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Alkali-Activated Mortars Incorporating Construction and Demolition Waste and Industrial By-products: A Fresh and Hardened State Evaluation

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Highlights

- This study aims to produce sustainable building materials by recycling waste.
- Various waste materials are used in alkali-activated composites.
- The findings reveal that alkali-activated composites can serve as an eco-friendly alternative.

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Abstract

This study examines the potential of alkali-activated composites to produce sustainable building materials by recycling construction and demolition waste (CDW). Various waste materials such as ground granulated blast furnace slag (GGBS), class F and C fly ash (FA), recycled waste clay brick powder (RWBP), and waste concrete powder (WCP) were used to produce different alkali-activated composites along with recycled concrete aggregate. The prepared mixtures were analyzed for their fresh-state properties, as well as their physical and mechanical characteristics, including workability, strength, ultrasonic pulse velocity (UPV), and resistance to high temperatures. The findings indicate that mixtures with class C fly ash achieved higher compressive strength, whereas F class fly ash positively affected workability and high-temperature resistance. Slag effectively enhanced the compressive strength of the alkali-activated composites. In particular, the B3 mixture (20% class F fly ash, 40% slag) exhibited a balanced set of properties in terms of workability, compressive strength, and high-temperature performance. This study provides a valuable resource for producing alkali-activated composites from CDW and industrial waste, with the potential to reduce the environmental impact of the construction sector.

1. INTRODUCTION

With the swift development of urbanization, increasing amounts of construction and demolition waste (CDW) are being produced. The disposal of such waste has drawn attention from scientists worldwide. Recycling this waste as building materials can effectively diminish the stockpiles of construction waste [1]. These wastes can be used as recycled aggregate to replace natural sand. Additionally, they can serve as a precursor powder alternative to conventional binders [2,3].

In recent years, geopolymer technology has been used, particularly in the construction sector, to ensure sustainability and reduce environmental issues as an alternative to cement. Various waste materials like fly ash and slag are considered potential raw materials for geopolymer production [4]. Additionally, CDW contains a substantial amount of waste clay brick, that is rich in silica-alumina species and has potential use as a supplementary cementitious material [2,3,5]. Many studies have been conducted and are ongoing to explore the utilization of clay brick powder in cement and geopolymer materials. In these studies, the materials used, and experimental designs vary.

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In previous studies, the possibility of recycling brick wastes in synthesizing geopolymers has been investigated by some authors mentioned below. Sharmin, et al. [6] investigated the influence of using recycled waste clay brick powder (RWBP) as an alternative geopolymer binder, instead of class F fly ash (F-FA), in proportions ranging from 10-40%, under ambient and thermal curing conditions. As the amount of RWBP increased, fresh mortar flow decreased. When the RWBP content exceeded 20%, it reduced compressive strength by 20% under ambient curing and by 14% under thermal curing in the early ages; however, it increased compressive strength by 16.5% under ambient curing and 17% under thermal curing at later ages. Ahmed, et al. [7] examined the potential of using RWBP as an alternative to conventional industrial waste (slag: GGBS and F-FA) in engineering geopolymer composites. When RWBP completely replaced F-FA, significant improvements in the composite's strength properties were observed. However, replacing RWBP with GGBS resulted in reduced workability, shorter setting time, and lower composite strength. Li, et al. [8] produced ternary geopolymer concrete such as GGBS, RWBP, and FA containing recycled fireclay brick aggregates. The best mechanical properties were obtained at a 10% RWBP replacement rate. Mahmoodi, et al. [9] examined the potential of using ceramic wall tile (RWT), recycled clay brick (RCB), and concrete waste (RCW) as binders in a ternary geopolymer system (metakaolin; MK, GGBS, class C fly ash (C-FA), and F-FA). The incorporation of GGBS at selected Na/Si and Si/Al ratios was effective in obtaining higher compressive strengths compared to MK and C-FA. However, among all supplementary cementitious materials, F-FA had the weakest effect on the mechanical performance of ternary geopolymers. Alhawat, et al. [10] investigated the microstructural, mechanical, and environmental properties of geopolymer concrete produced from CDWs (e.g., brick, concrete, tile, and glass). The research findings indicated that geopolymer concrete made solely from CDWs did not achieve sufficient compressive strength under all curing conditions. However, adding 25% GGBS to CDWs significantly improved the strength performance. Roy and Islam [11] used GGBS and varying proportions of RWBP and brick sand in geopolymer mixtures. Different molar concentrations of NaOH solutions (3M, 4M, and 6M) were tested in these mixtures. Results indicated that the optimal binder combinations for geopolymer mortars were achieved by using RWBP instead of 15% GGBS in 4M and 6M NaOH solutions. The compressive and flexural strengths of geopolymer mortars increased with higher NaOH concentrations; however, as the proportion of waste brick sand increased, the strengths decreased. Nisa and Singh [12] investigated the effects of varying ratios of GGBS and volcanic ash with natural sand and devri stone quarry dust on the mechanical properties of geopolymer concrete, including compressive strength and water absorption. Mixing GGBS with F-FA eliminated the need for heating to cure the concrete. Kaze, et al. [13] examined the effects of substituting up to 50% RWBP in volcanic scoria-based geopolymers on fresh and hardened properties. The results demonstrated that when the RWBP concentration increased, the geopolymer mixes' flowability and setting time decreased. However, RWBP powders increased the mixes' Al concentration, giving them a more compact structure and enhancing their compressive and flexural strengths. Kırgız, et al. [14] investigated whether the incorporation of waste from marble and brick industries in powder form as a mineralogical additive or substitute in cement manufacturing is a viable option. The pozzolanic properties of brick powder according to compressive and flexural strengths were three and fourteen times greater than the pozzolanic properties of marble powder. Based on previous research, one of the objectives of this study is to help fill the knowledge gap in this field by investigating the effects of using various waste materials in the production of geopolymer binders. Fly ash is widely recognized as a primary geopolymer precursor; however, as energy production shifts toward renewable sources, the availability of fly ash is expected to decrease, making it essential to identify suitable alternatives. RWBP can be a good source of aluminosilicate, which is vital for producing geopolymer binder material. Nevertheless, the combined use of both materials in geopolymer binder production has not been extensively studied.

It is seen that there are generally studies on ternary geopolymer composites in the literature. It is thought that the current study contributes to the literature in terms of producing quaternary alkali-activated composites. In the present study, four-component mixtures were prepared under normal and thermal curing conditions using GGBS, C-FA, F-FA, RWBP, and WCP. Waste concrete was used as the aggregate, and all components consisted of waste materials. The workability, mechanical properties, and high-temperature resistance of the alkali-activated composites produced in this study were investigated. This study aims to provide new knowledge into effective parameters for producing alkali-activated composites incorporating CDW and industrial waste, offering a potential solution for sustainable construction.

2. MATERIAL METHOD

2.1. Materials

In this study, GGBS, C-FA, F-FA, RWBP, and WCP were used for alkali-activated composite production. The chemical compositions of the precursor materials used in this study are given in Table 1. Concrete rubble and brick fragments obtained from completed demolition sites in urban transformation areas were ground to cement fineness. Sodium hydroxide (NaOH) with 98% purity in pellet form was used for alkali activation. For mortar production, a recycled concrete aggregate smaller than 4 mm was used. In the preparation of aggregates, firstly, concrete rubble was broken into small pieces with the help of a jaw crusher, then it was ground in a ball mill until small pieces were obtained and then subjected to a sieving process to obtain the desired dimensions. All powder components were used under 106 microns.

Table 1. *Chemical compositions of materials*

Chemical composition	F-FA (%)	C-FA (%)	RWBP (%)	WCP (%)	GGBS (%)
SiO_2	59.11	42.85	46.91	10.91	45.17
Al_2O_3	20.69	11.51	15.55	2.2	15.29
Fe_2O_3	8.22	7.17	9.4	1.89	0.97
CaO	3.94	16.68	10.47	48.41	25.61
MgO	1.59	7.62	5.17	2.93	9.35
SO_3	0.45	1.01	0.21	0.17	0.18
K_2O	1.98	3.17	1.9	0.31	1.11
Na_2O	1.64	1.03	1.04	0.11	0.32
P_2O_5	0.13	0.88	0.19	-	0.02
LOI	1,85	1,44	1,73	31,57	0,62

2.2. Mixture Proportions

Four different mixtures were prepared using five different powder materials to produce alkali-activated composites. The mixture proportions for the materials produced are presented in Table 2. The molarity of the mixtures was 10 molars, the aggregate/binder ratio was 1.0, and the water/binder ratio was 0.4. Waste brick powder and concrete powder were used at a constant rate of 20% for all mixtures.

Table 2. *Normalized mixture proportions (by binder mass = 1) and wet unit weight of the mixtures*

Sample Code	**Binder**						**Aggregate**	**Water**	**NaOH**	**Wet Unit Weight (g/cm³)**
	F-FA	**C-FA**	**RWBP**	**WCP**	**GGBS**	**Total**				
B1	-	0.2	0.2	0.2	0.4	1	1	0.4	0.16	2.063
B2	-	0.4	0.2	0.2	0.2	1	1	0.4	0.16	2.029
B3	0.2	-	0.2	0.2	0.4	1	1	0.4	0.16	2.051
B4	0.4	-	0.2	0.2	0.2	1	1	0.4	0.16	2.012

2.3. Preparation of Mixtures

During the preparation of the alkali-activated composites, a NaOH solution was first prepared. The solid NaOH was fully dissolved in water, and the solution was allowed to cool down to ambient temperature to dissipate the heat produced by the exothermic reaction. The mixing process began by combining the powder and aggregate. The dry mix was stirred in a mixer at 60 revolutions per minute (rpm) to ensure homogeneity. The pre-prepared alkaline solution was then added. The mixing continued at 60 rpm for one minute, after which the mixer was stopped for one minute to scrape the mixture from the sides of the container. Finally, the mixing was resumed at 120 rpm for two minutes to complete the mixing.

2.4. Specimen Preparation and Curing

To evaluate the compressive and flexural strengths of the alkali-activated composite mixtures, 40×40×160 mm specimens were prepared using steel molds. The prepared mixtures were placed in oiled molds, and compaction was performed. The tops of the molds were covered with plastic sheets to prevent water loss. The specimens were kept in the molds for one day at a temperature of 23 ± 2 °C and relative humidity of 50 ± 5%, after which they were demolded. The specimens were then subjected to thermal curing in an oven at 50 ± 2 °C for one day to accelerate their strength development. The specimens were covered with foil to keep the humidity constant while they were heated. Subsequently, the specimens were maintained under ambient condition for 7 and 28 days for curing and tested afterward.

2.5. Testing

Various tests were conducted on the specimens, including flow table tests, compressive strength tests, flexural strength tests, ultrasonic pulse velocity (UPV) measurements, and electrical resistance evaluations. Detailed descriptions of the testing methods are provided in the subsequent sections of this study.

2.5.1. Flow table

The consistency and workability of the alkali-activated composite mixtures were determined by flow table tests, which were conducted in accordance with the ASTM C1437 standard. The mortar specimens were placed in a truncated cone mold with dimensions of 100 mm for the bottom internal diameter, 70 mm for the top internal diameter, and 50 mm in height. After compaction in two stages, the mold was lifted to allow the material to spread under its own weight. The spread was measured in two perpendicular directions. Subsequently, the flow table was dropped 25 times from a height of 10 mm within 15 seconds, and the material's spread was recorded based on the perpendicular diameter measurements.

2.5.2. Flexural strength and compressive strength

Flexural strength tests were performed on prism-shaped specimens measuring 40×40×160 mm in accordance with TS EN 196-1, after curing for 7 and 28 days. The flexural strength was determined on at least three specimens per test, applying a constant load rate of 50 ± 10 N/s. Following the flexural tests, compressive strength tests were performed on the resulting prism halves, also in compliance with TS EN 196-1. At least six specimens from each mixture were tested under a constant load rate of 2400 ± 200 N/s. All tests were conducted on both 7 and 28 days.

2.5.3. Ultrasonic pulse velocity

The UPV test was conducted on oven-dried 40×40×160 mm prism specimens, using at least three identical specimens per mixture, with the average values recorded as the testing results. During the UPV test, the smooth surfaces of the specimen were first identified. The transducers were placed on two smooth surfaces, each coated with gel, and the time it took for high-frequency sound waves to travel from one transducer to the other was measured. Subsequently, the velocity value was calculated using the distance between the opposing surfaces. Additionally, it's important to note that UPV testing is typically used to assess the quality and uniformity of materials like concrete. Variations in the velocity can indicate the presence of defects, cracks, or variations in material composition, which can impact the overall structural integrity.

2.5.4. High-Temperature resistance

To compare resistance to high temperatures, the specimens were subjected to thermal treatment up to 400 °C. At the end of the 28-day curing period, the specimens were placed in a furnace and heated at a rate of 10°C/min until they reached a steady temperature of 400°C, which was maintained for two hours. Flexural and compressive strength tests were repeated on thermally treated specimens. Three specimens from each mixture were tested.

3. RESULTS AND DISCUSSION

3.1. Consistency

The flow percentage values of the specimens are shown in Figure 1. The amount of C-FA increased in mixtures B1 and B2, the flow percentage decreased. Conversely, in mixtures B3 and B4, the flow percentage increased with increasing amount of F-FA. In other words, F-FA contributed positively to workability, whereas C-FA had a negative impact. This can be attributed to the fact that an increased content of C-FA introduces more reactive calcium species into the medium, which trigger rapid geopolymerization and consequently reduce flowability. This situation is reflected in the 7th-day strength values, where B2 exhibits higher strength than B1. In the specimens with F-type FA (B3 and B4), due to the lower reactive CaO content of the fly ash and the fact that the specimens were prepared based solely on weight ratios without considering standard consistency, the surface topology and particle shapes of the fly ash and slag takes precedence over their chemical composition. So much so that, contrary to B1 and B2, F-FA which contains a relatively low amount of reactive calcium species and consists of spherical particles provides improved fluidity due to the low surface friction of these particles, as observed in the comparison of B3 and B4 specimens. Another reason why B4 exhibits higher flow than B3 is that GGBS has a rougher surface texture than fly ash, and a decrease in its amount results in an increase in flow [15]. To sum up, when comparing F-FA and C-FA, the effects of increasing the amount of each type of fly ash differ. These findings are consistent with the literature, as the lower calcium content of F-FA improved the mixture's fluidity. This result aligns with the findings of [6]. Additionally, in mixtures B1 and B2, a reduction in the GGBS content resulted in decreased workability, which is consistent with the results of [7,13].

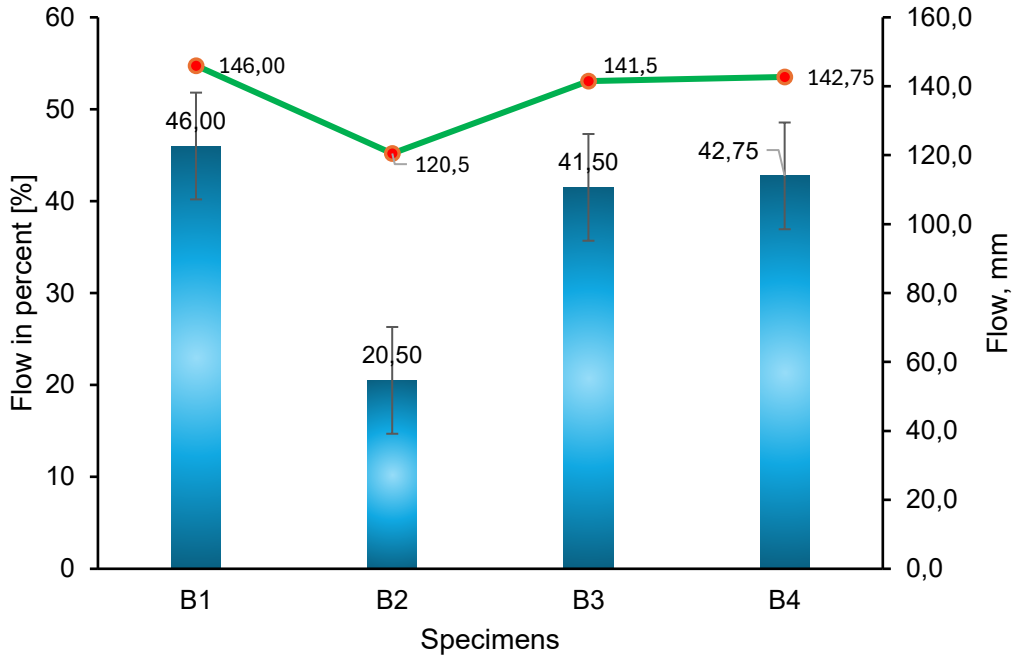

Figure 1. *Flow percentages of the specimens*

3.2. Compressive Strength and UPV

The 7- and 28-day compressive strengths and 28-day pulse velocities of the specimens are presented in Figure 2. When examining the mix ratios in Table 2 alongside Figure 2, it is observed that the 28-day compressive strengths of mixtures B1 and B2 (C-FA mixtures) are higher than those of mixtures B3 and B4 (F-FA mixtures). Additionally, increasing the C-FA content in the B1 and B2 mixtures, as well as increasing the F-FA content in the B3 and B4 mixtures, resulted in a decrease in the 28-day compressive strength. C-FA appears to be more effective than F-FA in terms of compressive strength at 28 days. Considering the 28-day results, with an increase in C-FA content, the compressive strength of B2 decreases

by 15.01% compared to B1, whereas an increase in F-FA content results in a 29.17% strength loss in B4 compared to B3. Among all mixtures, the highest 28-day compressive strength was observed in B1 (20% C-FA and 40% GGBS). Comparing C-type and F-type FAs, the high calcium content in C-FA contributes to the formation of a strong binding phase. GGBS is an effective component for enhancing the compressive strength of alkali-activated mixtures because of its reactive nature and calcium content, which strengthen the binding phases. GGBS improves the compressive strength when used in combination with C-FA or F-FA at 28 days. As discussed in the flow results, the increased C-FA content in the B1 and B2 mixtures led to higher early strengths at 7 days, due to the reactive calcium content of C-FA. On the other hand, the increased F-FA content in the B3 and B4 mixtures resulted in lower early strengths at 7 days. In other words, in the specimens containing F-type FA, the increased GGBS content enhanced the strength at 7 days due to the reactivity of the GGBS. In the present study, with the exception of B2 at 7 days, GGBS content reduction resulted in strength loss. This outcome aligns with the findings of [7-11].

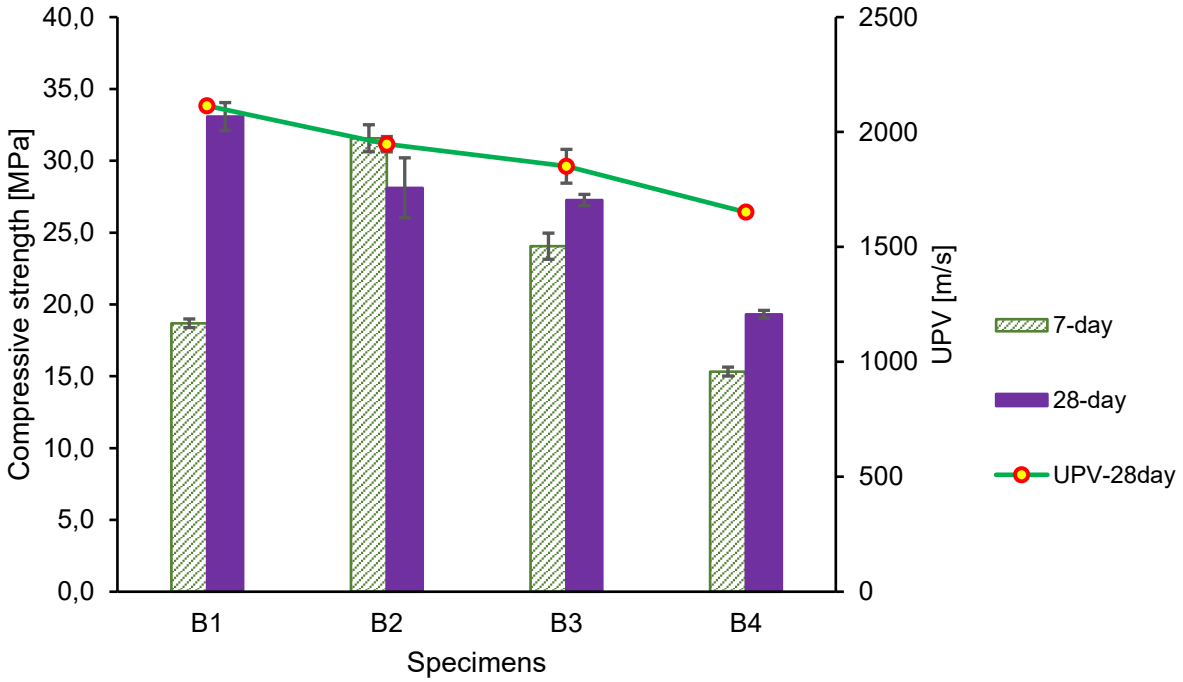

Figure 2. *7- and 28-day compressive strengths and pulse velocities of the specimens*

The UPV results at 28 days, shown in Figure 2, are affected by defects, voids, and cracks within the mortar. These factors, which also reduce strength, cause the sound waves to travel a greater distance, resulting in a lower velocity value. Since every factor contributing to strength also reduces the voids within the matrix, there is a good correlation between UPV and compressive strength. In this context, the relationship between the UPV values and the 28-day compressive strengths of the B1, B2, B3, and B4 mixtures was consistent within each group.

3.3. Compressive Strength and High-Temperature Resistance

The 28-day compressive strengths of the specimens and the 28-day compressive strengths and UPV values of the specimens exposed to thermal treatment at 400 ^{0}C are shown in Figure 3.

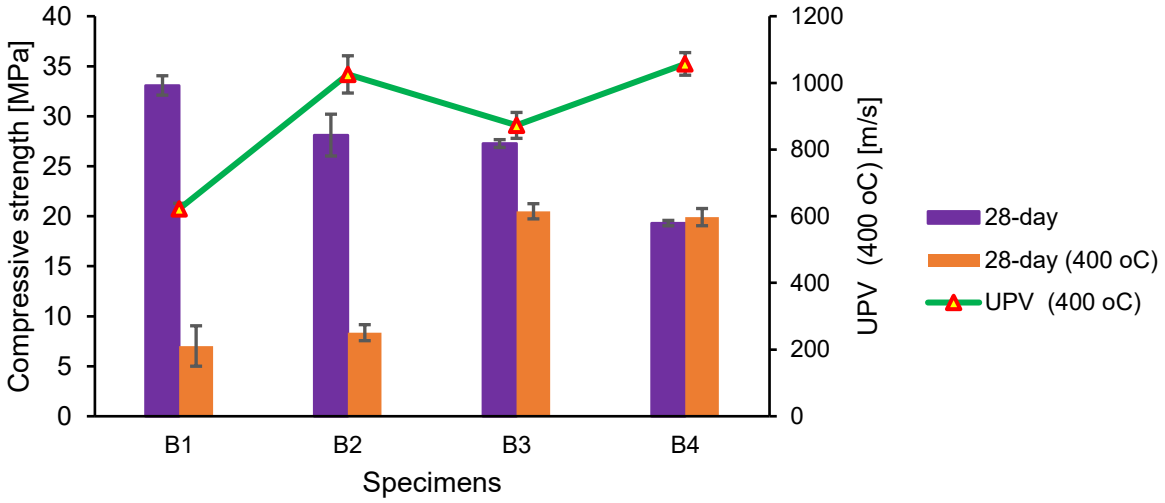

Figure 3. *Comparison of compressive strengths of specimens with and without heat curing*

When examining the mix ratios in Table 2 along with Figure 3, it can be observed that the 28-day compressive strengths of the B1, B2, and B3 mixtures, which were subjected to thermal treatment at 400°C, decreased compared to their 28-day strengths without thermal curing, whereas the B4 mixture showed a slight increase. The strength losses in the B1, B2, and B3 mixtures were 78.76%, 70.27%, and 24.84%, respectively, while the B4 mixture exhibited a strength increase of 3.09%. Additionally, in thermally cured specimens, the compressive strengths of the B1 and B2 mixtures (C-FA mixtures) were lower than those of the B3 and B4 mixtures (F-FA mixtures). In other words, F-FA demonstrated greater high-temperature resistance than C-FA. Furthermore, with the increase in C-FA content, the compressive strength of B2 increased by 18.97% compared to B1 in thermally cured mixtures. In the B3 and B4 mixtures, increasing the F-FA content did not significantly change the strength. Among all thermally cured mixtures, the highest compressive strength was observed in B3 (20% F-FA and 40% GGBS). F-FA positively affects high-temperature resistance, leading to a lower strength loss compared to mixtures containing C-FA. This is due to the degradation of amorphous aluminosilicate bonds in alkali-activated mixtures at high temperatures, which causes structural weakness. The binding structure of mixtures containing C-FA is more brittle due to their high calcium content, making them more prone to rapid degradation at high temperatures. Another factor contributing to the reduction in fire resistance of a binder phase with higher strength, and consequently lower porosity, in both cement and alkali-activated systems, is the evaporation of moisture within the binder phase under high temperatures, generating high pressure. In a low-porosity (and therefore high-strength) matrix, this high-pressure steam cannot escape, leading to the development of tensile stresses within the matrix and causing greater damage [16]. On the other hand, a decrease in strength likely indicates a more porous matrix structure, allowing the water vapor within the matrix to escape more easily. For instance, in a relatively low-strength mortar like B4, high temperatures may act as a curing effect rather than causing damage, potentially even leading to a slight increase in strength. The findings of this study indicate that F-FA contributes to the thermal stability of alkali-activated structures, making the results meaningful. GGBS, when used with F-FA, contributes to high-temperature resistance, demonstrating the thermal stability-enhancing effect of GGBS. The relationship between UPV values and 28-day compressive strengths of the B1, B2, B3, and B4 mixtures in thermally cured specimens was consistent among the groups.

3.4. Flexural Strength and High-Temperature Resistance

The 7- and 28-day flexural strengths of the specimens and the 28-day flexural strengths of the specimens exposed to thermal curing at 400 ºC are shown in Figure 4.

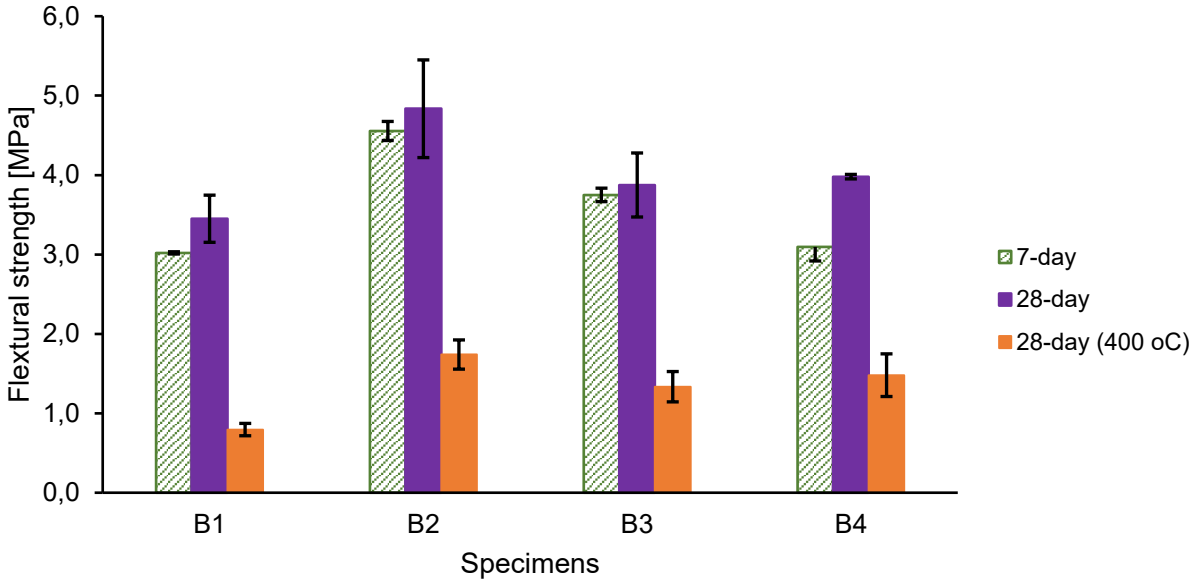

Figure 4. *Comparison of the flexural strengths of specimens with and without heat curing*

When examining the mix ratios in Table 2 along with Figure 4, it is observed that the 28-day flexural strengths of all mixtures exposed to thermal curing at 400°C decreased compared to the 7- and 28-day flexural strengths of mixtures without thermal curing. High temperatures cause thermal expansion and microstructural degradation in the alkali-activated matrix and amorphous aluminosilicate bonds, increasing the porosity. As the porosity increases, the material's compactness decreases, leading to strength loss. The binding structure of geopolymers degrades at high temperatures, resulting in structural weakness. Additionally, high temperatures cause the water in the alkali-activated matrix to evaporate and dry out. Moreover, temperatures exceeding 100 °C result in boiling and internal pressure, generating tensile stress within the alkali-activated matrix. These factors create internal stresses, leading to strength loss [17,18].

In mixtures B1 and B2, increasing the amount of C-FA, and similarly in mixtures B3 and B4, increasing the amount of F-FA leads to an increase in 28-day flexural strength. The flexural strength of B2 increased by 40.14% compared to B1, whereas that of B4 increased by 2.71% compared to B3. The increase in the C-FA content in the B1 and B2 mixtures also led to higher early flexural strengths at 7 days, whereas the increase in the F-FA content in the B3 and B4 mixtures resulted in lower early flexural strengths at 7 days. The 28-day flexural strength values demonstrate that B2 exhibited the highest strength, followed by B4, B3, and B1. However, after exposure to 400°C, significant strength losses were observed in B1 and B2, highlighting the brittle binding structure of C-FA due to its high calcium content. In contrast, B3 and B4, which contain F-FA, showed better thermal resistance, with B3 retaining the highest post-thermal strength and B4 experiencing minimal strength loss. This indicates that F-FA contributes significantly to high-temperature stability by forming a more resilient binding structure. Moreover, the combination of F-FA and GGBS in B3 resulted in superior thermal performance, as GGBS enhances the thermal stability of alkali-activated structures. Although B4's strength slightly decreased after thermal exposure, its minimal loss suggests that low initial strength matrices, like B4, allow water vapor to escape more easily, reducing internal stresses and enhancing thermal resistance.

In conclusion, the increase in temperature leads to a significant loss of strength in alkali-activated composite mixtures, particularly those containing C-FA. However, mixtures containing F-FA exhibit better thermal stability, providing a more durable structure at high temperatures.

In the present study, as the GGBS content in the mixtures decreases, the flexural strength of specimens cured under normal conditions shows an increasing trend. This result is consistent with the study by [13]. However, Roy and Islam [11] reported a decrease in the flexural strength of 4 molars and 6 molars, which may be due to the lower molarity of the mortars used in their study compared to those in the present study.

Alhawat, et al. [10] emphasized that relatively higher alkaline activator concentrations are required to activate low reactivity in the case of using waste materials.

4. CONCLUSIONS

This study investigated the production of alkali-activated composites using materials derived from the recycling of CDW. The materials used included GGBS, F-FA, C-FA, RWBP, and WCP, with recycled concrete aggregate as the aggregate. The alkali-activated composites were evaluated in terms of their workability, mechanical strength, and high-temperature performance. The key findings of this study are as follows:

- F-FA enhances workability and provides a homogenous and fluid structure. This property makes F-FA advantageous in terms of workability.
- Mixtures containing C-FA show superior performance in terms of compressive strength. The B1 mixture containing 20% C-FA achieved the highest 28-day compressive strength. An increase in the amount of C-FA also improved the early compressive and flexural strength.
- Increasing the amount of C-FA and F-FA increased the flexural strength.
- F-FA has a positive effect on high-temperature resistance. The B3 mixture (20% F-FA) yielded the best high-temperature resistance.
- GGBS effectively contributes to the compressive strength of alkali-activated composites because of its reactive structure and calcium content, which enhance the binding phases. When used with C-FA, GGBS improves the compressive strength, whereas when used with F-FA, it provides high-temperature resistance.
- Increase in the amount of relatively less reactive F-FA and the reduction in the amount of slag with a rougher surface texture resulted in an improvement in workability.

Based on these findings:

- For applications requiring moderate strength and high-temperature resistance, the “B3 mixture (20% F-FA and 40% GGBS)” may be an optimal choice.
- For applications requiring high compressive strength, the “B1 mixture (20% C-FA and 40% GGBS)” may be preferred.
- The B3 mixture (20% F-FA and 40% GGBS) can be considered a balanced, optimal mixture because it meets multiple performance criteria, including workability, compressive strength, and high-temperature resistance.

The experimental results demonstrate the recycling potential of CDWs as a sustainable building material. The findings reveal that alkali-activated composites could serve as an eco-friendly alternative in the construction sector, enabling the use of waste materials in this context.

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CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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