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ORIGINAL

Water absorption of untreated and thermally modified sapwood and heartwood of *Pinus sylvestris* L.

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Abstract Water absorption coefficients of untreated and thermally modified Scots pine (*Pinus sylvestris* L.) were determined on sapwood and heartwood in longitudinal, radial and tangential direction. Thermal modification was performed under atmospheric pressure and saturated steam at 190 and 210 °C for 3 h. The capillary water uptake of untreated and thermally modified heartwood was lower in all anatomical directions compared to sapwood. The two investigated treatment intensities showed contrary results for capillary water uptake.

1 Introduction

Thermal modification (TM) is a long-known method to improve the biological durability and dimensional stability of wood. In the conventional temperature range between 160 and 260 °C TM causes distinct changes in the chemical and microscopic structure of the cell wall. The cell wall becomes more hydrophobic, thus the equilibrium moisture content (EMC) is reduced. The extent of EMC reduction mainly depends on treatment intensity and wood species.

The hygroscopic sorption behaviour of thermally modified wood under steady-state climate conditions has extensively been studied during the last decade. However, there is a need to gain further insights into the alteration of the capillary water uptake owing to TM, especially with respect to sapwood and heartwood. The transport of liquid water is important for components exposed to rain (e.g. decking boards and claddings). In practice, it is often considered as benefit of modification, that it reduces the capillary water uptake and equalises the differences between sapwood and heartwood. One objective of this study was to evaluate this for capillary water uptake property. Beside the inner and outer surface wettability, the porosity (relative percentage of the pore volume) and the pore size distribution are considered as important characteristics influencing the water uptake.

Pfriem (2011) investigated water uptake of native and TM spruce (*Picea abies* (L.) Karst.) modified at 180 °C in an industrial dry process. TM samples showed decreased water uptake in radial and tangential direction, whereas the longitudinal uptake was increased. The changed porosity is considered as one reason for these changes.

Krackler et al. (2011) determined density, moisture sorption, water uptake and porosity of spruce, beech and ash, modified at 170–180 °C. Whereas the density of the hardwood was reduced by TM, that of spruce increased. Correspondingly, the porosity of beech and ash increased and that of spruce decreased. Metsä-Kortelainen et al. (2006) analysed moisture uptake due to flooding of pine sapwood and heartwood. Whereas uptake of heartwood decreased with treatment temperature, the uptake of sapwood was increased with lower temperatures up to 210 °C; only a stronger treatment at 230 °C led to a reduced moisture uptake.

Changes in chemical composition and microstructure after TM were investigated as well. Some of these changes may explain the modified wood-moisture relationship due to modification. Main effects are the partial decomposition and conversion of hemicelluloses and lignin, the formation

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of low-molecular compounds, in particular organic acids, as well as evaporation of both extractives (terpenes, resins) and products of thermal degradation (Popper et al. 2005). Thus, the cell wall thickness and density are reduced. The sorption behaviour is most influenced by the degradation of hemicelluloses as the most hygroscopic component of the cell wall. The chemical decomposition and alteration reactions also affect changes in the capillary-porous system, for example cell wall shrinkage and cracks along middle lamella, and thus the reaction to (liquid) water. The cell wall shrinkage and cleavage of the middle lamella induce formation of intercellular cavities (Biziks et al. 2013). The alteration of pits due to thermal modification was ascertained by for example Zauer (2012).

Zauer et al. (2013) investigated cell wall density and porosity of native and thermally modified Norway spruce (*Picea abies* (L.) Karst.), sycamore maple (*Acer pseudoplatanus* L.) and European ash (*Fraxinus excelsior* L.). TM was performed in nitrogen atmosphere at 200 °C and 4 h. The average porosity of oven-dry state of spruce was reduced by 2–3 % due to TM. However, for maple and ash, a very slight decrease was stated. For softwood, a decrease of the pore volume and an increase in hardwood due to TM have already been stated earlier by Krackler et al. (2011); for softwoods, a decrease in the proportion of smaller pores and an increase in the proportion of larger pores were determined.

Due to the different chemical and anatomical structure of sapwood and heartwood, these wood tissues differ also in their reaction to water. The water uptake of heartwood is considerably less than of sapwood. This can be explained by the smaller pore size (Stamm 1970), the general irreversible nature of pit aspiration (Thomas and Nicholas 1966), and the amount and type of extractives deposited on pit membranes in heartwood (Hillis 1987). In this study, thermally modified and untreated pine wood were investigated in respect of water uptake, to get a better understanding of differences in wood-water interaction and changes due to modification.

2 Materials and methods

Heartwood and sapwood of both untreated and thermally modified (TM) Scots pine (*Pinus sylvestris* L.) were used. Forty planks (twenty of each partition) of 1200 mm length, 54 mm thickness and different width (depending on portion of heartwood and sapwood) were thermally modified under atmospheric pressure and saturated steam at 190 and 210 °C for 3 h in a pilot-plant scale thermo kiln (type MAHILD MH 2000 TMT).

The capillary water absorption coefficient was determined in the three main anatomic directions radial (R), tangential (T) and longitudinal (L) according to EN ISO 15148 (2002). The dimensions of the specimens were $40 \times 40 \times 40$ mm^3 (R × T × L) for water uptake in R and T direction and $20 \times 20 \times 200$ mm^3 in L direction. A total of 320 specimens was tested, each 13 replicates for L and 14 for R and T. The specimens were conditioned at 20 °C and 65 % relative humidity (RH) until equilibrium moisture content (EMC) was reached. Subsequently, the specimens were sealed with a vapour-proof tape (SIGA® Rissan) to ensure water uptake in the desired anatomical direction. To get the water uptake, specimens were weighted after 24 h. The water absorption coefficient after 24 h was calculated by Eq. (1), representing the slope of the regression line:

$$A_{w,24} = \frac{\Delta m_t}{\sqrt{t}} \quad \left[\mathrm{kg}\left(\mathrm{m}^{-2}\mathrm{s}^{-0.5}\right)\right] \tag{1}$$

where Δm_t is the mass gain per area [kg m^{-2}] at a corresponding time t of the water uptake, which was calculated according to Eq. (2):

$$\Delta m_t = \frac{(m_t - m_i)}{A} \quad \left[\mathrm{kg\ m}^{-2}\right] \tag{2}$$

where m_t is the mass of the specimen at time t, m_i the initial mass of the specimen and A the water absorbing area. To evaluate the effect of the TM, an analysis of variance (ANOVA) was conducted using SPSS software with a confidence level of 99 %. The null hypothesis was that the thermal modification had no effect.

3 Results and discussion

Water absorption coefficients (average values) A_{W24} of the water absorption of untreated and thermally modified wood and statistical data and results of significance test are given in Table 1; average A_{W24} values are shown in Fig. 1.

The water absorption of sapwood was much higher than of heartwood, and the largest differences were determined in longitudinal direction. Untreated sapwood reached 53.12 kgm^{-2} s$^{-0.5}$ × 10^{-3}, while untreated heartwood only reached 9.11 kgm^{-2} s$^{-0.5}$ × 10^{-3}. Untreated sapwood absorbed within 23 h in radial direction only 6.99 kgm^{-2} s$^{-0.5}$ × 10^{-3} and in tangential direction 6.85 kgm^{-2} s$^{-0.5}$ × 10^{-3}, what is a ratio of 1:1:7 (R:T:L) for sapwood. Pit closure, incrustation and filling of resin canals with resin are consequences of heartwood formation, what can explain the much lower water absorption in all directions, but most in longitudinal direction, what is expressed in the changed ratio 1:1:4. The milder modification TM/190 led to increased water absorption of both sapwood and heartwood. In sapwood the absorption doubled and in heartwood it even increased sevenfold

Table 1 Water absorption coefficient A_{W24} after 24 h of untreated and modified sapwood and heartwood of Scots pine; analysis of variance; significance of untreated against modified variants (sign. level $\alpha = 0.01$)

Direction	Partition	Treatment	n	$\bar{x}$ [$kgm^{-2}\ s^{-0.5} \times 10^{-3}$]	σ [$kgm^{-2}\ s^{-0.5} \times 10^{-3}$]	V [%]	Significance
Longitudinal	Sapwood	Untreated	14	53.12	10.86	0.20	–
		190 °C	14	120.49	29.73	0.25	0.000
		210 °C	14	11.60	6.02	0.54	0.000
	Heartwood	Untreated	14	9.11	2.48	0.27	–
		190 °C	14	64.25	10.61	0.17	0.000
		210 °C	14	5.97	1.51	0.25	0.002
Radial	Sapwood	Untreated	13	6.99	1.86	0.27	–
		190 °C	13	34.27	7.52	0.22	0.000
		210 °C	13	23.88	2.66	0.11	0.000
	Heartwood	Untreated	13	2.43	0.72	0.30	–
		190 °C	13	1.54	0.07	0.05	0.008
		210 °C	13	0.58	0.02	0.03	0.000
Tangential	Sapwood	Untreated	13	6.85	2.21	0.32	–
		190 °C	13	10.89	1.29	0.12	0.000
		210 °C	13	12.92	2.22	0.17	0.000
	Heartwood	Untreated	13	6.43	2.49	0.39	–
		190 °C	13	1.25	0.77	0.59	0.000
		210 °C	13	0.63	0.31	0.52	0.000

compared to untreated wood. As a result of the stronger modification TM/210, the absorption in longitudinal direction decreased below the value of the untreated wood. The water uptake of modified sapwood was five times lower than of the untreated sapwood. The absorption coefficient (L) of modified heartwood was significantly reduced by ca. 50 %, compared to the untreated heartwood. The ANOVA showed significant differences between the two treatments and the untreated specimens in both partitions in all anatomic directions (Table 1).

The increase in water absorption due to TM/190 is primarily considered as a result of changes in permeability. At this temperature, cracks along the middle lamella, intercellular cavities and a degradation of the courts appear (Zauer 2012; Biziks et al. 2013). This may increase the porosity. However, investigations by Krackler et al. (2011) and Zauer (2012) identified a loss in porosity and a decrease in the average pore diameter of softwood. The decreased average pore diameter is resulting particularly from the increase of small pores and the decrease of larger pores. From this, a greater capillary suction tension and thus a faster water transport and higher water uptake are to be expected. In pine heartwood, the absorption is intensified, since hydrophobic extractives have been evaporated during thermal treatment. Above 200 °C, the thermoplastic flow of the torus could lead to a filling of the courts (Zauer 2012). This might be a reason for the decrease in water uptake at 210 °C. The reactions of lignin at high temperatures provide another explanatory approach. Because of the loss of methoxyl groups of the aromatic ring, cross-links may be formed within the lignin. Here, liberated OH groups are associated with depolymerisation products of the hemicellulose. After a thermoplastic phase up to 200 °C, cross-links were probably formed, which might close the existing and formed micro-pores or micro-cracks through thermal treatment. It is likely that the openings in the margo of the bordered pits are closed as well.

The water uptake of untreated specimens was less perpendicular to the grain than in longitudinal direction. In radial direction, the water uptake is considerably reduced due to the large cell wall thickness and the low micro-pore diameter (Rosenthal et al. 2010). Furthermore, the water absorption coefficient in sapwood in radial and tangential direction was higher after heat treatment of 190 °C (Fig. 1). In contrast to longitudinal direction, the absorption in radial and tangential direction after TM/210 increased, too. In addition to the described changes in water absorption in radial and tangential direction Boonstra (2008) indicated damages at the ray parenchymal cells and tangential cracks in latewood. This may provide an explanation for the increase in water uptake. In heartwood, an increase in treatment temperature implies a reduction of water uptake. The effect of the reduced cell wall thickness in TM wood on capillary water uptake and water penetration is assumed to be negligible.

As a general result, the milder modification at 190 °C led to an increased permeability of pine sapwood in all anatomical directions, compared to untreated wood,

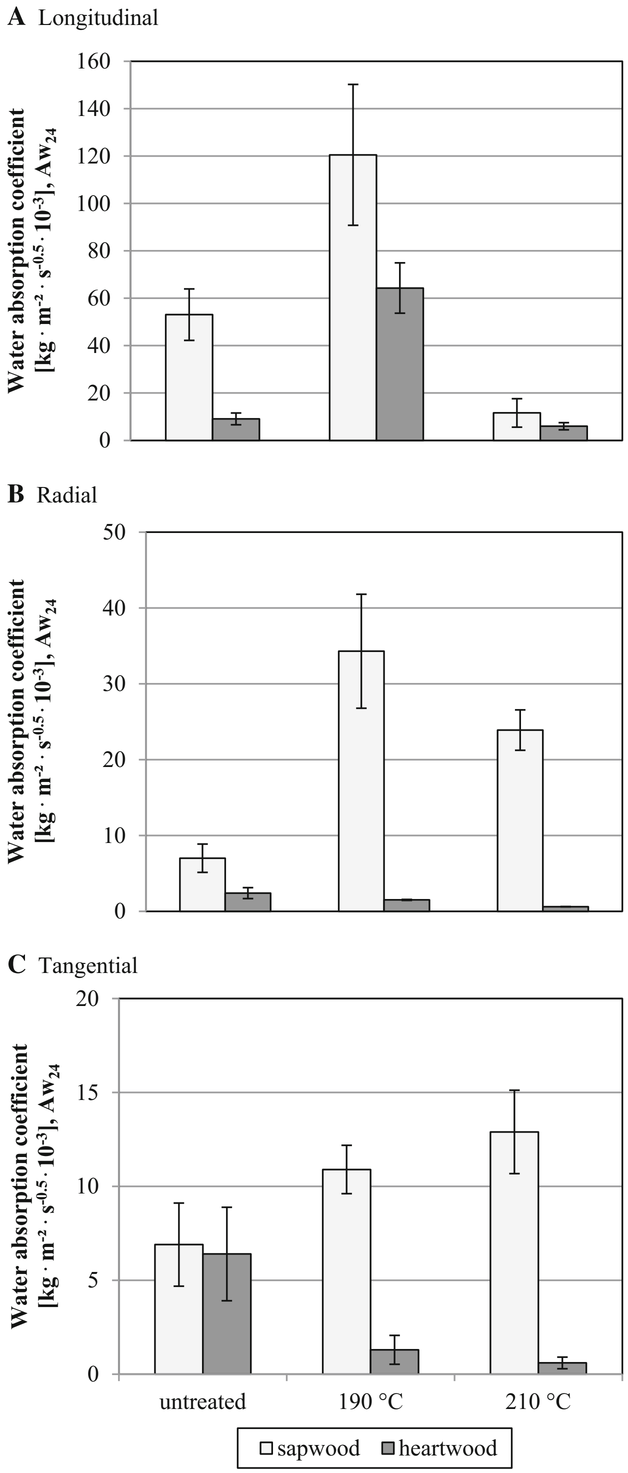

Fig. 1 Water absorption coefficient A_{w24} of sapwood and heartwood of untreated and thermally treated Scots pine in **a** longitudinal, **b** radial and **c** tangential direction (different ordinate scaling, adapted to data range)

whereas a stronger modification at 210 °C affected a decrease of the water absorption. This confirms findings by Metsä-Kortelainen et al. (2006). The difference in water absorption between sapwood and heartwood was changed by thermal modification. While there is a reduction parallel to grain, the difference perpendicular to grain grows with increasing treatment temperature, both in the radial and in tangential direction. The water absorption coefficient of Scots pine depended more on wood partition than on thermal treatment. The effect of wood partition was much greater in radial and tangential than in longitudinal direction. This implies that the thermal modification does not eliminate the difference between softwood and heartwood for capillary water uptake. The results of standardised regression analysis correspond with those of Metsä-Kortelainen et al. (2006), who likewise described for pine wood a greater influence of the wood partition than of the treatment.

Basically, the study confirmed the findings by for example Metsä-Kortelainen et al. (2006), Krackler et al. (2011), Pfriem (2011) and Zauer (2012), who found that water uptake of modified wood can be different and depends on wood species (softwood/hardwood; sapwood/heartwood), anatomical direction, and treatment intensity.

4 Conclusion

The study revealed significantly different water absorption behaviour of pine sapwood and heartwood. Compared to untreated sapwood, heartwood absorbed less water parallel and perpendicular to the grain. Even after thermal modification, significant differences in water absorption between sapwood and heartwood were detected. This could possibly result in difficulties for thermally modified pine in practice, when it contains both sapwood and heartwood. The different capillary water absorption may affect undesired distortions (warping), internal stress and subsequently cracks.

It should also be noted, that a clear influence of the treatment temperature on the water absorption coefficient of thermally modified pinewood was detected during the experiments. As a result of thermal modification at 210 °C, the water uptake decreased in sapwood and heartwood; in addition to the altered chemical composition, it provides a positive effect on biological durability. As a result of milder modification at 190 °C, increased water uptake was stated. Different structural and chemical changes in the wood substance at different treatment temperature have different consequences on the capillary water absorption.

Further and more detailed research could determine the temperature (intensity) threshold at which positive (desired) modification effects, like reduction of water uptake, occur. In further studies on water uptake, a differentiation between water absorbed within the cell walls and free water taken up in the pore system should be made. To determine the former, the cell wall total water capacity (CWTWC) should be calculated from values gained from determination of maximum swelling and ASE, as described by Biziks et al. (2014). This would provide additional information about behaviour of modified timber in wet conditions.

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