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Influence of the spruce strands hygroscopic behaviour on the performances of wood-cement composites

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HIGHLIGHTS

- An absorption model for wood strands is proposed and validated by NMR.
- Different water to binder ratios are calculated for wood wool composites.
- The pre-soaking of strands is quantified for according to the water to binder ratios.
- Flexural strength achieves 3.8 MPa by applying a water to binder ratio 0.5.

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ABSTRACT

In wood wool cement composites, the influence of natural fibres is the main factor leading to the instability of the final product. During the manufacture, small variations in wood properties result in inhomogeneous density and strength of the boards. Among the accountable factors, the hygroscopic behaviour of the wood can deeply affect the cement hydration. However, the competitive water absorption mechanism between wood strands and cement is not fully understood. This paper will address the absorption behaviour of wood wool strands in combination with cement. A model for calculating the water to binder ratio of the paste in presence of wood is proposed and validated by NMR and isothermal calorimetry. Finally, the mechanical performances of the composites are tested for different water amounts, verifying the proposed model and defining the conditions for the optimal bending strength.

1. Introduction

Due to the growing environmental concern, bio-based materials have become a common substitute for the conventional reinforcement in composites [1]. Natural fibres are often used in cement composites to increase both toughness and mechanical performances [2,3]. Moreover, they are employed due to their ease of production, the low density and the enhanced biodegradability, leading to applications for sustainable purposes in civil engineering [4–6]. On the other hand, the presence of wood introduces some critical factors, which affect the properties of the composites, compromising their final stability. Among those factors, the time of harvest, the wood species, the storage conditions, the composite manufacturing method and the moisture content [7] are playing a major role [8,9]. Therefore, even if the production process does not change, the variation in these other wood parameters creates heterogeneity in the final product properties [10]. Since 1940, the wood wool (called Excelsior) for wood wool composite boards (WWCB) manufacture is commonly used in Europe and Asia [11]. WWCB are used as fire resistant, sound absorbing walls and ceilings, but also as thermal insulation panels [12]. Although produced on a large scale, the composition and properties of the WWCB are variable, having an apparent density in the range of 300–500 kg/cm^3, a wood/cement ratio between 0.4 and 0.6, and a final bending strength lower than 10 MPa [13].

1.1. Factors influencing the stability of wood wool composites

In general, acceptable properties of an inorganic bonded board are dependent on both the amount and nature of the binder and on the wood properties [14]. Among the influencing factors, it is well known that the presence of wood extractives might inhibit the hydration of cement (PC) [15,16]. Granting the impossibility to fully avoid the presence of those extractives, some wood species, such as Spruce, normally do not cause the inhibition of the cement hydration, because of their lower content of those water-soluble compounds [17].

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Numerous factors can affect the bonding mechanism between cement and wood. Among them, the hygroscopic behaviour of the wood plays a major role in the cement hydration, by determining the amount of water available for the binder [18,19]. In presence of water, the ions exchange between cement and wood could lead to a strong bond between the two materials, due to the improved anchoring of the binder [10]. However, for excessively soaked strands, the migration of water soluble extractives is favoured, leading to the partial setting of the cement paste.

Therefore, a low initial moisture content of the wood means that part of the water used for cement hydration will be absorbed into the wood structure, instead [20,21]. Contrariwise, an excessive moisture content of the strands will provide an abundant amount of water for the cement hydration, increasing the final water to binder ratio (w/b) of the paste, but also causing the dissolution of extractives, resulting in a low strength development [22]. This is the reason why the manufacture of a composite must take into account both the water for the distribution and the reaction of the binder [10]. Until nowadays, the liquid absorption mechanism of Norwegian spruce in form of wood wool strands is not often investigated, leading to uncertainties about the quality of the bonding between wood strands and mineral binder. Moreover, in the face of the necessity to limit this ion exchange, the influence of the absorption behaviour of wood strands in presence of PC as well as their "competitive absorption" has not been investigated. The determination of the effective amount of water available for binder hydration is necessary to reduce the inhomogeneity during manufacture. Furthermore, a better understanding of the effective w/b ratio applied will ensure the maximization of the mechanical performances of the composite.

In this study, a characterization of Portland cement and Norwegian Spruce excelsior wood wool is provided. Thereafter, the liquid uptake of spruce strands is measured empirically and by solid state hydrogen nuclear magnetic resonance (NMR) results, which helps to differentiate the water located in the spruce structure and on the strands surface. Based on the results, the quantification of the pre-soaking water necessary for a precise w/b ratio in the binder is computed, considering the wood initial moisture content (MC_i), the binder water demand and the wood/binder ratio of the composite. The validation of the model is performed using isothermal calorimetry, by comparing the cumulative heat of the binder in presence and absence of wood, at 48 h. According to the same w/b ratio used in the validation, WWCBs are manufactured and tested for bending strength, by three-point flexural testing.

1.2. Boundary conditions for the liquid sorption model

The behaviour of wood strands in presence of water is directly related to the wood species, the structure of the wood cell, as well as their chemical composition. The main regions used for characterizing the wood moisture adsorption capacity in this study are displayed in Fig. 1, together with the water speciation in the wood cell, depending on the different moisture contents (MC). In oven dry conditions (0% MC) the wood structure is composed of cells, characterized by cell walls and empty lumens; no water is detected in the structure [23]. A second region is defined as the "hygroscopic region" [23], where the wood behaviour is mainly influenced by the presence of amorphous cellulose and hemicellulose [1,24]. Compared to crystalline cellulose, amorphous cellulose attracts more liquid and chemically bind the water molecules, due to the numerous available sorption sites (-OH groups) [23]. In the hygroscopic region, the cell walls are filling up until saturation, while no liquid is in the lumens [25]. In this study, the fibre saturation point (FSP) is considered equal to 30% MC (based on the oven dry mass of the wood) [25], which corresponds to the conditions where the cell walls are completely filled and the lumens are completely empty. The region over 30% moisture content is defined as "over-hygroscopic region", when the water is in the lumens, as the cell walls are already completely filled. This physical water absorption takes place only by capillary suction [23]. As measured in a preliminary study, fully saturated conditions (220% MC) are achieved when all the lumens and smaller pores are filled.

2. Methodology

2.1. Materials

In this study, Norwegian spruce is used as reference wood in the form of Excelsior wood wool, provided by Knauf Insulation (NL). Spruce is analysed in the form of strands 2 mm wide, 0.4 mm thick and 250 mm long. The binder applied in the study is CEM I 52.5 R white (PC) provided by ENCI (NL).

2.2. Methods

2.2.1. Materials characterization

The dry mass of the wood wool has been measured by drying the sample in an oven at 105° C, for 24 h [25]. Visualization of the spruce structure is performed by Scanning Electron Microscopy (SEM, Quanta 650 FEG, FE), coupling large field detector, GSED detection (LFD) and BSE- detector (low vacuum, chamber pressure 0.6 mbar, spot size 4.0, voltage 10 kV). The analysis of the chemical composition of spruce is done accordingly by HPAEC to Tappi T222, Tappi UM250 and Tappi T264 standards. A general chemical composition of the binder is measured by X-ray Fluorescence spectrometer (PANalytical Epsilon 3 range, standard less OMNIAN method), on pressed powder. The specific gravity is determined,

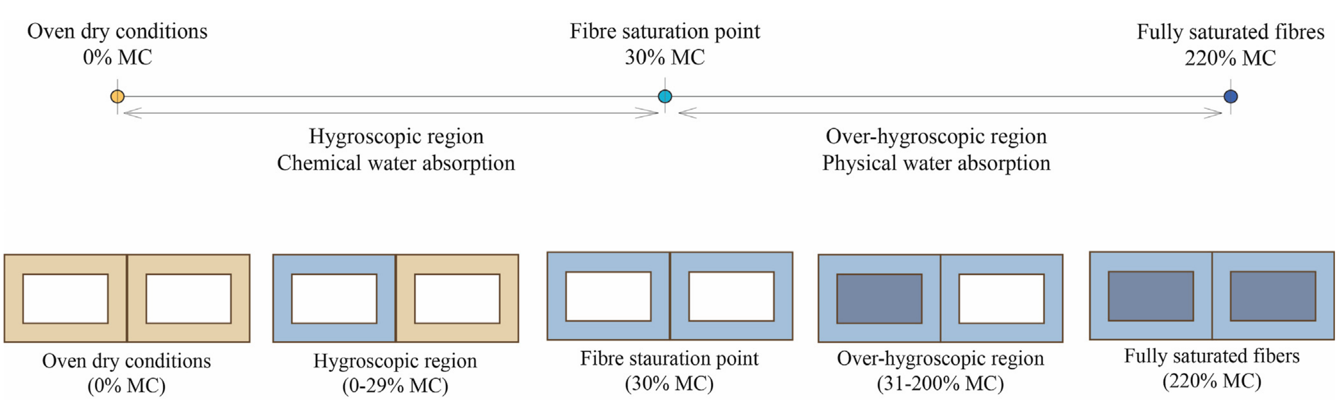

Fig. 1. Representation of the water speciation in an enlargement of wool wood cells, according to the increasing moisture content [19–20]. Wood moisture capacity is characterized by two main ranges: the hygroscopic region (0–29% MC) and the over-hygroscopic region (between 31% and 220% MC).