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Recycling timber waste into geopolymer cement bonded wood composites

Firesenay Zerabruk Gigar [a], Amar Khennane [a,*], Jong-leng Liow [a], Biruk Hailu Tekle [b], Elmira Katoozi [a]

[a] School of Engineering & IT, The University of New South Wales, Canberra 2600, Australia
[b] Institute of Innovation, Science and Sustainability, Federation University, VIC 3350, Australia

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ABSTRACT

Addressing critical societal challenges, such as climate change, resource depletion, and environmental protection, requires sustainable management of resources. This study reports on the results of an experimental program using waste wood, including chromium copper arsenic (CCA) treated wood, to produce ambiently cured geopolymer cement bonded wood composites (WGC), and the results are very encouraging. The composite exhibited a reasonable compressive strength, which ranged between 7 and 27 MPa inversely corresponding to the amount of wood per binder ratio ranging between 0.1 and 0.4, conferring it the possibility of being used as a building material. The compressive strength of the composite with 40% wood chips showed the lowest compressive strength with values of 9.79, 7.29, and 7.92 MPa for decontaminated, CCA-treated, and non-CCA-treated wood chips, respectively. The results indicated that for all the wood per binder ratios, the use of decontaminated wood chips significantly improves the compressive, flexural, and specific strength of the composites, as well as their ductility, compared to non-decontaminated CCA-treated and non-CCA-treated wood chips. This paves the way for using wood waste in sustainability oriented product development and manufacturing.

1. Introduction

The growing awareness of environmental issues has prompted efforts to seek alternative development strategies focussing on sustainability and green technologies. One focus area is the building and construction sector. The pressing issues of global warming and the extensive use of natural resources, coupled with high levels of waste generation, have highlighted the urgent need for sustainable eco-friendly building materials [1–5].

The incorporation of bio-based materials plays a significant role in advancing the sustainability of the construction sector by reducing carbon dioxide emissions and the reliance on virgin materials in construction practices. The use of recycled wood-based materials, such as old pallets and construction waste, bound together by cementitious material, presents a promising solution for the construction industry, offering diverse applications in building construction [6–8]. Wood-cement composites (WCCs) are an ideal candidate for use in green buildings as they are environmentally friendly and inexpensive to produce [9,10]. Their multiscale porosity and hygroscopic nature provide benefits in terms of sound, moisture, and heat regulation by absorbing sound and limiting hygrothermal transfer [9–11]. This results in a more comfortable building environment, reducing the energy demand of the buildings in both summer and winter [9,12]. Their thermal conductivity is comparable to that of glass wool and expanded polystyrene [13]. Bio-sourced construction materials such as WCCs can also sequester carbon [9]. Furthermore, WCCs also resist decay, fungi, and insects [11,14]. Bio-based materials are also suitable for modular construction and possess energy-dissipating properties [11,15]. They possess non-fragile elastic–plastic behavior leading to high deformability under stress. This high deformability is due to the highly flexible nature of the wood aggregate and is manifested by a lack of fracturing and marked ductility, which is the absorbance of the strains even after the maximum mechanical strength is reached [9]. WCCs are ideal construction materials, especially in warm and humid environments where termites and decays could be a concern. Given the numerous benefits, it is logical to shift toward using more bio-sourced materials, especially considering that new buildings are required to meet the 'zero energy criteria' or even the 'positive energy criteria' set by the latest building codes [9].

The production of wood-cement composites using recycled wood goes a long way toward the development of sustainable construction. However, the use of cement as an inorganic binder could still pose some challenges due to its high energy demand and carbon dioxide emissions.

* Corresponding author.
E-mail address: a.khennane@adfa.edu.au (A. Khennane).

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Fig. 1. General aspect of the wood chips: (a) CCA-treated wood chips; (b) Decontaminated wood ships; (c) Non-CCA-treated wood chips.

Additionally, while WCCs have numerous benefits, they have limited application as load-bearing structural elements due to their lower mechanical strength [9,11,13]. They are typically used as panels, and alternative applications have not been explored [11]. For example, the potential of using bio-sourced composites to build cinder blocks has not been fully explored. Considering their light weight, high toughness, and good insulating ability, WCCs could be ideal for building cinder blocks. The mechanical strength requirement of these blocks is not high, and composites with sufficient strength can reasonably be produced. Furthermore, the low workability of WCCs, which often require high-pressure compaction through a hydraulic press, is a hindrance to their broader application and needs to be addressed [16].

The presence of heavy metals and organic compounds in treated wood also poses a significant challenge to its recycling and reuse. Most of the wood intended for outdoor use is treated with chemicals like copper chrome arsenate (CCA) to protect it from aging and biological degradation. Telegraph poles, decking, fencing, landscaping, vineyard stakes, and picnic tables, for example, are usually treated with CCA [17]. CCA can extend the life expectancy of timber for up to 40 years [18]. Globally, it is estimated that about 20 million cubicmet cubes of wood are treated with CCA each year [19]. Australia is one of the world's largest per capita users of treated wood [18]. However, heavy metals and organic compounds in treated wood make it very dangerous for use and disposal. Lansbury and Beder [17] and Mohajerani et al. [18] have reported the hazardous effect of CCA-treated wood on humans and the environment. As a result of this limitation, CCA-treated woods often face challenges in terms of reusability, leading to their usual disposal in specially designed municipal landfills. These landfills serve the purpose of preventing the leaching of heavy metals from these woods into the surrounding environment. In Australia, about 160,000 m^3 of CCA-treated timber could be stockpiled annually by 2039 [20].

The production of wood-based composites to be used in the construction industry is one way of recycling end-of-life wood products treated with CCA [21–23]. Some studies have reported better performance when using CCA-treated woods. Increased flexural toughness and resistance to withdrawal of sticks embedded in cement have been reported by Schmidt et al. [21]. Good physical and mechanical property of CCA-treated wood-cement composites is also reported [22,23]. However, some studies argued that this is just a delay in disposal rather than avoidance, as the heavy metals could leach during service or disposal. This has necessitated the need for developing innovative ways of recycling preservative-treated wood waste [18]. Indeed, a novel idea could be managing the risk of CCA leaching by safely reducing the CCA content to an acceptable level before using it. This can avoid the need for expensive disposal of CCA-treated woods while taking advantage of its availability and desirable properties.

This study examined the feasibility of producing wood-geopolymer composites (WGC) with favorable mechanical properties. A novel method is developed to reduce the level of CCA (chromated copper arsenate) in wood. The impact of the wood/binder ratio on the mechanical properties of WGC is investigated. Additionally, the potential for creating moldable wood-based composites without requiring a hydraulic press is explored. The utilisation of otherwise disposable materials like wood and fly ash in WGC production significantly mitigates the environmental impact of the construction industry. By combining wood chips with geopolymer cement, the resulting composite material exhibits enhanced strength and durability compared to conventional wood cement composites. The cement binder protects the wood fibres against moisture absorption, minimising the risks of swelling, warping, or decay. As a result, these composites are well-suited for applications in wet or humid environments, offering improved resistance to expansion, contraction, and warping caused by changes in humidity or temperature. This characteristic proves especially advantageous in applications that require precise dimensional accuracy, such as flooring or panel construction.

Table 1
Properties of the wood chips.

Description	Density	Apparent density	Moisture content	Water absorption
	[kg/ m^3]	[kg/ m^3]	[%]	[%]
CCA- treated wood chips	1,149	428	13	147
Non-CCA-treated wood chips	1,396	443	11	154

2. Materials

2.1. Wood chips

This study used three types of wood chips as bio-aggregates: CCA-treated, decontaminated, and non-CCA-treated wood chips. The CCA-treated wood chips were produced from CCA-treated end-of-service poles collected from a vineyard in Griffith, Australia. These poles were in service for over 20 years. Some of these wood chips were decontaminated to reduce the CCA content to an appropriate level [24]. The wood chips contained final concentrations of 1.8, 1.9, and 2.1 mg/g for arsenic, chromium, and copper, respectively, after the decontamination process. Prior to decontamination, the wood chips had initial concentrations of 4.23, 4.21, and 3.9 mg/g for arsenic, chromium, and copper content, respectively. These initial concentrations fall under the H5 hazard class [25]. End-of-service pallets were also sourced from disposal tips. The pallets were made of Radiata Pine lumber and were not treated with CCA. The poles and pallets were chipped to size using a

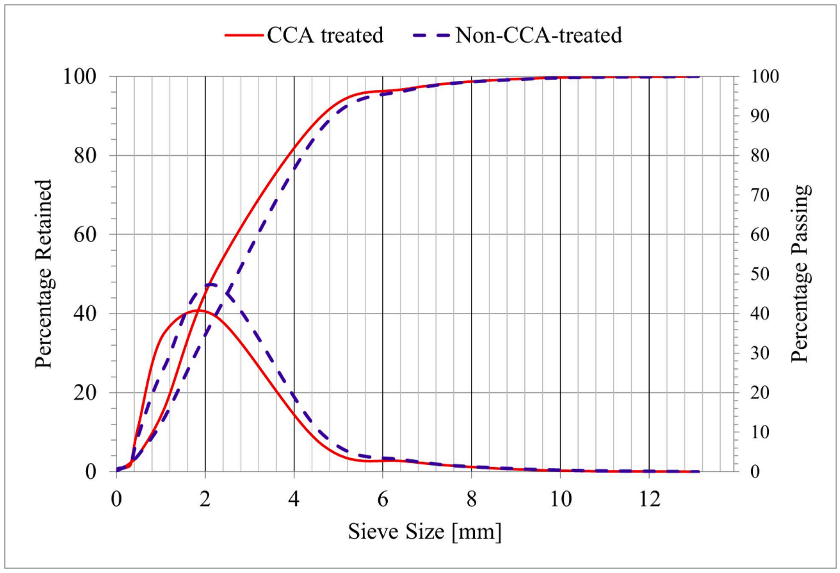


Fig. 2. Particle size distribution of wood chips.

Table 2
Elemental composition of fly ash and GGBS.

Compound (wt. %)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	LOI*
Fly ash	67.62	19.94	3.7	1.46	0.53	0.61	2.23	2.02
GGBS	34.38	13.31	0.71	41.25	4.75	0.35	0.28	<0.01

* Loss on ignition

Table 3
Physical properties of binders.

Characteristic particle diameters	**Fly ash**	**GGBS**
D_{90} (μm)	68.83	29.41
D_{50} (μm)	19.84	12.07
D_{10} (μm)	4.55	4.66

woodchipper. The morphology of the wood chips is shown in Fig. 1.

The wood chips' density, moisture content, and water absorption were calculated according to standard procedures [16,26,27] and are shown in Table 1. The particle size distribution of the wood chips is shown in Fig. 2. The particle size distributions of the wood chips produced from the vineyard poles and pallets were similar, and their effect on the mechanical properties is negligible.

2.2. Binders: Fly ash and slag

The aluminosilicate materials used for this study were fly ash and ground granulated blast furnace slag (GGBS), acquired commercially. Their chemical compositions were determined from an x-ray fluorescence (XRF) test and are shown in Table 2. The Binder's particle size distribution (PSD) was determined using a laser diffraction particle size analyzer and is reported in Table 3. The PSD was determined as the cumulative percentage below a certain grain diameter (CPF). The CPF below 10%, 50%, and 90% was classified as D_{10}, D_{50}, and D_{90}, respectively.

Fly ash-based geopolymer concretes are the most used geopolymer concretes. However, they need heat curing to gain strength. This additional energy requirement limits geopolymer concrete's versatility and inhibits its wide application. Hence, ground granulated blast furnace slag (GGBS), which is rich in CaO, was added to achieve ambient curing behavior.

2.3. Alkali activators

A combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was used as alkaline activators. The NaOH solution was prepared by dissolving NaOH flakes with 98% purity in water. A 12 M NaOH concentration was used for all mixes and was prepared at least 24 h before mixing due to its exothermic nature. A commercially available laboratory grade D sodium silicate solution with a 44.6 solid weight% and a SiO_2: Na_2O ratio of 2.05 was used. The dosage of the alkaline activator used is reported as the alkaline solid-to-binder ratio (AS/B) and sodium silicate-to-sodium hydroxide solid ratio. The AS/B ratio is the weight of the solid sodium silicate and solid sodium hydroxide divided by the weight of the binder (fly ash and GGBS). The sodium silicate-to-sodium hydroxide solid ratio (SSS/SSH) indicates the relative proportion of the solid part of the alkali constituent materials. These two ratios, based on the solid content of the alkalis, provide a clearer definition of the dose used without being entwined with the solution, which also contains water [28].

3. Experimental program

3.1. Preliminary experiments and mix design

One of the challenges in developing WGC and exploring their potential application for structural elements is the lack of a proper mix design method. To overcome this issue, a preliminary investigation was conducted to formulate a mix design that can help achieve desirable performance in strength and workability. Four sets of mixes were tested to study the effect of slag content, the wood-to-binder ratio, the AS/B ratio, and the SSS/SSH ratio on the compressive strength of the WGC. The slag-to-binder ratio for set 4 was 0.5, while all other sets used 0.4. The AS/B ratio was 0.12 for sets 1 and 2 and 0.18 for sets 3 and 4. The SSS/SSH ratio was 1.56 for all sets, except for set 1, which had a ratio of 2.50.

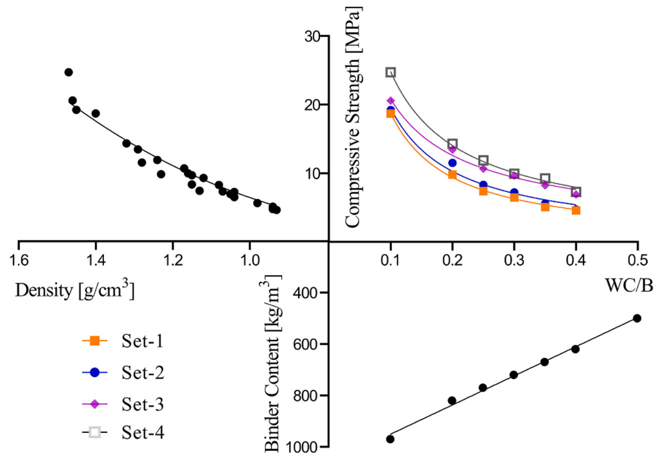


Fig. 3. Mix-design chart for WGC.

The presence of wood chips significantly affects the water content because of their high-water absorption capacity. This reduces the workability of the concrete. To overcome this problem, compensating water equal to the average water absorption of the wood chips was added to the mix to bring it to a saturated surface dry (SSD) condition, following the recommendation by da Gloria et al. [16]. This was done to produce a WGC with good workability and avoid the need for mechanical pressing, which could change the wood chip's original microstructure and lightweight characteristics while limiting its large-scale application. The compensating water was in addition to the water needed for the geopolymer binders. This means there are three types of water in the mix, water from alkali solutions, added water for geopolymer concrete, and compensating water. The compensating water depends on the amount of wood chips in the mix and was taken as 1.5 times the dry weight of the wood chips (WC) based on experimental observation. The rest of the water, taken as geopolymer water (GW), was kept constant at a ratio of 0.29 with respect to the geopolymer solid (GPS), i.e. GW/GPS = 0.29 based on a previous study [28]. Geopolymer solid (GPS) was taken as the binder's weight (fly ash and GGBS) and the alkali solution's solid parts. Based on this, an empirical formula for total water (TW), TW = 0.29GPS + 1.5WC, was developed. This considered the amount of water absorbed by the wood chips and enabled operating at relatively constant workability with varying wood content.

Based on an extensive analysis of the preliminary experimental results, a simple and reasonable method was developed to determine the binder content of WGC for different wood content. Fig. 3 shows the wood content, density, and compressive strength relationship. The wood content and alkali dosage are related to the binder content using the wood-to-binder ratio and the alkali solid-to-binder ratio. A summary of the analytical expression correlating the compressive strength, wood content, density, and binder content is given in Equations (1) to (3).

$$f_{cm} = K_1 \exp\left(-\alpha\left(\frac{WC}{B}\right)\right) \quad (1)$$

$$f_{cm} = K_2 \gamma^3 \quad (2)$$

$$Bindercontent = K_3 - K_4\left(\frac{WC}{B}\right) \quad (3)$$

where, f_{cm} is strength, B is binder, γ is density, $K_1 = 23$, $K_2 = 7$, $K_3 =$ 1,064, $K_4 = 11$, and $\alpha = 0.033$

The chart was used to design all the mixes in the main experimental program of this study. Developing a workable WGC with good strength was a major challenge at the beginning of this experimental study. Furthermore, finding a suitable binder content to obtain a cubic meter of WGC was also challenging. This is mainly due to a lack of mix design tools that can serve as a starting point for trial mixes. The simple mix design chart proposed in Fig. 3 can serve this purpose. It can be a good starting point for trial mixes in future works involving wood chips and geopolymer concrete.

3.2. Experimental design

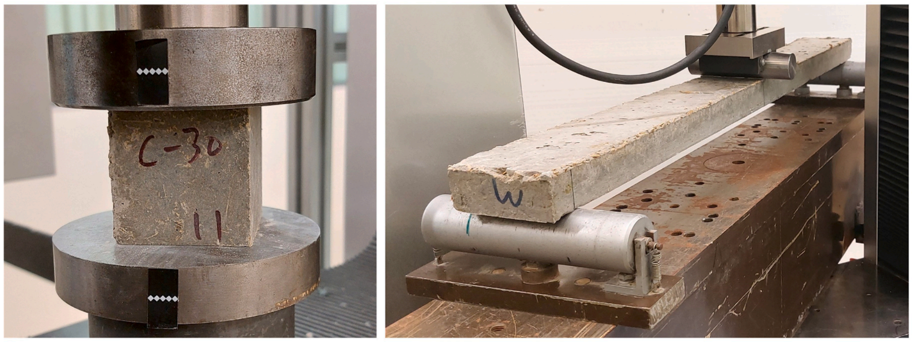
Once a mix design with appropriate workability was established, a 6 × 3 fractional factorial-based experiment design was developed to investigate the effect of wood decontamination and wood content on the mechanical property of WGC. The first factor comprised of three levels of wood chips: CCA-treated wood, decontaminated wood, and non-CCA-treated wood. The second factor consisted of six level of wood-to-binder ratios (WC/B), ranging from 0.1 to 0.4, with sufficient binder needed to encase the wood chips and create a cohesive material. According to previous study, inorganic bonded composites require 30% to 90% binders, and conversely, wood-binder composites may contain between 70% and 10% wood by weight [28]. Similarly, Moslemi and Pfister [29] reported that complete matrix formation might not occur for a WC/B ratio above 0.5, reducing composite strength. Thus, for this study, the WC/B ratios were limited to 10% to 40%. The factorial-based experimental design was chosen as it allows the simultaneous evaluation of the effect of varying multiple factors, in this case, different types of wood chips and their content. The response variables of the factorial design included compressive strength, modulus of elasticity, modulus of rupture, and stiffness, which were selected to assess the impact of wood decontamination and wood content on the mechanical performance of WGC.

Three sets of WGCs were produced, with different types of wood chips and content. The type of wood chip used is indicated by the following abbreviations; CCA for CCA-treated wood, Dec for decontaminated wood, and Pre for non-CCA-treated wood. The WC/B ratio, expressed as a percentage, was indicated by a number at the end. For example, CCA-10 represents a WGC made with CCA-treated wood with a 10% WC/B ratio. Mixes 1 to 6 (CCA-10 to CCA-40) were prepared with a wood-to-binder ratio (based on the dry weight of wood) of 10%, 20%, 25%, 30%, 35%, and 40%, using CCA-treated wood chips. Mixes 7 to 12 (Dec-10 to Dec-40) used decontaminated wood chips, while mixes 13 to 18 (pre-10 to pre-40) used non-CCA-treated wood chips sourced from recycled pallets. In all three sets FA/B ratio, AS/B ratio, SSS/SSH ratio, and GW/GPS ratio were kept constant, based on the preliminary study, at 0.5, 0.18,1.56, and 0.29, respectively.

The effect of CCA decontamination on the composite's mechanical properties was studied by comparing the samples with CCA-treated and decontaminated wood chips. Additionally, WGC with decontaminated wood chips was also compared to the non-CCA treated composites to evaluate the impact of wood decontamination. All three sets were used to investigate the wood percentage's effect on the WGC's mechanical properties. Analysis of variance (ANOVA) was performed to determine if the variables had a statistically significant effect on the mechanical property of the WGC. Tukey's studentized Test was also conducted at a 95% probability level. This helped to determine which specific values were significantly different from each other and contributed to a better understanding of the effects of CCA decontamination and wood content.

3.3. WGC production

In this study, over 400 cubes and prism specimens were cast and tested. The WGC were produced with a mixer under laboratory conditions. The binders (fly ash and GGBS) and dry wood chips were dry mixed for 3 min to ensure homogeneity of the mixture. Subsequently, the alkaline solution and water (compensating and geopolymer water) were added and mixed for an additional 5 min, for a total mixing time of 8 min. After mixing, the fresh WGC were weighed, placed, and compacted by hand in three layers. The samples were weighed to ensure uniformity during placing and compacting. All specimens were stored in



(a) (b)

Fig. 4. Mechanical testing: (a) Compressive test; (b) Three-point bending test.

a climate-controlled room at 20 ± 3 °C and 50% relative humidity for 24 hrs. After the 24 hrs., the samples were removed from the mold and cured in the same control room until the day of testing. During the curing process, the samples were sealed in a plastic bag. The density was measured according to EN 323 [30].

3.4. Test methods

3.4.1. Mechanical property

Cubic and prismatic samples were prepared and tested to determine the mechanical properties of the WGCs. Since there are no established standards for testing WGCs, the tests were conducted following recommendations found in publications and standards developed for concrete and wood products. The most widely used code for evaluating the mechanical property of wood-based composites is the ASTM [31] which was adapted for this study.

3.4.2. Compressive tests

The uniaxial compressive test was done using a universal testing machine according to ASTM D3501 [32] standard. Cube samples were tested for compression at 7-,14-, and 28-day. The 7- and 14-day compressive strength was performed on three samples, while the 28-day strength was performed on five samples. The test was conducted at a loading rate of 1 mm/min. The experimental setup is shown in Fig. 4a. Load and displacement data were taken continuously by a computer-controlled data acquisition system. The test results are summarized using the maximum compressive load and the stress–strain diagram. The specific compressive strength was calculated by dividing the compressive strength by the sample density.

3.4.3. Three-point bending tests

Three-point bending tests were conducted, according to ASTM D1037 [33] and ASTM D3043 [34], to determine the stiffness and flexural load-carrying capacity of WGC. For this test, prismatic beams of width 76 mm, depth 30 mm, and length 770 mm were produced. The selected span length minimizes the effect of shear deformations and provides a more accurate measurement of the composite's modulus of elasticity. The flexural tests were performed on six samples. The load was applied at the center, using a Shimadzu Universal Testing Machine, with a constant rate of 1 mm/min, giving at least 12 data points up to the proportional limit. The test setup is shown in Fig. 4b. The modulus of elasticity (MOE or E), the modulus of rupture (MOR), and flexural stiffness (K) were determined as follows:

$$MOE = \frac{L^3}{48I}\left(\frac{\Delta F}{\Delta U}\right) \tag{4}$$

$$MOR = \frac{3FL}{2bh^2} \tag{5}$$

$$K = \frac{48EI}{L^3} \tag{6}$$

where F is the applied load at peak, I is the moment of inertia, b is width, h is depth, L is the span length, ΔF is the change in the load measured on the linear part of the load–deflection curve ($\Delta F = F_2 - F_1$) where F_1 was approximately 10%, and F_2 was approximately 40% of the peak load. ΔU is the increment of deflection corresponding to (F_2 – F_1) in the load–deflection curve.

3.4.4. Flexural toughness

One of the major benefits of bio-based composites is their ability to absorb energy. Toughness is a measure of the material's ability to absorb energy and is represented by the area under the load–deflection curve for the three-point loading test. This metric can be used to determine the post-cracking energy absorption or resistance to failure after cracking. To compare the toughness of composites, toughness indices were utilized to identify the pattern of material behavior up to the selected deflection criteria. For brittle materials, the toughness index is equal to 1.0, as the area beyond peak load is zero. On the other hand, for steel fiber-reinforced concrete, it is around 5.0. ASTM C1018 [35] defines toughness indices (I_5) for fiber-reinforced concrete as the area under the load–deflection curve up to 3 times the deformation at the first crack divided by the area under the load–deflection curve to the first crack. The first crack is typically defined as a point where the load–deflection curve becomes nonlinear.

4. Results and discussion

Table 4 provides an overview of the experimental results obtained in the present study. The table summarizes the mean values of the

Table 4
Experimental results.

Designation	Compressive Strength [MPa]						Density	Flexural Strength [MPa]		
	7th day	s.d.	14th day	s.d.	28th day	s.d.	[kg/m3]	MOE	MOR	K
CCA-10	15.55	1.74	18.58	0.76	24.72	2.49	1,466	8,522	2.80	175.33
CCA-20	11.06	0.44	12.54	0.15	14.31	0.44	1,325	7,019	3.74	139.43
CCA-25	9.71	0.48	10.59	1.05	11.89	0.55	1,237	5,768	4.85	122.00

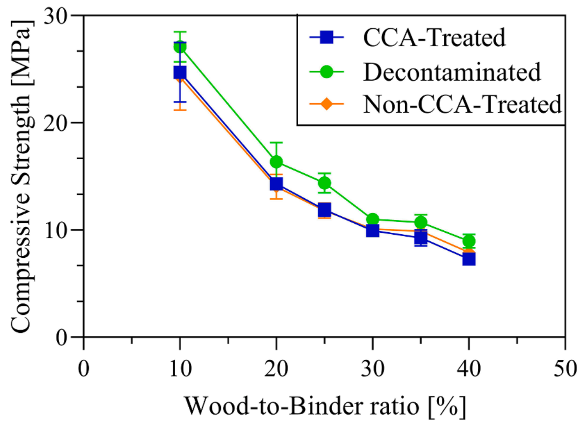


Fig. 5. Compressive strength for different wood chip types and wood content.

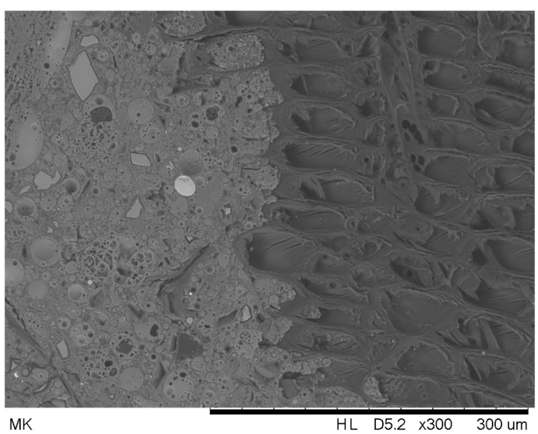


Fig. 6. Wood chips inside the matrix.

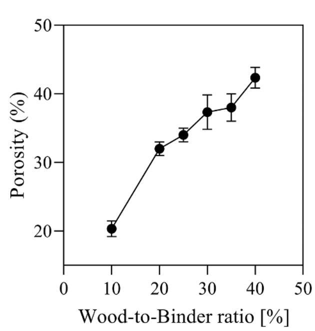


Fig. 7. Variation of porosity as a function of wood content.

compressive and flexural strength results. The compressive strength is presented for 7-, 14-, and 28-days. The density and standard deviations are provided. The modulus of elasticity, modulus of rupture, and stiffness results of the three-point bending test are also included in the table. It should be noted that all flexural failures in the bending test were initiated in tension.

4.1. Effect of wood percentage on the mechanical property

4.1.1. Compressive strength

The compressive strength of WGC with different WC/B is shown in Fig. 5. The results indicate that the wood content significantly affects the compressive strength, and as the percentage of wood increases, the compressive strength of the WGC decreases. The WGC with 40% wood chips showed the lowest compressive strength with values of 9.79, 7.29, and 7.92 MPa for decontaminated, CCA-treated, and non-CCA-treated wood chips, respectively. The ANOVA analysis also revealed a statistically significant ($p < 0.05$) decrease in compressive strength as the wood content increased. This trend of decreasing compressive strength with increased wood content has also been observed by others [36,37]. The effect is more pronounced in the 10 to 20% range, where the drop in strength is larger compared to the 20 to 40% range. This decrease in strength is attributed to the weak bond developed due to the binder's inadequate coating of the wood chips and the decrease in density [23,38]. The density of the composite is impacted by the porosity of the wood chips, as illustrated in Fig. 6. This can also be shown in Fig. 7, where the porosity of the composite increased as the wood content is increased. Nevertheless, this same porosity contributes to the insulation characteristics of wood-based composites. Some microcracks were also observed at the interface between the wood chips and geopolymer matrix, Fig. 8, contributing to a decrease in strength by weakening the interfacial transition zone. This weak interaction between biobased materials and the matrix was also observed by other researchers [12].

It should be noted here that the purpose of incorporating wood chips in the WGC is not to increase the compressive strength, as the strength of the binder is much higher than that of wood. Rather, the inclusion of wood chips serves to create a sustainable construction material that is lightweight and has good insulating properties. The wood chips also improve the ductility or fracture toughness of the WGC by blocking crack propagation, bridging across cracks, and providing post-cracking ductility [11,39]. This benefit was evident in the failure mode of the WGC samples, which showed less cracking and better energy absorption.

Moreover, despite the lower compressive strength, WGC can still play a major role in the development of sustainable construction materials by achieving an optimal balance between the amount of wood and binder. One potential application of WGC, with its lightweight and good thermal insulation and reasonable compressive strength, could be in the production of cinder blocks (masonry units) that could be used as wall materials in green buildings.

A review of the building code standards for the compressive strength requirements of cinder blocks supports the potential use of WGC as a wall-building material. For example, ASTM specifies a minimum compressive strength of 13.1 MPa [40] and 4.14 MPa [40] for load-bearing and non-load-bearing blocks, respectively. Meanwhile, British and Indian standards require a minimum strength of 3.5 MPa for masonry [41,42]. The results of the current study show that the compressive strength of WGC ranges from 7 MPa to 27 MPa, making it a suitable material for non-load-bearing and load-bearing wall-making blocks or masonry units.

4.1.2. Flexural strength

Table 4, Fig. 9, and Fig. 10 present the mean value of modulus of elasticity (MOE) and modulus of rupture (MOR) of WGC. The MOE is significantly affected as the WC/B ratio changes, with the average MOE of the WGC ranging from 2,191 to 9,151 MPa. These results are comparable to the results of Zhou and Kamdem [22] and Moslemi and Pfister [29], which are based on wood cement composites. The MOE decreased proportionally with increasing wood content exhibiting a minimum value at a WC/B of 0.4. A nearly linear relationship between MOE and WC/B ratio was also reported by Moslemi and Pfister [29]. According to Moslemi and Pfister [29], stiffness is a function of the WC/B, and the increase in MOE with a decrease in WC/B is due to the inherent higher rigidity of the binder compared to wood. Therefore, the MOE increases with a decrease in the WC/B or an increase in the binder content.

The WC/B also has a significant effect on the MOR of the WGC, with the mean value varying from 2.80 to 5.16 MPa. However, the relationship between MOR and the WC/B is markedly different from that of MOE. For the range considered, the MOR increased with the WC/B ratio peaking at a value of 0.25 and then decreased. Other studies have reported similar trends for the MOR, though the optimum WC/B ratio

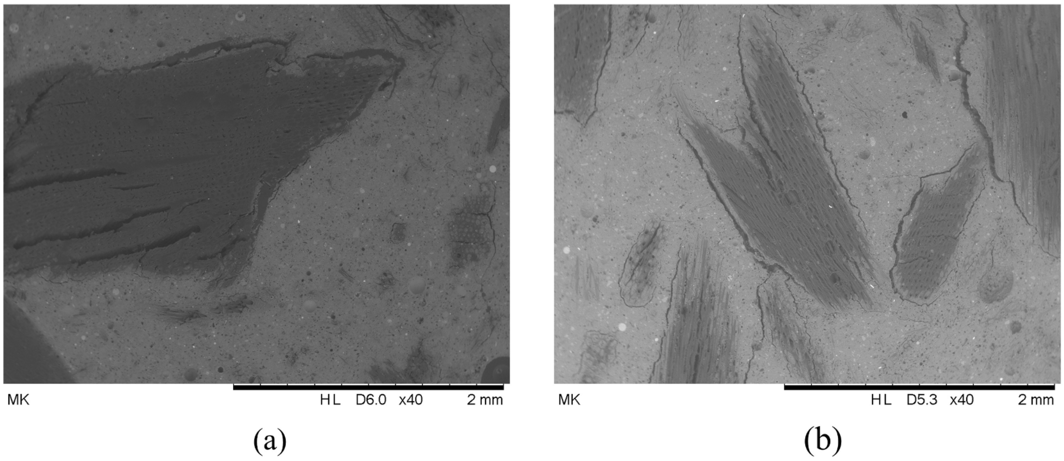


Fig. 8. Cracks at wood chips-binder interface with WC/B ratio of: (a) 0.3; (b) 0.4.

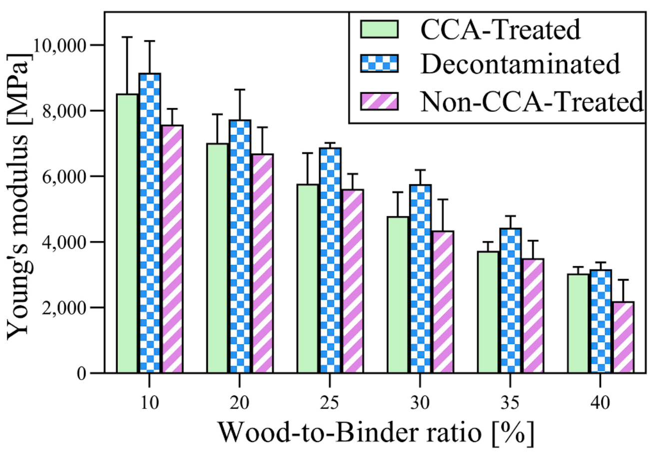


Fig. 9. Comparison of MOE.

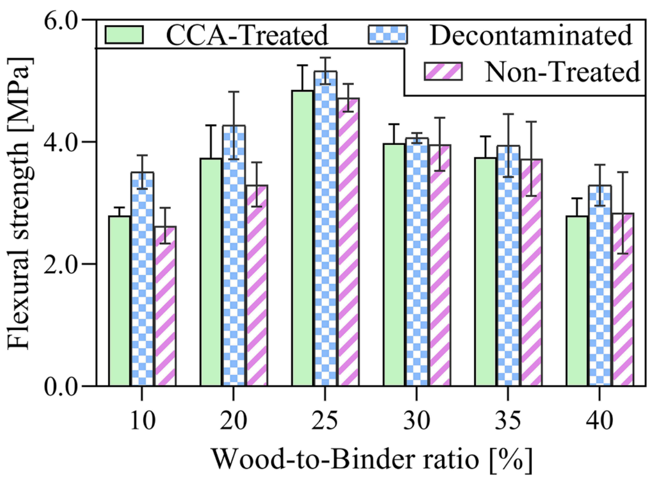


Fig. 10. Comparison of MOR.

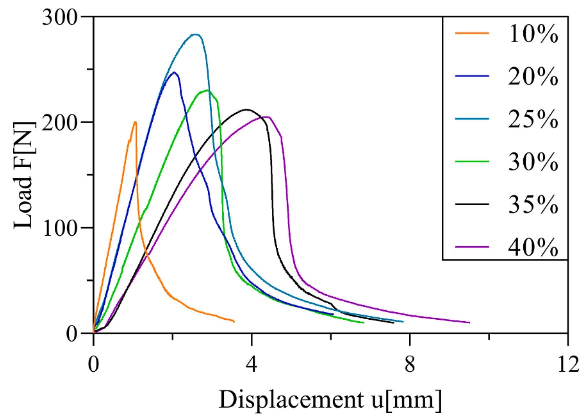


Fig. 11. Load displacement curves.

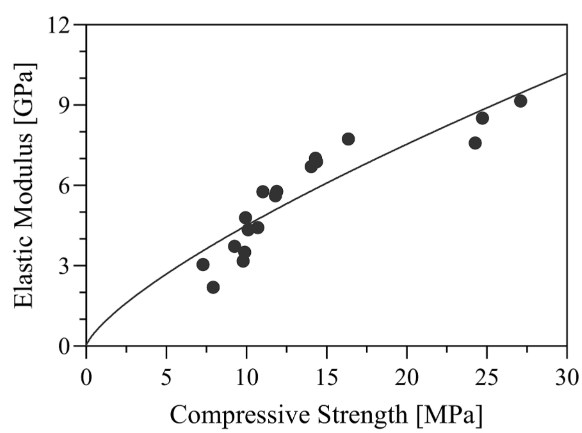


Fig. 12. Elastic modulus as a function of compressive strength.

observed differed. For example, Zhou and Kamdem [23] reported an optimum value of MOR at a WC/B ratio of 0.33. In contrast, Moslemi and Pfister [29] reported an optimum value of MOR at a WC/B ratio of 0.5.

The exact reason for the existence of an optimum WC/B ratio that results in the maximum MOR is not clear. Moslemi and Pfister [29] suggested that if a sufficient quantity of binder is available for complete matrix formation, the increase in wood content results in increased resistance to the applied stress as the region of stress concentration around adjacent particles becomes more diffused, reducing areas of high-stress concentration. Lee [43], however, argues that a higher WC/B ratio leads to poor bonding due to inadequate binder coating for the wood excelsior, while a lower ratio results in poor compaction and lower bending strength.

The effect of the WC/B on the WGC can also be seen from the load–displacement graph shown in Fig. 11. When the WGC is subjected

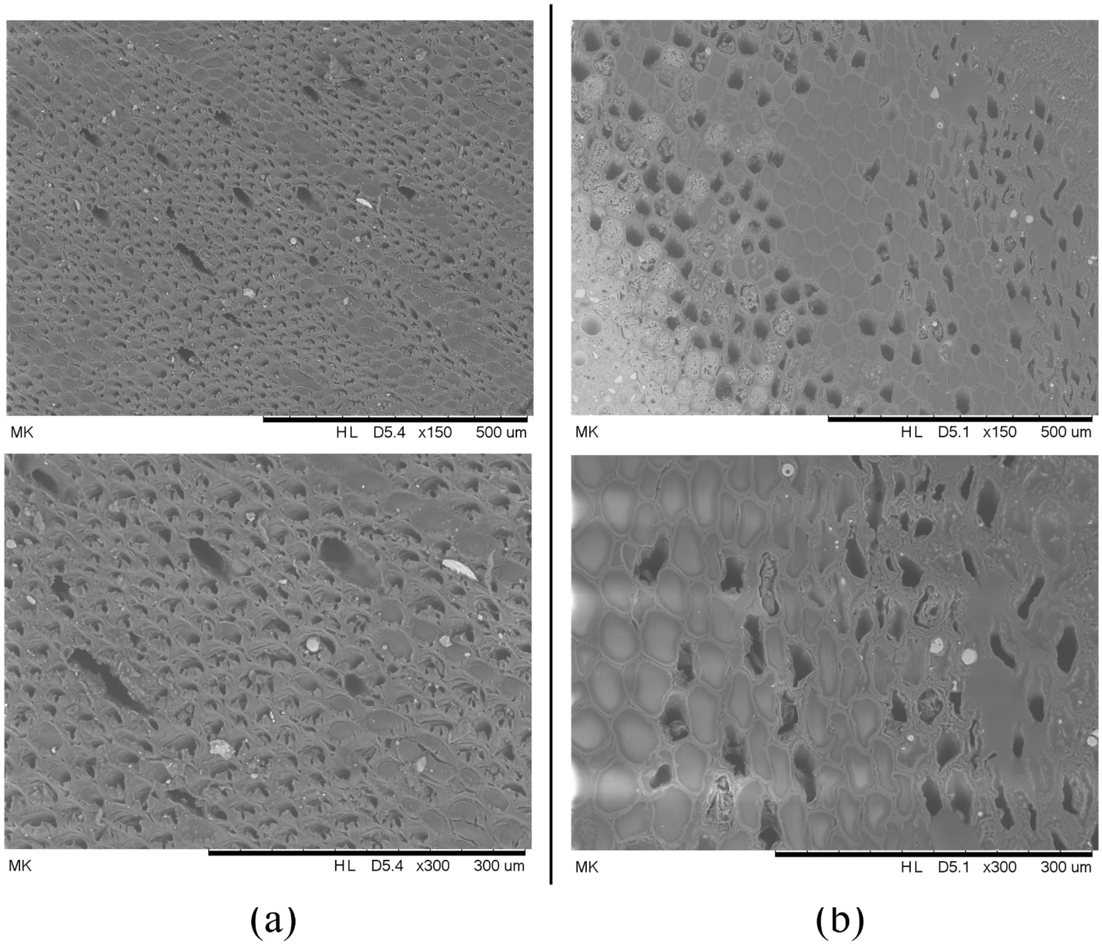


Fig. 13. Scanning electron microscopy (SEM) images with 40% wood content for samples with: (a) CCA-treated; (b) decontaminated wood chips.

to three-point loading, the typical load–displacement graph exhibits two failure modes. The initial part of the graph is linear and depends mainly on the stiffness of the geopolymer matrix. The linear elastic part was generally between 70 and 80% of the peak load. A non-linear part follows this initial linear stage and it is mainly attributable to the development of microcracks. At this stage, some of the load is transferred to the wood chips, limiting the failure of the geopolymer matrix by blocking crack propagation. This enables wood-based composites to accommodate higher loads in tension or display ductile failure [11].

A correlation was also observed between the MOE and compressive strength and Fig. 12 shows the established relationship, $R^2 = 0.81$. To accomplish this, an analytical relationship was developed by modifying the model proposed in the fib [44] Modle code, see Equation (7). The constraints in the model were calibrated using the experimental results of this study and are appropriate for samples with similar compositions.

$$E = k\left(\frac{f_{cm}}{10}\right)\exp(\beta) \quad (7)$$

Where f_{cm} is the compressive strength in MPa, E in MPa, $k = 4{,}509$ and $\beta = 0.74$.

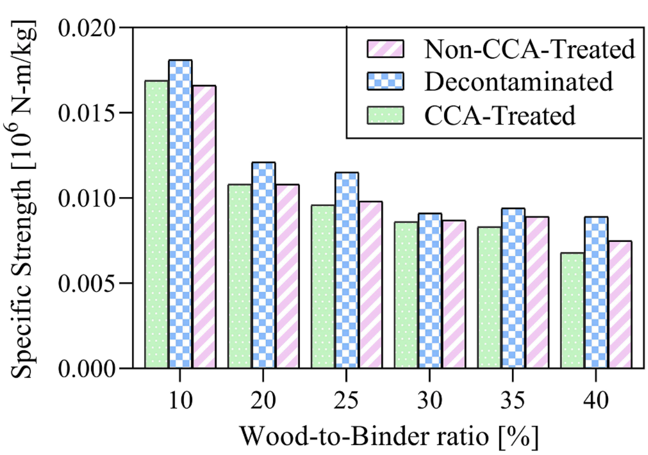


Fig. 14. Specific compressive strength.

4.2. Effect of wood decontamination on the mechanical property

The comparison of compressive strength in WGC made using CCA-treated, decontaminated, and non-CCA-treated wood chips is shown in Fig. 5. The results showed that the WGC made from decontaminated wood chips generally exhibited better compressive strength compared to those made from CCA-treated and non-CCA treated wood chips. Fig. 9 and Fig. 10 demonstrate the effect of different types of wood chips on flexural strength. The MOE and MOR values for WGC made from decontaminated wood chips were also higher than those made from CCA-treated and non-CCA-treated wood chips.

A two-way ANOVA analysis revealed a statistically significant difference ($p < 0.05$) when using decontaminated wood chips. Nevertheless, the difference was more pronounced for wood percentage than wood chips type. Tukey's studentized range test also showed a significant difference between the decontaminated and CCA-treated and decontaminated and non-CCA-treated for almost all wood content levels, except for a 0.3 WC/B. No statistically significant differences

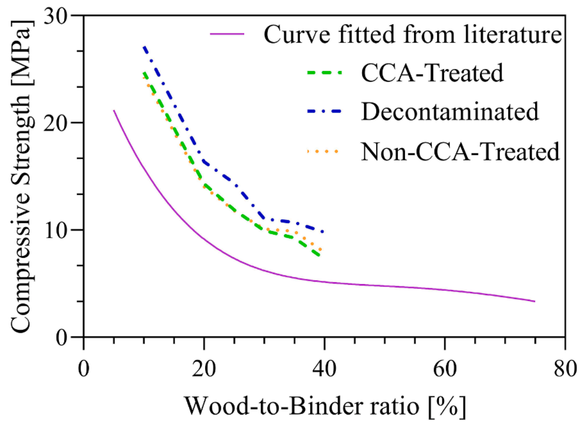


Fig. 15. Comparison with available results.

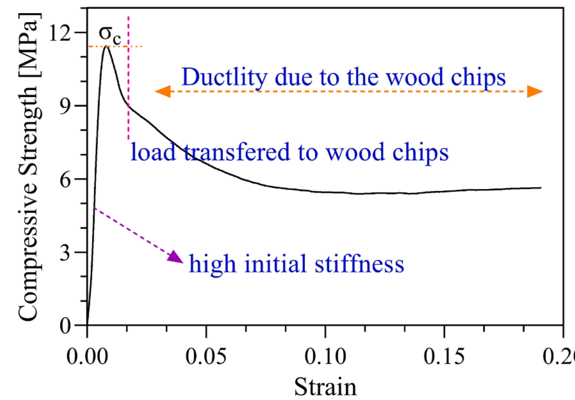


Fig. 16. Typical Stress-Strain diagram.

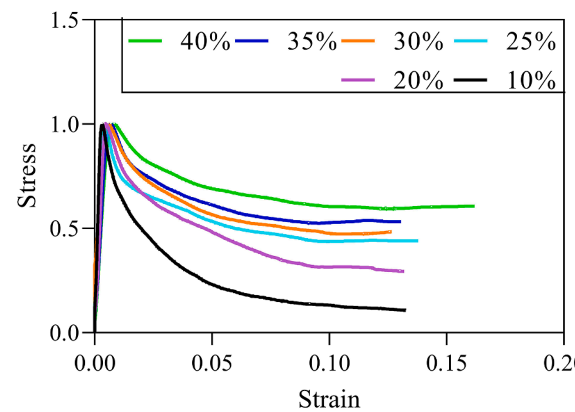


Fig. 17. Normalized Stress-Strain diagram.

were observed between CCA and non-CCA-treated wood chips.

The higher strength of WGC with decontaminated wood chips can be attributed to their higher density. The decontamination process altered the thickness of the wood chips, causing them to become loose and expand in volume [24]. As a result, they absorbed more geopolymer paste, creating a higher density and a stronger bond with the matrix system, which improved the compressive strength. Fig. 13 shows, a relatively larger volume of wood chip pores of the decontaminated sample is filled with the geopolymer paste, in contrast to the CCA-treated wood chips. Additionally, the decontamination process altered the surface texture of the wood chips, making them rougher and more fibrous. This increase in roughness improved the bond between the decontaminated wood chips and the geopolymer matrix, further contributing to the increase in strength.

The density of WGC plays a crucial role in determining the strength of the composite. To better understand the effect of decontamination on compressive strength, the impact of density was removed by calculating the specific compressive strength by dividing the compressive strength by the corresponding density. Fig. 14 illustrates the specific compressive strength obtained. The results indicate that the specific strength of WGC made with decontaminated wood chips was higher for all percentages of wood. There was no statistically significant difference between the specific strength of the WGC made with CCA and non-CCA-treated wood chips. This suggests that the difference in strength between the samples with decontaminated wood chips and those with CCA-treated and non-CCA-treated wood chips cannot be attributed solely to the difference in density and highlights the role the change in surface texture played in enhancing the strength of WGC.

Comparison of compressive strength with available results.

One of the goals of this study was to produce WGC with mechanical properties suitable for building applications such as cinder blocks. To assess the performance of the WGC in this context, it was necessary to compare its results to those reported in the literature for similar materials produced using Portland cement. Although direct comparison was not possible due to the differences in binders, wood species, wood treatment methods, water-cement ratios, mixing, curing, and testing methods used in different studies, a general assessment of the performance of ambiently cured WGC could be made by comparing its results to the results from the available literature. Accordingly, the compressive strength data from different studies [13,16,36,38,45–50] were collected and plotted based on varying WC/B ratios, and the results displayed significant variability or scatter. A curve was fitted to the collected data to provide a generalised comparison, as shown in Fig. 15. This comparison revealed that the ambiently cured WGC generally exhibited a reasonable compressive strength, indicating its potential use for building materials.

4.3. Stress–strain diagram

The stress–strain diagram in Fig. 16 illustrates the typical behavior of WGC in compression. It showcases the various stages of stress progression from start to failure. The stress–strain diagram can generally be divided into four segments. The first is the linear elastic region, where the stress–strain diagram demonstrates an initial linear elastic behavior until about 70 to 80% of the peak load, which represents the strength of the binder matrix. Then, the graph displays non-linear behavior up to the peak load. This nonlinearity is mainly due to the development of internal microcracks, as no visible cracks were observed at peak loads. The third segment is the initial stage of the descending branch, which drops rapidly. The ascending branch's initial high slope (stiffness) and the descending branch's rapid drop are typical of geopolymer concretes [51]. However, the rapid drop of the descending branch is reduced by the presence of the wood in the composite. This slowed down the rapid decrease in stiffness and even imparted ductility to the composite. This highlights the beneficial effect of wood chips in enhancing the ductility of the composite.

Fig. 17 presents the normalized stress–strain diagrams for selected samples with different wood percentage. In this figure, the stress–strain diagram is normalized by the peak load to highlight the effect of the wood chips. This is necessary due to the significant variation in strength, as shown in the previous section, of the composite with different wood contents. Comparing the stress–strain diagram with the WC/B of 10% and 40%, Fig. 17 shows the more pronounced effect of higher wood content on the ductility of WGC. This demonstrated the higher energy-absorbing capacity that the higher wood content imparted, highlighting the synergistic combination of wood and geopolymer. The geopolymer provides strength, durability, and protection from fire,

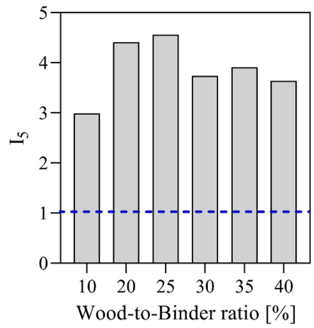


Fig. 18. Toughness as a function of wood content.

while the wood results in lightweight, better thermal insulation, and toughness. This makes the two materials highly complementary and ideal as sustainable construction materials.Fig. 18.Fig. 19..

4.4. Density

The strength of wood-based composites is significantly affected by density [38]. The density of the WGC with different WC/B ratios and different types of wood chips is shown in Table 4. The densities of the WGC with different WC/B ratios and wood chip types range from 1,069–1,466 kg/m^3, 1,099–1,499 kg/m^3, and 1,052–1,464 kg/m^3 for CCA-treated, decontaminated, and non-CCA-treated mixtures, respectively. These densities are comparable to those reported for other wood-based composites [22,23]. The densities of lightweight concrete, as stated by RILEM [52] typically fall between 300 kg/m^3 to 1800 kg/m^3, and WGC falls within this range.

The density of the WGC is positively correlated with its compressive strength and generally decreases with an increase in wood content. The lowest density was observed in the mix with 40% wood chips for all types of wood chips. The reduction in density as the wood content increases is attributed to the wood chips' multiscale porosity and their relative lightweight, see Fig. 6. This could also be seen in Fig. 7, where the porosity of the composite increased with wood content.

The compressive strength of the WGC as a function of dry density is given in Fig. 20. A curve with ± 5% confidence level is also fitted. This figure clearly shows the strong correlation between the compressive strength and density of the WGC, which aligns with the observations made by other researchers [38]. According to Bejo et al [53], the positive correlation between density and mechanical properties is due to enhanced wood densification, elimination of gaps, and improved connection between matrix and fiber.

5. Conclusion

An experimental program was carried out to investigate the effect of wood decontamination and wood content on the mechanical property of WGC. The main findings of the study are summarized as follows:

1. The study provided an encouraging result in producing ambiently cured WGC, a novel and sustainable construction material, without needing a hydraulic press.
2. The WGC with the decontaminated wood chips showed higher mechanical properties than both the samples with CCA-treated and non-CCA-treated wood chips.
3. The compressive strength and MOE decreased as the wood content increased, while the MOR increased with the wood content peaking at WC/B ratio of 0.25.
4. Encouraging results were obtained enabling the use of decontaminated wood chips for building application. The WGC with WC/B ratio of 0.1 to 0.25 meets the minimum requirement for making load bearing cinderblocks, while all the samples satisfy the minimum requirement for non-load bearing cinder blocks.
5. The toughness of the WGC increased with the wood content.
6. The compressive strength of the WGC generally showed a higher value when compared to similar purpose wood-Portland cement composites.

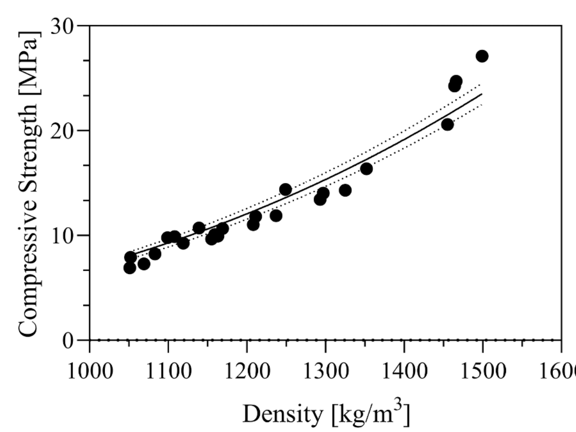


Fig. 20. Compressive strength as a function of density.

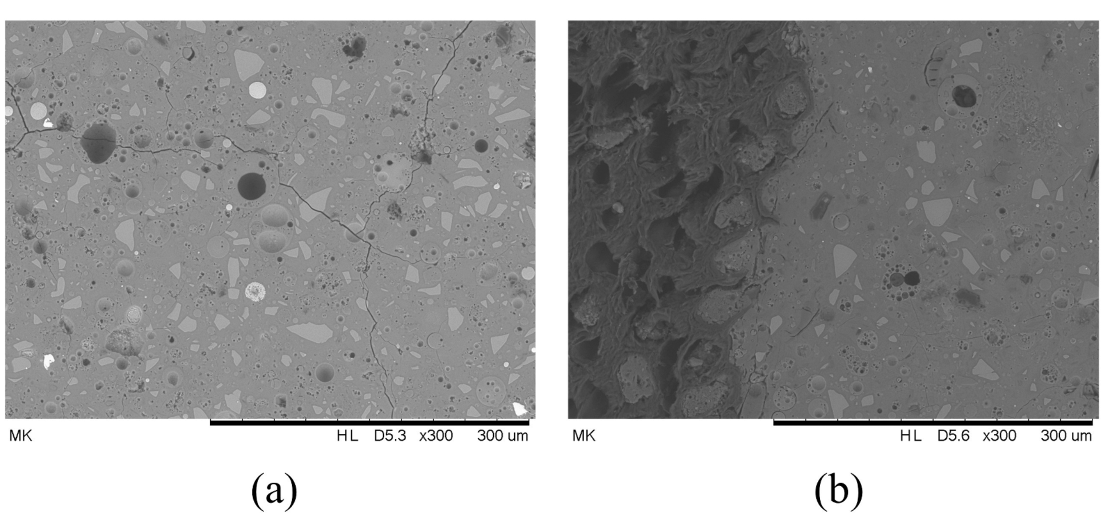


Fig. 19. Scanning electron microscopy (SEM) of micro cracks in WGC matrix on sample: (a) with no wood; (b) with wood.

7. Most importantly, this study has demonstrated the potential of using decontaminated wood chips in the production of WGC for building applications.
8. The results also show that decontaminated wood chips significantly improve the compressive, flexural, and specific strength of the composites, as well as its ductility, compared to CCA-treated and non-CCA-treated wood chips.
9. The comparison of the WGC with the literature on similar materials highlights its potential use as a building material.

CRediT authorship contribution statement

Firesenay Zerabruk Gigar (PhD Student): Investigation, Data curation, Formal analysis, Original draft. **Amar Khennane:** Conceptualisation, Methodology, Supervision, Writing, Project administration. **Jong-Leng Liow:** Conceptualisation, Methodology, Supervision, review and editing. **Biruk Hailu Tekle:** Supervision, validation. **Elmira Katoozi:** Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] C. Meyer, The greening of the concrete industry, Cem. Concr. Compos. 31 (2009) 601–605, https://doi.org/10.1016/j.cemconcomp.2008.12.010.
[2] T.O. Olawumi, D.W.M. Chan, A scientometric review of global research on sustainability and sustainable development, J. Clean. Prod. 183 (2018) 231–250, https://doi.org/10.1016/j.jclepro.2018.02.162.
[3] United Nations Environment Programme, 2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector, Nairobi, 2020.
[4] M. Wasim, T.D. Ngo, D. Law, A state-of-the-art review on the durability of geopolymer concrete for sustainable structures and infrastructure, Constr. Build. Mater. 291 (2021), 123381, https://doi.org/10.1016/j.conbuildmat.2021.123381.
[5] M. Wasim, R. Roychand, R.T. Barnes, J. Talevski, D. Law, J. Li, M. Saberian, Performance of Reinforced Foam and Geopolymer Concretes against Prolonged Exposures to Chloride in a Normal Environment, Materials 16 (1) (2023) 149, https://doi.org/10.3390/ma16010149.
[6] F. Berger, F. Gauvin, H.J.H. Brouwers, The recycling potential of wood waste into wood-wool/cement composite, Constr. Build. Mater. 260 (2020), 119786, https://doi.org/10.1016/j.conbuildmat.2020.119786.
[7] A. Ashori, T. Tabarsa, F. Amosi, Evaluation of using waste timber railway sleepers in wood–cement composite materials, Constr. Build. Mater. 27 (2012) 126–129, https://doi.org/10.1016/j.conbuildmat.2011.08.016.
[8] S.R. Karade, Cement-bonded composites from lignocellulosic wastes, Constr. Build. Mater. 24 (2010) 1323–1330, https://doi.org/10.1016/j.conbuildmat.2010.02.003.
[9] S. Amziane, M. Sonebi, Overview on Biobased Building Material made with plant aggregate, RILEM Tech. Lett. 1 (2016) 31–38, https://doi.org/10.21809/rilemtechlett.2016.9.
[10] L.T.T. Vo, P. Navard, Treatments of plant biomass for cementitious building materials – A review, Constr. Build. Mater. 121 (2016) 161–176, https://doi.org/10.1016/j.conbuildmat.2016.05.125.
[11] R.W. Wolfe, A. Gjinolli, Cement-bonded wood composites as an engineering material, in: The Use of Recycled Wood and Paper in Building Applications, 1996, pp. 84–91.
[12] W. Ahmed, R.A. Khushnood, S.A. Memon, S. Ahmad, W.L. Baloch, M. Usman, Effective use of sawdust for the production of eco-friendly and thermal-energy efficient normal weight and lightweight concretes with tailored fracture properties, J. Clean. Prod. 184 (2018) 1016–1027, https://doi.org/10.1016/j.jclepro.2018.03.009.
[13] M. Li, M. Khelifa, M. El Ganaoui, Mechanical characterization of concrete containing wood shavings as aggregates, Int. J. Sust. Built Env. 6 (2017) 587–596, https://doi.org/10.1016/j.ijsbe.2017.12.005.
[14] P. Coatanlem, R. Jauberthie, F. Rendell, Lightweight wood chipping concrete durability, Constr. Build. Mater. 20 (2006) 776–781, https://doi.org/10.1016/j.conbuildmat.2005.01.057.
[15] M. Li, M. Khelifa, A. Khennane, M. El Ganaoui, Structural response of cement-bonded wood composite panels as permanent formwork, Comp. Struct. 209 (2019) 13–22, https://doi.org/10.1016/j.compstruct.2018.10.079.
[16] M.Y.R. da Gloria, V.M. Andreola, D.O.J. dos Santos, M. Pepe, R.D. Toledo Filho, A comprehensive approach for designing workable bio-based cementitious composites, Journal of Building Engineering 34 (2021) 101696, https://doi.org/10.1016/j.jobe.2020.101696.
[17] N. Lansbury, S. Beder, Treated Timber, Ticking Time-bomb: The Need for a Precautionary Approach to the Use of Copper Chrome Arsenate (CCA) as a Timber Preservative, Faculty of Arts - Papers (Archive). (2005). https://ro.uow.edu.au/artspapers/41.
[18] M. Abbas, J. Vajna, R. Ellcock, Chromated copper arsenate timber: A review of products, leachate studies and recycling, J. Clean. Prod. 179 (2018) 292–307, https://doi.org/10.1016/j.jclepro.2018.01.111.
[19] D.G. Humphrey, The chemistry of chromated copper arsenate wood preservatives, Rev. in Inorg. Chem. 22 (2002) 1–40, https://doi.org/10.1515/REVIC.2002.22.1.1.
[20] J.L. Liow, A. Khennane, M. Muley, H. Sorial, E. Katoozi, Recycling of Chrome-Copper-Arsenic Timber Through Cement Particleboard Manufacture. in Role of Circular Economy in Resource Sustainability, Springer, Cham. (2022) 111–122. https://doi.org/10.1007/978-3-030-90217-9_10.
[21] Schmidt R, Marsh R, Balatinecz J J, Cooper P A, Increased wood-cement compatibility of chromate-treated wood, Forest Prod. J.; Madison Vol. 44, Iss. 7,8, . (1994).
[22] Chen Huang, Paul A. cooper, Cement-Bonded Particleboards Using CCA-Treated Wood Removed From Service, Forest Prod. J. 50 (2000) 49–56.
[23] Y. Zhou, D.P. Kamdem, Effect of cement/wood ratio on the properties of cement-bonded particleboard using CCA-treated wood removed from service. (Composites and Manufactured Products), Forest, Prod J. 52 (2002) 77–82.
[24] Elmira Katoozi, A green approach for decontamination and kinetics study of chromate copper arsenate (CCA)-treated timbers for potential re-use, Ph.D. Thesis (Submitted), Univesity of New South Wales , 2023.
[25] AS 1604.1, Specification for Preservative Treatment–Part 1: Sawn and Round Timber, Published by. Standards Australia. GPO Box 476. (2012).
[26] ASTM C128, Standard Test Method for Relative Density (Specific Gravity), and Absorption of Fine Aggregate, The American Society for Testing and Materials. (2015).
[27] ASTM C566, Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying, The American Society for Testing and Materials. (1997).
[28] B.H. Tekle, K. Holschemacher, Alkali activated cement mixture at ambient curing: Strength, workability, and setting time, Struct. Conc. 23 (2022) 2496–2509, https://doi.org/10.1002/suco.202100274.
[29] A.A. Moslemi, S.C. Pfister, The Influence of Cement/Wood Ratio and Cement Type on Bending Strength and Dimensional Stability of Wood-Cement Composite Panels, Wood Fiber Sci. (1987) 165–175. https://wfs.swst.org/index.php/wfs/article/view/592.
[30] EN 323, Wood-based panels - Determination of density - European Standards, (1993).
[31] P. Tittelein, A. Cloutier, B. Bissonnette, Design of a low-density wood–cement particleboard for interior wall finish, Cem. Concr. Compos. 34 (2012) 218–222, https://doi.org/10.1016/j.cemconcomp.2011.09.020.
[32] ASTM D3501, Standard Test Methods for Wood-Based Structural Panels in Compression, The American Society for Testing and Materials. (1994).
[33] ASTM D1037, Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials, The American Society for Testing and Materials. (2012).
[34] ASTM D3043, Standard Methods of Testing Structural Panels in Flexure, The American Society for Testing and Materials. (2000).
[35] ASTM. C1018, Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading), The American Society for Testing and Materials. (1997).
[36] M.Y.R. da Gloria, Romildo Filho, Influence of the wood shavings / cement ratio on the thermo- mechanical properties of lightweight wood shavings-cement based composites, 6th Amazon and Pacific Green Materials Congress and Sustainable Construction Materials LAT-RILEM Conference. (2016) 365–374.
[37] S. Sarmin, N. Salim, N.A. Mohammad, Effects of different wood aggregates on the compressive strength of fly ash and metakaolin-based geopolymer lightweight composites, Songklanakarin J. of Sc. and Tech. 41 (2019) 734–741. https://www.thaiscience.info/Journals/Article/SONG/10993127.pdf.
[38] K. Al Rim, A. Ledhem, O. Douzane, R.M. Dheilly, M. Queneudec, Influence of the proportion of wood on the thermal and mechanical performances of clay-cement-wood composites, Cem. Concr. Compos. 21 (1999) 269–276, https://doi.org/10.1016/S0958-9465(99)00008-6.
[39] R. Chen, S. Ahmari, L. Zhang, Utilization of sweet sorghum fiber to reinforce fly ash-based geopolymer, J. Mater. Sci. 49 (2014) 2548–2558, https://doi.org/10.1007/S10853-013-7950-0/figures/13.
[40] ASTM C90, Standard specification for loadbearing concrete masonry units, The American Society for Testing and Materials. (1999).
[41] IS 2185-1, Concrete Masonry Units, Part I: Hollow and Solid Concrete Units, Bureau of India Standard. (2005).
[42] BS EN-1-1: Eurocode 6, Design of masonry structures—General rules for reinforced and unreinforced masonry structures, British Standard Institution. (2005).
[43] A.WC. Lee, Effect of cement/wood ratio on bending properties of cement-bonded southern pine excelsior board, Wood and Fiber Science. (1985) 361–364.
[44] International Federation for Structural Concrete (fib), The Fib model code for concrete structures 2010, (2013).

[45] S.N. Sarmin, J. Welling, Lightweight geopolymer wood composite synthesized from alkali-activated fly ash and metakaolin, J Teknol. 78 (2016) 49–55, https://doi.org/10.11113/.v78.8734.

[46] F.F. Udoeyo, H. Inyang, D.T. Young, E.E. Oparadu, Potential of Wood Waste Ash as an Additive in Concrete, J. Mater. Civ. Eng. 18 (4) (2006) 605–611, https://doi.org/10.1061/(ASCE)0899-1561(2006)18:4(605).

[47] B. Asante, H. Ye, M. Nopens, G. Schmidt, A. Krause, Influence of wood moisture content on the hardened state properties of geopolymer wood composites, Compos. A Appl. Sci. Manuf. 152 (2022), 106680, https://doi.org/10.1016/j.compositesa.2021.106680.

[48] O. Sotannde, A. Oluwadare, P. Adeogun, Evaluation of cement-bonded particle board produced from Afzelia Africana wood residues, J. of Engrg. Sc. and Tech. 7 (2012) 732–743.

[49] A. Kumar Parashar, R. Parashar, Comparative Study of Compressive Strength of Bricks Made With Various Materials to Clay Bricks, Int. J. Sci. Res. Publ. 2 (2012). www.ijsrp.org.

[50] M.R. Ahmad, B. Chen, Influence of type of binder and size of plant aggregate on the hygrothermal properties of bio-concrete, Constr. Build. Mater. 251 (2020), 118981, https://doi.org/10.1016/j.conbuildmat.2020.118981.

[51] C.-K. Ma, A.Z. Awang, W. Omar, Structural and material performance of geopolymer concrete: A review, Constr. Build. Mater. 186 (2018) 90–102, https://doi.org/10.1016/j.conbuildmat.2018.07.111.

[52] RILEM, Functional classification of lightweight concrete, Mater. Struct. 11 (1978) 281–282.

[53] L. Bejó, Takáts P, Norbert V, Development of Cement Bonded Composite Beams, Acta Silvatica et Lignaria Hungarica. 1 (2005) 111–119.