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Recycling sawmilling wood chips, biomass combustion residues, and tyre fibres into cement-bonded composites: Properties of composites and life cycle analysis

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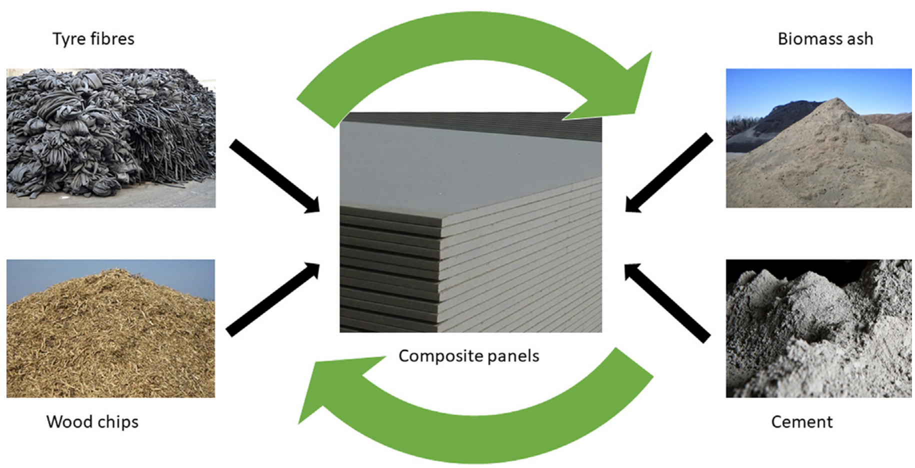
HIGHLIGHTS

- Waste tyre fluff containing rubber crumbs can be used to reinforce cement composites.
- Biomass combustion residues can be added up to 30% as replacement material for cement.
- As aggregate content increased, the strength properties increased in wood composites.
- High aggregate content negatively affected the strength of tyre based composites.
- Thermal conductivity was reduced by about 80% when wood residues was used in cement.

GRAPHICAL ABSTRACT



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ABSTRACT

This study investigated the properties and sustainability of cement-bonded composites containing industrial residues such as wood chips, tyre fibres and biomass combustion residues, i.e. bottom ash (BA) and fly ash (FA). The effect of cement-to-raw material (wood/tyre fibre) ratio (C/RM) and the aggregate content (BA and FA) on thermal and mechanical properties of the composites were investigated. Scanning electron microscopy (SEM) and life cycle analysis (LCA) were also conducted. The results revealed that as the aggregate content increased in wood composites, the mechanical properties also increased. The mean thermal conductivity and volumetric heat capacity of tyre composite samples were 0.37 W/mK and 1.2 MJ/m^{3}K respectively, while the respective values for wood composite samples were 0.29 W/mK and 0.81 MJ/m^{3}K. SEM analysis showed adequate bonding between wood/tyre fibres and cement matrix. LCA revealed that the materials share of the total primary energy use was about 60% for all analysed composites.

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1. Introduction

Industrial waste generation is closely associated with economic growth in metropolitan cities [1]. To meet the sustainable development objectives, there has been an increased interest in recycling waste materials into different value-added consumer products [2]. Valorization of waste materials in cement composites presents an economic, technically feasible and ecological approach to waste management and promoting a cleaner environment. Wood residues from sawmilling and tyre fibres from tyre recycling companies represent materials of increasing relevance, especially in product development. Although wood residues have found continued interest in bioenergy generation, the utilization of these materials in cement and concrete could help reduce the carbon footprint and emissions from conventional industrial processes [3]. Depending on the quality, wood residues may be recycled into panel and paper products, burnt for bioenergy or landfilled [4]. In the European Union (EU), approximately 60 million tons of wood waste were generated in 2014 [5]. In Sweden, sawmills generated about 20.6 million cubic metres of sawdust, wood chips and other residues in 2018 [6]. Wood panel production in Sweden is currently low compared to other EU countries due to growing competition with the bioenergy sector [7]. Despite an advanced bioenergy strategy, there is still a possibility to channel low quality wood residues into composite products. Globally, more than 1.5 billion units of tyres are produced annually, and approximately the same number reach the end of life [8]. Waste tyres are not readily recyclable due to the complexity of their chain structure and are often shredded and landfilled. In the EU, about 3.5 million tons of scrap tyres reach the end of service life annually, thus requiring a huge landfill space [9]. Landfilling waste tyres has been associated with pest breeding and leaching of heavy metals into the environment [8,10]. Consequently, the EU prioritized the reuse and recycling of rubber and ban tyre landfilling [8]. Although, recycled rubber from scrap tyres can be reused to an extent, other components, e.g. tyre fluff, are not recyclable. [11]. This material accounts for about 9–16% of the output of tyre recycling and is mainly used for co-incineration in cement kilns or landfilled [12]. In the EU, it is estimated that about 250,000 tons of tyre fluff are generated annually, which could be beneficial in other areas of application [2].

Wood and tyre recycling residues offer opportunities for a sustainable utilization in construction and building materials. The prospect for wood combined with tyre rubber particles has been studied on different composite materials, including oriented strand board (OSB) [13–15]. Wood residues can be effectively used with cement as a thermal insulation material for building envelope, and offer improved environmental profile when compared to conventional inorganic insulating materials [16]. Wood-cement composites have high durability, good mechanical properties and dimensional stability [17–19]. Similarly, tyre fibres have good insulation properties and have been used to reinforce cement and concrete with a positive influence on freeze–thaw resistance, fire-induced spalling, shrinkage behaviour and mechanical properties [20–23]. Although tyre fibres are usually contaminated with crumb rubber, uncleaned fibres did not negatively affect mechanical properties of concrete, but enhanced early age behaviour [2]. There are several studies on the effect of crumb rubber as aggregates in rubberized concrete [24–29]. However, very limited literature is available on the performance of tyre fluff in cement composite panels. Specifically, this study was aimed at incorporating a higher proportion of wood chips and tyre fluff in developing thermal insulating panels. The addition of wood and tyre to cement reduces mass density and increases ductility in the composite material [30]. This quality is important in insulating building elements that do not require elevated strength but ability to withstand deformation and reduce vibrations. In contrast to resin-bonded composites that compromise indoor air quality, cement-bonded composites present an environment-friendly alternative as they do not contain formaldehyde [1]. Although cement production is a major cause of greenhouse gases emission [31], the partial replacement of the cement base with industrial side streams such as combustion ash could reduce direct emissions since the contribution of the ash component is zero [32]. Although the incorporation of ash in cement could offer some environmental benefits [33–35], the processing and combustion of raw materials to generate ash could increase greenhouse gases emissions [7].

Bottom ash (BA) and fly ash (FA) are residues generated from the combustion of biomass, solid waste or coal in heating and power plants. With the increasing interest in bioenergy and the associated expansion of biomass plants, it is estimated that about 10 million tons of biomass ash are generated globally [36]. Depending on their source, these residues are usually landfilled, land spread or disposed in surface impoundment units. In Europe, leaching of potential toxic elements and heavy metals in aquifers has been a major consideration regarding current disposal options. As a result, there has been increased interest in low-impact areas of utilization of these residues. Cement and concrete composites offer a wide application for combustion ash but there is still a growing concern for this material due to their environmental profile [37–39]. Although several studies have been conducted on the prospects for coal, solid waste and biomass ash on concrete composites [40–46], very few studies have focussed on biomass ash as a replacement option for cement in wood and tyre-based panels. The rationale for using biomass ash as aggregates in this study were threefold; First was to investigate the environmental impact associated with these residues in blended cement. Second was to evaluate the effect of the residues on the durability of the composite product. The third was to promote a circular economy by incorporating industrial residues into construction products. It is therefore imperative to define the guidelines for accepting these residues as a replacement material for cement in sustainable construction. Whilst BA is less desirable due to its porous structure [47], the spherical particles of FA makes it an ideal substitute for cement in composite admixture [48,49]. The replacement of cement with combustion ash not only offers environmental benefits, but also improves composite's properties and reduces heat of hydration as well as product cost [50]. Biomass combustion ash plays a significant role on the strength and durability of cement composites. However, high concentration of ash can weaken neutralization capability in composites and reduce strength properties [40,50]. This effect can be controlled by the addition of pozzolanic materials, which improves the reaction of high volume fly ash–cement blend and also increases early-age compressive strength [51].

This study investigated the effect of wood residues and tyre fibres on the properties of cement composites, partially filled with biomass BA and FA. The proposed composite products could be used for building more economical and comfortable interior wall panels at low environmental cost. The study also aimed at evaluating the environmental impact over the life cycle of the products. This study would be thus useful for improving the sustainability of cement composites by substituting virgin materials with recycled materials, while maintaining or improving the composites' properties.

2. Materials and composite production

The composite production process is illustrated in Fig. 1. Wood residues (density, 144.67 kg/m^3) in the form of chips were collected from a sawmill in Southern Sweden (JG Anderssons Söner

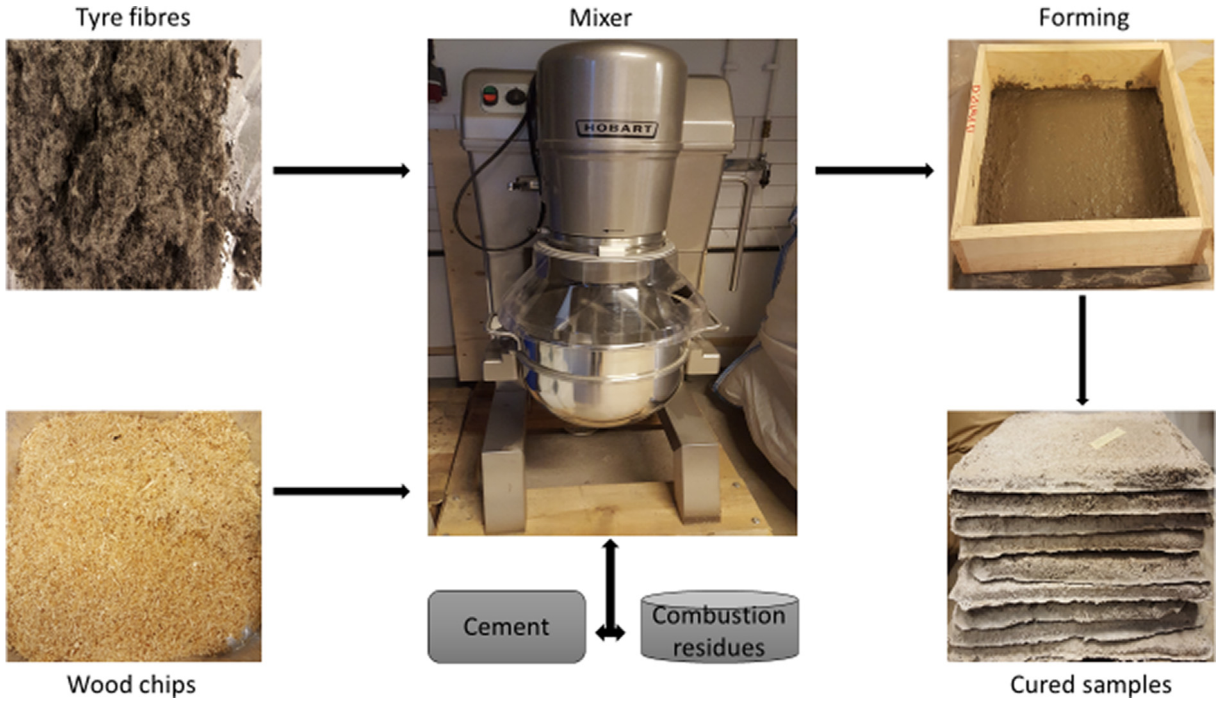

Fig. 1. Composite production process.

AB, Linneryd, Sweden). The residues were air-dried to a moisture content of 12% and thereafter screened to obtain 3–7 mm fractions. Tyre fibres (density, 126.48 kg/m^3) were obtained as fluff residues of tyre recycling from Ragn-Sells Heljestorp AB, Vänersborg, Sweden and were screened to remove over-sized crumb rubber particles. The uncleaned fibres (7–13 mm long) were collected for use. ASTM type II Ordinary Portland Cement (CEM II/A-LL, 42.5 R) was used as binding material in the study. Biomass combustion residues including fly ash (FA) and bottom ash (BA) were sourced from the power plant Växjö Energi AB, Växjö, Sweden and were added in partial replacement of the cement content. The wood chips and tyre fibres were used as reinforcement materials, whilst the ashes were used as aggregates in the cement. The CEM II, aggregates, and wood residues or tyre fibres were homogenously mixed with pre-determined amount of water for about 5 min in a mechanical mixer (Hobart HSM 30-F3E, Peterborough, UK). The composites were formed in a wooden mould (350 × 270 × 50 mm^3), and thereafter compressed to 12 mm thickness at 3 MPa for 10 min. The composites were subjected to 28 days air curing at 20 ± 2 °C and 60 ± 5% relative humidity (RH) before further testing. The cement-to-raw material (wood/tyre fibre) ratio (C/RM ratios at 3:1, 4:1 and 5:1, w/w), aggregate content (10, 20 and 30% of cement) and water-to-cement ratio (W/C ratios at 0.55, 0.6 and 0.65, w/w) were evaluated in terms of flexural and thermal properties. The different composite samples were marked from A-L based on the mixture formulations in Table 1. Within each C/RM ratio, the cement content was replaced by 10, 20 and 30% of aggregates, respectively. A control sample without aggregates was also produced for each C/RM ratio.

Table 1
Mixture formulations for composite boards.

Composite samples	C/RM	Aggregate content (%)	W/C
A	5:1	0	0.65
B		10	
C		20	
D		30	
E	4:1	0	0.6
F		10	
G		20	
H		30	
I	3:1	0	0.55
J		10	
K		20	
L		30	

C/RM: cement-to-raw material ratio; W/C: water-to-cement ratio

3. Measurement methods

3.1. Material characterization

The cement and biomass combustion residues were analyzed to determine their particle size distribution. High resolution images were captured using a scanner (Epson Perfection V850 Pro, Epson, Tokyo, Japan). The images were then analyzed using FibreShape PRO (X-shape, IST, Vilters, Switzerland). Bulk density of the materials was measured gravimetrically whilst elemental composition was analyzed using X-ray florescence (XRF) spectrometer (Malvern Panalytical, Malvern, UK).

3.2. Density and flexural test

The density of the composites was measured using samples 50 × 50 × 12 mm^3 on the basis of their weight and volume at laboratory conditions. Flexural properties were measured using 300 × 75 × 12 mm^3 samples according to ASTM D1037 [52] with an MTS Exceed Test System (MTS Systems Norden AB, Askim, Sweden) fitted with a 10 kN load cell at cross head speed of 6 mm/min. Modulus of rupture (MOR) and apparent modulus of elasticity (MOE) were derived at maximum load. The measurements were performed in triplicates and the mean values were plotted with their standard deviations.

3.3. Thermal properties

Samples with higher strength properties were selected for thermal analysis. Six samples with different aggregate content (B-D, F-H) were selected for each material (wood chips or tyre fibres), representing W1-W6 for wood-based composites and T1-T6 for tyre-based composites. The test was conducted based on the assumption that the composite samples are isotropic and homogenous. The geometry of the samples was 50 × 50 × 12 mm^3. The samples were conditioned in a climate room at 20 °C and 50% RH. The thermal properties of the samples, i.e. thermal conductivity, thermal diffusivity and heat capacity were determined using the transient plane source (TPS) method according to ISO 22007–2 [53]. The method involves clamping the TPS sensor between two surfaces of the samples to be tested (Fig. 2). The TPS sensor is a very thin double-metal spiral (10 mm thickness) sandwiched between two layers of Kapton (25 mm thickness). The samples were matched to make couples, i.e. W1 and W2, T1 and T2, with each sample having two surfaces (S1 and S2). Measurements were performed for a combination of surfaces in the same sample couple, e.g. W1W2S1S1, W1W2S2S2, etc.

3.4. Scanning electron microscopy

The fracture surfaces of the samples after the flexural tests, were characterized by scanning electron microscopy (SEM) (FEI Quanta FEG 250, Eindhoven, Netherlands). SEM was carried out to study the interfacial interaction and mode of fibre failure in the cement composite material. The SEM characterization was performed at an accelerating voltage of 10 kV and a working distance of 10 mm in a low vacuum mode (LV-SEM) of 7 kPa. Samples were collected using forceps at the fracture surface and no precoating was applied. Three samples were selected for each material category (wood chips and tyre fibres), comprising bottom ash, fly ash and a control sample, making a total of six samples for SEM.

3.5. Data analysis

The experiment was arranged in a completely randomized design (CRD) using SPSS Statistics V26 (IBM Corp., NY, USA). A two-way analysis of variance (ANOVA) procedure was conducted to analyze the effect of the C/RM ratios and aggregate contents on the density and flexural properties of the composites at 95% confidence interval. Duncan's multiple range test (DMRT) was used in the separation of means at 5% level of significance.

4. Life cycle assessment

The life cycle assessment (LCA) study was performed as a screening LCA and was structured according to ISO 14044 [54], which includes planning, inventory, environmental weighting assessment and interpretation. The environmental impact and energy requirement of the developed product was compared with that of a commercial fibre cement board using environmental product declaration (EPD) data [55].

4.1. System boundaries

The system boundary draws the lines between the environment and the technical system [56]. When comparing the environmental impact of different composites, the system boundaries are the same, which is a prerequisite for a robust comparison. The calculations were performed specifically for composite types where production was assumed to be local. Transports and materials were based on the most likely alternatives for achieving a sustainable production of the composites. The functional unit (FU) in this study was estimated as 1 m^2 composite, which is used for wall cladding similar to single layer conventional non-structural board. The choice of the FU was due to the size of the produced composite and that its industrial-scale properties are unknown. The impact assessment was carried out for impact categories as seen in Table 2.

It was assumed that the wood used comes from sustainably managed forests, where replanting takes place so that the absorption of CO_2 by the plants corresponds to later emissions of CO_2. Therefore, biogenic carbon was calculated as climate neutral, i.e. both biomass uptake and biogenic carbon emissions do not have a climate impact. Values chosen for the environmental impact are specific to the selected material and are representative of the Swedish or European market. Specific EPD data was used for cement in the study. For electricity, data from Ecoinvent 3.0 was used with Swedish electricity adjusted with trade of electricity abroad.

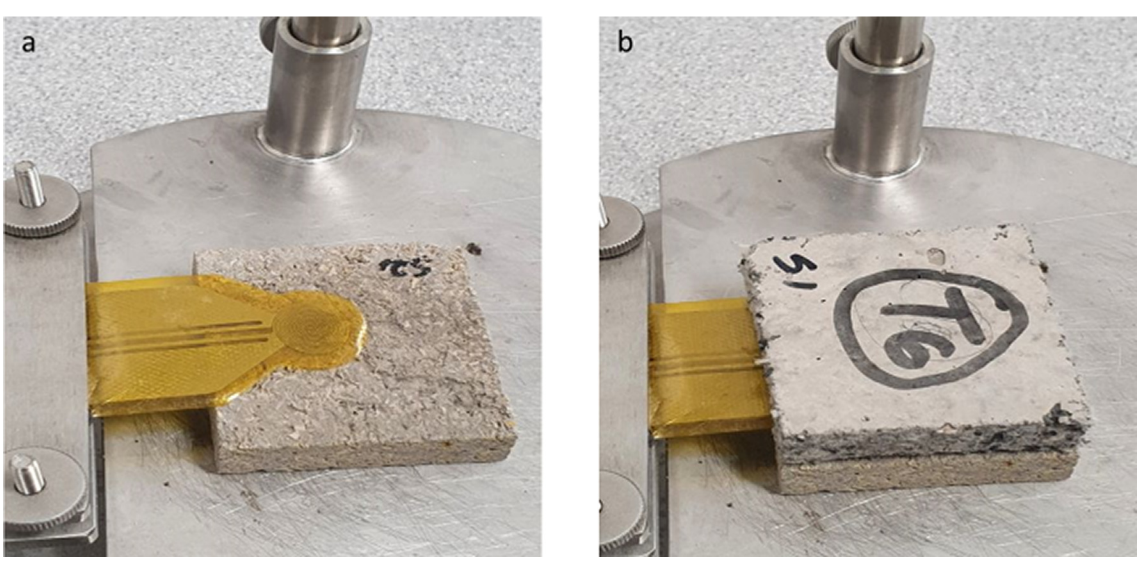

Fig. 2. Thermal properties evaluation: a) TPS sensor on sample; b) TPS sensor clamped between two samples.

Table 2
Impact categories used in the LCA.

Impact category	Unit
Climate impact, IPCC (GWP100)	kg CO_2-eq/FU
Acidification potential (AP)	kg SO_2-eq/FU
Eutrophication potential (EP)	kg PO_4^3-eq/FU
Photochemical ozone creation potential (POCP)	kg Ethene-eq/FU
Ozone depletion potential (ODP)	kg CFC11-eq/FU

GWP – global warming potential.

4.2. Inventory

LCA calculations of the composites were based on quantities of materials utilized. Specific data from producers in the form of EPD was used in the calculations. The EPDs are third-party reviewed and comply with EN 15804 [57]. Where EPDs are missing for certain materials, data was retrieved from Ecoinvent 3.0 or from the literature. Ecoinvent database possesses good transparency and reproducibility [56]. The inventory of the composites covers the entire life cycle from materials to manufacturing. The environmental information of the life cycle is divided into modules according to EN 15804 [57] (Table 3).

At raw material stage (module A1), EPD data specific to the Swedish market was used for cement. Data for wood residues was taken from a report on environmental data for sawn products [58]. Water production data was obtained from Ecoinvent 3.0. Bottom ash and fly ash are residual products from bioenergy plants and have not been assigned any environmental impact. For transport activities in modules A2 and A4, climate impact and primary energy were calculated using data from the network for transport measures (NTM) [59]. Since there is no available information about the road transports, default values for road transports in Europe were used. NTM default data were conservatively assessed to avoid low emission calculations.

Data for the manufacturing process (A3) consisted of the energy used in the production of the composites. These data have been adjusted to the composite size of 1 m2 in the FU of the study. Data for the use phase of a composite are usually related to the building's function and thus difficult to apply to the slab alone. Since the data for the use phase of the composites are not available, this phase has not been included in the analysis. When the building is demolished in module C, the material flows reach the study's system boundary and the demolition masses pass the system boundary as unallocated flows. After deconstruction in module C, several different scenarios are possible. In this study, it is assumed that the composites are sold and re-used in the existing state after deconstruction, which means that C3 and C4 do not contribute to the environmental impact. However, a short transport C2 of the composites to a warehouse has been included in the analysis, and the data was sourced from NTM. Information on data for the demolition phase C1 of the composites was not available. Therefore, this phase was not included in the analysis.

5. Results and discussion

5.1. Material characterization

Tables 4 and 5 show the chemical composition and physical properties of the cement and biomass combustion residues, respectively. According to ASTM C618, the FA used can be classified as high calcium ash since the CaO content is more than 20% [60]. CaO and SiO_2 are the main components that affect hydration and pozzolanic reactions, which are the major determinants of strength developments in cement composite materials [61]. The CaO/SiO_2 ratios in the materials were 3.45, 3.85 and 0.22 for CEM II, FA and BA, respectively. The high SiO_2 content in BA could be largely attributed to sand beds used in biomass combustion plants [62]. The FA particles were polydisperse with a mean geodesic length of 684.24 μm. The particle size distribution of FA ranged from 47.625 to 9996.209 μm, with 50% (d_{50}) of the particles larger than 277.245 μm. However, the BA particles were monodisperse with a mean geodesic length of 171.02 μm. The particle size distribution of BA ranged from 107.962 to 1129.498 μm, with 50% (d_{50}) of the particles larger than 185.303 μm. The CEM II were finer particles with a mean geodesic length of 44.45 μm. The particle size distribution ranged from 14.111 to 848.546 μm, with 50% (d_{50}) of the particles larger than 44.375 μm.

Table 3
Modules included in the LCA calculations.

Production stage			Construction process stage	End of life stage
A1	A2	A3	A4	C2
Raw material extraction	Transport to manufacturing	Manufacturing	Transport to building site	Transport of composites to warehouse

Table 4
XRF analysis of the cement and combustion residues Chemical composition (wt.%).

	CaO	MgO	SiO_2	Al_2O_3	MnO	Na_2O	K_2O	P_2O_5	SO_3	Fe_2O_3	ZnO	BaO
CEM II	64.2	1.12	18.6	5.19	0.48	0.05	1.7	0.12	5.29	2.87	0.04	0.06
FA	51.2	5.82	13.3	2.32	2.92	1.17	9.71	4.4	5.55	1.29	0.49	0.5
BA	13.7	2.89	63.4	5.2	0.86	1.1	9.05	2.42	0.78	0.94	0.26	0.24

Table 5
Bulk density and particle size distribution of the cement and combustion residues.

	Density (kg/m^3)	Feret diameter (μm)						
		d_0	d_5	d_{10}	d_{50}	d_{90}	d_{95}	d_{100}
CEM II	1250	14.111	19.394	21.036	44.375	108.627	140.379	848.546
FA	564.62	47.625	70.995	92.566	277.245	1515.507	2509.442	9996.209
BA	1021.82	107.962	130.185	138.622	185.303	263.018	326.308	1129.498

values represent the particle diameter at 0 – 100 percentiles (d_0 – d_{100}).

5.2. Density and flexural properties of composites with wood residues

The density values of the cement-bonded composites containing wood residues is presented in Fig. 3, and the flexural test results are presented in Figs. 4 and 5. The densities of composites containing BA ranged between 845 and 1152 kg/m^3 while composites containing FA had densities between 890 and 1174 kg/m^3. Although FA had a greater influence on density compared with BA, the difference was not significant (p > 0.05). The C/RM ratio had a significant effect on the density of composites containing BA and FA. As the C/RM ratio decreased, the density of the composites decreased significantly owing to differences in bulk density between cement and wood. At C/RM ratio of 5:1, the addition of FA and BA significantly increased the composites' density compared with the control. This could be due to the effect of ash micro-aggregates that fill up the cement composite pores, thereby increasing the density [63]. The result revealed that density had an influence on the flexural properties of the composites, as the MOE and MOR decreased with decreasing density. The pattern of variation in flexural properties is directly related to the aggregate con-

Fig. 3. Density of cement-bonded composites with wood residues. [Error bars represent standard deviations of three replicates. Within each C/RM ratio group, columns with the same letter (a, b, ab) are not significantly different (significance level α = 0.05)].

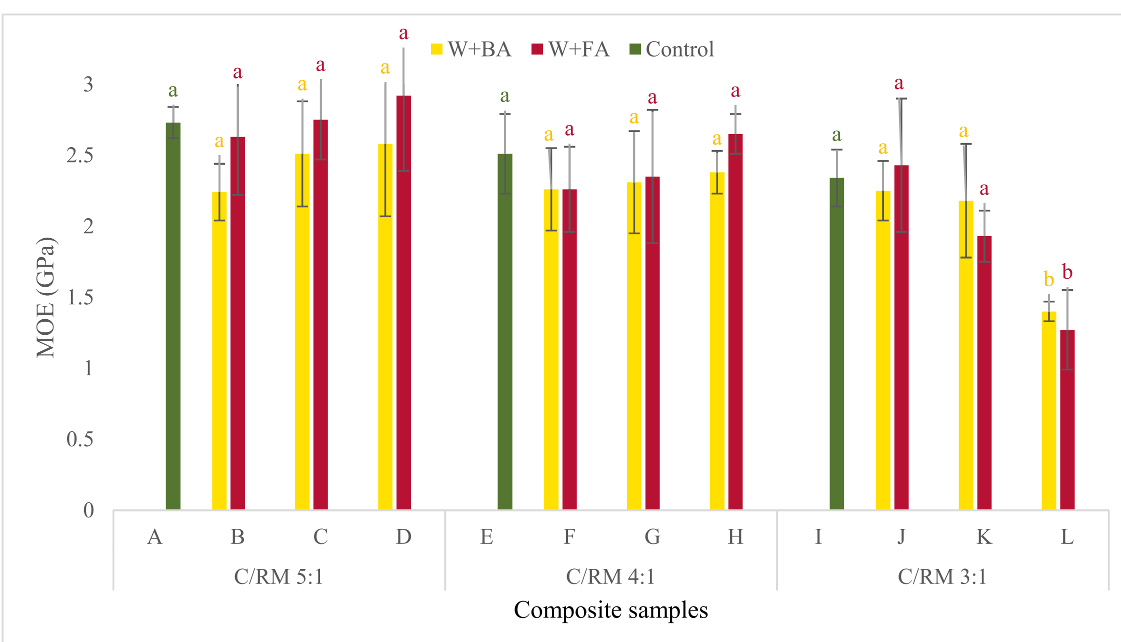

Fig. 4. MOE of cement-bonded composites with wood residues. [Error bars represent standard deviations of three replicates. Within each C/RM ratio group, columns with the same letter (a, b, ab) are not significantly different (significance level α = 0.05)].

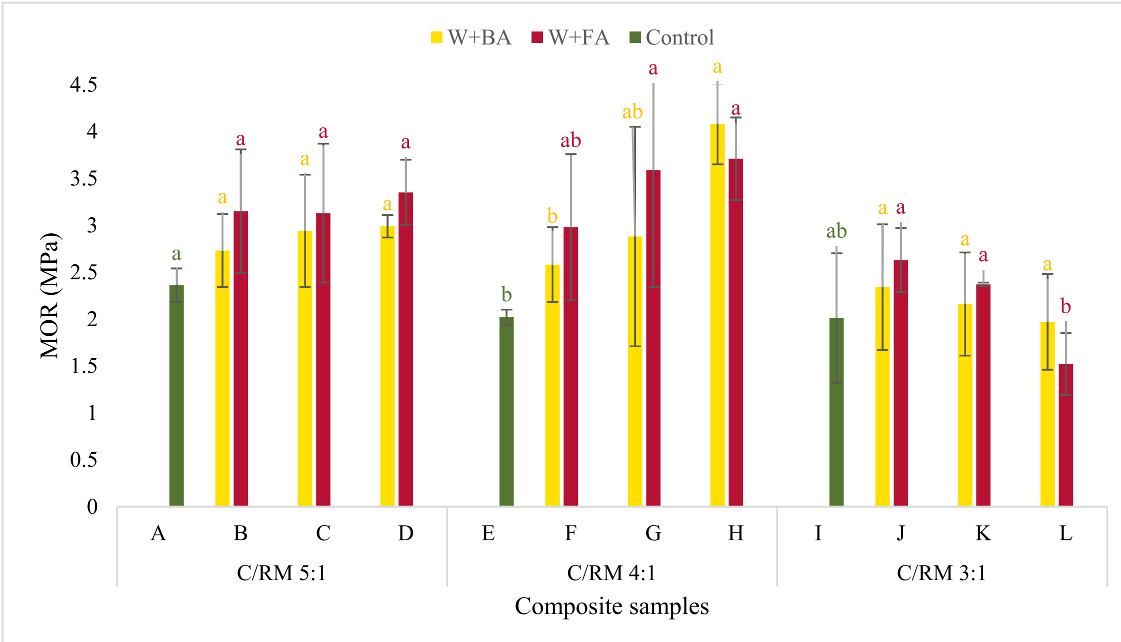

Fig. 5. MOR of cement-bonded composites with wood residues. [Error bars represent standard deviations of three replicates. Within each C/RM ratio group, columns with the same letter (a, b, ab) are not significantly different (significance level α = 0.05)].

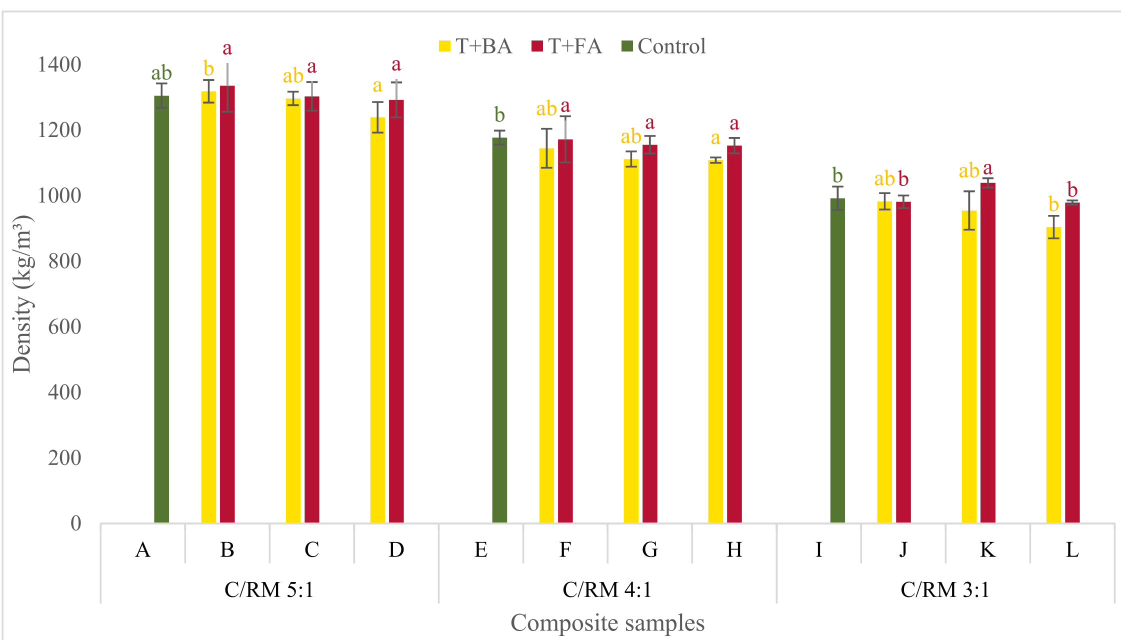

Fig. 6. Density of cement-bonded composites with tyre fibres. [Error bars represent standard deviations of three replicates. Within each C/RM ratio group, columns with the same letter (a, b, ab) are not significantly different (significance level α = 0.05)].

tent used as a substitute for cement. As the aggregate content increased for both FA and BA at high C/RM ratio, the MOE and MOR increased, but the difference was not significant ($p > 0.05$). The aggregates react with cement hydration products to form calcium silicate hydrate (C-S-H) gels, which improve the strength of the composites [63]. However, at C/RM ratio of 3:1, the flexural properties decreased significantly with increasing aggregate content. This could be due to lower amount of CaO and SiO_2 in the cement, which are needed to form strong C-S-H products. The comparatively higher amount of aggregate at low cement content resulted in the formation of weak hydration products due to unreacted CaO and SiO_2. This also results in poor interfacial bonding in composite materials [64]. Similar correlation was reported in other studies using different wood species [65,66]. The control samples showed a decrease in the flexural properties as wood content increased. This could be due to poor adhesion at the matrix-fibre interface owing to the hydrophilic nature of wood. Adamopoulos et al. [14] also observed a decrease in compressive strength of gypsum composites when wood and rubber proportions were increased from 25 to 50% by weight. Statistical analysis revealed that the effect of C/RM ratio was significant on the flexural properties, while the effect of the aggregate content was only significant

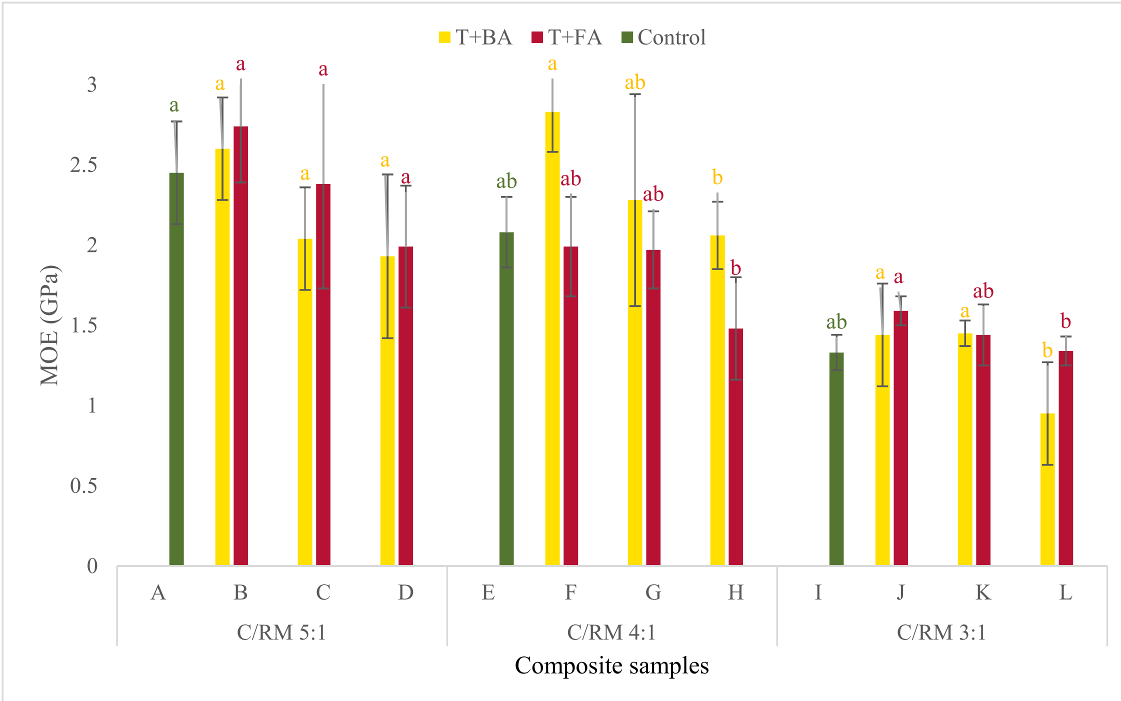

Fig. 7. MOE of cement-bonded composites with tyre fibres. [Error bars represent standard deviations of three replicates. Within each C/RM ratio group, columns with the same letter (a, b, ab) are not significantly different (significance level α = 0.05)].

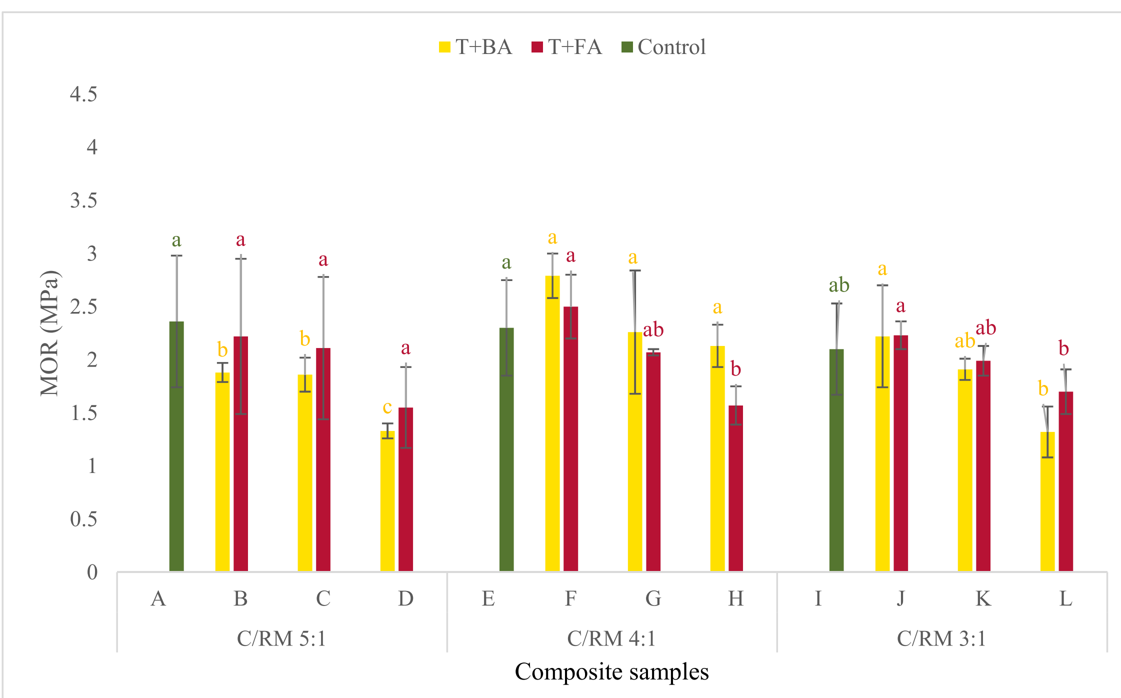

Fig. 8. MOR of cement-bonded composites with tyre fibres. [Error bars represent standard deviations of three replicates. Within each C/RM ratio group, columns with the same letter (a, b, ab, c) are not significantly different (significance level α = 0.05)].

on the MOR for composites containing BA. The C/RM ratio and aggregate content also had significant effects on the MOR for composites containing FA, however only the C/RM ratio had significant effect on the MOE ($p < 0.05$).

5.3. Density and flexural properties of composites with tyre fibres

The results of density and flexural tests of the cement-bonded composites containing tyre fibres are presented in Figs. 6-8. The

Table 6
Thermal properties of the cement-bonded composites.

Composite samples	Conductivity (W/mK)	Diffusivity (mm^2/s)	Heat capacity (MJ/m^3K)
T1T2S1S1	0.372	0.342	1.09
T1T2S2S2	0.349	0.309	1.13
T3T4S1S1	0.362	0.246	1.47
T3T4S2S2	0.359	0.446	0.81
T5T6S1S1	0.416	0.277	1.5
T5T6S2S2	0.343	0.289	1.19
Mean value	**0.367**	**0.318**	**1.198**
W1W2S1S1	0.292	0.335	0.872
W1W2S2S2	0.295	0.346	0.867
W3W4S1S1	0.308	0.38	0.798
W3W4S2S2	0.311	0.445	0.699
W3W6S1S1	0.275	0.336	0.819
W3W6S2S2	0.244	0.31	0.787
Mean value	**0.288**	**0.359**	**0.807**

T - tyre fibres, W - wood chips, S1 - surface 1, S2 - surface 2.

C/RM ratio had a significant effect on the density of the composites containing FA and BA, while aggregate content was only significant on BA containing composites ($p < 0.05$). It was evident that as the cement content decreased, the density of the composites decreased significantly. This is due to differences in densities between cement (1250 kg/m^3) and tyre fibres (126.48 kg/m^3). The density of the composites also decreased significantly as the BA content increased, due to lower density of BA compared to cement [67] and the bigger particle sizes of BA resulting in larger interfacial pores. At all C/RM ratios, composites containing FA had higher densities (978–1335 kg/m^3) compared to composites containing BA (903 – 1318 kg/m^3). This is attributed to better interparticle packing in the composites owing to the fine particle sizes of FA and cement (Table 5). Since density is a major determinant of the flexural properties of composites, samples containing FA had significantly higher strength and elasticity values than those containing BA, except for C/RM ratio of 4:1. Sample F had the highest MOR of 2.79 and 2.5 MPa when BA and FA were used as aggregates, respectively. Sample L had the lowest MOR and MOE (1.32 MPa

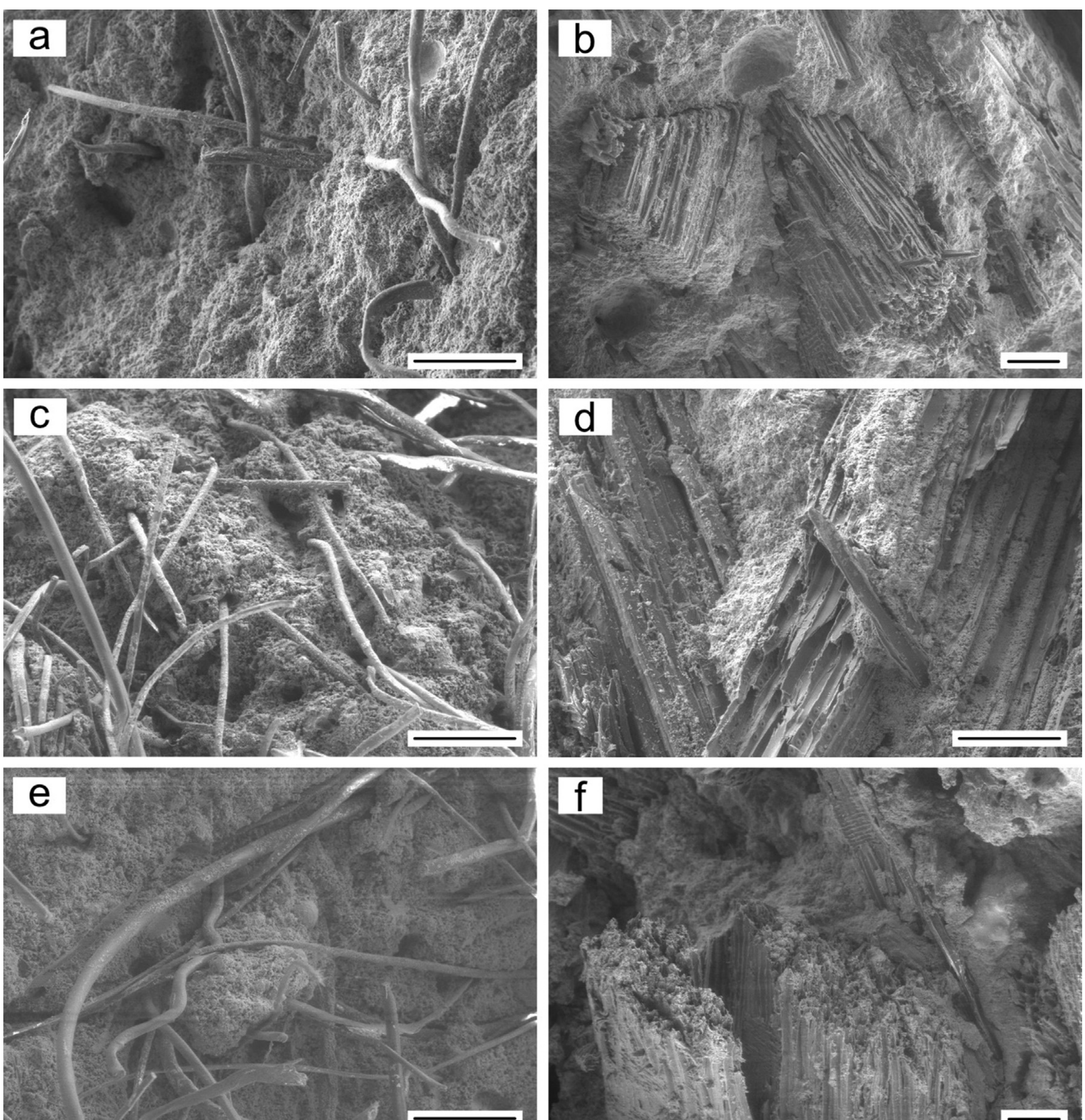

Fig. 9. SEM micrographs of composite samples containing: a – tyre fibres (A); b – wood residues (A); c – tyre fibres + bottom ash (H); d – wood residues + bottom ash (H); e – tyre fibres + fly ash (D); f – wood residues + fly ash (D) (scale bar – 200 μm; magnification – 120 ×).

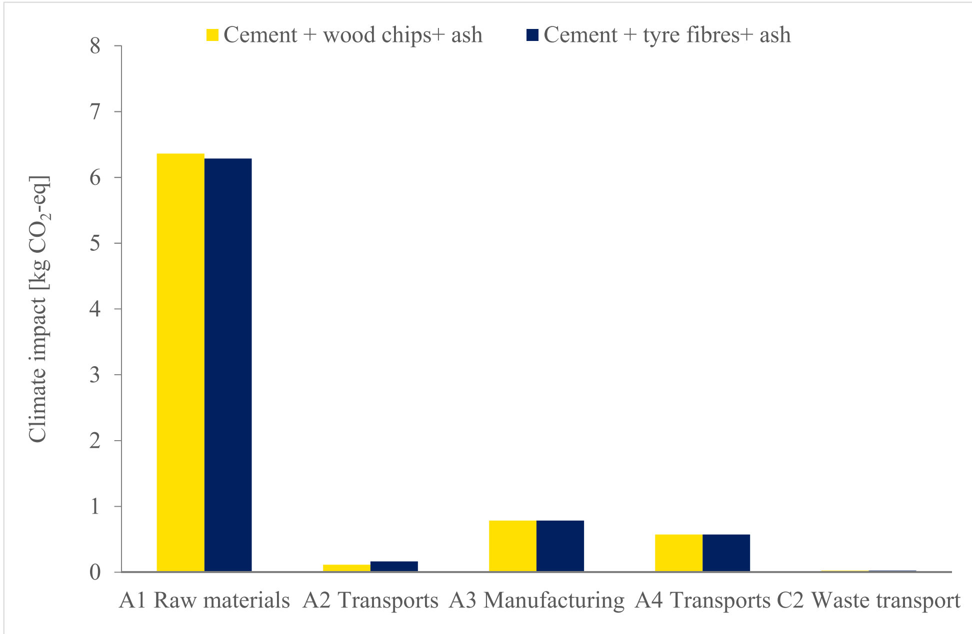

Fig. 10. Climate impact for production stages (A1-A3), transports A4 and C2 of the analysed composites.

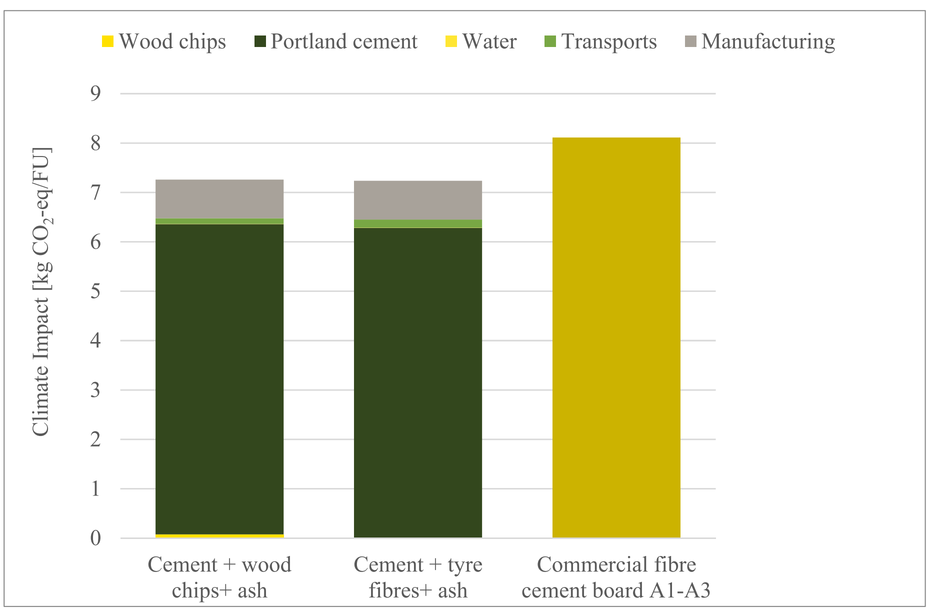

Fig. 11. Climate impact for the production stages (A1-A3) for the analysed composites compared with a commercial fibre cement board.

and 0.95 GPa) when BA was used but the MOR improved when FA was used. FA had a higher amount of CaO compared with BA, which is needed to form stable C-S-H products (Table 4), As already stated, the low strength values of sample L was due to low CaO/SiO_2 content, which resulted in weak C-S-H products. Statistical analysis revealed that the C/RM ratio and aggregate content had significant effects on the MOE and MOR when BA was used in the composites. The effects of the C/RM ratio and aggregate content were also significant on the MOE, while only the aggregate content had significant effect on the MOR when FA was used ($p < 0.05$). As the aggregate content increased, the flexural properties decreased but the difference was not significant. The low CaO/SiO_2 available for bond formation resulted in decrease in strength properties. The results also revealed that MOE and MOR decreased as the fibre content increased, which could be due to the low modulus of tyre fibres (0.8–1 MPa) [68]. Pacheco-Torgal et al. [69] also reported lower MOE in cement composites with rubber waste. However, MOR increased by 16% when tyre fibre dosage was doubled from 0.9 to 1.8 kg/m^3 in wet-sprayed concrete [23]. Although tyre rubber increased fracture energy and reduced crack formation in concrete [22,29], the strength decreased due to weak interfacial adhesion between rubber and cement matrix [30,70].

5.4. Thermal properties of the composites

The results of the thermal properties of the composites are presented in Table 6. The values are the mean measurements on three different specimens of the same composite material. The mean

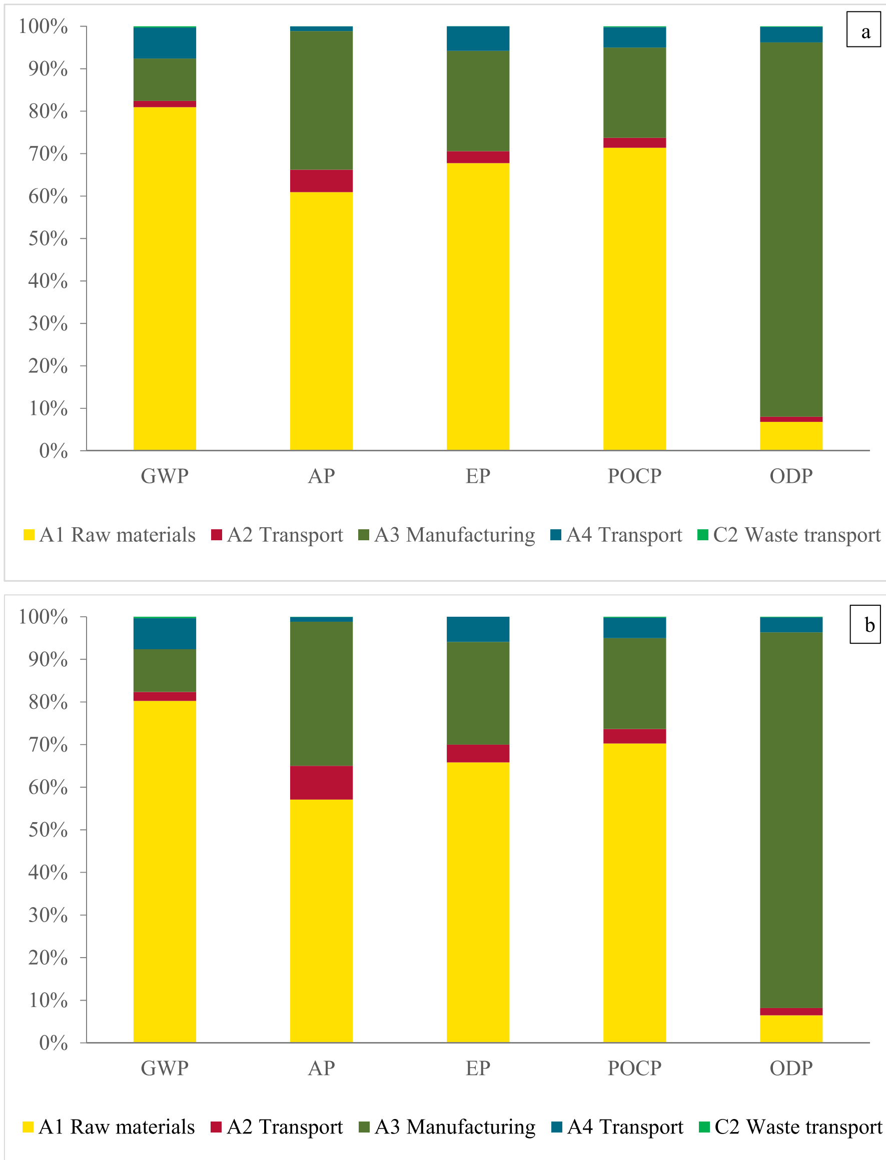

Fig. 12. Distribution of environmental impact categories over the life cycle phases for: a) cement composite with wood residues; b) cement composite with tyre fibres. GWP - global warming potential, AP - acidification potential, EP - eutrophication potential, POCP - photochemical ozone creation potential, ODP - ozone depletion potential.

thermal conductivity and heat capacity of composite samples with tyre fibres were 0.367 W/mK and 1.198 MJ/m^{3}K respectively, while those with wood residues were 0.288 W/mK and 0.807 MJ/m^{3}K, respectively. It was observed that the measured thermal properties of composite samples with tyre fibres varied more than those with wood residues. The variation of heat capacity in tyre containing samples could be attributed to non-homogeneity in the materials. The thermal conductivity of the wood containing composites is comparable to that obtained by Wang et al. [1] for cement-bonded particleboard (0.29 W/mK). The value is also comparable to that of solid wood panel (0.24 W/mK, at 1.0 g/cm^3) used for thermal insulation according to EN 13986 [71]. Irrespective of aggregate content, the thermal conductivity of the composites containing wood residues were similar. Caprai et al. [47] also made similar observations in wood cement composites containing bottom ash. Viet-Anh et al. [72] reported that thermal conductivity did not change significantly between 0 and 30% wood ash replacement levels in wood cement panels but the heat capacity increased with ash content. However, the thermal conductivity of cement composite was found to decrease as fly ash content increased from 10 to 90% [73]. There was a reduction in concrete conductivity by 81 and 76% when wood and tyre fibres were added respectively, compared to plain concrete (1.52 W/mK) [1]. Other studies also observed similar behavior in thermal conductivity of rubberized concrete. Medina et al. [24] reported a reduced conductivity of 48 and 58% when 100% fibre coated rubber and 100% crumb rubber were used respectively as aggregates in concrete. Hall et al. [74] also reported reduction of 28% in thermal conductivity when 30% of rubber aggregate was used in concrete. The reduction in conductivity could be related to increase in air pockets due to difficulty in mixing and the low thermal conductivity of tyre rubber [25]. On the contrary, Khern et al. [70] reported an increase in conductivity by 9.8% after chemical treatment of rubber aggregates used in concrete.

5.5. Scanning electron microscopy

The SEM micrographs of the selected samples are shown in Fig. 9. The analysis of the microscopy images of the samples helps explain some of the mechanical properties obtained. Less amounts

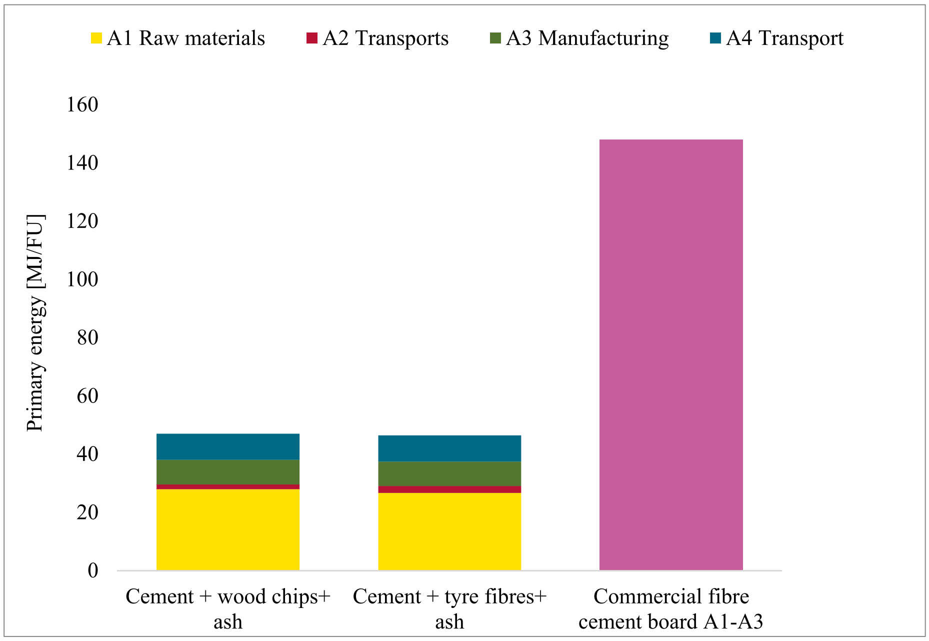

Fig. 13. Primary energy over the life cycle phases for the analysed composites compared with a commercial fibre cement board.

of air pores were seen in samples containing aggregates at high C/RM ratio. This is probably due to the formation of cement-aggregate hydrate products and better interparticle packing in the composite [75,76]. The result is an increase in flexural properties with increasing aggregate content at high C/RM ratio. The strength of composite materials is negatively correlated to total porosity and average pore diameter [1]. Regarding the mode of failure, samples containing wood residues failed by fibre pull-out from the cement matrix (Fig. 9b, d, f). This could be due to the small dimension of the wood particles used (3–7 mm), which has a resultant effect on the interfacial adhesion [64]. Although, the composite samples with wood residues had flexural properties comparable to those with tyre fibres, they exhibited brittleness when subjected to axial loading. At C/RM ratio of 3:1, the composites became filled with wood particles resulting in weak elastic deformation. The SEM images did not reveal any information about the effect of aggregates on the interfacial interaction, however it was observed that both wood residues and tyre fibres had relatively good bonding compatibility with the matrix, as the fibres were pulled out with surface crystals. Incrustation of matrix at fibre surfaces and fractured ends of pulled-out fibres are good indications of effective fibre reinforcement [77]. Compared to samples containing wood residues, composite samples with tyre fibres were more elastic and the fibres remained embedded in the matrix at the limit of its strength (Fig. 9a, c, e).

5.6. Life cycle assessment

5.6.1. Environmental impact

Fig. 10 shows the climate impact during the life cycle for both wood and tyre cement composites. The figure shows that the climate impact from the raw materials in the production of the composite containing tyre fibres is 98% of the climate impact from the production of the cement composites with wood residues. The bulk of the climate impact was from the cement used, since the biomass combustion residues were assigned zero impact. Cement industry is a major contributor to global emissions of greenhouse gases and volatile organic compounds (VOCs), although emissions of VOCs and other hydrocarbons (HC) are generally insignificant in cement production [78]. It should be noted that the manufacturing process and transport to site (A4) also contributed to the climate impact due to increased energy requirements. The analysis shows an insignificant climate impact from C2 waste transport. However, since the demolition and waste phases are not included in the analysis, it may neglect the impact of heavy metal leaching, which contributes to ecotoxicity [79].

Fig. 11 shows the climate impact for the production stages based on raw materials used in the composites, transport and manufacturing process. The figure clearly shows that cement used as binder caused the greatest climate impact. The wood residues have a value as a by-product and therefore have an impact from electricity and heat allocation during sawmilling. Other materials used in manufacturing of the composites such as bottom ash, fly ash and tyre fibres are considered as waste and do not contribute to the environmental impact except for transport of these materials. When compared with a commercial fibre cement board, the climate impact during the production stages of the cement board was about 10% more than the climate impact due to the produced composites.

Fig. 12 shows the distribution of environmental impact over the composites' life cycle phases for all analysed impact categories. For the cement-bonded composite with wood residues, the raw materials represent the biggest impact for all impact categories except the ozone depletion potential (ODP) (Fig. 12a). The environmental impact caused by the manufacturing process on the ODP was due to the emissions from the energy used in manufacturing. The cement-bonded composite with tyre fibres shows a corresponding distribution of environmental impact, but with a bigger contribution from transport to the impact categories- acidification potential (AP), eutrophication potential (EP) and photochemical ozone creation potential (POCP). This is mainly due to longer transports of the tyre fibres from the recycling company to the local manufacturing line (Fig. 12b).

5.6.2. Primary energy

The primary energy consists of the total energy from renewable and non-renewable resources, which is needed during the composites' life cycle, excluding the energy bound in the building materials. The amount of primary energy used over the life cycle of the composites is shown in Fig. 13. For all composites, most energy is used in the production of materials in module A1 in the production stage. However, the energy used in manufacturing the wood cement composite is about 5% higher than that required for tyre composites owing to additional processing of wood residues. As already stated, A2 transport of tyre fibres to the manufacturing plant consumed about 30% more energy than A2 transport of the wood residues. In comparison, the primary energy consumption during the production stages of the commercial fibre cement board was about 70% more than the energy consumed at the production stages of the composites. The large difference in energy consumption could be attributed to the small-scale laboratory production of the composites compared to industrial energy use. In addition, commercial fibre cement boards are produced from raw materials, which are usually processed before use. The processing and transport of such materials result to significant increase in energy consumption.

6. Conclusions

This study presented details on manufacturing, performance and sustainability of cement-bonded composites containing wood residues from sawmilling and tyre fibres from car tyre recycling. The optimum cement/raw material (C/RM) ratio for achieving maximum strength within the scope of the study is 4:1, while the optimum aggregate content is 30% for composites with wood residues and 10% for composites with tyre fibres. By further optimization of processing parameters, it is possible to tailor the desired properties of the composites to meet international standard requirements. The cement-bonded composites had moderate thermal conductivities like gypsum boards and can be suitable for use as components in insulating interior walls. Scanning electron microscopy revealed the possibility of good fibre reinforcement in the cement matrix.

The LCA calculations showed that the greenhouse gas emissions from the manufacturing of the cement-based composites with wood residues and tyre fibres was about 87% of total greenhouse gas emissions. It was also shown that cement contributed to the largest part of the climate impact in the production of the composites, since the biomass combustion residues had no impact. Cement also contributed most to other impact categories analysed in the LCA calculations, except for the ozone depletion potential (ODP). From the analysis, cement binder can be identified as environmental hot spots. During the production phase of the cement composites, approximately 30% more primary energy was used for A2 transport of tyre fibres compared to the wood residues. The materials share of the total use of primary energy over the life cycle was about 60% for all analysed composites. When compared with commercial fibre cement board, the climate impact and primary energy use during the production stages of the cement board was more than that obtained for the produced composites. Based on the conclusions of the study, biomass combustion residues (fly ash and bottom ash) can be incorporated in cement matrix for beneficial effects on the flexural properties and environmental profile.

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CRediT authorship contribution statement

Stephen O. Amiandamhen: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Stergios Adamopoulos:** Conceptualization, Methodology, Writing - review & editing, Project administration, Funding acquisition. **Bijan Adl-Zarrabi:** Investigation, Writing - review & editing. **Haiyan Yin:** Investigation. **Joakim Norén:** Investigation, Writing - original draft.

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.

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