



Circular economy approach to geopolymers development using construction and demolition waste

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Abstract

This study investigates the construction and demolition wastes (CDWs) valorization in geopolymer production under various conditions, emphasizing the criticality of reutilizing CDWs in a value-added manner. The CDW-based precursors used in this study were red clay brick (RCB), hollow brick (HB), roof tile (RT), glass waste (GW), and concrete waste (CW), along with blast furnace slag (BFS) as an industrial by-product. Recycled concrete aggregate (RCA) was employed as an aggregate, while sodium hydroxide (NaOH) used as the sole alkaline activator at varying dosages to activate the precursors. The influence of NaOH molarity, the form in which NaOH is added (solution, powder, or flakes), and precursor blends were evaluated by conducting flow table and compressive strength tests, alongside a cost comparison to analyze the effects of these parameters on economic performance. The results indicated that increasing the NaOH molarity improved both workability (~ 5%) and compressive strength (~ 95%), which can be attributed to the enhanced dissolution of aluminosilicate species and the subsequent geopolymerization reaction. CDW-based geopolymer mixtures reached compressive strengths ranging from 10 to 25 MPa after 28 days of ambient curing. Among the precursors used in this study, masonry-based precursors exhibited superior performance, particularly the HB samples, which demonstrated the highest mechanical performance. The method of NaOH addition had no noticeable influence on the engineering properties of the CDW-based geopolymer mixtures activated by solely 4M NaOH. Cost analysis showed that the alkaline activator, BFS content, and transportation expenses were the major factors to overall costs. The HB-containing mixture showed superior performance both in terms of cost per cubic meter and cost per 1 MPa, compared to other CDW-based precursors. Although the 100% BFS-based geopolymer mixture had a higher cost per cubic meter, its cost per MPa was slightly lower and comparable to that of the HB-containing mixture. This study provides insights to guide experimental design and support future research on sustainable waste-derived binder systems.

1. Introduction

As a consequences of increasing construction activities, the renovation and maintenance of aging infrastructure and superstructures, as well as the impacts of various natural disasters such as earthquakes and tsunamis, billions of tons of construction and demolition waste (CDW) are produced annually [1]. When these wastes are not included into the economy, they result in severe environmental damage, and these problems continue to grow quickly. CDWs can cause a variety of environmental problems, including air, soil, and groundwater pollution, together with the occupation and degradation of agricultural lands [2, 3]. Besides, when these wastes are not used or reintegrated into circular economy,

new demands for materials must be met through the extraction and consumption of virgin natural resources, which in turn accelerates the depletion of resources and intensifies environmental degradation. In general, instead of managing these wastes, they are simply dumped into landfill sites, which is relatively easier and more economical [4]. Therefore, billions of tons of waste are now stockpiled across the globe, awaiting disposal in landfill areas. Acknowledging the severity of this situation, increasing awareness in recent years has led to growing interest in utilizing these wastes as secondary raw materials within the circular economy model, thereby creating value-added products instead of low-grade applications [5].

The construction sector largely follows a conventional linear economic paradigm structured around the “take–make–dispose” principle, where raw materials are extracted, processed into construction products, and ultimately disposed of at the end of a building’s life cycle [6]. This approach yields significant resource depletion, high energy consumption, and huge amount of CDW. On the other hand, the circular economy, promotes a regenerative system in which materials are maintained in closed loops at their highest possible value [7]. Within the construction sector, this implies designing buildings for deconstruction, reusing components, and valorizing waste streams as secondary raw materials [8].

Instead of disposing of CDWs in landfills or using them merely as backfill or for low-tech purposes, the concept of upcycling has gained attention as a sustainable approach to transform them into high-value materials for diverse applications [9]. The use of recycled concrete aggregate (RCA) as a substitute for natural virgin aggregates has become more widespread, helping to reduce the consumption of virgin resources and enabling the large-scale reuse of waste materials [5, 10, 11]. In addition, the incorporation of CDWs into cement production, as allowed by TS EN 197-6, represents a significant step toward reducing the global CO₂ and hazardous gas emissions generated by cement manufacturing while simultaneously promoting the value-added recycling of CDWs [12–14]. Furthermore, recent studies in the field of construction materials have focused intensively on the potential use of CDWs as precursors in geopolymer systems—an alternative to traditional cementitious binders [15–17]. These materials are formed through the reaction between aluminosilicate source materials and alkaline activators, resulting in inorganic polymers with promising environmental and mechanical performance [18].

The potential use of CDWs as precursors in geopolymer production has recently gained increasing attention. This growing interest is mainly driven by the limited availability of conventional precursor materials, such as blast furnace slag, fly ash, and silica fume, which are also in high demand by the cement industry [19]. The limited availability of industrial by-products is further influenced by changes in steel production methods, the closure of coal mines, and the resulting reduction in fly ash generation. Compared to the early stages of geopolymer research, studies on CDW-based precursors have increased considerably, becoming an emerging research field. Even though, the publication count in this area has been progressively rising, the need to diversify experimental methodologies and research approaches remains undeniable. Several studies performed by Allahverdi and Kani [20], Komnitsas et al. [21], Reig et al. [22], Vasquez et al. [23], and Mahmoodi [24] et al. have provided that CDW-based materials can be successfully utilized in geopolymer production. Obtained results from CDW-based geopolymer were comparable to the that of traditional cementitious material or mainstream precursor-based geopolymers, showing compressive strength up to 80 MPa at

the end of 28-day. Along with mechanical and rheological properties, several researchers—such as Rahimpout et al. [25], Munir et al. [26], Ozcelikci et al. [27], Kul et al. [28]—have also investigated whether CDW-based geopolymer mixtures can serve as sustainable and environmentally friendly alternatives to traditional cementitious binders, highlighting their potential as green binder systems. However, despite these promising results, major research gaps remain unclear. Variations in the types and concentrations of alkaline activators, the composition and source of precursor blends, and the physicochemical characteristics of CDW materials all contribute to inconsistencies in the reported results. Therefore, further experimental verification and broader validation under different conditions are required to enhance the reproducibility and generalizability of the reported findings.

In the scope of this study, the influences of different types of CDWs, the industrial secondary raw material blast furnace slag (BFS), and varying alkaline activator dosages on the fresh and hardened properties of CDW-based geopolymer mixtures were examined. Furthermore, the effect of mix design variations on overall production costs was evaluated through a comparative cost analysis, and the potential environmental benefits associated with the recycling of CDW materials were emphasized. The outcomes of this study are expected to provide valuable insights for researchers working in this field, offering guidance on critical aspects to be considered during experimental design and serving as a foundation for future studies aiming to develop sustainable binder systems based on waste-derived materials.

2. Experimental Program

2.1. Materials

In this study, CDW-based precursors including red clay brick (RCB), hollow brick (HB), roof tile (RT), glass waste (GW), and concrete waste (CW), together with blast furnace slag (BFS) as an industrial by-product, were used for the geopolymer synthesis. The CDW-based precursors were collected from demolition sites in coarse fractions or rubble form. They were first crushed into smaller particle sizes (<2mm) using a jaw crusher and subsequently ground into fine powder using a laboratory-type tumbling ball mill for one hour with 70 rpm and ball to powder ratio of 20%, as in the previous studies conducted [9, 19, 29]. No grinding aids were employed for the milling, ensuring pure material behavior. The chemical compositions of the precursors used in the scope of this study are given in the Table 1. Besides, their particle size distributions, another critical parameter for geopolymerization, are demonstrated in Fig. 1.

Recycled concrete aggregate (RCA) smaller than 2 mm was utilized as an aggregate in the CDW-based geopolymer mixtures. The RCAs were obtained by sieving crushed concrete waste. No surface treatment or improvement process was followed.

Table 1. Chemical composition of precursors

%	HB	RCB	RT	GW	CW	BFS
SiO ₂	39.7	41.7	42.6	66.5	31.6	38.2
Al ₂ O ₃	13.8	17.3	15.0	0.9	4.8	13.0
Fe ₂ O ₃	11.8	11.3	11.6	0.3	3.5	0.7
CaO	11.6	7.7	10.7	10.0	31.3	35.3
Na ₂ O	1.5	1.2	1.6	13.6	5.1	0.1
MgO	6.5	6.5	5.3	3.9	0.9	6.5
SO ₃	3.4	1.4	0.7	0.2	0.5	0.5
K ₂ O	1.6	2.7	1.6	0.2	0.7	0.9
TiO ₂	1.7	1.6	1.8	0.1	0.2	1.0
P ₂ O ₅	0.3	0.3	0.3	0.0	0.1	0.0
Cr ₂ O ₃	0.1	0.1	0.1	0.0	0.1	0.0
Mn ₂ O ₃	0.2	0.2	0.2	0.0	0.1	1.4

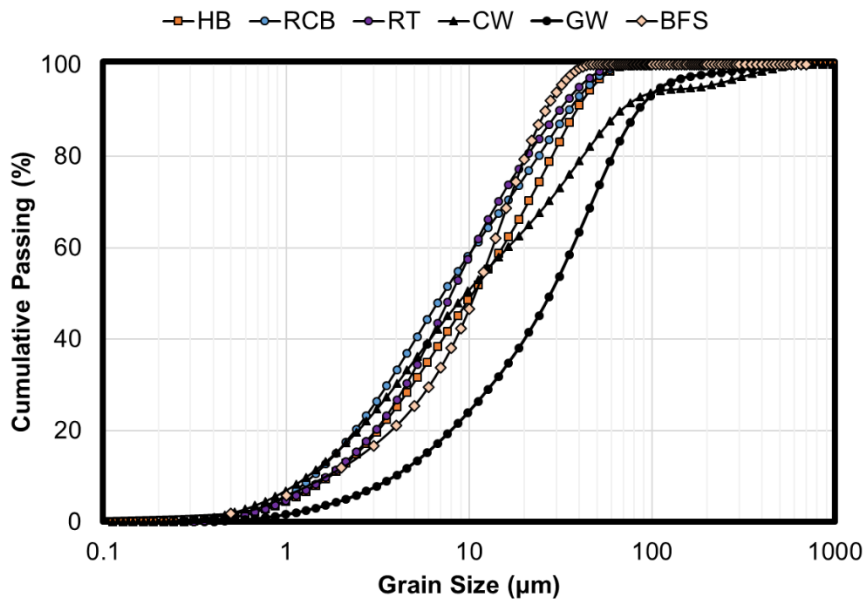


Fig. 1. Particle size distribution of precursors

Sodium hydroxide (NaOH) in flake form was employed as the sole alkaline activator for geopolymerization.

2.2. Mixture design

A total of fourteen mixtures (M1–M14) were designed in this study and mixture details are provided in Table 2. The first series (M1–M5) was designed to examine the influence of NaOH molarity while keeping the water-to-binder ratio (w/b) and aggregate-to-binder ratio (a/b) constant at 0.39 and 0.50, respectively. NaOH molarity was varied from 2 M to 6 M across these five mixes. Two just-add-water mixes (M6 and M7) were prepared to examine the influence of the NaOH addition method. While the conventional geopolymer practice is to prepare the NaOH solution, allow it to cool, and then add it to the dry components, M6 and M7 were formulated by adding NaOH directly to the dry blend. One-part geopolymer systems offer advantages over two-part systems, including improved handling safety, reduced abrasiveness, and greater practicality for on-site applications. In M6 the NaOH was

included in flake form, and in M7 the NaOH was included in powdered form; both were kept at w/b = 0.39 and a/b = 0.50. The next series (M8–M12) was designed for studying the influence of utilizing single CDW precursors together with BFS. Each of these mixes includes one CDW type (RCB, HB, RT, GW, or CW) combined with BFS to examine the co-use effect. M13 was designed to evaluate a BFS-only precursor system, while M14 was formulated to examine a masonry-based geopolymer.

2.3. Mixing procedure and curing

For the mixtures activated with NaOH solution (except for M6 and M7), the preparation process started with the preparation of the alkaline solution. The NaOH solution was prepared by dissolving the certain amount of NaOH flakes in tap water to achieve the desired molarity. Since the dissolution reaction is exothermic and increase the temperature of the solution, it was allowed to cool to room temperature before mixing.

Table 2. Mixtures design

Mixture ID	Precursor Blends						Aggregate	w/b	Alkaline Activator
	RCB	HB	RT	GW	CW	BFS			
M1	150	150	150	50	200	300	500	0.39	2M
M2	150	150	150	50	200	300	500	0.39	3M
M3	150	150	150	50	200	300	500	0.39	4M
M4	150	150	150	50	200	300	500	0.39	5M
M5	150	150	150	50	200	300	500	0.39	6M
M6	150	150	150	50	200	300	500	0.39	4M
M7	150	150	150	50	200	300	500	0.39	4M
M8	700	0	0	0	0	300	500	0.43	4M
M9	0	700	0	0	0	300	500	0.37	4M
M10	0	0	700	0	0	300	500	0.39	4M
M11	0	0	0	700	0	300	500	0.34	4M
M12	0	0	0	0	700	300	500	0.36	4M
M13	0	0	0	0	0	1000	500	0.38	4M
M14	233.33	233.33	233.33	0	0	300	500	0.39	4M

Then, all dry ingredients were put into the mixing chamber and dry-mixed for 1 minute. The NaOH solution was then included within 30 seconds, followed by an additional 120 seconds of mixing to get a homogeneous mixture. In the mixtures where NaOH was added in dry form (M6 and M7), the NaOH was directly included to the dry blend. After 1 minute of dry mixing, the certain amount of water was added within 30 seconds, and the mixing was continued for another 120 seconds to reach uniform distribution and activation of the binder components. The specimens were ambient-cured under laboratory conditions at 23 ± 2 °C and $50 \pm 5\%$ relative humidity.

2.4. Testing methods

In this study, the fresh properties of the mixtures were examined using the flow table test following the ASTM C1437-15. The mechanical properties were evaluated through compressive strength tests on $50 \times 50 \times 50$ mm cubic specimens, conducted at a loading rate of 0.9 kN/s in accordance with ASTM C109 standards. For each mix, three cubic specimens cured under ambient conditions were tested at 7 and 28 days, and the results were averaged to maintain reliability. Additionally, a cost comparison was performed to assess the influence of major parameters on overall production costs. This simplified analysis considered items such as initial material costs, damping, transportation, crushing, milling, and mixing. The aim of this comparison was to characterize how each parameter effects the total cost and to present guidance for more efficient mix design.

3. Results and Discussion

3.1. Fresh properties of mixtures

The flow table test results of the CDW-based geopolymer mixtures are demonstrated in Fig. 2. As seen, increasing NaOH molarity resulted in slight enhancement in workability, with flow values increasing by approximately 5%. This behavior can be ascribed to the increased dissolution of the

precursors at higher alkalinity, which decreases interparticle friction because of changes in particle geometry, even though the system gets a more viscous alkaline solution with increasing NaOH molarity [19, 30, 31]. There is no significant difference observed between one-part and two-part geopolymer systems. This can be explained by the relatively low molarity level; the small amount of NaOH incorporated, combined with the heat released upon contact with water, was insufficient to accelerate the reaction significantly. Considering the existence of other dry ingredients, the temperature rise was not sufficient to influence the overall system substantially. For the mixtures M6–M14, flow values were set to show similar workability, and the need water content to obtain this target was considered as the basis for comparison. The results showed that RCB negatively influenced workability, HB enhanced it, and RT showed an intermediate effect. GW and CW precursors showed better workability than masonry-based precursors. Similarly, the BFS-only mixture also demonstrated better performance compared to masonry-based precursor mixtures.

3.2. Mechanical performance

The compressive strength results of CDW-based geopolymer mixtures cured under ambient conditions for 7 and 28 days are given in Fig. 3. Although specimens activated with 2 M and 3 M NaOH did not significantly harden after 1 day, the 7-day tests showed compressive strengths of approximately 10 MPa. Increasing NaOH molarity resulted in higher strengths, possibly because higher alkalinity improves precursor dissolution and promotes geopolymerization [32, 33]. The method of NaOH addition did not yield any noticeable increase or decrease in strength, which can be ascribed to the relatively low molarity tested; under these conditions, the reaction environment was poorly altered to notably affect geopolymerization. These results showed that, at low molarity, NaOH can be included directly to the dry mix without preparing a solution.

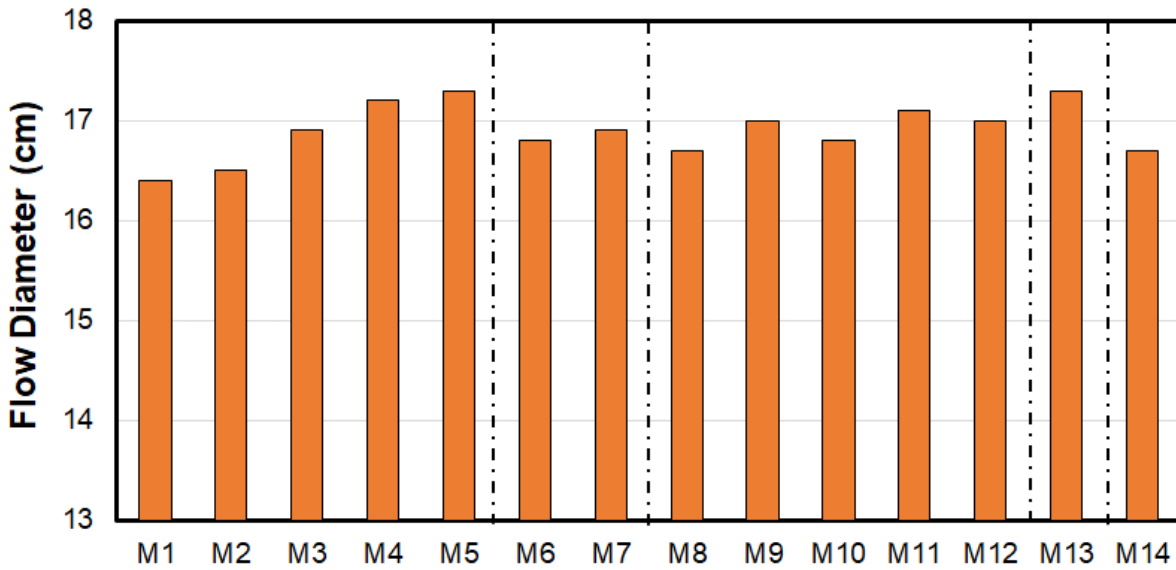


Fig. 2. Flow table test results

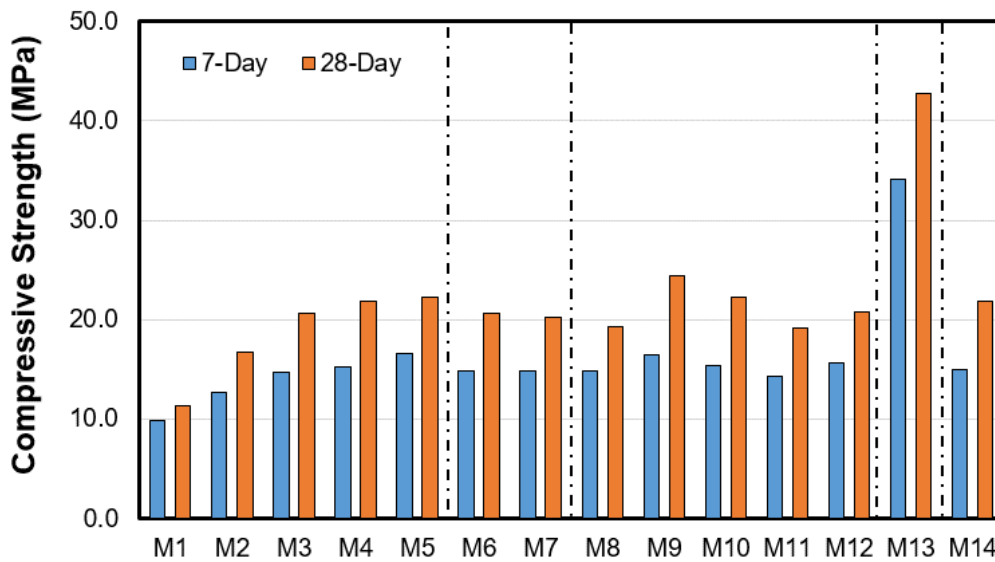


Fig. 3. Compressive strength test results

However, it is important to note that, as NaOH can absorb moisture from the air even under ambient conditions, potentially altering its performance. The results also showed that mixtures containing a high proportion of RCB (M8) demonstrated lower compressive strengths compared to other single masonry-based precursors (M9-M10). This behavior can be attributed to the higher water content needed to reach similar workability, yielding in a weaker matrix [34]. Additionally, it may be related to the limited solubility and reactivity of RCB at 4 M NaOH. Among the M8–M12 series, the highest strength was reached for the mixture containing HB as a single precursor together with 30% BFS, possibly due to its lower water demand and higher reactivity [35]. The RT mixture showed lower strength than HB but higher strength than other CDW-based precursor mixtures. Mixtures containing only CW or GW as single CDW precursors (M11 and M12) displayed lower compressive strengths compared to masonry-based counterparts, despite having lower water

demand. The mixture containing 100% BFS reached the highest compressive strength among all mixes, reaching approximately 43 MPa at 28 days. These can be ascribed to the improvement of the microstructure of the inner structure with increased reactivity of the precursor content, as BFS can provide more available Ca²⁺ ions for geopolymerization, and the self-cementitious properties of BFS may promote gel formation [29, 36, 37]. The masonry-blend mixture (M14) did not show a notable difference compared to single-precursor mixtures.

Overall, these findings show that while CW and GW reduce water demand, their lower reactivity and limited Si/Al content prevent substantial strength gains when used alone. Therefore, combining them with other masonry-based CDW precursors can be more effective. Among masonry precursors, the best performance was observed in HB-activated systems at 4 M NaOH. It should be noted that these results are specific to the tested materials and NaOH

molarities; different molarities may lead to different outcomes, as solubility and geopolymerization potential can vary depending on the reaction medium.

3.3. Cost comparison of geopolymer

A simple cost analysis was performed to compare the influences of mixture variables on overall material costs. Details such as equipment depreciation, labor costs, and other overheads were not considered, as the primary target was to conduct a comparative analysis and to identify major factors to consider during mixture design. Since these excluded costs are common to all mixtures, they do not affect the relative comparison. The analysis primarily considered the costs of the precursors, aggregates, alkaline activators, and water. Specifically, the initial cost of each material was identified. For waste-derived materials, a negative value was assigned to account for the avoided disposal cost (i.e., the cost that would have been experienced if the material were sent to a landfill). Transportation costs for all materials, electricity consumed during crushing and milling of the waste, and energy used during mixing were considered while calculation. Using this approach, a total cost comparison was conducted for producing 1 m³ of material. To account for differences in mechanical performance, an additional comparison was performed considering the cost per unit compressive strength, expressed as the cost needed to achieve 1 MPa of compressive strength per cubic meter. This approach provides a more realistic basis for comparison, as simply comparing costs per cubic meter may be misleading due to variations in strength. The results of this analysis are demonstrated in Fig. 4. It should be considered that the calculated costs per cubic meter are not representative of industrial-scale production and include several assumptions and neglected factors. The primary aim of this analysis is to emphasize the influences of mix-design-specific parameters rather than to provide exact industrial cost estimates.

In geopolymer mixtures, the parameters with the greatest influence on overall cost were identified as the alkaline activator, BFS content, and transportation expenses. Increasing the NaOH molarity consistently raised the unit cost per cubic meter. Among the mixtures containing individual CDW precursors blended with 30% BFS (M8–M12 series), the unit costs per cubic meter exhibited similar trends. The mixture composed entirely of BFS resulted in the highest cost per cubic meter. However, when the results were normalized based on compressive strength (i.e., cost per MPa of 1 m³ mixture), the increase in NaOH molarity initially reduced the cost per MPa up to 4 M due to strength enhancement, but further increases led to a rise in cost per MPa as strength gains decelerated while activator cost continued to rise. Within the M8–M12 series, the most cost-effective performance was achieved by the mixture containing HB. Although the 100% BFS mixture had the highest cost per cubic meter, it showed the lowest unit cost when expressed in terms of cost per MPa, demonstrating its superior efficiency in strength development relative to cost.

3.4. Environmental benefit through CDW-based geopolymer technology

The utilization of CDW-based wastes in next-generation green construction materials within a circular economy framework provides great importance from both economic and environmental perspectives. To prevent construction activities—intended to create a more livable world—from paradoxically contributing to an unlivable one, the recycling or reintegrating of CDWs as inputs into the construction sector has become not merely an option but a necessity. Through the upcycling of billions of tons of waste materials, it will be possible to reintroduce these resources into the economy while reducing disposal challenges.

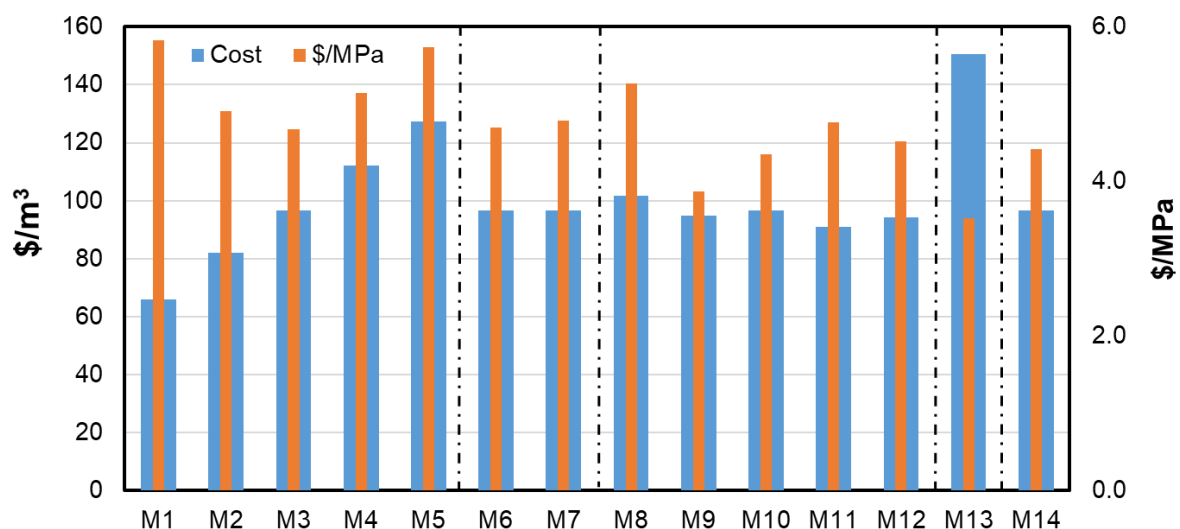


Fig. 4. Cost comparison results

In turn, this approach will help mitigate issues such as the loss of farmable land, air, soil, and water pollution, and the depletion of natural resources due to new construction activities, ultimately contributing to a more sustainable built environment. Therefore, this study is significant in terms of raising awareness on this issue, discussing possible approaches for the reuse of these wastes, and bringing the topic into focus.

4. Conclusions

The following conclusions have been drawn from the current research:

- Alkaline activator dosages and precursors content have considerable influences on the fresh properties of CDW-based geopolymer mixtures.

- CDW materials were successfully utilized in geopolymerization, achieving compressive strengths ranging from 10 to 25 MPa after 28 days of ambient curing. The highest strength was recorded for the mixture incorporating HB as the sole precursor combined with 30% BFS.

- In the geopolymer system activated with 4 M NaOH, the method of NaOH addition did not produce any noticeable influence on the engineering properties.

Declaration

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Author Contributions

H. İlcan: Investigation, Methodology, Conceptualization, Data curation, Writing – original draft, Methodology. M. Şahmaran: Validation, Supervision, Project administration, Methodology, Writing – review & editing.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Ethics Committee Permission

Not applicable.

- The cost analysis revealed that while the alkaline activator, BFS content and transportation are the most influential parameters on overall cost, mixtures incorporating CDW-based precursors—particularly those containing HB—offered the most cost-effective performance, demonstrating that waste-derived materials can achieve competitive strength-to-cost efficiency when appropriately optimized.

- The use of CDW should be promoted and its valorization into high value-added applications should be encouraged by addressing issues such as the low cost of landfill disposal, the lack of strict regulations and enforcement, and the limited availability of incentives.

The findings of this study contribute to the advancement of current knowledge and provide a practical framework for the value-added utilization of CDW in geopolymer systems. However, the results are specific to the types and characteristics of wastes used in this study, and broader generalization requires further experimental validation with different CDW sources and mix designs. In addition, a comprehensive life cycle assessment is necessary to quantitatively evaluate the environmental performance and sustainability potential of the proposed system. Future research should therefore focus on expanding the material database and conducting detailed environmental impact analyses.

Conflict of Interests

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

Use of generative AI and AI-assisted technologies

The authors used AI tools for language polishing and have reviewed and take full responsibility for the final content.

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