Fly ash valorisation in geopolymer synthesis: effect of activator composition and curing conditions on mechanical performance

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Keywords: geopolymers, fly ash, mechanical properties, sustainable construction materials, circular economy
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Geopolymers are inorganic aluminosilicate polymers with an amorphous structure, synthesized under highly alkaline conditions at temperatures below 100°C. Their structure is formed through the polycondensation of SiO_4- and AlO_4- tetrahedra, resulting in a three-dimensional gel network of the N–A–S–H type, which constitutes the main binding phase in these materials. Due to their high mechanical strength, chemical and thermal resistance, and lower environmental impact compared to Portland cement-based materials, geopolymers are increasingly considered a promising alternative binder in sustainable construction applications (Sbahieh, McKay, and Al-Ghamdi 2023; Nergis et al. 2018).

Various aluminosilicate-rich raw materials can be used for geopolymer synthesis, including natural materials such as metakaolin and industrial by-products such as fly ash. In particular, fly ash is considered a highly suitable precursor due to its pozzolanic properties, chemical composition, and characteristic spherical particle morphology (Farhan, Johari, and Demirboğa 2020; Wu et al. 2025). Additionally, its reactivity may be enhanced through mechanical activation processes, including grinding, which increases the specific surface area and improves the mechanical performance of the resulting geopolymeric materials (Fernández-Jiménez et al. 2019; Kehinde et al. 2025).

The geopolymerization process involves dissolution of amorphous aluminosilicate phases in an alkaline environment, transport of dissolved silicon and aluminum species, and their subsequent polycondensation into a geopolymeric gel structure. In calcium-rich systems, additional C–(A)–S–H phases may also form, affecting both the microstructure and mechanical performance of the material (Gökçe, Tuyan, and Nehdi 2021). The final properties of geopolymeric materials strongly depend on synthesis parameters, including alkaline activator composition, activator-to-precursor ratio, and curing conditions. Literature reports indicate that NaOH concentrations in the range of 10–14 M are considered optimal for geopolymer synthesis, while elevated curing temperatures usually accelerate geopolymerization and contribute to the formation of denser and mechanically stronger matrices (Somna et al. 2011; Mortar et al. 2020; Abdullah et al. 2011).

In this study, geopolymer materials based exclusively on fly ash as an aluminosilicate precursor were investigated in the context of industrial waste valorisation and circular economy principles. The research focused on evaluating the influence of alkaline activator composition and curing conditions on the development of microstructure and mechanical properties of the obtained geopolymeric materials.

Geopolymer mixtures were prepared using a 10 M NaOH solution combined with sodium silicate solution (water glass). The investigated variables included the mass ratio of NaOH to water glass (NaOH:WG) and the activator-to-fly ash ratio (A:S). Sample identification and preparation conditions are summarized in Table 1.

Table 1. Summary of sample preparation conditions.

ID	A:S	NaOH:WG	CT, °C	ID	A:S	NaOH:WG	CT, °C
G_0,3_1_40	0,3	1	40	G_0,35_1_80	0,35	1	80
G_0,3_1_60	0,3	1	60	G_0,35_1,5_40	0,35	1,5	40
G_0,3_1_80	0,3	1	80	G_0,35_1,5_60	0,35	1,5	60
G_0,35_0,5_60	0,35	0,5	60	G_0,4_1_60	0,4	1	60
G_0,35_0,5_80	0,35	0,5	80	G_0,4_1_80	0,4	1	80
G_0,35_1_40	0,35	1	40	G_0,45_1_60	0,45	1	60
G_0,35_1_60	0,35	1	60	G_0,45_1_80	0,45	1	80

All specimens were initially cured in moulds for 24 h and subsequently thermally cured at 40°C, 60°C, or 80°C (CT) for an additional 24 h. After thermal treatment, samples were stored at 23°C until testing. Mechanical performance was evaluated based on compressive and flexural strength measurements performed after 7, 14, 21, and 28 days of curing.

The obtained results demonstrated that curing time had a significant positive effect on the development of mechanical strength, with progressive increases in both compressive and flexural strength observed during geopolymer maturation. The results also indicated that both the NaOH:WG ratio and curing temperature influenced the mechanical performance of the produced materials. The highest strength values were observed for selected mixtures cured at elevated temperatures, suggesting enhanced geopolymerization and formation of a denser binding matrix.

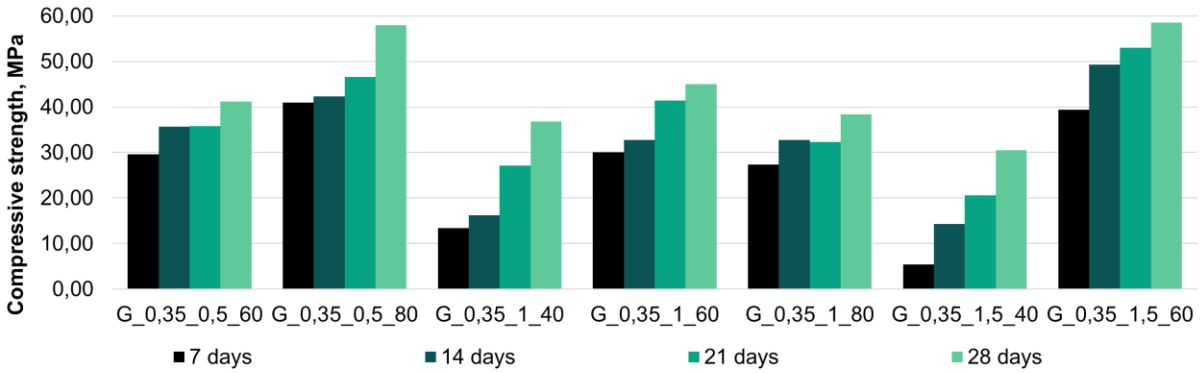

Fig. 1. Compressive strength results for specimens with an A:S ratio of 0.35

Additionally, scanning electron microscopy (SEM) analysis was performed for both raw fly ash and selected geopolymer samples at different curing stages. SEM observations confirmed the characteristic spherical morphology of fly ash particles and revealed the gradual formation of a compact geopolymeric gel structure during curing. Samples characterized by improved mechanical performance exhibited a more homogeneous and denser microstructure with a reduced number of unreacted particles.

a) b)

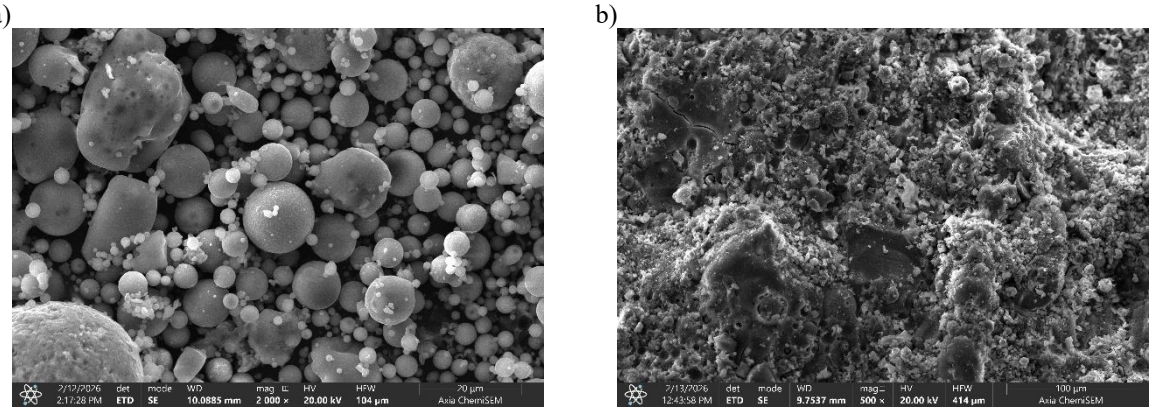

Fig. 2. SEM images: a) fly ash – the used precursor; b) geopolymer G_0.35_1_60 after 28 days of curing

The conducted research confirmed the potential of fly ash as a valuable precursor for geopolymer synthesis and demonstrated the possibility of producing alternative binder materials with promising mechanical properties. The obtained results support the utilization of industrial by-products in sustainable construction materials and align with circular economy strategies aimed at reducing waste generation and limiting the consumption of conventional cement-based binders.

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