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## Research Article

# Development of a sustainable geopolymer structural element with waste glass powder: Mechanical characteristics

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## ABSTRACT

In this study, the potential of converting waste glass powder, sourced from glass manufacturing processes in Turkey, into sustainable and environmentally friendly construction materials was explored. A novel approach was adopted by producing geopolymeric building elements using only waste glass powder, water, and varying concentrations of sodium hydroxide (2%, 4%, and 6%) in a completely cement-free system. This distinguishes the study from previous works, as it focuses solely on waste glass powder as the primary aluminosilicate source without incorporating additional binders such as fly ash or slag. The physical and mechanical properties of the produced samples were evaluated through unit weight, ultrasonic pulse velocity, compressive strength, flexural strength, and tensile strength tests. The results indicated that the mixture containing 4% sodium hydroxide provided optimal performance, demonstrating superior mechanical strength, structural integrity, and durability. Notably, the specimens produced with 4% NaOH exhibited higher durability than aerated concrete and achieved strength and density values close to conventional bricks, suggesting their potential applicability in non-load-bearing structural elements. Furthermore, this study addresses a significant gap in the literature regarding the standalone use of waste glass powder in geopolymer systems and contributes valuable data on its performance in solid form. The findings also highlight the material's potential to reduce reliance on Portland cement, thereby lowering carbon emissions and promoting the circular economy through effective waste utilization. Overall, the study offers an innovative and practical solution for sustainable construction by demonstrating the feasibility of producing high-performance geopolymer elements entirely from waste-derived materials.

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## 1. Introduction

In recent years, sustainability, environmental impact reduction, and the adoption of circular economy principles have become increasingly critical in the construction industry (Charef et al. 2022). In this context, the high carbon emissions and energy consumption associated with the production of traditional Portland cement have driven research into alternative binder systems. Geopolymers, produced through the alkali activation of alumi-

nosilicate-rich industrial by-products such as fly ash, blast furnace slag, and metakaolin, have emerged as environmentally friendly and low-carbon alternatives to conventional cementitious materials (Davidovits 2015; Ślosarczyk et al. 2023; Nasir et al. 2024). These materials not only offer comparable or superior mechanical performance and durability but also significantly reduce the environmental footprint of construction materials (Sbahieh et al. 2023; Imbabi et al. 2012). Additionally, the flexibility of geopolymer technology allows for the incur-

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poration of various locally available waste materials, such as waste glass powder, further enhancing its sustainability potential and applicability across different regions. Furthermore, the utilization of waste materials in geopolymer production contributes to waste valorization and offers economic and ecological advantages, supporting broader goals of sustainable development in the built environment (Kriven et al. 2024; Hegyi et al. 2023; Gao et al. 2023). Accordingly, recycling waste streams such as expired cement and aged roof tile powders as alternative binders can reduce industrial waste while lowering natural resource consumption and supporting more environmentally friendly mortar and concrete production (Ünal and Canbaz 2025). Moreover, the rapid growth of electronic waste and end of life rubber products has created pressing environmental and public health concerns, prompting their evaluation as secondary raw materials in cementitious and alternative binder systems (Bulut 2024). Similarly, the reuse of waste fiber reinforced polymer composite laminates originally produced for structural strengthening can support circular economy targets by reducing composite waste (Çelik et al. 2024).

Waste glass powder, due to its high silica content and amorphous structure, has attracted considerable attention as a potential precursor for geopolymer synthesis (Luhar et al. 2019; Siddika et al. 2021). Recycled materials such as waste glass powder are widely used, especially in lightweight building elements, geopolymers, fillers, and briquette production. These types of materials are often preferred in non-structural or semi-structural applications such as interior wall blocks, insulation elements, and decorative coatings. When finely ground, waste glass becomes highly reactive, enabling the formation of binding gels such as sodium-alumino-silicate-hydrate (N-A-S-H) upon alkali activation (Zhang 2015; Manjunath and Narasimhan 2020). The incorporation of glass powder into construction materials has been shown to improve mechanical properties, enhance durability, and reduce water absorption (Asokan et al. 2010). In addition, waste glass powder contributes to the formation of a more compact matrix by improving the microstructure of concrete thanks to its pozzolanic properties and fine grain structure (Barbhuiya et al. 2025; Amin et al. 2024). Some studies have shown that glass powder, especially when finely ground, promotes C-S-H gel formation, thereby enhancing its binding effect (Lam et al. 2024; Lai and Chen 2024). Additionally, it has been reported that glass powder can reduce the risk of alkali-silica reaction (ASR) at low usage rates, thereby posi-

tively affecting long-term durability (Almakrab et al. 2024). These findings highlight the potential of waste glass powder as an effective additive in concrete and present an important opportunity for sustainable material design. Moreover, utilizing waste glass in construction helps address environmental issues related to glass disposal and reduces the demand for natural raw materials, contributing to resource conservation and landfill reduction. These benefits align with the broader strategies for achieving carbon-neutral construction practices and mitigating the environmental impact of urban development (Huovila et al. 2022).

In this study, the use of waste glass powder sourced from glass manufacturing processes in Turkey was investigated for the production of completely cement-free geopolymeric construction materials. While existing literature includes studies where waste glass is used in combination with other materials such as fly ash or slag (Siddika et al. 2021), Research focusing solely on waste glass powder and sodium hydroxide as the activating agent remains limited. This study differentiates itself by employing only waste glass powder and varying concentrations of sodium hydroxide (2%, 4%, and 6%) to evaluate their effects on the physical and mechanical properties of the resulting geopolymer. This study differs by utilizing 100% waste glass powder as the sole aluminosilicate source in a completely cement-free geopolymer system, addressing the gap in literature regarding its standalone use and structural applicability in building elements. The goal is to determine the optimal alkali content for maximizing performance and to demonstrate that waste glass can serve as a viable precursor in geopolymer production. By doing so, this research contributes both to environmental sustainability and to the advancement of eco-friendly, lightweight, and durable construction materials.

## 2. Experimental Study

In the production of geopolymers, the glass powder whose chemical, physical, and particle size distribution properties are presented in Table 1 was used. As the activator, sodium hydroxide commonly known as caustic soda was selected due to its widespread use. In geopolymer production, sodium silicate and/or sodium hydroxide are typically preferred as activators. However, due to the high silica content of the glass powder, sodium silicate alone was not chosen. In mixture, Eskişehir tap water, whose properties are given in Table 2, was used.

**Table 1.** Chemical, physical, and particle size distribution properties of the waste glass.

	SiO <sub>2</sub> (%)	Na <sub>2</sub> O (%)	CaO (%)	MgO (%)	Al <sub>2</sub> O <sub>3</sub> (%)	Density (gr/dm <sup>3</sup> )	10 % (mm)	50 % (mm)	90 % (mm)
Fine glass waste	72.5	13.7	9.8	3.3	0.4	2.504	<0.01	<0.04	<0.13

**Table 2.** Chemical analysis of the water (mg/l).

pH	Na <sub>2</sub> O	Ka <sub>2</sub> O	Cl <sup>-</sup>	SO <sub>4</sub>	Zn	Pb	P <sub>2</sub> O <sub>3</sub>	NO <sub>3</sub>	∑alkalinity	Color
7.7	54	10	63	21	10	0.05	1.6	0.2	8	Crystal clear

For geopolymer production, the required amounts of sodium hydroxide were first determined based on the ratios provided in Table 3 and then mixed with water. The resulting solution was combined with glass powder to obtain a binder paste mixture. As the parti-

cle size of the glass powder decreased (i.e., as it became finer), the surface area increased, leading to a higher water demand. Therefore, higher water-to-glass powder ratios were used to achieve the same plastic consistency.

**Table 3.** Mixing ratio.

Na, %	2	4	6
Caustic soda / Fine glass waste	0.035	0.070	0.105
Water/ Fine glass waste	0.70	0.70	0.70

The prepared mixtures were poured into prismatic molds, each with three compartments measuring 4x4x16 cm, as shown in Fig. 1. Subsequently, the mixtures were compacted using a table vibrator, and the surfaces were leveled with a trowel. The samples were demolded after 24 hours and placed in an oven at a constant temperature of 60 °C for 3 hours. Afterwards, the samples were stored under standard curing conditions to gain strength. After 28 days from the production date, the dimensions, weights, and ultrasonic pulse velocities of the samples

were measured. Flexural strength was tested by applying load at the midpoint of the specimens. Two additional tests were conducted on the broken parts: one part was used to measure the splitting tensile strength, while the other part was subjected to a compressive strength test by placing 4x4 cm plates on the top and bottom surfaces. All experiments were conducted on at least three different samples, and during this process, the unit weights, ultrasonic pulse velocities, compressive, flexural, and tensile strengths of the samples were determined.



**Fig. 1.** Production, sampling and testing.

### 3. Results and Discussion

According to the results as seen in Fig. 2, a noticeable change was observed in the unit weight values of geopolymer mortars with increasing sodium content. The unit weight of the mixture containing 2% sodium was 1.577 kg/dm<sup>3</sup>, which increased by 10.78% to 1.747 kg/dm<sup>3</sup> with 4% sodium content. However, when the sodium content was raised to 6%, the unit weight decreased to 1.62 kg/dm<sup>3</sup>, representing a 7.28% reduction compared to the 4% sodium mixture. These findings indicate that increasing the sodium hydroxide content initially leads to a denser matrix structure, thus increasing the unit weight. Nevertheless, at 6% sodium, the excess alkali likely caused increased micro-porosity or disrupted the homogeneity of the reaction products, leading to a decrease in density. This suggests that exceeding the optimum sodium content may compromise structural integrity, negatively affecting both mechanical and physical properties.

Ultrasonic pulse velocity test results shown in Fig. 3 provide valuable insights into the internal structural integrity and density of geopolymer mortars. At 2% sodium content, the pulse velocity was 0.66 km/s, which increased by 55% to 1.023 km/s at 4% sodium. This significant increase indicates that the higher sodium hydroxide content enhanced reactivity and gel formation, resulting in a more compact and homogeneous structure. However, when the sodium content reached 6%, the pulse velocity dropped to 0.843 km/s—approximately 17.6% lower than that of the 4% mixture. This decline suggests that excess sodium may have induced microstructural voids or cracks within the matrix, reducing wave transmission speed. The results indicate that the optimum sodium content is around 4%, providing a denser and more cohesive geopolymer matrix, whereas higher levels weaken structural integrity.

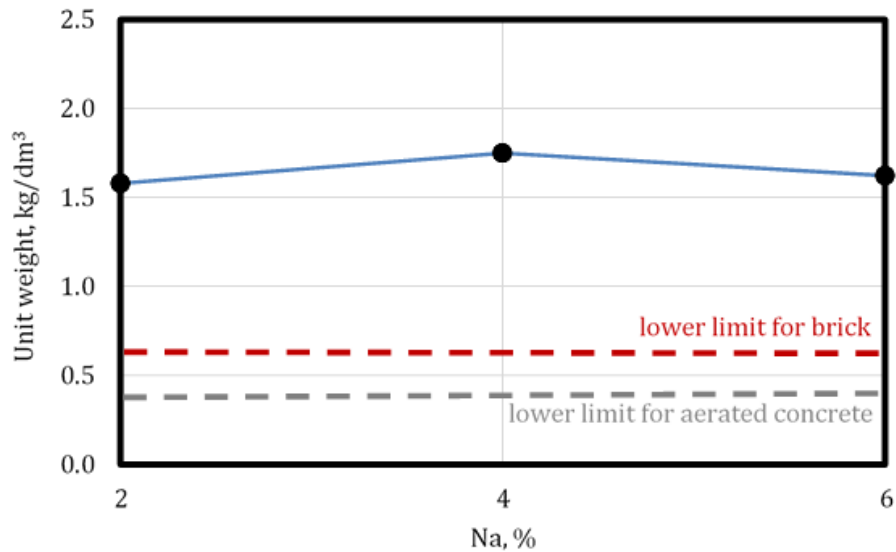


Fig. 2. Unit weight values of geopolymer specimens.

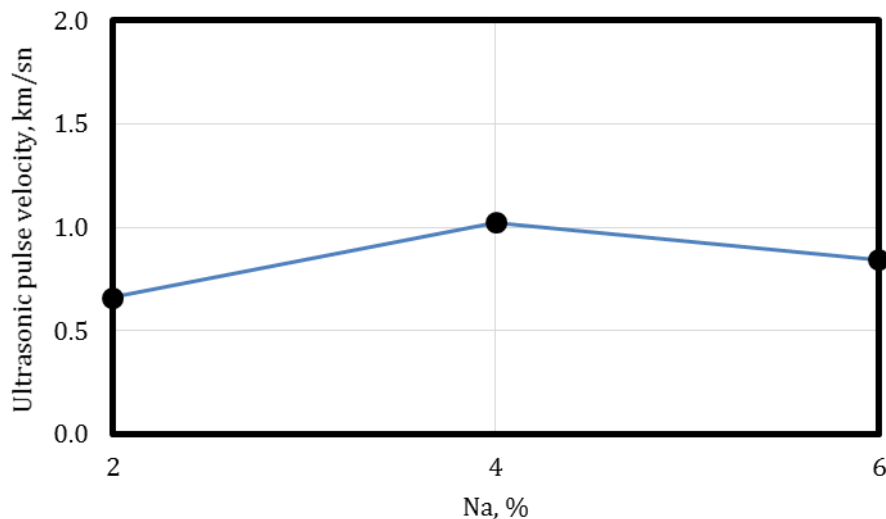


Fig. 3. Ultrasonic pulse velocity values of geopolymer specimens.

Flexural strength results as seen in Fig. 4 clearly demonstrate the influence of sodium hydroxide content on the mechanical properties of the geopolymer mortar. The flexural strength of the mixture with 2% sodium was 1.83 MPa, which increased by approximately 25.7% to 2.3 MPa at 4% sodium. However, when the sodium content was increased to 6%, the flexural strength dropped to 1.777 MPa, showing a 22.7% decrease compared to the 4% mixture. These findings suggest that 4% sodium is the optimum level at which the binder is most effectively activated. While an increase in sodium content initially improves the solubility of glass waste and the degree of geopolymerization, excessive alkali conditions beyond 4% may disrupt the reaction balance and increase the formation of microcracks, ultimately leading to strength reduction. Therefore, flexural strength data underscore the critical importance of optimizing sodium content for improved geopolymer performance.

Compressive strength results shown in Fig. 5 further highlight the significant effect of sodium hydroxide content on the mechanical performance of geopolymer mortars. In the mixture with 2% sodium, the compressive strength was measured at 6.77 MPa. This value increased by approximately 64.3% to 11.12 MPa at 4% sodium. This improvement is attributed to increased solubility and reaction rates within the binder system, contributing to the formation of a more compact and robust matrix. However, with 6% sodium content, the compressive strength slightly decreased to 10.85 MPa—about 2.4% lower than at 4% sodium. Although this decrease is relatively small, it may still indicate a disruption in the reaction balance caused by excessive sodium, leading to microstructural voids or weak bonding. These findings confirm that the optimal sodium level for compressive strength is around 4%, where the binder achieves its highest activation efficiency. Careful control of sodium content is thus essential to avoid adverse effects on mechanical performance.

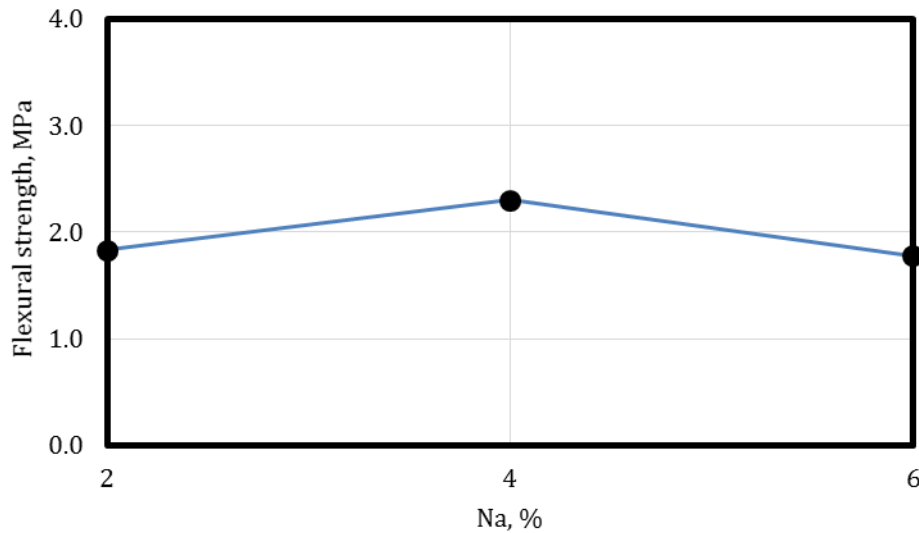


Fig. 4. Flexural strength values of geopolymer specimens.

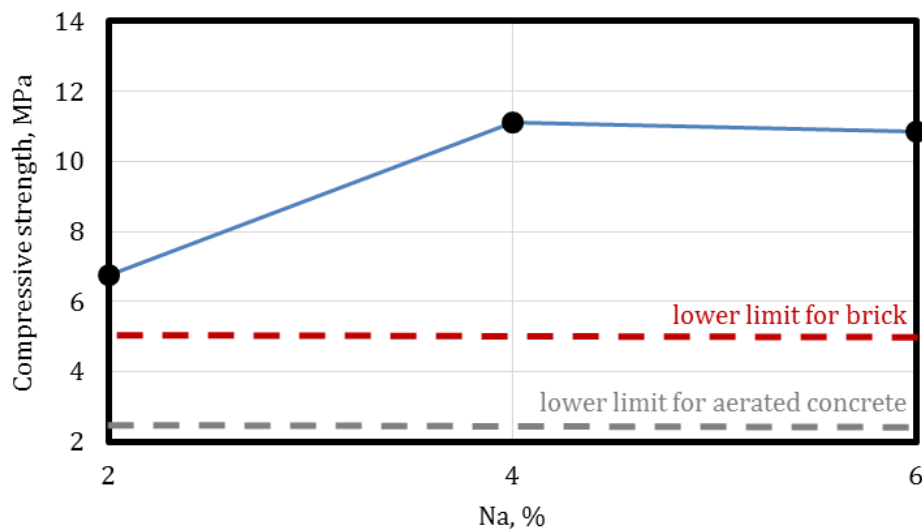


Fig. 5. Compressive strength values of geopolymer specimens.

Splitting tensile strength results reveal a distinct influence of sodium hydroxide on the tensile properties of geopolymer mortars in Fig. 6. At 2% sodium, the splitting tensile strength was 0.61 MPa, increasing by approximately 25.7% to 0.767 MPa at 4% sodium. This enhancement reflects improved gel formation and structural integrity due to increased sodium content. However, at 6% sodium, the strength dropped to 0.592 MPa, showing a 22.8% decrease compared to the 4% mixture. This reduction suggests that excessive alkali content can cause microcracking and poor bonding, negatively impacting internal structure. The results indicate that 4% sodium content represents the optimum level for tensile strength. Lower contents result in insufficient activation, while higher levels disrupt structural integrity. Therefore, optimizing alkali content is critical in geopolymer systems to achieve desirable mechanical performance.

Fig. 7 presents the internal structure images and elemental analyses of the geopolymer samples. In the analyses conducted using a scanning electron microscope (SEM), the internal structure and elemental distribution

of the geopolymer produced from fine glass powder and sodium hydroxide solution were examined in detail. The SEM images revealed that the glass powder particles reacted with the sodium hydroxide solution to form a binding matrix. At lower magnifications (250X and 500X), the formation of pores on the surface and the binding phase were observed, while at higher magnifications (1000X and 5000X), amorphous phases within the matrix and unreacted glass particles were detected. Elemental analysis confirmed that the matrix contained sodium-aluminum-silicate-hydrate (N-A-S-H) phases, which are characteristic of geopolymers. It was determined that silicon, aluminum, and sodium were homogeneously distributed across the surface, indicating the formation of the binding phase. Additionally, the presence of a small amount of calcium was found to contribute to the stability of the matrix. These findings suggest that the binding phase within the internal structure of the geopolymers is optimized in terms of both chemical and microstructural strength. However, a more homogeneous structure could be achieved by reducing porosity and the amount of unreacted particles.

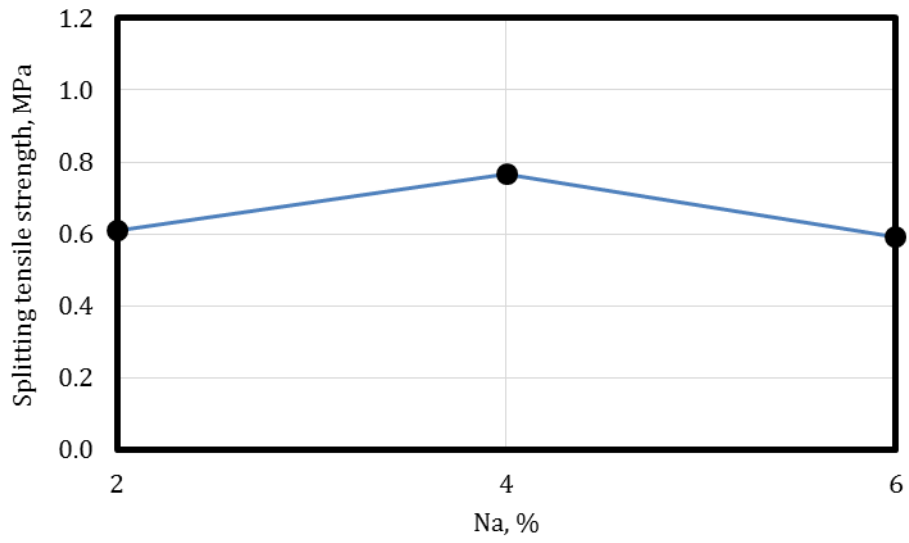


Fig. 6. Splitting tensile strength values of geopolymer specimens.

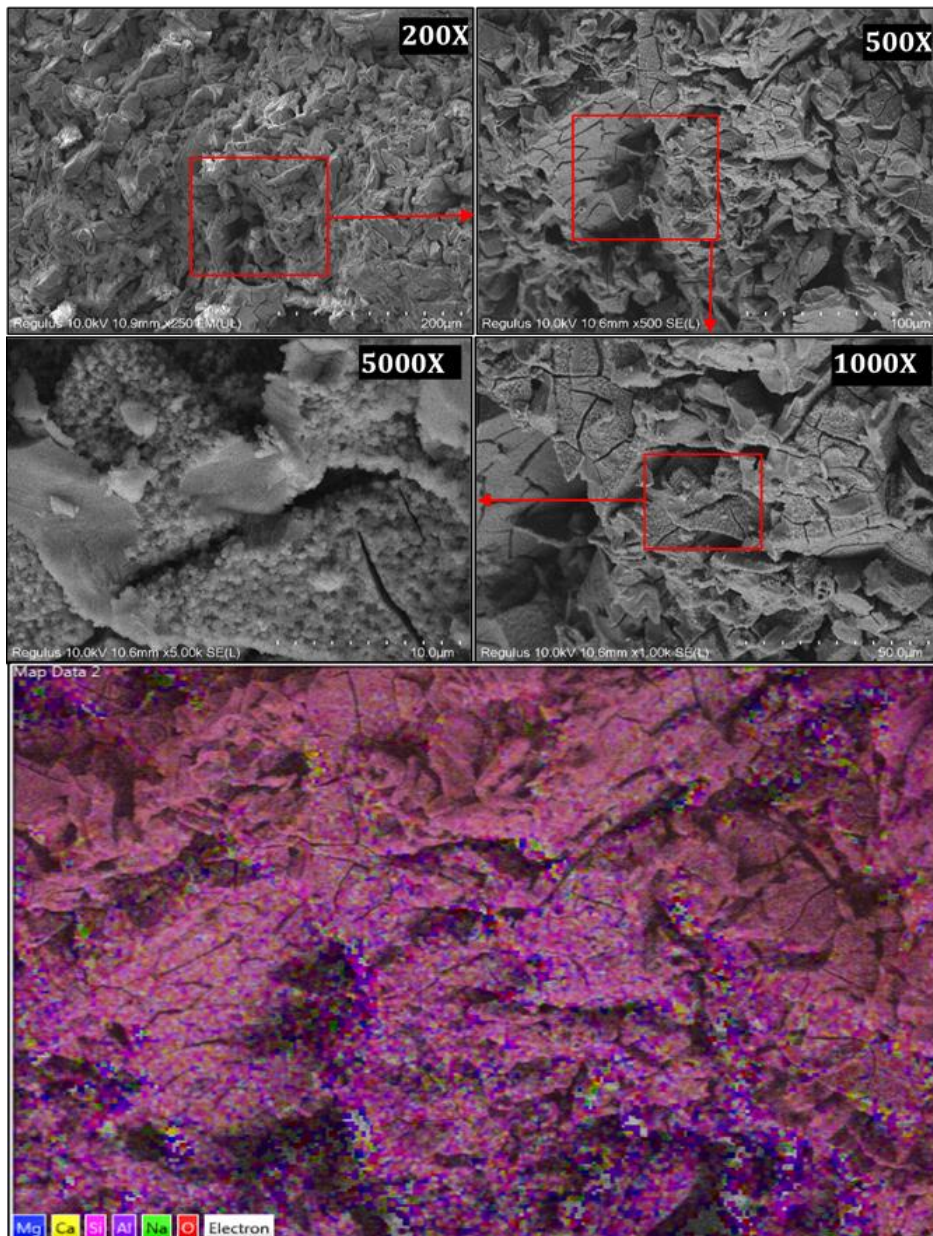


Fig. 7. Microstructure and elemental analysis of geopolymer formed with fine glass powder.

#### 4. Conclusions

This study demonstrated that geopolymer building materials can be successfully produced using only waste glass powder and sodium hydroxide, without the need for traditional cement. The experimental results revealed that the sodium hydroxide content plays a crucial role in determining the physical and mechanical performance of the geopolymer matrix. Among the three tested activator ratios (2%, 4%, and 6%), the mixture containing 4% sodium hydroxide exhibited the most favorable properties in terms of unit weight, ultrasonic pulse velocity, and strength values. Specifically, this mixture achieved a denser internal structure, higher ultrasonic pulse velocity, and superior mechanical strength, including compressive, flexural, and tensile strengths. These enhancements are attributed to the effective activation of the silica-rich glass powder and the optimal formation of binding gels at this concentration.

On the other hand, increasing the sodium hydroxide content to 6% resulted in a decline in performance, indicating that excessive alkali levels may disrupt the geopolymerization process by increasing porosity and microcracking within the matrix. Microstructural analyses conducted via SEM and energy dispersive x-ray spectroscopy (EDS) further supported these findings by con-

firmed the formation of sodium-alumino-silicate-hydrate (N-A-S-H) gels and identifying a homogenous distribution of key elements, including silicon, aluminum, and sodium, in addition to a minor presence of calcium that contributed to matrix stability. These observations validate the chemical and structural soundness of the material at the optimum sodium hydroxide level. In conclusion, the use of 4% sodium hydroxide is recommended to obtain the best mechanical and physical properties.

Ultimately, the glass powder-based geopolymer developed in this study presents a lightweight, durable, and environmentally responsible alternative to conventional construction materials. With physical and mechanical properties close to those of brick and superior to aerated concrete, the material holds significant promise for practical applications in non-load-bearing and insulating building components. Moreover, the valorization of waste glass in this context contributes to circular economy goals and aids in reducing the carbon footprint associated with cement production. Thus, this research provides a viable and scalable approach for integrating industrial glass waste into sustainable construction practices. Future studies should explore the long-term durability, microstructural development, and large-scale application potential of waste glass powder-based geopolymers under various environmental conditions.

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#### Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

#### Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

#### AI Assistance

No AI-based tools were used in the preparation of this manuscript.

#### Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

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