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Toward energy efficiency through an optimized use of wood: The development of natural hydrophobic coatings that retain moisture-buffering ability

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A B S T R A C T

The hygroscopicity of a wooden material or the ability to absorb, store and release moisture helps to naturally regulate the indoor climate by dampening humidity variations and avoiding extremes. This phenomenon, known as moisture buffering, is an energy-efficient way of moderating moisture levels in a living space, improving air quality, and influencing the health and comfort of the occupants. This work focused on developing a surface treatment that preserves the natural ability of timber to buffer moisture vapor while increasing the resistance to liquid water. For this purpose we suggest a method based on a natural non-continuous coating of hydrophobic Carnauba wax particles. The coating was compared, in terms of water repellency and moisture buffering efficiency, to a continuous wax film and conventional coating methods like lacquer and linseed oil. The resistance of the surfaces to liquid water was studied by contact angle measurement. Moisture buffering experiments were conducted by exposing the surfaces to cyclic changes in relative humidity. It was found that coating with wax particles resulted in more hydrophobic surfaces with enhanced moisture buffering ability, while the rest of the coatings examined either reduced moisture buffering drastically (wax film, lacquer) or were not sufficiently hydrophobic (linseed oil).

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1. Introduction

For centuries, wood has been used extensively by humankind. Renewability, strength, visual appearance and good thermal insulation properties made it the material of choice for many applications, including building construction and furniture manufacture. During recent decades, however, new materials such as concrete, steel and, most recently, synthetic polymers or plastics have gradually replaced wood and in some application areas timber has become almost entirely disregarded as a building material. On the other hand, recent environmental and sustainability concerns have driven industry to look for new substitutes for fossil-based materials and the demand for green and renewable materials, including wood, is increasing.

Another important property of wood is hygroscopicity or, in other words, the ability to attract, hold, and release water molecules [1]. Hygroscopicity is often considered to be a negative characteristic of wood, as the exposure of timber to wet conditions can create many end use problems for non-treated surfaces, when used both outdoors and indoors. Excess water causes dimensional instability in the material due to swelling and shrinkage of the cell wall and lumen. Additionally, wet conditions create a very favorable environment for the growth of various wood degrading biological organisms (e.g. diverse fungi, bacteria, and insects). Therefore, it is very important to understand wood–water interactions and, if necessary, alter them [2–6]. To avoid problems of wood degradation and to enhance durability and easy maintenance, wood is often hydrophobized. Surface hydrophobization methods include, but are not limited to, treatments with silicon containing compounds [7–9], the deposition of metal oxide nanoparticles [10,11] and surface impregnation with various waxes, oils, polyelectrolytes and other compounds [12–15]. Many of these approaches have a negative environmental impact and cause damage to the ecosystem because of the possibility for biocidal chemicals to leak from the surface [16].

Nevertheless, recent findings suggest that the hygroscopicity of wood can also be rather beneficial. The ability of a wooden material to store and release moisture helps it to regulate the indoor climate naturally, and to decrease humidity variations. This phenomenon, known as moisture buffering, is an efficient way of passively

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moderating the moisture level in a living space [17,18]. The use of hygroscopic materials together with a well-controlled ventilation system may further reduce the energy consumed for heating and cooling and increase the overall energy-efficiency of a building [19,20]. Maintaining certain levels of relative humidity (RH) will also increase the perceived air quality and influence the occupants' health and comfort [21–24]. Especially during hot periods, the dynamic moisture storage in hygroscopic materials reduces the moisture in the air, leading to increased comfort and consequently a reduced need for cooling, resulting in *indirect* savings. However, it has been shown that since the indoor air humidity is reduced, the indoor air enthalpy is also reduced and consequently less energy is needed for cooling, which leads to *direct* energy savings [19]. The storage of moisture inside a hygroscopic material such as wood also means thermal storage, which can lead to passive heating or cooling of the building during the adsorption and desorption of water, and increased thermal comfort [25,26].

To maximize the effect of moisture buffering, the surface area of wooden materials in interiors should be increased. This could be achieved by introducing more wooden surfaces into a living space, e.g. wooden floors, walls, ceilings, furniture, etc. Timber used indoors is certainly less susceptible to UV- and biodegradation by living organisms compared to wood used outdoors, but certain modification might still be required to improve the material properties and increase the lifetime of the material.

In order to be able to utilize the moisture buffering capabilities of timber, the influence of surface coatings and modification techniques should be studied with special care. However, while comprehensive literature is readily available on the topic of wood modification [1,27,28], little information could be found on the influence of finishings or coatings on the moisture buffering performance of timber. Studies conducted on various building materials, including wood, generally suggest that paints and coatings decrease the moisture buffering effectiveness of the treated surfaces [29–33].

The aim of this work was to develop modification techniques that preserve the natural ability of wood to buffer moisture vapor while increasing its resistance to liquid water. Special focus was placed on the sustainability of the approach and therefore only natural materials were used, making the treatment green and the final product nontoxic for humans and nature. The treatment developed is fundamentally different to conventional wood modification techniques. It does not form a continuous film on the surface as many commercial paints and lacquers do and therefore does not limit moisture buffering. Instead, the method is based on the effect of hydrophobic wax microparticles that form a discontinuous surface layer, which repels water, slowing down penetration, but allowing moisture vapor permeation. The performance of wooden surfaces coated with wax particles was compared with that of a solid wax film and commercially available wood treatments (lacquer and linseed oil) in terms of water repellency and moisture buffering efficiency. Carnauba wax was chosen for the production of the wax particles because it is the hardest of the natural waxes and may, therefore, produce a durable coating. It is a natural wax produced by the leaves of Carnauba palm and has a melting point of 83–86 °C [34]. This wax is also hypoallergenic, chemically inert and is not a food source for humans, and thus does not raise ethical issues when used in wood modification.

2. Experimental

2.1. Materials

Kiln dried spruce boards were obtained from a sawmill in Finland. For comparative purposes, all experiments were carried out on both radially and tangentially cut surfaces.

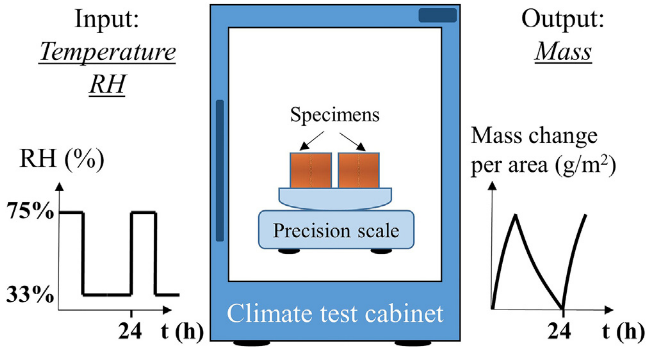

Fig. 1. Schematic representation of experimental setup for the determination of MBV.

2.1.1. Wax coatings

Refined carnauba wax was purchased from Sigma–Aldrich in the form of pellets.

The wax particles used to form the discontinuous coating were produced by melting the wax and dispersing it in water using a Polytron homogenizer PT2000 (Kinematica AG). The wax particles that were obtained were mostly spherical in shape and had a size distribution ranging from hundreds of nanometers to tens of micrometers. In order to make the coating less visible on the surface, the dispersion was filtered using qualitative grade paper filter retaining particles bigger than 12–15 μm. After filtration, the suspension was stable and the concentration was around 3.5 g/L. In this article, final dispersion is further referred to as colloidal wax particles. The filtered dispersion was applied to the wooden surface, allowed to dry and then buffed with a cotton cloth to distribute the particles evenly.

A continuous carnauba wax film coating was obtained by dipping the wood sample into molten wax. A thicker film was achieved by increasing the number of immersions of the sample into the molten wax. The area density was used to estimate the thickness of the coating and averaged 138 g/m^2 for the thin wax coating and 380 g/m^2 for the thick coating.

2.1.2. Commercial coatings

Two coats of commercially available linseed oil (Pellavaöljy, Tikkurila Paints Oy, Finland) and spray lacquer (PROF, Matta spraylakka, Rautakesko Ltd., Finland) were applied to the wooden samples, following the manufacturers instruction.

2.2. Moisture buffering

The moisture buffering experiments were performed in accordance with the NORDTEST method [17]. Experimental setup is schematically represented in Fig. 1. In order to evaluate the effectiveness of moisture buffering, the Practical Moisture Buffer Value ($MBV_{practical}$ (kg/(m^2%RH)) was calculated. $MBV_{practical}$ defines the amount of moisture transported in to or out of a material per unit of open surface area, during a specified period of time, when the material is exposed to cyclic variations in relative humidity. In order to determine $MBV_{practical}$, the weight gain during absorption and the weight loss during drying were calculated, then averaged and normalized per open surface area and ΔRH. Average of weight gain and weight loss is taken for each cycle, and consequently $MBV_{practical}$ is calculated as the average of three cycles [14]. Further in this work, $MBV_{practical}$ will be referred to as simply as MBV.

Wood samples, around 2 cm thick, were sealed with aluminum adhesive tape on all but one side, leaving 4 cm^2 of surface available for moisture buffering. For each treatment, two parallel samples were tested. Before the measurements, all samples were

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