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The recycling potential of wood waste into wood-wool/cement composite

F. Berger, F. Gauvin *, H.J.H. Brouwers

Department of the Built Environment, Eindhoven University of Technology, P. O. Box 513, 5600 MB Eindhoven, The Netherlands

HIGHLIGHTS

- Wood waste is used as a substitute for spruce in WWCB.
- Wood waste from pallet wood has a microstructure similar to spruce.
- Strands made from wood waste have good compatibility with cement.
- Up to 30% of wood waste can be used in WWCB without decreasing the properties.
- The environmental assessment shows no hazardous leaching from these composites.

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ABSTRACT

Nowadays, the recycling potential of wood waste is still limited and in a resource cascading approach, recycling wood waste in cement composite materials, such as wood wool cement board (WWCB) appears as a promising solution. The quality of the wood waste is the main factor leading to the instability of the final product which can affect the mechanical properties or the wood cement compatibility. However, the possibility to recycle wood waste as a spruce replacement for WWCB manufacture needs more investigation in order to assess the impact of wood waste on the mechanical performances of the final product, but also to characterize the behavior of hazardous substances embodied in a cement matrix. This paper addresses the characterization of two types of wood waste, from pallets and demolition waste and their influence on the manufacturing process, mechanical properties and chemical compatibility when used in WWCB. A comprehensive approach is provided to define the influence of wood waste on the hydration reaction of the cement and the chemical and physical properties of the composite are assessed by isothermal calorimetry, leaching measurement and microscopy. Finally, the mechanical properties of WWCB are tested for different wood waste content in order to define the best wood/wood waste ratio and thereby confirming the possibility to reuse the wood waste in fiber/cement composite for building application.

1. Introduction

Nowadays, wood waste represents an important economic and environmental issue. Recently, a study has estimated that 50 million cubic meters of wood waste are generated each year in the European Union [1]. Currently, the recycling potential of wood waste is still low, mainly caused by a lack of sustainable reusing or recycling applications [2,3]. In fact, the main part of wood waste can be treated in different ways (e.g., heat, chemical or mechanical treatment) and this involves a large amount of preservative-treated wood that contains organic and inorganic contaminants [4,5]. Those contaminants represent a real issue in waste management that can conduct to health and environmental issues during the end of life of wood [6]. Currently, wood waste can be either used as energy recovery (e.g., following the Renewable Energy Directives) or reused as a building material. However, several environmental assessments show contradictory results about these two options because of the presence of contaminants in wood products, which limits considerably the recycling or reuse of wood waste [7].

This current study focuses on the possibility to find sustainable applications in order to recycle wood waste into wood-cement composites. In these applications, wood is turned into wool, which are thin strands of wood of 0.5–3 mm of thickness and can be used in state-of-the-art materials. Wood wool cement boards (WWCB) are an example of advanced wood-cement composites. They are made of wood wool which is usually spruce (softwood) or poplar

* Corresponding author.
E-mail address: f.gauvin@tue.nl (F. Gauvin).

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(hardwood), mixed with a binder which is commonly ordinary Portland cement (OPC) or white cement (WC) [8]. Since 1940, WWCBs are commonly used in Europe and Asia, thanks to their good resistance to decay and insects but also for their good thermal and acoustical insulating properties and low density (300–500 kg/m^3) [9,10]. WWCBs are used for many applications, such as ceiling tiles, insulation wall panels with better physical properties than conventional medium density fiberboards while being more sustainable [11]. Additionally, WWCB's structure is an excellent substrate for air purification by photocatalysis, showing that this type of composite can be a great prospect of many advanced applications in the future [12].

Nowadays, the wood used for the manufacture of WWCB comes from forest harvesting only [2], because a slight change (e.g., composition, structure, water content, age...) in the wood can significantly affect the overall properties of the composite, which explains why using anything else than raw spruce or poplar is a great challenge [13,14]. Indeed, heterogeneity of wood waste is a critical factor because, as shown in several studies, depending on the wood species, its hygroscopic behavior, cement compatibility and effect on cement hydration can be significantly different due to the carbohydrate and saccharides contents in the fibers but also because of the different morphologies of the wood strands [15–17]. In addition, the use of wood waste can generate environmental issue because of the various treatments of the wood which leads to numerous contaminants that can be leached out, disturbing the wood cement compatibility and also limiting the potential range of application due to the toxicity of the waste [18–22]. On the other hand, some studies show favorable results and good potential for the use of wood waste into wood cement composite, since its mechanical proprieties are very closed to commercial wood products [23]. Moreover, many other lignocellulosic wastes, such as wheat and rice straw, bark, coir or bagasse has already been used for various building applications [11,14,24–26]. Therefore, the development of new applications for wood waste is possible, but in order to expand the range of applications of these products, many issues persist, especially concerning health and safety.

Among the available wood waste, construction and demolition (C&D) debris is a very important source, averaging 30 Mt of waste only in the USA [27]. However, as shown by the UK Waste and Resources Action Program, 74% of wood waste which comes from construction and building site is treated with chemicals [28]. Indeed, during the past 40 years, *Chromated copper arsenate* (CCA), *Penta* and *Creosote* are the three most used preservative treatments for wood products [29]. Furthermore, the use of CCA treatment was the main preservative for housing or decking applications in order to prevent or delay decay caused by fungi or termites, especially in Australia, New Zealand and the United States [5]. CCA contains 38–45% chromium, 23–25% copper, and 30–37% arsenic and these elements can react during the cement hydration reaction. Some studies show that CAA treatments can sometimes increase the properties of the final products as compared to virgin wood [5]. This phenomenon is due to the acidic washing of the wood associated with the CCA treatment which removes a part of the extractives present in the wood and reduces their water solubility [30]. Moreover, since the early 2000s, several countries around the world and particularly in the EU set up severe regulations regarding CCA and wood waste recycling, due to leaching of heavy metals and arsenate poisoning [18,19,21,31]. Therefore, a huge amount of CCA treated wood still remains in service worldwide and will be concerned about disposal and recycling applications. Furthermore, an environmental study is needed in order to analyze if these hazardous elements are a direct problem when the CCA treated wood is used in composites.

Additionally, other cleaner wood waste streams can be used, such as pallet waste, which represents 19% of the total wood waste worldwide [27,32]. The wood from pallets is generally only heat-treated for environmental and recycling reasons leading to a clean wood resource for biomass or reuse applications. Moreover, softwood is mostly used for pallet manufacturers in the EU, with different species such as Southern yellow pine, Douglas pine or fir. However, the use of hardwood has risen in the last decade because of its large availability in the US. Contrariwise, construction and demolition wood waste show different issues for sustainable recycling solutions.

Currently, it is still impossible to predict the behavior of the treated wood into WWCB, these results show a positive future for using wood waste in WWCB. In this study, the mechanical and chemical properties of the two wood waste samples provided by Nedvang (Pallets and C&D) are studied in order to compare them with conventional spruce wood, used as a reference. The wood-cement compatibility is assessed as well as the leaching behavior of the wood waste by various methods, such as pH measurement, isothermal calorimetry and scanning electron microscopy (SEM). Then, wood strands are processed and studied (mechanical behavior, microstructure). Thereafter, the mechanical, physical and leaching properties of WWCB manufactured with different percentages of wood waste (steps of 10% until 100%) are compared to conventional and commercial WWCBs.

2. Methodology

2.1. Materials

In this study, the spruce wood is taken as reference in the form of Excelsior wood wool (or also called *strand* in this study) and is provided by Knauf Insulation. These strands are conventionally used for the industrial manufacture of WWCB. The studied wood wastes are provided by Nedvang (NL) and come from pallets and construction & demolition sites, respectively. The binder applied in the study is CEM I 52.5 R white (PC) provided by ENCI (NL).

2.2. Methods

2.2.1. Scanning electron microscopy

Microstructure analysis of the wood waste strand is performed by Scanning Electron Microscopy (SEM, Phenom pro-X) with a back-scattering electron detector (5 kV). The wood waste strand has been coated with a 20 nm gold layer before the microscopy. The moisture content of the wood waste has been limited by drying the material in an oven at 60 °C, for 2 h prior to analysis.

2.2.2. Leachates characterization

The leaching of wood waste is studied by using the TCLP extraction methods to obtain the leachate solution. The samples are reduced to a particle size of less than 1 cm. Subsequently, the leachate is prepared according to the TCLP standard, the waste was added to a determined extraction fluid and mixed during 18 h at 30 rpm at room temperature. Thereafter, the solution is filtrated through a 0.6–0.8 μm glass fiber filter. The leachate obtained is analyzed by inductively coupled plasma mass spectrometry (ICP-MS) in order to measure the concentration of heavy metal and other potential contaminants released by the wood.

2.2.3. Isothermal calorimetry

The hydration kinetics is studied by isothermal calorimetry with a TAM Air Isothermal calorimeter set at a constant temperature of 20 °C for 72 h. The wood samples and the binder were first well mixed in an ampoule before the water was added. After the addition of water, the mixture was mixed for 3 min before being loaded in the calorimeter. The heat evolution rate data were calibrated by subtracting the heat evolution of ampoules with water as a baseline.

2.2.4. Mechanical properties of the wood strands

Mechanical properties of wood strands are measured by using an Instron 5967 bench equipped with a 2530–100 N load cell and 2710-111 wedge grip with rubber jaw faces. Tensile tests are conducted in displacement control with a crosshead speed of 5 mm/min. More than 15 samples for each condition are tested. Tensile strength (cN/tex) and Young's modulus (N/tex) are measured as a function of the linear density of the strand (tex) by measuring the length and the weight of each strand prior to analysis.

2.2.5. Manufacture of the composites

WWCB composites are manufactured following the so-called dry method, which is currently applied in the production plant of various manufacturers. Wood strands are pre-soaked with water and then sprinkled with a dry binder. Then, these strands are mixed with PC in a plastic bucket. The mixture is then placed into a steel mold (30 $\times$ 60 cm) and pressed for 24 h, using a mechanical press. Successively, the sample is cured in a plastic sheet for 7 days and then left drying at ambient conditions for another 3 days. In order to achieve the same moisture content before testing, the boards are dried in the oven for 2 h at 50 °C. In order to evaluate the mechanical performances of the composite according to different Wood waste/spruce wood ratio (called *W/S ratio* in this study), WWCBs are manufactured with 10 different chosen ratios (0.1 to 1), named PW/S0.1 to PW/S1.0 for pallets wood. Fig. 1 shows the cross-section of the reference sample, showing the characteristic interface between the cement and the wood strand: This later is covered with a thick layer (50 μm) of cement which acts as a mineral adhesive in this open composite.

2.2.6. Mechanical performances of the composites

The bending strength is measured at 10 days by a three-point flexural test (Instron 5967) on a sample with dimensions of 5 $\times$ 20 $\times$ 1.5 cm, using a testing speed of 5 mm/min, and a support span of 15 cm. Three samples of each W/S ratio are tested. As reference values, the dimensional stability has to be satisfied, by a maximum thickness of 15 mm and a minimum bending strength of 1.7 MPa, according to the BS EN 12089, *Thermal insulating products for building applications* standard.

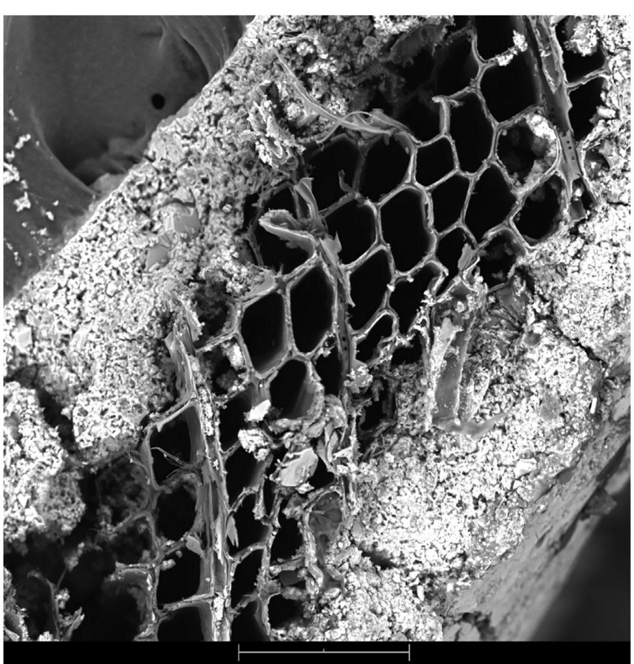


Fig. 1. Cross-section of a WWCB. The cement layer is visible in white around the porous spruce strand.

2.2.7. Thermal conductivity measurement

Thermal conductivity is measured on WWCB by a heat transfer analyzer *ISOMET 2104*. As a reference, commercial WWCBs with a thickness between 15 and 30 mm have a thermal conductivity range of 0.08–0.11 W.m^{-1}.K^{-1} according to the BS EN 12089, *Thermal insulating products for building applications* standard.

3. Results and discussion

3.1. Wood waste characterization

In order to characterize the two streams of wood, microscopy and isothermal calorimetry are performed. The micrographs in Fig. 2 shows the surface of spruce (in the form of strands) and pallet wood (waste strands). These two kinds of wood are closed to each other and depict the same microstructure and surface aspect. Tubular cell walls are visible for both types of wood and the lumens (red arrows) have the same shape and almost the same size, with around 7 μm for the pallets wood and 5 μm for the spruce. Additional cell walls are visible with the wood waste (blue arrows) indicating some heterogeneity. In addition, the pallet wood shows no noticeable signs of contaminants at its surface. Moreover, as compared to the reference, the surface of the wood waste seems to have less wax and lignin. These observations indicate a potential good wood/cement compatibility. A very similar structure also indicates that the manufacture of WWCB with wood waste from pallets would be not problematic because a similar pore size means the same water demand and the same cement coating during the process.

However, wood waste from construction and demolition (C&D) sites seem more problematic, even if its structure remains quite closed to the spruce because its cell walls and its surface show the presence of contaminants (Fig. 3). These particles can be heavy metals such as chromium or inorganics substances that have been mixed with the wood wastes. These substances can disturb the manufacturing process by delaying the hydration reaction of the cement, reducing the wood cement compatibility, or limiting the range of applications due to health and environmental issues involved by the leachates.

3.2. Compatibility with cement

Results of the calorimetry of the three kinds of wood are depicted in Fig. 4, showing the chemical compatibility between the wood and the cement. From the results, the two types of wood waste (building and pallets) are really close to each other. As compared to the reference, the hydration peaks have been delayed by 1.5 h due to the presence of the wood waste. A probable hypothesis is that the wood waste is slightly degraded, especially at its surface, as it can be seen by SEM (i.e., lack of matrix at the surface of the wood). The hemicellulose degradation creates monosaccharides and polysaccharides that are mixed in the cement paste and can delay the cement hydration. However, this retardation is not very important and indicates that both wood wastes have a low sugar content and will not affect the manufacturing process nor the final properties of the WWCB. In addition, the maximum released heat is 20% lower in the presence of wood inside the cement paste. This decrease does not have a significant impact on the reaction as it

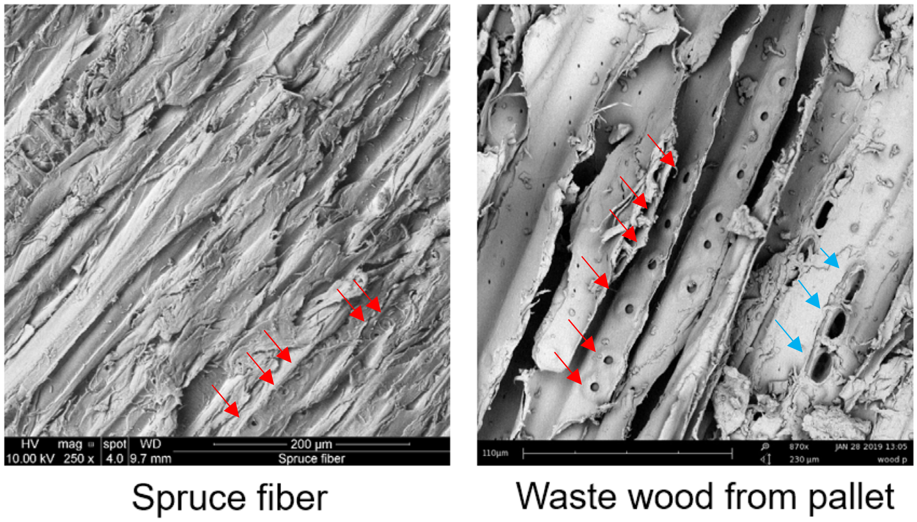
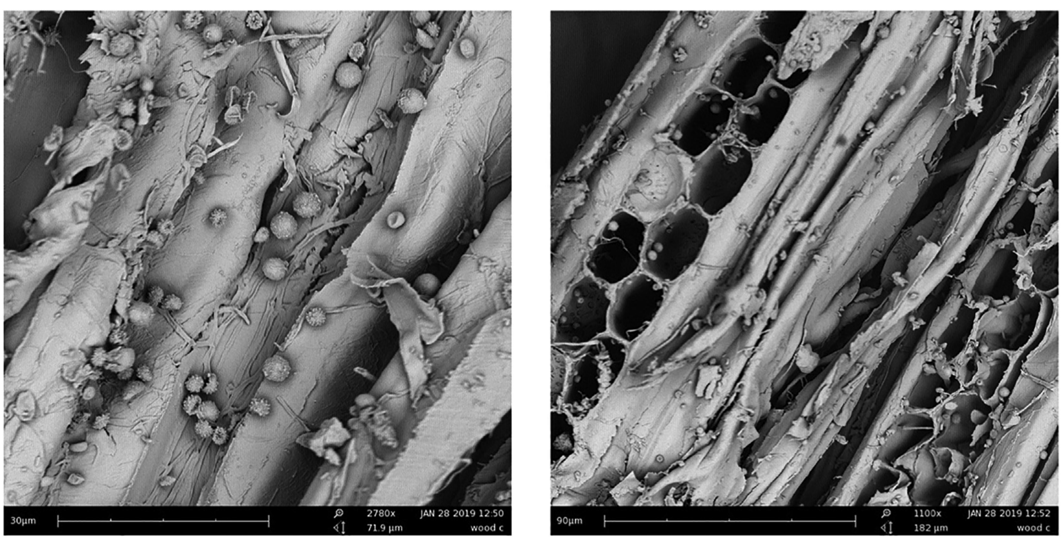


Fig. 2. SEM microscopy of wood waste from pallet and spruce strand, which is used in WWCB manufacture.



(A) **(B)**

Fig. 3. SEM microscopy of C&D wood.

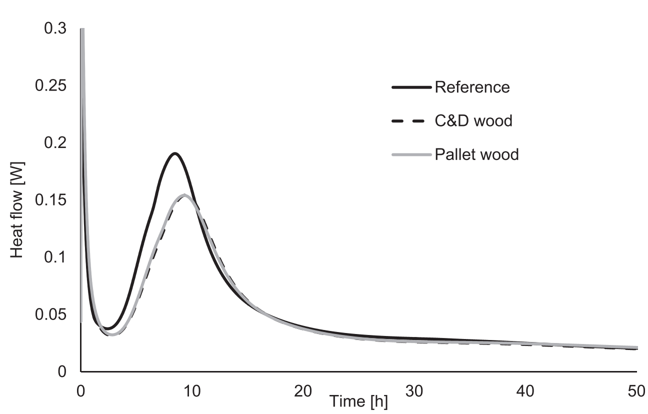


Fig. 4. Isothermal calorimetry of the 2 wood streams as compared to the reference (i.e., white cement), showing the effects of the wood wastes on the cement hydration.

remains low and also it can be explained by the presence of sugars involved by wood wastes.

From these results, it appears that both types of wood waste have good chemical compatibility with cement. Moreover, the wood waste from pallets is surprisingly close to the spruce strand and would be a perfect candidate to replace it due to its similar microstructure. Therefore, in this study, only wood waste from pallets is to be turned into strands and used in WWCB.

3.3. Pallet wood strand manufacture

Strands made of pallets are manufactured on a laboratory scale using thin layers of pallet cut with a ribbon saw and then turned into strands with a wood plane. Fig. 5 depicts the process, which resulted in wood wool with a very similar aspect than regular wood wool manufactured from spruce (Fig. 5-C).

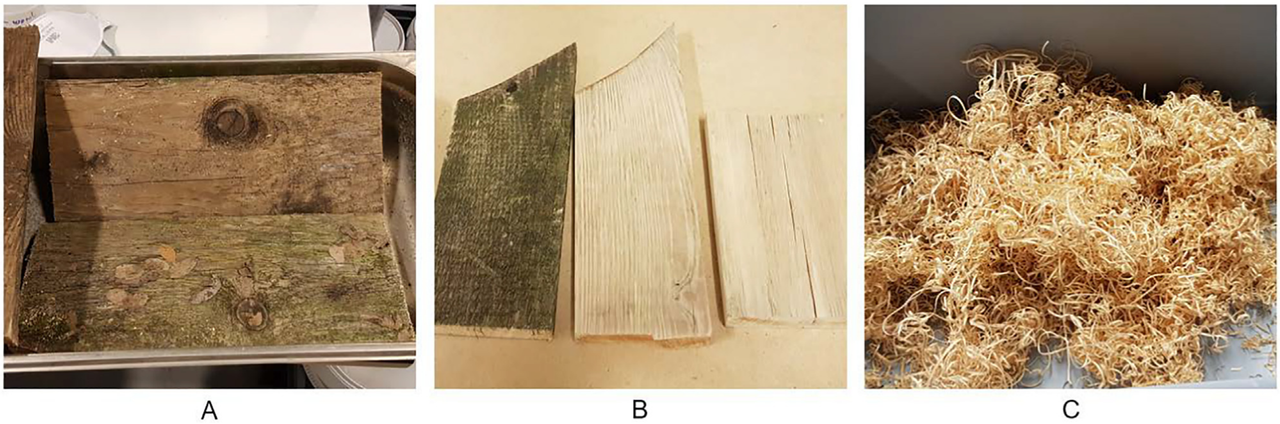


Fig. 5. Pallet wood strand manufacture. A: Pallet is cut into pieces, washed; B: wood is sanded and dried; wood is cut into 10–15 cm strands.

3.4. Mechanical properties of wood strands

The tensile test of strands highlights the variation of the mechanical properties between the pallet wood and the spruce in the form of strands. These results average 30 tests on each type of wood strands and are displayed in Fig. 6 and Table 1.

The tensile strength of the pallet strands is slightly lower than the spruce one, with a decrease of approximately 20%. On the other hand, the modulus of elasticity is almost 50% lower. Many phenomena can affect the mechanical behavior of the strand (e.g., external degradation, differences in morphology or composition…) but here, SEM characterization has shown that spruce and pallet woods are very similar.

First of all, it is unlikely that the pallet wood is degraded. SEM characterization has shown very clean wood and isothermal calorimetry has shown almost no impact on cement. If the wood would have been degraded, the tensile strength of the strand would have been critically affected since the degradation would have affected the wood structure. Here, only the modulus of elasticity of the pallet wood is significantly different, and this characteristic is directly related to the cellulosic fibrils within the structure of the wood [33]. Therefore, the difference between the two types of wood can be explained by an internal degradation of the cellulose but also by the orientation of the cellulose fibrils depending on the cutting axis of the strands. The first hypothesis is very unlikely, because the isothermal calorimetry shows no real difference between the two types of wood, and degradation of the cellulose would also mean a major hemicellulose degradation, thereby inducing a critical amount of polysaccharide in the system.

A more probable explanation would be that these differences can be related to the manufacturing process or the morphology of the strands. The spruce strands are made thanks to an industrial process, using wood logs whereas the pallet strands have been made differently because the conventional process is not applicable for a recycled material due to the variation in terms of shape and size. The industrial process is specially developed to obtain the greatest mechanical properties for each strand, following the cell walls of the wood, with an optimum orientation of the cellulose fibrils.

Fig. 6. Average stress/strain curve of the two types of strands.

Table 1
Summary of the mean results of the tensile tests.

Sample	Modulus [cN/tex]	Tensile strain [cN/tex]
Pallet strands	770	812
Spruce strands	1332	663

SEM microscopy of the pallet wood strand confirms these observations. It does not show matrix degradation and support the fact that the microstructure of both wood sample is the same (as compared to Fig. 3). However, the structure of the wood (following the black arrow in A) is slightly tilted as compared to the cutting direction (in the box), which can explain the low modulus of elasticity. As shown in Fig. 7, spruce strands are well oriented alongside the right axis, in order to have the cellulose in the tensile direction (red box) whereas the pallet wood strands are heterogeneous because it was cut randomly. Therefore, the anisotropy of wood causes a difference in Young's modulus. But this significant decrease is not very problematic in the composite strength because WWCBs are tested in flexural mode, and the rigidity of the boards is not a requirement in the existing standards.

3.5. Mechanical properties of WWCB

Flexural strength of WWCB containing 10–100% of pallet wood strands (as replacement of spruce) is measured, as well as the density of these boards. The results are shown in Fig. 8 and Table 2.

On average, WWCB made industrially with spruce have a flexural strength of 2 MPa, for low-density range (300–400 kg/m^3). When wood waste is added to spruce in WWCB, results can be regrouped into three groups.

Between 10 and 30% of wood waste (light grey dashed lines), WWCBs are always above the acceptable limit since all tested specimens have a flexural strength above 1.7 MPa. An important standard deviation is visible for the PW/S0.3 board but only because some specimens have shown extraordinary results, which are not representative.

When more than 30% of wood waste is added to spruce (dark grey, horizontal lines), results are acceptable. PW/S0.4 average flexural strength of 1.7 MPa and PW/S0.5 is always slightly above the limit. It proves that up to 50% of spruce can be replaced with wood waste, without causing issues.

However, above 50% of wood waste (black dots), the flexural strength of WWCBs significantly decrease, with an average value from 1 to 0.6 MPa. Increasing the weight fraction of wood waste also leads to a decrease in the density of the boards. This phenomenon is explained by the expansion of boards after compression during the manufacturing process: Boards with more than 50% of wood are 1–2 cm bigger than boards made with more than 50% of spruce wood. As it was explained before, pallet wood strands are very heterogeneous, and the strand orientation is not optimal. It means that some strands have the tendency of being curled as compared to spruce wood strands which are always straight (see Fig. 9-A). Besides, the relationship between the density and the strength is clear in Fig. 9-B, showing that the macrostructure of the board has a greater effect than the wood strength itself, as it was characterized by other methods such as tensile strength of the strands.

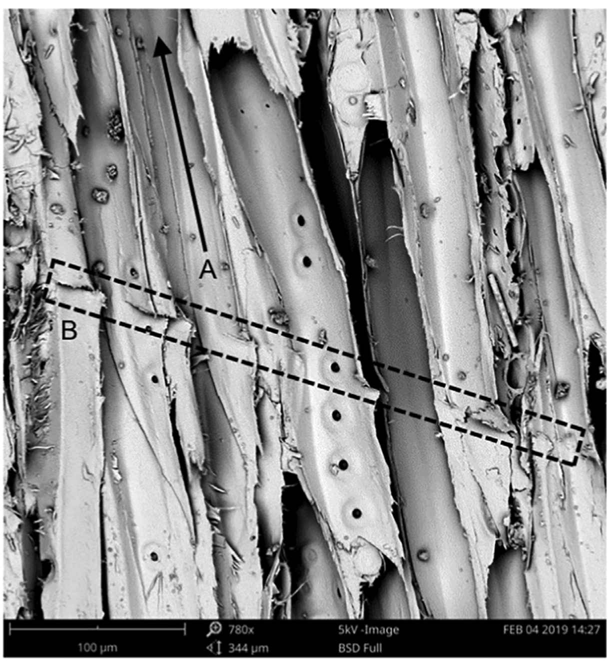


Fig. 7. SEM microscopy wood strand made of pallet. The cell direction is indicated with the black arrow (A). The cutting direction is indicated in B, with scratching marks.

3.6. Thermal properties of WWCB

Thermal conductivity of WWCB containing 10–100% of pallet wood strands (as replacement of spruce) is measured and the average results are shown in Fig. 10.

The first observation is that the thermal conductivity of all the manufactured boards is way below the acceptable limit (0.11 W.m^{-1}.K^{-1}), which can be explained by the low density of all the boards, due to the selected recipe design.

Moreover, the differences in the thermal conductivity are mostly due to the density difference, as Fig. 10 shows some correlation between these two properties. Since the microstructure of the two kinds of wood is very close, only the porosity and the macrostructure of the composite can explain this phenomenon. Besides, it is also noticeable that using a higher fraction of wood waste help to decrease the thermal conductivity because of the higher porosity formed by the curled-strands in the structure, as shown in Fig. 10.

3.7. Environmental assessment

Leaching analysis of the wood waste is performed on its leachate and the results are shown in Table 3, showing heavy metal contaminants as well as some alkali ions and earth alkali. From the EU 2009/894/EC legislation, when recycled wood is used in wood-based materials, some elements such as arsenic, lead or copper should not exceed a limit value, indicated in the table.

Here, leaching values of all elements are far below the limit, which means that the wood can be used freely in WWCB. Moreover, these values are measured prior to manufacturing meaning that the concentration of the WWCB leachate would be even lower, due to the complexation of some elements with cement.

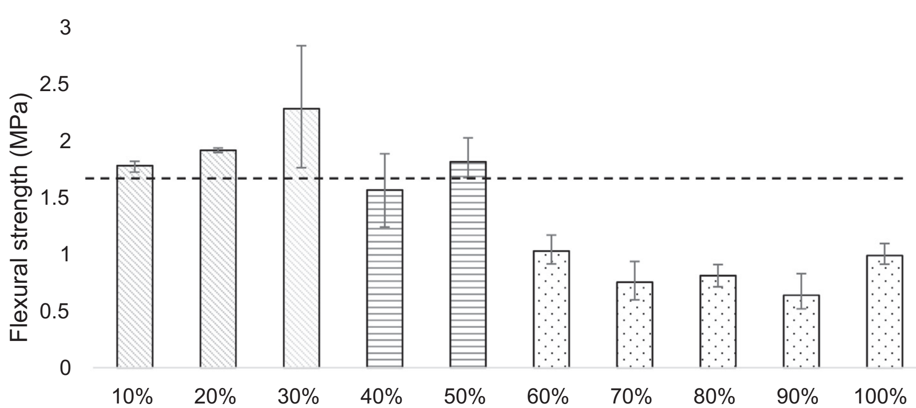


Fig. 8. Flexural strength of WWCB containing 10 to 100% of wood waste (mixed with spruce wood). The dashed line is set at 1.7 MPa, which is the acceptable limit for boards.

Table 2
Density measurement of the different WWCB containing 10 to 100% of wood waste (mixed with spruce wood).

PW content	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Board density (kg/m^3)	314	302	361	309	341	286	235	294	262	295

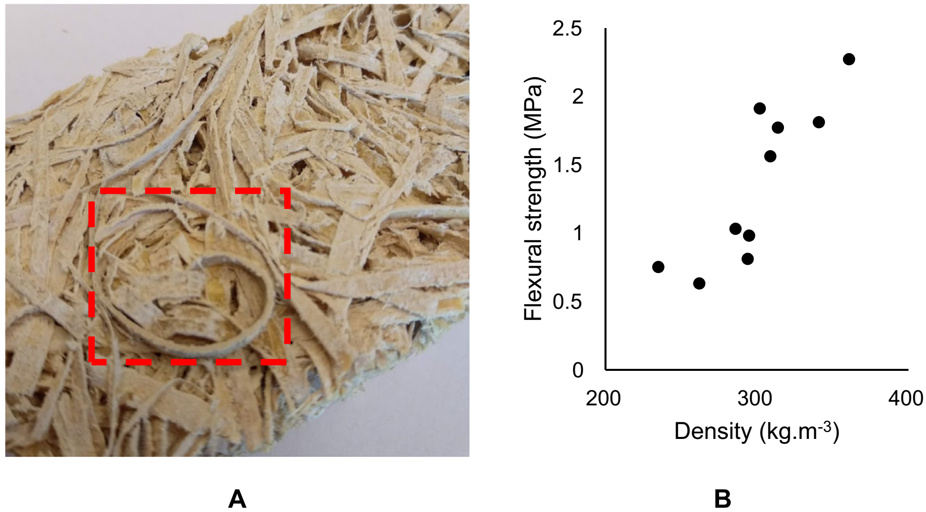


Fig. 9. A) WWCB made of 100% of wood waste. In the red box, a strand is curled, explaining the higher porosity of WWCBs containing a high fraction of wood waste; B) Graph showing the quasi-linear relationship (R^2 = 0.73) between the density of the WWCBs and their flexural strength. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

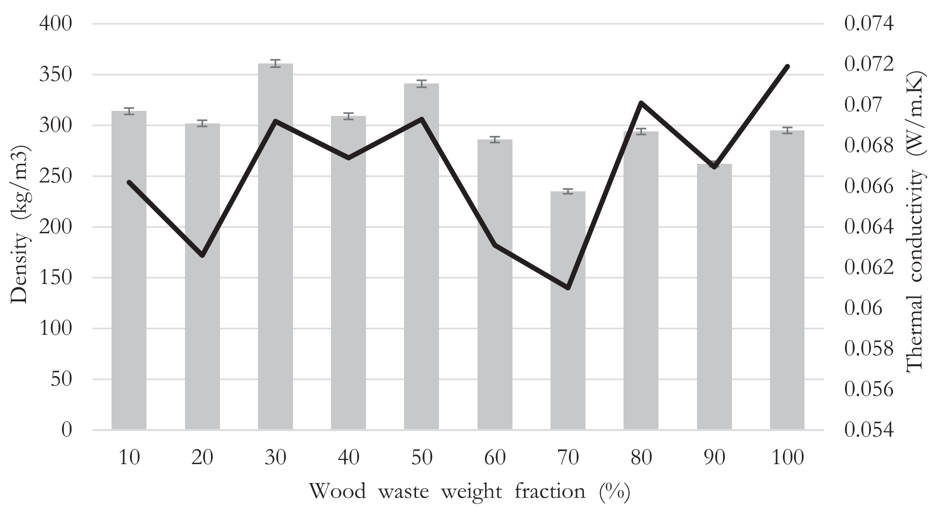


Fig. 10. Average thermal conductivity of WWCB as well as the boards' density.

Table 3
Element concentration (mg/L) in wood waste leachate.

Element concentration (mg/L)	As	Al	Ba	Cd	Co	Cr	Cu	Fe	Li
	0.031	0.200	0.163	–	–	0.022	0.115	0.085	0.021
Limit values from EU 2009/894/EC	25	–	–	50	40	25	40	–	–
Element concentration (mg/L)	Ni	Pb	Sr	Ti	Zn	Na	K	Mg	Ca
	–	0.057	0.218	0.007	0.971	100	50	30	100
Limit values from EU 2009/894/EC	100	90	–	–	–	–	–	–	–

4. Conclusions

In this study, wood waste has been used in order to replace conventional spruce wood in wood wool cement boards (WWCB), a composite that is used for ceilings or walls. Following the experimental results, the following conclusions can be drawn:

- Wood from pallets is an excellent candidate for WWCB because its structure is very similar to the spruce industrially used in the manufacture of these composites. On the other hand, using wood from construction and demolition sites is more challenging, because this wood is more heterogeneous (i.e., more than one type of wood is used in this kind of application) and can be contaminated.
- Wood waste is quite compatible with white cement, which is used in the production of WWCB. Measured by isothermal calorimetry, the effect of wood waste on cement is not significant. Moreover, the environmental assessment made on wood waste shows no traces of contaminants in wood, paving the way for its usage in composites.

- Making wood strands from waste material is challenging because the conventional industrial process is not designed for wood waste. Yet, in this study, an alternative method has been used, turning successfully pallet wood into strands, with microstructure and mechanical properties very close to spruce wood. The only noticeable issue is the difficult control of the anisotropy of the wood, leading to strands not always oriented in the right direction (alongside the cell walls of the wood).
- WWCBs have been made mixing 10–100% of wood waste strands with spruce strands. Results show that up to 50% of wood waste, boards are above the acceptable limit (1.7 MPa). Above 50% of wood waste, flexural strength and density of the boards decrease significantly. The thermal properties of these boards are always acceptable, with very good values below 0.08 $W.m^{-1}.K^{-1}$.

In conclusion, wood waste from pallets can be a good option to replace spruce in WWCB. So far, its replacement level is successful until 50%. Above this limit, the strand morphology is too heterogeneous to guarantee a good reinforcement. Better processes or another source of wood can be evaluated in the future, as well as another kind of *green* binder, in order to create a more sustainable composite for building applications.

CRediT authorship contribution statement

F. Berger: Investigation, Methodology, Writing - original draft. **F. Gauvin:** Validation, Supervision, Writing - review & editing. **H. J.H. Brouwers:** Funding acquisition, Supervision, Project administration.

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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