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PRINTED SENSORS FOR MONITORING WOOD MOISTURE CONTENT INSIDE TIMBER BUILDING ELEMENTS

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ABSTRACT: Moisture accumulation in wood constructions can lead to severe damage and premature construction failure. This is especially problematic for covered areas such as wet rooms (e.g. cross laminated timber (CLT) ceilings and covered dry walls), where moisture accumulation can occur without being noticed for a long time. The current paper describes the development and application of novel printed moisture sensors, that can be integrated directly into wooden construction elements, such as CLT or Glulam. This allows continuous *in-situ* monitoring of wood moisture content. A special wood primer was developed for the inkjet-printing process that is required to obtain high printing resolution and efficiency. The optimal sensor geometry on wood for highest measurement sensitivity was found by systematic variation of geometric details of the sensors and measuring conductance and impedance during a climate trial. The relative humidity was gradually increased while keeping the temperature constant within the chamber. After each step of moisture increase, impedance, phase angle and deduced variables at different voltages, currents and frequencies were measured. Furthermore, a proprietary measurement system was used. With the novel printed moisture sensors, it was possible to reliably monitor accumulation of moisture within CLT elements.

KEYWORDS: printed moisture sensor, moisture sensing, timber building, impedance measurements, capacitive moisture measurements

1 INTRODUCTION

Moisture accumulation can have severe consequences in wooden constructions. Short periods with higher moisture contents can be considered unproblematical, since wood destroying fungi need a wood moisture content at or above fiber saturation point (FSP) over longer time periods to grow. On the other hand, if the time of wetness is limited, the durability of the construction is usually not negatively affected [1]. It is therefore crucial to detect moisture entry into the construction as quickly as possible. According to Ott & Aondio [2], the design details of buildings play an important role here. For example, water penetration into a cross laminated timber ceiling is detected much later than on a beam ceiling. If drying of the wooden elements is restricted, moisture accumulation will enable fungal growth, leading to severe damage and premature construction failure. This is especially problematic for areas that are at least partially covered, such as CLT elements in wet rooms behind a dry wall. Moisture accumulation can occur without detection for many years. When finally detected, costly renovation is inevitable. For that purpose, standards such as the ÖNORM B 2320 [3] require either at least two layers of bituminous sheeting with 8 mm thickness or an inspection port. Both can be avoided, if a moisture monitoring system is installed.

Several methods for measuring wood moisture content are available. While the gravimetric method gives by far the most accurate results, moisture monitoring on wood constructions is not possible as it is a destructive method. According to Dietsch et al. [4] requirements of a moisture monitoring system are as follows:

- The measurements must be taken without damaging the structure or taking samples
- The accuracy of the method should be consistent
- The system must be mountable on the structure itself
- Digital logging of the measurement results on different spots must be possible

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- The timber moisture content should be measured and recorded in equal time intervals (e.g. one hour)

Generally, wood moisture content strongly affects the electrical properties of wood below the fibre saturation point [5]. Extractives which are not soluble in water are expected to decrease conductivity while the opposite is true for water soluble extractives [5,6].

The electrical resistance method fulfils all the requirements of a moisture monitoring system and is therefore available in many commercial systems [4]. However, electrodes must be placed inside the wood and is therefore destructive to a certain extent. Furthermore, the moisture measurements are locally restricted, as the moisture content is measured just between the two electrodes.

Aside from electrical resistance, capacitive moisture measurements of wood are also possible. Additionally, they do not need electrodes inside the wood and are therefore completely non-destructive. Measurements are taking place on the surface and an average wood moisture content near the surface (<35 mm) is measured [4]. Capacitive moisture measurements use the property that the dielectric constant of the wet wood increases with increasing moisture content, as the permittivity of water is higher than that of dry wood [7]. Since the relative permittivity of water ($\varepsilon_r \sim 80$) is many times higher than oven dry wood ($\varepsilon_r \sim 1.4$-4), capacitive techniques are well-suited for moisture measurements [7, 9]. Grain orientation is known to affect the dielectric properties of wood, where the complex dielectric constants are 20% to 50% higher in longitudinal direction compared to the direction perpendicular to the grain [7]. The dielectric constant of wood increases with increasing wood density [9]. Additionally, the dialectical properties of wood are affected by temperature and AC frequency [5, 10]. The higher the AC frequency of the measurement signal, the lower the dielectric constant [10]. However, it has to be noted, that the lower practical limit for most electrical meters is of the order of 6-8% and the highest limit is about 25% to 30% [11]. A low-cost capacitance sensor for wood moisture content was developed by Korkua and Sakphrom [12].

Another electrical method i.a. for wood moisture content is the measurement of the electrical impedance (Z). The impedance can be represented as a complex quantity with the resistance as real part and the (capacitive and inductive) reactance as imaginary part [6]. Since the impedance can be measured at several frequencies, this method is often described in the literature as electrical impedance spectroscopy (EIS) [6]. Impedance measurement was successfully used for evaluating the moisture content of sugi logs to monitor the drying process [13]. EIS was also used to determine wood decay [14].

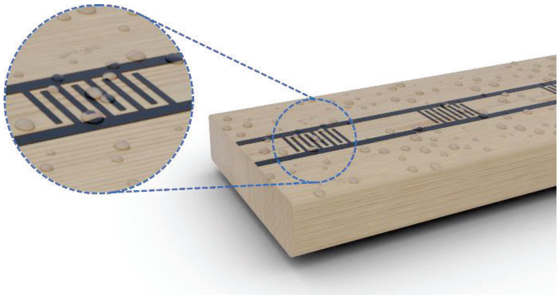

Figure 1: *Schematic of moisture sensors printed onto wood.*

The aim of the current study was the development of novel printed moisture sensors on wood. These sensors would allow *in-situ* monitoring of the moisture dynamics within construction elements such as CLT during use. In contrast to the resistance method, the printed sensors allow extensive area moisture monitoring, using an interdigitated electrode design (Figure 1). In terms of printing technology, digital inkjet printing offers many advantages over other printing techniques such as high throughput and flexibility of the printing pattern. Alternatively, screen printing was also investigated as a possible printing technique. In each case, carbon-based inks were used in order to not impose a problem for the recycling process after use of the construction elements.

2 MATERIAL AND METHODS

2.1 MATERIALS

For all printing trials, wood blocks measuring 150 mm x 75 x mm x 20 mm from Norway Spruce (*Picea abies, L.*), free from knots and with growth ring orientation of 5-45° (quarter-sawn) were used. All samples were planed and conditioned for at least one month in a climate room at 23°C and 50% RH to constant weight. Equilibrium wood moisture content was therefore at app. 9%.

For the inkjet printing process, a carbon-based Sicrys™ RI-6DM-3 ink with low viscosity (~3-5 cP) was used. For the dispensing and screen printing trials, a carbon-based Ink SE1502 from ACI materials with high viscosity was used. Screen printing was conducted using a commercial screen with mesh size 90T.

Two wood primers as pre-treatment for inkjet printing were investigated. The first primer was based on a highly viscous UV-curable putty "UV putty" for roller application. This variant was used with or without intermediate sanding. The second primer was based on a waterborne acrylic wood coating.

Wood primers were applied either by roller application (UV putty) or by spraying (water-borne coating). No primer was used for screen printing.

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2.2 METHODS

For preliminary trials to obtain an optimal printing pattern, a dispensing printing process was used. The dispensing device was developed by Profactor GmbH and essentially consist of a motorized maneuverable platform with a controllable syringe head.

Inkjet printing was performed using a Süss LP50 printer with a KM512 print head from Konika Minolta. The cartridge temperature and the nozzle temperature were kept at room temperature.

Screen printing was performed manually without primer. Sintering for all samples was done at 120°C for 30 min in an oven.

Climate chamber tests were performed in a climate chamber SK40420 of Simtech (AT). The climates and corresponding equilibrium wood moisture contents are shown in Table 1. Each climate was kept constant, until the wood samples reached equilibrium. This was usually the case after 3 weeks. The samples were weighed at regular intervals, until the difference in mass was below a 0.3 g threshold, which was considered stable. After the end of the climate chamber tests, the samples were measured and weighted.

Table 1: *Climate settings and corresponding equilibrium wood moisture content (EMC) during the climate chamber test.*

Relative Humidity	Temperature	Corresponding EMC
50%	23°C	~9 %
71%	23°C	~13%
85%	23°C	~18%
93%	23°C	~22%
98%	23°C	~25%

Impedance and phase angle at different voltages, currents and frequencies were measured during the climate chamber test with an LCR measurement bridge, HM8118 from Rohde&Schwarz. For estimating the optimal printing pattern for maximizing sensitivity of the printed moisture sensors towards moisture uptake, a base pattern of interdigitated electrodes was varied systematically. The width, length and number of the strips were varied and regressed against the actual wood moisture content during the climate test. For the main tests, the optimized geometry was used and only the thickness of the ink-layer and the growth ring orientation were varied. Three samples for each variant were used.

3 RESULTS AND DISCUSSION

3.1 DEVELOPMENT OF INKJET-PRINTING PROCESS ON WOOD

For inkjet printing, inks with very low viscosity are required. Consequently, direct inkjet-printing on wood is not optimal, as a lot of ink is soaked into the wood. This significantly reduces efficiency, as the ink inside the wood hardly improves conductivity. Furthermore, the printing resolution is affected, as the ink gets transported, preferentially along the fibre direction, thus blurring the printing pattern. Therefore, several primers were investigated as suitable pre-treatment for the subsequent inkjet printing. Some of the pre-treatments were air drying while other systems were UV-curing.

Microscopic analysis revealed that the UV-primer with and without intermediate sanding led to interdiffusion of carbon ink particles into the coating which was reducing the conductivity (Figure 2). Better results were achieved with a water-borne primer where no visible interdiffusion occurred.

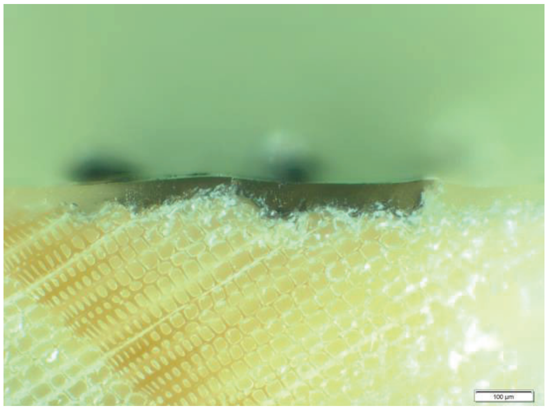

Figure 2: *Result of inkjet printing process on wood with UV-putty as primer; interdiffusion of ink into the coating. Cross section of spruce wood with clear primer and black printing under the microscope.*

The final results of the inkjet printing process, using the water-borne primer, revealed an interdigitated sensor pattern with very high resolution and sharp edges (Figure 3). The main advantage of the inkjet-printing process compared to other printing technologies is its high versatility and adaptivity. Hence, the printing pattern can be adjusted almost instantly and could be fine-tuned for optimal printing on the substrate almost in real-time. The downside of the inkjet process is the need for a primer, which inhibits direct contact between wood and printed sensors. This would be a major drawback for resistive sensors but not for capacitive sensors, as the primer can be seen as just another dielectric layer.

Figure 3: *Result of Inkjet printing process on wood with water-borne acrylic primer*

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An alternative method used in this study is screen printing. Due to the higher viscosity of the screen printing ink, there is no need for a primer. This has the main advantage that the ink is in direct contact with the wood substrate, thus being able to measure the moisture directly without any layer in between. The printing quality of the printed electrodes is lower than those printed via inkjet (Figure 4), but still suitable for this purpose. The sharpness of the edges depends on the meshsize of the screen. Finer meshes (e.g. 90T or even 120T with 50µm/45µm mesh opening) allows printing of much finer details. However, the thickness of the ink-layers gets reduced, thus limiting the bulk conductivity. Nevertheless, the conductivity of the prints with meshsize 90T was still good enough for the intended purpose while the printing quality was high.

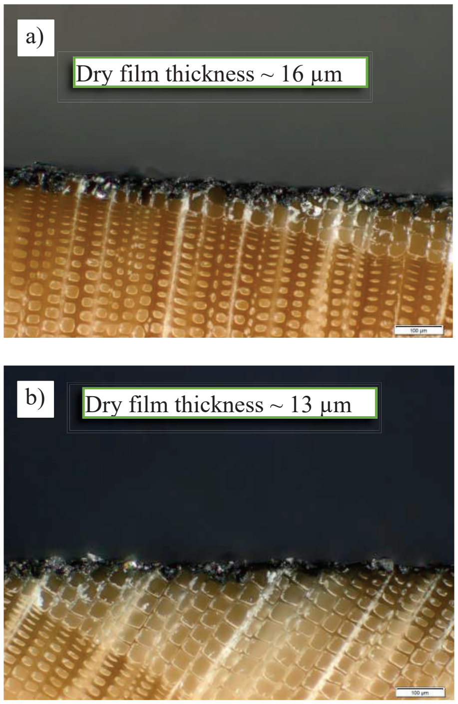

Figure 4: *Influence of screen printing meshsize on the dry film thickness of ink on wood; a) meshsize 43T; b) meshsize 90T.*

All inks needed sintering at elevated temperatures (120°C for 30 mins). Thus, wood moisture content had to be low (around 9%) before sintering to avoid cracking during the process. A systematic variation of the sintering times and temperatures revealed higher conductivity with higher sintering temperatures. Lower temperatures (100°C) for longer periods did not lead to the same conductivity.

3.2 OPTIMIZATION OF SENSOR GEOMETRY

The optimal sensor geometry for measuring the moisture content of wood was determined by a systematic variation of the sensor pattern from a base pattern of interdigitated electrodes. In this test, the number of electrode fingers, the distance between the fingers but also the thickness of the electrode fingers itself were varied systematically. During a test in the climate chamber, the response in terms of impedance and phase angle with increasing wood moisture content was measured.

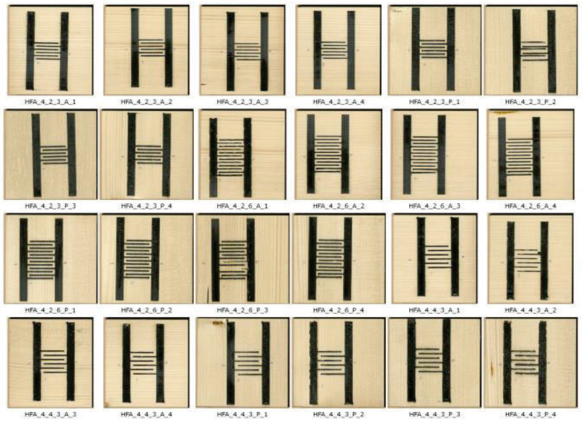

Figure 5: *Result of inkjet printing process on wood with UV-putty as primer; interdiffusion of ink into the coating. Cross section of spruce wood with clear primer and black printing under the microscope.*

The highest correlation of the measured impedance and phase angle to the actual wood moisture content was achieved with the pattern shown in Figure 6). The results revealed that the best correlation of the measured impedance with the increasing wood moisture content was with the highest sensor surface area and with the greatest number of interdigit probes.

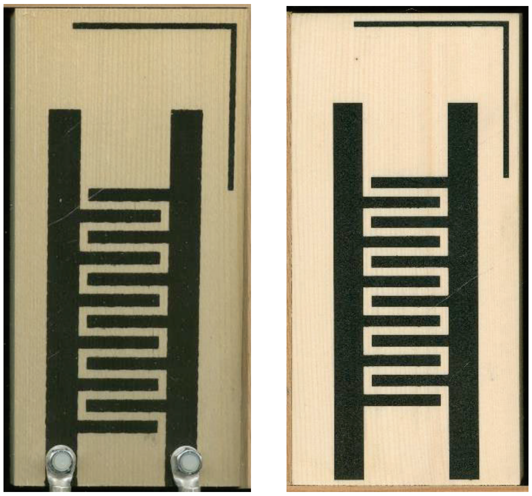

Figure 6: *Left: Screen printed moisture sensor: Right inkjet-printed moisture sensor. The optimal pattern was obtained from measurements during a climate test.*

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3.3 CORRELATION BETWEEN ELECTRICAL SIGNALS AND WOOD MOISTURE CONTENT

For determining the relationship between the measured impedance and phase angle as well as derived values (e.g. capacity) with the wood moisture content, samples with the optimized sensor geometry were again subjected to tests in a climate chamber. Again, the moisture content within the chamber was increased gradually, until the equilibrium wood moisture content was reached. During this trial, the impedance and phase angle of the printed sensors were measured with different AC frequencies.

It was observed that the phase angle was frequency dependent and lower phase angles were seen with higher frequencies (Figure 7). This indicates lower capacitive reactance with lower frequencies compared to higher frequencies. This was expected, as the capacitive reactance decreases with increasing frequency and with increasing capacitance.

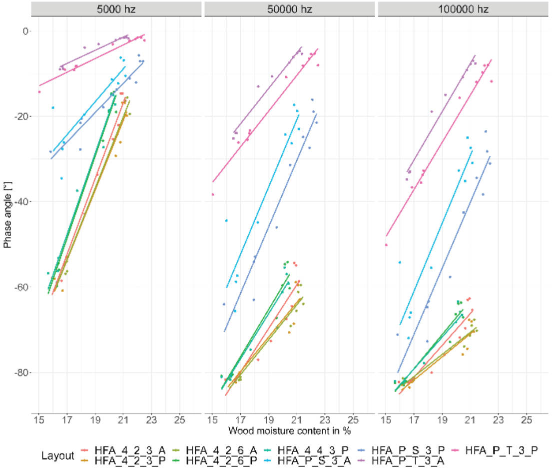

Figure 7: Phase angle vs. wood moisture content at different AC frequencies during a climate chamber test

In Figure 8, the impedance as function of the wood moisture content at different AC frequencies is shown. Generally, a strong correlation of the measured impedance with the wood moisture content was observed. Again, a clear influence of the measurement frequency was seen. The results revealed the highest regression coefficient/steepest slopes of the regression line with lower frequencies, e.g. 5000 Hz.

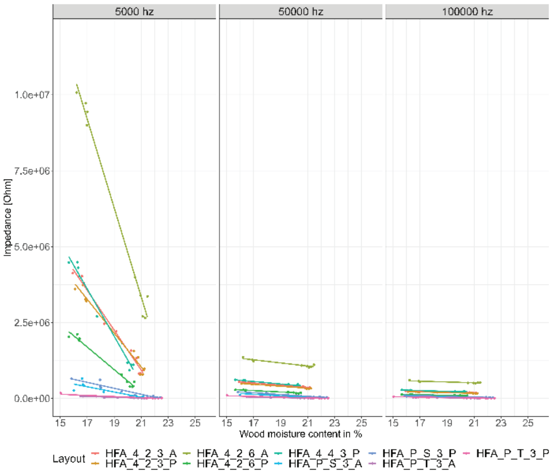

Figure 8: Impedance vs. wood moisture content at different frequencies during a climate chamber test

In figure 9, the influence of the voltage on the impedance for different wood moisture contents is shown. It is evident that the voltage does not seem to have a significant effect on the measurement result. Hence, the voltage was kept the same in later trials.

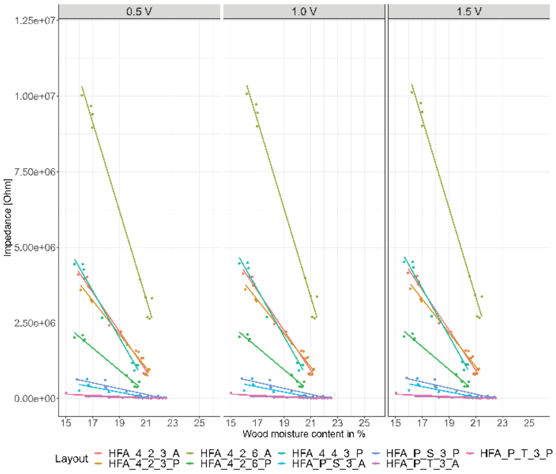

Figure 9 Impedance at different voltage levels vs. wood moisture content during a climate chamber test

The results reveal that the measured impedance at a frequency of 5000 Hz and a voltage of 1 V predicts the wood moisture content, with $R^2 = 0.94$, $F(1, 1155) = 2.03*10^4$, $p < 2.2*10^{-16}$.
It can be stated that the wood moisture can be monitored accurately with the printed moisture sensors. Since all the criteria mentioned by Dietsch et al. [4] for moisture monitoring systems are met, the developed method is highly suitable for monitoring the wood moisture content in timber constructions.

4 CONCLUSIONS

Two printing methods for conductive paths on wood were developed. Inkjet printing gave better printing quality but required a waterborne acrylic primer to achieve the desired printing quality. Screen printing was possible without primer and is therefore in direct contact with the wood surface.

The optimal printing pattern with highest sensitivity towards moisture accumulation during a climate chamber test was found. From the AC frequencies measured in these tests, a frequency of 5000 Hz showed the highest regression coefficients for predicting wood moisture content. As all requirements of a moisture monitoring systems are met, the developed method based on printed moisture sensors is highly suitable for monitoring the wood moisture content in timber constructions.

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