Use of advanced measuring and calculative procedures for moisture assessment of building elements

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ABSTRACT

There is an obviously increasing importance for assessing the moisture behaviour of building elements, especially in connection with questions concerning the rehabilitation of constructions and the elevated requirements for thermal insulation in future. On an European basis and within the frame of CEN there are efforts going on for using calculative methods in this field in an intensified way, to improve them and prepare new procedures for standardisation. Recently extensive investigations have been carried out in the Fraunhofer Institute of Building Physics for the experimental determination of necessary material properties as well as for the development of improved calculative methods. There are new findings for a physically correct description of moisture transport processes, tested measuring procedures and advanced programs for the calculative moisture assessment of building constructions. The contribution explains basic reflections including measuring examples and points out important consequences under practical aspects. Two one-dimensional examples - the annual moisture variance of an exposed natural stone facade and the comparison of the moisture behaviour of a brick masonry with and without the application of water repellent agent -are shown as well as one two-dimensional example which demonstrates the influence of a mortar joint.

1.   INTRODUCTION

Scientific, as well as practical efforts during the last years, have shown that there is an increasing interest in using calculative methods in order to assess moisture behaviour of building components. Current demands, such as ways of preserving historical buildings or the restoration or thermal insulation of external building components of existing construc-

tions, are closely related to questions concerning the moisture conditions or the development of moisture behavour after intervention in an existing building structure. Regarding the expensive and time-consuming experimental investigations of the moisture behaviour of building components on a 1:1 scale, it is obvious that calculative procedures must be taken into consideration. Among other things they will provide a useful means for assessing the consequences and tendencies after any constructive modifications or the effects arising under different climate conditions.

Furthermore, current discussions about the increased requirements for thermal insulation in future lead to questions concerning moisture effects: how much is the sorption moisture affected by changes of temperature on the inside of building components? How can vapour permeability, capillary action or vapour barriers be evaluated in combination with different insulation materials? Are the existing requirements for moisture effects satisfactory, exaggerated or do they need updating when used to approve or to assess new constructions? To what extent do the so-called secondary moisture effects (moisture dependent heat conduction, latent heat, air convection) have an influence on the future level of thermal insulation? In order to use the know-how available at the "Fraunhofer-Institut für Bauphysik" and to use corresponding possibilities for practical purposes, further developments of calculative and experimental methods have been carried out recently.

Considering the calculative techniques of 15 years ago [1], they are in fact more advanced than the possibilities which previously existed. The investigation of the moisture dependent material properties, however, still remains complex when applying the techniques of that time. The partially very difficult measurements which had been carried out have shown that a relatively simple determination of the neces-

sary coefficients and dependencies was possible under the following conditions: a modified theoretical basis of reflection, new measurement methods and a consideration of the conventional moisture dependent material properties. We thereby still proceed from the fact that vapour diffusion and liquid transport processes take place simultaneously and overlap and that there is a continuous function of moisture storage that describes the total water content that can in reality appear inside the building material. A simplified theory, in which vapour and liquid transport processes were reduced to only two potentials, created the basis for more convenient ways of measurement and calculation. The following paper explains this approach and gives practical examples.

2.   FUNDAMENTAL PRINCIPLES AND MEASUREMENTS

The moisture behaviour of water-absorbent building materials is defined by the moisture storage capacity as well as by the transport processes, which take place on the inside of building materials, either at a gaseous or liquid stage. We will now report ways of how to determine these decisive material qualities and the corresponding measurement methods and examples.

2.1   Moisture Storage

For practical purposes there are three important mechanisms responsible for moisture storage in porous building materials, i.e.

– the vapour adsorption at free pore spaces (water vapour / air-mixture)
– absorption of water molecules at the pore surfaces by surface forces (absorbed water, range of hygroscopic moisture content)

− the absorption of free capillary water in capillary pores which can be moistened (filled pore spaces, range of super-hygroscopic moisture content).

The decisive material qualities are moisture behaviour and pore structure, while an increase of the concentration of the water vapour in the pore space can practically be neglected when there is a simultaneous storage of liquid (sorption, capillary water).

The adsorbed water of a porous hygroscopic material is, as we know, dependent on the surrounding relative humidity. It is characterised by the sorption isotherm when an isothermal equilibrium is obtained. The relatively simple, but mostly time-consuming gravimetric determination of the sorption isotherm can be accomplished in a moisture range with an upper limit of 90 or even 95 % r.h. (relative humidity). Since the sorption isotherm of most building materials shows an extremely steep gradient when exposed to higher values of relative humidity, an unambiguous sorption measurement is no longer possible at this point and a graph of the functional water content against relative humidity cannot be clearly drawn. At this point the free water absorption or the capillary water range starts. We can make the following assumption using the cylinder capillary model for capillary porous hygroscopic materials with a regular dispersion of pore size: a maximal pore size still filled with water can be related to any water content up to the stage of free water saturation. This relationship presupposes that all the pores that have been reached by the water are in connection with one another and that the smaller pores with a higher suction force draw water from the bigger pores until a capillary pressure equilibrium is obtained at a defined water content. There is also a characteristic dependency for superhygroscopic water contents, the so-called capillary pressure or water retention curve. This curve can be

obtained for common mineral building materials with the help of a water retention measurement arrangement. This procedure, which is described in detail in [2], uses water as a medium for the measurements in opposition to the mercury pressure porosimetry. This quarantees a more realistic description of state, as the genuine interaction between water and the pore surface - as under natural conditions - is beeing recorded. These measurements cover the whole range of water content that are of practical interest, from free saturation down to filled pores of about 10^{-8} m radius.

The sorption isotherm and the water retention curve both indicate the water content with dependency on real potential quantities, i.e. the relative humidity φ as a relation of the vapour pressure versus saturation vapour pressure and the capillary radius r as a characteristic value of the capillary pressure.

Both quantities are connected with each other by the thermodynamic equilibrium condition according to Kelvin's law:

$$\varphi = \exp\left[-\frac{2\sigma\cos\theta}{r\,\rho_w RDT}\right] \tag{1}$$

The symbols used mean:

σ [N/m]   surface tension of the water
θ [°]   contact angle
R_D [J/(kgK)]   specific gas constant for steam
T [K]   absolute temperature

The water content in the range of a hygroscopic and super-hycroscopic moisture content can thereby be presented as a closed function of either φ or r. To choose the relative humidity as a general moisture storage potential means that it can be universally applied and is more easily understood in practical terms. As

for any building materials with no potential for capillary action, such as in most insulation layers, it seems to be the vapour pressure or the relative humidity and not the capillary pressure or the water retention that is defined. By connecting both curves, the sorption isotherm and the suction force, we obtain the so-called moisture storage function, which practically contains all the important moisture storage properties of a porous building material up to free water saturation. This moisture storage function can be applied with dependency on a real, material-independent potential quantity.

Figure 1 shows, with lime silica brick serving as an example, how the moisture storage function is generated by

− the sorption isotherm,
   upper left, indicating the threshold value of a free water saturation

− the suction force curve,
   upper right, indicating the relative humidity which is directly related to the pore radii according to the Kelvin's law-relation.

This example shows that different measurement methods for lime silica brick, as a porous building material, result in a continuous function, which is able to describe the total range of its free water-absorbing capacity.

2.2   Vapour Diffusion

It is a known fact that measurements of the vapour diffusion resistance for porous building materials according to DIN 52615 lead to different results depending on the employed humidity range: generally there is a significant smaller diffusion resistance under moist conditions than there is under dry conditions. This increase of vapour permeability found under isothermal conditions is generally attributed to

moisture influences which accelerate the diffusion flow. Measurements for sorptive building materials under isothermal moisture conditions have shown that there is a sorption water gradient along the pore walls parallel to the vapour pressure gradient on the inside of the pore spaces. It is in this adsorbed water film where the liquid transport processes take place. The driving potential of these liquid transport processes in the upper range of hygroscopic moisture content (wet-cup-range) is the relative humidity. When measuring diffusion, these liquid transport processes overlap with actual diffusion flow. We may assume that this liquid flow leads to the measured increase of the total mass flow. If this effect does account for the measured reduction in vapour resistance under isothermal conditions the following conclusion could be drawn: in the case of opposed gradients for vapour pressure and relative humidity (non-isothermal conditions) a reduced mass flow should be measured.

In order to verify the stated hypothesis, several measurements of diffusion were repeatedly carried out for different hygroscopic building materials, under isothermal and non-isothermal conditions. A measurement apparatus was expecially designed for these purposes and is described in detail in [3]. Herewith the temperature gradient could be adjusted over the specimen profile in such a way that a gradient of the relative humidity respectively sorption moisture gradient opposed to the partial pressure gradient was obtained. A model of the transport processes is schematically represented in fig. 2. A sample of natural sandstone was used as a measuring example. The boundary conditions for the isothermal experiment are represented above and for the non-isothermal experiment (temperature gradient) below. The total mass flows and the µ-values were determined by these measurements and are also listed. The vapour diffusion resistance was found to be

almost twice as high under non-isothermal conditions than under isothermal conditions for the same vapour pressure gradient and the same mean range of moisture content. The µ-value, which was thus determined, is not a characteristic value for the vapour diffusion process of the material since it is affected by effects of liquid transfer and other boundary conditions. For that reason the µ-value can only count as a proper material quality for the vapour diffusion as long as it is measured under dry conditions, without any moisture influences. It follows that, in order to calculate diffusion processes, it would be appropriate to start off from a constant µ-value determined under dry conditions. Supposing that our measurements already carried out have got sufficient value as evidence, the following conclusions can be drawn:

− A general description for moisture transfer processes (liquid or vaporous) as a moisture-dependent diffusion for hygroscopic building materials under practical non-isothermal conditions, is not valid. The measurement results obtained under these conditions are incorrect.

− Diffusion or moisture calculations for such building materials require a separate consideration for diffusion and liquid flow processes; for diffusion, a diffusion resistance value has to be determined first under dry conditions (dry-cup-range); for liquid flow processes, a parameter for transport processes is necessary and will be described in the following chapter.

2.3 Liquid Transfer Process

The treatment of liquid transfer processes in porous building materials requires a differentiated examination. According to experience so far there are basically three effects that

need to be distinguished for a sufficient description for practical purposes:

a) The capillary suction with water contact resulting in high transfer intensities, characteristic for the upper ranges of water content (super-hygroscopic).

b) The capillary redistribution withour water contact, resulting in generally lower flow intensities.

c) The sorption moisture transfer resulting in relatively low transfer intensities, but still within the range of diffusion intensities, characteristic for the lower range of water content (hygroscopic).

The occurrence of these three liquid transfer mechanisms depends on the qualities of the pore spaces of the material, the local moisture conditions on the inside of the building material and the actual climatic boundary conditions at the surfaces.

As already shown in [1], it is necessary to introduce liquid transfer coefficients, dependent on the water content, to give a more detailed description of water content distributions, which under natural conditions are variable in time and place. A fairly reliable, but approximate value of the liquid mass flow in porous building materials with a regular dispersion of pore size can be determined by the empirical potential equation:

$$m_{Fl} = \rho_w \cdot D_w(u) \cdot du/dx \qquad (2)$$

The transfer coefficient $D_w(u)$, which has to be multiplied by the water content gradient du/dx can be quoted for the full range of water absorption with dependency on the water content. Taking this approach as a starting point, extensive measurements have been carried out recently, in order to determine the

coefficients crucial to the three above mentioned liquid transfer processes.

NMR equipment, which was especially designed for these purposes - as described in [2, 4] - served to measure non-destructively and continuously the water content distributions in prismatic test samples during the capillary suction experiment, but also during the capillary redistribution after an interruption of the water feed. These distributions, measured at different points of time, also served to determine with the aid of a relatively rapid automatic evaluation procedure the liquid transfer coefficients for capillary suction and redistribution. The coefficient for the liquid transfer in the sorbated phase can also be determined by isothermal diffusion measurements, according to the processes mentioned in the preceding chapter. In this connection, the difference between the mass flows measured under dry and under wet conditions indicates the ration of liquid transfer processes to the other transfer processes.

The measurements for a sample of lime silica brick served to illustrate how the three coefficients of liquid transfer processes, according to the above mentioned methods, are determined and are plotted in figure 3. It can be seen that both coefficient functions, i.e. the one for capillary suction and for capillary redistribution are clearly distinguishable. Both functions are highly dependent on moisture, and in this case they correspond to an exponential function with a high approximation (a straight line on a semi-logarithmic scale). Extrapolated over the whole range of water content the curve showing the capillary redistribution covers almost two decimal powers and the suction curve about three decimal powers. Both curves meet at the lower moisture range, since at this point the terms of capillary suction and resdistribution cannot be applied for the sorption moisture. Here the liquid transfer process takes place in the sor-

bated phase. The plotted value of the coefficient of this process, which had been obtained by two diffusion measurements, i.e. according to a totally different measurement procedure, closely matches the results obtained by NMR measurements for the redistribution within this moisture range. As for dry conditions both curves go towards zero. Here they lie outside the range of measurable quantities, but this is practically of minor importance. These findings, which were also supported by investigations of other building materials, lead to the following conclusion: the liquid transfer behaviour of porous, hygroscopic building materials can be described with the aid of two coefficient functions, dependent on water content, covering the total range of moisture and boundary conditions, which lie within the field of practical interest.

3.   CALCULATION MODEL

The results reported so far have shown that moisture transfer processes in porous building materials are due to differences in vapour pressure and water content. A legitimate technique in physics, which is also advantageous for practical purposes, is to indicate the driving forces for transport processes with real potential quantities. Potential quantities are not dependent on the material, they show a steady behaviour and even at the boundary layers of two different materials they do not show any discontinious change. Since the water content does not represent a potential quantity, it is advisable to replace it by the relative humidity, particularly as the moisture storage function also indicates the water content as a function of the relative humidity. By using the vapour pressure and the relative humidity as potential values all the processes of moisture storage and moisture transport should thereby be covered. Since the gradients of both potentials often go in opposite

directions within the same building component - the vapour pressure on the inside of a building is generally higher than on the outside due to the higher temperature, whereas the opposite applies for the relative moisture - a generally applicable calculation model has to explicitly take into account both moisture potentials.

3.1   Transport Equations

In the following, the differential equations for the simultaneous heat and moisture transport in multilayer building components, which form the basis for the data processing program WUFI [5], are briefly summed up, stating the essential material parameters for one-dimensional conditions. By taking into account the influence moisture has on the heat storage capacity and the heat conduction we obtain the following equation for the heat balance:

$$\left(\rho_M c_M + u\rho_w c_w\right)\frac{\partial\vartheta}{\partial t} = \frac{\vartheta}{\vartheta x}\left[\lambda(u)\frac{\partial\vartheta}{\vartheta x}\right] + h_v\frac{\partial}{\partial x}\left[\frac{\delta\partial p_D}{\mu\,\partial x}\right] \quad (3)$$

The storage term appears on the left and the term for the heat conduction and the latent heat transport by vapour diffusion on the right.

The equation for the moisture flow process is:

$$\rho_w\frac{\partial u}{\partial\varphi}\frac{\partial\varphi}{\partial t} = \rho_w\frac{\partial}{\partial x}\left[D_w(u)\frac{\partial u}{\partial\varphi}\frac{\partial\varphi}{\partial x}\right] + \frac{\partial}{\partial x}\left[\frac{\delta}{\mu}\frac{\partial}{\partial x}\right] \quad (4)$$

On the left hand side of the equation moisture storage is expressed in terms of a moisture storage function. The two terms on the right hand side show the liquid transfer as dependent on moisture and vapour transfer as inde-

pendent of water content. The symbols of both equations mean:

ϑ	[°C]	temperature
u	[-]	moisture content volume by volume
P_D	[Pa]	vapour pressure
φ	[-]	relative humidity
$\lambda(u)$	[W/(mK)]	heat conductivity with dependence on moisture
h_v	[kJ/kg]	enthalpy of evaporation
ρ_M	[kg/m³]	dry bulk density of the building materials
ρ_W	[kg/m³]	density of water
c_M	[kJ/(kgK)]	specific heat capacity of the building material
c_W	[kJ/(KgK)]	specific heat capacity of water
$D_W(u)$	[m²/h]	liquid flow coefficient with dependence on moisture
δ	[kg/(mhPa)]	vapour diffusion coefficient
μ	[-]	vapour diffusion resistance number under dry conditions
t	[h]	time
x	[m]	place co-ordinate

The term $\partial u/\partial \varphi$ represents the derivation of the moisture storage function, which had already been described for the examples of lime silica brick. The material qualities essential for the calculation are the moisture dependent heat conductivity, the value of resistance of vapour diffusion under dry conditions, the liquid transfer coefficients with dependency on moisture and the moisture storage function. Whereas the first two material qualities are generally known or can be easily found out, the determination of the liquid transfer coefficients and the moisture storage functions of building materials, with capillary action, is more complex. Preliminary reckoning, however, allows an approximate calculation of the liquid transfer coefficient by the water absorption coefficient (w-value), as shown in [6] and by a simple drying experi-

ment. Similar operations can be applied for the moisture storage function, which can be approximated quite accurately, if the sorption moisture at 80 % r.h. (actual moisture content of the building) and the poresize distribution is known [7].

The simultaneous transport equations (3) and (4) are programmed for one-dimensional and two-dimensional cases of application. The calculative technique has been verified and can be applied to any multilayer structure and material combinations.

3.2   Boundary Conditions.

In order to obtain accurate and valid measured results not only the calculation model but also the material properties are important. It is the choice of the correct boundary and transient conditions, which is at least of equal importance. The calculation model takes into account all the essential climatic parameters, such as air temperature, air moisture, effects caused by the sun or rain. Special attention is paid to the realistic determination of the actual effects on the surfaces of walls caused by driving rain. As the calculations of the energy demand of buildings necessitate a comparability of the calculation results and a standardised point of reference, test reference years have been established which gather the data on an hourly basis for the most important climate parameters for different regions. Like energy calculations, realistic moisture calculations also need climate data obtained on an hourly basis, as it is pointless for some parameters, like the rain, to be registered as a longer-term mean value.

4.   EXAMPLES OF APPLICATION

Two one-dimensional examples - the annual moisture variance of an exposed natural stone

facade and the comparison of the moisture behaviour of a brick masonry with and without the application of water repellent agent - are shown as well as one two-dimensional example which demonstrates the influence of a mortal joint.

4.1   Exposed natural stone facade

The first example illustrates the investigation of moisture behaviour in a section of west-facing natural stone facade. The experiment was carried out on prisms of stone 25 cm in length, with sealed flanks, having a sectional area of 5 x 5 cm^2. These prisms were installed in dry condition in the west facade of an unheated test hall. The inner face of the prisms was sealed to protect it against condensation while the outer face was exposed to natural weathering. From the moment of installation a continuous recording was made of the solar radiation (western exposure), outside air temperature and humidity, and driving rain which was measured by a drop-counter integrated into the facade at the same height as the prisms. These climatic data are shown in Fig. 4 (top) in the form of daily average values or totals for an observation period of 80 days. In this same period room air temperature declined relatively steadily from 21 ^{o}C to 10 ^{o}C. The humidity of the interior air is not significant since the prisms are sealed on the back. The moisture uptake and release behaviour of the natural stone prisms under the conditions described was recorded by regular weighing of the prisms. In addition, the moisture profiles in the prisms were recorded by NMR at specific intervals. To calculate the moisture behaviour of a natural stone facade under the conditions described here, average hourly values of the recorded climatic parameters were used.

Fig. 4 (bottom) shows the calculated curve for the water content of the natural stone facade

averaged over the total width of 25 cm in comparison with the measured moisture change of three natural stone prisms for an observation period of 80 days following the start of exposure. Measurement and calculation, which agree relatively well, show a rise (interrupted by brief periods of drying) in water content due to driving rain (most apparent in the middle of Fig. 4) which has still not reached a state of equilibrium even after 80 days. The moisture profiles established in the facade specimens are shown in Fig. 5 for four distinct points in time. The profile at Time 1 shows the moisture of the stone after the first period of rain. Similar to the situation in a laboratory absorption test this shows a narrow moisture front. At Time 2 - following a lengthy period of fine weather - this moisture front has flattened out by the time it reaches the middle of the prism as a result of drying and redistribution. The chart at Time 3 shows a moisture profile in stormy weather with low relative humidity, known in the foothill areas of the Alps as the foehn. Evident here is the steep water content gradient in the surface zone resulting from the high rate of drying under these climatic conditions. The moisture profile at the end of the 80-day observation period (Time 4) shows a relatively uniform moisture gradient in the facade with approximately capillary water saturation of the exterior surface while there continues to be only very low water content in the area of the interior surface. At all four points in time there is excellent agreement between measurement and calculation.

The long term moisture behaviour of building components can be approximated by a calculation over several years applying the same meteorological data of an average year again and again until no differences in the transient profiles during consecutive years can be discerned. In such a dynamic equilibrium state a mean moisture profile and the range of short term changes of the water

content over the cross section of a construction element can be determined. Figure 6 shows the mean moisture profile (solid line) and the yearly variations (hatched area) in the natural stone wall measured by use of the NMR-equipment (above) and the calculated ones (below). The climate conditions affect the long term moisture profiles significantly up to a depth of ca. 20 cm.

The surface is subjected to the greatest variations in water content but it is interesting to note that the average moisture at the surface is lower than in the layers underneath. The mean water content at the sandstone surface corresponds approximately to their respective equilibrium moisture at 80 % r.h. The annual mean relative humidity of the meteorological data employed is also 80 % r.h. That means that the additional moisture supply to the surfaces by driving rain and the drying effects due to solar radiation seem to cancel each other out. The highest average water content in the natural stone wall, which can also dry out to the inside, is reached in a depth of about 5 cm from the surface and mounts more than half of the capillary saturation. Information of the depth of climatic influences and the frequency of relevant hygrothermal changes cannot only help to understand certain damage processes (e.g. decay due to salt accumulation below the surface where the water content is on average higher than in other parts or mechanical degradation by frequent hygrothermal expansions or contractions). It might also be important for the choice of protective surface treatments or maintenance measures.

4.2 Brick masonry with and without impregnation

Single layer brick walls of old buildings often lack sufficient protection against driving rain and may thus exhibit elevated moisture contents, especially on the weather side. This further reduces the mostly low thermal resistance of these walls, which may in some cases even fall below the minimum heat insulation required for hygienic reasons. Additionally, an elevated moisture content entails the danger of frost damage close to the facade. Installing an interior heat insulation, e.g. to increase thermal comfort, aggravates this danger since the drying process of the wall is slowed down and its mean temperature reduced. Prerequisite for a better thermal quality and a better protection against moisture of these walls is therefore an increased rain protection. One possibility of several to achieve this is hydrophobing the facade. If done carefully, this measure can almost completely prevent the uptake of rain water. It also retards drying-out, however, since the transport of capillary moisture to the outside surface is interrupted by the impregnated layer.

The measurements are done on two facade elements of dimensions 60 by 60 by 24 m³, built from unrendered solid bricks masonry with lime-cement mortar. These elements have been incorporated into the west-facing facade of a testing hall on the Holzkirchen test area, the inside climate being 20 °C and 50 % relative humidity. Their weight was taken at regular intervals to determine their moisture content. Since after about 6 months of exposure to unusually dry weather they still had not acquired much moisture, they were artificially humidified at the end of May 1993 using a lawn-sprinkler. Since the absolute water content of the elements and the moisture distribution after the irrigation are unknown, a uniform initial moisture content of

10 Vol.-% has been assumed for the calculation.

After this artificial moistening, the exterior surface of one of the elements has been hydrophobed, while the other element has been left untreated. Then the moisture content of the elements was monitored for more than one year by weighing them about once a month. At the same time, the exterior air temperature and relative humidity, the west radiation and the driving rain close to the elements were registered hourly. These data, together with the interior climate of the experimental hall, furnish the boundary conditions for the calculation.

In Fig. 7, the calculated courses of the mean water content of the two elements are compared to the corresponding measurements. During a period of 14 months, the hydrophobed fair-faced solid brickwork has been continuously drying out, down to a moisture content of about 1 Vol.-%, whereas the untreated facade element has accumulated a noticeable amount of water in the first summer and stays more or less at this moisture level. The alternating effects of driving rain and drying phases keep the mean moisture content of this element between about 10 Vol.-% and 18 Vol.-%. In both cases, the calculated curve and the measured points agree very well. This confirms the choice of the material properties of the brickwork and the surface transfer coefficients. The following simulations of the drying-out behaviour of representative solid brick walls may therefore be trusted to yield realistic results.

The drying-out after hydrophobing of a 40 cm thick fair-faced brickwork exposed to driving rain is shown in Fig. 8 for two different interior vapour diffusion resistances (interior rendering and vapour tight coating, resp.). The exterior vapour diffusion thickness due to the hydrophobing is 0.2 m. Since hydrophobing

measures are usually carried out in summer, the simulation was started on October 1. According to DIN 4108 [8], the practical moisture content of brickwork is 1.5 Vol.-%, corresponding to 6 kg/m² in Fig. 8. The wall with a permeable interior rendering (s_{di} = 0.2 m) reaches this level after 2 ½ years. The wall with a vapour tight inner coating (s_{di} = 10 m) reaches it after about 5 years. The marked differences in the behaviour of the two walls are illustrated in Fig. 9 which compares moisture profiles at different points in time. The outwards drying is in both cases not affected by the type of interior rendering and proceeds quite continuously, as can be seen from the moisture distribution close to the facade. The inwards drying, however, depends on the interior rendering: capillary moisture conduction causes a temporary accumulation of moisture beneath the tight coating, whereas this does not happen in the permeable wall.

Neglecting any exterior or interior rendering, assuming a dry heat conductivity of 0.6 W/mK and regarding the initial moisture content, the solid brick walls under consideration have a thermal resistance of 0.41 m²K/W. This is below the hygienic minimum thermal insulation according to [8]. Having dried out to a practical moisture content of 1.5 Vol.-%, the solid brick walls have a thermal resistance of 0.60 m²K/W, thus meeting the hygienic minimum requirements.

4.3 Influence of a mortar joint

The influence of a mortar joint is of special interest for masonry made of natural sandstone. For this investigation two-dimensional calculations are necessary. But two-dimensional calculations using hourly mean values needs too much calculation time and results in a non analysable amount of data. For simplification the moisture behaviour of a initially dry wall section is computed after a representa-

tive duration of driving rain followed by a dry period. According to [9] three hours of precipitation during the first day is chosen continued by two days without. With a mean outside temperature of 10 °C, a r.H. of 80 % and a solar radiation of 80 W/m²K a representative cycle for the humidification and drying of a western oriented facade is created which is suitable for the calculative approximation of moisture effects near the mortar gaps of a wall. The wall with a thickness of 40 cm is made of a typical natural sandstone with an A-value of about 0.05 kgm²√s and a water vapour resistance number of 30. The mortar of old buildings normally have a high capillar activity and a low vapour resistance. For the following calculations a mortar with an A-value of 0.2 kg/m²√s and a µ-value of 12 is chosen.

Figure 10 shows the resulted two dimensional moisture distribution in a section of a natural stone masonry after three hours of intensive driving rain and after the following drying period. The quick advance of the water front in the capillary highly active mortar gap is obvious in Fig. 10 left side above. The natural sandstone is adsorbing the water not only by the surface but also from the mortar gap. During the consecutive drying period the mortar is drying faster especially because of its low vapour resistance. After a drying period of 48 hours the highest moisture content is found near the mortar gap in a depth of about 5 cm. These results also show that the long term maximum of moisture content is not at the surface of a fair faced masonry but even more with mortar gaps in a depth of several centimetres. This corresponds with measurements on old building, which often show the concentration maxima of salts beneath the surface, too [10]. The accumulation of water (and salt) of the mortar gaps can serve as an explanation for the frequently observed decay in the vicinity of the mortar gaps (see Fig. 11).

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Figure 1   Development of a moisture storage function for the hygroscopic and super-hygroscopic moisture range from the sorption isotherm (upper right) and the water retention curve (upper left) with lime sillica brick serving as an example.

Figure 2   Model of superimposed liquid transport and vapour diffusion processes in pore spaces of hygroscopic building materials under isothermal and non-isothermal boundary conditions. A sample of natural sandstone was used as a measuring example. The set parameters and the total mass flow measured in both cases, i.e. for the same partial pressure difference and the same mean sorption moisture, are indicated. The µ-values were calculated according to the diffusion approach.

Figure 3 The graph shows the dependence of the coefficients of liquid transfer processes for the capillary suction and redistribution on the water content related to capillary saturation. The data were obtained by moisture profile measurements with the help of NMR equipment for a sample of lime silica brick. In addition to that, a calculated value for the coefficients of liquid transfer processes in the adsorbed phase is plotted. It was obtained by moisture dependent diffusion measurements.

Figure 4   Measured profile of outside air temperature and west sunlight (top) as well as relative humidity and rainfall (middle) for better depiction in the form of daily average values or totals over an 80 day period of obervation. The moisture profile calculated using these climatic parameters (in the form of hourly average values) of a wall of natural stsone, 25 cm thick and initially dry is shown in comparison with measurements on 3 natural stone facade specimens (bottom).

Figure 5 Comparison of calculated and measured moisture profiles for Sander sandstone in four distinct weather periods: following the first major rain fall after sstart of the experiment, following a week-long period of fair weather, in dry blustery weather following rain and in a length period of cold, wet weather at the end of the observation period.

Figure 6   Measured (above) and calculated (below) annual variation (hatched areas) and annual means (solid lines) of the water content of a fair facade west oriented natural stone wall made of Sander sandstone.

Figure 7 Comparison of the calculated and the measured variation in water content of 24 cm thick brick masonry under natural conditions. The initial water content (marked with an arrow) was reached by artificial spray wetting of the facade elements.

Figure 8 Drying-out behaviour of unrendered 40 cm thick exposed brick walls
after the treatment with water repellent agents. The vapour resis-
tance of the indoor finishing described as equivalent stagnant air
layer thickness represents a normal interior plaster resp. bathroom
or kitchend tiles.

Figure 9   Moisture distributions at different time points (exterior is left hand side) in the walls described in Fig. 8).

Figure 10   Two dimensional moisture distributions, plotted as isolines, in a section of natural stone masonry after three hours of intensive driving rains and during the following drying period. The blocks of the anisotropic Eichenbühler sandstone are layered horizontally resp. vertically.

Figure 11   Photographs of damates at a pillar (left) and at a wall section of the cathedral of Cologne. The more severe decay in the vicinity of the mortar gaps is noticeable.