Investigation report
on the creation of three material datasets for the hygrothermal simulation of cross-laminated timber (CLT) using the WUFI® software

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Table of Contents

1 Introduction

The following investigations were carried out by the Fraunhofer Institute for Building Physics in cooperation with the Office for Timber Construction and Building Physics (holz[bau]physik), Dipl.-Ing. (FH) Daniel Kehl, Leipzig. The commission for this work was granted as part of the research project *“Quality assurance in modern multi-storey timber and timber-hybrid construction (HolzQS) – Development of protection concepts and monitoring systems to protect timber structures from harmful moisture during the manufacturing, construction and usage phases”*.
The research project is funded by the Federal Ministry of Food and Agriculture, project management: Agency for Renewable Resources (FNR).
The aim of this study is to provide a comprehensive description of the building physics properties of cross-laminated timber (CLT) for hygrothermal component simulation using the WUFI® software developed by the Fraunhofer Institute for Building Physics. This comprehensive material description comprises three sets of material data, already implemented in WUFI 7 under the following names:

- Spruce radial, tangential (2026),
- Spruce longitudinal (2026) and
- CLT adhesive layer

Using various measurement methods and values known from the literature, the hygrothermal material parameters of spruce and the adhesive joint are determined, which are necessary for modern, transient hygrothermal simulation methods.
The following parameters are required for a complete material dataset for WUFI®:

- dry bulk density ρ_0
- true density ρ_m
- porosity Φ / max. water content w_{max}
- thermal conductivity, dry λ_0, humidity- and temperature-dependent $\lambda(w;T)$
- sorption isotherm (moisture storage function) w(T;RH)
- free water saturation (w_f)
- water vapour diffusion resistance factor μ [-]
- water absorption coefficient (w or A)

In order to create a material dataset from the measured values, additional tests using Nuclear Magnetic Resonance (NMR) measurements are required, particularly for the determination of moisture transport coefficients.

- water absorption including NMR measurement
- redistribution test including NMR measurement
- drying test including NMR measurement

During the creation of the material dataset, individual parameters may be adjusted due to the variability of the material. The final material datasets are compiled in a summary at the end of the report.

2 Material properties – measurements and literature

2.1 bulk density, oven-dried ρ_0 [kg/m³]

The bulk density ρ is defined as the density of a solid, which is the ratio of the mass of the solid substance to the volume it occupies [kg/m³]. The volume comprises the solid material including the pore space of the material sample. If the bulk density is determined in the oven-dried state, this is referred to as the dry bulk density ρ_0. The dry mass is usually determined by drying at 103°C to constant weight in accordance with [EN ISO 12570: 2018]. The sample size for spruce was 60 x 30 x 30 mm (air-dried). The detailed measurement results can be found in Appendix 5.1.

The determined dry bulk density ρ_0 of the spruce examined is 407 kg/m³.

2.2 true density ρ_m [kg/m³]

The true density ρ_m is defined as the density of a solid, which is the ratio of the mass of the solid substance to the volume it occupies [kg/m³]. The volume consists of solid material excluding the pore space of the material sample [kg/m³]. True density is also referred to as solid density.

For wood, the true density ρ_m can be assumed to be 1500 kg/m³ with sufficient accuracy for hygrothermal considerations.

2.3 open porosity Φ_0 [m³/m³, or Vol.%]

Open porosity Φ_0 is the ratio of the open pores accessible to water relative to the total volume of the sample. Porosity is calculated from the dry bulk density and true density using the solid volume. It describes the total available pore space.
For wood, the following porosity is obtained from the determined bulk density (dry) ρ_0 of 407 kg/m³ and the assumed true density of 1500 kg/m³ for spruce.

$$\Phi = 1 - \frac{\rho_0}{\rho_m} = 1 - \frac{407}{1.500} = 0{,}73\ m^3/m^3$$

Φ_0	*[m³/m³]*	*open porosity*
ρ_0	*[kg/m³]*	*bulk density (dry)*
ρ_m	*[kg/m³]*	*true density or solid density*

2.4 max. water saturation w_{max} [kg/m³]

The maximum water saturation, also referred to as the maximum water content w_{max}, is determined by the porosity and the bulk density of water. At maximum water saturation, all pores would be filled with water.

$$w_{max} = \Phi_0 \cdot \rho_w = 0,73 \cdot 1.000 = 730 \frac{kg}{m^3}$$

w_{max}	*[kg/m³]*	*maximum water content*
Φ_0	*[m³/m³]*	*porosity (average porosity)*
ρ_w	*[kg/m³]*	*bulk density of water (1000 kg/m³)*

2.5 free water saturation $w_{f,28d}$ [kg/m³]

Free water saturation w_f is the volume-related quantity of water that a material absorbs when stored in water without additional external forces (overpressure or vacuum). Due to trapped air pores, it is always below the maximum water saturation w_{max}. The determination of free water absorption at atmospheric pressure is carried out for timber in accordance with [EN 13755: 2008]. The test specimens measuring 100 x 100 mm² and 10 mm thick are first dried in a drying oven until their weight remains constant. The samples are then placed on a wire rack in a water bath (23°C), covered with water, removed from the water bath after 28 days, dabbed dry and weighed.
The process of water absorption up to free water saturation generally takes a very long time, even with small samples. As experiments on wood show, wood that absorbs water via the radial/tangential direction must remain in water for a long time to reach free water saturation (fig. 1; lower curve). As such time periods do not occur, or occur only extremely rarely, in construction practice, free water saturation w_f is defined after 28 days. Due to this time limit, the direction of cut and sample size influence the result. To determine the free water content as quickly as possible, the samples were cut (longitudinally / 10 mm thick) so that as much water as possible penetrates the sample via the end grain.

The free water saturation w_f of spruce is thus 723 kg/m³ or 178 wt.-%.

A comparison between the NMR measurement (explanation in Chapter3.3.3) and the corresponding simulation has shown that the selected 28-daytest duration and the sample size are appropriate for wood.

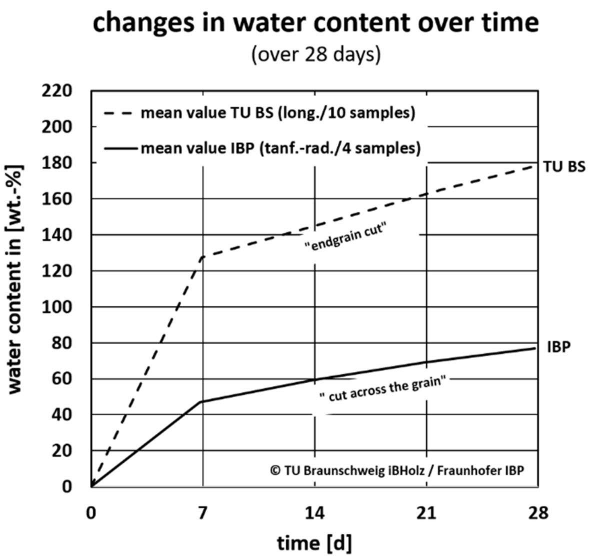


fig. 1: Free water saturation w_f – values after 7 and 28 days are linearly related. w_f is not reached for radial/tangential (Source: IBP and iBHolz at TU Braunschweig)

2.6 thermal conductivity λ [W/m·K]

The thermal conductivity (λ) of a material describes the heat flux (W) flowing through a 1 m thick layer of the material due to a temperature gradient (K). In the case of wood, it depends primarily on the dry bulk density and moisture content.
As the thermal conductivity of wood has been well researched, it is no longer measured and is assumed here for kiln-dried wood as follows:

$$\lambda_{\perp,0} = 0{,}0217 + 0{,}1887 \cdot 10^{-3} \cdot \rho_0 = 0{,}0217 + 0{,}1887 \cdot 10^{-3} \cdot 407 = 0{,}095\ W/m \cdot K$$
$$\lambda_{||,0} = 0{,}0217 + 0{,}4443 \cdot 10^{-3} \cdot \rho_0 = 0{,}0217 + 0{,}4443 \cdot 10^{-3} \cdot 407 = 0{,}20\ W/m \cdot K$$

λ [W/m·K] thermal conductivity, dry (⊥ perpendicular to the grain; || parallel to the grain)
ρ_0 [kg/m³] bulk density (air-dried) here 407 kg/m³

Effect of moisture on thermal conductivity

The effect of wood moisture content (u) on thermal conductivity is also well understood up to fibre saturation. The thermal conductivity of wood increases by 1.25% per percentage point of moisture content.

$$\lambda_u = \lambda_0 \cdot (1 + 0{,}0125 \cdot u)$$

u [wt.-%] wood moisture content
λ_0 [W/m·K] thermal conductivity, dry (⊥ perpendicular to the grain; || parallel to the grain)

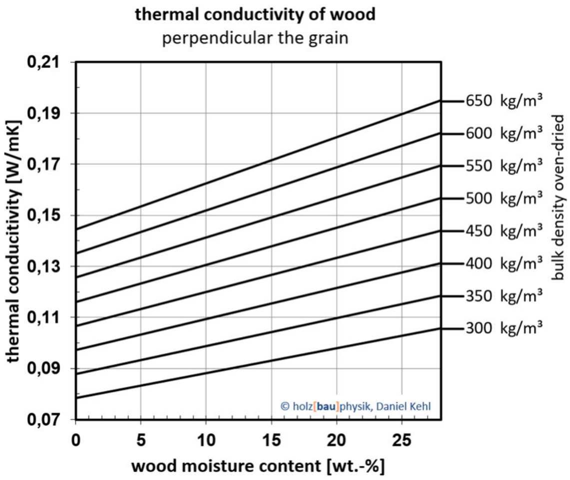


fig. 2 : Relationship between bulk density, wood moisture content and thermal conductivity (Source: HBP)

2.7 specific heat capacity c_0 [J/kg·K]

The specific heat capacity c_0 of a material is the amount of heat in J required to raise the temperature of 1 kg of the material by 1 K [J/kg·K]. In the hygrothermal material dataset, the specific heat capacity refers to the dry state of the material. The specific heat capacity of water c_w is added during the hygrothermal simulation depending on the calculated water content.
The specific heat capacity c_0 of wood can be set at 1400 ± 50 J/kg·K and that of water (c_w) at 4190 J/kg·K [Kollmann 1982].

$$c_m = (\frac{u}{100+u}) \cdot c_w + (1 - \frac{u}{100+u}) \cdot c_0$$
$$c_m = (\frac{u}{100+u}) \cdot 4190 + (1 - \frac{u}{100+u}) \cdot 1400$$

c_m	*[J/kg·K]*	*average heat capacity of wood at a wood moisture content u*
u	*[wt.-%]*	*wood moisture content*
c_0	*[J/kg·K]*	*specific heat capacity (wood)*
c_w	*[J/kg·K]*	*specific heat capacity (water)*

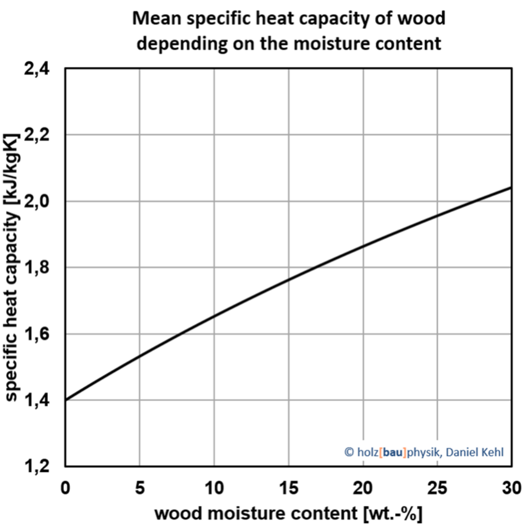


fig. 3 : Relationship between wood moisture content and specific heat capacity (Source: HBP)

2.8 sorption isotherm / moisture storage function w (T, RH)

2.8.1 sorption in the hygroscopic range

The sorption isotherm / moisture storage function w (T, RH) describes the water content of a building material in equilibrium with the respective ambient conditions (temperature (here 23°C) and relative humidity). When determining the storage properties, a distinction must be made between the hygroscopic sorption moisture range and the superhygroscopic range. In the sorption moisture range, the samples are stored in an environment set using a salt solution or a climatic chamber, and the equilibrium moisture content is determined by weighing the sample. By varying the relative humidity (50% to 97% RH), the absorption isotherm is obtained; conversely, the desorption isotherm is obtained using the reverse procedure. The measurement procedure is regulated within [EN ISO 12571: 2022]. The sample dimensions at cutting were 50 x 40 x 20 mm. The measurement results can be found in the appendix 5.2.

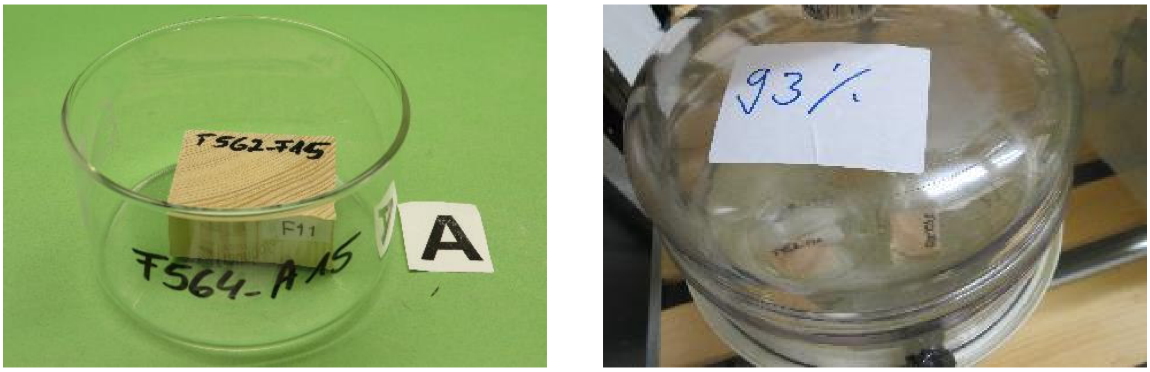


fig. 4 : Glass dish with sample (left) and desiccator with samples (right) (Source: IBP)

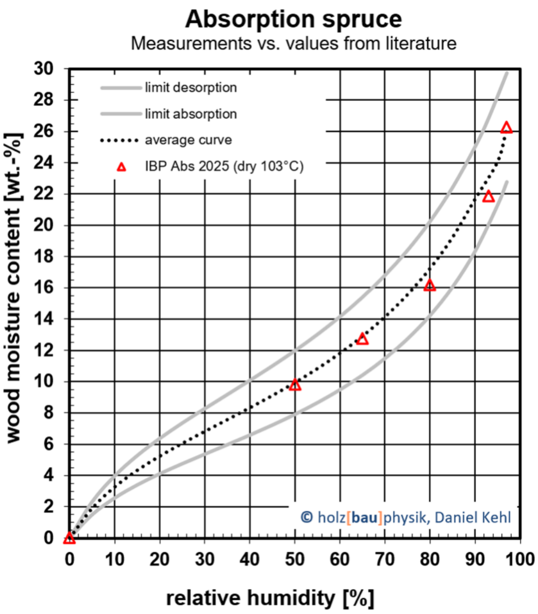


fig. 5 : Absorption values from the measurements (red triangles) compared to the expected range based on literature values (grey lines). (Source: IBP / HBP)

2.8.2 moisture storage function in the superhygroscopic range

The moisture storage function in the superhygroscopic range is generated mathematically from the material moisture contents at 65%, 80%, 93% and 97%RH, as well as the free water saturation w_f and the maximum water saturation w_{max}.

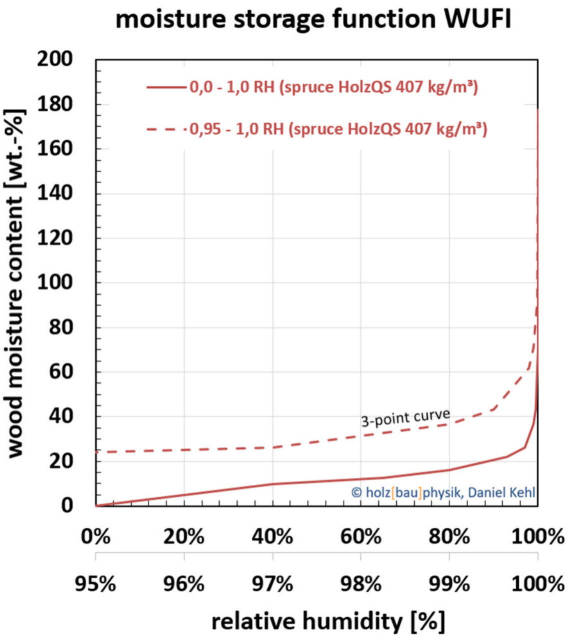


fig. 6: Complete moisture storage function from the hygroscopic and super-hygroscopic ranges

3 moisture transport

3.1 moisture transport model

When modelling moisture transport in materials, WUFI® distinguishes between diffusion and capillary transport. The transport processes can only be measured separately to a limited extent. For example, the reduction in the diffusion resistance factor μ (or the measured increase in water vapour permeability) when the average material moisture content increases is based on moisture transport in the liquid phase superimposed on diffusion. Different transport potentials act on both transport mechanisms, strictly speaking, combining both transport types into a moisture-dependent diffusion resistance factor is not correct [Krus 1995]. In wood, this superposition of transport processes already occurs at low relative humidity levels (< 50% RH), as evidenced by numerous diffusion measurements in the literature.

In [Fitz et al. 2004], the diffusivity model approach of WUFI® is described as follows: *"Although the capillary transport coefficient is actually a flow phenomenon, liquid transport in the pore spaces can be described with sufficient accuracy for building physics purposes using a diffusion approach"*. *The **liquid transport coefficient for the suction process D_{ws}*** (diffusivity $_{water\text{-}suction}$) *describes the capillary water uptake when the component surface is fully wetted. In the* *context of building physics, this corresponds, for example, to the component being sprayed with water or a water absorption test. The suction process is determined by the larger capillaries, as although they possess a lower suction force than the small capillaries, they also have an even more significantly reduced flow resistance*. For the suction process in mineral building materials, a relationship can be derived between D_{ws} and the A-value (water absorption coefficient) by an approximation method [Holm 2001], which is also implemented in the WUFI® software. As simulation tests carried out as part of the project have indicated (results not shown here), the method is unsuitable for wood. Therefore, in this research project, the liquid transport coefficients were explicitly adjusted iteratively using the results of the NMR measurement.

The **liquid transport coefficient for redistribution**, $\mathbf{D_{ww}}$ (diffusivity $_{\text{water-redistribution}}$), describes the redistribution of the absorbed water once wetting has ceased, no further water is penetrating the material, and the existing water begins to redistribute. This redistribution is determined by the smaller capillaries, as their greater suction power draws the water out of the larger capillaries. To obtain correct liquid transport coefficients for wood, corresponding recalculations of various tests are required.

3.2 water vapour diffusion (µ-value and s_d-value)

water vapour diffusion resistance factor µ [-] and
water vapour equivalent air layer thickness (s_d-value)

The water vapour diffusion resistance factor (µ) describes the water vapour diffusion resistance of a material in comparison to a layer of air with the same thickness. The water vapour diffusion resistance factor of air is therefore 1, whereas that of many building materials is generally higher. The measurement of the so-called µ-value is carried out in accordance with [EN ISO 12572: 2025]. As a rule, a distinction is initially made only between the dry-cup method (between 3 and 50% RH) and the wet-cup method (between 50 and 93% RH). The measurement is carried out under isothermal conditions at 23°C.

If the thickness of the material is taken into account, this results in the water vapour equivalent air layer thickness (s_d-value). The s_d-value [m] is calculated from the water vapour diffusion resistance factor µ [-] multiplied by the thickness of the building material [m]. The s_d-value is therefore a measure of the diffusion resistance of a building material compared to an air layer of the calculated thickness.

3.2.1 Measured values and literature values for spruce

The sample size of the spruce wood samples used in the tests is approx. 100 x 100 x 20 mm³. The samples initially consist of two stacked, not glued samples, each 10 mm thick. To determine the µ-value of the adhesive, the samples are later glued together. The moisture difference is generated using silica gel (3% RH – ‘dry cup’), a saturated salt solution of ammonium dihydrogen phosphate (93% RH – ‘wet cup’) and a climate chamber (50% RH).

fig. 7: Determination of the water vapour diffusion resistance factor μ using cup measurement (here wet-cup: 50 – 93% RH). (Source: IBP)

table 1: Determined water vapour equivalent air layer thickness s_d of **spruce without adhesive**

	dry-cup 3 – 50%			wet-cup 50–93%		
	average thickness [mm]	**average μ-value [-]**	**s_d-value [m]**	**average thickness [mm]**	**average μ-value [-]**	**s_d-value [m]**
radial/tangential	20.5	151	3.10	21.1	31	0.65
longitudinal	20.3	3.1	0.06	20.7	2.4	0.05

In wood, the diffusion resistance factor μ decreases as moisture content increases. As described above, moisture transport consists of both diffusion and capillary transport. In a simplified approach, for the material datasets generated here below 50% RH, the entire moisture transport is attributed to diffusion. Above 50% RH, moisture transport consists of diffusion and capillary transport.
The analysis of our own measurements and numerous data points from the literature yielded the following curve for moisture transport below 50% RH for the radial/tangential direction (fig. 8). Using this curve ofthe diffusion resistance, the ‘dry-cup’ test can be recalculated by simulation. When recalculating the ‘wet-cup’ test, liquid transport (see below) is added to the diffusion. Consequently, the curve of the water vapour diffusion resistance factor does not coincide with the μ-value of the ‘wet-cup’ test.

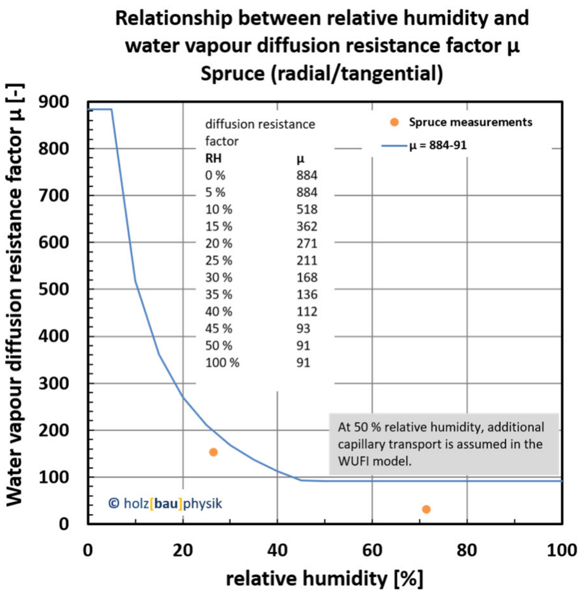


fig. 8: Water vapour diffusion resistance factor of spruce (radial/tangential) derived from our own measurements and values from the literature. Diffusion and capillary action occur from 50% relative humidity. (Source: HBP / IBP)

3.2.2 Measured values of adhesive layer

As the adhesive has a very thin layer thickness, it makes more sense to express the diffusion resistance solely in terms of the s_d-value rather than the µ value and its thickness. Furthermore, for numerical reasons, adhesive layers are assumed to be 1 mm thick in the WUFI® simulation software.

The samples from the previous test (without adhesive) were bonded with a PU adhesive after measurement, and the diffusion flux was measured again using the cup tests. This yielded the following values for the spruce samples including adhesive (table 2). To determine the s_d-value of the adhesive, the s_d-value of the spruce samples without adhesive (table 1) is subtracted from those with adhesive (table 2).

table 2: Determined water vapour equivalent air layer thickness s_d of **spruce with adhesive**

	dry-cup 3 – 50%			**wet-cup 50 – 93%**		
	average thickness [mm]	**average µ-value [-]**	**s_d-value [m]**	**average thickness [mm]**	**average µ-value [-]**	**s_d-value [m]**
radial/tangential	20.1	251	5.04	19.8	65	1.28
longitudinal	20.1	4.9	0.10	20.2	3.9	0.08

table 3: From the s_d-value without adhesive (table 1) and with adhesive (table 2), the μ-value and s_d-value for a hypothetical 1 mm thick adhesive layer can be determined.

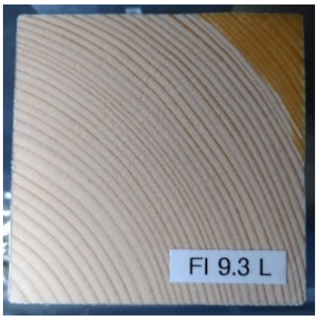
	dry-cup 3 – 50%			wet-cup 50–93%		
	thick-ness[1)] [mm]	average μ-value [-]	s_d-value [m]	thick-ness[1)] [mm]	average μ-value [-]	s_d-value [m]
radial/tangential	1	1940	1.94	1	630	0.63
longitudinal	1	40	0.04	1	30	0.03

1 In the WUFI® software thin layers are assumed to be 1 mm thick for numerical reasons.

3.3 liquid transport coefficients

3.3.1 water absorption coefficient w [kg/m²√h] or A [kg/m²√s]

The water absorption coefficient (w-value [kg/m²√h] or, internationally, A-value [kg/m²√s]; w-value = 60 x A-value) expresses the water absorption of a defined area per unit of time. The A-value is determined in accordance with [EN ISO 15148: 2018]. To do this, a sample sealed at the sides is placed 5 mm into water and removed at specific intervals; excess droplets are dabbed off whilst wet and the sample is weighed. This results in a typical square-root function over time (see fig. 9).



Note: Spruce is one of the so-called heartwood trees. Heartwood has lower water absorption properties than sapwood. There is no visible colour difference between heartwood and sapwood, so that sapwood may be present in the samples during cutting. Consequently, there may be greater variation in the A-value. This is only evident in the longitudinal direction.

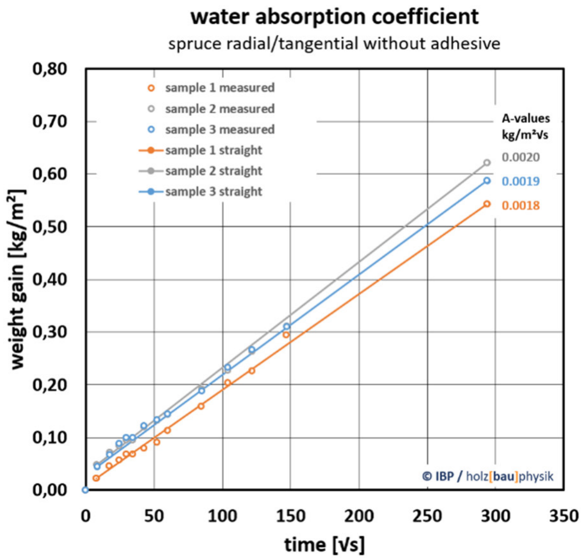


fig. 9 : Results of A-value measurements in the radial/tangential direction. On average, the water absorption coefficient is 0.002 kg/m²√s. (Source: IBP)

The measured A-values fall within a typical range and the associated standard deviation. Differences arise from material variation and the selected sample size.

table 4 : Determined A-values for spruce (IBP/HBP) and values from the literature

	IBP measurement A-value (10 x 10 x 1 cm)	**HBP measurement A-value (8 x 8 x 8 cm)**	**References Min - Max**
longitudinal A-value [kg/m²√s]	--	0.0102 – 0.0112	0.0105 – 0.019 mean value: 0.0135
radial/tangential A-value [kg/m²√s]	0.0018– 0.0020	0.0012 – 0.0013	0.0014 – 0.0038 mean value: 0.0023

3.3.2 liquid transport coefficients D_{ws} and D_{ww}

To determine the behaviour of the liquid transport coefficients D_{WS} and D_{WW}, various tests must be resimulated and the material parameters adjusted iteratively. The higher the information density, the more accurately the liquid transport coefficients can be determined.

- diffusion test (dry-cup)
  → testing µ-value up to 50% RH
- diffusion test (wet-cup)
  → testing µ-value and liquid transport from 50 – 93% RH
  water absorption test (water absorption curve)
  → test of liquid transport D_{WS}

- water absorption test (moisture profile via NMR scanner)
  → test of liquid transport D_{WS} and D_{WW}
- redistribution test (moisture profile via NMR scanner)
  → liquid transport test D_{WW}
- drying test (drying process)
  → liquid transport test D_{WW}
- drying test (moisture profile via NMR scanner)
  → liquid transport test D_{WW})

3.3.3 NMR scanner

Using the Nuclear Magnetic Resonance measurement (NMR, fig. 10), the moisture profile can be recorded along the length of a sample during a test. The received signal is converted into wood moisture content. The moisture profiles thus provide information on how quickly and how far the water has been transported into the sample. Such profiles help to iteratively adjust the liquid transport coefficients so that they can be verified by means of hygrothermal simulation. The sample size is limited to 40 x 40 x 80 mm by the scanner.

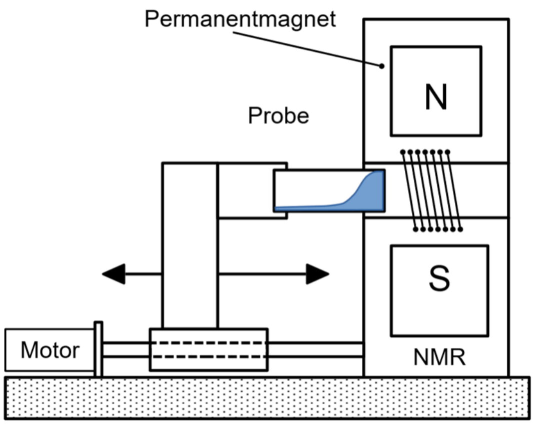


fig. 10: Schematic diagram of the NMR scanner (Source: HBP / IBP)

fig. 11 shows two examples of measured moisture profiles following a 3-day water absorption test. The left image shows that, after 3 days, the sample has absorbed hardly any water in the radial/tangential direction and that the water has only distributed to a depth of approx. 20 mm. On the right is a sample that has absorbed significantly more water through the end grain and transported it longitudinally almost to the end of the sample (80 mm).

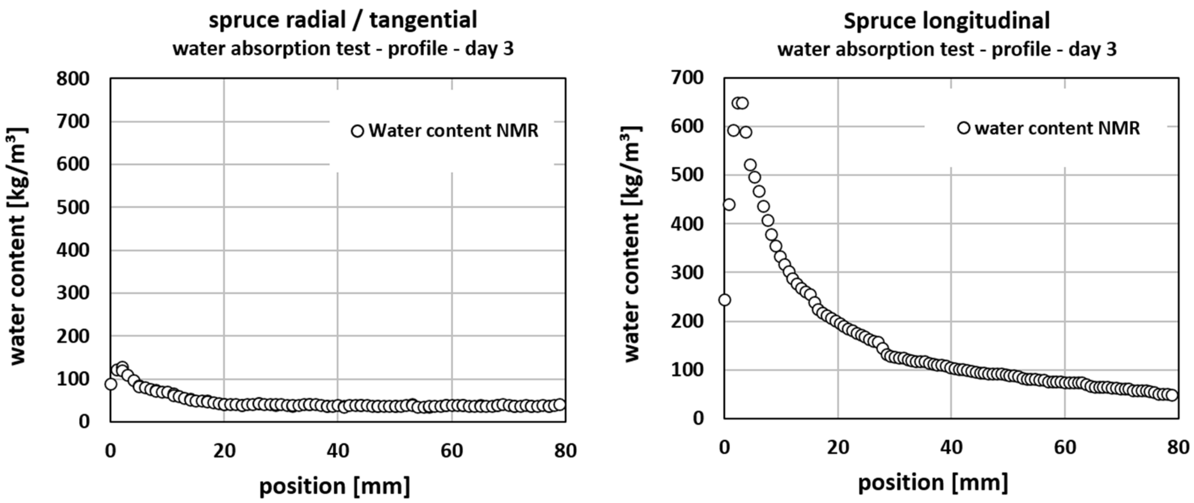


fig. 11: Measured moisture profile from the NMR scanner after 3 days of a water absorption test in both directions. (Source: IBP / HBP)

3.3.4 water absorption test - moisture profile (D_{WS})

The increasing water content from the water absorption test (suction test) should be reproducible in simulation using the liquid transport coefficient for suction (D_{WS}). The same applies to the moisture profile within the cross-section. As can be seen from fig. 12 (radial/tangential) and fig. 13 (longitudinal), both tests can be simulated using the generated material datasets. The difference between the measured and calculated values for the first millimetre is to be expected given the test procedure. The samples are removed from the water at defined intervals and dabbed dry whilst still damp. After weighing, their moisture profiles are scanned in the NMR device. During this process, the surface has dried out slightly.

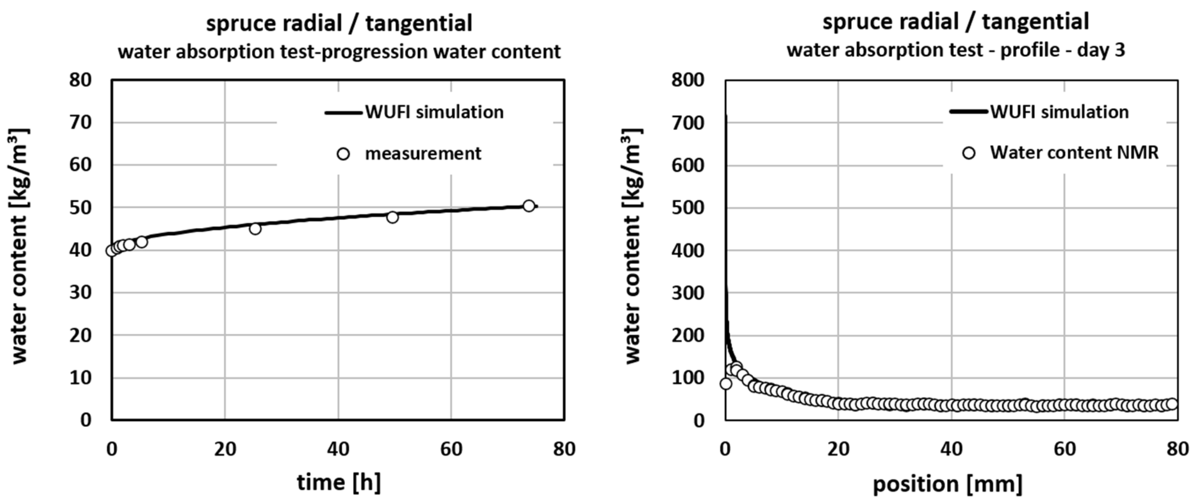


fig. 12: **radial/tangential direction**: water absorption test: Comparison between measurement (circles) and simulation (line). Left: Water content over time / Right: Moisture profile after 3 days of the test. (Source: IBP / HBP)

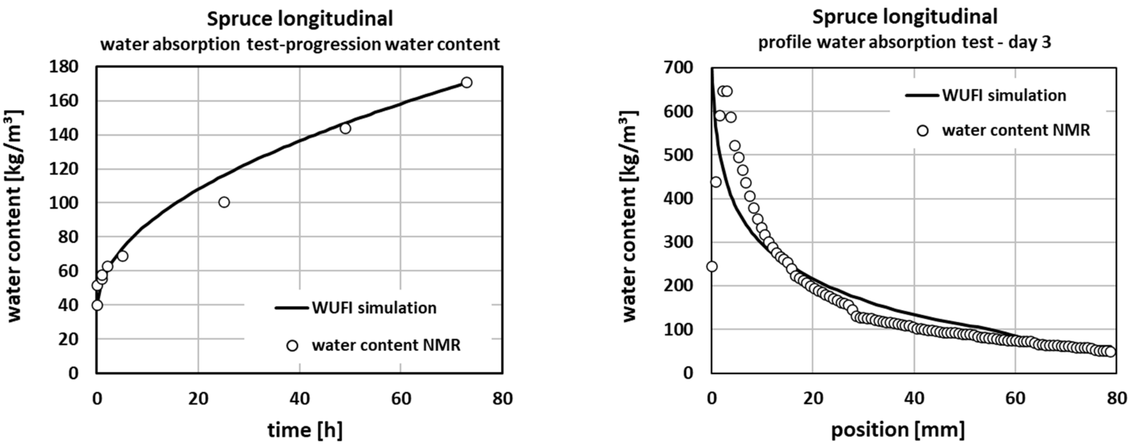


fig. 13: **longitudinal direction**: water absorption: comparison between measurement (circles) and simulation (line). Left: water content over time / Right: moisture profile after 3 days of the test. (Source: IBP / HBP)

The A-value for spruce was determined, on the one hand, using the standard A-value test (table 5, columns 1 and 2) and, on the other hand, using the water absorption test, in which water uptake and moisture profiles were recorded during and at the end of the test using an NMR scanner (table 5, column 3). In addition, the tests are recalculated, yielding a A-value. It is to be expected that the A-values determined from all the measurements carried out will be more or less the same. As shown in table 5 , the values nevertheless differ from one another. The deviations can be attributed both to sample-specific factors (material variation, sample size; see Section 3.1.2) and to method-related influences (measurement inaccuracies, measurement procedure). For example, the minimal drying during the NMR scans can lead to a reduction in the A-values, particularly in the radial/tangential direction, where even small differences have a significant effect due to the already low A-values. Nevertheless, all values remain within the usual tolerance ranges.

table 5: Comparison of A-value test / suction test including NMR measurement and recalculation

	IBP measurement A-value (10 x 10 x 1 cm)	**HBP measurement A-value (8 x 8 x 8 cm)**	**IBP measurement (NMR) (4 x 4 x 8 cm)**	**WUFI material Verification experiments**
longitudinal A-value [kg/m²√s]	--	0.0102 – 0.0112	0.0152 – 0.0167	0.0188
radial/tangential A-value [kg/m²√s]	0.0018 – 0.0020	0.0012 – 0.0013	0.0012 – 0.0015	0.0020

3.3.5 water distribution test – moisture profile (D_{WW})

After a 3-day water absorption test, the water contact is interrupted, and the end faces are sealed with a vapour-tight film. The absorbed water then continues to distribute within the samples without drying out. The moisture profiles are recorded at defined time points using an NMR scanner. The redistribution following the absorption test should also be reproduced in simulation using the appropriate liquid transport coefficient D_{WW}. The capillary transport coefficients for redistribution D_{WW} were determined iteratively, so that the profiles could be recalculated using the hygrothermal simulation programme WUFI® (fig. 14 and fig. 15).

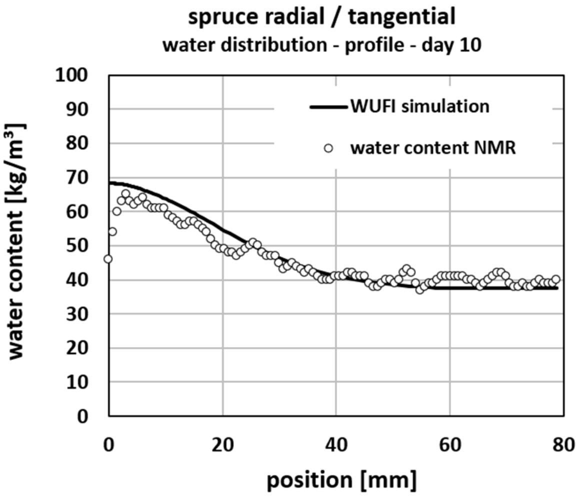


fig. 14: **water distribution radial/ tangential:** Comparison between measurement (circles) and simulation (line). Moisture profile after 10 days of the water distribution test (Source: IBP / HBP)

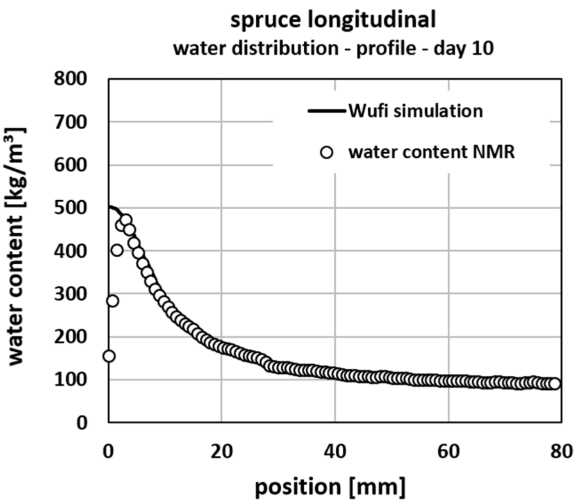


fig. 15: **water distribution longitudinal**: Comparison between measurement (circles) and simulation (line). The moisture profile after 10 days of the water distribution test. (Source: IBP / HBP)

3.3.6 drying test – moisture content over time (D_{WW})

The saturated samples (free water saturation after 28 days, see Chapter 2.5) are sealed on five sides so that they can dry out only through one side. They are stored in a constant climate of 23 °C and 50% RH and weighed regularly until a constant mass is reached. Under these conditions, moisture in the samples is transported to the air via convection at the surface, vapour diffusion and the capillary transport of liquid water. It is to be expected that the moisture profiles, which could be well simulated in the transport experiment with D_{WW}, are also appropriate for the drying process. Therefore, the drying experiment is recalculated for the radial/tangential direction to verify the D_{ww} values determined from the transport experiment. (see fig. 14 and fig. 15)

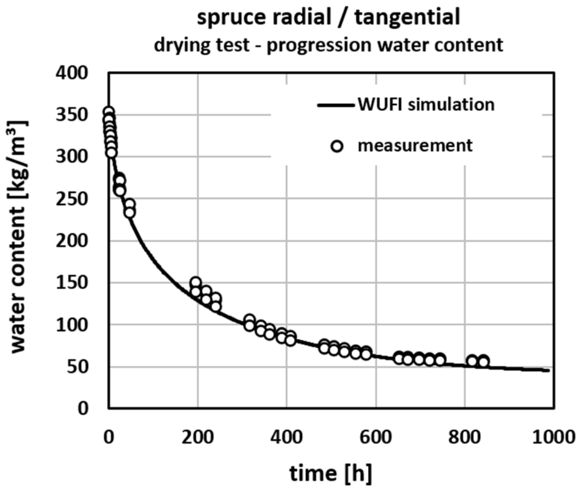


fig. 16: **radial/tangential direction**: Comparison between measurement (circles) and simulation (line). Change in water content during the drying test (Source: IBP / HBP)

The previously determined liquid transport coefficients (D_{WS} and D_{WW}) for spruce (radial/tangential) and spruce (longitudinal) are given in the summary of material data in Chapter4 .

3.3.7 Adhesive layer radial/tangential

The moisture distribution determined using the NMR scanner following the suction test on the bonded samples shows that the adhesive layer exhibits virtually no capillary water transport. (fig. 17). Consequently, in hygrothermal simulations, the adhesive layer is assigned exclusively a diffusion resistance (μ-value).

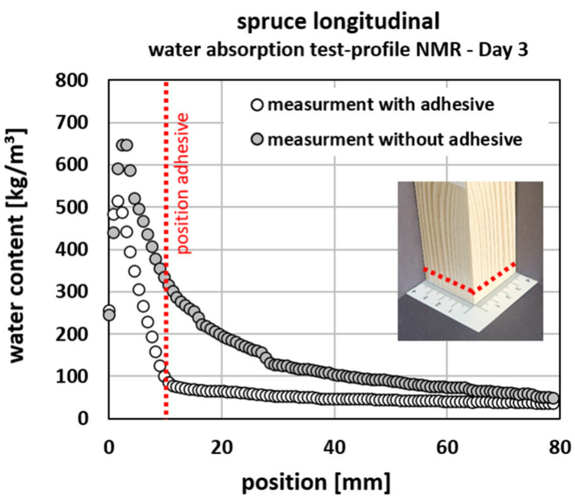


fig. 17 : **Spruce longitudinal:** Moisture profile after a 3-day water absorption test with and without an adhesive layer. (Source: IBP / HBP)

To determine the diffusion resistance, the dry-cup and wet-cup tests are simulated using WUFI®. The calculated values are compared with the measured values.

table 6: s_d-values[1)] of the adhesive layer. The simulation produces the same diffusion flux as the measurement.

direction	**dry-Cup 3 – 50%** s_d**-value**[1)] **[m]**		**wet-cup 50–93%** s_d**-value**[1)] **[m]**	
	measurement	**simulation**	**measurement**	**simulation**
radial/tangential	1.94	1.70	0.63	0.65

1) In the WUFI® software a thin layer of 1 mm is assumed.

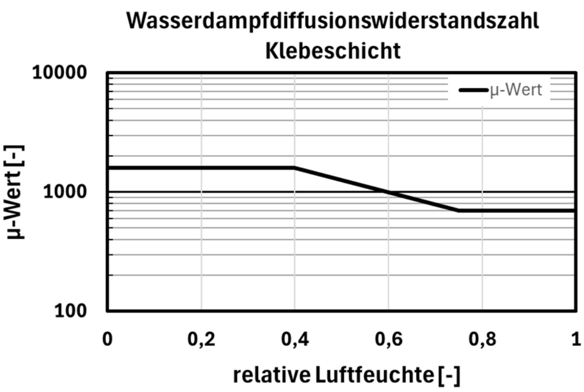


fig. 18: Trend in the water vapour diffusion resistance factor (μ) (Source: IBP / HBP)

4 Summary of material data

table 7 : Measured and calculated material properties of **Spruce longitudinal (2026)**

<table>
<tr><th>property</th><th>unit</th><th colspan="3">results</th></tr>
<tr><td>bulk density (dry)</td><td>kg/m³</td><td colspan="3">407</td></tr>
<tr><td>porosity</td><td>-</td><td colspan="3">0.73</td></tr>
<tr><td>specific heat capacity</td><td>J/kgK</td><td colspan="3">1400</td></tr>
<tr><td>moisture content at
23°C / 50%</td><td rowspan="5">kg/m³ / w-.%</td><td colspan="3">40 / 9.8</td></tr>
<tr><td>23°C / 65%</td><td colspan="3">52 / 12.8</td></tr>
<tr><td>23°C / 80%</td><td colspan="3">66 / 16.3</td></tr>
<tr><td>23°C / 93%</td><td colspan="3">89 / 21.8</td></tr>
<tr><td>23°C / 97%</td><td colspan="3">107 / 26.5</td></tr>
<tr><td>free water saturation $w_{f, 28d}$</td><td>kg/m³ / w.-%</td><td colspan="3">723 / 178</td></tr>
<tr><td>max. water saturation w_{max}</td><td>kg/m³ / w.-%</td><td colspan="3">730 / 180</td></tr>
<tr><td>thermal conductivity (dry)</td><td>W/m·K</td><td colspan="3">0.20</td></tr>
<tr><td>diffusion resistance μ (23°C/3–50%)[1)]
diffusion resistance μ (23°C/50–93%)[1)]</td><td>-</td><td colspan="3">3.1
2.4</td></tr>
<tr><td rowspan="5">diffusion resistance factor μ
(Derived from measured values and simulated using dry-cup and wet-cup tests)</td><td rowspan="5">% | -</td><td>RH</td><td colspan="2">μ</td></tr>
<tr><td>0</td><td colspan="2">3.2</td></tr>
<tr><td>25</td><td colspan="2">3.2</td></tr>
<tr><td>50</td><td colspan="2">2.75</td></tr>
<tr><td>100</td><td colspan="2">2.75</td></tr>
<tr><td>water absorption coefficient w_{24h}
$A_{24h} = w_{24h} / 60$</td><td>kg/m²√h
kg/m²√s</td><td colspan="3">1.13
0.0188</td></tr>
<tr><td rowspan="6">liquid transport coefficients
D_{WS} / D_{WW}</td><td rowspan="6">kg/m³ | m²/s</td><td>water content</td><td>D_{WS}</td><td>D_{WW}</td></tr>
<tr><td>40</td><td>3E-11</td><td>3E-11</td></tr>
<tr><td>89</td><td>9E-10</td><td>9E-10</td></tr>
<tr><td>107</td><td>4E-9</td><td>4E-10</td></tr>
<tr><td>251</td><td>2E-9</td><td>4E-11</td></tr>
<tr><td>354</td><td>5E-11</td><td>2E-12</td></tr>
<tr><td colspan="5">[1)] measured values</td></tr>
</table>

table 8: Measured and calculated material properties of **Spruce radial/ tangential (2026)**

<table>
<tr><th>property</th><th>unit</th><th colspan="4">results</th></tr>
<tr><td>bulk density (dry)</td><td>kg/m³</td><td colspan="4">407</td></tr>
<tr><td>porosity</td><td>-</td><td colspan="4">0.73</td></tr>
<tr><td>specific heat capacity</td><td>J/kgK</td><td colspan="4">1400</td></tr>
<tr><td>moisture content at
23°C / 50%</td><td rowspan="5">kg/m³ | w.-%</td><td colspan="4">40 / 9.8</td></tr>
<tr><td>23°C / 65%</td><td colspan="4">52 / 12.8</td></tr>
<tr><td>23°C / 80%</td><td colspan="4">66 / 16.3</td></tr>
<tr><td>23°C / 93%</td><td colspan="4">89 / 21.8</td></tr>
<tr><td>23°C / 97%</td><td colspan="4">107 / 26.3</td></tr>
<tr><td>free water saturation $w_{f,\,28d}$</td><td>kg/m³ | w.-%</td><td colspan="4">723 / 178</td></tr>
<tr><td>max. water saturation w_{max}</td><td>kg/m³ | w.-%</td><td colspan="4">730 / 180</td></tr>
<tr><td>thermal conductivity (dry)</td><td>W/m·K</td><td colspan="4">0.095</td></tr>
<tr><td>diffusion resistance μ (23°C/3–50%)[1)]
diffusion resistance μ (23°C/50–93%)[1)]</td><td>-</td><td colspan="4">151
31</td></tr>
<tr><td rowspan="7">diffusion resistance factor μ
(derived from measured values and the literature, and simulated using dry-cup and wet-cup tests)</td><td rowspan="7">% | -</td><td>RH</td><td>μ</td><td>RH</td><td>μ</td></tr>
<tr><td>0</td><td>884</td><td>30</td><td>168</td></tr>
<tr><td>5</td><td>884</td><td>35</td><td>136</td></tr>
<tr><td>10</td><td>518</td><td>40</td><td>112</td></tr>
<tr><td>15</td><td>362</td><td>45</td><td>93</td></tr>
<tr><td>20</td><td>271</td><td>50</td><td>91</td></tr>
<tr><td>25</td><td>211</td><td>100</td><td>91</td></tr>
<tr><td>water absorption coefficient w_{24h}
$A_{24h} = w_{24h} / 60$</td><td>kg/m²√h
kg/m²√s</td><td colspan="4">0.12
0.002</td></tr>
<tr><td rowspan="6">liquid transport coefficients
D_{WS} / D_{WW}</td><td rowspan="6">kg/m³ | m²/s</td><td colspan="2">water content</td><td>D_{WS}</td><td>D_{WW}</td></tr>
<tr><td colspan="2">40</td><td>8.0E-11</td><td>8.0E-11</td></tr>
<tr><td colspan="2">89</td><td>1.1E-10</td><td>1.1E-10</td></tr>
<tr><td colspan="2">107</td><td>1.1E-10</td><td>--</td></tr>
<tr><td colspan="2">377</td><td>2.0E-13</td><td>2.5E-09</td></tr>
<tr><td colspan="2">723</td><td>5.0E-15</td><td>2.5E-09</td></tr>
<tr><td colspan="6">1) measured values</td></tr>
</table>

table 9: Determined material properties of **the CLT adhesive layer**

property	Unit	material properties		
		RH	μ	sd
Diffusion resistance factor μ (refers to a 1 mm thick layer of material)	% | - | m	0	1700	1.7
		40	1700	1.7
		75	650	0.65
		100	650	0.65
The total moisture transport of the adhesive layer is attributed to the diffusion resistance. The liquid transport coefficients (DWS and DWW) are not available. The remaining data correspond to those for spruce (radial/tangential)				

5 Appendix (detailed measurement data)

5.1 bulk density, oven-dried ρ_0 Spruce

table 10: Determined dry bulk densities ρ_0 Spruce (dried at 103°C) (HBP)

No. HBP	Mass dry [g]	Volume dry [mm³]	Single value ρ_0 [kg/m³]	Average ρ_0 [kg/m³]
FI 1	20.282	50,784.2	399.4	**407.0**
FI 2	20,237	50,903.2	397.6	
FI 3	22,546	49,888.1	451.9	
FI 4	21,042	51,051.0	412.2	
FI 5	20,137	51,128.7	393.8	
FI 6	20,281	50,866.3	398.7	
FI 7	20,718	50,375.5	411.3	
FI 8	20,464	50,904.9	402.0	
FI 9	20,190	50,622.8	398.8	
FI 10	20,496	50,643.6	404.7	

5.2 Sorption moisture

table 11: Determined wood moisture contents u at corresponding relative air humidity levels (IBP)

No. IBP	Climate	single value u [wt.-%]	average u [wt.-%] / [kg/m³]
F564_A15	23°C / 65% Climate chamber	12.71	12.8 / 52
F564_A16		12.85	
F564_A17		12.79	
F564_A18	23°C / 80% Climate chamber	16.33	16.3 / 66
F564_A19		16.29	
F564_A20		16.27	
F564_A21	23°C / 93% Desiccator1) Ammonium dihydro-gen phosphate	21.9	21.8 / 89
F564_A22		21.8	
F564_A23		21.8	
F564_A24	23°C / 97% Desiccator1) Potassium sulphate	26.94	26.5 / 107
F564_A25		25.89	
F564_A26		26.68	

5.3 Water vapour diffusion resistance factor μ or s_d-value

table 12: Determined water vapour diffusion resistance factor μ for spruce (radial/tangential) (IBP) **without adhesive**

No. IBP	**dry-cup 3 – 50%**		**No. IBP**	**wet-cup 50 – 93%**	
	single value μ [-]	average μ [-]		single value μ [-]	average μ [-]
F564_A10T	161	151	F564_A10F	27	31
F564_A11T	117		F564_A11F	29	
F564_A12T	167		F564_A12F	34	
F564_A13T	174		F564_A13F	34	
F564_A14T	138		F564_A14F	30	

table 13: Determined water vapour diffusion resistance factor μ of spruce, radial/tangential (IBP) **with adhesive**

No. IBP	**dry-cup 3 – 50%**		**No. IBP**	**Wet Cup 50–93%**	
	single value μ [-]	average μ [-]		single value μ [-]	average μ [-]
F564_A10T_nV	247	251	F564_A10F_nV	65	65
F564_A11T_nV	235		F564_A11F_nV	56	
F564_A12T_nV	277		F564_A12F_nV	76	
F564_A13T_nV	280		F564_A13F_nV	72	
F564_A14T_nV	219		F564_A14F_nV	54	

table 14: Calculated s_d value of the adhesive, radial/tangential (dry-cup) (IBP)

without adhesive		with adhesive		adhesive alone	
thickness[1)] [mm]	s_d-value [m]	thickness[1)] [mm]	s_d-value [m]	s_d-value [m]	average [m]
20.7	3.34	20.0	4.95	1.61	
20.3	2.38	20.0	4.71	2.33	
20.6	3.45	20.0	5.55	2.10	1.94
20.5	3.56	20.0	5.62	2.06	
20.3	2.78	19.9	4.36	1.58	

[1] The unbonded samples may be thicker than the bonded samples due to a joint.

table 15: Calculated s_d-value of the adhesive, radial/tangential (wet-cup) (IBP)

without adhesive		with adhesive		adhesive alone	
thickness[1)] [mm]	s_d-value [m]	thickness[1)] [mm]	s_d-value [m]	s_d-value [m]	average [m]
21.1	0.58	19.8	1.28	0.70	
21.4	0.61	19.7	1.11	0.50	
21.2	0.72	19.8	1.50	0.78	0.62
21.0	0.72	19.8	1.42	0.70	
20.9	0.62	19.7	1.06	0.44	

[1] The unbonded samples may be thicker than the bonded samples due to a joint.

table 16 : Determined water vapour diffusion resistance values μ for spruce, longitudinal (IBP) **without adhesive**

No. IBP	**dry-cup 3 – 50%**		**No. IBP**	**wet-cup 50 – 93%**	
	single value μ [-]	average μ [-]		single value μ [-]	average μ [-]
F564_A5T	3.1	3.1	F564_A5F	2.3	2.4
F564_A6T	3.2		F564_A6F	2.4	
F564_A7T	3.1		F564_A7F	2.5	
F564_A8T	3.0		F564_A8F	2.4	
F564_A9T	3.0		F564_A9F	2.4	

table 17 : Determined water vapour diffusion resistance factor μ for spruce samples, longitudinal (IBP) **with adhesive**

No. IBP	**dry-cup 3 – 50%**		**No. IBP**	**wet-cup 50 – 93%**	
	single value μ [-]	average μ [-]		single value μ [-]	average μ [-]
F564_A5T_nV	5.0	4.9	F564_A5F_nV	3.7	3.9
F564_A6T_nV	5.2		F564_A6F_nV	4.0	
F564_A7T_nV	4.8		F564_A7F_nV	3.8	
F564_A8T_nV	4.3		F564_A8F_nV	3.5	
F564_A9T_nV	5.1		F564_A9F_nV	4.3	

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