Development of Sustainable One-Part Alkali-Activated Binders Derived from Construction and Demolition Waste ("Just Add Water" Approach)

Hüseyin Ulugöl*

Ankara University, Department of Civil Engineering, Faculty of Engineering, 06590 Ankara, Turkey

Abstract. This study investigates the effect of alkali concentration on the mechanical performance of one-part alkali-activated binders produced using construction and demolition waste (CDW) as a precursor material. Four different alkali concentrations (0.30, 0.35, 0.40, and 0.45) were applied in mixtures where the alkali-to-binder ratios were 0.22, 0.26, 0.30, and 0.35, respectively, and the water-to-binder ratios were adjusted between 0.51 and 0.42. The sand-to-binder ratio was kept constant at 2.2 for all mixtures. Results revealed that increasing alkali concentration improved the reactivity and strength development of both brick and concrete waste-based binders. The highest compressive strength values were obtained at an alkali concentration of 0.45 for both waste types, indicating enhanced polymerization and matrix densification at higher activator levels. Unlike traditional geopolymer systems requiring the preparation of alkaline solutions, this binder can be easily produced by simply adding water to the dry mix, providing a practical and user-friendly approach for field applications. The findings demonstrate that the use of CDW as a cement-free binder not only provides satisfactory mechanical performance but also offers a sustainable alternative to conventional cement, contributing to environmental conservation and green transition in construction.

1 Introduction

Alkali-activated materials and their low-calcium subgroup, geopolymers, are recognized as environmentally friendly alternatives, leading researchers to conduct extensive studies aimed at developing substitutes for cement-based binders. Although the earliest studies on geopolymers primarily focused on creating fire-resistant binding materials [1-3], their mechanical properties—comparable to or even superior to those of traditional cementitious binders— [4], and their durability, which rivals that of cement-based systems, [5], have made geopolymers a viable and competitive alternative. Most of the studies on geopolymers have concentrated on raw materials such as ground granulated blast furnace slag (GGBFS), fly ash (FA), and pozzolans already used in the cement industry, or on metakaolin (MK), which is relatively expensive. However, in recent years, even construction and demolition waste

*Corresponding author: hulugol@ankara.edu.tr

(CDW) has been explored as a potential precursor for geopolymer production in accordance with the principles of sustainability. The early use of CDW in geopolymers required heat treatment to achieve sufficient strength [6]. With advances in processing techniques, however, it has become possible to produce CDW-based geopolymers under ambient curing conditions [7]. CDW-based geopolymers can also be employed in specific applications similar to cement-based materials. For example, they have demonstrated strain-hardening behavior, [8], which enables self-healing capability [9]. Moreover, the increasingly popular 3D concrete printing method has also been successfully applied to CDW-based geopolymers, yielding adequate performance in terms of bond strength, rheology, and other key parameters [10].

Geopolymer research often highlights the environmental advantages of these materials compared with cementitious binders. The main reasons are the high CO_2 emissions from the cement industry—responsible for about 7% of global emissions—and its substantial consumption of natural resources and energy [11, 12]. In contrast, the production of most geopolymer systems involves minimal direct CO_2 emissions. Nevertheless, metakaolin-based geopolymers still contribute to emissions due to the calcination step in metakaolin production and the use of virgin raw materials. While the energy consumption of cement production is substantial, the alkali activators used in geopolymers are not entirely free from environmental impact due to their manufacturing processes. However, geopolymers generally require smaller activator quantities than cement requires clinker, and their chemical composition can be tailored for lower environmental impact. The sustainability of a geopolymer system can therefore be improved by selecting less energy-intensive activators. For instance, even when the same activator is used, the source of sodium hydroxide (NaOH)—locally produced or imported—can significantly affect life-cycle assessment results [13]. Although some studies describe geopolymers as more environmentally benign according to life-cycle assessments (LCA), others suggest that cementitious binders may sometimes perform better depending on boundary conditions and local resources.

Parallel to these environmental considerations, a one-part geopolymer system based on CDW can serve as a promising green binder. In this context, the present study aims to evaluate brick waste and concrete waste as raw materials for the development of a one-part geopolymer binder.

2 Experimental Program

2.1 Materials

CDW-based materials; concrete waste (CW) and brick waste (BW) were obtained from a demolition site in Ankara. Both materials were crushed to particles approximately 2 mm in size, followed by grinding in a ball mill for one hour. **Table 1** presents the particle size distribution parameters of brick waste and concrete waste powders. A combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) was used as the alkaline activator in powder form. NaOH pellets with a purity of 99% were ground for 10 minutes to achieve a fine powder form, which was determined as the optimum milling time [14]. Anhydrous sodium metasilicate (M_s = 0.95) was already in powder form; therefore, no further grinding was required. No drying or calcination treatment was applied to either powder. Both alkali materials were stored in airtight polypropylene containers at 20 ± 2 °C to prevent moisture absorption until use. The ratio of sodium silicate to sodium hydroxide was adjusted to obtain an overall silica modulus of 0.8. Recycled concrete aggregate (RCA) obtained from the concrete waste, with a maximum particle size (D_{max}) of 2 mm, was used as the aggregate in

mortar production. Due to its high-water demand, the RCA was sieved through a 75 μm sieve to remove finer particles.

Table 1. Particle size parameters of brick waste and concrete waste (μm).

Raw material	Surface-weighted mean diameter ($D_{3,2}$)	Volume-weighted mean diameter ($D_{4,3}$)	D_{10}	D_{50}	D_{90}
Brick waste (BW)	2.8	15.6	1.2	7.6	46.9
Concrete waste (CW)	3.1	43.1	1.4	15.4	85.5

2.2 Preparation and testing of paste mixtures

Powder materials (sand, sodium silicate, ground sodium hydroxide and brick or concrete waste) were mixed in a 5 L laboratory mixer at 60 rpm for 60 seconds. Then, same mixing procedure was repeated after adding the required amount of water. A final mixing step was carried out for 120 seconds at 120 rpm to obtain a homogeneous geopolymer mortar. For each mixture and curing age (3, 7, and 28 days), three prismatic specimens (40×40×160 mm) were prepared and tested for both flexural and compressive strength. Specimens were kept in the molds for 24 h at 20 ± 2 °C, then demolded and stored under laboratory ambient conditions (20 ± 2 °C, 50 ± 10 % RH) until testing at 3, 7, and 28 days.

Flexural and compressive strength tests were conducted in accordance with EN 196-1 (three-point bending, span = 100 mm; compressive testing on the two halves resulting from flexure). The loading rates followed the standard requirements (50 ± 10 N/s in flexure and 2400 ± 200 N/s in compression). Specimen identifications (IDs) are listed in **Table 2**.

Table 2. Mixture designs of one-part geopolymer binders.

ID	Water (g)	NaOH (g)	Na_2SiO_3 (g)	Brick Waste (g)	Concrete Waste (g)	Sand (g)	Alkali Conc.	Alkali/ binder	Water/ binder
B1	350	14.1	135.9	540	-	1520	0.30	0.22	0.51
B2	350	17.9	172.1	540	-	1605	0.35	0.26	0.48
B3	350	21.7	208.3	540	-	1695	0.40	0.30	0.45
B4	350	27.3	262.7	540	-	1830	0.45	0.35	0.42
C1	350	14.1	135.9	-	540	1520	0.30	0.22	0.51
C2	350	17.9	172.1	-	540	1605	0.35	0.26	0.48
C3	350	21.7	208.3	-	540	1695	0.40	0.30	0.45
C4	350	27.3	262.7	-	540	1830	0.45	0.35	0.42

Alkali conc. – Alkali concentration

Samples starting with the letter “B” (B1, B2, …) represent mortars containing brick waste, while those starting with “C” (C1, C2, …) represent mortars with concrete waste. The sodium silicate/sodium hydroxide ratio, corresponding to a silica modulus of 0.8 (M_s = 0.95 for sodium metasilicate), was kept constant at 9.6 in all mixtures. The main variable among the mixtures was the alkali concentration, defined as the unitless mass ratio of total alkali solids to the combined mass of alkali solids and water, i.e., $(NaOH + Na_2SiO_3) / (NaOH + Na_2SiO_3 + Water)$. According to the literature [15], an increase in alkali concentration (from

0.30 to 0.35 and 0.40) enhances the geopolymerization process, promoting the formation of reaction products that fill the voids between unreacted particles. Therefore, this study evaluated alkali concentration values of 0.30, 0.35, 0.40, and 0.45 (unitless). The alkali-to-binder ratio, defined as the mass ratio of alkali solids to the total mass of alkali solids and precursor, was 0.22, 0.26, 0.30, and 0.35 (unitless), respectively. Similarly, the water-to-binder ratio, defined as the mass ratio of water to the total mass of alkali solids and precursor, was 0.51, 0.48, 0.45, and 0.42 (unitless). All specimens were prepared with a constant sand-to-binder ratio of 2.2. The alkali concentration, alkali-to-binder ratio, and water-to-binder ratio are expressed as unitless mass ratios.

3 Results and Discussion

3.1 Flexural Strength

Fig. 1 and **Table 3** present the average flexural strength results of geopolymers produced with brick waste (BW) and concrete waste (CW). Each reported strength value represents the mean of three specimens (n = 3), and the error bars in the **Fig. 1** indicate the corresponding standard deviation. For specimens containing brick waste, a consistent increase in strength was observed with curing time. Specimen B1, which had the lowest alkali concentration (0.30), exhibited the minimum flexural strength among all brick waste mixtures. Increasing the alkali concentration to 0.35 (B2) resulted in a 28-day flexural strength of 6.2 MPa. Although B3 and B4 achieved strengths of 5.3 and 5.4 MPa, respectively, both values were slightly lower than that of B2, indicating that an alkali concentration of 0.35 can be considered optimal for brick waste in terms of 28-day flexural strength. However, it should be noted that the results of B2, B3, and B4 were relatively close to each other, showing that higher alkali concentrations did not significantly improve flexural performance.

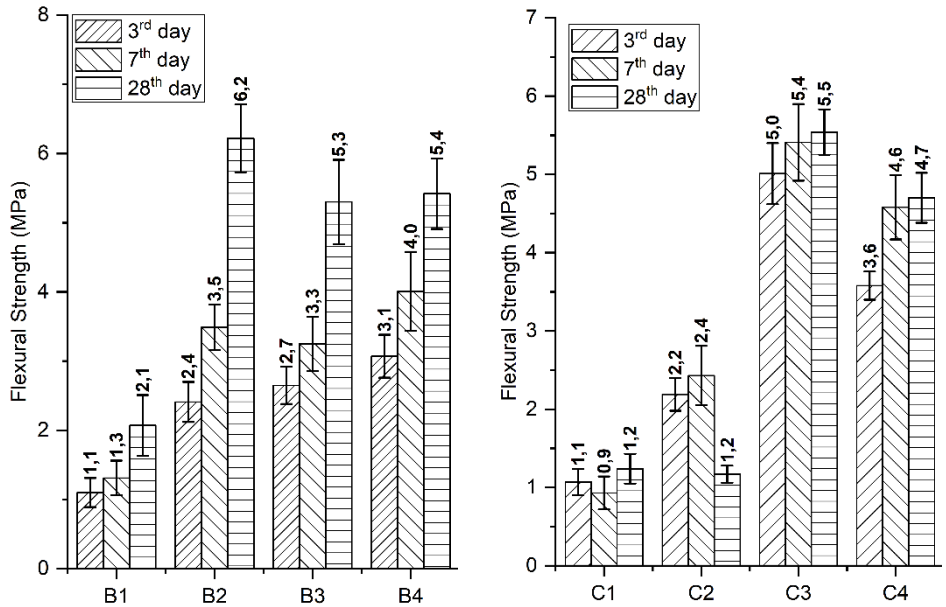

Fig. 1. 3-, 7- and 28-day flexural strengths (mean ± SD, n = 3) of one-part binders prepared with brick waste (B-series) and concrete waste (C-series). Curing conditions: 20 ± 2 °C and 50 ± 10 % relative humidity. Error bars indicate ± standard deviation.

For specimens incorporating concrete waste, all samples exhibited lower flexural strengths compared with their brick waste counterparts, except for C3 (5.5 MPa) and B3 (5.3 MPa), which demonstrated comparable results. This difference can be attributed to the chemical composition of the precursors. Brick waste acts as a complete geopolymer precursor, containing sufficient SiO_2, Al_2O_3, and a relatively low amount of CaO, which allows for a more efficient geopolymerization process. Conversely, concrete waste contains higher CaO content but insufficient SiO_2 and Al_2O_3, which limits the geopolymer reaction and subsequently hinders strength development. While the primary reaction product in Si- and Al-rich systems is sodium aluminosilicate hydrate (N–A–S–H) gel, the coexistence of calcium leads to the formation of calcium aluminosilicate hydrate (C–(A)–S–H) or hybrid gels.

In the present case, the concrete waste precursor contained a considerable amount of CaO but a limited proportion of reactive SiO_2 and Al_2O_3 species. This chemical imbalance restricted the complete geopolymerization of aluminosilicate networks, thereby reducing matrix densification and ultimate flexural strength. This limitation was particularly evident in specimen C2, where a reduction in strength was observed after 7 days due to incomplete geopolymerization. It is important to note that both adequate SiO_2–Al_2O_3 content and a proper *Si/Al* ratio (typically between 2 and 3) are essential for a well-developed geopolymer network [16]. Another possible reason for the reduced strength in concrete waste-based mixtures is the presence of excessive calcium species. According to Barbosa et al. [17], an excess of sodium ions—responsible for charge balancing—can promote carbonation when their concentration becomes too high. In the present study, the interaction between calcium species from the concrete waste and sodium species from NaOH likely caused localized carbonation within the pore structure. This pore filling due to carbonation may have restricted ionic mobility and hindered further strength development.

Table 3. Flexural and compressive strength results of all specimens

ID	Precursor	Alkali conc.	Flexural strength (MPa)			Compressive strength (MPa)		
			3 days	7 days	28 days	3 days	7 days	28 days
B1	Brick waste	0.30	1.1 ± 0.2	1.3 ± 0.3	2.1 ± 0.4	2.2 ± 0.5	2.4 ± 0.9	5.3 ± 0.9
B2	Brick waste	0.35	2.4 ± 0.3	3.5 ± 0.3	6.2 ± 0.5	6.7 ± 0.6	9.7 ± 1.9	19.8 ± 1.5
B3	Brick waste	0.40	2.6 ± 0.3	3.3 ± 0.4	5.3 ± 0.6	5.8 ± 0.6	11.1 ± 1.9	16.8 ± 1.1
B4	Brick waste	0.45	3.1 ± 0.3	4.0 ± 0.6	5.4 ± 0.5	12.3 ± 1.4	16.7 ± 2.0	25.8 ± 1.7
C1	Concrete waste	0.30	1.1 ± 0.2	0.9 ± 0.2	1.2 ± 0.2	2.7 ± 0.3	2.7 ± 0.5	3.3 ± 0.6
C2	Concrete waste	0.35	2.2 ± 0.2	2.4 ± 0.4	1.2 ± 0.1	6.2 ± 0.5	6.3 ± 0.5	5.7 ± 0.6
C3	Concrete waste	0.40	5.0 ± 0.4	5.4 ± 0.5	5.5 ± 0.3	10.3 ± 0.7	11.2 ± 1.3	11.6 ± 1.1
C4	Concrete waste	0.45	3.6 ± 0.2	4.6 ± 0.4	4.7 ± 0.3	10.9 ± 0.8	11.6 ± 0.9	14.0 ± 1.1

Alkali conc. – Alkali concentration

3.2 Compressive Strength

Compressive strength results of specimens can be seen in **Fig. 2 and Table 3**. Compressive strength results are expressed as the mean values obtained from three specimens (n = 3), with the error bars representing the standard deviation. Similar to the flexural strength results, an

alkali concentration of 0.35 appears to be a threshold value for specimens with concrete waste. While B1 had a compressive strength of 5.3 MPa at 28 days, B2 reached 19.8 MPa, which is almost four times higher. A further increase in alkali concentration up to 0.40 led to a decrease in compressive strength for B3 (16.8 MPa). This concentration-dependent trend is consistent with the findings of Zhang et al. [15], who reported that increasing the activator concentration from 30 % to 35 % in one-part metakaolin–fly ash binders led to a significant improvement in compressive strength from approximately 20 MPa to 48 MPa at 28 days. The enhancement was attributed to higher alkali availability, which promoted the dissolution of aluminosilicate species and accelerated the formation of N–A–S–H and C–(A)–S–H gels.

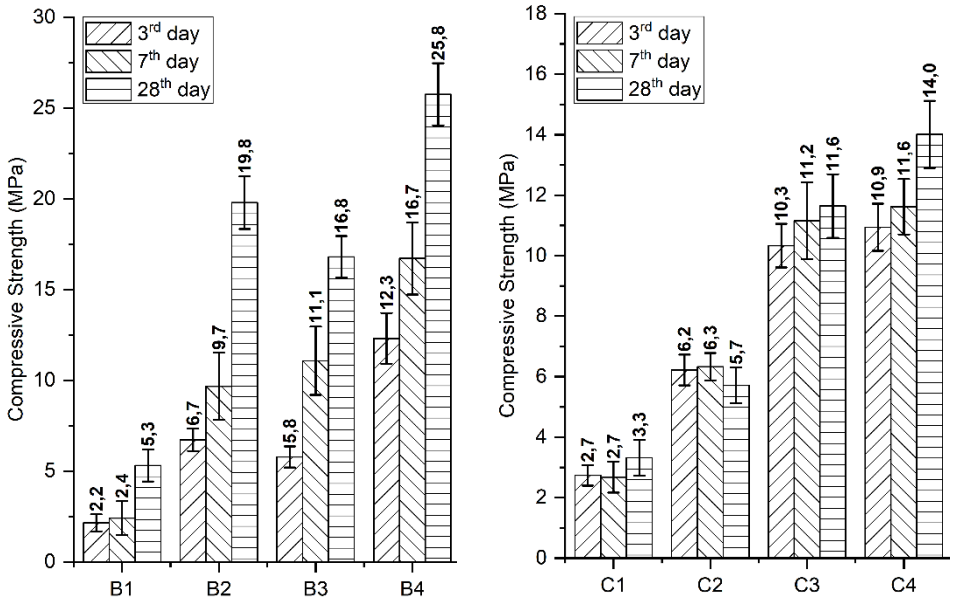

Fig. 2. 3-, 7- and 28-day compressive strengths (mean ± SD, n = 3) of one-part binders prepared with brick waste (B-series) and concrete waste (C-series). Curing conditions: 20 ± 2 °C and 50 ± 10 % relative humidity. Error bars indicate ± standard deviation.

Although the 7-day compressive strength of B3 (11.1 MPa) was higher than that of B2 (9.7 MPa), their 28-day results revealed that later geopolymerization reactions are as important as early reactions for strength development. The disruption of later geopolymer reactions in B3 is attributed to the fact that higher alkali ratios introduce an excessive amount of silica species, leading to uncontrolled gelation and an early-formed heterogeneous structure. This heterogeneous structure may inhibit continuous geopolymerization by hindering oligomer movement, and these trapped oligomers result in coagulated regions within the matrix. A similar phenomenon was reported by Luukkonen et al. [14], who observed that excessive or uneven silica availability can cause localized gelation and the development of a non-uniform microstructure in one-part binder systems, thereby limiting further geopolymerization.

At an alkali concentration of 0.45, the brick-waste-based binder achieved the highest 28-day compressive strength of 25.8 MPa, while the concrete-waste-based binder reached 14.0 MPa at the same concentration. The superior performance of brick waste is likely related to its higher amorphous content and finer particle reactivity, which improve the geopolymerization process through enhanced dissolution of aluminosilicate phases and the formation of a denser reaction gel. This denser gel promotes more efficient particle bonding

within the matrix compared with concrete waste. In contrast, the crystalline phases and lower dissolution capacity of concrete waste limited its reaction extent. When comparing brick waste and concrete waste at early ages, only a slight difference in compressive strength was observed. However, the specimens incorporating concrete waste exhibited limited long-term strength development due to their lower reactive SiO_2 and Al_2O_3 contents.

Although the presence of CaO species in concrete waste contributes to early strength gain through the formation of C–(A)–S–H–type gels, the deficiency of reactive silica and alumina restricts subsequent geopolymerization reactions. As a result, the later formation of N–A–S–H or hybrid gels is hindered, leading to an incomplete matrix structure and lower 28-day compressive strength compared with the specimen with brick waste. A precursor must not only be reactive but also contain sufficient SiO_2 and Al_2O_3 species to sustain strength development beyond the early stages. For instance, Zerzouri et al. [18] reported a 28-day compressive strength of 46 MPa in a slag-based one-part binder activated with a hybrid activator (Na_2SiO_3/NaOH = 2.5). The high reactivity and CaO-rich composition of the slag promoted the coexistence of C–(A)–S–H and N–A–S–H gels, resulting in a highly dense and continuous microstructure. In contrast, the lower reactivity and limited availability of silica–alumina species in CDW precursors constrained long-term geopolymerization and matrix densification under ambient curing.

When comparing alkali concentration, alkali-to-binder ratio, and water-to-binder ratio in terms of their effect on 28-day compressive strength, the alkali concentration showed the strongest influence, with a Pearson correlation coefficient of 0.878 and 0.983 for brick waste and concrete waste, respectively. The second most significant factor was alkali-to-binder ratio, with a Pearson coefficient of 0.887 for brick waste which is almost same with alkali concentration and 0.978 for concrete waste.

4 Conclusions

The findings of this experimental study demonstrate that increasing the alkali concentration from 0.30 to 0.45 significantly enhanced the reactivity and compressive strength of one-part alkali-activated binders produced from both brick and concrete waste. Among the parameters examined, the alkali-to-binder ratio proved to be the most influential factor controlling strength development. The optimum performance was observed at an alkali concentration of 0.45, which produced compressive strengths of 25.8 MPa for brick waste and 14.0 MPa for concrete waste after 28 days. The superior performance of brick waste can be attributed to its more amorphous structure and higher pozzolanic activity compared with concrete waste, leading to greater reactivity under alkaline activation. The study further confirms that the one-part binder formulated from construction and demolition waste can be readily prepared by simply adding water to the dry mixture, thereby removing the need for handling liquid alkaline solutions. This feature, combined with its cement-free and waste-derived composition, positions the binder as a promising sustainable alternative to traditional Portland cement, with potential contributions to low-carbon and circular construction practices. To deepen the understanding of the reaction mechanisms governing these binders, future work will include microstructural characterization through XRD, SEM, and FTIR analyses.

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Data Availability
The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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.

Reference

1. J. L. Provis and S. A. Bernal, Geopolymers and related alkali-activated materials, Annu. Rev. Mater. Res. **44**, 299–327, (2014). https://doi.org/10.1146/annurev-matsci-070813-113515.
2. R. E. Lyon, P. N. Balaguru, A. Foden, U. Sorathia, J. Davidovits, and M. Davidovics, Fire-resistant aluminosilicate composites, Fire Mater. **21**(2), 67–73, (1997). https://doi.org/10.1002/(SICI)1099-1018(199703)21:2<67::AID-FAM596>3.0.CO;2-N.
3. J. Davidovits, Properties of Geopolymer Cements, First Int. Conf. Alkaline Cem. Concr. 131–149, (1994).
4. K. Neupane, High-Strength Geopolymer Concrete- Properties, Advantages and Challenges. Adv. Mater. **7**(2), 15-25, (2018). https://doi.org/10.11648/j.am.20180702.11.
5. W. K. Part, M. Ramli, and C. B. Cheah, An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products. Constr. Build. Mater. **77**, 370-395, (2015). https://doi.org/10.1016/j.conbuildmat.2014.12.065.
6. H. Ulugöl *et al.*, Mechanical and microstructural characterization of geopolymers from assorted construction and demolition waste-based masonry and glass. J. Clean. Prod. **280**, 124358, (2021). https://doi.org/10.1016/j.jclepro.2020.124358.
7. Y. D. Adufu, S. O. Sore, P. Nshimiyimana, A. Messan, And G. Escadeillas, Effect of calcium-rich additions on the mechanical and microstructural properties of metakaolin-based geopolymer concrete cured in ambient sub-Saharan climate. Constr. Build. Mater. **453**, 139009, (2024). https://doi.org/10.1016/j.conbuildmat.2024.139009.
8. M. Ohno and V. C. Li, A feasibility study of strain hardening fiber reinforced fly ash-based geopolymer composites. Constr. Build. Mater. **57**, 163–168, (2014). https://doi.org/10.1016/j.conbuildmat.2014.02.005.
9. H. Ulugöl, M. F. Günal, İ. Ö. Yaman, G. Yıldırım, and M. Şahmaran, Effects of self-healing on the microstructure, transport, and electrical properties of 100% construction- and demolition-waste-based geopolymer composites. Cem. Concr. Compos. **121**, 104081, (2021). https://doi.org/10.1016/j.cemconcomp.2021.104081.
10. N. C. Demiral *et al.*, Mechanical anisotropy evaluation and bonding properties of 3D-printable construction and demolition waste-based geopolymer mortars. Cem. Concr. Compos. **134**, 104814, (2022). https://doi.org/10.1016/j.cemconcomp.2022.104814.
11. K. Neupane, Evaluation of environmental sustainability of one-part geopolymer binder concrete. Clean. Mater. **6**(2), 100138, (2022). https://doi.org/10.1016/j.clema.2022.100138.
12. B. Sari, Ş. Y. Geyik, and O. Keskinkan, Çimento Üretim Sektöründe ISO 14001 Çevre Yönetim Sisteminin Enerji Kazanımı ve İklim Değişikliği Üzerine Etkilerinin İncelenmesi. Çukurova Univ. J. Fac. Eng. Archit. **35**(4), 847 - 858, (2020). https://doi.org/10.21605/cukurovaummfd.867373
13. D. A. Salas, A. D. Ramirez, N. Ulloa, H. Baykara, and A. J. Boero, Life cycle assessment of geopolymer concrete. Constr. Build. Mater. **190**, 170–177, (2018).

https://doi.org/10.1016/j.conbuildmat.2018.09.123.
14. T. Luukkonen, Z. Abdollahnejad, J. Yliniemi, P. Kinnunen, and M. Illikainen, Comparison of alkali and silica sources in one-part alkali-activated blast furnace slag mortar. J. Clean. Prod. **187**, 171–179, (2018). https://doi.org/10.1016/j.jclepro.2018.03.202.
15. H. Y. Zhang, J. C. Liu, and B. Wu, Mechanical properties and reaction mechanism of one-part geopolymer mortars. Constr. Build. Mater. **273**, 121973, (2021). https://doi.org/10.1016/j.conbuildmat.2020.121973.
16. Y. Chen *et al.*, Synthesis, solubility and thermodynamic properties of N-A-S-H gels with various target Si/Al ratios. Cem. Concr. Res. **180**, 107484, (2024). https://doi.org/10.1016/j.cemconres.2024.107484.
17. V. F. F. Barbosa, K. J. D. Mackenzie, and C. Thaumaturgo, Synthesis and characterisation of materials based on inorganic polymers of alumina and silica: sodium polysialate polymers. Int. J. Inorg. Mater. **2**(4), 309–317, (2000). https://doi.org/10.1016/S1466-6049(00)00041-6.
18. M. Zerzouri, R. Hamzaoui, L. Ziyani, and S. Alehyen, Influence of slag based pre-geopolymer powders obtained by mechanosynthesis on structure, microstructure and mechanical performance of geopolymer pastes. Constr. Build. Mater. **361**, 129637, (2022). https://doi.org/10.1016/j.conbuildmat.2022.129637.