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Combining electrical resistance and 3-D X-ray computed tomography for moisture distribution measurements in wood products exposed in dynamic moisture conditions

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Strength and durability of wood-based products are substantially influenced by moisture. It is, therefore, crucial to monitor the moisture content (MC) distribution in wood products to fully understand their behaviour in dynamic moisture conditions. In this paper, we present a combined X-ray CT method and an adapted version of the electrical resistance MC measurement method for detailed studies on MC distribution in wood products. The X-ray CT method is evaluated using the gravimetrically recorded MC of solid wood. Subsequently, the recorded MC of electrical method is evaluated by using X-ray CT method. Three wood products are used for this purpose, i.e. solid wood, plywood and oriented strand board (OSB) panels. It is proven that X-ray CT method can accurately determine the MC of wood products and thus has great potential for non-destructively measuring the MC distribution in 3D. Furthermore, the results show that electrical method can effectively record the local MC when the MC distribution in this region is even. Otherwise, the position of the electrodes, with regard to specific wood properties has a substantial influence on its performance. Compared with solid wood and OSB, the electrical method performs best in plywood due to its layered structure. The adapted electrical method is an effective tool for continuously monitoring the MC distribution of wood products, taking into account that the electrodes are installed correctly according to the structure of the material and research questions. Combined with X-ray CT scanning, MC distribution of wood-based products under in-service applications, can be monitored.

1. Introduction

Wood is increasingly used as a construction material in the building industry because of its sustainability, renewability and flexible usability. However, as a natural material, wood is prone to attack by fungi when water is available and environmental conditions favour growth. The optimal condition for decay by the most active white and brown rot fungi is the moisture content (MC) above fibre saturation point (FSP). The MC of wood, therefore, is usually considered as the key factor that determines whether or not fungi can grow, and thereby wood rot can occur [1]. It is well known that the MC also has an important influence on the physical and mechanical properties of wood-based materials [2]. Hence it is crucial to monitor MC when wood is used outdoors to better understand its behaviour when subjected to dynamic outdoor conditions with possible liquid water ingress. Previous study by Van den Bulcke and co-workers [3] introduced the CMM method, with continuously weighing of plywood exposed outdoors for calculation of the average MC of the samples. Moisture distribution is a key factor as well. To further monitor this distribution, one could cut the samples into small sections, weighing them individually to reconstruct the moisture distribution [4], yet this technique is obviously a destructive one, hindering long-term recording. The electrical resistance method is another method to continuously record moisture, being non-destructive and reasonably accurate. Long-term electrical measuring MC of rather large samples, made of pine, spruce and fir, has been tested before as a feasible approach [5,6]. More advanced techniques exist as well. Magnetic resonance imaging is a non-destructive modality that has been used too as a tool for monitoring the free water movement in wood and wood-based products [7,8]. Other researchers [9,10] have proven that X-ray scanning, also

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as a non-destructive approach, could efficiently reveal density distributions in wood products and wood-based composites. There is a linear relationship between CT number and density of wood containing both wood substance and water [11]. According to the density in different positions of the wood, moisture distribution was further derived from these scans [12,13]. Neutron imaging is similar to X-ray methods but not as common as the latter. It was also used to test wood density and moisture in previous studies [14,15].

Clearly many approaches have been applied for monitoring the MC content and distribution of wood products, but there is not a single method that can simultaneously monitor accurately, continuously and non-destructively the MC distribution in dynamic moisture conditions. Hence, in this research, an X-ray CT method was searched for to accurately map the MC distribution of wood products in three dimensions. This method was then used to evaluate whether an adapted version of the electrical resistance measurement as described by Brischke et al. [5] can be the preferred non-destructive and effective method to continuously monitor the water distribution in different wood species and wood-based panels. Several specimens of solid wood, plywood and OSB were immersed in water for 16 days (384 h). All specimens were scanned on a regular basis with high-throughput X-ray CT to link the actual local MC inside the specimens and the MC as recorded with the electrical resistance measurements. Furthermore, the relationship between the microstructure of the specimens and the electrical MC measurement performance was analysed using the volumetric X-ray data.

2. Material and methods

2.1. Specimens without electrodes

A set of specimens was used to assess the accuracy of X-ray CT method for moisture distribution monitoring. Solid wood specimens measuring 50 × 50 × 15 mm^3, were prepared from four wood species: poplar (*Populus* spp.), Scots pine heartwood and sapwood (*Pinus sylvestris*) and birch (*Betula* spp.). All specimens were without decay, knots and obvious defects. The specimens were conditioned in a conditioning room at 65% RH and 20 °C until constant mass after which all specimens were weighed. The specimens were immersed for 48 h in a container filled with demineralized water. During this period, the specimens were weighed and scanned after 0, 1, 4, 8, 24 and 48 h of immersion. After 48 h of immersion, the specimens were oven-dried, weighed and scanned. With each scan also a plastic vial containing demineralized water was scanned along.

2.2. Specimens with electrodes

For evaluation of the electrical resistance method, solid wood specimens were prepared from six different wood species: poplar (*Populus* spp.), spruce heartwood (*Picea abies*), Scots pine heartwood and sapwood (*Pinus sylvestris*), okoumé (*Aucoumea klaineana*) and birch (*Betula* spp.), all measuring 70 × 50 × 15 mm^3 and 50 mm along the grain direction. Also PF (phenol formaldehyde) glued plywood, and OSB panels with isocyanate glue, were prepared and sawn to the size of 70 × 50 × panel thickness mm^3 (Table 1). All specimens were without decay, knots and obvious defects. Two holes of 4 mm diameter were drilled in the specimens. The distance between the centres of the holes was 30 mm orthogonal to the grain. Inside the 4 mm drill hole, another small hole with 1 mm diameter was drilled starting from the bottom of the former drill hole (Fig. 1). Then, these specimens were conditioned in a conditioning room at 65% RH and 20 °C until constant mass after which all specimens were weighed. After weighing, all sides of the solid wood

Table 1
The details of the wood-based panels.

Type	Wood species	# of plies	Thickness [mm]
Plywood	Pine	7	18
Plywood	Spruce	5	15
OSB	Spruce + Pine	–	17

specimens except one end grain face (cross section) were sealed, while, for plywood and OSB panels, only four sides were sealed. This way, the water was allowed to enter the specimens in one direction only. Next, the wires were glued in the predrilled holes with conductive and isolating glue as described in Brischke et al. [5].

These electrodes were made of stripped commercial wires. In order to avoid beam hardening and metal artefacts in X-ray CT scanning, thick metal wires such as described in Brischke et al. [5], are not suitable. Hence, wires with plastic cover having a diameter of 0.2 mm were used in this experiment. Furthermore, in order to decrease possible noise, the following protocols had to be followed: the wires in the small holes at the bottom of the large drill holes were fixed using conductive glue to make sure these electrodes could effectively test the MC at the region of interest (further called ROI, see Fig. 1). We assume that the measurements are mainly influenced by the MC in this region. As is well known, water movement in wood mainly takes place along the grain direction and the speed of movement is not identical for different wood species. Hence, for solid wood, the distance (X) between end grain face and the electrodes is different according to the anticipated absorption of the different wood species (Fig. 2). These distances are listed in Table 2. All electrodes were positioned at the same depth, i.e. 7 mm from the top face. It is the aim of electrical resistance method to measure the general MC distribution instead of accurate regional MC of different wood products. Electrical loggers (Materialfox Mini), with the same formula to convert electrical

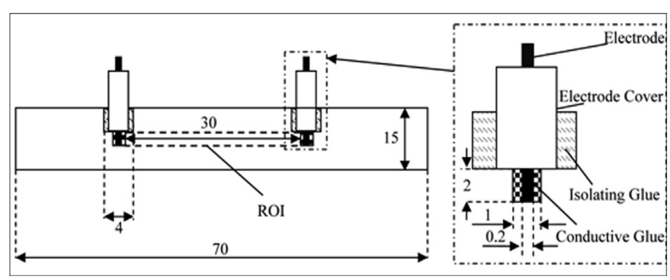

Fig. 1. Detailed view of electrodes (all dimensions in mm).

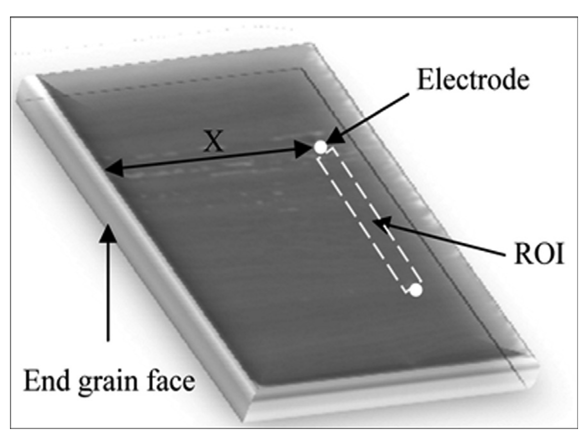

Fig. 2. Overview of solid wood specimen.