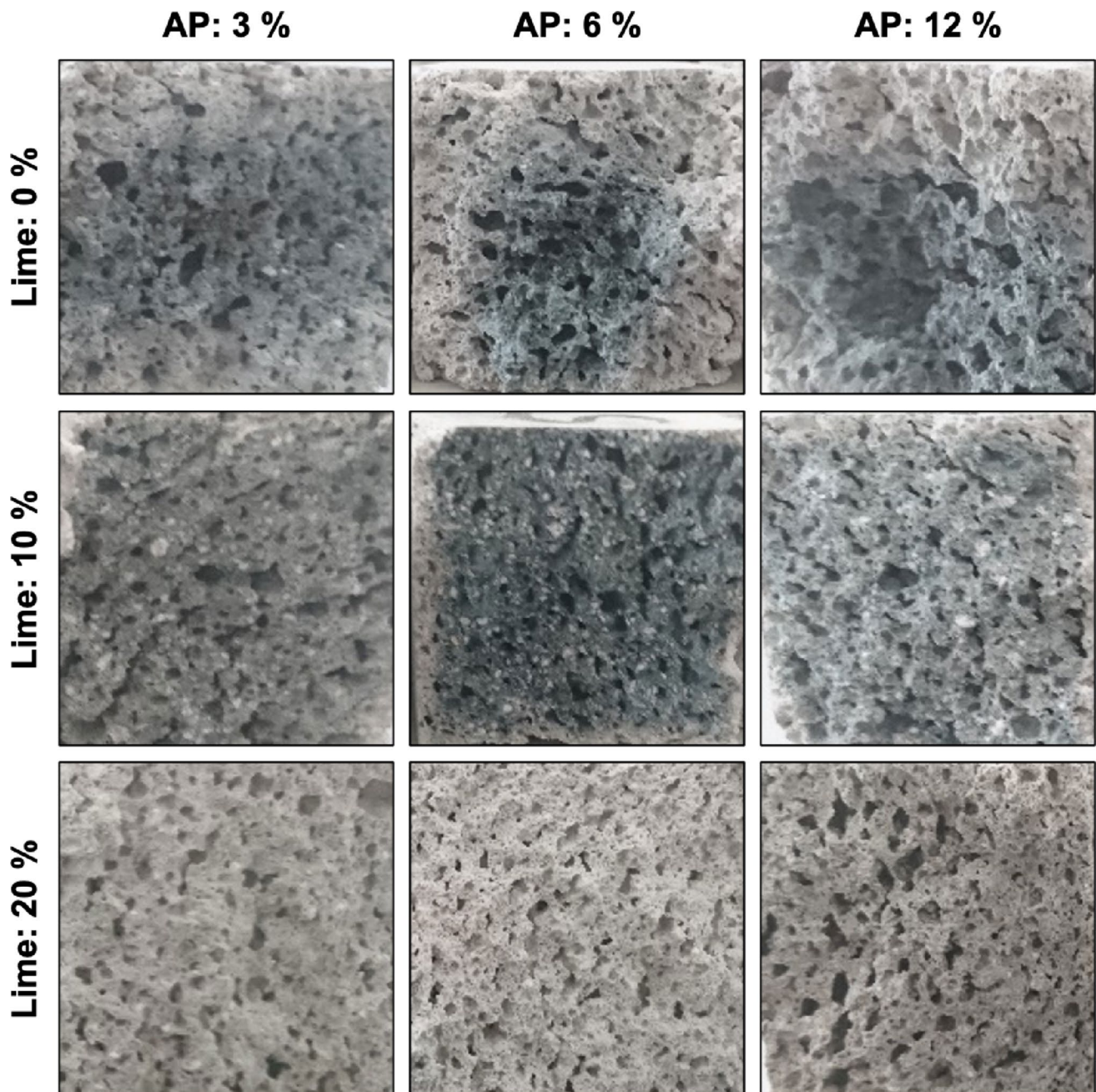
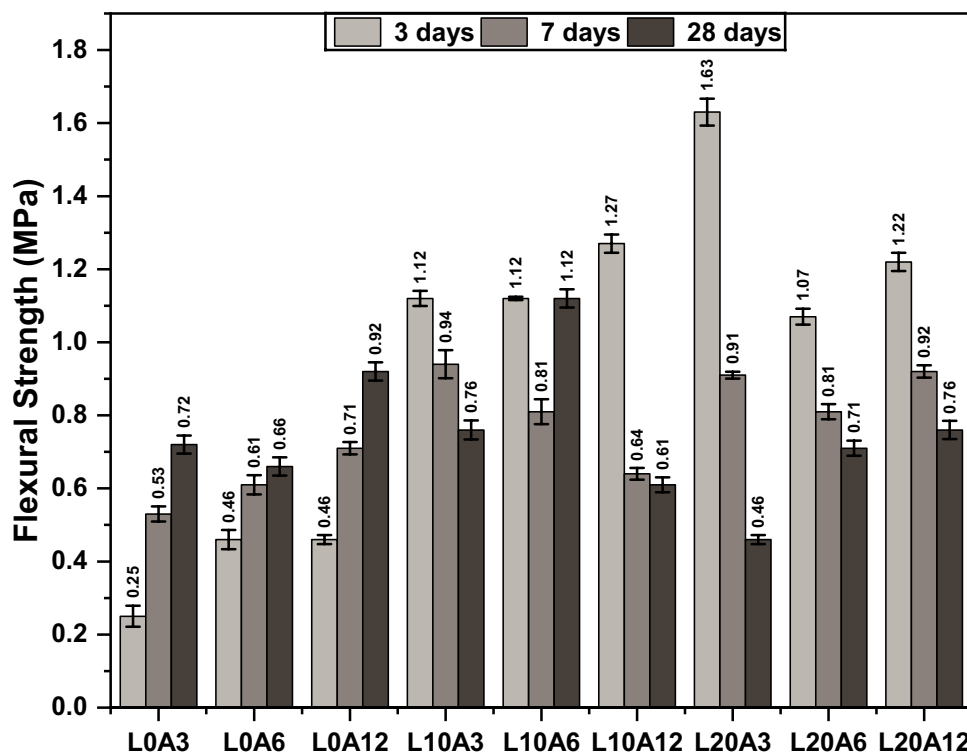


Fig. 5 Photographs of foamed geopolymers with varying amounts of lime and Al powder

be more strongly affected by porosity and density variations than compressive strength [42]. Nevertheless, these explanations remain hypothetical because parameters such as shrinkage, mass loss, and microcrack development were not directly measured in the present study. Further experimental investigations are therefore required to clarify the mechanisms responsible for the observed long-term flexural strength behavior.

This trend is also in agreement with the existing studies (e.g., [43]), which reported age-related reductions in strength in lightweight geopolymer foams, attributed to a gradual loss of internal cohesion and increasing pore connectivity as the material matures. In addition, flexural strength is particularly sensitive to surface imperfections, weak interfacial bonds, and localized stress concentrations. These effects become more pronounced in mixtures containing coalesced or irregular pores, which are more frequently observed in lime-rich systems. SEM

Fig. 6 Flexural strength of foamed geopolymers having various percentages of lime and Al powder (values represent mean $\pm$ standard deviation ($n=3$), with error bars indicating $\pm$ SD)



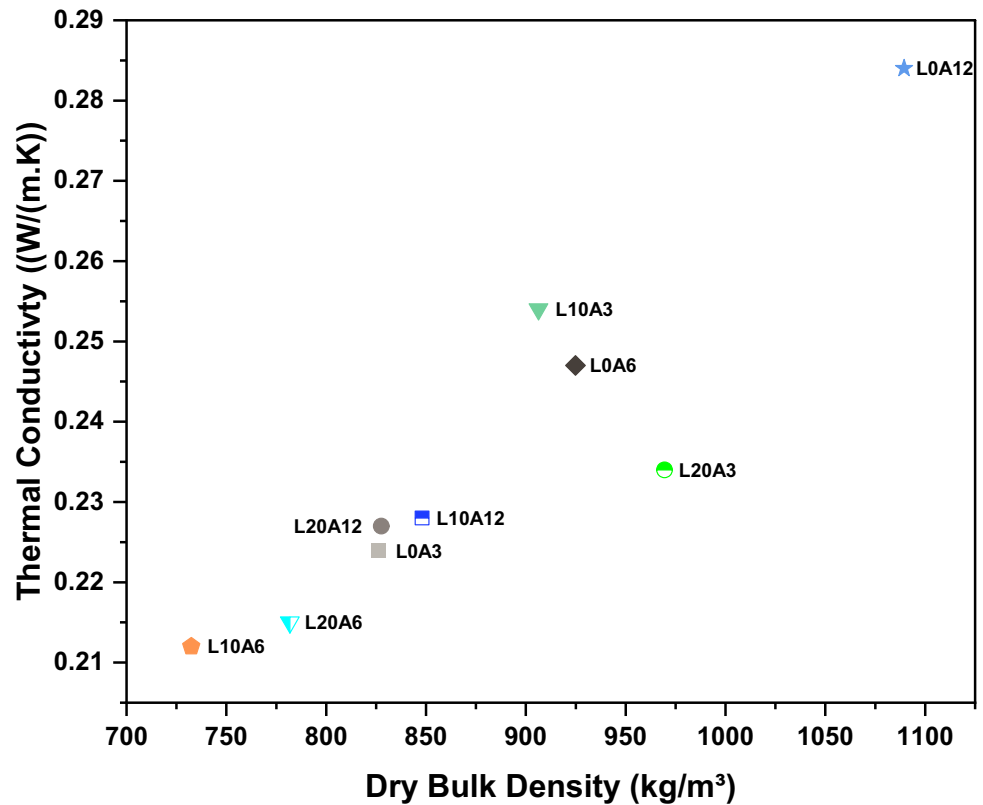
images (Fig. 16) further support this mechanism by showing more extensive microcracking and uneven pore morphology in samples with decreasing flexural strength. Existing studies highlight the inherently lower flexural strength of foamed geopolymers and propose various strategies to enhance it, such as fiber reinforcement. For instance, Liu et al. [44] and Wang and Tan [45] developed foamed composites that achieved flexural strengths of <1 MPa and below <2 MPa, respectively.

3.4 Thermal conductivity

Figure 7 presents the relationship between dry bulk density and thermal conductivity of foamed geopolymers with different percentages of lime and Al powder. The thermal conductivity of lime-containing samples decreased with increasing Al powder content. A similar trend has been observed in previous studies (e.g., [20, 33, 40]). Whereas, in lime-free samples, thermal conductivity increased with increasing Al content, consistent with the increase in dry bulk density.

As a non-porous matrix in geopolymer foams has a similar chemical composition, thermal conductivity is primarily affected by porosity and the distribution of pores. Given that adding Al powder increases porosity, it reduces the thermal conductivity of foamed geopolymers. In other words, Al powder reduces the solid matrix with high thermal conductivity while increasing the number of gas-filled pores, which have lower thermal conductivity. At the same Al powder content, the effect of lime content on thermal conductivity appears to be non-linear. When the Al powder dosage was 3 g, adding 10% lime increased thermal conductivity, whereas a further increase in lime content decreased it. In contrast, et al. powder dosages of 6–12 g, adding 10–20% lime led to a significant decrease in conductivity. These variations suggest a coupled influence of lime and Al powder on the development of pore structure and density. A strong statistical link was found between density and thermal conductivity. The coefficient of determination (R^2) for the relationship between dry bulk density and thermal conductivity was 0.8446, indicating that 84.46% of the variance in thermal conductivity may be attributable to variations in dry bulk density, thereby validating the higher thermal conductivity of the solid matrix relative to gas-filled pores. The existing literature (e.g., [46]) reports the absence of a relationship or a strong relationship

Fig. 7 Relationship between dry bulk density and thermal conductivity of foamed geopolymers containing varying amounts of lime and Al powder. *The variation among specimens was within approximately $\pm 2\%$



between density and thermal conductivity. These differing perspectives can be linked to changes in the types and methods of foaming agents used, binder types, curing regimes, and other influencing factors.

3.5 High-temperature resistance

Mass loss of foamed geopolymers having various percentages of lime and Al powder, subjected to high temperatures (300 °C, 600 °C, 900 °C, and 1200 °C) is shown as Fig. 8. All specimens were furnace-cooled for 30 min prior to testing (as detailed in Table 2) to minimize thermal shock effects. High-temperature degradation was quantified by mass loss (%) as an indicator of moisture removal and structural changes within the matrix. At a given Al powder and lime content, mass loss increased with temperature up to 900 °C but decreased for some samples at 1200 °C. The mass losses observed at 300 °C, 600 °C, 900 °C, and 1200 °C can be attributed to the loss of free water, the release of chemically bound water and decomposition, structural degradation, and sintering/melting effects, respectively [47]. Since most of the mass loss in geopolymers is due to moisture evaporation, a higher number of pores results in greater mass loss. Accordingly, most samples containing 20% lime exhibited greater mass loss, which increased with the Al powder content.

A temperature-dependent variation in composition effects was observed. For example, at 300 °C and 600 °C, most samples with 10% lime exhibited the lowest mass loss, followed by those without lime and those with 20% lime. In contrast, at 900 °C, most samples without lime exhibited lower mass loss than those containing lime. Finally, at 1200 °C, except for L10A3, samples containing 10% lime exhibited lower mass loss than those without lime or those containing 20% lime. As with lime content, the impact of Al powder content is also influenced by exposure temperature. Overall, samples containing 0–10% lime and a lower amount of Al powder exhibited lower mass loss compared to the other samples tested.

Figure 9a-b shows residual compressive strength and percentage compressive strength loss of foamed geopolymers, following exposure to high temperatures (300 °C, 600 °C, and 900 °C). At 1200 °C, specimens exhibited

Fig. 8 Mass loss of foamed geopolymers having various amounts of lime and Al powder. *The variation among specimens was within approximately $\pm 2\%$

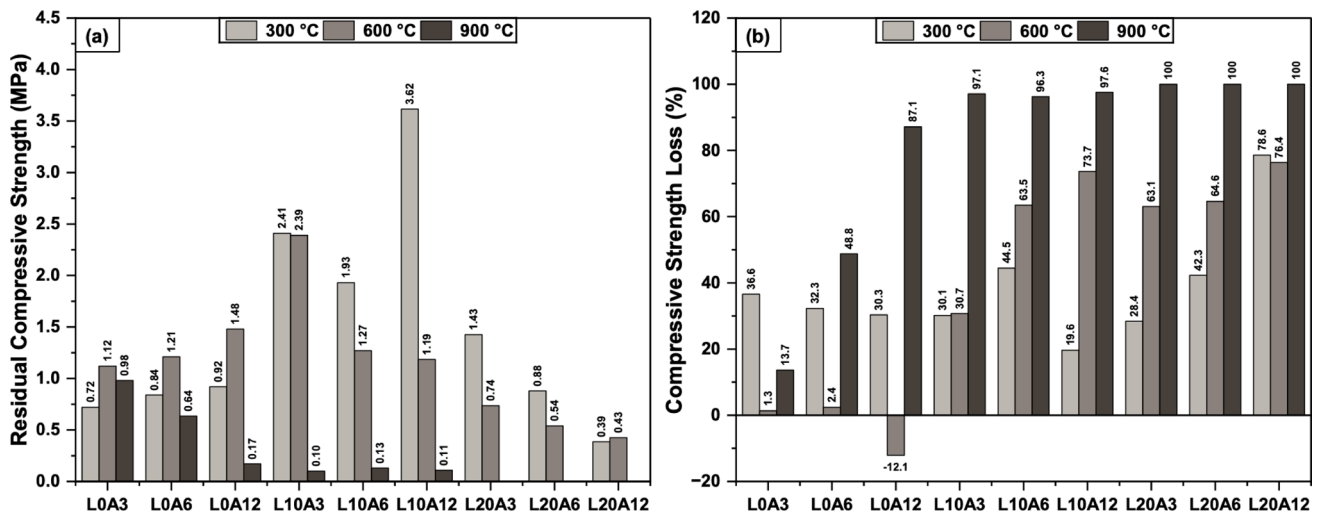
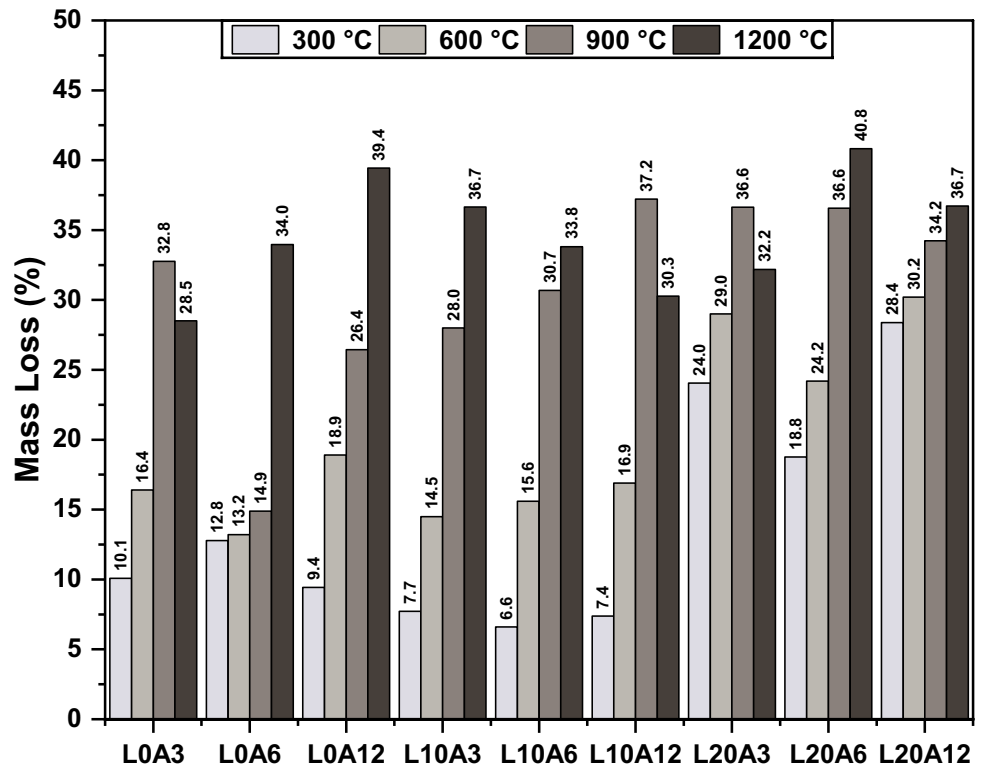


Fig. 9 **a** Residual compressive strength and **b** percentage compressive strength loss of foamed geopolymers containing varying amounts of lime and Al powder. *The variation among specimens was within approximately $\pm 2\%$

severe spalling and structural deterioration, preventing compressive testing. However, differences in mass loss and residual strength at intermediate temperatures (300–900 °C) were influenced by pore connectivity and binder composition. Lime-free samples showed lower compressive strength loss despite initially lower strength, suggesting more open pore networks that allowed for pressure dissipation during dehydration. In contrast, denser, lime-rich matrices may have resisted vapor escape [48], increasing internal pressure and spalling risk, highlighting a trade-off between room-temperature performance and thermal resilience.

As with lime, the effect of Al powder on the residual compressive strength of foamed geopolymers at elevated temperatures was inconsistent and highly temperature-dependent. In lime-free samples, increasing the

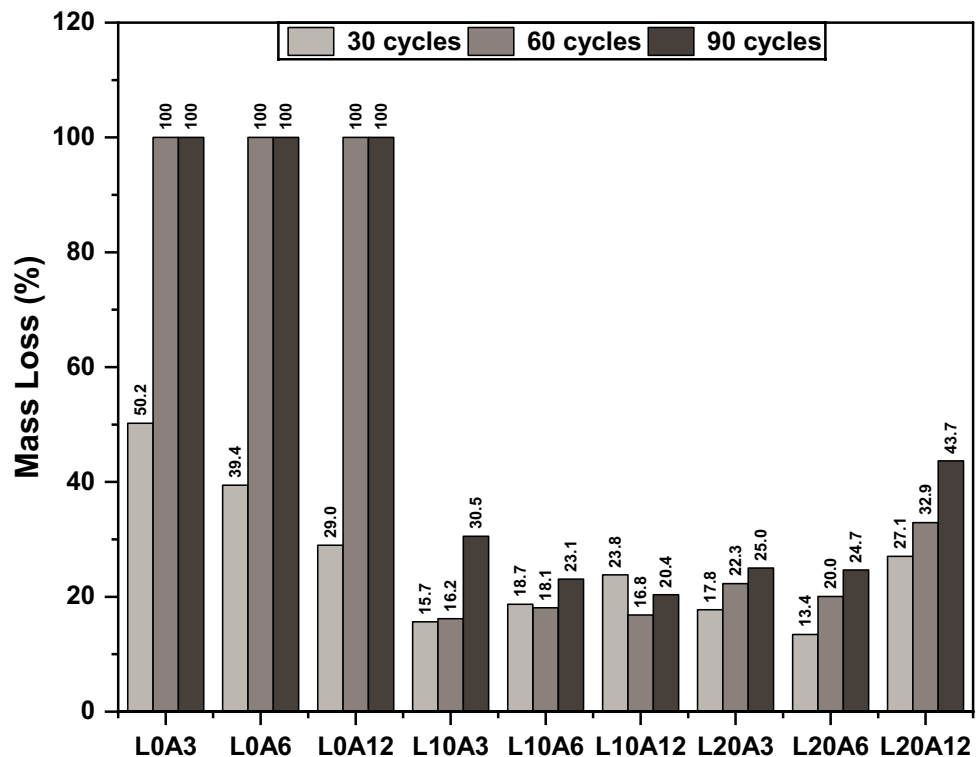
Al powder dosage enhanced residual strength at 300 °C and 600 °C, likely due to better initial pore formation and a more stable matrix. However, this trend reversed at 900 °C, where higher Al content corresponded with greater strength loss, probably due to increased porosity and thermally unstable pore walls. In samples containing 10–20% lime, a consistent decline in residual strength was observed as Al content increased across all tested temperatures. This suggests that while Al powder may enhance strength in the as-cured state, its influence on thermal stability is limited. The interaction between excessive pore generation and lime-induced matrix modification likely compromises the system's thermal integrity. Overall, Al powder appears beneficial for early mechanical enhancement but offers limited or even adverse effects on high-temperature performance, especially in lime-rich systems.

3.6 Freeze–thaw resistance

Figure 9 shows the mass loss of foamed geopolymers subjected to FT cycles (30, 60, and 90 cycles). The figure shows that the mass loss of most samples increased with increasing the FT cycles, irrespective of lime and Al powder dosage. Incorporating lime improved the samples' FT resistance, as evidenced by reduced mass loss. However, the optimal lime content was found to be 10%. Beyond this level, further increases in lime led to a slight increase in mass loss, though it remained lower than that of samples without lime. The addition of Al powder had an inconsistent effect on the samples' FT resistance, with the mass loss of samples without lime decreasing as the Al powder dosage increased. In contrast, the mass loss of samples with 10% lime slightly increased at an Al powder dosage of 6 g, but further increases in Al powder reduced the mass loss, although a few fluctuations were observed. For samples with 20% lime, incorporating 6 g of Al powder reduced mass loss compared with 3 g of Al powder. However, further increases in Al powder led to greater mass loss. This confirmed that incorporating Al powder into foamed geopolymer can enhance FT resistance, though the degree of improvement varies slightly with lime dosage (see Fig. 10).

Figure 9a–b shows residual compressive strength and percentage compressive strength loss of foamed geopolymers, following exposure to high temperatures (30, 60, and 90 cycles). The figure shows that the residual

Fig. 10 Mass loss of foamed geopolymers having different amounts of lime and Al powder, exposed to FT cycles (30, 60, and 90 cycles). *The variation among specimens was within approximately $\pm 2\%$



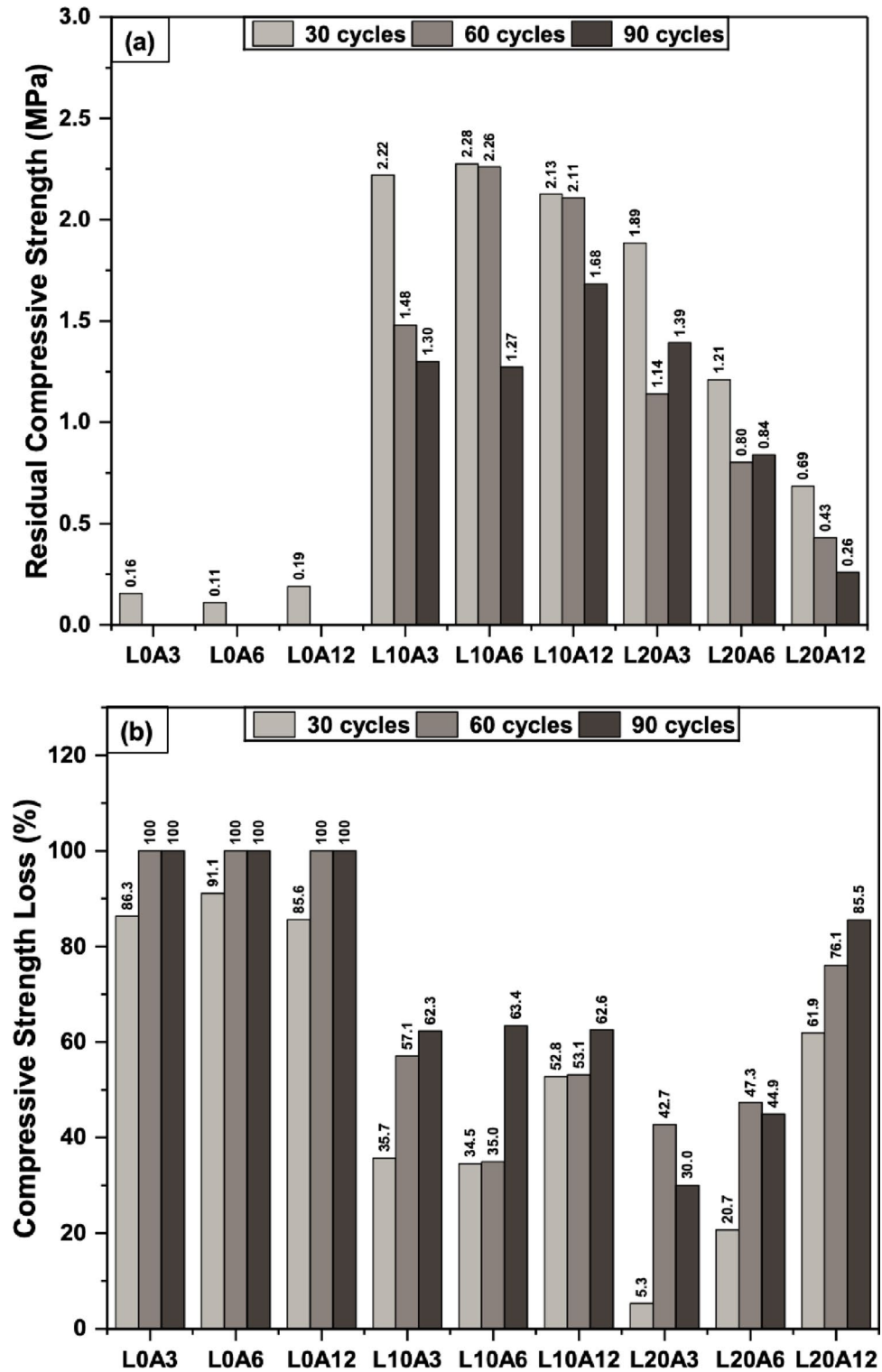
compressive strength of foamed geopolymers decreased, and the compressive strength loss increased with increasing FT cycles. Moreover, the residual compressive strength and compressive strength loss of the samples are aligned with their respective mass losses, indicating that samples with greater mass loss generally exhibit lower residual compressive strength and higher compressive strength loss. However, some fluctuations were observed; for example, L20A3 exhibited the lowest compressive strength loss but a higher mass loss than other geopolymers containing 20% lime. This suggests that the response of foamed geopolymers to FT is quite complex, possibly due to the presence of pores with variable characteristics. Overall, the compressive strength loss of geopolymers after FT cycles is proportional to the amount of foaming agent (Al powder in this research), which can be linked to a decrease in the solid content and increased porosity due to the increase in foam dosage. This is aligned with findings from previous studies (e.g., [49, 50]). As per JGJ/T 341–2014 [51], foamed concrete is deemed to have undergone frost heaving failure when its mass loss rate extends 5% or its compressive strength loss rate extends 25%, whichever occurs first. According to JGJ/T 341–2014 [51] criteria, only mixes with 10% lime and 3–6 g aluminum (e.g., L10A3, L10A6) demonstrated sufficient resistance to FT cycles. These mixes combine moderate porosity with limited pore connectivity, reducing water ingress and freeze-induced damage. Excessive lime (20%) or aluminum (12 g) led to higher pore volumes and larger pore diameters, which likely accelerated crack propagation during FT cycling. This is corroborated by post-FT SEM analysis showing increased microcracking and pore deformation in L20A12 (see Fig. 11).

FT in foamed composites refers to the process in which water infiltrates the pores and freezes at temperatures below zero, causing pore expansion and crack formation. An increase in humidity increases ice volume and the number of macropores, causing alterations and damage to pore diameter [52]. Thus, the smaller the pore size and the fewer the interconnected pores, the lower the water infiltration and the greater the FT resistance [53]. Given this, most samples with smaller pore dimensions demonstrated better frost resistance, as shown in Fig. 12. However, Fig. 12 illustrates that some samples, such as L20A3, exhibited higher pore dimensions yet still showed greater frost resistance. This suggests that, in addition to pore dimensions, pore connectivity has a significant impact on determining the frost resistance of foamed composites. This impact can be justified by Fig. 13, which shows the pore size of foamed geopolymers with varying amounts of lime and Al powder. The relatively large error bars reflect the inherent heterogeneity and the broad pore-size distribution of the foamed geopolymer matrix. The samples with better frost resistance have either smaller pore sizes or lack interconnected pores, while those with lower frost resistance typically exhibit larger pore sizes and limited pore connectivity.

3.7 Carbonation depth

Figure 14 illustrates the carbonation depth of foamed geopolymers with varying percentages of lime and Al powder, exposed to carbonation. The carbonation depth of the samples is aligned with their respective pore quantities and sizes. For example, a comparison of Figs. 13 and 14 reveals that samples with a greater number and larger size of pores exhibit higher carbonation depth, and vice versa. However, a few fluctuations are also observed contingent on the addition of lime and Al powder. For instance, increasing the amount of Al powder reduced carbonation resistance, as reported in prior research [54]. However, the specific amount of Al powder at which the sample exhibits the greatest carbonation depth varies; although lime influences this effect, the reason for the variation is unclear. Moreover, Hajimohammadi et al. [55] observed that using Al powder as a foaming agent in foamed geopolymer consumes part of the sodium hydroxide, thereby reducing carbonation resistance. The authors suggest that the approximately similar carbonation depths observed in samples without lime and those with 10% lime, despite the higher density and strength of the latter (which should theoretically resist CO₂ ingress), can be ascribed to the unreacted Ca(OH)₂ reacting with CO₂ to form CaCO₃. This suggests the occurrence of a competitive mechanism between pore availability (or pore structure) and the reaction among unreacted Ca(OH)₂ and CO₂, which determines carbonation resistance of such composites. This is more evident in the

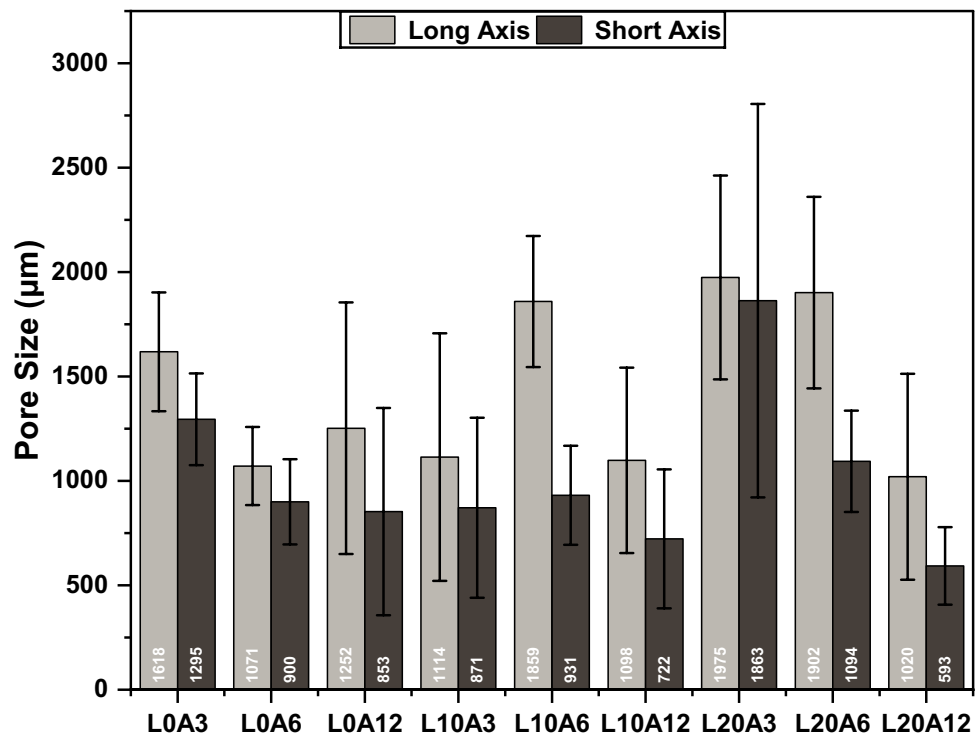
Fig. 11 **a** Residual compressive strength and **b** percentage compressive strength loss of foamed geopolymers having various amounts of lime and Al powder, subjected to FT cycles (30, 60, and 90 cycles). *The variation among specimens was within approximately $\pm 2\%$



samples containing 20% lime, which have larger, more numerous pores and a higher lime content, resulting in a greater carbonation depth.

Figure 15 shows the digital images of foamed geopolymers subjected to carbonation. The images reveal that samples with a higher lime content (20%) exhibit a partially colored carbonation front, in contrast to those without lime or with 10% lime. The images of the samples are aligned with the carbonation depth

Fig. 12 Pore size of foamed geopolymers having various amounts of lime and Al powder. Pore size was determined by averaging more than three measurements of the long and short axes, with variability reported as standard deviation (error bars)



values, as samples containing lime exhibit larger uncolored regions compared to those without lime. Similarly, samples with higher Al content show a greater colored region upon interacting with the phenolphthalein indicator. However, previous studies suggest that the phenolphthalein indicator method may not accurately distinguish partially carbonated regions because it reflects only changes in pH rather than the actual extent of carbonation reactions [56]. Therefore, future research should focus on achieving a more accurate assessment of the carbonation depth of these geopolymers by integrating thermogravimetric analysis (TGA) with pH measurements.

3.8 Microstructural analysis

Figure 16 presents SEM images of the foamed geopolymer mixtures. The micrographs confirm the highly porous nature of all specimens while highlighting significant differences in pore morphology, size distribution, and connectivity as a function of lime and aluminum powder content. Among the investigated mixtures, those containing 10% lime, particularly L10A6, exhibited the most refined microstructure, characterized by uniformly distributed, predominantly spherical closed pores and a limited presence of microcracks. By contrast, mixtures without lime and those containing 20% lime displayed more irregular pore geometries, pronounced pore coalescence, and a greater density of microcracks, features generally associated with inferior mechanical and durability performance. The optimized pore structure observed in the 10% lime mixtures appears to have contributed to their enhanced thermal insulation and carbonation resistance. The predominance of closed pores likely restricted moisture movement and CO₂ penetration, thereby reducing the susceptibility of the matrix to environmental degradation. In contrast, mixtures with higher aluminum powder dosages or excessive lime content showed evidence of interconnected porosity, suggesting that the percolation threshold [29] had been exceeded. The formation of continuous pore networks is known to reduce load-bearing capacity and weaken the material compared with systems dominated by isolated closed pores [49]. Pore coalescence was evident

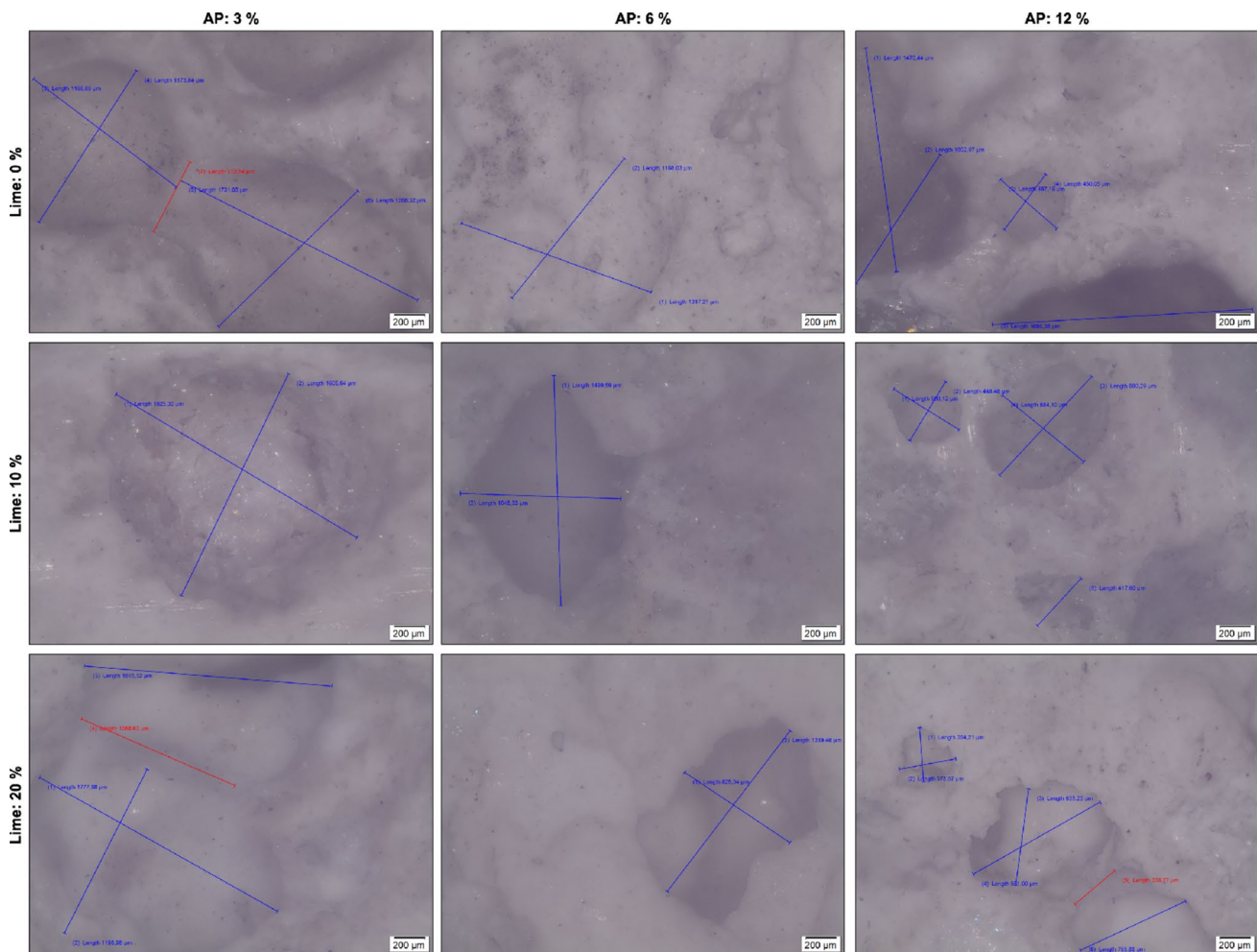


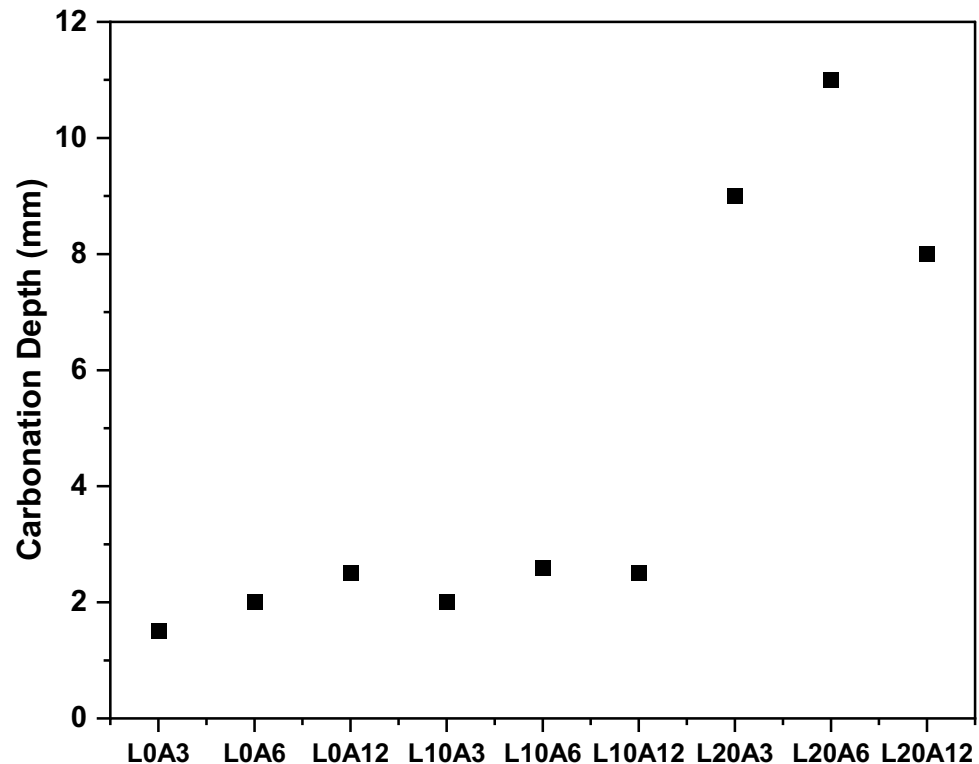
Fig. 13 Pore diameter of foamed geopolymers having various amounts of lime and Al powder

in nearly all mixtures outside the 10% lime series, providing a microstructural explanation for their lower mechanical and durability performance. Moreover, the quality of the pore structure generally deteriorated with increasing aluminum powder content, an effect that was particularly noticeable in mixtures containing 12 g of aluminum powder. Conversely, the 10% lime mixtures maintained a more homogeneous pore distribution and consistent pore geometry, even at higher aluminum dosages. Many of these pores were partially covered by reaction products, likely needle-like ettringite, especially in L10A6. This refined and well-connected microstructure is believed to have played a key role in achieving a favorable balance between low density, adequate strength, and enhanced durability.

4 Recommendations

To strengthen the understanding of foamed geopolymer behavior and address the limitations identified in this study, several research directions warrant further attention.

Fig. 14 Carbonation depth of foamed geopolymers subjected to carbonation.
*The variation among specimens was within approximately $\pm 2\%$



1. The long-term mechanical performance of foamed geopolymers is governed by complex interactions between pore structure evolution, shrinkage, and microcrack formation. In the present study, the observed reduction in flexural strength with age was attributed to these mechanisms based on indirect evidence and existing literature. However, direct confirmation was not possible because parameters such as shrinkage, mass loss, and crack development were not measured. Future studies should therefore incorporate drying shrinkage measurements, mass-loss monitoring, and quantitative crack-density analyses to better understand the mechanisms governing long-term flexural behavior and structural stability.
2. The identification of 10% lime as the optimal content is based on the experimental conditions and mixture compositions considered in this work. While the results provide valuable insights, further research is needed to establish broader composition–performance relationships and determine whether the observed trends remain valid under different material systems and curing regimes. Recent studies have demonstrated the effectiveness of statistical modeling, machine learning, and optimization techniques in evaluating complex cementitious and geopolymer mixtures [57]. The dataset generated in this study offers a useful foundation for such approaches. Future work should therefore employ data-driven modeling and multi-objective optimization frameworks to identify optimal mixture designs while simultaneously considering mechanical, thermal, and durability requirements.
3. The assessment of carbonation depth using visual indicators, such as phenolphthalein staining, may not fully capture the actual extent of CO_2 penetration and the associated chemical changes within the matrix. A more comprehensive evaluation of carbonation behavior is therefore required. Future investigations should combine TGA with direct pH measurements and advanced microstructural characterization techniques to better

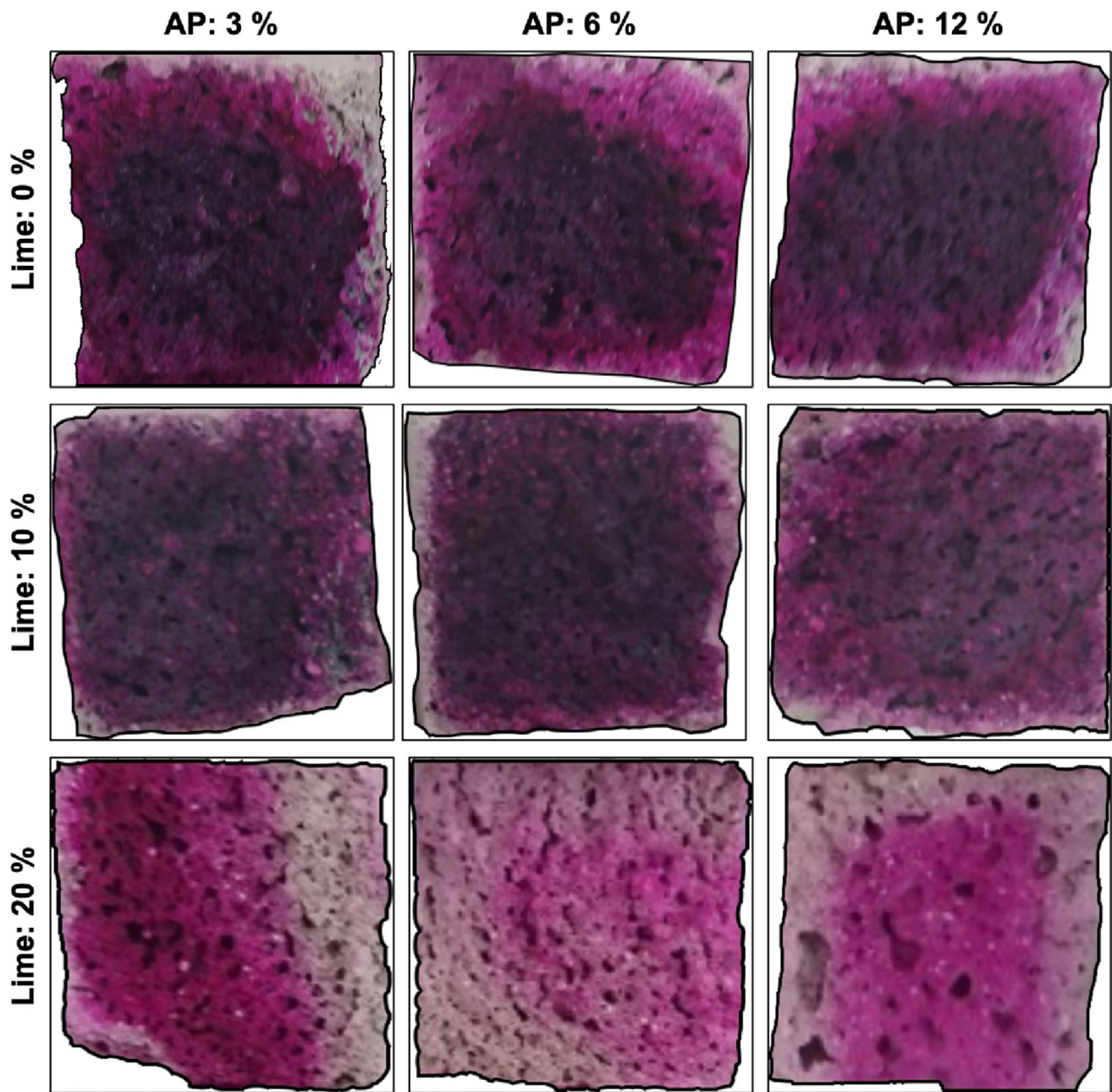


Fig. 15 Photographs of foamed geopolymers having various amounts of lime and Al powder subjected to carbonation

elucidate carbonation mechanisms, reaction products, and their influence on long-term durability. Such an integrated approach would provide a more reliable assessment of carbonation resistance in foamed geopolymer systems.

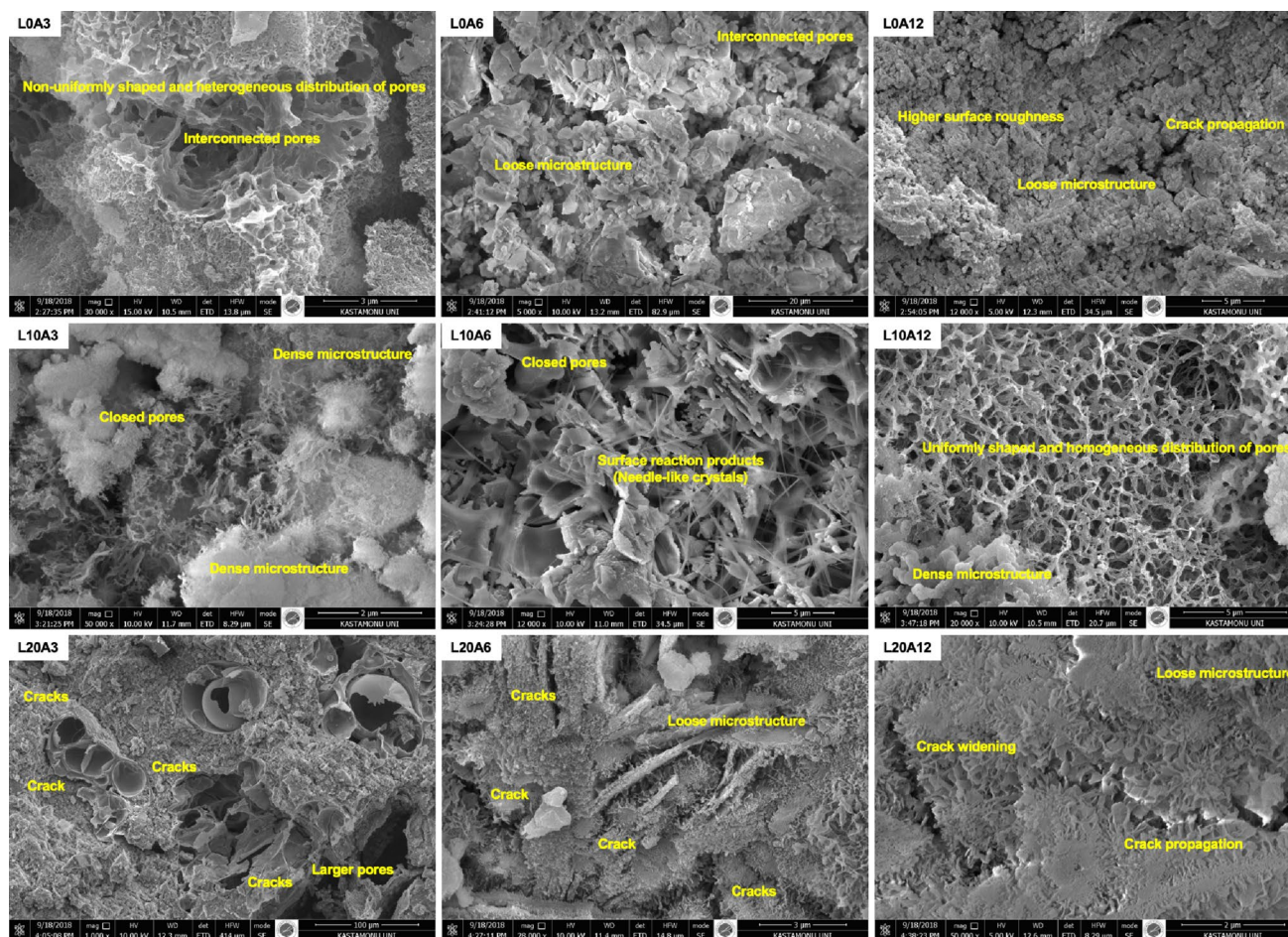


Fig. 16 SEM images of foamed geopolymers containing different amounts of lime and Al powder

5 Conclusions

This study examined the combined use of aluminum powder as the primary foaming agent and lime as both a supplementary foaming aid and a partial precursor replacement in the production of lightweight foamed geopolymers. Based on the experimental findings, the following conclusions can be drawn:

1. Lime played a key role in controlling pore development and improving microstructural quality. Incorporating 10% lime promoted more efficient hydrogen retention, resulting in a more uniform pore distribution with fewer microcracks and reduced pore coalescence, as evidenced by SEM observations.
2. The influence of aluminum powder depended on both its dosage and the lime content of the mixture. In lime-free systems, increasing the aluminum dosage mainly increased porosity without providing significant mechanical benefits. In contrast, mixtures containing 10% lime and 6–12 g of aluminum powder exhibited a more favorable balance between pore structure refinement and strength development.
3. The highest compressive strength was obtained for the L10A12 mixture, indicating that the combined action of lime and aluminum powder can enhance matrix stability and promote the formation of a stronger reaction-product network. Nevertheless, mixtures with lower aluminum contents generally showed better thermal insulation and durability performance because of their lower degree of interconnected porosity.

4. The most favorable freeze–thaw and carbonation resistance was observed in the L10A3 and L10A6 mixtures. Their superior durability is attributed to a refined pore structure dominated by isolated or weakly connected pores, which limited moisture transport and reduced CO₂ ingress into the geopolymer matrix.
5. Although L10A12 exhibited the highest mechanical strength, L10A6 provided the best overall balance of mechanical, thermal, and durability properties. Therefore, the mix with 10% lime and 6 g Al powder (L10A6) is recommended as the optimal formulation for practical applications.
6. The developed foamed geopolymer composites, particularly L10A6, demonstrate strong potential for light-weight and sustainable construction. With compressive strength exceeding 4 MPa, dry density below 1200 kg/m³, and thermal conductivity of 0.215 to 0.284 W/m.K, lime- and Al powder-based foamed geopolymers satisfy requirements for non-load bearing elements such as partition walls, insulating panels, and subfloor fills (e.g., EN 771–3 and ASTM C332). Overall, the proposed system offers a scalable and lower-carbon alternative to conventional autoclaved aerated concrete and foamed OPC-based materials, with tunable properties suitable for energy-efficient building applications.

Data availability Data will be made available on request.

Declarations

Conflict of 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.

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