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Fabrication of energy-efficient cement panels from construction waste for sustainable building application

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ABSTRACT

Building panels in several forms have attracted scientific research lately as one of the most used building materials. However, the issue of low energy efficiency leading to high energy consumption as a wall component is predominant. This study's prime objective is to investigate the potential of recycled glass and wood sourced from construction waste for energy-efficient cement panels for sustainable building applications. The hardened cement panels' thermal efficiency, heat loss, durability properties, and strength were determined. The experimental work indicated that cement panels made from construction waste-inspired materials could be an alternative to cement sand panels with improved operation. The main findings showed that annual energy consumption savings could be achieved by 70% compared to the typical cement sand panel. In addition, the cost and CO_2 reductions of the cement panels can reach up to 18% and 3.3%, respectively. Other engineering features, including density and heat loss, exhibits improved performance. The study indicates that glass and wood waste could be utilized as cost-effective and sustainable construction materials that outperform natural sand as alternatives in energy efficiency performance as a building envelope. It offers a greener alternative for sand winning and construction waste disposal.

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Cement panel; construction waste; durability; energy efficiency; cost saving; eCO2 emission

Introduction

Energy and waste conservation have emerged as critical concerns for protecting our environment (Esmeray & Atıs, 2019). In particular, the construction industry's fast expansion produces unsustainable waste and consumes significant energy (Hung Anh & Pásztory, 2021). Construction waste (CW) describes everything created during construction and afterward abandoned, whether it has been processed or hoarded. Conversely, CW consists of materials from demolition, building, retrofitting, demolition, and road maintenance (Lam, Ann, Wu, & Poon, 2019). The generation of CW is projected to be around ten billion tons globally (Wu, Zuo, Zillante, Wang, & Yuan, 2019), amounting to a total of 25%–40% of solid waste, which is a considerable quantity that has become a critical environmental concern that requires immediate attention (Alsheyab, 2022; Datta, Rana, Assafi, Mim, & Ahmed, 2022). Besides, natural aggregates for construction works are overexploited (Mallick, Radzicki, Zaumanis, & Frank, 2014) and contribute to environmental uncertainty (Akanni, Oke, & Akpomiemie, 2015). For instance, sand and gravel are significant ingredients in

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building projects, and a reliable supply is essential for developing rising cities' infrastructure. However, sanding and gravel winning have harmed the natural environment significantly. Umesh and Murthy (2014) acknowledged that the theoretical concern of sand winning threatens our water bodies, soil erosion, and landslide concerns. To tackle this problem, the recyclability of several CW materials is explored for possible reuse in constructions (Anandaraj, Rooby, Awoyera, & Gobinat, 2019), as challenges associated with disposing of CW have steadily risen in recent years, with a significant proportion ending up in landfills.

That being said, rapid construction activities and expansion have drawn attention in an era where energy consumption continues to rise. Access to inexpensive, dependable, sustainable, and contemporary energy has emerged as a critical aim for sustainable development (Jiang, Yu, Xue, Chen, & Mi, 2020). Energy consumption grows as cities expand, elevating it to a more crucial concern (Ustaoglu, Yaras, Sutcu, & Gencel, 2021). Inadequate sustainability in cities contributes significantly to increased heat in the built environment and higher energy demand for cooling (Mahmoud & Ragab, 2021). Buildings account for 30%–40% of global energy needs (Park & Nagy, 2018). For this reason, sustainability is seen as the primary objective of contemporary architecture (Thanu, Rajasekaran, & Deepak, 2022; Zaryoun & Hosseini, 2019) to design and construct buildings with lower embodied energy and fewer environmental emissions required for applications (Walker & Pavía, 2015).

Previous studies have provided insight into the recyclability of CW materials, such as Glass and wood, to produce construction products. Using glass powder as a precursor in geopolymer has proved to be potentially advantageous and suited to produce eco-cement, lightweight artificial aggregates. A significant step toward recycling waste glass as a green building resource and for the benefit of the industry (Jiang, Ling, Mo, & Shi, 2019). For instance, the microscopic study of recycled glass aggregates and concretes produced by Szeląg, Zegardło, and Andrzejuk (2019) found that the structure and texture of shattered Glass on the edges are crystalline and irregular. It explains why recycled Glass attaches better to the cement matrix than sand–gravel aggregates. Letelier, Henríquez-Jara, Manosalva, Parodi, and Ortega (2019) added that glass powder has influential parameters on porosity, absorption, and capillarity qualities. To benefit from the low density of hollow glass microspheres and the solid mechanical performance of carbon nanofibers, Aslani, Wang, and Zheng (2019) examined lightweight engineered cementitious composite by combining hollow glass microspheres and carbon nanofibers in a novel way. Due to the additional reinforcing effect of carbon nanofibers, the created lightweight engineered composite can attain lightweight without compromising mechanical strength compared to traditional regular-weight concrete. The new lightweight designed cementitious composite has a density of less than 1820 kg/m^3 with improved mechanical strengths achieved. Adewoyin, Adesina, and Das (2022) evaluated mortars formulated to fabricate lightweight, thermally efficient wall panels utilizing glass aggregates. Various proportions of expanded glass were incorporated into the construction of mortars to establish their effect on the mortar's qualities. The thermal conductivity of mortars was lowered by up to 78.4% when the ratio of cement to expanded glass was increased to 1:5. Despite the decrease in compressive strength caused by the inclusion of expanded glass. These mortars are, however, suitable for the manufacture of wall panels.

Wood, on the other hand, is a natural material with excellent thermal properties for insulation functions. For this reason, Corinaldesi (2012) and Corinaldesi, Mazzoli, and Siddique (2016) similarly substituted ordinary sand with wood processing by-products to produce lightweight mortars. Different substitution percentages of ordinary sand were tested: 2.5%, 5%, and 10% by volume. Before being added to the mortar mixture, wood waste was placed in water and a calcium hydroxide aqueous solution to mineralize the wood. The authors observed that a supreme of 5% wood waste should be added to mortar to prevent an extreme loss of mechanical strength and a drop in thermal conductivity of roughly 25%. However, satisfactory mechanical performance was achieved with a 10% wood waste addition. Adili, Lachheb, Brayek, Guizani, and Nasrallah (2016) also reported the production of lightweight mortars using expanded polystyrene beads and wood shavings. The elaborated materials' density and thermal characteristics were improved. The achieved findings show that the densities and thermal conductivities of the elaborate samples have increased by 71% and 36%, respectively. Therefore, it is anticipated that buildings will use less energy. Usman et al. (2018) effectively utilized sawdust wood waste in self-compacting cement pastes. It was demonstrated to effectively reduce shrinkage strain (reduction range of 45%–80%) and with minimal strength loss. The benefits of sawdust wood integration were attributed to its inner curing agent. The reduced shrinkage produced by sawdust wood allows for a considerable reduction in shrinkage-related microcracking. This is especially relevant in structures built in hot areas with higher surface area-to-depth ratios, such as road pavements, roof slabs, and flooring. Also, Pedreño-Rojas, Morales-Conde, Pérez-Gálvez, and Rodríguez-Liñán (2017) developed a novel construction application from new composite materials from wood waste as eco-efficient acoustic and thermal conditioning ceiling plates.

These studies, however, have drawbacks and limitations. The reported investigations have focused little on thermal properties, energy assessment, cost, and CO_2 reductions. For instance, Song, Lee, and Kim (2014) used an efficient methodology to boost the utilization of crushed stone powder to design cement panels. Some properties, such as compressive strength and fire resistance, were conducted. However, the drawback of this study is that it did not consider the thermal performance coupled with the energy efficiency of the produced cement panels. Similarly, Roy and Sairam's (2019) investigation stressed the need to compare the strength parameters of geogrid and ferro cement panels. Again, Mustafa, Prieto, and Ottele (2021) and Mahrous, Giancolab, Osmanc, Asawad, and Mahmoud (2022) work focused on the feasibility of the surface geometry of cement panels for building envelopes.

The above literature indicates that researchers need to learn more about the effects of glass and wood waste as composite materials in fabricating energy-efficient cement-bonded panels. Against this backdrop, the novelty of the present study is to produce less energy-consuming cement panels made with recycled glass powder (GP) and wood powder (WP) as natural sand replacements in different mix ratios towards sustainable applications. In order to achieve the stated study aim, lower thermal properties, reduced surface area heat loss, enhanced durability properties, adequate compressive strength, low cost, and CO_2 savings and quantification of energy consumption savings of the resulting hardened cement panels have been studied. Replacing natural sand with GP (20%, 50%, and 100%) and WP (10%, 20%, and 100%). Lightweight and energy-efficient panels are valuable materials for the thermal insulation of structures. The current study gives insightful information for creating and implementing sustainable, energy-efficient cement panels and avoiding the threat of sand and gravel, winning a resource-saving potential. Additionally, averting construction waste disposal originating from glass and wood formwork for low environmental impacts.

Experimental work

This study section provides insight into the whole work's methodological approach, as seen in Figure 1.

Raw materials

The raw materials (cement, natural sand, and recycled waste) used in producing the cement-mortar panels are described in detail below.

Cement and natural sand

Ordinary Portland cement type II was the binding material used for the mortar samples with a bulk density of 1.45 g/cm^3 and fine modulus of 2.01, suitable for high-stress concrete elements in major building activities. In compliance with the single European Specification No. 197-1/2011. Natural river sand with a specific gravity of 2.67 g/cm^3, bulk density of 1.52 g/cm^{3,} and fine modulus of 3.5 was used as fine natural aggregates.

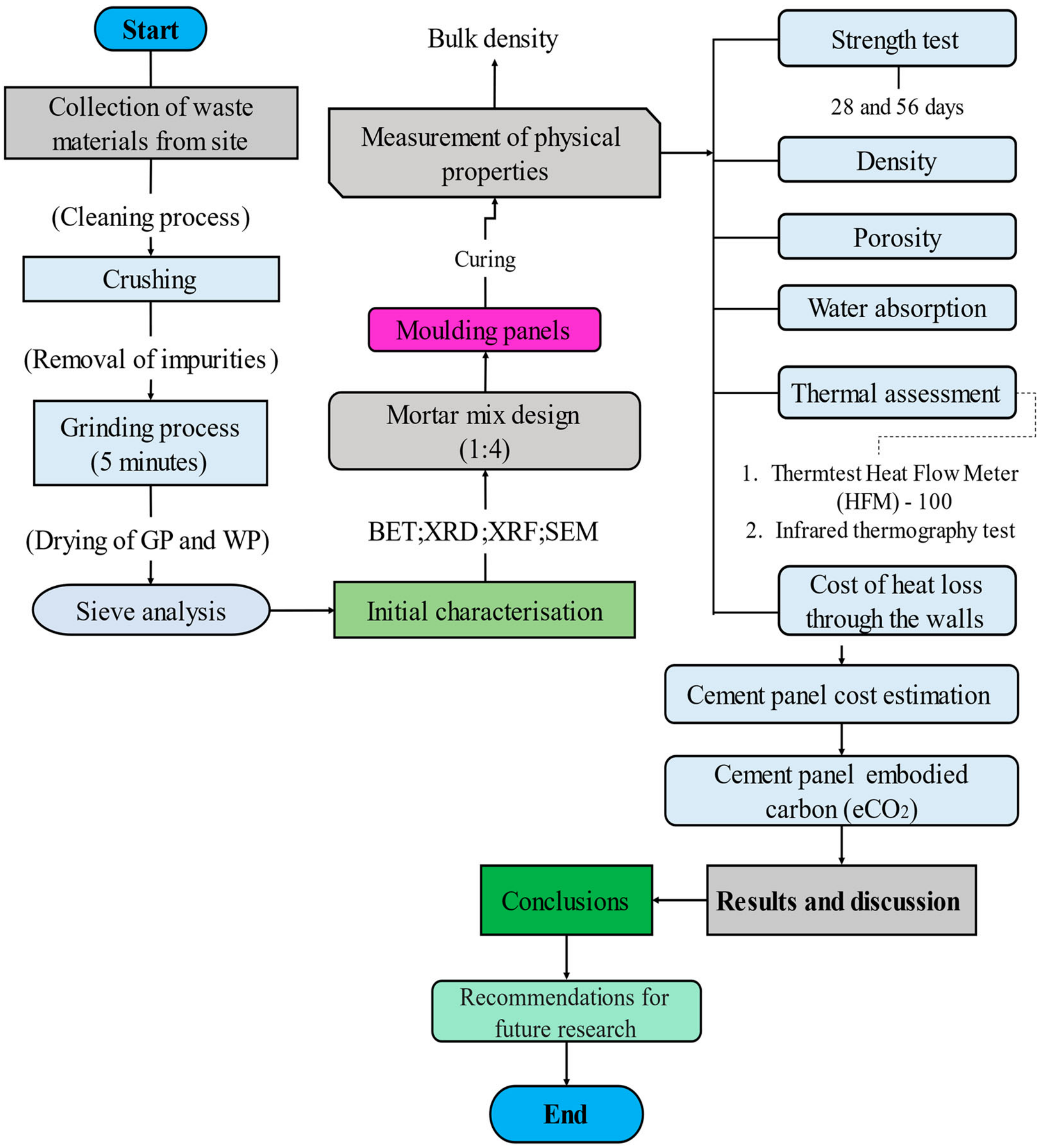

Figure 1. Overall roadmap of the study.

Recycled glass and wood

The massive amount of recycled glass and wood waste, specifically windowpanes/shatter proofing glass and hardwood marine board waste, was sourced from construction sites. The glass and wood waste were first broken into small pieces after a cleaning process to eliminate contaminants. Then a universal high-speed grinder type MDY-600 in the laboratory was employed in grinding the waste materials into glass powder (GP) and wood powder (WP) for 4 mins. The GP and WP bulk densities were 1.58 and 0.32 g/cm^3, respectively. The particle size of the GP and WP are shown in Table 1.

Mix proportions and mix design

The dry GP and WP were first soaked in water for 24-h and allowed to oven dried for 10-h at 100°C. This approach increased the impact of concrete mixed with GP by soaking the GP in water for 24 h

Table 1. The particle size of recycled waste aggregates.

Recycled aggregate	Sieve size	Cumulative % passing
GP	0.43	83.23
	0.15	48.08
	0.075	25.45
WP	1.18	95.27
	0.6	64.53
	0.3	21.96
	0.15	15.20
	0.075	9.12

before adding it to the concrete to dissolve the SiO_2, CaO, and Na_2O ions that make up the GP (Elaqra, Abou Haloub, & Rustom, 2019). At the same time, the WP was pre-soaked in water and mixed with calcium hydroxide $Ca(OH)_2$ for 24 h to attain wood mineralization before adding it to the mortar mixture (Corinaldesi et al., 2016).

The cement panels samples' mixed proportions are shown in Table 2 below. OPC was the binding material used for all samples. Natural river sand was partially replaced with fine recycled aggregates (GP and WP) to investigate the impact of various types of waste on strength, density, porosity, water absorption, and thermal performance, with a 0.42 water-to-cement (w/c) ratio. The recycled GP and WP were utilized as fine aggregates for natural sand replacement in the mortar mixes at different proportions of (20%, 50%, and 100%); and (10%, 20%, and 100%) respectively. The dry ingredients for GP and WP were mixed for 2 mins via B-20 mixer, then water and admixture (ADDIBON 65) of 0.25 kg/m^3 content was added for further mixing; each mix took 5 mins. The initial mixture was made with OPC, and natural aggregates were denoted as the control sample (CS). The second and third mixes contained M1 (GP-100%) and M2 (WP-100%). The fourth mix contained M3 (GP-50%, WP-20%). The fifth mix included M4 (GP-20%, TP-10%).

Experimental methods

Sieve analysis

Several sieves ranging from 75 um to 12.5 mm sizes were used with an electronic sieve shaker (between 1 and 5 min) to determine the respective particle sizes of the employed raw materials for the mortar mixture. The raw materials were weighed on an electronic scale and then placed in the sieve for the shaking device to displace and retain respective particle sizes in the used sieves. Finer particles took 5 min to shake, whereas coarse particles took a minute. Then the retained particles were again weighed to determine the respective retained weight to calculate further the cumulative % passing by weight of the retained materials. Equation (1) below calculated the percentage of passing particle sizes. The total weight (*Wt*) and retained cumulative weight (*Wr*), respectively.

$$\text{Cumulative \% passing by weight} = \frac{Wt - Wr}{Wt} \times 100 \tag{1}$$

Table 2. Mix proportions of cement-mortar panels.

Mix ID	Cement (g)	Recycled waste (%)		Cement (g)	Sand (kg)	w/c
		GP	WP			
CS	513	0	0	513	2.27	0.42
M1	513	100	0	513	–	0.42
M2	513	0	100	513	–	0.42
M3	513	50	20	513	0.68	0.42
M4	513	20	10	513	1.59	0.42

Material characterization

Scanning electronic microscope (SEM), Brunauer–Emmett–Teller (BET), and X-ray fluorescence (XRF) analysis were employed to determine the recycled waste aggregates' surface texture, specific surface area, pore size, and chemical composition.

Density

According to UNE-EN 1015-10 (2000), the density was estimated directly by dividing the dry mass (*M*) of the mortar sample by its volume (*V*) using the method given in equation (2).

$$\text{Density} = \frac{M}{V} \tag{2}$$

The density test used an electronic scale with a maximum capacity of 15 kg and ±0.1 g accuracy to weigh all specimens. Five cube samples (10×10×10 cm) were employed. This was performed on 28 and 56 days of the curing process.

Water absorption

The water absorption of the hardened mortar mix was computed according to standard UNE-EN 1015-18 (2003) using the formula given in equation (2). First, the specimens were dehydrated in an oven at 110 °C for 24 h, and the dry weight was determined (*A*). The samples were then immersed in water for 5, 10, 15, 30, and 45 min and left for 24 h. The saturated weight was determined for each sample (*B*). Lastly, the weight of the sample suspended in water was determined, yielding the submerged weight (*C*).

$$\text{Absorption} = \frac{B - A}{A} \times 100 \tag{3}$$

Porosity

A critical factor that contributes significantly to a material's thermal conductivity is its porosity (Asadi et al., 2018). The hardened samples were taken to the laboratory to measure the porosity, and the water-accessible porosity (Pa) was computed by UNE-EN 1015-18 (2003) using the ratio derived from equation (4).

$$\text{Porosity (Pa)} = \frac{B - A}{B - C} \times 100 \tag{4}$$

Compressive strength

A compressive testing machine (CTM) with a maximum capacity of 3000 kN was used to assess the compressive strength resistance. Following the UNE-EN 196-1 standard (2018), two 10×10×10 cm^3 specimens were evaluated for each series at 28 and 56 curing days to determine the resistance to compression strength.

Thermal performance

The thermal conductivity (k-value) and resistance (u-value) tests were conducted to determine how much heat is transferred through the cement-based products. For minimal energy consumption, cement mortar with less thermal conductivity and a maximum specific heat capacity is ideal in houses (Shafigh et al., 2018). The k-value and u-value were measured in the study using Thermtest Heat Flow Meter (HFM) – 100. This precision instrument is ideally suited for determining flat specimens' steady-state heat transfer properties following ASTM C518-10. Following ISO and CEN standards, the heat conductivity coefficient of >0.065 K·m/W is measured as a construction material. The cement panels samples were used for the testing as required by the apparatus (see Figure 2). First, the cement panel samples' thermal performance was determined from the HFM, which establishes steady-state one-dimensional heat flux through the cement panel sample between the two parallel plates (hot and cold) at constant but different temperatures. Further, by appropriately calibrating the heat flux transducer with standards and measuring the plate's temperatures and separation. The temperature difference of 20°C was set. The thermal conductivity is computed following Fourier's Law of heat conduction in the form of the equation:

$$\frac{\Delta Q}{\Delta t} = K.S.\frac{\Delta T}{d} \tag{5}$$

where: $\frac{\Delta Q}{\Delta t}$ is the heat flow (W); **K** is the coefficient of thermal conductivity (W/m.k); **S** is the surface through which heat flow is measured (m^2); ΔT is the temperature difference between the top plate and the bottom plate (T); **d** is the sample thickness (m).

Infrared thermography test

The heat penetration rate of composites containing CW aggregates was determined for 45 min using an infrared thermal imaging camera (Testo 872, Testo Australia). The infrared thermography test relies on producing a thermal gradient in the subject material by importing energy into the target using an artificial external heat source so that a large amount of heat transfer happens within the material (Milovanović & Banjad Pečur, 2016). Panel samples of (200 * 150 * 50 mm) samples were placed in the opening of an enclosed square chamber for the experiment. An electrical heater (Delonghi HVYW30) was placed inside the chamber as the heating source. In compliance with ISO and CEN standards, the thermal infrared camera captured the surface temperature distribution on the other side of each respective sample panel, as illustrated in Figure 3.

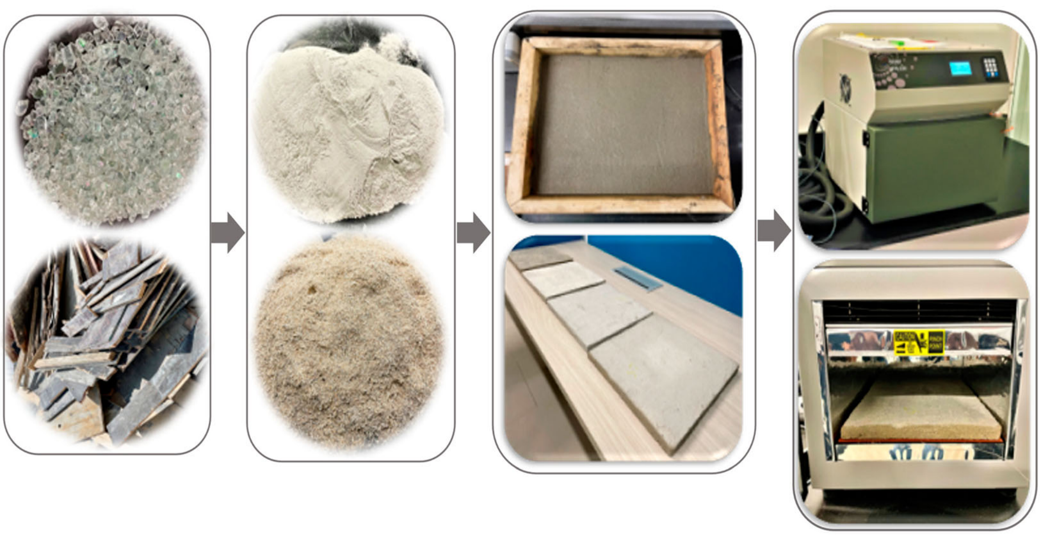

Figure 2. Process of the thermal conductivity test.

Energy analysis

Energy consumption of buildings is a significant component for its inhabitants to conserve resources and cost saving primarily. This portion of the study considers determining the energy consumption when waste aggregates are employed as a walling component for cost reduction. The exterior walls (113 m^2) of the design model adopted for the study are considered for determining the cost of heat loss rate through the walls. The achieved thermal conductivity coefficients were used in the calculation. The temperature differences between the inner and outer surfaces of the external walls are considered. As stated previously, it is assumed that the home was constructed in Greater Accra, Ghana, with an average outer temperature of 31°C and inner temp of 28°C, respectively, for 24 h. The price of electricity is $ 0.081 per kWh for households in Ghana, after the PURC announced an increment of traffic of 89.04 Ghana pesewas, reported by (Ntow, 2022). Below presents the equations for computing the cost of energy consumption:

$$\text{Cost of energy consumption} = \text{Energy}(Q) \times \text{Price of electricity} \tag{6}$$

$$Q = KA\,\frac{(T1 - T2)^{\circ}\mathrm{C}}{th} \tag{7}$$

Cost estimation

For the prospects of commercialization, the cost is an essential measure. This section seeks to determine the cost of incorporating GP and WP as replacements for natural sand in mortar production compared to conventional mortar. The residential family house model was used to estimate, and only the external walls were considered for the computation.

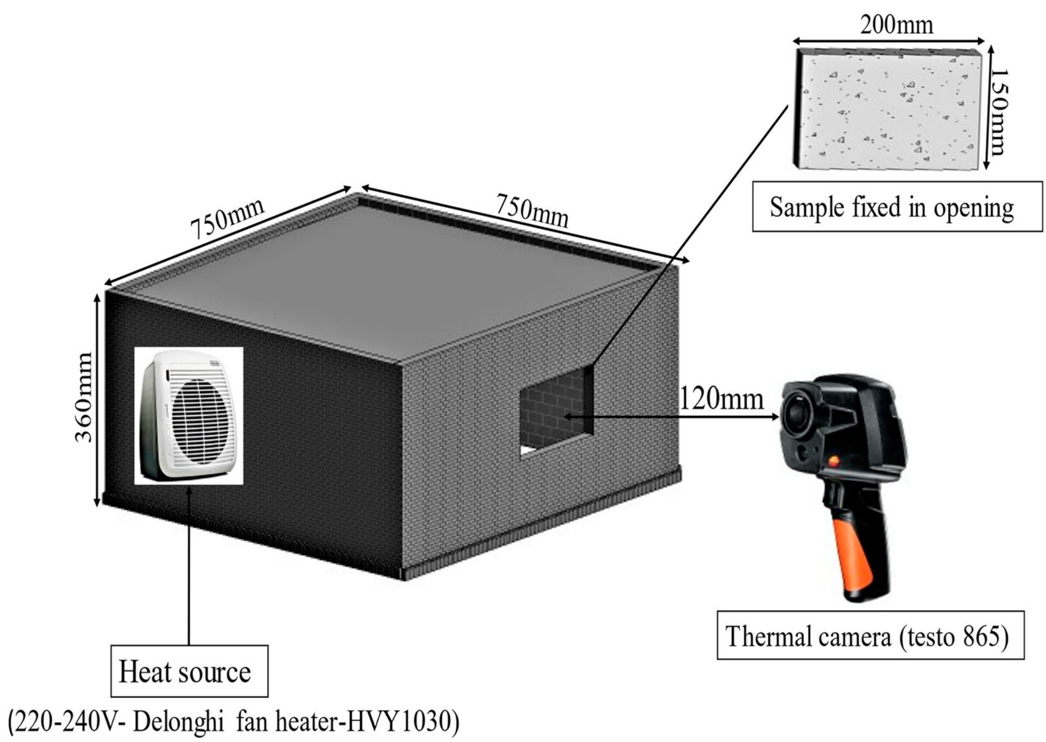

Figure 3. Schematic view of surface temperature test.

The total wall area (Wa) of 190.74 m^2 was determined by adding the internal walls and walls, then deducting all openings, doors (Drs), and windows (Wds) obtained from the architectural design. The total number of panels was determined by dividing the Wa by the panel area (Pa) with a size of 30×30×2 cm. A 5% wastage of panels was considered. The prices of the building materials considered at the time of the study in September 2022 are presented in Table 3. Date-specific Ghanaian cedi-to-U.S.-dollar exchange rates were used to determine the total price. It is essential to mention that the study did not consider the transportation cost of materials and equipment and quality control aspects that affect the overall mortar cost.

Environmental assessment

Energy usage and carbon dioxide (eCO2) emissions during cement production are critical causes of worry as cement mortar is frequently employed in masonry and construction applications. Approximately 8% of anthropogenic eCO2 emissions are emitted into the atmosphere during cement manufacture due to the quantity of fuel burned and the specific disintegration of limestone (Wu, Ng, & Chen, 2022). As a result, there is a need to take the carbon footprint very seriously. Materials' total embodied energy and carbon footprints were utilized to assess environmental performance and calculated based on the overall energy consumption and eCO2 emission from materials during production. The mortar mixture in terms of the material constituents per kg/m^3 was used for the embodied energy and eCO2 emissions. The calculation considered the transportation and the fabrication of emissions of the mortars.

Case study model via Revit Autodesk

An architectural design was adopted using 'Autodesk Revit Architecture' version 2023 for the design. Several authors (Tahmasebinia et al., 2022; Ur Rehman et al., 2022) have used this tool conveniently in their previous study model, justifying its use for economic analysis. Revit also has conceptual massing capabilities, which use fundamental shapes to simulate building form and orientation earlier in the design process. It is the modeling phase of the workflow for Energy simulation. Therefore, it is widely utilized in the AEC sector for design purposes. A residential family house model was designed for the study assessment. It is a self-standing building life cycle that requires passive houses. The design comprises various rooms with a total floor area of 120 m^2. The detailed plan and 3D view are illustrated in Figure 4, and the list of rooms, including the respective areas, is stated in Table 4. It is presumed that the house was constructed in Greater Accra, Ghana.

The geographical setting of Accra is known for its voluminous construction activities, primarily residential projects, due to the high demand for housing facilities. However, the high temperatures in Accra cannot be overlooked. Usually, mechanical air-conditioning systems or passive methods, such as window opening and solar control measures, such as external window shade, provide comfortable cooling in Ghanaian residential structures. It shows a rise in warming conditions. According to the weather spark data, the current mean outdoor air temperature for Accra, the capital city of Ghana, is approximately 89°F daily high and 91°F monthly Figure 5 shows the mean outdoor climate and average (high and low) temperature monthly profiles in Accra.

Table 3. Price of building materials.

Building material	Quantity	Price (Ghc ₵)	Price Dollar ($) equivalent
Cement	50 kg bag	70.00	6.70
Fine aggregate	10 m^3	800.00	76.56
Water	500-liter Rambo polytank	250.00	23.92

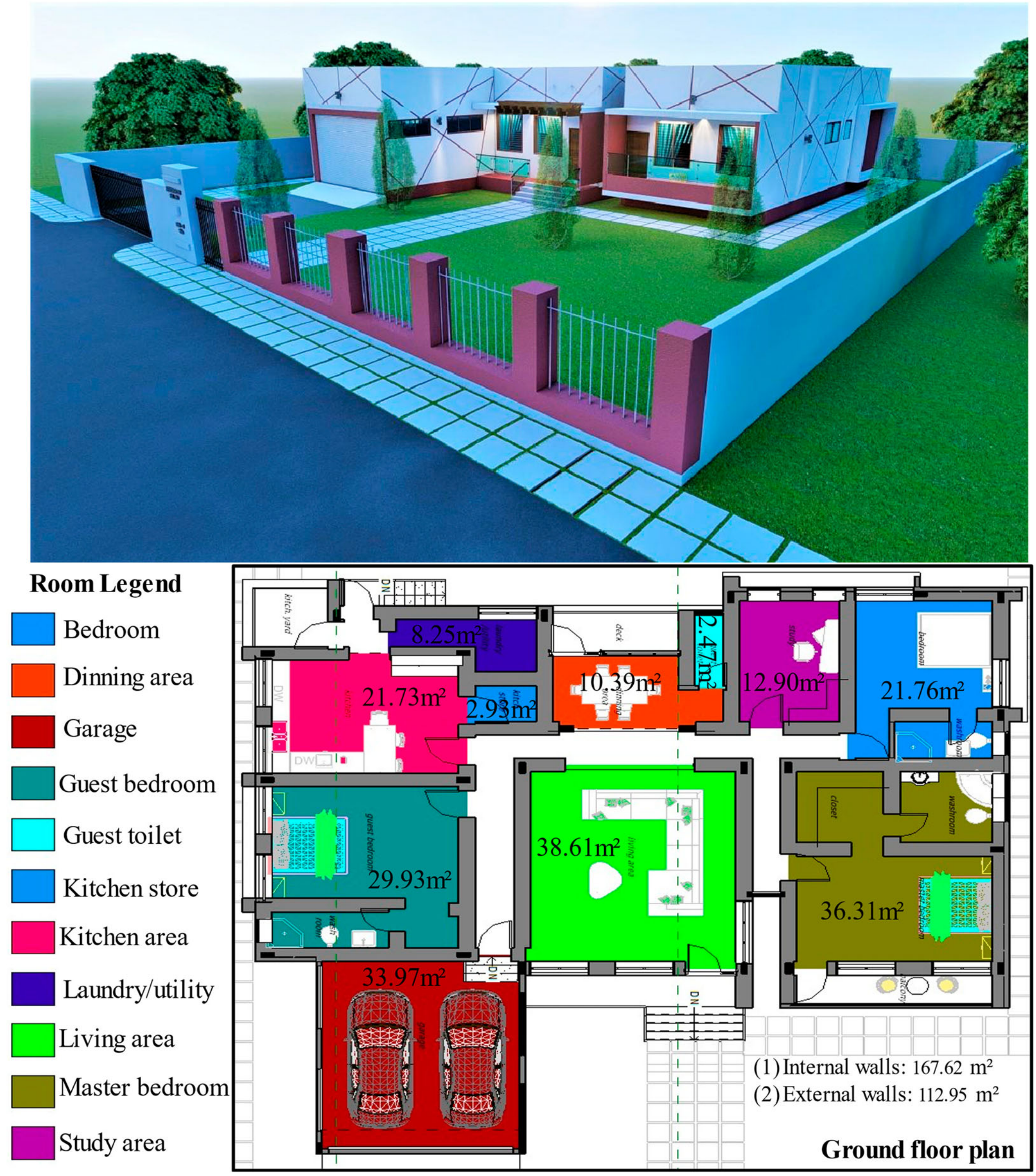

Figure 4. 3D view and ground floor plan of the architectural design.

Table 4. BET and XRF properties of the recycled waste aggregates.

Recycled waste	BET (m^2/g)	Total pore volume (cm^3/g)	Mean pore diameter (nm)	Top elemental composition (%)	
				SiO_2	CaO
GP	–	–	–	51.8	–
WP	0.70	0.01	62.82	–	87.0

Note: Silicon dioxide (SiO_2); Calcium oxide (CaO).

Results and discussion

Characterization

Figure 6 presents the XRD analysis to ascertain the silica phase's crystal structure and amorphous nature. From the results, GP shows no clear crystalline peaks. This implies that the GP was essentially amorphous of silica present with extremely low-intensity quartz peaks and crystallinity of 7.95%. On the contrary, WP displays two peaks of significant compounds, Calcite ($CaCO_3$) and Quartz (SiO_2). The WP recorded a more crystallinity value of 30.34%, indicating its high crystal structure compared to GP. It can be deduced from the study that the GP and WP modification efficiencies contribute differently to secondary reactions due to the elemental compositions.

Further, Figure 7 shows the microstructure for both GP and WP via an SEM analysis. It was noticed that the GP displayed sharp edges and a smooth surface, whereas the WP showed a narrow shape and porous texture; this gives it the tendency to absorb more water compared to GP. A similar microstructure for fine glass aggregates by Bisht and Ramana (2022) was described, and wood waste was informed by Xu et al. (2019) in their studies, respectively. The BET analysis revealed that the WP contained macropores with an average pore size of 62.82 nm (see Table 4). The GP did not give any pore size due to its non-porosity. Increasing porosity permits NO2 to access new reaction sites (Patel, Orlov, Ariyachandra, & Peethamparan, 2021). The porosity led to an increase in the specific surface area of the WP. The XRF analysis presented that GP and WP's dominating chemical elements were SiO_2 and CaO above 50%, respectively. Glass and wood chemical composition consists of various oxides. However, glass is made up of silicate as the primary element in glass preparation, and SiO_2 can take on different crystal structures depending on how it is processed, making it an appropriate material for geopolymerization (Pourabbas Bilondi, Toufigh, & Toufigh, 2018). On the contrary, the expansion of wood during exposure to liquid might be linked to the probable hydration of lime and silicates contained in

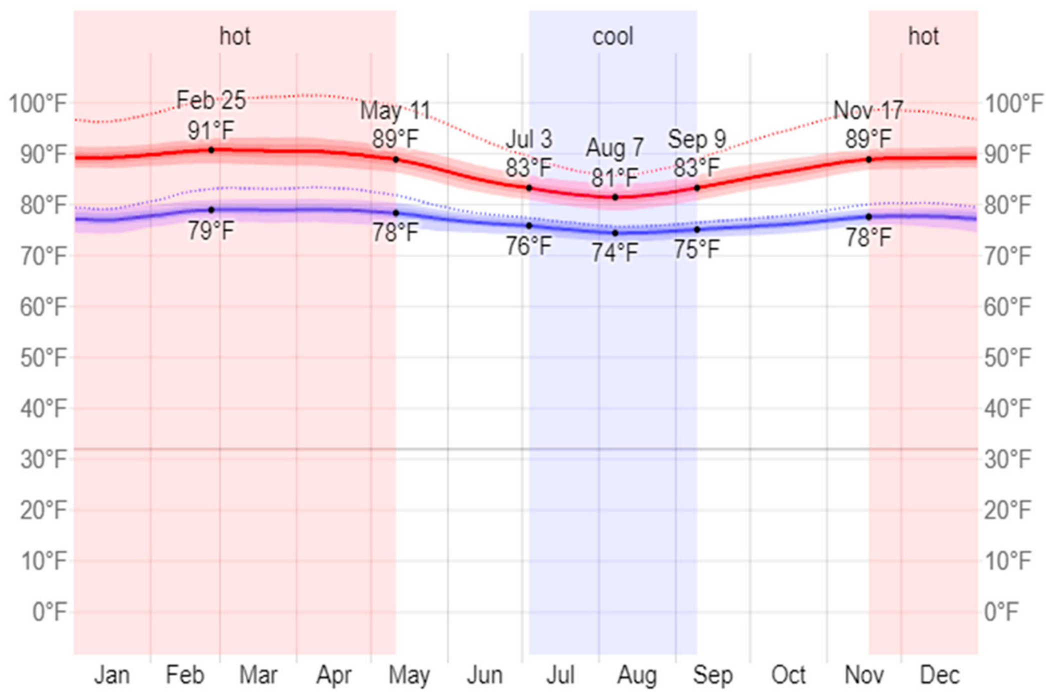

Figure 5. Average high and low temperatures in Accra. Source: Adopted from Weather Spark (2022).

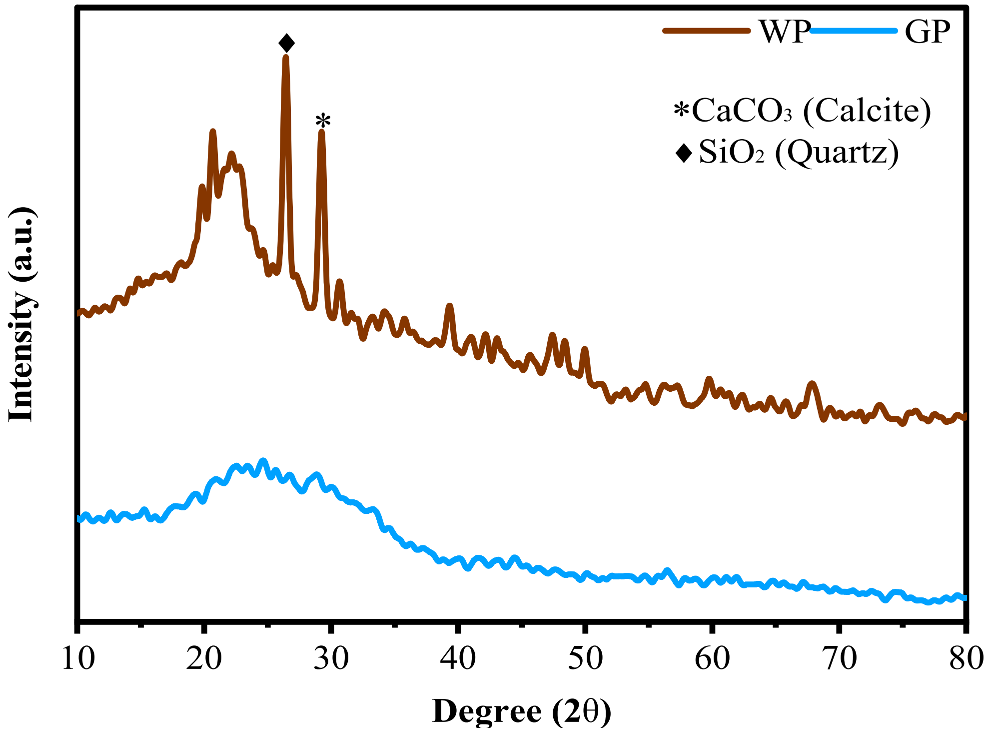

Figure 6. XRD patterns of the recycled waste (GP and WP).

the wood (Chowdhury, Mishra, & Suganya, 2015). CaO is an essential component for making a binder such as cement. Hence, the high presence of the chemical element in the wood makes it a suitable aggregate in the cement paste mix.

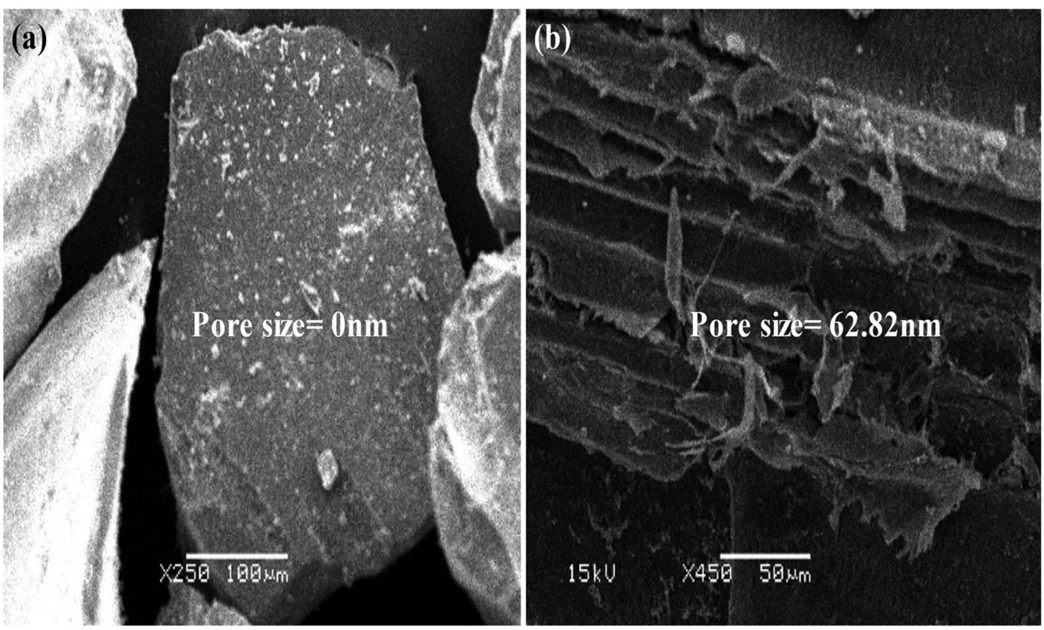

Figure 7. Microstructure of (a) GP and (b) WP.

Density

Figure 8. shows the effect of the incorporated waste aggregates on the density of the cement panels. Overall, the cement panel made from GP and WP exhibited a lower density than the CS. The decrease in density can be attributed to the lightweight nature and low bulk density of the recycled waste aggregates. Also, the entrapped air volume in the mixing process and the porous nature of the cement panels can be considered for reduced density. On the other hand, it was observed that glass inclusion results in excess free water and the replacement of sand, and the typical cement sand mortar had a higher density than alkali-activated slag mortar with GP due to specific gravity differences. 100% of WP exhibited the lowest density, followed by 50% and 20% substitution of GP and WP, showing a slightly higher density value. These outcomes agree with the study of Djelal, Page, Kada, and Vanhove (2020), noticing a decline in the density when the percentage of wood waste in the mortar mixture increased. Furthermore, the observation also aligns with Shoaei, Ameri, Musaeei, Ghasemi, and Cheah (2020) investigation.

Water absorption and porosity

The water absorption and porosity of the hardened cement panels are presented in Figure 9. It was clear from the findings that cement panels with GP and WP aggregates exhibit a high rate of water absorption compared to the typical cement sand panel. WP as natural sand replacement in the mortar mix absorbs water to about 32.81%, the highest among the cement panel samples due to the morphos nature of the WP aggregate, which can expand and contract. Also, GP's replacement of natural sand upsurges the water porosity due to the dilution effect. A more significant proportion of wood waste in mortar mixes above 20% produces a rise in water absorption because the

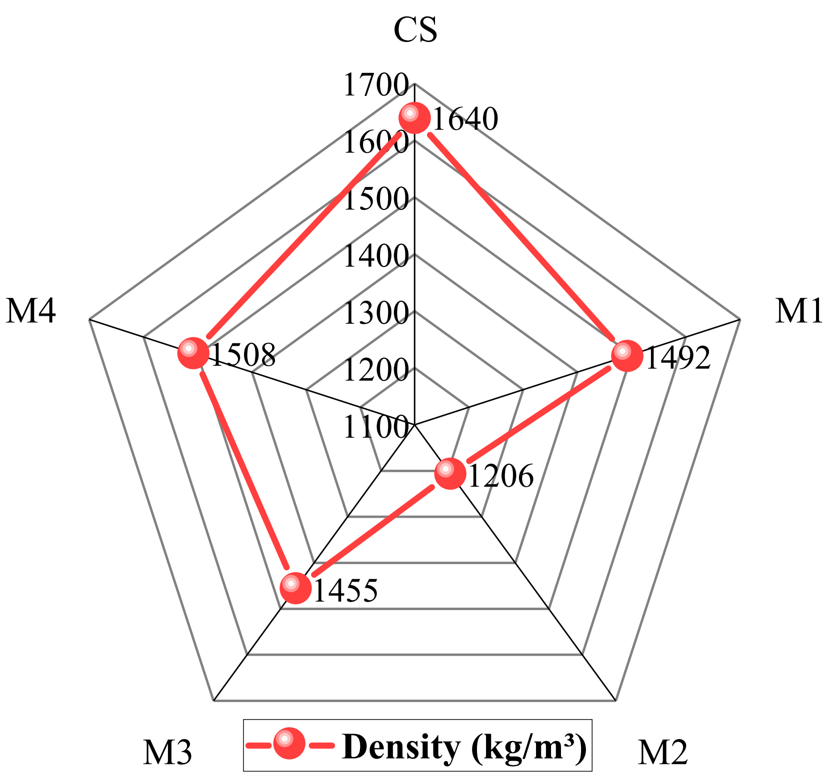

Figure 8. Density of cement panel.

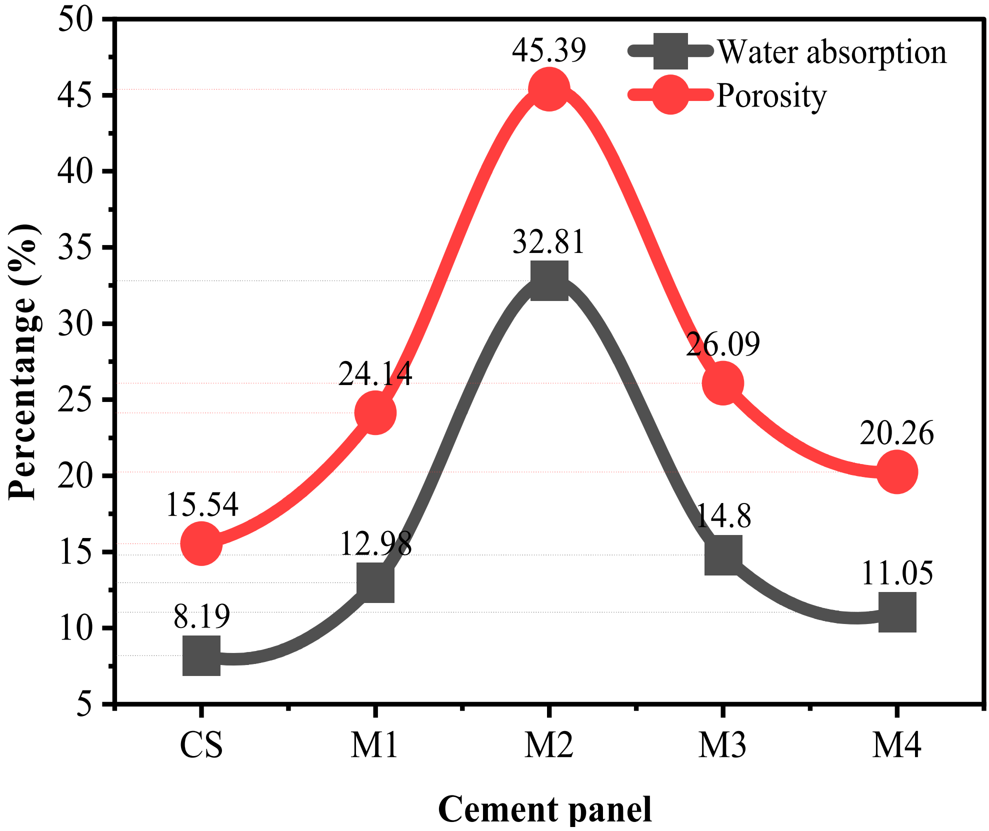

Figure 9. Water absorption and porosity results.

hygroscopicity of wood overlaps with the effect of expanding capillary pores (Baltazar, 2021). For the porosity of the cement panels, specimen M2 is more porosity than the reference sample. This can be attributed nature of wood particles and the maximum proportion of the fine wood aggregates replaced by 100% of natural sand. Also, the higher porosity further indicates how porous the WP aggregates are, as shown from the microstructure in Figure 7.

However, it was noticed from the study that a slight reduction in absorption and porosity was exhibited when GP aggregates were combined with WP aggregates to fabricate the panel samples, which closed some pore spaces limiting the samples' ability to absorb more water leading to less porosity. The addition of GP content limited the high-water absorption rate from the WP as much difference was observed in the 50% and 20% addition of GP content for the last two mortar mixes. Research by Guo, Meng, Nassif, Gou, and Bao (2020) avowed that the smooth nature of glass aids decreases in water absorption.

Compressive strength

This section presents the compressive strength breaks of the cement panels. Figure 10 shows the compression test results after 28-d and 56-d curing. The introduction of WP as a fine aggregate substitute considerably noticed a dramatic drop in strength. Mortar mix with a 100% dosage of fine wood aggregates resulted in the worst mechanical resistance to compression, although they present significant results when a small dosage is added to the mortar mixes. It was observed from the study that the WP does not contribute considerably to the hydration reaction of the cement panel binding process. Therefore, it does not play a significant position in the strength

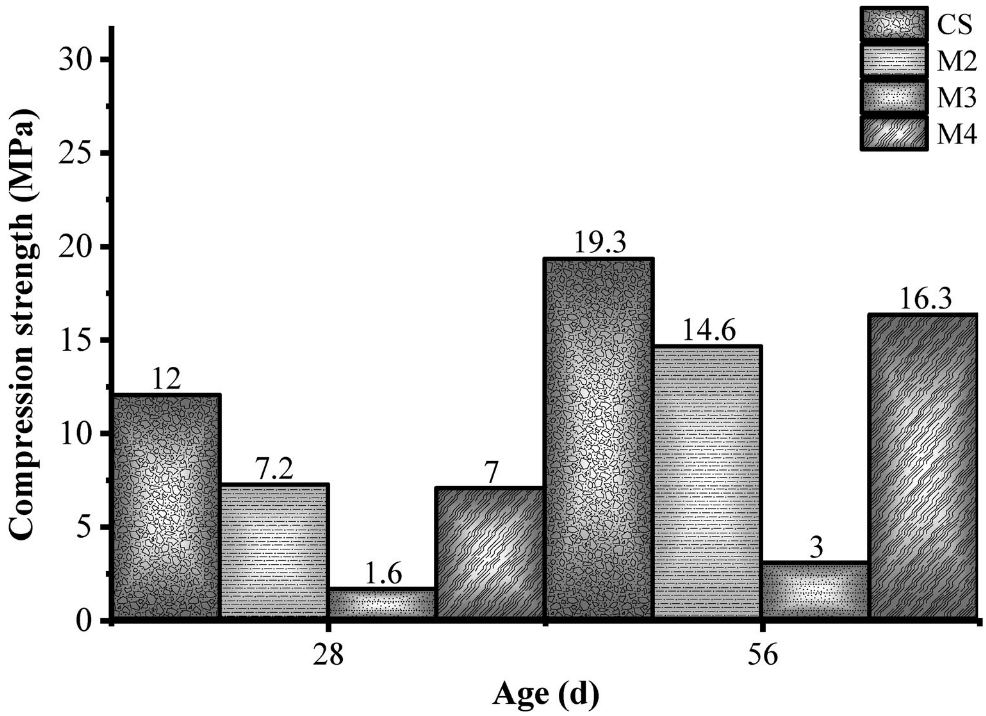

Figure 10. Compressive strength results.

properties of the mortar mixes, weakening the bond of the mortar mix. Baltazar's (2021) study demonstrated that integrating wood waste diminishes strength resistance due to the copious open porosity. However, the study recorded some achievements. The maximum strength value was 16.3 MPa achieved from a sample incorporating 20% and 10% of GP and WP at 56-d. Closely followed was a strength value of 14.6 MPa with 100% WP. Specimen M1 and M4 met the traditional values of ASTM C1329 mortar types: N-type mortar (6.2 MPa) for exterior and above-grade applications, and S-type mortar (14.5 MPa) for below-grade and bears soil and wind pressure, also seismic conditions. These findings vary with Morales-Conde, Rubio-de-Hita, and Pérez-Gálvez (2018) investigation reporting a 6.85 MPa resistance to compression strength when 2.5% wood waste was replaced in the mortar mix compared to 20% replacement, which presented a worse compression strength. Overall, the control mortar mix recorded the optimum strength.

Thermal performance

Figure 11(a) presents the thermal conductivity coefficients of the cement panels. The thermal variations in this study are lower at a minimum of 52% in most cases; therefore, the recorded conductivities can be used as practical values for natural sand replacement. In the cement-based panel, the reference sample reaches a conductivity value of 0.973 W/mk. However, it was observed that the inclusion of WP significantly reduces the cement panel's thermal conductivity compared to the reference panel. From the results, the M2 cement panel attained the lowest thermal conductivity. This could be attributed to the WP being hydrophilic and a good conductor of heat, influencing enhanced thermal conductivity. The reduced thermal conductivity can be ascribed to the wood particles' low bulk density and high porosity. According to Berger, Gauvin, and Brouwers (2020), employing more wood waste reduces heat conductivity due to the increased pores created by the coiled

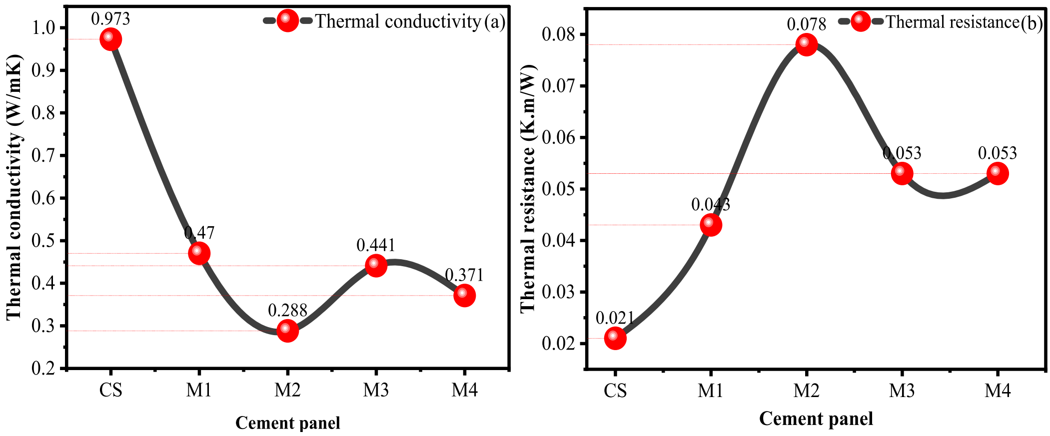

Figure 11. Thermal conductivity and resistance test results.

strands in the structure (Berger et al., 2020). However, this contrasts with the findings of Xu et al. (2019), who reported increased thermal conductivity when the wood fiber content is increased.

On the other hand, incorporating GP also reduces thermal conductivity by up to 20%. The low density of GP compared to natural sand can be attributed to the decreased thermal conductivity of the GP cement panels. Similarly, Flores-Ales et al. (2020) reported that when natural aggregate is replaced with GP, the thermal conductivity values of the specimens noticeably drop, suggesting that the change in thermal diffusivity significantly influences this behavior. On the contrary, Sikora, Horszczaruk, Skoczylas, and Rucinska (2017) and Arias-Erazo, Villaquirán-Caicedo, and Goyes (2021) reported a thermal conductivity between 0.60 and 0.71 K·m/W with mortar containing 100% GP.

It was further observed that the lower the thermal conductivity, the higher the thermal resistance values. Figure 11(b) displays an increase in the temperature difference between the two faces of the waste-cement panels to the rate of heat flow per surface area compared to the typical cement sand panel. The presence of fluid in the case of high water absorption between the contacting surfaces of the panels contributes to temperature differences depending on the panel's thermal conductivity, thickness, and hardness. The significant temperature difference between the surfaces was also due to the composing heat exchange by radiation that occurred across the gaps between the contacting surfaces of GP and WP mixtures. The variations in temperature of the cement panels incorporated with GP and WP fall within 0.043–0.078 K.m/W. The results contradict Bida, Abdul Aziz, Jaafar, Hejazi, and Abu Bakar's (2021) findings, where a 2.48 K.m/W thermal resistance for precast sandwich concrete panels was obtained. It can be inferred from the study results that the cement-based waste panels' low thermal conductivity exhibits strong heat flow resistance, so their use can help limit heat transmission into buildings. Following ISO and CEN standards, the heat conductivity coefficient > 0.065 K·m/W is considered a construction material.

Infrared thermography test

Figure 12 displays the captured thermal images of the surface heat flow of the sample panels. It can be observed that after applying heat for 45 min, the panel specimen integrated with GP and WP reduced the average heat flow compared to the reference sample panel (CS). The decrease in temperature ranged between 48.8°C and 49.5°C against 53.5°C. Thermal energy is promulgated by diffusion beneath the surface, while an infrared camera detects the surface's temperature variation (Meola, 2007). The study results agree with Yousef et al. (2020), indicating that utilized waste aggregates in mortars can be included in the building envelope or non-load bearing features such as wall partitions as thermal resistance to minimize energy consumption in residential structures.

Energy analysis via external walls by conduction

Table 5 shows the values of the heat transfer via the external walls by conduction and the cost of energy consumption in a day when construction waste aggregates are used to develop walling components compared to the conventional walling component. Substantially, the utilization of construction waste aggregates outperformed the typical walling component in reducing the cost of energy consumption. It was observed that incorporating 100% of WP exhibited a 70% reduction in the cost of energy consumption in a day, the lowest recorded, compared to the control sample walling.

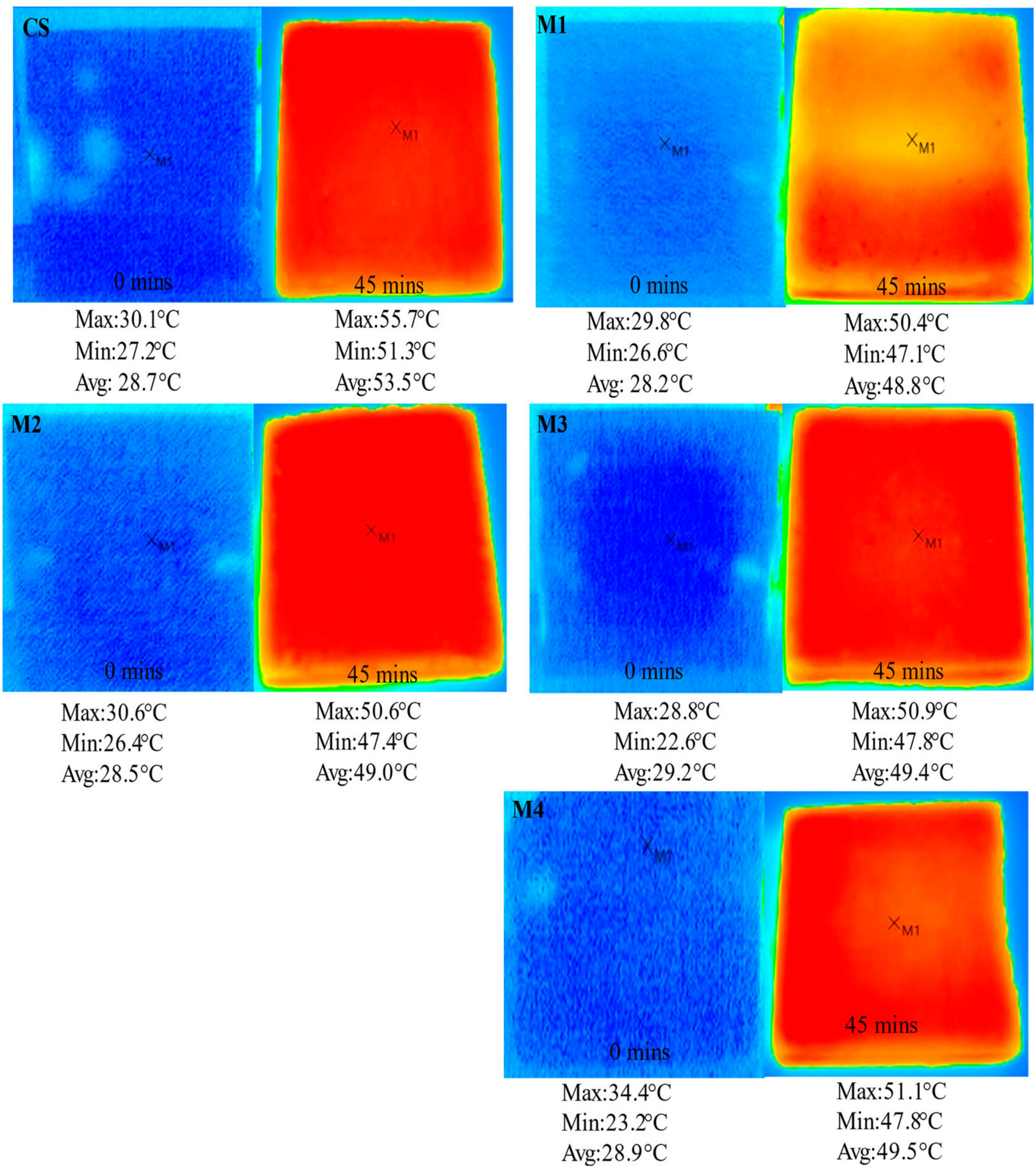

Figure 12. Surface heat flow of cement panels.

Closely followed was the composite walling component developed with 20% and 10% glass and timer powder, with an energy consumption of $1.22. The highest cost noticed was $3.21 from the CS walling component per day.

Furthermore, Figure 13 presents the annual energy consumption of the different walling components. The construction waste aggregates as walling components exhibit between 51% and 70% annual energy consumption savings. Using CW in the panel business can be more effective when combined with the matrix of the panel preparation, resulting in lower energy costs.

Estimated cost of cement panel fabrication

The cost of the fresh mortar mixes of the cement panels substituting waste materials with natural sand is determined. As mentioned, the calculations exclude materials transportation, equipment, and mortar for joint bonding. The estimation showed a slight reduction of the waste incorporation cement panels was noticed compared to the typical cement sand panel. A 17.98% cost reduction was noticed, around $180, for a 191 m^2 wall area using $30 \times 30 \times 2$ cm cement panels. Samples M1-M4 achieved a similar reduction. This is so because the cost component of sand was eliminated since the waste aggregates were used in replacement and did not attract any cost. In addition, the slight cost reduction can be attributed to the fact that cement constituted a significant proportion of the mix ratio and remained constant. This presents a potential for further investigation on partially replacing cement with cementitious waste materials.

Embodied carbon emissions of cement panel mixes

The carbon emissions results are given in Figure 14 for the embodied carbon contribution through the production process and transportation. According to the outcomes, the CO2 emissions of the reference sample was 1437 kg eCO2/m^3 mortar. CS has the highest emission production and transportation (river sand traveled an average of 98 km from Bator in the volta region via dumpers) among the mortar mixes. Mix 3 (100% WP) recorded the lowest as 1390 kg eCO2/m^3 mortar. It indicated a 3.3% reduction in eCO2 emissions compared to the reference mix. At the same time, the other mixes with CW materials exhibited lower eCO2 emissions. This agrees with previous works of Bostanci (2020) and Ince, Tayançlı, and Derogar (2021), in which eCO_2 emissions reductions were reported after waste materials were incorporated as a replacement.

Conclusions

The study aimed to produce sustainable cement panels utilizing glass and wood powder as substitute aggregates for natural sand, limiting natural resource consumption for potential construction materials. Several test measurements (BET, XRF, XRD, SEM, density, porosity and water absorption, compression strength, thermal conductivity, resistance, and infrared thermography) were investigated. The following conclusions are drawn from the study results:

Table 5. Cost of energy consumption via the walls.

Wall code	Heat transfer via walls by conduction (kWh) for 24 h	Cost of energy consumption per day	
		Ghc	$
CS	39.6	35.24	3.21
M1	19.2	17.09	1.56
M2	11.76	10.47	0.95
M3	18.0	16.02	1.46
M4	15.12	13.46	1.22

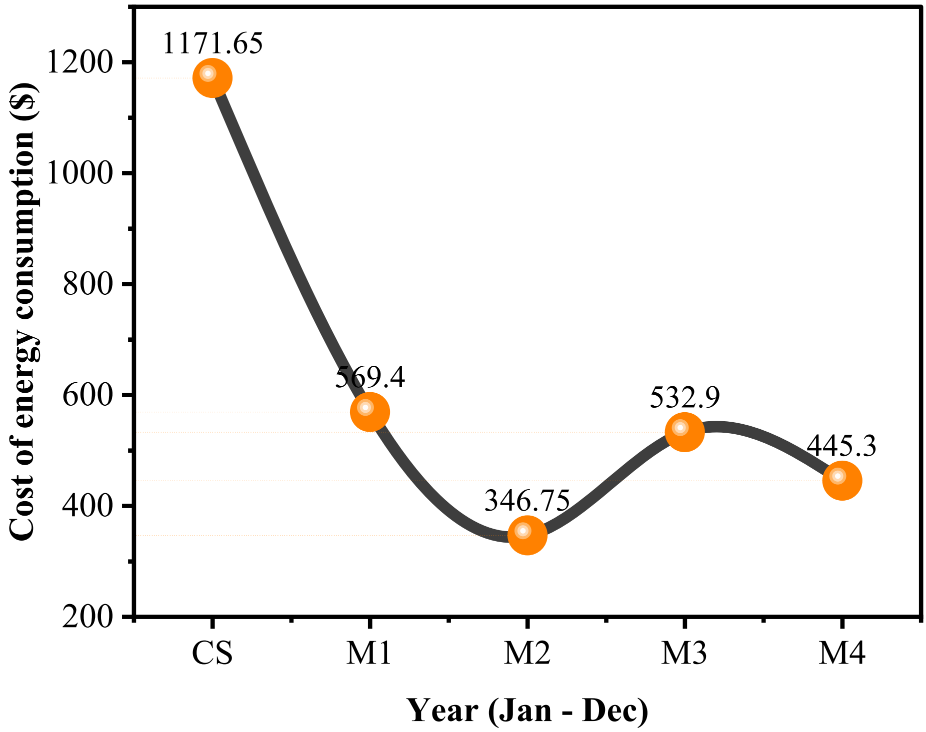

Figure 13. Cost of energy consumption.

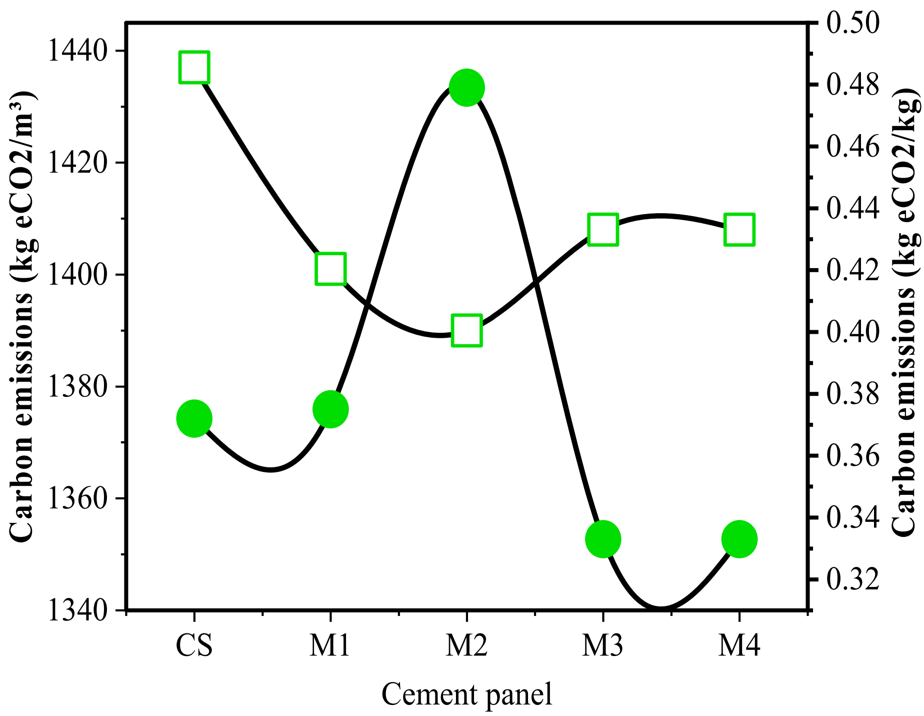

Figure 14. Embodied eCO_2 emissions of the cement panel.

- Cement panels utilizing wood powder to partially replace natural sand as fine aggregate had the lowest hardened density, thermal conductivity, and highest water absorption and porosity. In contrast, cement panels utilizing glass powder as fine aggregate demonstrated the highest compressive strength, low porosity, water absorption, and hardened density. Meanwhile, replacing glass powder and wood powder as a composite mixture decreased the thermal conductivity. The incorporation of glass powder partly filled the pores in the cement panels but had little effect on the hardened density, porosity, thermal conductivity, and compressive strength of the panels.
- Cement panels using glass powder and wood powder exhibited significant ambient heat reductions leading to a high energy reduction for optimum efficiency when employed as a building envelop walling component. The reduced energy consumption can also be attributed to the lower thermal conductivity values obtained from the study.
- Despite a slight reduction in cost and carbon emissions from the waste incorporated waste aggregates as a natural sand substitute, it did not essentially impact the panel cost and eCO_2 emissions reductions. This is because cement constituted a significant proportion of the mortar mix.
- The study informs that the proposed methodology is helpful to manufacturers of building materials, specifically, as they will be able to verify anticipated adjustments not only from the perspective of functional property enhancement but also by taking environmental considerations into account by reducing both waste and energy consumption.

Recommendations for future studies

This study used wood powder as a natural sand replacement but was limited in achieving adequate compressive strength resistance. For further studies, it is recommended to incorporate a water-reducing agent and enhance mechanical performance. Also, the partial replacement of ordinary cement with cementitious materials is recommended for investigation. It is recommended that future studies assess the binding performance of the cement-waste bonded panel's microstructure.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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