Introduction of a Drying Coefficient for Building Materials

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ABSTRACT

Hygrothermal building component simulation requires a complete set of storage and transport functions. Such functions are typically determined by the aid of material models defining a set of functions that are adjusted to basic material data. Basic material data consists of either single parameters or measured functional courses of, for example, water uptake or drying. For parameter adjustment during material modeling, functional courses are most reliable. For a simple comparison of material properties, though, single number material parameters are more appropriate.

The drying behavior of building materials is rather complex, which is the reason why a single-number drying coefficient does not yet exist. Some first attempts to standardize drying data have been made. However, these did not yet result in a consistent drying coefficient definition.

The paper briefly introduces the different dependencies of the drying process. Data from experimental and numerical investigations is provided and discussed. On this basis, a new drying coefficient for building materials is defined. This coefficient is ultimately discussed with regard to its meaning as well as its additional information content compared to other moisture transport coefficients.

INTRODUCTION

The moisture transport properties significantly influence the application, durability, and particular structural behavior of building materials. Investigations of such behavior are either done experimentally or by numerical simulation (Pedersen 1989; Künzel 1994; Janssen et al. 2007; Nicolai et al. 2010). The moisture transport behavior is important in both cases and can be derived for the different moisture content ranges from vapor diffusion, water absorption, and drying experiments.

The water absorption experiment provides information about the material's transport properties for liquid water. The measurement conditions comprise water contents close to saturation.

The vapor diffusion experiment provides information about the material's moisture transport properties in the hygroscopic moisture range. It comprises mainly vapor transport. Measurements at higher relative humidities include unsaturated liquid transport as well.

The drying experiment provides information about liquid and vapor transport properties. It comprises the whole range from saturated liquid to only vapor transport and, hence, marks the link between the two other experiments.

This is the reason why the drying experiment is considered to be very important for the hygric material characterization (Krus and Holm 1999; Scheffler 2008). It reveals moisture transport information within the largest range of moisture stages. Drying is an integral transport experiment that does not require expensive equipment to be performed. However, the drying is much more dependent on the boundary and transfer conditions than the other two experiments. Therefore, all of these conditions have to be known for a proper data analysis.

At present, the drying experiment is not standardized, and a simple material parameter to be derived does not exist.

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Therefore, this paper first investigates the drying process and its governing influences and then reviews some first attempts to derive a simple material coefficient. On that basis, the authors propose a new drying coefficient for building materials and discuss its meaning and its correlation to the other transport parameters.

Basics of the Drying Process

In general, drying is a three-dimensional heat and moisture transport phenomenon that includes evaporation cooling, which leads to a temperature and also to a moisture profile. The drying behavior of porous materials depends on the following:

- material properties (moisture storage and transport)
- climatic conditions (temperature and relative humidity)
- transfer conditions for heat and vapor (air velocity and surface roughness [Worch 2004])

The material properties influence how quickly moisture can be transported inside the material. The combination of climatic and transfer conditions—i.e., the boundary conditions—defines the speed and quantity of moisture that can be transported to the surrounding atmosphere. Figure 1, left side, illustrates these influences. This also becomes visible in a material's drying curve (Figure 1, right side). Two distinct phases, called first and second drying phase (Krischer and Kast 1992), can be distinguished. The first drying phase is characterized by an almost linear weight loss in time. During this phase, the material transports moisture faster to the evaporation surface than what can evaporate. During the first drying phase, the drying is limited by the boundary conditions.

In the second drying phase, this physical phenomenon reverses. The moisture transport becomes slower and the boundary conditions allow more moisture movement toward the surrounding air than actually arrives at the surface. The process is slowed and a distinct moisture content profile develops inside the material. During the second drying phase, the drying is limited by the material properties.

When performing these drying experiments, this is the interesting part of the results because it reflects the material behavior. Adjustment and approximation procedures, as introduced by Krus and Holm (1999), Scheffler (2008) and Scheffler and Plagge (2010) can interpret the physics of the second drying phase. For a more detailed analysis of the drying process and how to measure and interpret such data, see Scheffler and Plagge (2005).

Since the drying is influenced by many conditions, it is important to conduct drying experiments under standardized conditions or measure all influencing parameters—i.e., relative humidity and temperature of the environment and surface temperature of the evaporation surface. Until now, a standard for drying experiments does not exist. Moreover, it is very difficult to maintain constant and reproducible conditions during the drying. Therefore, it is recommended that all conditions be measured (Scheffler and Plagge 2005).

Problems in Drying Coefficient Derivation

The different dependencies of the drying experiment on geometrical, initial, and boundary conditions, as well as on the material properties, make the derivation of a simple single-value material parameter very difficult. Within the German national research project MASEA, aimed at developing a material database for old existing building materials (see also, BINE 2007), discussions on a drying coefficient were started.

It quickly became clear that time and sample height play an important role and must be combined. Krus et al. (2007) published their first considerations and proposed to plot the

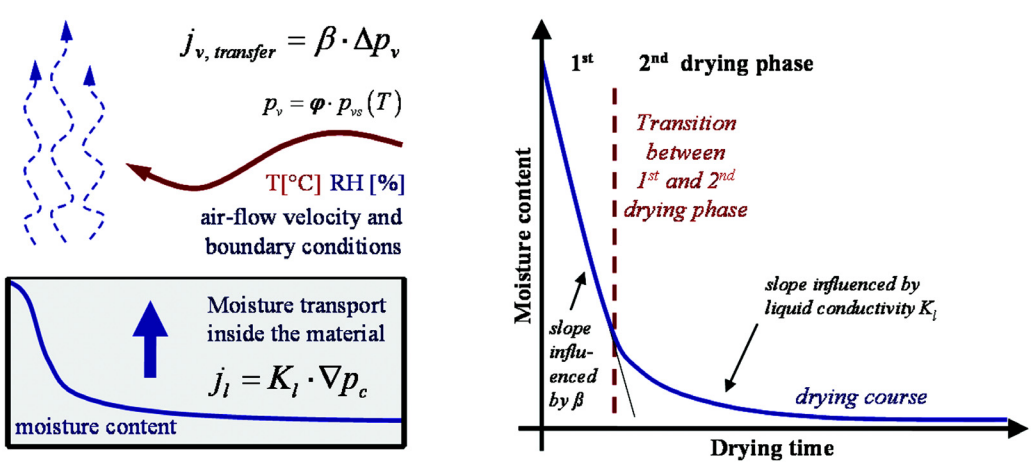

Figure 1 *The drying process: boundary conditions and material properties influencing the drying process (left) and example integral drying curve with a distinction of the two drying phases indicating its influencing parameters (right).*

duration of the first drying phase versus sample height. Based on a simulation study with constant climatic conditions, they had obtained a square root of sample height relationship. Similarly to the water absorption coefficient, the drying coefficient was proposed to be the slope of this curve in a square root of sample height scale (Figure 2).

However, this relationship could not be proven by experimental investigations on other materials. Scheffler (2008) showed measurement results for a calcium silicate insulation material and a ceramic brick. Both materials have a distinct first drying phase. All results indicated a linear relationship between first drying phase duration and sample height. One chart of these results is shown in Figure 2 at the right. The study was performed with samples of different diameter and height and for different vapor transfer conditions to study these influences as well. All results showed a perfectly linear relationship.

These discrepancies stipulated an additional study to investigate how these differences can occur and understand what influence on the drying process might have caused them.

ANALYSIS OF THE INFLUENCES ON THE DRYING

The analyses compared measurement against simulation results, one-dimensional models against three-dimensional reality, and different materials with different sample heights. From this, a set of possible influences to investigate was compiled:

1. Influence of heat and vapor transfer coefficients
2. Influence of the applied material and simulation model
3. Influence of accounting for or neglecting the three-dimensional heat transport
4. Influence of the initial moisture content
5. Influence of the investigated sample heights

Investigating these would shed light not only on the particular discrepancy between measurement and simulation, but also on the influences of the drying experiment in general.

Heat and Vapor Transfer (1)

The heat and vapor transfer conditions significantly influence the slope of the drying curve during the first drying phase, and by that also the first drying phase duration. This becomes clear when looking at the left chart of Figure 3, where simulation results of a ceramic brick drying are shown. The only changed parameter is the vapor transfer coefficient ß. Not only the first drying phase duration, but also the moisture content at its end are influenced by the transfer conditions at the material surface.

$$\beta = \frac{\alpha}{R_v \cdot T \cdot c_{p,a} \cdot \rho_a} \cdot LE^{m-1} \qquad (1)$$

where

LE	=	Lewis number for water vapor given with $LE = 0.87$
m	=	dimensionless parameter, according to Baer and Stephan (2003), $m = 1/3$
α	=	heat transfer coefficient
R_v	=	gas constant for water vapor
T	=	Kelvin temperature
$c_{p,a}$	=	specific heat capacity (isobaric condition)
ρ_a	=	density of air

The simulation study of Krus et al. (2007) used the analogy between heat and vapor transfer coefficient, also known as the LEWIS-relation (Equation 1). Evaluation of drying measurements indicated that this relation does not always hold

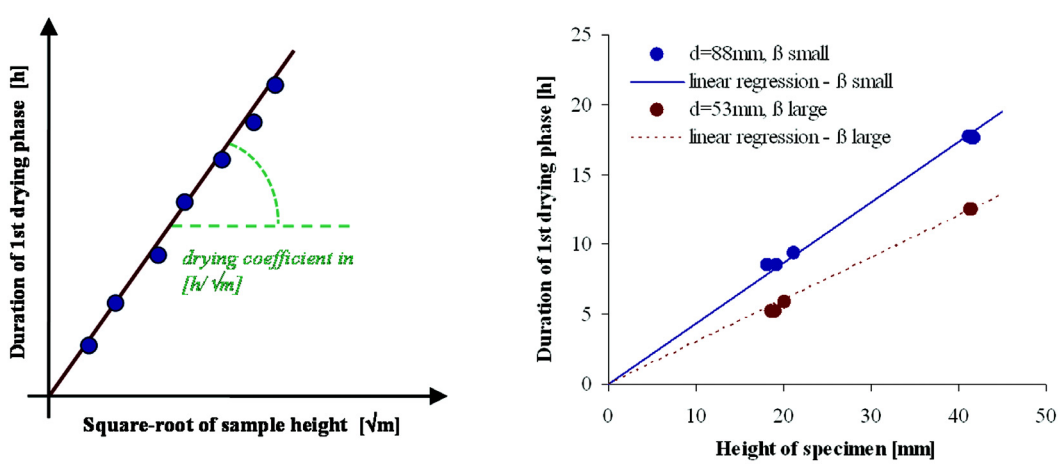

Figure 2 *(Left) Duration of the first drying phase plotted versus square-root of sample height. Qualitative representation of the simulation results for an aerated autoclaved concrete and (right) duration of the first drying phase plotted versus sample height for a ceramic brick (measured data).*

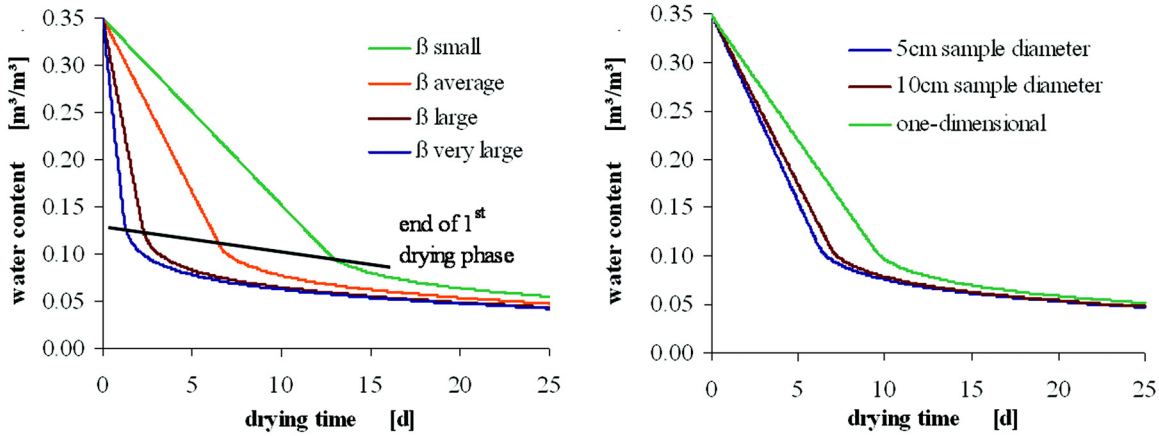

Figure 3 *Simulation results of a ceramic brick drying. The left chart shows the influence of the vapor transfer coefficient ß while all other conditions remained the same. The right chart shows results of radial-symmetric 3-D simulations where only the sample diameter was changed. The influence of the 3-D heat transport on the drying course becomes clearly visible.*

for experiments with higher airflow velocities. However, this is only important if experiment and simulation are compared. For a simulation study using the same heat and vapor transfer coefficients in all cases, this does not lead to different results.

Material and Moisture Transport Model (2)

The quality of the applied material functions is an often disputed problem whenever numerical simulations are carried out. The approximation quality of the material functions is crucial for any calculation where the results need to be correct. To exclude any such influences from the discussion, drying simulations were performed with two different material and transport models according to Krus and Holm (1999) and Scheffler and Plagge (2010).

The material functions were adjusted according to these models to measured brick data. Drying simulations were performed while the liquid transport function was slightly varied (for both the whole function or only in the lower moisture content range). These calculations produced different but very similar results. All of them showed a linear dependence between first drying phase duration and sample height. Therefore, the applied model and the approximation quality do not explain the differences and are of minor importance here.

Three-Dimensional Heat Transport (3)

Due to the cooling effect of evaporation, the drying surface of a material sample is significantly colder than the surrounding air. As the sample has a finite dimension, heat is not only transferred from the top (air) and bottom (material sample) surfaces, but also from the lateral sides of the sample. This leads to a distinct temperature distribution at the drying surface, which in turn causes a vapor pressure distribution there. Consequently, the evaporation rate is not the same everywhere at the drying surface.

As the lateral heat flow increases the temperature, this effect increases the evaporation rate and, hence, the drying speed. This becomes visible in the right-side chart of Figure 3. Here, radial-symmetric three-dimensional simulation results for a ceramic brick drying are displayed. The only varied parameter is the sample diameter, where one-dimensional corresponds with an infinite sample diameter.

The influence is clearly visible. This effect is particularly important when comparing experimental data with simulation results, and the main reason why cylindrical samples should be used for drying experiments (Scheffler and Plagge 2005).

The simulation results according to Krus et al. (2007) were done one-dimensionally. This might lead to deviations between measured and calculated drying curves, but it does not change the relationship between first drying phase duration and sample height from linear to square root. The influence of three-dimensional heat transport is therefore not the reason for the observed deviations.

Initial Moisture Content (4)

The initial moisture content has a significant influence on the first drying phase duration. The more water needs to be evaporated through a certain surface, the longer it takes. Figure 4 illustrates this with simulation results of a ceramic brick drying starting from different initial moisture contents.

As the initial moisture content is very important for the first drying phase duration, it should receive special attention. In order to make results comparable, all investigations should use the same initial moisture content. For a simulation, any moisture content can be adjusted and assigned in an even

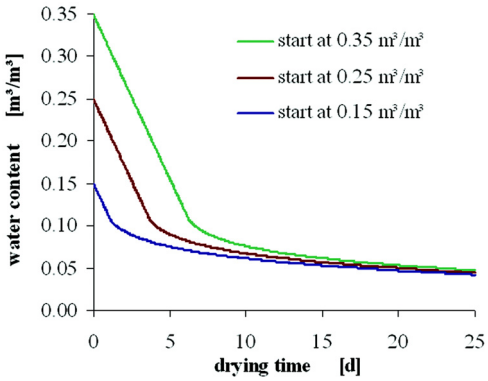

Figure 4 *Comparison of simulation results of ceramic brick drying for different initial moisture contents.*

distribution. For an experiment, this is not easily possible. The experimental drying normally starts after a completed water absorption experiment. This means that the mean moisture content that is established inside the sample will range between capillary and effective saturation. A drying simulation should therefore start from the moisture content reached after a water absorption experiment.

Note that this requirement is not very satisfactory. At the end of a water absorption experiment, i.e., when the moisture front has reached the sample top, a moisture content profile is still present over the sample. Leaving the sample in water contact for a longer period of time slightly increases the overall moisture absorbed, but does not equilibrate this moisture profile entirely. A perfectly uniform moisture distribution will, hence, hardly be established.

However, the discussion shows that possibly a high and practically reachable moisture content should be used as initial condition for the drying experiment.

Sample Height (5)

The sample height is already part of the equation. It is, though, recommended to use sample heights according to the laboratory practice. This means 1 to 10 cm (ca 0.4 to 4 in.), depending on the material, should typically be used.

The height of the sample determines the duration of the overall drying and the information content to be gained from the data. A material like concrete with a very low liquid conductivity has a short first and a very long second drying phase. For a drying experiment on concrete, a small sample height is suitable. A material like ceramic brick, on the other hand, has a high capillary conductivity. Here, drying experiments would provide more meaningful results when higher sample heights are used.

Discussion of the Influences

The initial moisture content and the sample height remained somehow unclear in their impact on the first drying phase duration. Therefore, some additional calculations were performed for aerated autoclaved concrete, where both sample height and initial moisture content were varied. The results are shown in Figure 5.

The top charts in Figure 5 show results where the drying was started from a moisture content lower than capillary saturation. Two interesting effects can be seen in these charts. One is that the first drying phase duration does follow the sample height in square-root form. The other effect is that there appears to be a threshold sample height up to which a relationship exists between first drying phase duration and sample height. Samples higher than this threshold have all the same first drying phase duration.

The lower charts of Figure 5 show results where the drying was started from capillary saturation. Sample heights up to 50 cm were chosen to illustrate that for this material and these conditions, the first drying phase duration shows a more-or-less square-root dependence to the sample height.

The explanation for this can be found in the moisture transport processes occurring during the first drying phase. This drying phase is characterized by a linear drying throughout the whole material sample. A clear moisture profile does not yet form. The first drying phase ends when a distinct moisture profile establishes inside the material. The moisture content at which this happens is called *critical moisture content*.

If the moisture content at the beginning of the drying is smaller than the critical moisture content, the first drying phase consists only of the formation of a moisture profile. This affects only the boundary range of the material. For samples higher than the affected range, this becomes independent of the sample height. We can observe this in top charts of Figure 5.

If, at the other extreme, the drying starts at a moisture content very much higher than critical moisture content, the linear drying without establishing a moisture profile is the main process. Its length is characterized by the amount of water to be dried out linearly. This is directly proportional to the sample height, and we observe a linear relationship between first drying phase duration and sample height. This is the case for the brick shown in Figure 2 at the right.

For cases in between these two extremes, the first drying phase is partly characterized by a linear drying and partly by the establishment of a distinct moisture profile. For such cases we do not see a linear behavior but a relationship that does, more or less, follow a square-root behavior over the sample height (Figure 5, bottom charts).

To confirm this reasoning, the differential equation of moisture diffusion (Equation 2) was solved analytically for an infinite plate.

$$\frac{\partial \theta_l}{\partial t} = D \cdot \frac{\partial^2 \theta_l}{\partial x^2} \tag{2}$$

where θ_l is the moisture content and D is the moisture diffusivity.

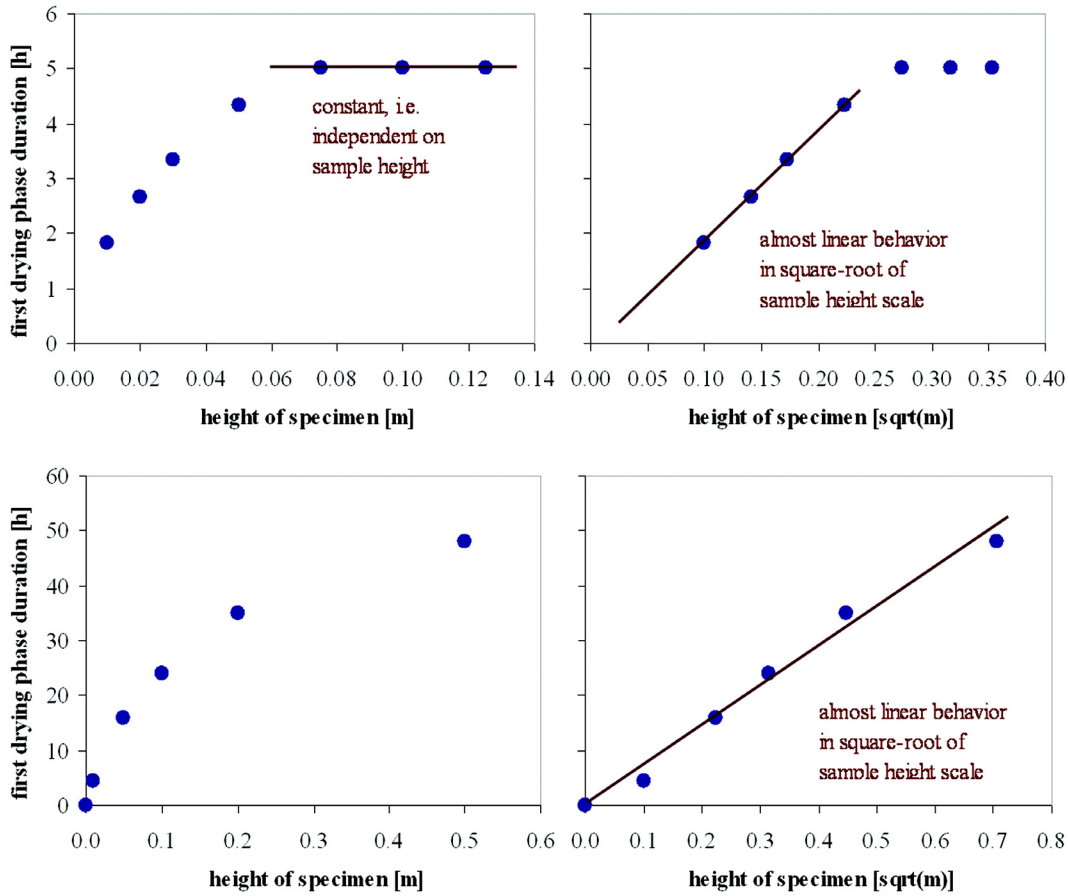

Figure 5 *First drying phase duration versus sample height for aerated autoclaved concrete. Left and right charts show the same data but in a different abscissa scaling. The drying was started at different moisture contents. Upper charts data started at 0.15 m^3/m^3; lower charts data started at 0.22 m^3/m^3.*

The results of the analytic solution are shown in Figure 6. They were obtained for constant boundary conditions and a constant moisture diffusivity. For the exact steps of this analysis, refer to Scheffler (2008).

The left-side chart of Figure 6 presents the development of the boundary moisture content over time for different sample heights (each line corresponds with one sample height). It becomes apparent that there is an upper bound that is not exceeded. Once reached, the course of boundary moisture content is independent of the sample height. The right-side chart of Figure 6 confirms this. Here, the first drying phase duration is plotted versus sample height. For the chosen conditions of this analysis, the first drying phase duration becomes height independent at around 15 cm (5.9 in.).

Two conclusions can be drawn from these analyses. First is that the first drying phase does not have a clear dependence on the sample height, which could be used for the definition of a drying coefficient. Second is the summary of influences and dependencies of the drying process, which is compiled in Table 1.

INTRODUCTION OF A NEW DRYING COEFFICIENT

We have shown that the first drying phase duration is not a suitable measure for a drying coefficient. The derivation of a drying coefficient still has to cope with the different dependencies of the drying process. Numerical simulation has proven to be a valuable tool of such investigations, as climatic influences can easily be controlled. Indeed, if boundary temperature and relative humidity are kept constant and, for simplicity, a one-dimensional problem is assumed, only the following parameters remain: material properties, initial moisture content, and drying height. These have to be combined in a single-number drying coefficient.

For constant boundary conditions, a homogeneous material, and a fully developed moisture profile, the signal velocity of this profile inside the material is constant over the square root of time. This is well known and frequently observed for water absorption, but it applies similarly for the drying. The main difference is that the moisture profile does not develop as quickly. In fact it is the end of the first drying phase that is characterized by the completed development of a distinct moisture

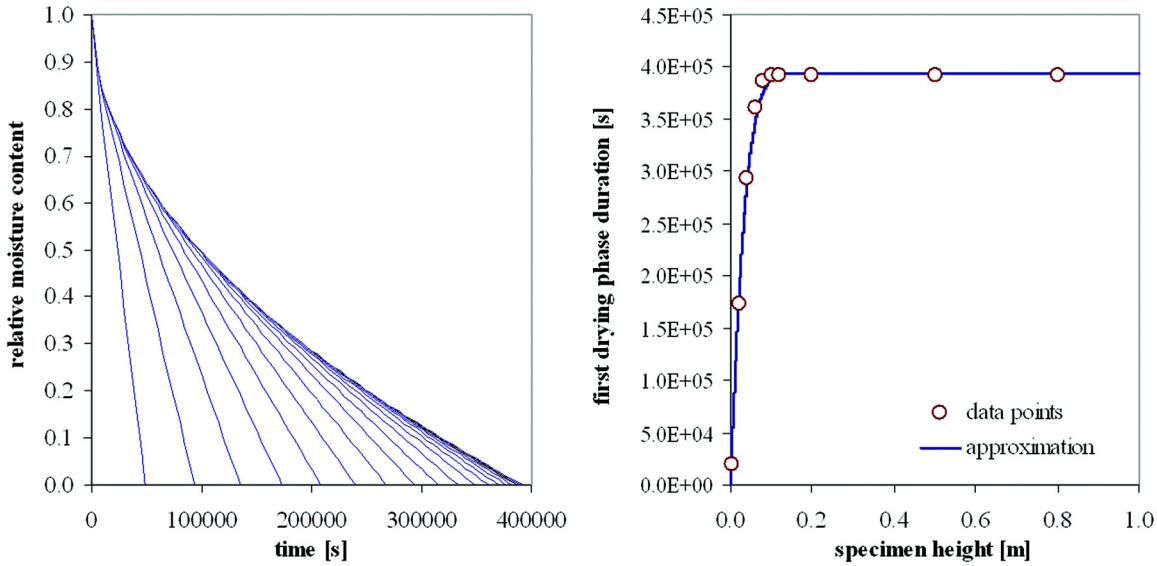

Figure 6 *Analytic solution of the drying problem. (Left) Boundary moisture content versus time and (right) first drying phase duration versus sample height.*

Table 1. Parameters Influencing the Drying and Their Significance

Parameters	Influence	Significance
Material properties, particularly the moisture transport properties	Strong influence on the drying, responsible for the first drying phase duration as well as for the drying course of the second drying phase	Very significant, the actual reason why drying experiments are performed
Boundary temperature and relative humidity	Influence on the vapor pressure difference and hence on the evaporation rate	Significant during the first drying phase, important parameter of the drying process which needs to be monitored
Surface temperature	Determines the vapor pressure at the surface and by this the evaporation rate, very sensitive parameter of the drying process	When measured, the surface temperature can be used to calculate the vapor transfer coefficient and to determine the end of the first drying phase
Airflow velocity (vapor transfer conditions)	Influence on the evaporation rate, limiting factor during the first drying phase	Very important parameter of the first drying phase, should be kept constant, can be determined indirectly
Initial moisture content	Influences the duration of the whole drying process	Very important parameter, especially concerning reproducibility and comparability, should be always adjusted to effective saturation.
Sample diameter/ influence of lateral heat flow	Influences the surface temperature and by this the evaporation rate	Important when comparing measured and simulated material behavior, should be therefore consistent, is in general of less significance
Sample height	Influences the duration of the drying process	Very important parameter of the drying process

profile. Once this profile is there, the end of the drying process should only depend on the signal velocity and the height of the material sample. The duration of the second drying phase must, therefore, increase quadratically with the sample height, provided that the drying was started at a moisture content sufficiently high to allow a clear distinction between first and second drying phases.

This was investigated by a simulation study on drying of four different materials: calcium silicate brick, ceramic brick, aerated autoclaved concrete, and calcium silicate insulation. The material properties were taken from Scheffler (2008). The drying was calculated one-dimensionally for different sample heights with constant boundary conditions of 20°C (68°F) and 50% RH. It was started at effective saturation. The results are

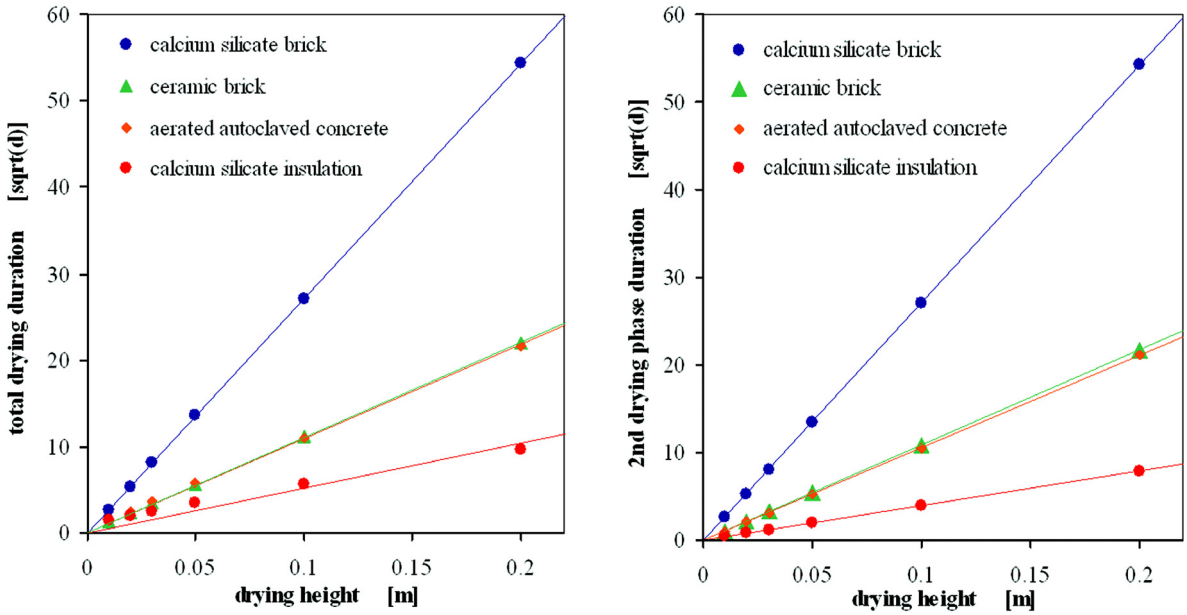

Figure 7 *Square root of drying duration versus sample height. Left chart shows total drying duration. Right chart shows only duration of the second drying phase. The square root of the second drying phase duration shows a perfectly linear relation to the sample height.*

presented in Figure 7. The left chart shows the total drying duration versus sample height; the right chart shows only the second drying phase duration versus sample height.

The results confirm the above reasoning. The duration of the second drying phase increases quadratically with the sample height. In other words, the square root of the second drying phase duration plotted versus sample height gives a linear relation (see right-side chart of Figure 7).

We therefore propose the following relation (Equation 3) as the definition of the new drying coefficient for building materials:

$$D_d = \frac{\sqrt{t_{d,2nd}}}{h} \tag{3}$$

where

D_d = drying coefficient in $\sqrt{d/m}$

$t_{d,2nd}$ = drying time of the second drying phase in d

h = sample height in m

The second drying phase duration $t_{d,2nd}$ is the time between the deviation from the linear drying and the end of the drying process (see also Figure 1). In other words, it is the time between the end of the first drying phase and the moment where the equilibrium moisture content is reached everywhere inside the sample. For measured data, this depends on the frequency of measurement as well as the boundary temperature and relative humidity and might, therefore, be susceptible to error. It is proposed to use calculation results of the drying process normalized to standard conditions. From such data, the second drying phase duration $t_{d,2nd}$ can be easily determined.

Table 2. Moisture Transport Coefficients of Typical Building Materials

Material	Drying Coefficient $D_d[\sqrt{d/m}]$	Vapor Diffusion Resistance μ, dimensionless	Water Absorption Coefficient $A_w[kg/m^2\sqrt{s}]$
Calcium silicate insulation	40	4	1.10
Autoclaved aerated concrete	105	8	0.04
Ceramic brick	107	14	0.23
Calcium silicate brick	268	40	0.05
Gypsum rendering	164	12	0.37
Rehabilitation rendering	355	33	0.03
Loam	112	11	0.18
Granite (weathered)	175	54	0.08

For most materials, the first drying phase duration is negligible in the overall drying time. This allows simplifying the found relationship to be true also for the total drying time and not only for the second drying phase duration for which it is strictly correct. The left-side chart in Figure 7 shows the total drying time versus sample height. The linear relationship holds for all materials except the calcium silicate insulation, which has a very high porosity (90%) and a very long first drying phase.

This new drying coefficient gives a measure for the time it takes to one-dimensionally dry out one meter of material. As discussed before, for most building materials this is correct for the total drying time even though it is strictly only valid for the second drying phase. Example values for drying coefficients of typical building materials are given in Table 2.

Discussion of the Proposed Drying Coefficient

The drying coefficient gives a measure of the time required to dry out 1 m of material. By that, it has a particular meaning and is a practically useful material parameter. The question is now, however, whether this parameter contains additional information in comparison with the other two moisture transport parameters, i.e., vapor diffusion resistance and water absorption coefficient. For that reason, these coefficients were related to each other for numerous building materials (drying coefficient of material A divided by drying coefficient of material B and so on, and similarly for vapor diffusion resistance factors and water absorption coefficients). These related coefficients are plotted against each other in Figure 8 in order to visualize any possible correlation.

If the corresponding properties are correlated, the related values of different building materials should follow some kind of curve. Between drying coefficient and vapor diffusion resistance, a positive linear correlation is observable, though with a lot of scatter. Between drying coefficient and water absorption coefficient, a negative linear correlation can be found, again with significant scatter.

A weak correlation is not a surprise, since all these coefficients are the result of the material's specific pore structure and pore connectivity. Some kind of distinct correlation between drying coefficient and vapor diffusion resistance seems to be obvious, since vapor diffusion dominates the drying process to quite some extent. However, the left-side chart in Figure 8 indicates there is only a weak correlation. Therefore, the drying coefficient cannot contain exactly the same information as the vapor diffusion resistance. It must contain its own, drying-specific information as well. In order to investigate this further, the sharp-front model according to Hall and Hoff (2002) and Hens (2007) is applied as follows.

The sharp front model distinguishes between two cases that can be treated in a simplified way. The first case comprises stages above critical moisture content. Water transport can be described by liquid conduction. The second case comprises stages below critical moisture content. Water transport is described by vapor diffusion. Due to the high permeabilities for liquid conduction, this treatment leads to a small gradient for liquid transport and a high gradient for vapor transport. This sharp front has given the model its name.

Applying this to the drying problem leads to the model shown in Figure 9. Assuming the drying starts above critical moisture content, the drying rate is determined by a constant vapor transfer at the material surface. This process—the first drying phase—continues until critical moisture content is reached at the material surface. Then the surface dries out entirely and a steep moisture front is established, which moves slowly into the material. The drying rate is now determined by the vapor diffusion from the moisture front to the material surface.

The first drying phase can be modeled by the normal diffusion equation (Equation 2) for which analytic solutions can be found in the literature (e.g., Baehr and Stephan 2003; Hens 2007; and Tautz 1971). The second drying phase is assumed to start at critical moisture content. Then the following balance (Equation 4) can be written:

$$\frac{p_s(1-\varphi)}{\frac{1}{\beta}+\frac{\mu}{\delta_a}\cdot x}dt = (\theta_{crit}-\theta_{hyg})\rho_l \cdot dx \tag{4}$$

where

p_s = saturation vapor pressure
β = surface transfer coefficient for vapor
φ = relative humidity
μ = vapor diffusion resistance factor
δ_a = diffusion coefficient in air
ρ_l = density of water
θ_{crit} = critical moisture content
θ_{hyg} = hygroscopic equilibrium moisture content

Solving this equation for x yields the actual position of the moisture front according to Equation 5.

$$x = \frac{\delta_a}{\mu\cdot\beta}\left(\sqrt{1+\frac{2p_s(1-\varphi)\frac{\mu}{\delta_a}\beta^2 t}{(\theta_{crit}-\theta_{hyg})\rho_l}}-1\right) \tag{5}$$

This can be rearranged for t yielding the second drying phase duration in dependence of the sample height x. For $\mu/\delta_a \ll 1/\beta$, Equation 5 can be simplified to Equation 6.

$$x = \sqrt{\frac{2p_s(1-\varphi)\cdot\delta_a}{\mu(\theta_{crit}-\theta_{hyg})\rho_l}}\cdot\sqrt{t} \tag{6}$$

This can be directly rearranged yielding the drying coefficient according to Equation 3.

$$\frac{\sqrt{t}}{x} = D_d = \frac{1}{\sqrt{\frac{2p_s(1-\varphi)\cdot\delta_a}{\mu(\theta_{crit}-\theta_{hyg})\rho_l}}} \tag{7}$$

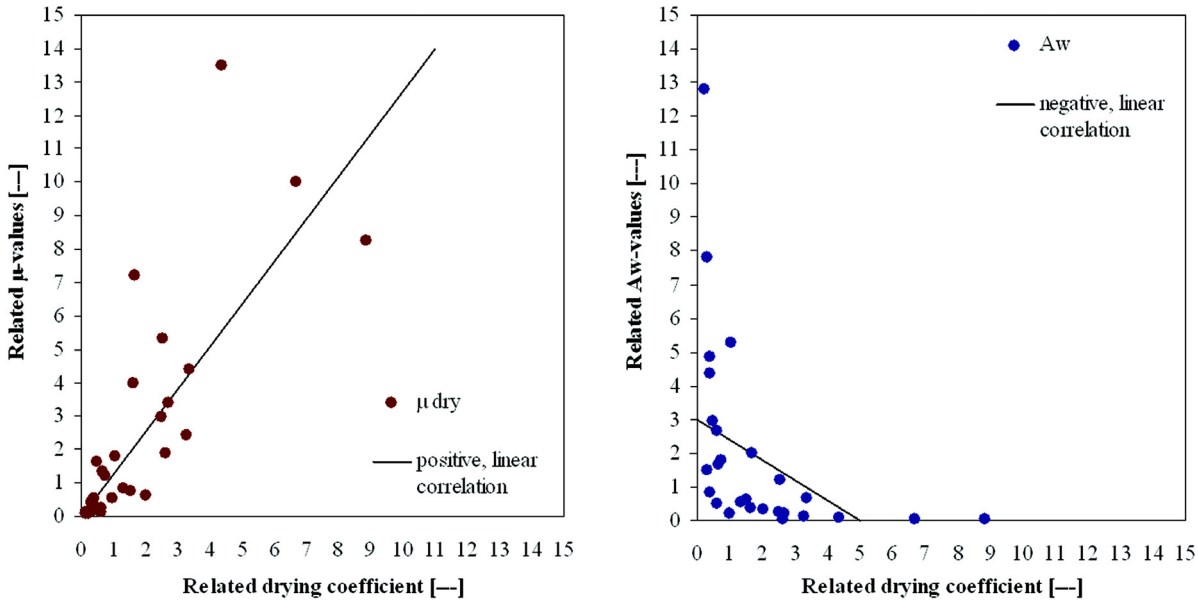

Figure 8 *Correlation between the drying coefficient and other moisture transport parameters. Left chart shows the relation to the dry-cup vapor diffusion resistance µ, right chart shows it to the water absorption coefficient Aw.*

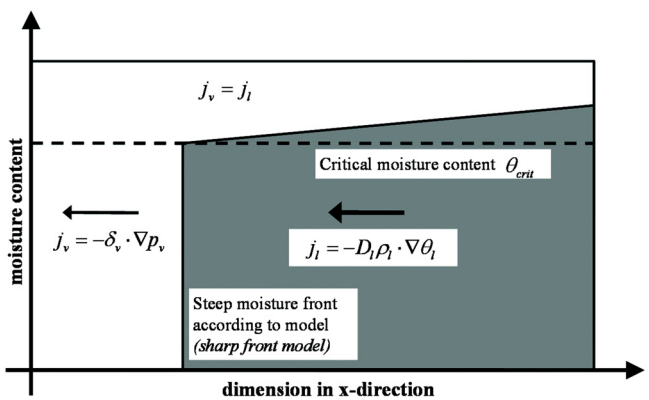

Figure 9 *Drying according to the sharp front model. Above critical moisture content, the moisture is transported by liquid flow to the surface. Below critical moisture content, a sharp moisture front establishes and transport to the surface proceeds via vapor diffusion.*

It becomes apparent that the drying coefficient is indeed correlated with the vapor diffusion resistance factor µ. However, it is also particularly dependent on the critical moisture content. This critical moisture content is defined as the moisture content at which a continuous liquid phase is apparent in the pore system, enabling considerable liquid transport. Typically, the moisture content at which the liquid permeability starts to strongly increase is taken, which is not a satisfying definition.

On the other hand, the drying coefficient can be used to determine the critical moisture content. This was done for the building materials listed in Table 2. With these values, the sharp-front model was used to calculate the required drying times. These times corresponded with an error of less than 1% with the times obtained by a full hygrothermal numerical simulation.

It can be concluded that the proposed drying coefficient does not contain exactly the same information as the vapor diffusion resistance. Both parameters are weakly correlated, but the drying coefficient contains additional information about liquid transport in the unsaturated over-hygroscopic moisture range.

The proposed drying coefficient is hence a useful additional material property that allows for describing these moisture transfer properties of building materials by one single number.

The drying coefficient is an additional single-value material property. It describes the ability of a material to dry out. With this drying coefficient, designers obtain a new assessment criterion for material selection similar to other material properties such as density, compressive strength, or thermal conductivity. This is particularly valuable for cases where drying and unsaturated moisture transport are important, as for example, capillary-active internal insulation for energy retrofit of the historic building stock, where vapor open, fast drying materials are desired. Another useful application of the drying coefficient is the estimation of required drying time. This

might be of interest, for example, for the drying out if built-in moisture or in damage cases (flood, drainage defect, etc.), where materials have become wet and need to dry out again.

The drying coefficient is hence useful for both comparing different materials with regard to their moisture transport properties and estimating the required time to dry a material of a certain thickness.

CONCLUSION

This paper presented a comprehensive analysis of the drying process and its influencing parameters. The governing processes were identified and a new, single-number drying coefficient for building materials was proposed. It is defined as the square root of the second drying phase duration divided by the sample height. For its correct determination, the drying should start at saturation, and the climatic conditions should be relatively constant. For most building materials, instead of the second drying phase duration, the overall drying time can be used. The drying coefficient gives a measure for how long it takes to dry out a certain thickness of wet material.

In addition, it was shown that the proposed drying coefficient contains additional information about the moisture transport behavior within the unsaturated, over-hygroscopic moisture range. It is only weakly correlated with the water absorption coefficient and the vapor diffusion resistance factor. The drying coefficient forms a valuable addition to these well-established moisture transport material properties. It allows a better selection and distinction of building materials based on its relevant moisture transport properties. It is therefore desirable that this coefficient will be used and accepted by both building research and practice.

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NOMENCLATURE

$c_{p,a}$	=	specific heat capacity (isobaric condition), J/(kg·K)
D	=	moisture diffusivity, m^2/s
D_d	=	proposed drying coefficient, $\sqrt{d}/m$
LE	=	Lewis number for water vapor given with $LE = 0.87$, dimensionless
m	=	dimensionless parameter according to Baer and Stephan (2003) $m = 1/3$
p_c	=	capillary pressure, Pa
p_v	=	vapor pressure, Pa
p_{vs}	=	saturation vapor pressure, Pa
R_v	=	gas constant for water vapor, J/(kg·K)
T	=	Kelvin temperature, K
t	=	time, s
$t_{d,2nd}$	=	duration of the second drying phase, d
α	=	surface transfer coefficient for heat, $W/(m^2 \cdot K)$
β	=	surface transfer coefficient for vapor, $kg/(m^2 \cdot s \cdot Pa)$
δ_a	=	vapor permeability of air, kg/(m·s·Pa)
φ	=	relative humidity, dimensionless
μ	=	vapor diffusion resistance factor, dimensionless
θ_l	=	volumetric moisture content, m^3/m^3
θ_{crit}	=	critical moisture content, m^3/m^3
θ_{hyg}	=	hygroscopic equilibrium moisture content, m^3/m^3
ρ_a	=	density of air, kg/m^3
ρ_l	=	density of water, kg/m^3

Subscripts

crit	=	critical
hyg	=	hygroscopic
l	=	liquid/water
v	=	vapor
a	=	air

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