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DETERMINATION OF HYGRIC MATERIAL PROPERTIES AND CALCULATION OF THE MOISTURE BALANCE OF WOODEN PRISMS

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1. THE PROBLEM

The building material wood is particularly susceptible to moisture damage, which may involve the building owners and users in considerable expense. If the water content of wood is too high for longer periods of time, it may be attacked by fungus growth. Some types of fungus destroy the structure of the timber; the wood begins to rot. In view of the allergenic effects and the toxins produced by some varieties of mould fungus it may also impair the health, in particular, of the building's inhabitants [1]. In order to determine the moisture balance of building components and building materials it is possible either to carry out lengthy and expensive experiments or to employ the WUFI program [2], developed by the Fraunhofer Institute for Building Physics for calculating heat and moisture transport processes. With this program it has been possible, using simple material parameters [3] to achieve excellent correspondence between calculated and experimental results for mineral building materials even under the complex boundary conditions of natural weathering (see for instance [2 - 4]). For wood, the properties of which differ greatly in many respects from those of mineral building materials, the extent to which measurements and calculations agree has not yet been clarified. The aim of this paper is to show how the material properties of wood required for calculations can be determined and to compare calculations with measurements in the case of laboratory experiments as well as under natural weathering conditions.

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2. DESCRIPTION OF THE MATERIAL INVESTIGATED

Wood differs from other capillary-porous materials, for it is a living material and is composed of cells. One important difference lies in the fact that in the hygroscopic range the cell walls swell and shrink to a relatively great extent as they absorb and release moisture. Wood is an anisotropic material in which many material properties, particularly its moisture transport properties, differ very greatly in the three different axial directions. Because of the differences between duramen (heartwood) and alburnum (sapwood), between spring wood and autumn wood, because of knots, the varying width and density of the annual rings, timber is also a very inhomogeneous material. For the present investigations described in detail in [5], coniferous timber (softwoods) is represented by spruce and deciduous timber (hardwoods) by oak. In the frame of this publication the results are shown only for axial direction, which is most effective for water transport.

3. DETERMINATION OF THE HYGRIC MATERIAL PROPERTIES

To calculate the moisture balance of a building material, two transport properties are required: the vapour diffusion coefficient and the capillary transport coefficient. The material's thermal characteristics such as thermic conductivity and their dependence on moisture content, as well as its specific thermal capacity are taken from scientific literature [6].

3.1 Vapour diffusion coefficients

The vapour diffusion resistance factors determined by cup tests at various RH are shown in Fig. 1. For comparison purposes, values taken from scientific literature have also been added ([6, 7]). From the results of the measurements for axial transport in oak (Fig. 1, left), it can be seen that there is good correspondence with the values given in the literature. The resistance factor declines rapidly as RH rises. All in all, this wood is very permeable for diffusion in axial direction. In the case of spruce (Fig. 1, right) the values are even lower, also with resistance dropping steeply as RH increases. Diffusion resistance factors of 1 or less are measured in the high moisture range. This can only be explained by assuming that in this moisture range some considerable liquid transport is superimposed on the diffusion (see [8]).

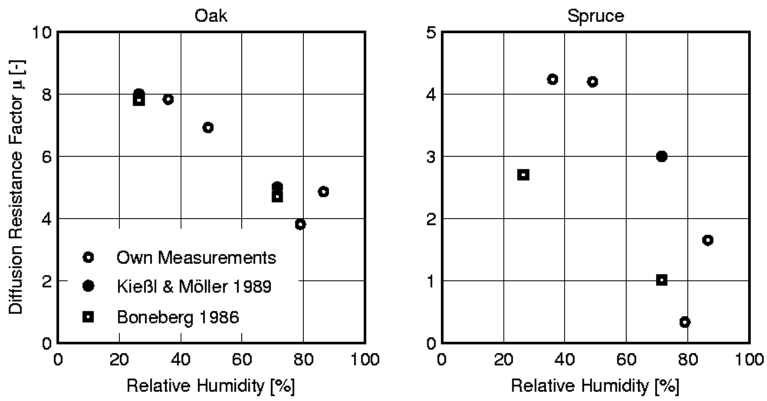

Figure 1 Measured vapour diffusion-resistance numbers in dependence on the average RH and comparison with data quoted in scientific literature.

3.2 Capillary transport coefficients

The water content profiles for the axial direction of absorption determined with the NMR equipment set during the absorption experiment are shown in Fig. 2. Despite the extremely long absorption time of approxim. 1300 hours, the penetration depth (defined here as point of inflexion of the moisture distribution at approx. 50% saturation) is only about 4 cm for oak (Fig. 2, left) and 5.5 cm for spruce (Fig. 2, right). Spruce exhibits higher moisture contents due to its greater capillary saturation. The capillary transport coefficients shown in Fig. 3 are calculated from the distributions measured. For oak (Fig. 3, left) the results give moisture-independent capillary transport coefficients below a water content, related to saturation, of 0.8. Above this moisture content, the coefficient rises. Spruce exhibits a similar picture

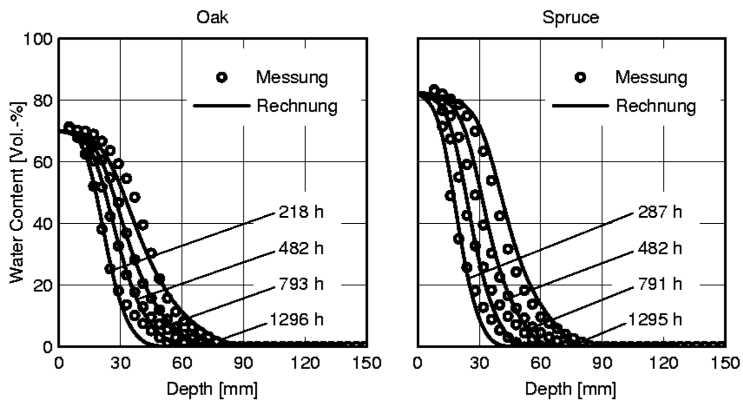

Figure 2 Measured (dots) and calculated (lines) profiles during absorption.

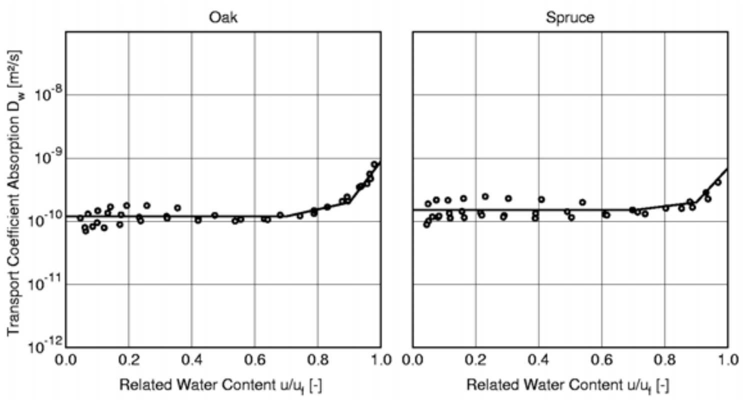

Figure 3 Capillary transport coefficients for absorption as determined from measured moisture profiles(see Fig. 2). The mean coefficients used for the calculation are represented by solid lines.

with one difference: only above a related moisture content of 0.9 a rise can be observed. The measurements to determine the transport coefficients for capillary redistribution, carried out after the absorption experiments, result in moisture profiles which scarcely change after the imbibition of water is interrupted (see Fig. 4). This means that no or, at most, only extremely slight redistribution takes place. This was observed for both types of wood. For this reason, it is not possible to determine the transport coefficients for this process.

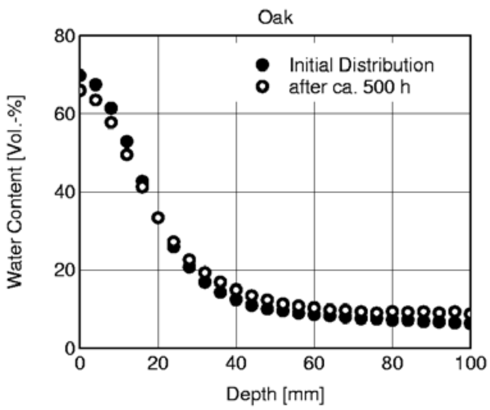

Figure 4 Moisture profiles as measured during redistribution. Even after 500 hours the initial profile has not changed considerably.

4. COMPARISON OF MEASUREMENTS AND CALCULATED RESULTS

4.1 Laboratory investigations

The course of water absorption during a 23-day absorption experiment is recorded as points in Fig. 5. For both oak and spruce there is, as is to be expected, a good correspondence between the calculated results (solid line) and the measurements. Fig. 5 also shows the course of water loss during the subsequent drying phase. It can be seen that drying is initially very rapid for both types of wood, thereafter asymptotically approaching equilibrium state. For the calculations in accordance with the NMR measurements it has been assumed here that no redistribution takes place. It is obvious that the calculations do not agree with the measurements.

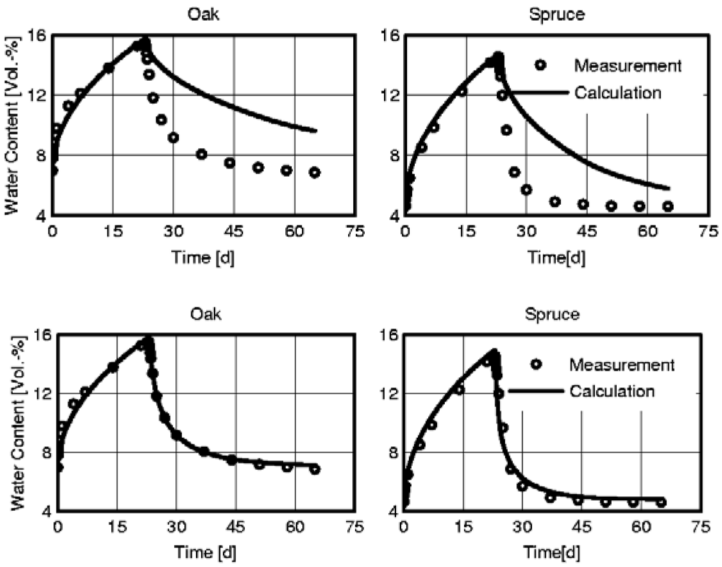

Figure 5 Course of average water content during absorption and drying experiment under laboratory conditions. Whereas good correspondence between calculation (line) and measurements (dots) can be achieved for absorption there is considerable disagreement for drying (Figures above). If the approximated transport coefficient is employed, good correspondence between calculation (line) and measurements (dots) can be achieved for drying, too (Figures below)

For this reason the coefficients for redistribution are additionally determined by an approximation procedure (see [9]). Here the loss of weight during the drying of samples originally saturated and then exposed to well known boundary conditions is determined and the transport coefficients worked out by iterative fitting of the calculated and measured drying courses. The basic hygric properties are listed in Table 1 together with the exponentially approximated transport coefficients. For the absorption process they are only slightly dependent on moisture content, similar to those determined by NMR measurement. One surprising feature, however, are the transport coefficients for drying. In contrast to mineral building materials, where these are always smaller than those for the absorption process, and in particular contrast to the results of the NMR measurements for redistribution, the coefficients here are several magnitudes above those. Calculations carried out with these transport coefficients provide good correspondence with the measurements for water absorption and drying for both types of wood (compare Fig. 5).

Table 1 Compilation of hygric material properties. D_{wo} and D_{wf} mean the transport coefficients practical moisture content resp. capillary saturation.

Type of wood	Bulk density	Capillary saturation	Practical water content	Diffusion-resistance factor	Water-absorption coefficient	Capillary transport coefficients exponential approximation Absorption		Redistribution	
	ρ [kg/m³]	u_f [Vol.%]	u_{80} [Vol.%]	μ [-]	A [kg/m²√h]	D_{wo} [m²/s]	D_{wf} [m²/s]	D_{wwo} [m²/s]	D_{wwf} [m²/s]
Oak	685	50	11	8	0.6	$2\cdot10^{-10}$	$4{,}2\cdot10^{-10}$	$2\cdot10^{-10}$	2
Spruce	455	60	8	4.3	0.7	$2\cdot10^{-10}$	$3\cdot10^{-10}$	$2\cdot10^{-10}$	100

4.2 Natural weathering

The course of the average water content over an observation period of almost 80 days is presented as measured points in Figs. 6. Starting with a water content of around 45 kg/m³ corresponding to the sorption moisture at 50% RH, the water content of oak rises to a maximum of 75 kg/m³, due to the driving rain during the investigation period, but then dries out almost back to the initial water content (Fig. 6, top). Spruce exhibits a similar course at a somewhat higher level but with a lower range of variation.

For the calculation of the moisture behaviour, the problem of selecting the suitable transport coefficients poses itself. The NMR measurements produce extremely low coefficients for redistribution, while the drying experiments provide coefficients which are considerably higher than those of the absorption process. As a compromise for the calculations it is thus assumed that the transport coefficients for redistribution and drying are the same as those for absorption (solid line). For both oak and spruce the calculations over the first 40 days show very good correspondence with the measured values, and for the next 40 days this correspondence is still good with the average values slightly too high and the variation range somewhat too small. In addition, the courses which would result from employing the transport coefficients for redistribution taken from the drying experiment (dotted line) and if calculations assume no redistribution at all (broken line)is shown. With transport coefficients from the drying experiment constantly increasing water contents which are considerably higher than the measured values are obtained. Without redistribution, the courses are a little below the solid lines and are, surprisingly, even closer to the measured values.

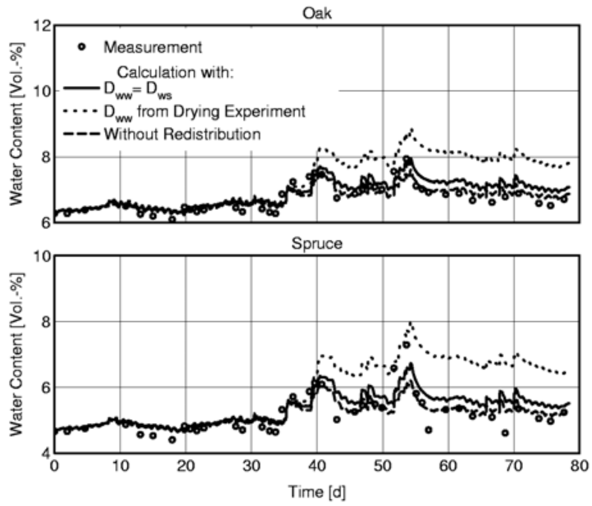

Figure 6 Course of the average moisture content of a wood specimen exposed to weathering over a period of almost 80 days.

5. SUMMARY

In order to be able to calculate the behaviour of moisture in wooden building components, the hygric material properties for oak as a representative of deciduous timber (hardwood) and for pine as a representative of coniferous timber (softwood) are determined. Determination of the redistribution coefficients by means of iterative fitting of the calculated drying process to that actually measured leads to a surprising result. The transport coefficients thus determined are not, as in the case of mineral building materials, smaller than those for the absorption process, but higher by many orders of magnitude. For pure redistribution however, transport coefficients that are higher than for the absorption process are not physically plausible, which means that an additional transport mechanism must be present here. Given the material involved, it is a fair assumption that the reason for this unusual behaviour lies in the extreme capacity of timber to swell. The difference between redistribution and drying lies in the fact that redistribution involves the transport of moisture into the dry, unswollen wood. The suction tension of the small capillaries which, during redistribution, suck the big capillaries dry and transport moisture to the interior of the material is apparently not sufficiently large to permit actual transport. During the drying process, transport takes place from the swollen state. The extremely high transport coefficients determined for this arouse the impression that the water is "pressed" out of the wood. Although the simulation software for transient heat and moisture does not distinguish between transport coefficients for redistribution and for the drying process, it can be demonstrated with wood specimens under natural weathering conditions that for the course of water content (but certainly not for moisture profiles) a good correspondence between the results of calculations and the actual measurements can be achieved.

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