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Adapting Construction and Demolition Waste to Circular Building Materials and Evaluation of Life Cycle Environmental Impacts

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Abstract. *Upcycling of construction and demolition wastes (CDWs) into value-added building materials that can be used for rapid construction and housing in developing countries and disaster-prone areas is important and offers a fast, cost-effective, and eco-friendly solution. The objective of this study is to investigate the feasibility of using different-size recycled concrete aggregates (RCAs) in geopolymers made entirely from CDW-based masonry components including hollow brick (HB), red clay brick (RCB), and roof tile (RT) as precursors. To improve the strength development, thermal curing was applied to the developed geopolymer mortars. Compressive strength test was used for mechanical characterization. To assess the environmental impact of geopolymer mortars, a cradle-to-gate life cycle assessment (LCA) was carried out. Findings revealed that RT-based geopolymer mortars were with the highest compressive strength level reaching 66.2 MPa based on different mixture and curing parameters. Compressive strength increased with the reduction in the maximum RCA size. According to LCA analysis, CDW-based geopolymer mortars resulted in similar strength but significant reduction in CO_2 emissions (up to 60%) and are with comparable energy consumption to the Portland cement-based mortars.*

Keywords: *Geopolymer; Construction and demolition waste (CDW); Interfacial transition zone; Compressive strength; Life cycle assessment.*

1 Introduction

Geopolymers have gained attention as an alternative binder to traditional cement due to their potential to reduce carbon emissions by 60-90% (Davidovits, 2015). Geopolymer is a low-calcium subset of the alkali-activated materials family, produced by polymerizing aluminosilicate precursors using alkaline liquids and/or soluble silicates. Synthesis of geopolymers includes a multi-step and complex mechanism that results in the formation of a 3D network of silico-aluminate structures. Factors affecting the properties of the end product include molar concentration of alkaline liquids, curing regime, and precursor characteristics. Fly ash and ground blast furnace slag are the most common precursors in geopolymer production due to their suitable SiO_2 and Al_2O_3 content. The residues generated from the combustion of coal, such as fly ash, and those produced from the processing of metals, such as slag, have become increasingly valuable commodities in the construction industry, with their market value approaching close to that of Portland cement. As a result, there has been a growing trend to utilize the geopolymer technology to recycle waste materials that have lower demand and are locally available under current conditions.

Construction and demolition waste (CDW) is one of the most troublesome wastes, constituting 46% of total waste in Europe with an annual generation of 820 million tons (Gálvez-Martos et al., 2018). CDW is a major environmental concern due to its negative impact on the environment and human health. Traditional disposal methods, such as landfilling and incineration, are not sustainable and contribute to the depletion of natural resources. However, recycling and reusing CDW are essential to sustainable development and avoiding ecological imbalances caused by depleting precious land resources that could be used for other purposes or returned to nature. Masonry-based materials such as hollow/red clay bricks and roof tiles are highly suitable for geopolymerization due to their high aluminosilicate content. Recent studies have shown the feasibility of using ceramic/masonry wastes as precursors in geopolymer production (Yildirim et al., 2021; 2022; Ozcelikci et al., 2023; Ilcan et al., 2023). The results showed that CDW-based geopolymers can achieve similar or better mechanical performance than conventional materials, such as Portland cement mortar and concrete. Furthermore, CDW-based geopolymers have the potential to reduce the environmental impact of CDW. However, the production of geopolymers also requires energy and resources, and their environmental impact needs to be comprehensively evaluated. Life cycle assessment (LCA) can help identify the most environmentally friendly production processes for CDW-based geopolymers, as well as the optimal end-of-life scenarios. This analysis can also provide information on the carbon footprint, water use, and other environmental impacts of CDW-based geopolymers, which can help inform decision-making and policy development in the construction industry. Several studies have investigated the environmental impact of CDW-based geopolymers using LCA. For instance, in the LCA study of Mir et al. (2023), CDW-based geopolymer composites have been shown to have lower environmental impact compared to traditional construction materials such as Portland cement-based composites. Similarly, Fořt et al. (2018) found that the CDW-based geopolymer mixture with a 3:7 ratio of Portland cement to other materials achieved comparable mechanical performance to the Portland cement mixture, while reducing energy consumption and greenhouse gas emissions by 45% and 72%, respectively.

This study aims to develop environmentally friendly materials alternative to Portland cement-based counterparts and add value to CDW by upcycling it in the construction industry. To achieve this goal, the focus was placed on the development of geopolymer mortars using CDW-based components such as hollow brick (HB), red clay brick (RCB), and roof tile (RT). Recycled concrete aggregates (RCA) was used as the aggregate phase in mixtures. 33 mixtures were produced by changing different parameters such as precursor type, sodium hydroxide molarity, curing temperature, RCA/binder ratio and RCA size. Compressive strength tests were performed along with the Life Cycle Assessment (LCA) analysis to reveal mixtures' environmental impacts.

2 Experimental Program

CDW was obtained from an urban transformation area after being sorted. Geopolymer mortars were prepared by utilizing CDW-based hollow brick (HB), red clay brick (RCB), and roof tile (RT) as precursors. To pulverize each precursor, a two-step crushing-grinding process was employed. The chemical composition and fineness of the CDW-based precursors were given in Table 1 together with the properties of recycled concrete aggregates (RCA). The RCA used in this study were obtained by crushing the waste concrete collected from a demolition site and sieving it to the sizes shown in Table 1. Sodium hydroxide (NaOH) was used for the alkaline activation of CDW-based precursors in the mixtures.

Table 1. Properties of CDW-based materials

Properties	**CDW-based precursors**		
	HB	**RCB**	**RT**
Chemical composition (%)			
SiO_2	53.5	52.4	49.3
Al_2O_3	19.3	19.9	20.0
Fe_2O_3	7.45	7.92	8.16
CaO	4.21	4.18	5.16
MgO	2.61	2.84	3.29
Na_2O	1.50	1.58	1.23
Loss on ignition	4.91	4.68	6.64
Fineness (µm)			
d(0.1)	0.97	1.06	0.89
d(0.5)	5.39	8.50	4.75
d(0.9)	28.42	51.85	28.38
Properties	**RCAs (mm)**		
	4.75-2.00	**2.00-0.85**	**0.85-0.10**
Specific gravity	2.44	2.32	2.11
Water absorption (%)	4.07	6.81	13.09
Porosity (%)	9.48	14.76	24.42

This study contained two steps. In the first step, mixtures were manufactured with three different types of CDW-based precursors (HB, RCB, RT), sodium hydroxide concentrations (10M, 15M, 19M), and curing temperatures (105 °C, 115 °C, 125 °C). The mixture proportions are shown in Table 2. The mixture IDs represent the precursor material, sodium hydroxide concentration, and curing temperature, respectively (Table 2). Throughout the first step, the maximum size of RCA was kept constant at 0.85 with the RCA/precursor ratio of 0.45 and water/binder ratio of 0.35. Based on the compressive strength results from the first step, the type of CDW precursor, NaOH molarity and curing temperature were decided to be used in the second step of the study. In the second step, selected parameters were used to manufacture new mixtures to observe the effects of differences in the RCA size (as shown in Table 1) and RCA/precursor ratio (0.36, 0.45 and 0.55). Before mixing, first, the sodium hydroxide solution was prepared and kept at room temperature for one day to cool down. Then, the mixtures were mixed using a mixer and poured into cubic samples with 50 mm dimensions. The mixtures were then subjected to oven curing at different temperatures for 72 hours. After the end of curing, compressive strength test was performed according to ASTM C109 standard by using a device with a 100-ton capacity at a loading rate of 0.9 kN/s. For each parameter considered, three separate samples were used and the results were averaged.

Table 2. Mixture designs

Mixture ID	HB (g)	RCB (g)	RT (g)	NaOH (M)	Water (g)	RCA (g)
HB-10-105/115/125	1000	-	-	10	350	450
HB-15-105/115/125	1000	-	-	15	350	450
HB-19-105/115/125	1000	-	-	19	350	450
RCB-10-105/115/125	-	1000	-	10	350	450
RCB-15-105/115/125	-	1000	-	15	350	450
RCB-19-105/115/125	-	1000	-	19	350	450
RT-10-105/115/125	-	-	1000	10	350	450
RT-15-105/115/125	-	-	1000	15	350	450
RT-19-105/115/125	-	-	1000	19	350	450

3 Results and Discussion

3.1 Compressive Strength

3-day compressive strength test results of the mixtures from the first step are presented in Figure 1. For each curing temperature and NaOH molarity, RT-based mixtures exhibited the highest strength results among all the precursors with an average compressive strength of 55.4 MPa, followed by HB and RCB with 44.4 MPa and 42.5 MPa, respectively. The reason for RT-based mixtures to show the highest strength was attributed to the higher fineness of RT. As known, an increase in the fineness of the precursor leads to a higher degree of geopolymerization and formation of a denser geopolymeric gel in the matrix due to increase in the material surface area (Tan et al., 2022). Aluminum-silicate content of CDW-based materials also has a significant effect on the compressive strength. HB, RCB, and RT precursors show a sufficient aluminum-silicate content of 72.8%, 72.3%, and 69.3% total silicon and aluminum oxide, respectively, for a successful geopolymerization (Alhawat et al., 2022). While the three different curing temperatures (105 °C, 115 °C, and 125 °C) generally had similar effects, it was observed that 105 °C and 115 °C usually resulted in the highest compressive strength, while a decrease in compressive strength was observed as the temperature increased to 125 °C. This indicates that there is a threshold temperature for optimal strength development in geopolymerization and exceeding this threshold results in a decrease in compressive strength most probably due to reasons such as excessive moisture loss, shrinkage cracks, and degradation of reaction products (Tuyan et al., 2018). Considering the effect of NaOH molarity on compressive strength, it was observed that 10M yielded the lowest results for all precursors, while 15M yielded the highest results for all precursors except HB, and a decrease was observed for 19M. This indicates that there is an optimum NaOH molarity for each precursor based on its average particle size and chemical composition, which provides the greater silicon and aluminum leaching. The excessive increase in NaOH molarity is associated with a negative impact on precursor dissolution and leaching performance due to increased viscosity (Alhawat et al., 2022).

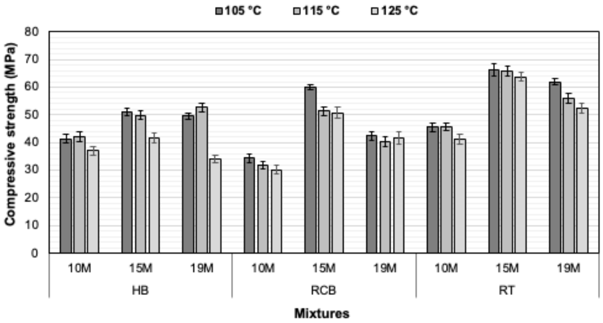

Figure 1. Compressive strength results of mixtures from the first step

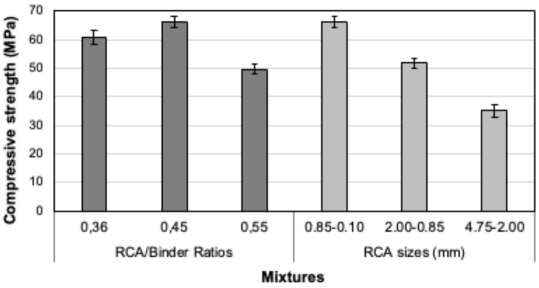

Figure 2. Compressive strength results of mixtures produced with different RCA ratios and sizes from the second step

In order to examine the effect of RCA/binder ratio and RCA particle size on compressive strength in the second step of the study, samples were produced by using the optimum parameters (15M NaOH molarity, RT as the precursor type, and curing temperature of 105°C) acquired from the first step. Average compressive strength results of these samples are presented in Figure 2. The results indicate that an increase in the RCA/binder ratio from 0.36 to 0.45 led to a 9% increase, while an increase from 0.45 to 0.55 resulted in a 24.9% decrease in the compressive strength. Furthermore, the compressive strength consistently increased as the RCA particle size decreased. This can be attributed to the particle packing effect, resulting in a denser aggregate-to-paste bonding, and improved mechanical performance (De Rossi et al., 2019). The contribution of geopolymeric gel formation from the old cohesive mortar on the fine RCA particles can also be associated with the observed results. It is noteworthy to mention that the failure predominantly occurred in the paste phase, as depicted in Figure 3. The interfacial transition zone (ITZ) posed a challenge solely in the case of coarser RCA with particle sizes exceeding 2 mm. However, the presence of ITZ did not result in significant consequences or substantial alterations in mechanical performance.

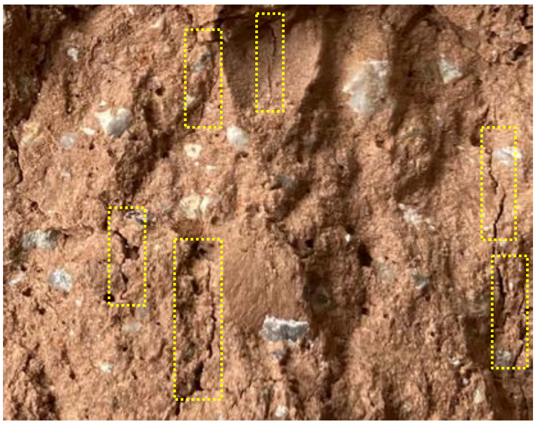

Figure 3. Representative failure mode of geopolymer mortars

3.2 Life Cycle Assessment

To understand the environmental footprint of CDW-based geopolymer mortars, a cradle-to-gate LCA was conducted on selected mixtures. Figure 4 illustrates the system boundary to produce

CDW-based mortars. The environmental impacts of the mortars were assessed using SimaPro 9.0 and the Ecoinvent 3.0 database, based on the Life Cycle Inventory (LCI) analysis. For conducting the environmental assessment, the TRACI 2.1 V1.05/US 2008 (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) method, as recommended by the U.S. Environmental Protection Agency (EPA, 2006), was utilized.

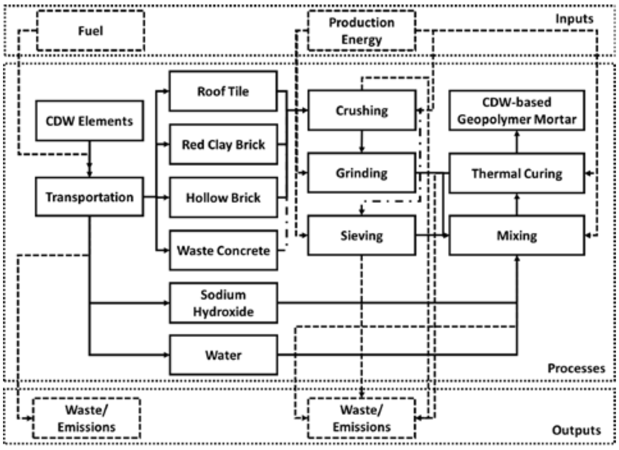

Figure 4. System boundary for production of CDW-based geopolymer mortars

Environmental impact assessment of CDW-based geopolymer mixtures per impact categories of ozone depletion potential (ODP), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), fossil fuel depletion (FFD) is presented in Table 3. According to the findings, the increased molar concentration resulted in a significant increment in the environmental impact for all categories. This was related to the chloralkali process employed in the production of sodium hydroxide, which involves the use of carbon tetrachloride to extract chlorine from gas streams (Imtiaz et al., 2021). On the other hand, changing parameters had no considerable effect on other comparison parameters, including aggregate size and thermal curing. Only a slight reduction of environmental impact was recorded for the increase in aggregate content, due to reduced need for precursor and alkali activator phase to produce a cubic meter of geopolymer mixture.

Table 3. Environmental impact assessment of CDW-based geopolymer mortars

Changing parameters	**Impact category**	**ODP (kg CFC-11 eq)**	**GWP (kg CO_2 eq)**	**AP (kg SO_2 eq)**	**EP (kg N eq)**	**FFD (MJ surplus)**
Molarity	RT-C-10-0.45	1.15E-04	177.460	0.940	1.188	183.161
	RT-C-15-0.45	1.67E-04	250.147	1.328	1.678	257.161
	RT-C-19-0.45	2.03E-04	301.561	1.603	2.025	309.503
Aggregate size	RT-A-15-0.45	1.71E-04	257.264	1.366	1.726	264.422
	RT-B-15-0.45	1.70E-04	254.862	1.354	1.710	261.972
	RT-C-15-0.45	1.67E-04	250.147	1.328	1.678	257.161
Aggregate content	RT-C-15-0.36	1.74E-04	260.609	1.384	1.749	267.825
	RT-C-15-0.45	1.67E-04	250.147	1.328	1.678	257.161
	RT-C-15-0.55	1.59E-04	239.348	1.271	1.605	246.154
Thermal curing	RT-C-15-0.45	1.67E-04	250.147	1.328	1.678	257.161
	RT-C-15-0.45[1]	1.67E-04	250.243	1.329	1.679	257.263
	RT-C-15-0.45[2]	1.67E-04	250.340	1.329	1.680	257.365

[1]Related mixture was subjected to thermal curing at 115°C; [2]Related mixture was subjected to thermal curing at 125°C

Figure 5 demonstrates the contribution analysis of CDW-based mixtures. It was revealed that the share of processes and materials, including precursor production, aggregate production, mixture production, thermal curing, alkali activator, and transportation, was similar for all mixtures. The impact of the alkali activator's production was found to have the highest share. This was followed by the precursor production and thermal curing (for GWP, AP and EP) or transportation (for ODP and FFD). Other parameters were less effective on overall environmental impact, and their shares in contribution were not significant. Considering the abovementioned outputs, the higher negative burden of the alkali activator phase of CDW-based geopolymers can be lessened by optimizing other ingredients in such a way that there is no loss of strength.

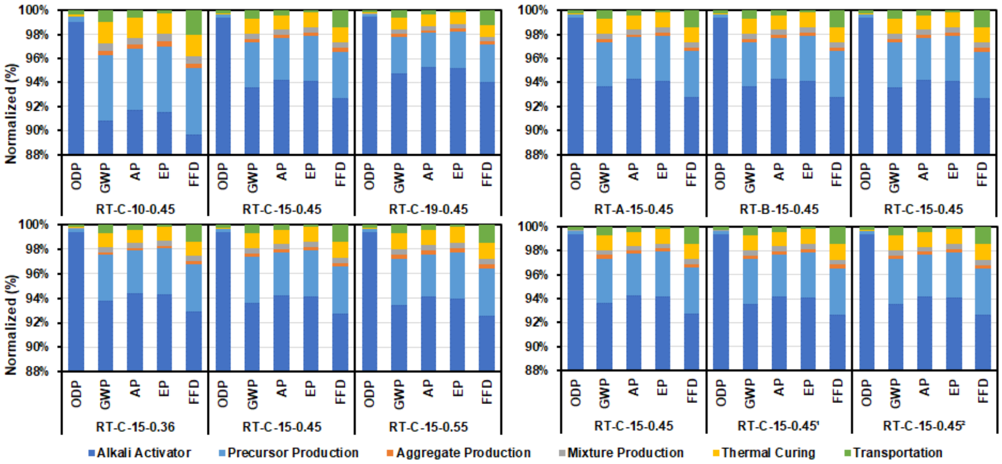

Figure 5. Contribution analysis of CDW-based geopolymer mortars

4 Conclusions

This study focused on the development of geopolymer mortars using CDW-based masonry elements as precursors and recycled concrete as aggregates and investigated the effect of various parameters such as precursor types, NaOH molarity, curing temperatures, RCA/binder ratios and RCA size on the compressive strength. Life cycle assessment (LCA) was also conducted on the developed CDW-based geopolymer mortars. RT-based mixture had the highest 3-day average compressive strength of 55.4 MPa, followed by HB- and RCB-based mixtures with 44.4 MPa and 42.5 MPa, respectively. A decrease in compressive strength was observed as the curing temperature increased to 125 °C, and 10M NaOH yielded the lowest strength results for all precursors. An increase in RCA/binder ratio led to an increase in compressive strength, while a decrease was observed at higher ratios. The use of smaller RCA particles resulted in higher compressive strength. Increasing the molar concentration of sodium hydroxide had a significant impact on the environment, with the alkali activator phase having the highest share. Optimization of other ingredients can help reduce the negative impact of the alkali activator phase.

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