STUDY OF DIFFERENT SPRUCE STRANDS AND THEIR EFFECT ON THE PROPERTIES OF WOOD-CEMENT COMPOSITES

F. Gauvin*, K. Kochova, V. Caprai, K. Schollbach and H.J.H. Brouwers

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

*Corresponding author; e-mail: f.gauvin@tue.nl

Abstract

Wood-wool cement boards (WWCB) are a type of composite made of softwood strands (e.g. spruce wood) and cement (e.g. white cement) and have been extensively used for decades in many applications thanks to their good thermal and acoustical properties. Recently, some problems have been noticed during the manufacture of these composites: When the wood has poor quality, a lot of problems occur such as important delay of the cement hydration or also low flexural strength of the composites. Besides, the quality of the wood is very hard to assess, especially since a very slight and almost no noticeable difference between two types of wood can have a significant effect on the final composite. This study focuses on the characterization of two types of spruce woods, harvested from the same forest (Hungary) at the same time, but with very different performances. The objective is to understand which parameters affect the wood and therefore, the properties of the wood-cement composites.

Keywords:
Composite, Cement compatibility, Wood, Microstructure, Mechanical Properties.

1 INTRODUCTION

Wood-cement composites have been used for many applications as a building material, especially for thermal or acoustic insulation. Recently, their popularity is increasing due to the recent concerns about sustainability in the building industry. Wood wool cement boards (WWCB) are a type of wood-cement composites, produced by using wood wool strands and a very high wood/cement ratio, where the cement only connects the fibers together, creating a very porous and light structure. Since wood is a natural material, its properties can vary even within the same species so consistent quality and quality control is a critical factor during the manufacture of any lignocellulosic composites [Doudart de la Grée 2014] [Ashori 2011].

For these reasons, industrial WWCB production often uses spruce wood from commercial forests. The wood is cut into logs and then stored for several months prior to manufacture of composites. This method neutralizes the sugar-rich wood extractives and also lowers the moisture content inside the wood. Polysaccharides and other organic materials are the main reason for low wood cement compatibility because they can delay the cement hydration and can decrease the strength of the composites [Kochova 2017].

Consistent moisture content and water adsorption of the wood are important, because cement requires a specific water/cement ratio in order to harden, typically 0.35-0.5. If the moisture content of wood is too high, it can release the water and increase the effective water/cement ratio. This can lead to a porous binder with low strength. It is also possible that the wood absorbs too much water needed for the hydration of cement. In that case, part of the cement cannot hydrate, also leading to low strength of the composite [Caprai 2018].

During the industrial production of WWCB, the stored wood logs are cut into wood strands and it has been observed that during this process, the quality of wood wool is highly dependent to the mechanical performance of the boards. Therefore, bad batches of spruce can lead to defective boards with either insufficient flexural strength (i.e. 1.7 MPa for 15 mm thick boards) or swelling/loss of cohesion of the board after demolding.

In order to investigate the cause of the failures, two batches of the same wood are investigated. The first one, named wood A, has shown no issue during the manufacture whereas the second one, wood B, is highly problematic and the boards cannot fulfill the requirement. The wood strand mechanical strength and microstructure are measured as well as the wood cement compatibility by isothermal calorimetry. The objective of the study is to identify the main cause of the problem and how to prevent it in the future.

2 MATERIALS

Two types of spruce wood (A and B) are provided by Knauf Insulation, the Netherlands. White cement CEM I

52.5 R is provided by ENCI, the Netherlands, and is used as a binder for the manufacture of WWCB.

3 METHODS

3.1 Manufacture of WWCB

Spruce strands are wetted prior to board manufacture and then, a dry binder is added on them. After mixing, the wood-binder mixture is in a mechanical press for 24 h under a mechanical press. Successively, the board is cured in plastic sheets for 7 days and left at room temperature for three days. Finally, the board is dried at 50 °C for 2 h before prior mechanical testing. The water to binder ratio used in this study is 0.5, while the wood to binder ratio is 0.75.

3.2 Flexural strength

Mechanical performances of the WWCB are tested by three-point bending test (Zwick 2020) on a sample with dimension of 20 x 15 x 1.5 cm, using a testing speed of 1.5 mm/min and a support span of 15 cm. As reference values, the dimensional stability should be satisfied by a maximum thickness of 1.5 cm and a minimum bending strength of 1.7 MPa.

3.3 Tensile properties of wood strands

Mechanical properties of wood strands are measured by using an Instron 5967 bench equipped with a 2530-100 N load cell, 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 fiber (tex) by measuring the length and the weight of each fiber prior to analysis.

3.4 Isothermal calorimetry

Wood-cement compatibility is assessed by using a TAM Air Isothermal calorimeter at a constant temperature of 20 °C. Fibers with a size of 2-4 mm are mixed with white cement and water. The water/cement ratio is kept constant for all prepared mixes (w/c = 0.45) and the fiber/cement ratio is set at 0.075.

3.4 Microscopy

Scanning electron microscope (SEM) analyses are performed by using an FEI quanta 600 environmental scanning electron microscope to observe the surface and the cross-section of the wood. Micrographs are recorded by using both secondary and backscattering electrons detectors at 10 kV with a spot of four, in low vacuum mode (0.6 mbar).

4 RESULTS

4.1 Mechanical performances of the wood wool composites

The WWCB mechanical performances are displayed in Tab. 1. The board with wood A has a flexural strength way above the board made with the wood B with an increase of 66%, reaching almost 5 MPa, which is largely above the minimum flexural strength (1.7 MPa as described in the BS EN 12089 standard). The board with the wood B is not fulfilling the minimum flexural strength and therefore is not eligible for WWCB application. The density of boards is also measured and the values are slightly different (± 5%), which can be explained by the different moisture content of the two wood (6.5% wt. vs 13.5% wt. for wood A and B, respectively). This phenomenon can affect the effective mass of wood used for the WWCB manufacture since the wood strands are weighted prior to manufacture without moisture correction. However, these very small differences in moisture content and thus in wood amount do not justify the big gap between the boards' performances, so other factors must affect the wood in the composite and are evaluated in this study.

Tab. 1: Flexural strength of WWCB manufactured with wood A and B.

	Wood A	Wood B
Flexural strength (MPa)	4.59	1.55
Density (kg/m³)	575	550

Among the potential factors that can affect wood, chemical, mechanical and microstructural analyses are performed, in order to study all the differences between wood strand A and B.

4.2 Chemical compatibility

It is well known that lignocellulosic materials and cement can interact because of the leaching of polysaccharides in the matrix, delaying the cement hydration. In order to study this effect, isothermal calorimetry measurements (heat flow as a function of the time) of the two types of wood mixed with white cement are performed (Fig. 1).

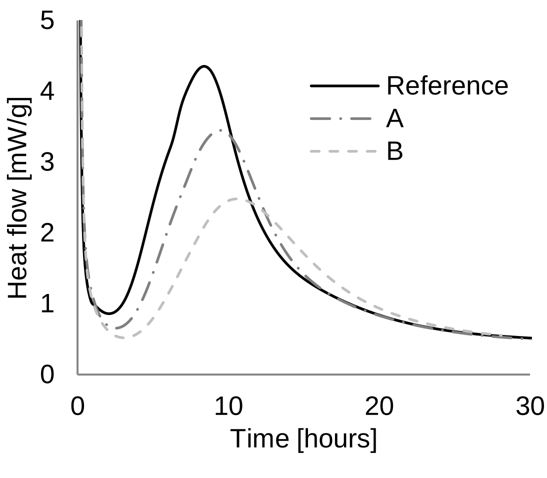

Fig. 1: Heat flow of wood A (dark gray dashed-dotted line) and wood B (light gray dashed line) when mixed with white cement, as compared to pure white cement (reference; black line).

Results show that the addition of wood A to the cement paste slightly decreases the heat flow and slows down the cement hydration. However, wood B has more significant influence both on the heat flow and the delay: Indeed, the maximum peak of the cement hydration is slow down by more than 2 h with wood B. This means that wood B leached out extractives that stop the cement hydration by diffusing into the cement paste and hindering the formation of C-S-H [Na 2014]. Based on these results, it appears that wood A releases fewer polysaccharides and extractive than wood B, which eventually causes more problems when mixed with cement. It means that from a chemical point of view, wood B might have been degraded, and part of its hemicellulose could have been transformed into various polysaccharides, as described in Fig 2.

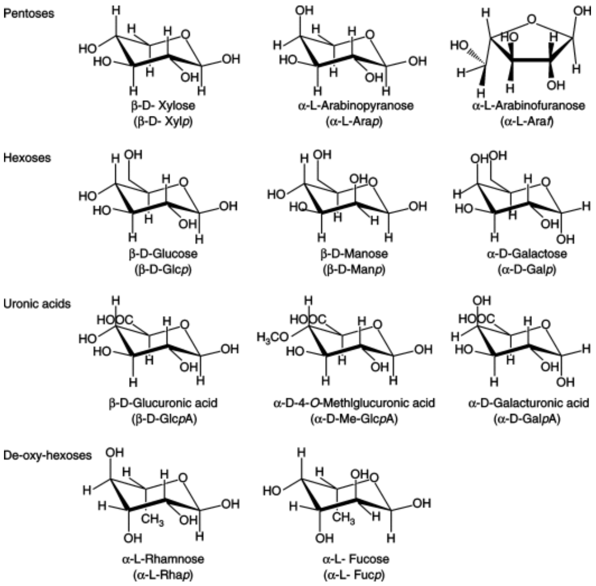

Fig. 2: List of the hemicellulose monosaccharides [Pereira 2007].

4.3 Mechanical characterization of wood strands

The tensile strength of individual wood fiber has been done to evaluate the quality of wood when turned into strands, which is used in the final product, namely WWCB. The two types of wood have been tested and the average results are shown in Fig. 3.

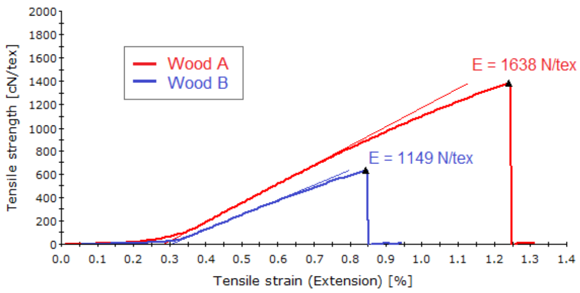

Fig. 3: Average stress/strain curve for both kinds of wood strands. In red: Wood A; in blue: Wood B.

Results show significant differences between the two samples of wood. Wood B has a tensile strength two times lower than wood A, with value going from 1316 cN/tex to 512 cN/tex. Additionally, the tensile modulus of the strands have also been measured and in this case, wood A has still greater values than wood B (+ 20%), but considering the important standard deviation of the measurement (± 15%), this decrease cannot be considered statistically as significant.

Results point out a problem that could happen prior to the wood strand production, and could affect the microstructure of the wood B. Indeed, the wood A and B are coming from the same batch and has grown under the same conditions, meaning that initially, the two types of wood had the same microstructure. Moreover, it has to be noticed that these two kinds of wood have validated the standard quality controls, meaning that initially, no problems were detected.

This very important decrease in the tensile strength of wood B can be explained by a modification of the wood microstructure (Fig 4). Wood is a lignocellulosic material, which can be considered as a fiber-reinforced composite, with cellulose fibrils as reinforcement, and hemicellulose as a matrix.

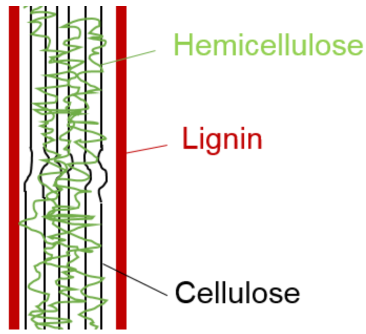

Fig. 4. The microstructure of wood constituted of lignin, hemicellulose and lignin.

Here, the tensile moduli of the wood A and B are sensibly the same, showing that the cellulose has not been affected by the internal degradation: indeed, the intrinsic mechanical properties of wood (i.e. Young's modulus) are coming from the cellulose fibrils inside the hemicellulose and lignin matrix [Nairn 2007]. On the other hand, the tensile strength of the wood B strands decreases a lot as compared to wood A, because the tensile strength of the fibers (and a composite in general) is not only defined by the cellulose (i.e. the reinforcing fiber in the composite) but also any defects that can be present at the fiber surface (i.e. stress riser), or the interfacial properties between the fiber (i.e. cellulose) and the matrix (i.e. hemicellulose and lignin).

In order to answer this hypothesis, further microstructural analyses are performed

4.4 Surface characterization of wood strands

Among the hypothesis explaining the performances of wood B, a probable one would be that the hemicellulose has been degraded during the wood storage. This slight degradation has a negligible effect on the wood properties because it was not visible during the quality control of the wood but when cut into strands, this effect is much more noticeable, as it was characterized in the previous sections (e.g. decrease of the mechanical properties, inhibiting effect on cement hydration…). Morphology analyses are done by SEM in order to study this phenomenon. Fig 5 and 6 show the surface of wood strand A and B.

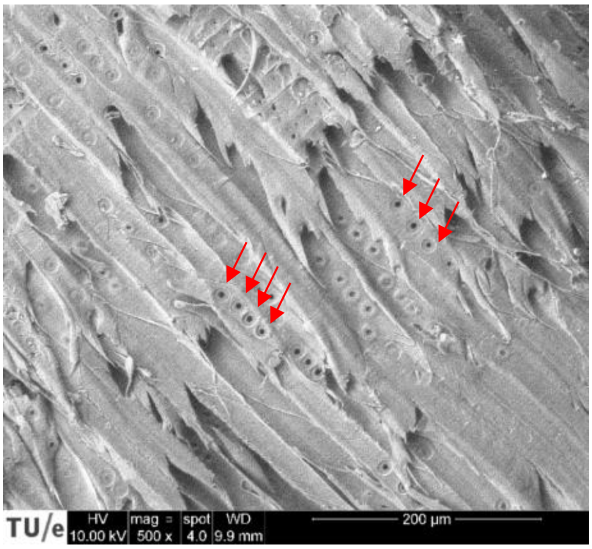

Fig. 5: SEM micrograph of wood A surface.

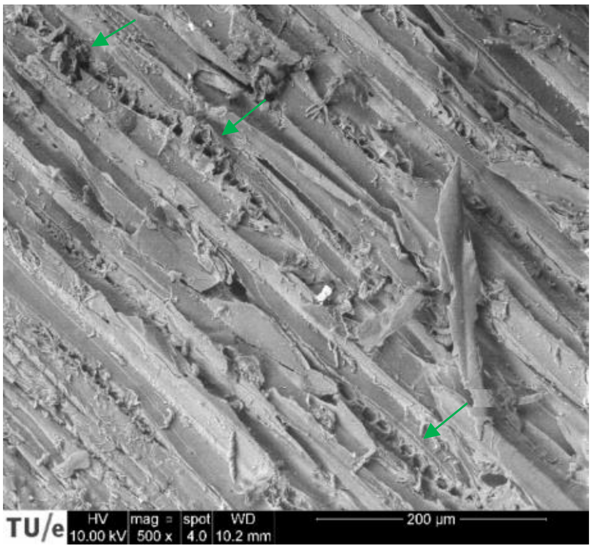

Fig. 6: SEM micrograph of wood B surface.

The surface of the wood A is similar to conventional spruce wood strands, where the pits (red arrows) are easily observable and aligned [Gindl 2006]. The hemicellulose/lignin matrix is uniformly dispersed at the surface. However, the surface of wood B is very different. Indeed, the pits are not well defined and are damaged (green arrows). From the literature, this phenomenon is very similar to brown-rot fungi bio-degradation, with fungal hyphae coming out of the pits [Durmaz 2016]. This degradation type is quite common with wood, where the fungi digest the hemicellulose. But in this micrograph, it appears that the matrix is completely destroyed, which happen exclusively at the pits' surface. Further characterization is done by observing the transverse section of wood A and B, showing the cells inside the wood (Fig. 7 and 8). Both wood strands have a very similar structure, with well-defined cell walls, which are not degraded.

Here, the wood cells of both kinds of wood are intact, with no visible shrinkage or distortion, which can be visible in comparable studies in the literature [Tamburini 2018]. Moreover, no fungal hyphae are observable inside the cell walls in both micrographs.

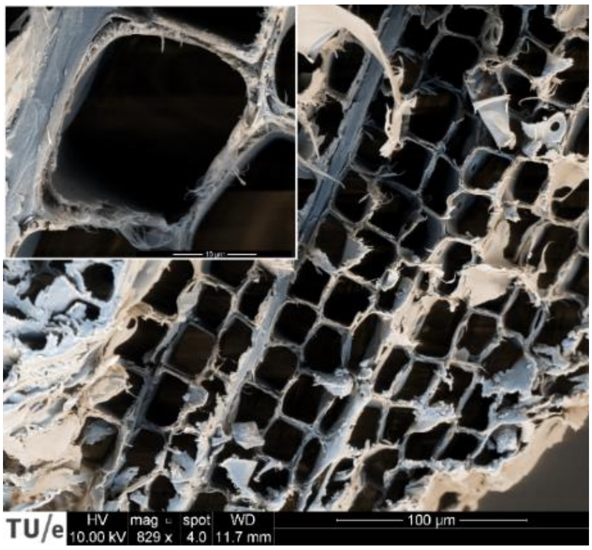

Fig. 7: SEM micrograph of the transverse section of wood A.

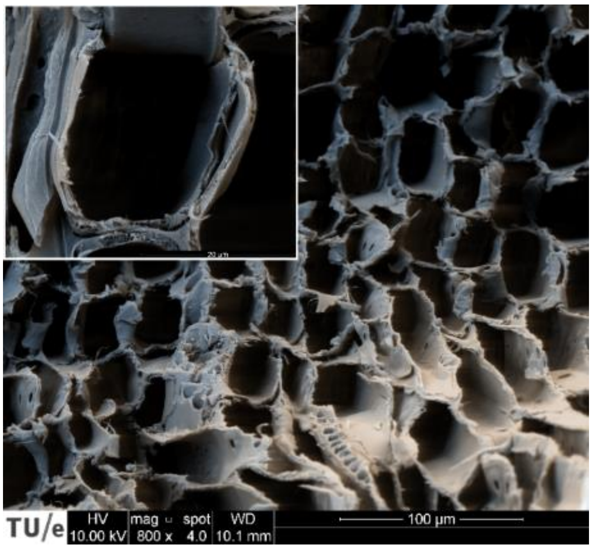

Fig. 8: SEM micrograph of the transverse section of wood B.

4.5 Discussion

From these results, several conclusions can be drawn. First, wood A is intact, with no traces of any kind of degradation, neither at the surface nor inside the cells. The microstructure of this wood is very similar to the conventional spruce which is used in WWCB. Therefore, wood A can be considered as a reference wood On the other hand, wood B has degraded. Interestingly, this degradation only occurs close to the surface pits, but inside the cells, where the cellulose fibrils are located. It explains the mechanical behavior of wood B, with a significant strength decrease, explained by the local destruction of the hemicellulose matrix leading to an important stress concentration factor, but a relatively unchanged Young's modulus because the cellulose fibrils, with high tensile modulus, have not been damaged.

Additional characterizations must be done to completely assess the degradation, such as chemical analysis of the two type of woods as well as their leachates measurements. In overall, if the fungi attack around wood pits is clearly identified, different solutions can be applied in order to limit this degradation. Among the conventional methods, most of them are toxic or/and harmful for the environment and can be realistically used to treat wood strands for composite applications [Ritschkoff 1996]. Since this degradation only occurs close to the pits, it would be interesting to develop a method that can only target this location, which will be evaluated in the near future.

5 SUMMARY

In this study, two similar types of spruce wood have been characterized. When cut into strands and mixed with cement, wood B cannot fulfill the required standard for flexural strength of WWCB (< 1.3 MPa) whereas wood A is performing very well in composites (flexural strength of WWCB = 4.6 MPa). Various methods such as isothermal calorimetry, tensile test of wood strands and electron microscopy show that wood A is not damaged at all and can be comparable to fresh spruce wood, as described in the literature. However, wood B, similar in many ways, has different properties, in terms of chemical compatibility, mechanical properties and surface microstructure. Results show that the degradation is most likely coming from brown rot fungi formation around the pit at the surface of the strand, eventually degrading the hemicellulose and lignin, which drastically decrease the strength of the wood, and therefore, the strength of the composite.

6 ACKNOWLEDGMENTS

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