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Quantitative determination of water sorption in glued multilayer boards by means of neutron imaging

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Abstract: *Quantitative determination of water sorption in glued multilayer boards by means of neutron imaging.* Diffusion processes into multilayered samples of Norway spruce (*Picea abies* [L.] Karst.) exposed to a differentiating climate (dry side / wet side) have been determined and quantified by means of neutron imaging (NI). The experiments were carried out at the neutron imaging facility NEUTRA at the Paul Scherrer Institute (PSI) in Villigen (Switzerland). With NI the influence of different adhesives (urea resin, 1C PUR) on the diffusion process could be detected by varying the layer number of adhesive joints of the samples. Neutron transmission images were used to measure time-dependent water profiles in diffusion direction. Using Fick's second law, diffusion coefficients for radial and tangential water transport in spruce wood and in the adhesive joints were calculated depending on moisture content (MC).

Keywords: diffusion coefficient, neutron imaging, non-destructive testing, spruce wood, adhesive

INTRODUCTION

In recent years, glued solid wood materials such as glued laminated timber or multilayered solid wood panels have gained in importance. In this context, the diffusion of water vapour within wood and the barrier effect of adhesive joints are of high relevance in the field of building physics: this is particularly the case when the hygroscopic behaviour and the water transfer in building elements as well as the humidity exchange with the room is regarded. While diffusion processes of wood have been the subject of many investigations [e.g. Stamm [6], [7], Skaar [5], Frandsen *et al.* [1], the influence of adhesive joints on the diffusion processes has scarcely been studied. One of the few studies done on this topic was carried out by Frühwald [3]. He investigated in detail the influence of bond lines of a phenolic resin between the veneers of beech plywood by varying the number of bond lines and films per line.

The aim of this study was to investigate the phenomenon of the moisture-depending diffusion resistance of different adhesives: urea formaldehyde resin (UF) and one-component polyurethane (1C PUR). Neutron radiography was used to detect the water content within wood [according to Mannes *et al.* [4]. The advantage of this non-destructive method is its high sensitivity to hydrogen what allows the visualising of time-dependent water diffusion processes in wood.

1 MATETRIAL AND METHOD

1.1 Material

20 samples from Norway spruce (*Picea abies* [L.] Karst.) of approximately 120 mm (length) x 15 mm (width) x 30 mm (height) were prepared for testing bound water diffusion. The diffusion process was run from the top to the bottom of the sample. Two of the samples

were used to determine the diffusion in the radial and tangential direction of solid wood. The other 18 samples were added with one to five bond lines at half height or rather regularly distributed over the height in order to investigate the influence of bond lines on the diffusion processes. For these samples, the diffusion in the spruce wood occurs in the tangential direction.
The applied adhesives are used for load-bearing timber structures, UF (cold gluing) in dry conditions and 1C PUR even in humid conditions. All adhesive joints were bonded at 20°C and 65% RH. Table 1 gives an overview.

1.2 Experimental setup

The experiments were performed at the neutron radiography facility NEUTRA of the spallation neutron source SINQ at the Paul Scherrer Institute (PSI) in Villigen, Switzerland [Lehmann *et al.* [3]]. The samples were tested in two series over a period of about ten weeks. During this time, the preliminarily oven-dried samples were exposed to a differentiating climate (20°C/85% RH to almost 0% RH). The moisture of the samples was measured with neutron radiation after defined time intervals in order to follow the diffusion process into the sample. The measurements took place after 0, 1, 3, 7, 23, 29, 59, 74 days. Thereby, at the beginning of the tests the samples (dried at 103°C until weight constancy) were insulated with aluminium tape on the four edges, leaving only the top and the bottom planes (the orthogonal planes of the required diffusion direction) unsealed. Each sample was then fixed on a cup filled with silica gel that was closed with a slotted aluminium plate. The sample was arranged above the opening of the slot, which had the same length and width as the sample (Figure 1). The first neutron radiation measurement was still made with the dry sample to obtain a reference image. For the measurement, the cup with the sample was positioned in front of the neutron detector (a combination of a neutron sensitive Li doped ZnS scintillator and a CCD-camera). The tangential-longitudinal plane (and in one case the radial-longitudinal plane) of the sample was so exposed to a parallel beam of neutron radiation for a defined time. The neutron scintillator converts the neutron signal into visible light, which is led via a mirror onto a cooled 16 bit CCD camera.

Fig. 1. Cup with silica gel and the sample above, isolated on four sides with aluminium tape

1.3 Data evaluation

The attenuation of the neutron radiation within a sample can be described by the exponential law of radiation attenuation (Beer-Lambert law). The aim of the measurements was to detect the distribution of the water content within the sample in the diffusion direction. Table 1 shows the mean water content of the samples as MC and as water concentration.

2 RESULTS AND DISCUSSION

The influence of the number of bond lines on the diffusion process is shown in Figure 2. For the samples with a single bond line, the diffusion process has nearly finished after 74 days. Observation of samples with three and five bond lines reveal that the diffusion process just reaches the bottom of the sample. In the case of sample 8 (1C PUR with 5 bond lines) the water only reaches as far as the fifth bond line. This indicates a high diffusion resistance of the hardened adhesives, particularly of 1C PUR, which is also visualised with the steps in the distribution of the MC at each bond line. The high diffusion resistance of the adhesives could be verified with the PDE-calculation. Regarding 1C PUR, the difference between the diffusion coefficients of wood and adhesive increases from one to about three orders of magnitude with increasing MC. Moreover, the diffusion coefficient of 1C PUR shows only a slight dependency on the MC and partly even a negative slope (concerning the increase of the diffusion coefficient with increasing MC).

Table 1. Overview of the tested samples and the applied adhesives at the beginning of the measurements (oven-dry) and the mean moisture content ($MC_{mean.end}$)) respectively water concentration ($C_{mean.end}$ at the end of the measurements after 70 days (series 1) exposed to a differentiating climate (20°C/85% RH to 0% RH)

Material/Adhesive	*No.*	*Direction of diffusion*	*Joint No. (-)*	*Oven-dry density (kg/m³)*	*$MC_{mean.end}$ (%)*	*$C_{mean.end}$ (g/cm³)*
Spruce wood	1	Tangential	-	418	12.8	0.054
	2	Radial	-	402	12.5	0.050
Urea	3	Tangential	1	398	12.5	0.050
	4	Tangential	3	441	10.6	0.047
	5	Tangential	5	457	9.6	0.044
PUR	6	Tangential	1	403	12.0	0.048
	7	Tangential	3	430	7.9	0.034
	8	Tangential	5	476	6.1	0.029

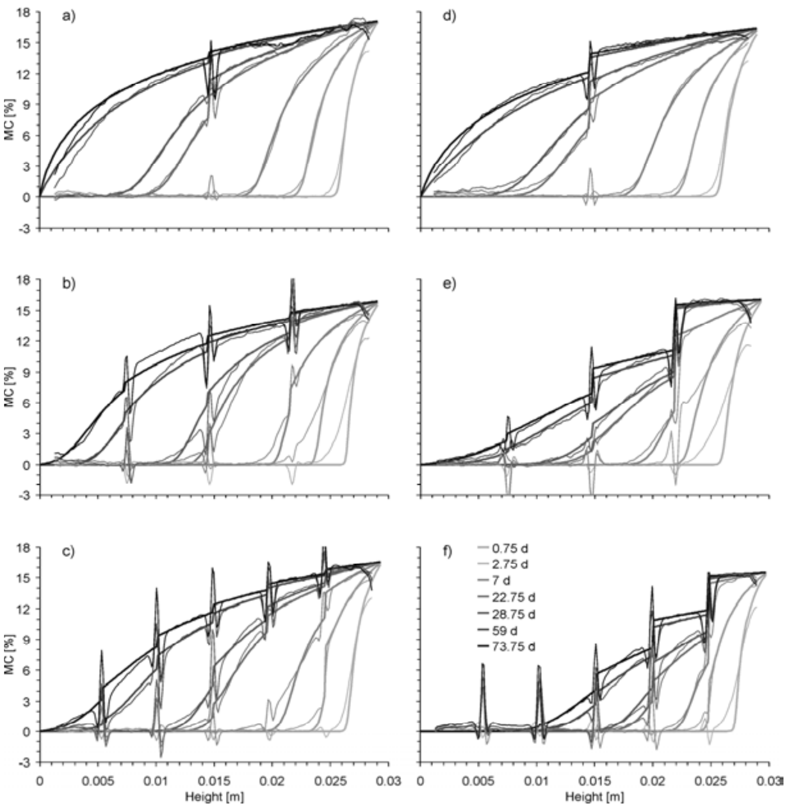

Fig. 2. Vertical profiles of the MC through the samples with 1, 3 and 5 adhesive joints of series 1 during the diffusion experiment (experimental results = fine lines; model curves = fat lines):
a – c) UF, d – f) 1C PUR

3 CONCLUSION

It was possible to detect time dependent diffusion processes within wooden samples containing bond lines by localising and quantifying the water content in the diffusion direction. On the basis of the received data, both, the MC dependent diffusion coefficients of the spruce wood as well as of the bond lines, were calculated in the form of an exponential function relative to MC with good agreement to the measured data. The diffusion resistance of the bond lines strongly depends on the adhesive type and on the MC. 1C PUR show up to three orders of magnitude lower diffusion coefficients at high MC compared to spruce wood and have a high barrier effect on water sorption over the whole measured MC range. In contrast UF had a lower barrier effect and clearly depends on the MC.

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