Experimental Methods to Derive Hygrothermal Material Functions for Numerical Simulation Tools

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ABSTRACT

A particular advantage of numerical simulation is that the investigation of constructions consisting of different materials under various climatic loads requires relatively little work in comparison to field experiments. Thus, a hygrothermal assessment of constructions can be evaluated in a short time. Construction building details and building materials can be optimized using the numerical simulation, and renovation measures can be planned. Since the quality of simulation results depends on known hygrothermal material parameters, there is a great need for reliable material functions.

The present paper describes a database of hygrothermal material property functions for numerical simulation tools. The proposed multimodal physical functions for the thermal properties and the complete moisture storage and transport in the hygroscopic and overhygroscopic range are available for more than 70 building materials.

The distinguished phase transport functions are separated into liquid and vapor phases. The chosen functions are able to smooth and interpolate between scattered measurement data and provide a complete, unbroken, and consistent description of the material. The verification of each material data set, where the proposed functions are evaluated by independent transport measurements, is an advantage.

INTRODUCTION

There has been a change in trends in the European building sector from new constructions to insulation, retrofitting, and restoration of existing buildings. Thus, building reconstruction has an outstanding position in the building market in Europe. This is based on the fact that a comparatively large number of older buildings exists that are worth preserving. Taking a closer look at the East European countries that have recently joined the EU, this aspect of building will become even more important. Many buildings in the stock have to be improved considerably by means of additional thermal insulation of the building envelope. Safe wall construction in connection with an appropriate thermal insulation is generally done by computational prognosis.

The rapid development of the modern hardware and software tools, e.g., CHAMPS, DELPHIN and WUFI, enable the simulation of the hygric and thermal behavior of building components under transient climatic boundary conditions. Meanwhile, building simulation programs are generally used in research projects and engineering applications as well. The simulation of building components, e.g., constructive details, is part of the whole building simulation or integrated building simulation. Here the hygrothermal behavior of the building envelope and the microclimate close to the construction surfaces are the main focus of interest. Despite an adequate description of the material configuration (layering, dimensions, etc.), the quality of simulation results generally depends on the material properties and climatic boundary conditions.

Climatic data, such as temperature, relative humidity, short- and long-wave radiation, precipitation, wind velocity, and wind direction are generally available from weather services, but still the problem of local climate is not solved. The determination of microclimatic data locally at a given building façade position from weather station general climatic

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data, especially regarding driving rain and surface heat or mass coefficients, is a difficult task. Other major problems are the respective hygrothermal properties of building materials. Published data usually lack an adequate general material description, and often the data sets are incomplete. Very often the measured data are not documented and the sets consists of results coming from different laboratories and do not represent the same material batch. Another problem arises from the requirements of the simulation codes themselves. The numerical solution of coupled differential equations uses moisture- and temperature-dependent transport and storage functions (Grunewald et al. 2002). Laboratory experiments deliver material parameters that have to be interpreted in terms of material functions to be useful for simulation models.

This paper presents the experimental investigations and the resultant database on hygrothermal material property functions for numerical simulation tools. Based on works proposed by Hoffmann et al. (1995, 1996) and Plagge et al. (2002), the engineering model approach proposed by Grunewald et al. (2001) and improved in stages by Grunewald and Häupl (2002), Häupl et al. (2001), and Plagge et al. (2007) is consequently applied to a large data set and leads to a complete set of hygrothermal material functions: moisture storage, liquid moisture conductivity, water vapor diffusivity, and thermal conductivity. In addition, the approach delivers the pore volume distribution function and the moisture diffusivity. The proposed material functions smooth and interpolate between scattered measurement data, providing a complete, unbroken, and consistent material description. An important property of the database is the calibration of each single material set, where the proposed functions are evaluated using independent experiments and inverse simulation.

METHODS

The hygrothermal material parameters are determined by laboratory experiments that are already standardized and additional experiments that were found to be important to characterize a building material according to thermodynamical requirements (Grunewald 1997; Grunewald et al. 2001; Plagge 1991; Plagge et al. 2002). Recent research showed considerable uncertainty of the laboratory results. The comparison of measurements of internationally renowned building physical laboratories revealed that the actual level of standardization is not sufficient to ensure measurements of high quality (Scheffler et al. 2007a, 2007b; Krus 1995; Roels et al. 2004a, 2004b).

The applied standardized laboratory experiments are related to German/international standards, namely the following:

- Bulk density, matrix density, and porosity (DIN 2001a)
- Thermal conductivity (DIN 2001b)
- Hygric sorption isotherm (DIN 2000)
- Water uptake coefficient, (DIN 2003)
- Water vapor diffusion resistance factor (DIN 2001c)

This set of experiments is generally applied to deliver a minimum of information for a hygrothermal material characterization, a usual practice in building material characterization. These techniques are well known in experimental practice and defined by international standards, so no further details are given in the present paper.

Since the overhygroscopic range is not adequately represented, additional measurements have to be carried out to increase the quality of the material data. Experimental parameters are as follows:

- Moisture retention at various capillary pressures
- Moisture conductivity at different moisture content
- Water vapor diffusion in terms of a wet cup experiment

Moreover, the calibration of the derived functional material characteristics requires two additional experiments:

- Determination of the water uptake course
- Determination of the drying course, especially in the second drying period

Since the experimental procedures and equipment for the overhygroscopic range are not common in building physics, the additional experiments are generally described in the following section. The moisture retention measurements by the pressure plate apparatus originated in soil physics and have been adapted to building materials. The other experimental setups, measurement techniques, and procedures have been designed and built at the IBK Lab (Building physical laboratory of the Institute of Building Climatology at the Dresden University of Technology; see Figures 1–5) (Plagge 1991, 2004). So far, more than 70 different building materials have been analyzed and tested so that the equipment and measurement methods used are optimized and have been intensively proved and verified.

Moisture Retention Characteristics

The relation between the pore water content and the capillary moisture potential is a fundamental part of the characterization of the hygric properties. The function relates a capacity factor (moisture content) to an intensity factor (the energy state of pore water called capillary pressure). The moisture potential can be expressed in unit energy per unit mass, volume, or weight. Energy per unit volume is dimensionally equivalent to force per unit area or pressure.

The moisture storage is measured in the hygroscopic and the overhygroscopic range by means of saturated salt-in-water solutions in desiccator chambers and pressure plate extractors. Since pressure plate extractors enable only the drainage of the specimen, the desorption characteristic can be measured over the entire range. To prevent the effect of capillary hysteresis on the results, the desorption characteristics of the hygroscopic range are also used in this investigation.

$$\theta_l(p_c) = (m_{pc} - m_d)/(\rho_w \cdot V) \quad (1)$$

and

$$\theta_l(\varphi) = (m_\varphi - m_d)/(\rho_w \cdot V) \quad (2)$$

where m_{pc}, m_φ, and m_d are the masses of a sample at the respective capillary pressure, pc (Pa), and relative humidity, φ (–), at dry conditions; θ_l and ρ_w are the volumetric water content ($m^3 \cdot m^{-3}$) and the density of the water phase ($kg \cdot m^{-3}$), respectively; and V is the volume of the respective specimen (m^3).

To determine the water retention characteristics, a pressure plate apparatus is used (DIN 1993). Depending on the range of capillary potential, mid-range and high-range systems for measurement between 3 and 1500 kPa pressure head are used. The components are shown in Figure 1A.

In principle the apparatus consists of the following:

- A set of mid- and high-range pressure chambers
- A set of ceramic plates with different air entry pressures of 50, 100, 300, 500, and 1500 kPa
- Gas pressure supply and bleed-type regulation systems capable of pressure regulation between 3 and 1500 kPa

Before measurement, the specimens are disposed on a ceramic saturation table, which can become capillary saturated. Subsequently the samples are placed on ceramic plates, where filtration paper (low pressures) or a special silt/kaolin mixture provide an optimal contact between the ceramic system and the material specimen. For measurement, the plate is placed into a pressure plate extractor where a defined gas pressure can be applied to the samples in the pressure chambers. The pressure step leads to water drainage of the material, and the water content can be measured by weighing the specimen after a static equilibrium is attained. Then the specimens are replaced in good contact with the ceramic plates and the next pressure step is set. In most cases, 11 pressure steps of 0.03, 0.06, 0.1, 0.3, 0.6, 1, 2, 3, 4, 8, and 15 bar pressure were applied.

Some building materials are characterized by large pores or cracks. To measure the effect of those large pores on the moisture retention, the hanging water column method is used. The setup, as shown in Figures 1b and 1c), consists of a ceramic plate funnel, which is connected to a graduated pipette by a flexible PVC capillary tube. Ceramic funnel, capillary, and pipette are completely filled by deairated water, where the water level in the pipette is adjusted to the surface of the ceramic plate in the funnel. A special flushing system provides an air bubble-free water content.

For measurement, a saturated material specimen is placed in contact with the ceramic plate, and the water meniscus in the pipette is lowered below the ceramic plate. The difference in the vertical distance in the cm water column corresponds to the suction applied to the material specimen and is shown by the arrow in Figure 1c; the 1 cm water column equals 0.981 hPa. This small pressure head difference may cause an outflow of water, which corresponds

Figure 1 *Pressure plate apparatus with a working range of 3 to 1500 kPa (a) and hanging water column apparatus with a working range of 0.1 to 2 kPa (b and c) to determine the water retention characteristic in the overhygroscopic range.*

to the suction induced drainage and delivers the moisture retention close saturation at low capillary pressures.

Liquid Moisture Conductivity

The liquid moisture conductivity is a measure of the ability of porous materials to transmit water through the pores and has the dimensions of a velocity (ms^{-1}). Depending on the degree of saturation, the parameter is called saturated or unsaturated moisture conductivity.

To determine the saturated moisture conductivity, K_{eff}, a head permeameter is used (Figure 2). For preparation, the specimens are laterally sealed to provide one-dimensional vertical percolation and then saturated in a water bath (Figure 2a). After conditioning, each sample is fixed in a permeameter head (Figures 2b and 2c) and then put into a temperature controlled water bath at 23°C (Figure 2d). In total, six sample heads can be measured parallel. Each permeameter is connected to a special flask by a capillary polytetrafluroethylene (PTFE) tube, where a two-level vacuum controlling system is used to adjust a respective constant partial vacuum. This suction causes a water flow through the specimen via the PTFE capillary toward the bottle. After establishing steady-state conditions, the total flow rate is measured by sequential weighing of the sampling flask. To prove the linear flow conditions defined by the proportions between flux and gradient, the experiment is repeated at different hydraulic gradients.

The determination of the unsaturated moisture conductivity is based on the same steady-state principles as described above. The apparatus shown in Figure 3 uses a two-level vacuum controlling system to adjust desired constant partial vacuum connected to a suction-controlled ceramic plate and a tension infiltrometer (Figure 3a). The so-called steady-state

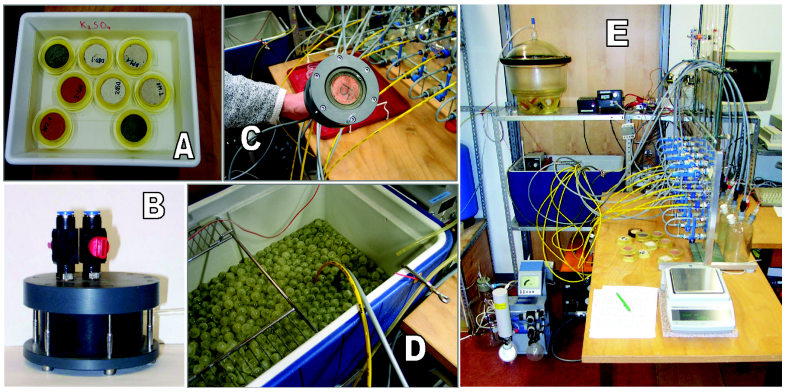


Figure 2 *Lateral sealed material specimen (a), head permeameter with fixed sample (b and c), temperature-controlled water bath with evaporation protection (d), and conductivity measurement system (e) with a two-level vacuum controller and a balance for measurement of the water flux.*

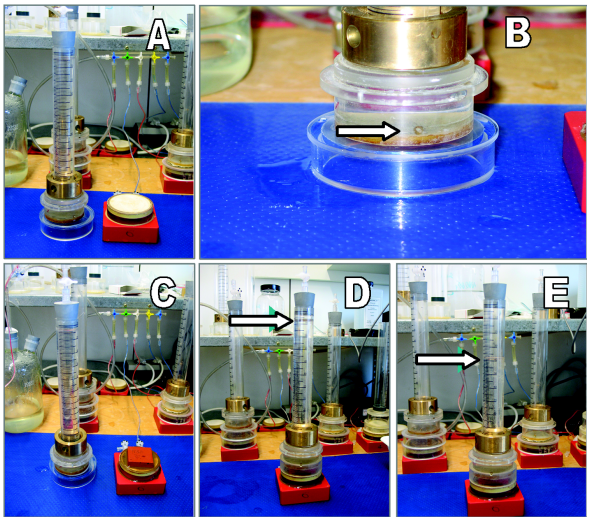


Figure 3 *Tension infiltrometer and suction-controlled ceramic plate (a), infiltration tube with capillary hole of defined diameter (b), specimen in capillary contact with the ceramic plate (c), and tension infiltrometer at work with different water levels in the graduated tube (d and e).*

tension infiltrometer method consists of a graduated water-filled tube with high porous ceramic at the bottom. A capillary hole of defined diameter connects the inner tube to atmosphere pressure and defines a threshold pressure. If suction is applied at the porous infiltrometer ceramic, which is bigger than the threshold pressure, air bubbles will enter the capillary hole (the arrow in Figure 3b). As a consequence, a volume of water corresponding to the air bubble can leak through the bottom ceramic plate. In this manner, the negative pressure in the tension infiltrometer is kept constant, while the infiltration rate can be measured by the graduated tube.

For measurement, a moistened material specimen is placed on the ceramic plate and brought to equilibrium with the applied partial vacuum at the ceramic (Figure 3c). The introduction of a defined suction leads to corresponding drainage of water and results in a defined degree of saturation. Afterward, the tension infiltrometer is placed on top of the specimen where a ring prevents lateral evaporation of the sample. Since the applied suction at the ceramic plate is bigger than the threshold pressure of the tension infiltrometer, air bubbles enter the capillary hole and water leaks into the specimen and is transported further to the ceramic plate. The constant partial vacuum at the bottom ceramic plate and the infiltrometer ceramic plate define the potential gradient, and the flux rate is given by the change in water level in the graduated infiltrometer tube (Figures 3d and 3e, visualized by the arrows).

The whole experimental apparatus consists of ten single sets, where optional degrees of moisture saturation are received by various suctions at the ceramic plates. Different infiltration rates can be obtained by various capillary holes of distinct diameters of the inner tube of the tension infiltrometer.

The moisture conductivity can be calculated using Equation 3:

$$K_{eff} = \frac{q \cdot \left(l - \frac{V_f}{F}\right)}{A \cdot t \cdot h} \tag{3}$$

where K_{eff} is the Darcy velocity or apparent velocity at an effective degree of saturation, i.e., the volume of liquid phase passing through the unit cross-sectional area of the material in a unit time, t (s); q is called volume flux density (ms^{-1}) and h is the pressure head difference (m) causing the water flow; l and A correspond to the length of the material specimen (m) and the sample cross-sectional area (m^2); and V_f and F are total sample volume (calculated using over all geometric data) and the sample missing volume (material failures effecting the volume of sample) (m^3). The effective saturation is given by the volumetric water content of the sample and can be calculated using the following:

$$\theta_l = (W_w - W_d)/(\rho_w V_s), \tag{4}$$

where W_w and W_d are the wet and dry weight of the specimen, ρ_w is the density of water, and V_s is the sample volume.

Water Vapor Diffusion Coefficient

The hygric material parameter, μ (dimensionless), is defined as the quotient between the water vapor diffusion coefficient of air and the material tested. Thus, μ is a measure of the water vapor resistance of the material in comparison to an air layer of the same thickness at the same temperature. Based on Fick's law and the general concept of state variables for ideal gasses, the water vapor flux density, j [$kg \cdot h^{-1}$], can be described as follows:

$$j = -\frac{D}{R_D T} \cdot \frac{\Delta \rho_D}{\Delta x} \tag{5}$$

where D is the water vapor diffusion coefficient ($m^2 \cdot h^{-1}$) and R_D is the universal gas constant of water vapor ($N \cdot m \cdot kg^{-1} \cdot K^{-1}$) at the actual temperature, T (K). The water vapor concentration gradient is given by the difference in the water vapor partial pressure φ_D (Pa) and the distance x (m).

To determine the water vapor diffusion coefficient, the material samples are fixed in PVC sampler lids and laterally sealed by a water vapor dense-type of paraffin (ocozerite) to provide one-dimensional flow through the sample during measurement. Afterward, the specimens are preconditioned in desiccators at defined relative humidities until a static mass is reached. The chosen humidity depends on the moisture range of interest and the applied water vapor concentration gradient. For the actual measurements, the chosen relative humidities for the precondition are given in Table 1.

After equilibration, the PVC sampler lids with the specimen are tightly fixed on a complementary cup containing the corresponding salt-in-water solution (see Table 1). For measurement, the cup is placed into a climate chamber where temperature and relative humidity are controlled. For the duration of the experiment, the total mass of the cup is recorded periodically. Steady-state conditions are reached when the weight change of the cup is constant in time. These mass changes can be used for the calculations of μ using the following:

$$\mu = \frac{1}{s}\left(\rho_a \cdot A \cdot \frac{\rho_1 - \rho_2}{j} - s_a\right) \tag{6}$$

where s is the sample thickness (m), ρ_a is the water vapor permeability of air ($kg \cdot m^{-1} \cdot h^{-1} \cdot Pa^{-1}$) and A is the cross section of the sample (m^2); s_a corresponds to the mean thickness of the air layer between the bottom of the material and the salt-in-water solution in the cup; $\rho_1 - \rho_2$ are the water vapor partial pressures at the top and the bottom of the material specimen (Pa). To determine μ, the water vapor permeability of air has to be known and can be calculated by the following:

$$\rho_a = \frac{0.083}{R_D T} \cdot \frac{\rho_0}{\rho} \cdot \left(\frac{T}{273}\right)^{1.81} \tag{7}$$

Here, R_D is the universal gas constant of water vapor with a value of 462 ($N \cdot m \cdot kg^{-1} \cdot K^{-1}$), while ρ_0 and T correspond to

Table 1. Saturated Salt-in-Water Solutions and Drying Agents Used for Preconditioning of Samples and for the Realization of Different Constant Boundary Conditions During the Measurements

Precondition		Measurement		
Saturated Salt Solutions	Relative Humidity, %	Saturated Salt Solutions	Relative Humidity of Used Salt, %	Relative Humidity in the Climatic Chamber, %
Potassium acetate	22.8	Silica gel	5–8	35
Magnesium chloride	32.9	Silica gel	5–8	50
Potassium carbonate	43.2	Magnesium chloride	32.9	50
Sodium bromide	58.2	Sodium chloride	75.4	50
Sodium chloride	75.4	Ammonium-dihydrogen-phosphate	93	50
Potassium chloride	84.6	Potassium sulphate	97.4	75

the atmospheric pressure at standard condition of 1013.25 (hPa) and the absolute temperature (K).

Calibration Experiments

To calibrate the material functions derived from the application of the engineering model approach, two experiments are used. These are the measurement of the water uptake course and the moisture drying course. For this purpose, an automatic water uptake apparatus and wind channel drying apparatus have been designed and built at the IBK lab (see Figures 4 and 5).

The automatic water uptake measurement is based on the standard water uptake test. While the standard procedure delivers the water uptake coefficient, the automated apparatus allows the measurement water uptake course as a function of time. A picture of the experimental set up is shown in Figure 4 and it consists of the following:

- An insulated chamber with a vertically adjustable water basin, where the temperature is held stable and the relative humidity is kept above 95%
- A material sample with a special fixture and holder to locate the sample in a defined way upon the free water plane (see Figure 4B)
- A balance (±0.01 g) where the material sample including holder can be measured while hanging below the balance. A computer is used to record the balance readings automatically

The automatic water uptake measurement delivers the continuous increase of water content versus time. The water uptake coefficient as well as the water content as a capillary saturation can be derived from the data. The water uptake experiment can be separated into two parts. The first part describes the capillary-dominated part and can be approximated by a straight line. The second part reflects the influence of the dispersion of the waterfront when reaching the top of the sample and the contribution of, for example, dissolution of entrapped air into water. The break point is often called capillary moisture content ($kg \cdot m^2$) and is equal to the mean moisture content of the specimen, θ cap/h. The automated measurement delivers much important information; for example, it allows one to obtain divergences from a linear mass increase over the square root of time, effect of layers, or cracks. More information on the experiment and the data interpretation is given by Plagge et al. (2005).

The drying apparatus is designed to measure the drying behavior of building materials under defined boundary conditions. The drying process is not only influenced by the material properties but also by the boundary temperature, the relative humidity, and the airflow conditions. To evaluate the experiment properly, it is important to know all those conditions listed. As an additional result, the experiment delivers the surface exchange coefficient of the respective material. More informations on the experiment and the data interpretation is given in Scheffler and Plagge (2005).

DATA PROCESSING AND MANAGEMENT

The hygric material data are available for discrete points only, but simulation models require complete material functions, for example, over the whole moisture range. Thus, it becomes important to interpolate between the data points. Common interpolation procedures as linear and polynomial spline interpolation in combination with scattered data coming from different methods may lead to unsteady oscillations and can cause dramatic errors, especially when derivatives of the material functions have to be used. Alternatively, the functional relationships can be derived on the basis of complex physical pore models, where the moisture retention and sorption isotherm are used to derive a pore size distribution in combination with a transport law Grunewald and Häupl (2002). These models offer the possibility of describing the complex storage and transport of liquid water and water vapor in capillary porous media by means of a physical-based model. These functional relationships represent the material characteristics as a common model.

Early studies by Grunewald et al. (2001), Hoffman et al. (1995), Plagge (1991), and Plagge et al. (2002) use a van Genuchten-type description and inverse modelling to deduce the transport parameters from simple transport measurements. A new and advanced approach is the so-called engineering model from Grunewald et al. (2001), Grunewald and Häupl

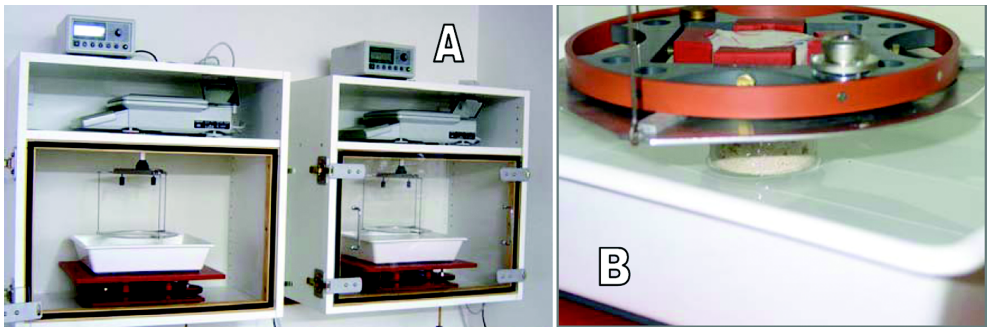


Figure 4 *Automated water uptake apparatus (a) designed at the IBK lab, with the water bath and the specimen in the sample holder for continuous registration of water absorption (b).*

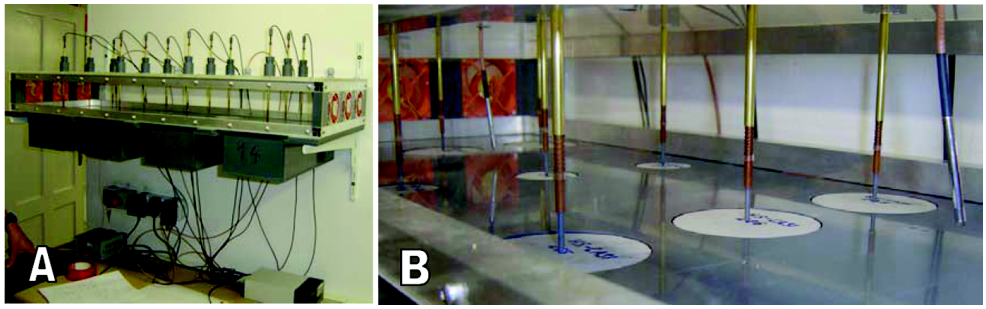


Figure 5 *Automated wind channel drying apparatus (a) designed at the IBK lab for 12 samples. The air velocity is controlled by fans, and different types of sensors are used: anemometers, relative humidity and temperature sensors, and surface temperature sensors for each material sample (b).*

(2002), Scheffler et al. (2004), and Scheffler et al. (2007a, 2007b). Here the material modelling and the interpretation of the laboratory measurement is the essential task to generate material functions that describe the material behavior adequately. The material model contains a set of material functions, including the material and modelling parameters and an instruction to their determination. A rough picture of the basic methodology of the material modeling is given as follows:

1. Adjustment of the moisture storage function to the measured data and derivation of the pore volume distribution
2. Derivation of the transport functions from the pore volume distribution using a physical transport model and adaptation of the conductivity functions for liquid water and water vapor
3. Calibration of the overhygroscopic moisture range by simulating the water uptake experiment and comparison of measured and calculated data
4. Calibration of the transition range between hygroscopic and overhygroscopic ranges by simulating the drying experiment and comparison of measured and calculated data; with the exact knowledge of the boundary and exchange conditions and with the possibility of radial symmetric three-dimensional simulation, the influence of initial and climatic conditions and also of the temperature on the drying process can be taken into account.

The material model introduced attains a good level of agreement between measured and calculated material behavior for relatively homogeneous and isotropic porous materials and is used to generate physically based material functions from the measured data. The model may certainly be limited due to the treatment of water uptake and drying processes by one set of material functions. More information on the engineering model, its application, and the physical data interpretation is given by Scheffler et al. (2004, 2007b) and Scheffler and Plagge (2005). It is expected that the model will not be able to characterize all materials in the same quality. Its applicability will probably be limited in terms of materials that cannot be referred to as capillary porous media (e.g., foils, foams, mineral wool) or which change their properties under the influence of moisture (e.g., swelling, shrinking, chemical reactions).

The model may certainly be limited due to the treatment of water uptake and drying processes by one set of material functions. Accounting for the anisotropy of building materials is the exception. Modeling the process dependencies of material functions, hysteresis and the consideration of transport properties in multiphase systems are current topics of research.

The engineering model of hygrothermal material characteristics supports the knowledge transfer from research to application in the engineering practice where a compromise between effort and precision must often be found. The model requires a minimum number of performed experiments, as presented above. Raising the measurement expenditure, for example, with a higher amount of measuring points at the moisture storage function, allows for the precision of the material characterization to be improved. The introduced material model complies in the whole range with the physical principles, i.e., it describes the relevant transport processes according to their thermodynamic correct driving potentials. This provides a basis for further research in direction of durability of material as, for example, the modeling of salt transport, salt crystallization, and the coupling of hygrothermal and mechanical issues. The material functions are able to smooth and interpolate between scattered measurement data, providing a complete, unbroken, and consistent material description (Scheffler et al. 2007a).

The example for the Indian Humayun Tomb sandstone is exemplarily presented in Figure 6, where the functions of the hygric sorption isotherm, the moisture storage, the pore volume distribution, the liquid moisture conductivity, the water vapor diffusivity, and the moisture diffusivity are also given. Since moisture diffusivity is a product of the moisture conductivity and the reciprocal slope of the moisture retention characteristics, the function shows oscillations, where the slope of the moisture retention curve becomes very small. An important property of this hygrothermal material property database is the calibration of each single material set, where the proposed functions are evaluated using the experiments described in the previous chapter: water uptake course and moisture drying course.

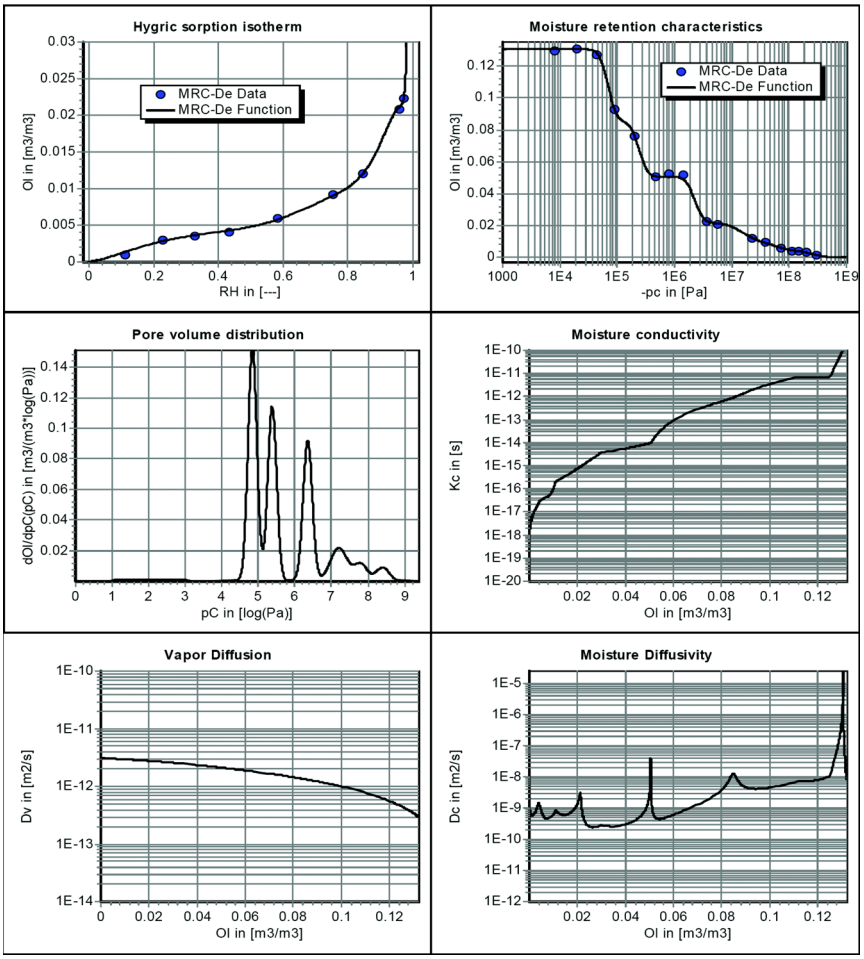


Figure 6 *Characteristic material functions for Humayun sandstone derived from material data. The application of the engineering model delivers the functions of the hygric sorption isotherm, the moisture storage, the pore volume distribution, the liquid moisture conductivity, the water vapor diffusivity, and the moisture diffusivity in terms of data vectors.*

The good agreement between measured and simulated courses make clear that the material model is suitable to deliver confident material functions for simulation codes.

Hygrothermal Material Property Database

The material characterization comprises several steps of data generation, from the measurement of original data in the laboratory to the representation of material parameters/functions in dialogs of materials database software.

Original Data. Single numbers and data columns are determined by hand or automatically collected at the measuring device. The data are processed in laboratory-internal formats and stored together with information on specimen ID and measuring method used.
Raw Data. Copies of relevant parts of original data are collected on data sheets specific to the measuring method. They comprise values from sets of specimens prepared for statistical analysis.
Summary Data. This is extracted from raw data representing material properties of a single material by a bandwidth of values (mean, minimum, maximum). It also contains general information on the material, for example, picture, producer, sampling method, and a graphical representation of the calibration results are given (see Figure 8).
Engineering Model Data. Material functions are represented by basic material parameters, model parameters, and data vectors in software specific format. Simulation data result from the evaluation of summary data after the application of the material model involving mathematical approximation algorithms and adjustment of model parameters by numerical simulation of laboratory experiments (see Figures 6 and 7).

Thus, the hygrotherm material property database consist of the following:

- Directly measurable material parameters
- Engineering model parameters
- Generated data vectors

The material information is given in terms of the summary page data as shown in Figure 8 and engineering model data as visualized in Figures 6 and 7.

The data sets are collected in specific categories for easy selection. Up to three possible categories for any material can be selected, providing a proper selection from the database. Thus, an insulation plaster is associated with both plaster and mortar categories as well as insulation material. Possible categories according to Fitz et al. (2007) and Plagge et al. (2007) and general information on possible material assignments are listed as follows:

- *Coating.* Coating for inner and outer wall, bituminous coatings, etc.
- *Plaster and mortar.* Gypsum, cement lime, lime, loam, screeds, etc.
- *Building brick.* Lime sand brick, aerated concrete, pumice, concrete block, etc.
- *Natural stones.* Limestone, granite, pumice, marble, silt, tuff, etc.
- *Cement containing building materials.* Concrete, aerated concrete, screeds, lightweight concrete, cement lime plaster, etc.
- *Insulating materials.* Thermal insulation plaster, natural insulating materials, foamed plastic, fibre materials, in-situ foams, etc.
- *Building boards.* Gypsum plaster board, derived timber products, OSB, fiber boards, loam building board, etc.
- *Timber.* Derived timber products, timber, fiber boards, latticed framework, etc.
- *Natural materials.* Loam, reed, hemp, flax, cellulose, straw, turf, etc.
- *Soil.* Sand, loam, humus, soil, gravel, peat, etc.
- *Cladding panels and ceramic tile.* Facing shells, tile, cleaving clinker, etc.
- *Foils and waterproofing products.* In-situ foams, bitumen felt, PTFE, vapor barrier, etc.
- *Miscellaneous.* Metal, glass, roof tile, air film, etc.

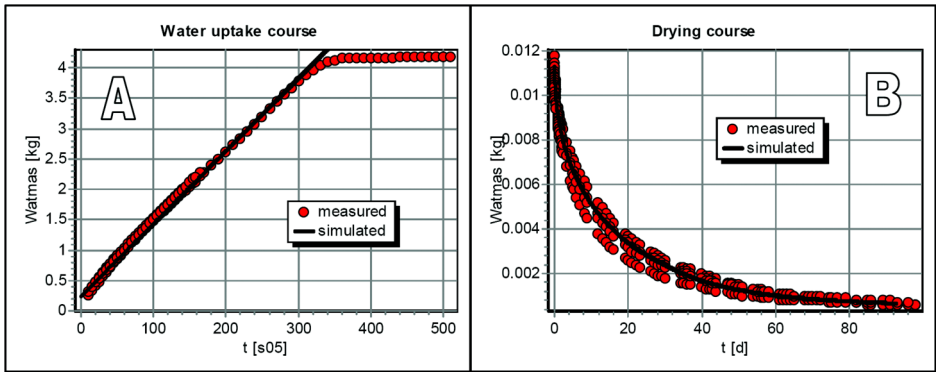
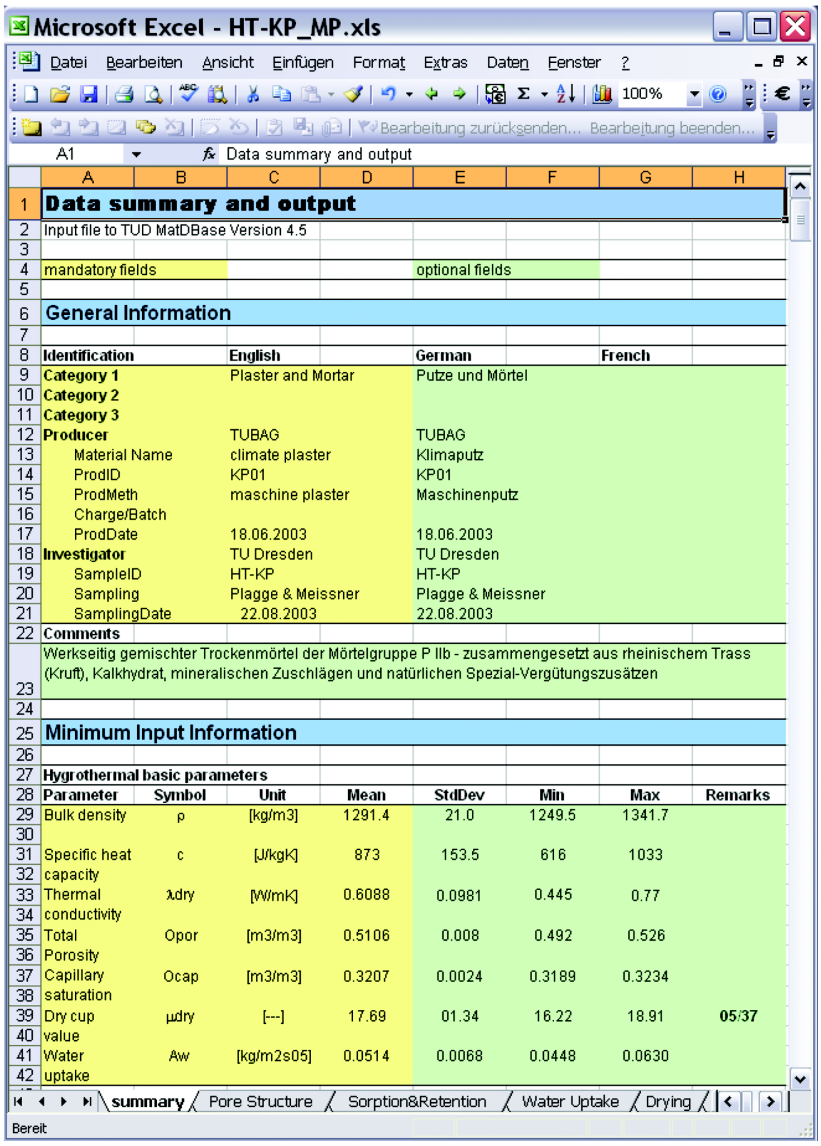


Figure 7 *Comparison between measured and calculated water uptake (a) and measured and calculated drying behavior (b) of the Indian Humayun tomb sandstone. Differences in the absolute water mass of the wetting and drying courses are due to different sample sizes.*



Microsoft Excel - HT-KP_MP.xls

Datei Bearbeiten Ansicht Einfügen Format Extras Daten Fenster ?

A1 Data summary and output

	A	B	C	D	E	F	G	H
1	**Data summary and output**							
2	Input file to TUD MatDBase Version 4.5							
3								
4	mandatory fields				optional fields			
5								
6	**General Information**							
7								
8	**Identification**		**English**		**German**		**French**	
9	**Category 1**		Plaster and Mortar		Putze und Mörtel			
10	**Category 2**							
11	**Category 3**							
12	**Producer**		TUBAG		TUBAG			
13	Material Name		climate plaster		Klimaputz			
14	ProdID		KP01		KP01			
15	ProdMeth		maschine plaster		Maschinenputz			
16	Charge/Batch							
17	ProdDate		18.06.2003		18.06.2003			
18	**Investigator**		TU Dresden		TU Dresden			
19	SampleID		HT-KP		HT-KP			
20	Sampling		Plagge & Meissner		Plagge & Meissner			
21	SamplingDate		22.08.2003		22.08.2003			
22	**Comments**							
23	Werkseitig gemischter Trockenmörtel der Mörtelgruppe P IIb - zusammengesetzt aus rheinischem Trass (Kruft), Kalkhydrat, mineralischen Zuschlägen und natürlichen Spezial-Vergütungszusätzen							
24								
25	**Minimum Input Information**							
26								
27	**Hygrothermal basic parameters**							
28	**Parameter**	**Symbol**	**Unit**	**Mean**	**StdDev**	**Min**	**Max**	**Remarks**
29	Bulk density	ρ	[kg/m3]	1291.4	21.0	1249.5	1341.7	
30								
31	Specific heat	c	[J/kgK]	873	153.5	616	1033	
32	capacity							
33	Thermal	λdry	[W/mK]	0.6088	0.0981	0.445	0.77	
34	conductivity							
35	Total	Φpor	[m3/m3]	0.5106	0.008	0.492	0.526	
36	Porosity							
37	Capillary	Φcap	[m3/m3]	0.3207	0.0024	0.3189	0.3234	
38	saturation							
39	Dry cup	μdry	[---]	17.69	01.34	16.22	18.91	05/37
40	value							
41	Water	Aw	[kg/m2s05]	0.0514	0.0068	0.0448	0.0630	
42	uptake							

summary | Pore Structure | Sorption&Retention | Water Uptake | Drying

Bereit

Figure 8 *Data summary output. The extract consists of raw data representing material properties of a single material by a bandwidth of values (mean, minimum, maximum). Additional general information regarding the material testing and the material are also presented.*

So far, more than 70 different building materials have been measured using the proposed laboratory experiments and interpreted in terms of the engineering model. These data are collected in the hygrothermal material property database and can be used by CHAMPS, DELPHIN, and WUFI simulation software.

CONCLUSIONS

The actual paper presents a number of additional experiments, which were found to be important for characterizing building materials. The experiments are able to provide numerical simulation tools with reliable and secure/safe material information. Classical methods and extended experimental procedures are meanwhile applied to a large number of building materials. In total, more than 70 different materials have been tested by the proposed experiments and procedures.

The proposed material data in combination with the engineering model approach deliver functional relationships on the basis of complex physical pore models. The moisture retention and sorption isotherm are used to derive a pore size distribution. In combination with a transport law and measured transport data, all required information can be received. The proposed material functions are suited to smooth and interpolate between scattered measurement data, providing a complete, unbroken, and consistent material description. An

important property is the calibration of each single material set, where the proposed functions are evaluated.

The experimental summary data and the physical material functions are collected in the hygrothermal material property database for advanced simulation software. This provides a basis for further research in the direction of durability of material as, for example, the modeling of salt transport. The modelling of process dependencies of material functions, hysteresis, and the consideration of transport properties in multiphase systems are in preparation and will support and enhance the database. Moreover, future laboratory activities will help enable the material property database to grow.

REFERENCES

DIN. 1993. Soil quality: Determination of the water-retention characteristic—Laboratory methods. DIN ISO 11274, Deutsches Institut für Normung e.V., Berlin, Germany.

DIN. 2000. Wärme- und feuchtetechnisches verhalten von baustoffen und bauprodukten—Bestimmung der hygroskopischen sorptionseigenschaften. DIN EN ISO 12571, Deutsches Institut für Normung e.V., Berlin, Germany.

DIN. 2001a. Bodenbeschaffenheit—Bestimmung der trockenrohdichte. DIN ISO 11272, Deutsches Institut für Normung e.V., Berlin, Germany.

DIN. 2001b. Wärme- und feuchtetechnisches verhalten von baustoffen und bauprodukten—Bestimmung der wasserdampfdurchlässigkeit. DIN EN ISO 12572, Deutsches Institut für Normung e.V., Berlin, Germany.

DIN. 2001c. Wärme- und feuchtetechnisches verhalten von baustoffen und bauprodukten—Bestimmung des wärmedurchlasswiderstandes nach dem verfahren mit dem plattengerät und demwärmestrommessplattengerät—Trockene und feuchte produkte mit mittlerem und niedrigem wärmedurchlasswiderstand. DIN EN ISO 12664, Deutsches Institut für Normung e.V., Berlin, Germany.

DIN. 2003. Wärme- und feuchtetechnisches verhalten von baustoffen und bauprodukten—Bestimmung deswasseraufnahmekoeffizienten bei teilweisem eintauchen. DIN EN ISO 15148, Deutsches Institut für Normung e.V., Berlin, Germany.

Fitz, C., K. Lengfeld, M. Krus, H. Künzel, R. Plagge, F. Meissner, P. Häupl, S. Klaus, and G. Hauser. 2007. Datensammlung für die energetische altbausanierung. Research project funded by German Ministry of Economy, BMWA.

Grunewald, J. 1997. Diffusiver und konvektiver stoff- und energietransport in kapillarporösen baustoffen. Dissertation, Department of Architecture, Institute of Building Climatology, Dresden University of Technology, Dresden, Germany.

Grunewald, J., and P. Häupl. 2002. Ein modell zur beschreibung der feuchteabhängigen dampfleitfähigkeit kapillarporöser materialien. *Bauklimatischen Symposium, Band 1 (S.286–294), TU Dresden, Germany.*

Grunewald, J., R. Plagge, and M. Bomberg 2001. Introduction to material characterization for input to HAM models. *Proceedings of the ICBEST 2001 Conference, Ottawa, Canada, and the International Council for Research and Innovation in Building and Construction W40 meeting, New Zealand.*

Grunewald, J., R. Plagge, and P. Häupl. 2002. A 2-levelled hygrothermal material database for the numerical simulation program Delphin4. *Proceedings of the International Symposium on Building Physics in Nordic Countries, University of Trondheim, Norway,* pp. 39–46.

Häupl, P., R. Plagge, and H. Fechner. 2001. Hygrische materialfunktionen von porösen baustoffen. Gesundheitsingenieur, Haustechnik, Bauphysik, Umwelttechnik, 122. pp. 305–16.

Hoffmann, D., K. Niesel, and R. Plagge. 1995. Water retention and conductivity of porous media. *American Ceramic Society Bulletin* (74)11:48–50.

Hoffmann, D., K. Niesel, and R. Plagge. 1996. Relationship between pore structure and other physico-technical characteristics of stone. *Proceedings of the 8th International Congress on Deterioration and Conservation of Stone Volume 1, Berlin, Germany,* pp. 461–72.

Krus, M. 1995. Feuchtetransport- und speicherkoeffizienten poröser mineralischer baustoffe—Theoretische grundlagen und neue meßtechniken. Dissertation, Fakultät Bauingenieur und Vermessungswesen Universität Stuttgart.

Plagge R. 1991. Bestimmung der ungesättigten hydraulischen leitfähigkeit im boden. Diss. Bodenökologie und Bodengenese, Heft 3, pp. 151.

Plagge, R. 2004. Experimental technique to measure material parameters related to moisture flow. *Proceedings of the 2004 NRIC Symposium on Study of Moisture Problems Related to the Conservation of Historical Stone Monuments and Buildings, Tokyo, Japan,* pp. 19–32.

Plagge, R., P. Häupl, J. Grunewald, and H. Fechner. 2002. Functional description of water storage and transfer in capillary porous building materials. *Bauklimatischen Symposium, Band 1, TU-Dresden, Germany,* pp. 338–50.

Plagge, R., G. Scheffler, and J. Grunewald. 2005. Automatic measurement of water uptake coefficient of building materials. *Proceedings of the 7th Symposium on Building Physics in the Nordic Countries*, Reykjavik, Iceland, pp. 15–22.

Plagge, R., G. Scheffler, F. Meissner, P. Häupl, C. Fitz, K. Lengfeld, M. Krus, H. Künzel, and S. Klaus. 2007. MASEA—Material property database of old and new building materials for software tools in building construction. *Proceedings of the 12th Symposium on Building Physics, Dresden, Germany.*

Scheffler, G., and R. Plagge. 2005. Defined drying behaviour measurement for building materials. *Proceedings of the*

7th Symposium on Building Physics in the Nordic Countries, Reykjavik.

Scheffler, G., J. Grunwald, and P. Häupl. 2004. Calibration of an engineering model of hygrothermal material characterisation. *Council for Research and Innovation in Building and Construction W40 Meeting*, *Glasgow*, *Scotland, UK*.

Scheffler, G., J. Grunewald, and R. Plagge. 2007a. Evaluation of functional approaches to describe the moisture diffusivity of building materials. *Journal of ASTM International* 4(2).

Scheffler, G., R. Plagge, and P. Häupl. 2007b. *Hygrische Materialmodellierung als Grundlage neuer Erkenntnisse*, Bauphysik, Heft 3. Berlin: Ernst & Sohn.