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CT SCANNING OF CAPILLARY PHENOMENA IN BIO-BASED MATERIALS

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Abstract:

X-ray computed tomography (CT) is a powerful tool for the non-destructive study of dynamic moisture processes in wood and other bio-based materials. In the CT facilities at Luleå University of Technology, it is possible to study wood-moisture relations such as water absorption, drying and related material deformation under a temperature- and humidity-controlled environment.

An increase in the use of bio-based materials in building construction has led to an increased interest in capillary phenomena in these materials, because of an increasing number of moisture-related damage in timber and hybrid-timber buildings. This article shows some examples of how different bio-materials used in construction interact with liquid water over time. The overall purpose has been to develop the CT technique as a powerful tool for the determination and visualization of capillary flow that can be a base for modelling and an increased understanding of moisture flow in new bio-based building materials.

Early-stage observation of the behaviour of different traditional and new bio-based building materials shows that CT scanning, combined with image processing, has a high potential to be used in performing non-destructive and non-contact tests that can help to increase the knowledge of water-material interactions and develop building materials with an optimized performance.

Key words: *X-ray computed tomography; wood; water flow.*

INTRODUCTION

The use in construction of building materials based on residues from forest and agricultural activities is growing as society moves towards a bio-based economy. This represents an opportunity to turn waste material from these activities into profitable by-products. One common use for this type of material is as thermal insulation for buildings. The durability and functionality of bio-based insulation materials depends to a high degree on their behaviour and interaction with water. Capillary water is of crucial importance for the durability and long-term performance, because of the severe damage that can occur in a relatively short time. Current knowledge about material-water relations for many bio-based materials is inadequate, especially for the newest products such as insulation materials from recycled paper, flax, jute and wood fibres. Furthermore, the standards that are accepted for the determination of certain physical properties may not be easily applicable to newly developed materials with a composition and structure that differ substantially from the products that they may substitute and for which the standards are developed. For that reason, new ways of studying the interaction of new bio-based materials with moisture is of crucial importance for their durability and performance as competitive building materials.

In their natural state, bio-based materials from the forest and the agricultural sector are biodegradable and strongly hygroscopic, in contrast to materials from non-renewable sources. When new bio-based materials are introduced into e.g. the building sector, questions related to how the materials and structures interact with moisture will arise.

A better understanding of material properties is therefore necessary for architects, designers and other professionals involved at an early stage in the design and development of buildings. An example of poor performance was the external wall insulation system EWIS in Swedish single-family houses that quickly led to severe moisture and mould problems, and also to health problems for people living in the houses (Swedish High Court Judgement 2015). Experience from history of how wood in particular has been used in an unfortunate way is frightening, both in construction and in the way it has been handled during the building phase. The most common problems involve moisture-related damage, and such problems are often presented as a serious objection to an increase in the use of bio-based materials and they show the need for further development.

Another crucial aspect is that the climate change is expected to lead to new material requirements particularly with regard to their functioning under an increased moisture stress during extreme rainfall and floods.

Capillary water transport in bio-based materials is a particularly critical feature that can lead to unfavourable moisture levels. Unacceptable discoloration caused by mould growth and fungal decay, critical delamination of coating or adhesive, dimensional instability, deterioration in mechanical performance and in insulating capacity are examples of building material properties flawed by poor moisture control (Dvinskikh *et al.* 2011).

Capillary flow is three-dimensional and non-gradient driven. Experimental studies and models for capillarity are not trivial, since capillarity is governed by small-scale variations on a microstructural scale in the material. Species-related properties also have a significant influence on the capillary flow. Monocotyledons, for example, have a special layer on their external surface consisting of waxes that dramatically influence the contact angle and thus the capillary properties (Barthlott *et al.* 1997). This is of great importance for the usability of Reed canary grass and other agricultural raw materials in construction materials (Trischler and Sandberg 2014).

Capillary-driven flow in a hygroscopic material has traditionally been modelled as a diffusion process. It is well known, nevertheless, that it is not actually a proper diffusion process. An increasing number of experimental results indicate that the diffusion approach cannot correctly describe some essential parts of the process (see e.g. Salin 2006), and the knowledge level of the mechanism of capillarity in many bio-based materials is low. One approach for modelling capillary flow is the percolation approach where the material is viewed as a porous material with cavities of different sizes (Stauffer and Aharony 1994). The influence of time and how time enters into capillary flow are, however, somewhat unclear, since flow cannot be instantaneous. Capillary flow has been studied relatively thoroughly for wood (Petty 1974, Spolek *et al.* 1981, Perre and Turner 2001, Segerholm and Claesson 2008, Zelinka *et al.* 2016). Several other hygroscopic materials have been studied by e.g. Peishi and Pei (1989), Segura and Toledo (2005), and Zhu *et al.* (2012). Nearly all these authors indicate that a basic understanding of the underlying mechanisms for capillary flow in the bio-based materials studied is deficient, and this leads to a poor output from modelling work on capillary flow. This is an argument for the more detailed study of the capillary flow phenomenon presented in this paper.

For a bio-based material to be competitive in most building applications, it is necessary to find means to enhance its performance and service life. A possible way to accomplish this is through modification. Three fundamentally different wood modification methods have recently been commercialized: acetylation, furfurylation and thermal modification (Hill 2007, Navi & Sandberg 2012).

At the Wood Science and Engineering department at LTU in Skellefteå a score of PhD theses have been produced based on research that has been built up around the use of computer tomography (CT) in wood. The results of these CT studies have totally changed the understanding of water flow in the capillary regime during wood drying (Morén and Sehlstedt-Persson 2000, Wiberg 2001, Sehlstedt-Persson *et al.* 2006, Schepers *et al.* 2007, Johansson and Kifetew 2010, Hansson and Cherepanova 2012, Vikberg *et al* 2012). Nevertheless, there is a lack of knowledge regarding bio-based materials, which are particularly complex due to the fact that they are both porous, and also consist of fibre walls that are hygroscopic and absorb water vapour from the air. For the same reason, the loss of capillary water from bio-based material during drying must be explored in detail. In addition to this lack of knowledge in the field, this project deals with the lack of standardised tests to study capillary absorption phenomena in porous materials. Thus, the first efforts are being focused on the design of the experiments.

The long-term vision driving this project is that by-products from the forest or agricultural biomass will be used to replace materials in building applications where fossil and non-renewable materials are currently being used, and that the use of bio-based materials will increase to a level which supports a sustainable development.

Computed tomography

Since it was introduced in the 1970s, X-ray computed tomography (CT) has proven to be a powerful tool in the medical field and its use in materials science is now widespread. It is an imaging technique based on measurements of the amount of X-ray radiation that is able to pass through a body of a given material, a property that is defined by the attenuation coefficient of the material (Kalender 2011). The theoretical background of CT lies in Lambert-Beer's law, which shows an exponential relationship between the intensity of the radiation and the attenuation coefficient:

$$I = I_0 e^{-\mu d} \tag{1}$$

where: I is the intensity of the transmitted X-ray beam, I_0 is the intensity of the incident X-ray beam, μ is the linear attenuation coefficient of the material along the transmission path and d is the thickness of the body.
CT images are in a grey scale and, for most biological materials, the grey scale values are almost linearly related to density, being darker for lower density and brighter for higher density

OBJECTIVES

The purpose of this paper is to show ways in which different bio-materials used in construction interact with liquid water over time. The main parameter taken into account is the absorption of liquid water above the water level when the material is partially submerged. Other parameters like bound water gradient, material structure and a comparison between modified and unmodified materials are also considered and studied.

MATERIALS, METHODS AND EQUIPMENT

The studied materials were classified in two groups: (1) "solid materials", i.e. wood and traditional wood-based materials. Even though these materials are actually porous, they are referred to here as solid materials to distinguish them from the materials in the other group. (2) Porous materials, such as various low-density insulation materials produced from forest and agricultural by-products, recycled newspapers, pulp, jute, wood fibres, etc. As an example of modified wood, specimens of thermally modified timber have been included in the tests. The specimens were obtained as boards (15 to 30mm thick) or panels (45 to 65mm thick) and cut to a dimensions of 230x160mm. The specimens were conditioned at a temperature of 20°C and 60% RH for seven days before the tests started.

A medical CT-scanner Siemens Somatom Emotion Duo with a field of view of 500x500mm^2 represented in a 512 x 512 pixel image, which gives a resolution of 0.98mm, was used. By applying different reconstruction algorithms, images with a higher resolution can be generated, up to 0.1mm, but with the side-effect that properties of the images such as noise and sharpness are altered. The scanning depth ranges from 1mm to 10mm, thus the smallest voxel that can be represented in an image is 0.1x0.1x1mm^3. This piece of equipment was the main tool around which the research took place. The scanning time of this scanner is around 1s for a single scan. In this case, the scanning is performed in a spiral along a distance of about 900mm, which produces nearly 300 single 3mm thick scans that are taken in a continuous manner. This process takes about 70s. In order to perform experiments in a controlled and monitored environment, a drying chamber that works in combination with the scanner was used, allowing the scanning of the interior of the chamber as the temperature and relative humidity were controlled and regulated with time.

A rig of acrylic plastic in which specimens were held in a vertical position was manufactured specifically for these experiments (Fig. 1). The rig allows water to be filled to a certain level so that the specimens were partially submerged in a constant level of water (around 15mm) and so that they could be scanned. Three plastic balls filled with water were placed in the rig (visible in Figs. 1 and 2), for spatial coordinate references in the evaluation of the CT images. CT scans were performed periodically in order to observe the transport of water within the samples. These images were processed so that both visualization tools and models of the phenomena can be developed at a further stage in the project.

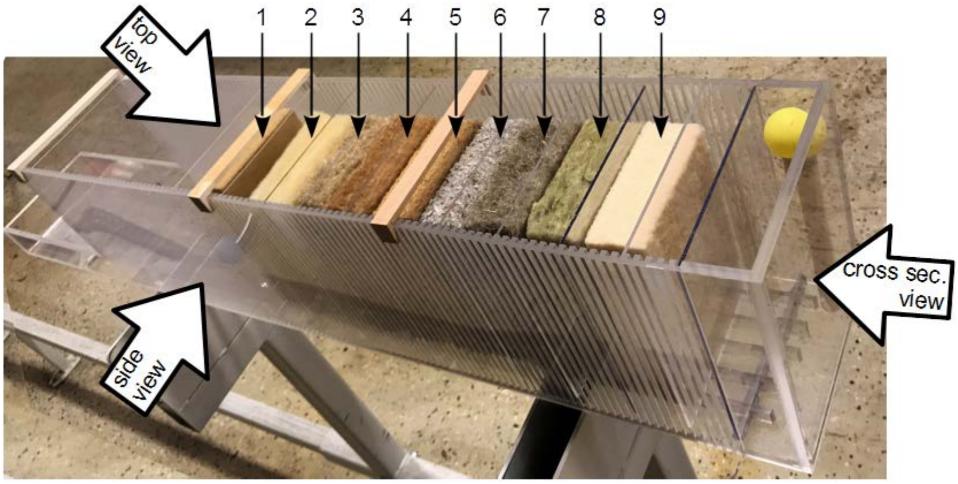

Fig. 1.
Experimental setup. Tested bio-based insulation material in the rig are:
(1) Pavatherm combi (wood fibers), (2) Glass fiber, (3) Thermohanf Premium (hemp), (4) Thermojute (jute), (5) STEICOflex (pine wood fibers), (6) iCell (newspaper), (7) Isolina (linen), (8) Stone wool, (9) Thermocell (pulp).

RESULTS AND DISCUSSION

Fig. 2 shows how different materials can be visualized simultaneously and how the water uptake can be compared. The image shows clearly the different levels of water absorption in three different materials (Fig. 2b,c,d), and the rise of capillary water to a higher level inside fibres (Fig. 2d). In this kind of material made of vegetal fibres and particles, a large moisture gradient can be seen rising (Fig. 2b,c). This could be due to capillary absorption in fibres with a small diameter that are not visible at this resolution level, which would allow a higher level of capillary absorption, or it could be due to a rise in the moisture content level in the cell-wall material that remains.

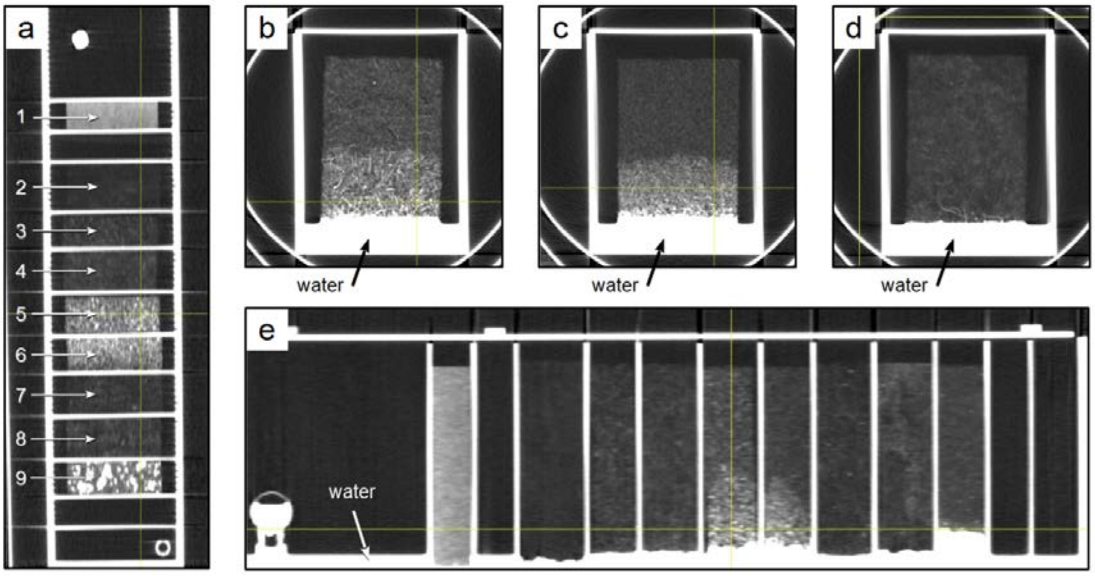

Fig. 2.
CT images of the experimental setup: (a) top view of the rig including 9 different insulating materials according to Fig. 1, (b-d) Cross section view of three different insulation materials submerged in water for 24h: (b) pine wood-fibre (Fig. 1 (5)), (c) recycled newspaper (Fig. 1 (6)), and (d) jute panel (Fig. 1 (4)). (e) side view of the rig. Cross section, top and side views are according to Fig. 1.

In the group of solid materials, various interesting and unexpected phenomena were seen. Fig. 3 shows the difference in water uptake (white colour) between aspen heartwood and sapwood within a single piece, where it can be seen that sapwood absorbs more water than heartwood.

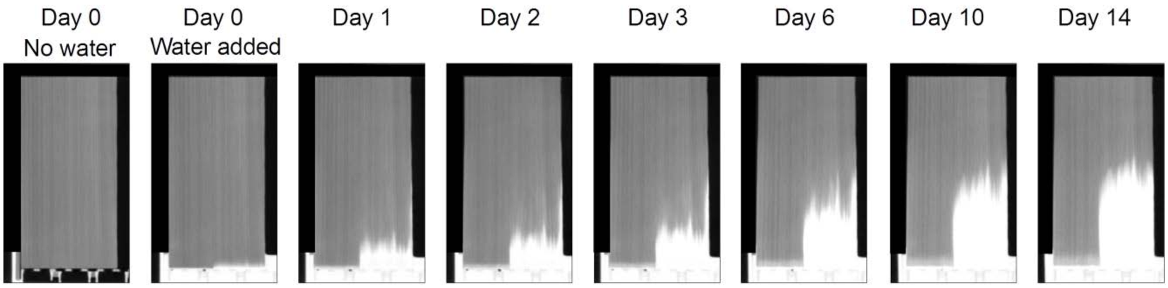

Fig. 3.
Water absorption (white area) in an aspen specimen containing sapwood and heartwood in cross section view according to Fig. 1.

Thermal modification is a process where wood is heated to about 200°C in order to decrease the hygroscopicity and increase the dimension stability of the material. Water absorption in solid aspen and birch wood gets dramatically reduced after thermal treatment. This is clearly visible in the CT images and it is possible to follow as a function of time (Fig. 4).

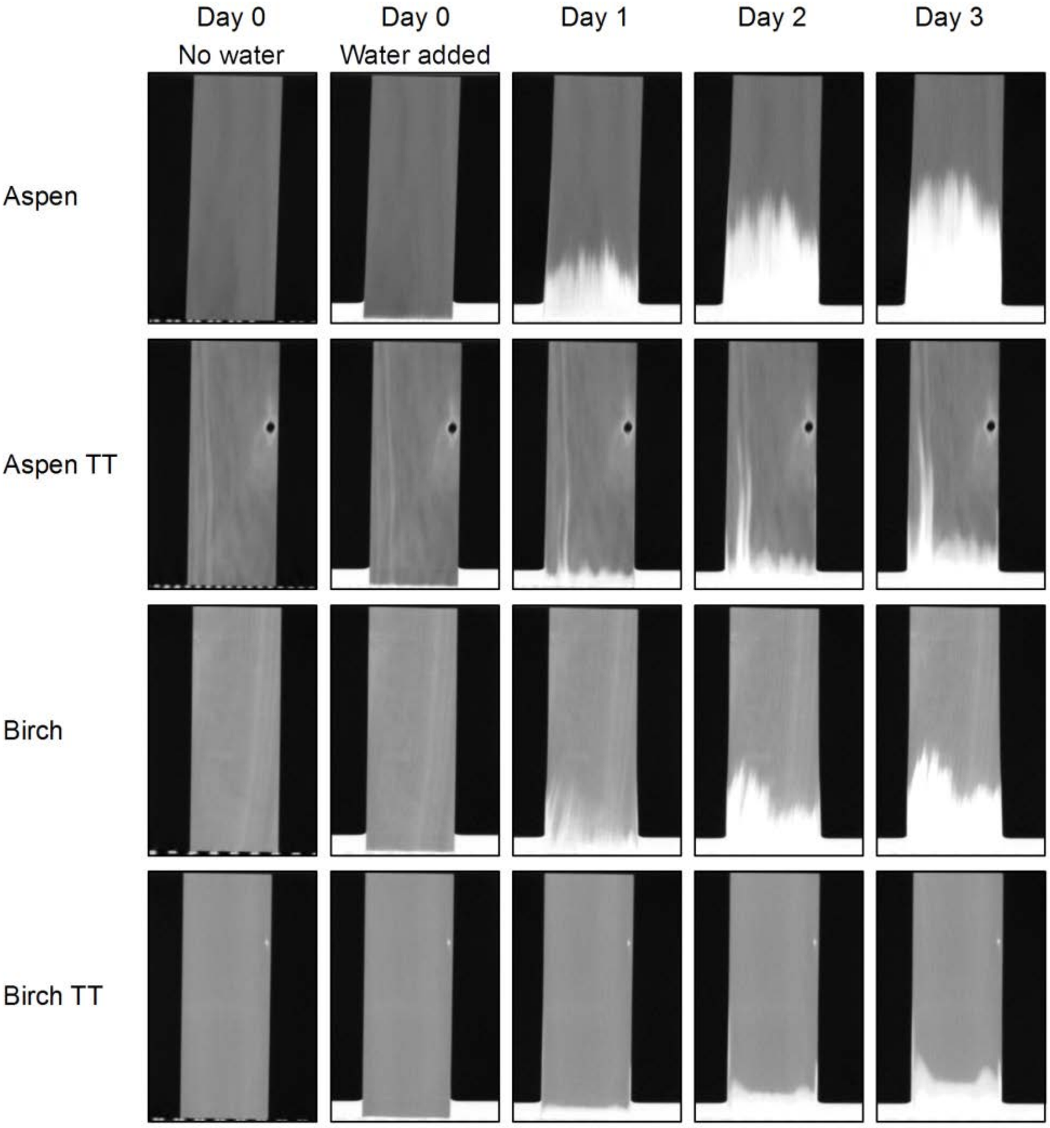

Fig. 4.
Water absorption (white area) in unmodified and thermally treated (TT) aspen and birch in cross section view according to Fig. 1.

Future work

More tests are planned using specimens from both groups of materials and different parameters and experimental setups. The over-all aim of the project is to introduce CT scanning in temperature- and humidity-controlled environments, combined with image processing, as a tool for continuous non-destructive and non-contact 4D-studies of bio-based building materials exposed to water. The management and editing of the large amount of images that the experiments provide are a technical challenge for future experiments. Nevertheless, the work in programming and image analysis has already started so that it can be applied in the next stage of the project. The objectives of the future work are the visualization of dynamic flow in real-time (which involves developing image-processing algorithms), relating the dynamic flow process to the characteristics of the material under study and, finally, the installation of demonstration sites where bio-based materials can be exposed and monitored so that data from in-situ sensors can be validated against the results of the CT experiments.

CONCLUSIONS

X-ray computed tomography (CT) scanning combined with image processing is a powerful tool for continuous non-destructive and non-contact 4D-studies of water flow in bio-based building materials. It reveals capillary phenomena and provides data that can help an understanding of these phenomena. Within a single specimen of insulation material it is possible to appreciate differences in the behaviour of different parts in materials such as those formed by larger fibres, which clearly show how the capillary absorption is higher within these fibres than between them. In solid wood, the different levels of water flow between heartwood and sapwood can be studied. Knots, sapwood-heartwood, fibre orientation and other anatomical characteristics can also be studied in relation to their interaction with water. Water flow in thermally modified timber (birch and aspen) is less than that in unmodified timber, and the moisture gradient formed above the liquid water is also reduced. The examples given in this paper provide an overview of the potential of CT scanning for testing different materials with regard to their interaction with water, which in turn opens up new opportunities for improving the performance of newly developed building materials.

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