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Moisture Buffering of Building Materials

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Moisture Buffering of Building Materials

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Summary

Building materials and furnishing used in contact with indoor air may have a positive effect to moderate the variations of indoor humidity seen in occupied buildings. Thus, very low humidity can be alleviated in winter, as well as can high indoor humidity in summer and during high occupancy loads. This way, materials can be used as a passive means of establishing indoor climatic conditions, which are comfortable for human occupancy, or for safe storing of artefacts which are sensible to humidity variation.

But so far there has been a lack of a standardized quantity to characterize the moisture buffering capacity of materials. The objective of the NORDTEST project on Moisture Buffering of Building Materials has been to develop such a definition, and to present it in the form of a NORDTEST method. Apart from the definition of the *Moisture Buffer Value*, the project declares a test protocol which expresses how materials should be tested. The test protocol constitutes the project's proposal for a NORDTEST method, and can be seen as Appendix 1 of this report. Furthermore, as a part of the project some Round Robin Tests have been carried out on various typical building materials.

Contents

Nomenclature

Symbol	Explanation	Unit
a	Thermal diffusivity	m^2/s
A	Area	m^2
Bi	Biot number	-
b_m	Moisture effusivity	kg/(m²·Pa·s^{½})
c_p	Specific heat capacity	J/(kg·K)
d_p	Penetration depth	m
D_w	Moisture diffusivity	m^2/s
g	Moisture flux	kg/(m^2·s)
G	Moisture uptake	kg/m^2
L	Length	m
Le	Lewis number	-
MBV	Moisture Buffer Value	kg/(m^2·%RH)
Nu	Nusselt number	-
p	Water vapour pressure	Pa
p_s	Saturation vapour pressure	Pa
q	Ventilation rate	m^3/s
R_v	Gas constant for water vapour = 461.5	J/(kg·K)
RH	Relative humidity	$\%$
t	Time	s
t_p	Period	s
T	Temperature	K
u	Moisture content	kg/kg
v	Air velocity	m/s
V	Volume	m^3
w	Moisture content	kg/m^3
x	Length coordinate	m
Z_p	Vapour diffusion resistance	Pa·m^2·s/kg
Z_v	Vapour diffusion resistance	s/m
α_c	Convective heart transfer coefficient	W/(m^2·K)
β_p	Moisture transfer coefficient	kg/(Pa·m^2·s)
β_v	Moisture transfer coefficient	m/s
δ_p	Water vapour permeability	kg/(m·s·Pa)
δ_v	Water vapour permeability	m^2/s
φ	Relative humidity	-
λ	Thermal conductivity	W/(m·K)
ν	Water vapour concentration	kg/m^3
ν_s	Saturation vapour concentration	kg/m^3
ρ	Density	kg/m³
ξ_u	Specific moisture capacity	kg/kg
ξ_w	Specific moisture capacity	kg/m^3

Intermittently throughout the report are referred to properties which either assume vapour pressure, p, or vapour concentration, ν, as the driving potential for water vapour diffusion. It is possible to calculate from one to the other set of units using the factor $R_v \cdot T$ (the gas

constant for water vapour multiplied with the absolute temperature).

Thus: $p = R_v \cdot T \cdot v$
For instance at 23°C: $p = 461.5$ J/(kg·K) · 293 K · $v = 136{,}604$ N·m/kg · v

And: $\delta_p = \dfrac{\delta_v}{R_v \cdot T}$

Another convention that may differ, concerns the unit used to express moisture content in materials. Either the moisture content is specified per dry weight of the material (u), or per volume of the material (w).

The relationship between u and w is: $u = \dfrac{w}{\rho_0}$, where ρ_0 is the dry density of the material.

Foreword

This document constitutes the reporting of NORDTEST project 04023, Moisture Buffering of Building Materials.

The project has run in two parts over the years 2004 and 2005. The project was initiated after successful completion of a NORDTEST Workshop on *Moisture Buffer Capacity* August 21-22, 2003 at the Technical University of Denmark (Rode, 2003), NORDTEST proj. 1627-03. The workshop concluded that there was a need to work on the definition of a stringent term for moisture buffer capacity, to elaborate on the related test methods, to disseminate about the subject and to declare the relevance for industry.

Partners in the project have been:
- Norwegian Building Research Institute (NBI);
- Technical Research Centre of Finland (VTT);
- Lund University, Sweden (LTH);
- Technical University of Denmark (DTU) (as project leader).

The following companies and industry organizations have contributed to the project:
- Wood Focus, Finland (FIN)
- BetonelementForeningen (DK)
- Gyproc AB (SE)
- Annebergs Limtræ A/S (DK)
- OPTIROC A/S (DK)
- H+H Celcon A/S (DK)
- Kalk- og teglværksforeningen (DK)
- Tretknisk Institutt & Tresenteret (N)

These partners have contributed both financially and with supply of materials for test and, not least, by showing their sincere interest in the subject of the project. We thank for this participation!

The project has had an international reference group with participation of:
- Professor Graham Galbraith, Glasgow Caledonian University UK;
- Dr. Monika Woloszyn, INSA-Lyon, France;
- Professor Hugo Hens, KU Leuven, Belgium;
- Dr. Andreas Holm, Fraunhofer Institut für Bauphysik, Germany;
- Professor Nathan Mendes, Pontifical Catholic University of Paraná, Brazil;
- Professor Vasco Freitas, Faculdade de Engenharia da Universidade do Porto, Portugal.
- Dr. Tim Padfield. Consultant in preventive conservation, Harbertonford, UK.

The international reference group has contributed with constructive criticism throughout the execution of the project. Their contributions are gratefully acknowledged!

1 Introduction

Indoor humidity is an important parameter to determine the occupants' perception of indoor air quality, and is also an important parameter as a cause of harmful processes that may occur on surfaces of materials, such as microbial growth. Thus, it is known that humidity has an impact on both the working efficiency and health of occupants. But due to the varying loads, the indoor humidity exhibits significant daily or seasonal variation. Materials that absorb and release moisture can be used positively to reduce the extreme values of humidity levels in indoor climates.

The use of building materials to moderate the *thermal* indoor environment has been a topic of research in hygrothermal conditions for buildings since at least the beginning of the 1980's, and the results have been used in building design and analyses since then. There is now an increasing interest in including in the analyses the *moisture* buffering properties of absorbent, porous building materials.

In all climate zones it is possible to improve indoor humidity conditions by appropriately applying hygroscopic building materials. Methods to characterize moisture buffer effect have been proposed by Time (1998) and Padfield (1999). Evaluation of moisture buffer effect based on simple measurements (continuously weighing of the specimen, density, permeability, and sorption) has been proposed by Hansen et al. (2000). An example is given by Simonson et al. (2002) of the way in which moisture transfer between wood based structures and indoor air significantly reduces the peak indoor humidity (by as much as 35 %RH) and increases the minimum indoor humidity (up to 15 %RH). A method to calculate the moisture penetration depth has been described by Arfvidsson (1999). Full-scale measurements of moisture buffering in building materials have been carried out by Mitamura et al. (2001).

More results were presented and discussed during the NORDTEST Seminar on Moisture Buffer Capacity in August 2003 (Rode, 2003a) and (Rode, 2003b). The Workshop which attracted some 30 Nordic and other international academics, including some few representatives of manufacturers of building materials and consultants, focused on the following five subjects:
1. Which quantity to standardize?
2. Experimental techniques - what should one measure?
3. Reference material/start of Round Robin
4. Commercial application and exploitation
5. Modelling - can we extrapolate?

The Workshop concluded that the phenomenon "is real" and an issue of public and industrial interest and debate - although the appraisal of moisture buffering materials has so far been based on a variety of definitions, so manufacturers could choose the one definition that seemed most suitable for a given cause. Therefore, there is a need for a robust definition of the term, which is technically appropriate, yet comprehensible and indisputable for the industry and users that will apply it. There is also a need for further elaboration of the possible benefits and relevance of deploying moisture buffer capacity of materials as a passive way of conditioning air, in relation to using other means to ensure healthy indoor environments of buildings by active conditioning systems.

There are many Nordic building products and materials used in furnishing that can be expected to perform well as moisture buffers. There are therefore significant industrial interests associated with the establishment of a term for moisture buffer capacity.

In the following, some recent studies on the moisture buffering are presented:

Padfield (1999) investigated a range of different porous building materials to find their moisture buffer capacity on the indoor air humidity. A specially constructed climate chamber (volume about 0.5 m^3) was used to measure the moisture buffering, when there was a periodically varying vapour flux. End grain wood panels showed the best buffering capacity due to the rapid diffusion and the great moisture capacity of wood. On the other hand, cellular concrete covered by a thin gypsum plaster turned out to be the best buffering commercial construction.

Mitamura et al. (2001) used a room size test cell to investigate the moisture buffer capacity of plasterboard, chipboard, cellular concrete, plywood, wood panels and painted plasterboard. The relative humidity of the test cell was a result of given rates of moisture release and removal to/from the cell air and the moisture exchanged with the materials. The highest buffer capacity was measured for wood panels and cellular concrete. The same set-up was used in investigations, where the layers of a light-weight interior wall were added successively and walls of aerated cellular concrete were tested with and without surface treatment Mortensen et al. (2005). The results pointed out the great reduction of the moisture buffer effect even when rather permeable surface treatments and layers were applied.

An approach to develop a test method and device to test the effective moisture capacity of structures or material layers is described in Salonvaara et al. (2004). The results showed that pine with moisture transport along the grain has the highest moisture buffer capacity while painted gypsum board has the lowest. These small scale tests were supplemented by a full-scale experiment together with numerical investigations. The inner surfaces of two identical test rooms were covered by either unpainted or painted gypsum boards, unpainted wood or aluminium foil. Also these results pointed out the significance of surface treatments on the moisture buffering.

Ramos and de Freitas (2004) studied numerically and experimentally the hygroscopic inertia of some covering materials and proposed the use of inertia classes for characterization of materials. The tests were performed with 12/12 hrs cyclic steps between 65 and 85%RH.

The role of interior furnishing on the total moisture buffer capacity of a room was studied experimentally and numerically in Svennberg et al. (2004). Pieces of furniture were added step-by-step in the test room with a given moisture production/removal rate. The results showed that it is necessary to include the moisture buffering effect of furniture when studying whole buildings.

An attempt to derive the moisture buffer capacity of various insulation materials by using different dynamic experiments was done in Peuhkuri et al. (2004). Both isothermal and non-isothermal tests were used. The results pointed out the great sensibility of the resulting moisture buffer capacity on whether one is using parameters from steady state measurements or one of several types of dynamic measurements.

In addition, investigations from members of the reference group of this project have show also surface transfer coefficient and sample sizes will be important and these issues must be addressed (Roels and Janssen, 2005).

The workshop in August 2003 and the information about recent or ongoing activities on the subject was the background for starting this NORDTEST project, which has comprised the following activities:

- To establish a robust **definition** of the moisture buffer property of materials and material systems used in the indoor environment.
- To define and present a **test method** to measure the moisture buffer property according to the definition.
- To carry out a **round robin test** in order to ensure that testing laboratories are able to handle the test methods, and to establish the first reference measurements on a limited number of representative materials and material systems.
- To indicate possibilities for **commercial exploitation** by showing how the moisture buffer capacity term has a relevance for building products used and manufactured in the Nordic countries.
- Most of these efforts should be backed up by **dissemination** activities directed diversely to the academic community, to the industry, and to the general public.

The primary objective of the project has been the development of a NORDTEST method with a test protocol on how materials and systems should be tested for their moisture buffer property. This project delivery can be found as Appendix 1 of this report.

After initiation of the project it appeared that a Japanese standard (JIS A 1470-1) had been published recently on a related topic: *Test method of adsorption/desorption efficiency for building materials to regulate an indoor humidity – Part 1: Response method of humidity*. There are indeed some similarities in the methods – but also some differences. The Japanese Standard is only for building materials, where the NORDTEST project is also for other materials and systems exposed to indoor air.

2 Theory

2.1 Definitions of Moisture Buffer Value and relations to standard properties

2.1.1 Different levels of Moisture Buffering

The moisture buffer performance of a room is the ability of the materials within the room to moderate variations in the relative humidity. These variations can be seasonal or diurnal. Most attention is paid to the moisture buffering of diurnal variations. The moisture buffer phenomena of a room can be described with the scheme of Figure 2-1.

Moisture Buffer Performance

Room level

> Moisture buffering in the entire room related to**,** among other things, **exposure areas** of the surface **materials present**, **moisture load**, **ventilation rate** and **indoor climate**.

Moisture Buffer Capacity

System level

> **Practical Moisture Buffer Value, $MBV_{practical}$**

Moisture Effusivity, b_m	**Ideal Moisture Buffer Value, MBV_{ideal}**

Material level

Material Properties for stationary conditions

Density	Porosity	Water vapor permeability	Sorption properties	etc. …

Figure 2-1. Definition scheme for the moisture buffer phenomena in the indoor environment divided into three descriptive levels – material level, system level and room level. On the material level the quantities are determined with negligible influence from the surrounding climate, e.g. boundary air layers. The system level includes material combinations where the simplest form of a material combination is a homogeneous material with the convective boundary air layer normally present in indoor environments. Systems may also comprise composite products. The room level includes the building and furnishing materials exposed to the indoor air as well as moisture loads, ventilation rate, indoor climate and other factors influencing the moisture buffering in the room.

The moisture buffer performance depends on the moisture buffer capacities of each material combination and furniture in the room together with the moisture production and air change rate and ratio between the material surface area and the air volume. The simplest material combination is a homogenous material with a thin layer of stagnant air. The thickness of the boundary air layer will be determined by the air velocity in the room.

On the next level, the system level, the moisture buffer value, which is the subject for this test proposal, depends on the air velocity, area, and thickness of the sample.

In order to have both a theoretical and more physical definition, as well as a simple and easily understandable method for categorization, a twofold description of the moisture buffer capacity has been chosen: A theoretical and a practical.

2.1.2 Moisture effusivity: b_m

The theoretical description of moisture buffer capacity on the material level is based on the heat-moisture transfer analogy. Well known from heat transport theory is the thermal effusivity, b which expresses the rate of heat transfer over the surface of a material when the surface temperature changes. The thermal effusivity is defined as the square root of the product of material density, ρ, specific heat capacity, c_p, and thermal conductivity, λ. By introducing the moisture effusivity, b_m [kg/(m²Pa·s$^{1/2}$)], Equation (1) in a similar way to the definition of thermal effusivity, we can describe the ability of a material to absorb or release moisture.

$$b_m = \sqrt{\frac{\delta_p \cdot \rho_0 \cdot \frac{\partial u}{\partial \varphi}}{p_s}} \tag{1}$$

where δ_p [kg/(m·s·Pa)] is the water vapour permeability, ρ_0 [kg/m³] dry density of the material, u [kg/kg] moisture content, φ [-] relative humidity, and p_s [Pa] saturation vapour pressure. Apart from p_s, which is given by the test conditions, the other parameters in the definition of b_m are all standard material properties.

The moisture effusivity constitutes one theoretical possibility to express the rate of moisture absorbed by a particular material (i.e. as a material property) when it is subjected to a sudden increase in surface humidity. The use of this quantity could be extended to cases where the humidity increase takes place in the surrounding air, if the convective mass transfer coefficient tends to infinity. In such an *ideal* case the boundary layer in air presents no resistance to the moisture exchange.

2.1.3 Ideal Moisture Buffer Value

From the heat transport theory it is known also how to handle surface transport phenomena in cases not only when the surface temperature suddenly jumps from one level to another, but also when it varies according to a sine function (harmonic variations). Furthermore, by using Fourier analysis, these results can be transformed into cases with other functional forms of the time variation of the surface conditions.

One such functional form is the signal function, which is a steadily repeating function with a high level of the surface condition for one duration of time, and a low surface condition for another period of time. Of interest for this project is a signal function of humidity where the

high humidity is maintained for 8 hours, and the low humidity lasts for 16 hours. This function is illustrated in Appendix 3 (in its Figure 3-2). Fourier analysis makes it possible to predict the surface moisture flux vs. time, $g(t)$, for such a exposure. The accumulated moisture uptake $G(t)$ [kg/m^2], respectively moisture release, that both happen within the time period t_p is found by integrating the moisture flux over the surface $g(t)$ as in Equation (2):

$$G(t) = \int_0^t g(t)dt = b_m \cdot \Delta p \cdot h(\alpha) \sqrt{\frac{t_p}{\pi}} \tag{2}$$

where

$$h(\alpha) = \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{\sin^2(n\pi\alpha)}{n^{3/2}} \approx 2.252 \left[\alpha(1-\alpha)\right]^{0.535} \tag{3}$$

α [-] is the fraction of the time period where the humidity level is high. For the 8/16 hrs scheme, α=1/3, which makes $h(\alpha)$=1.007 and the accumulated moisture uptake can be expressed in a simpler form:

$$G(t) \approx 0.568 \cdot b_m \cdot \Delta p \sqrt{t_p} \tag{4}$$

The moisture uptake within 8 hours corresponds to the moisture release during 16 hours.

We define a Moisture Buffer Value as a characteristic of the material based on this moisture uptake/release. The Moisture Buffer Value is expressed based on the moisture exchange from Equation (4) normalized with the change in surface relative humidity, ΔRH, and we abbreviate it as MBV. The MBV is proportional to the moisture effusivity b_m times the square root of the time period, $t_p^{1/2}$ [s$^{1/2}$]. The thus defined theoretical, or *ideal*, value of MBV is given by Equation (5), which is derived from Equation (4).

$$MBV_{ideal} \approx \frac{G(t)}{\Delta RH} = 0.00568 \cdot p_s \cdot b_m \cdot \sqrt{t_p} \tag{5}$$

The moisture effusivity is theoretically based on material properties which are determined under steady state and equilibrium conditions. However, the buffer property represents a dynamic characteristic. There *may* be some discrepancy between the basic material properties depending on whether they have been determined under steady state or dynamic conditions, and this may have some influence on the determination of the moisture buffer value.

Since the ideal experimental conditions rarely exist, and therefore Equation (5) is only an approximation, a calculation tool, *MoistBuff*, has been developed that simulates numerically the same type of experiment as used for determination of Moisture Buffer Value using the same stationary material properties as for the calculation of moisture effusivity. Further information on the background and theoretical approach to *MoistBuff* is given in the *MoistBuff* manual, Appendix 2.

The ideal moisture buffer capacity is based on the assumption that the materials studied have a thickness that exceeds the penetration depth of that material or material combination.

According to Equations (4) and (5) the hygroscopic moisture absorption follows the square root of time, so it may seem obvious to treat it like a liquid water uptake test where the absorbed moisture is presented versus square root of time elapsed. The slope of the moisture uptake vs. square root of time is the water absorption coefficient, and likewise, one could define a hygroscopic moisture absorption coefficient. However, the possibility will not be pursued further since the method requires that the initial moisture content of the material is uniform throughout, which is not the case when the exposure varies in a cyclic mode.

2.1.4   Practical Moisture Buffer Value

For practical categorization of materials the Moisture Buffer Value based on an experimental method can be used. The determination of a practical Moisture Buffer Value should involve a run time which corresponds to that of typical exposure in practice – typically a daily variation. Likewise, it should be useful for the material thickness, surface mass transfer conditions and surface coatings normally used in practice.

> The practical Moisture Buffer Value ($MBV_{practical}$) indicates the amount of water that is transported in or out of a material per open surface area, during a certain period of time, when it is subjected to variations in relative humidity of the surrounding air. When the moisture exchange during the period is reported per open surface area and per % RH variation, the result is the $MBV_{practical}$. The unit for $MBV_{practical}$ is $kg/(m^2 \cdot \% RH)$.

The concept of the practical moisture buffer value can easily be appreciated and understood from an experimental standpoint, and likewise, it is relatively straightforward to measure.

The practical Moisture Buffer Value is determined in an experimental set up where the sample is exposed to cyclic step-changes in RH between high and low values for 8 and 16 hours respectively. For example the normal case will be a periodical exposure of 8 h at 75% RH and 16 h at 33%, the size of the RH-interval will then be 42% RH. This kind of measurement sequence is shown in Figure 2-2.

The value is a direct measure of the amount of moisture transported to and from a material when the exposure is given. The value is mainly, but not only a property of the material. Also the mass transfer coefficient at the boundary plays a role, and thus, the moisture buffer value becomes a true material property only in the limit of the convective mass transfer coefficient tending to infinity. For many materials the internal resistance to moisture transport is considerably large than the convective surface resistance.

Furthermore, the practical and the ideal moisture buffer value will only be similar if the material is homogenous and its thickness is equal or exceeding to the penetration depth of the material (see Section 2.2)

Indeed, the practical Moisture Buffer Value can be determined also for systems that comprise combinations of different material layers, e.g. for materials with a surface coating, and for materials that are thinner than the penetration depth. Only, the direct comparison with a theoretical buffer value is no longer possible.
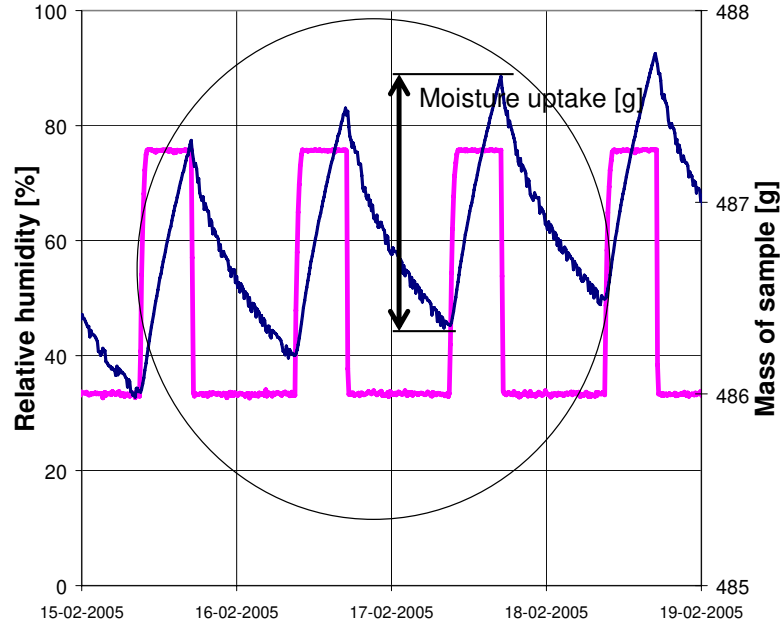
Figure 2-2: Determination of MBV$_{practical}$ from dynamic measurements. Definition of quasi-steady state (the 3 cycles inside the ellipse) and the moisture uptake and release. Also RH for the cyclic steps is given. The rising tendency of the mass is due to the initial conditions that have been lower than the average of the quasi steady state conditions that will arise after some cycles.

2.2 Penetration depth

This section presents a simplified method to calculate the moisture penetration depth in a porous material which is subjected to a periodic relative humidity variation at its surface. However, since the involved moisture transport properties may be highly non-linear, i.e. not being constants, a more comprehensive analysis is found in Appendix 3. The method given below assumes sinusoidal variation, while the present NORDTEST method applies for a stepwise changing exposure. Therefore, the simple method to determine moisture penetration depth can only be seen as an approximation.

If we assume sinusoidal variation of the moisture content *u* on the material surface, with an amplitude Δu_s, the amplitude at a certain depth *x* in the material Δu_x, is given by

$$\frac{\Delta u_x}{\Delta u_s} = e^{-x\sqrt{\frac{\pi}{D_w t_p}}} \tag{6}$$

Where D_w is the moisture diffusivity of the material:

$$D_w = \frac{\delta_p \, p_s}{\rho \, \xi_u} = \frac{\delta_v \, v_s}{\xi_w} \tag{7}$$

The penetration depth, is the depth where the amplitude of moisture content variations is only 1% of the variation on the material surface. $d_{p,1\%}$ is then given by

$$d_{p,1\%} = 4.61\sqrt{\frac{D_w t_p}{\pi}}$$

(8)

The method is strictly valid only for a semi-infinite (or "very thick") material. In Appendix 3, the theory to determine the undisturbed moisture level is given in detail, and a calculation method to determine the penetration depth is presented.

2.3 Surface coefficients

In the previous determination of penetration depth, the periodic changes were supposed to take place on the material surface. But in reality, the changes happen in the ambient air and a surface resistance to moisture transfer exists which slows down the moisture exchange. In the following, a way is given to determine the magnitude of the surface transfer coefficient as a function of the air velocity. As mentioned in Section 2.1.2, the correlation between the theoretical moisture effusivity and the measured MBV can be found only when the convective mass transfer coefficient tends to infinity – the ideal situation.

When water vapour is transmitted from within a material to the ambient, the primary resistance to this flow is quite often within the material itself, $Z_{p,m}$. However, there is also a relatively small resistance, $Z_{p,s}$, related to the convective moisture flow over the surfaces of the material.

The convective surface coefficient for moisture transfer should be $\beta_p = 2.0 \cdot 10^{-8}$ kg·m^2·s/Pa ($\beta_v = 2.7 \cdot 10^{-3}$ s/m). This corresponds to a convective surface resistance for moisture transfer of $Z_{s,p} = 5.0 \cdot 10^{7}$ Pa/(kg·m^2·s) ($Z_{s,v} = 370$ m/s). These are normal values for environments with an ambient air velocity around 0.1 m/s. Deviations up to ±25% of the specified quantities can be accepted.

Appendix 4 presents some procedures according to which the convective surface coefficient/ resistance can be estimated based on the influence from free and forced air flows over the surface.

The influence of the surface resistance on the moisture transfer depends on the resistance of material itself. This influence and significance can be evaluated by using the so called moisture Biot-number which gives the relation between the transfer resistance inside and at the surface of a body. The definition and use of moisture Biot-number is also found in Appendix 4.

3 Round Robin tests

A Round Robin Test was carried out within the project to try the test method and to obtain some initial results for typical building materials. In addition, and to guide the formulation of the test protocol, a preliminary test was carried out on some spruce plywood boards that were distributed to all project partners. The materials tested and the institutions participating in the Round Robin tests are listed in Table 3-1. Each material is tested by three partners.

Table 3-1. Materials tested in the Round Robin, and indication of institutions performing the tests.

Material/Product	DTU	VTT	LTH	NBI
Spruce Plywood (pre-test)	x	XX	x	x
Spruce boards from *Woodfocus*, FIN	x	XX		x
Concrete from *Betonelementforeningen*, DK	XX		x	x
Gypsum from *Gyproc*, S		x	XX	x
Laminated Wood from *Annebergs Limtræ*, DK	XX	x		x
Light weight aggregate concrete from *maxit*, DK	XX		x	x
Cellular concrete from *H+H Celcon*, DK	XX	x	x	
Brick from *Kalk- og Teglværksforeningen*, DK	XX	x	x	
Birch wood panels from *Tresenteret*, N		x	x	XX

XX - country responsible for supplying the material

More detailed information on the tested materials and the samples are found in Figure 3-1 and Table 3-2. In addition, some of the experimental conditions in the involved laboratories are found in Table 3-3.

Spruce boards   Concrete
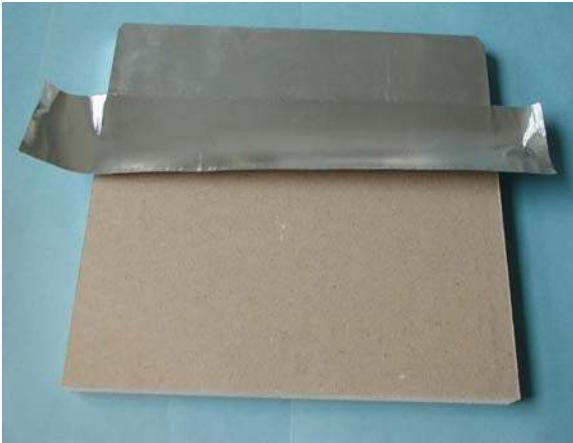
Gypsum boards (from rear)

Laminated wood with varnish

Light weight aggregate concrete with stucco

Aerated cellular concrete

Brick

Birch panels

Figure 3-1: Examples of tested material samples with their sealing.

Table 3-2: The tested sample sizes and their exposed area, thickness and information about if the exposure was one or two sided.

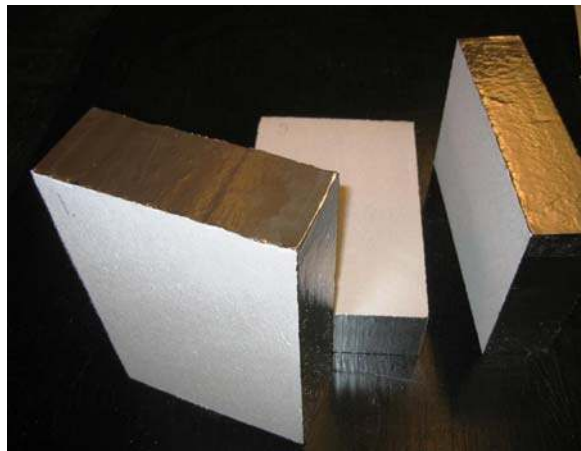| Material/ Product		Sample size [mm]	Exposed area [m^2]	Thickness [mm]	1- or 2-sided exposure
Spruce Plywood	ALL				
Spruce boards	DTU	250 x 349	0.087	14	1
	VTT	250 x 250	0.063	15	1
	NBI	222x293, 226x298, 223x295	0.066	14	1
Concrete	DTU	350 x 100	0.035	25	1
	LTH	173 x 100	0.016	26	1
	NBI	60 x 100	0.006	27	1
Gypsum	VTT	250 x 250	0.063	13	1
	LTH	201 x 202	0.038	12.5	1
	NBI	200 x 200	0.040	13	1
Laminated Wood	DTU	250 x 250	0.063	15	1
	VTT	250 x 250	0.063	65	1
	NBI	199x250, 198x251, 197x250	0.050	15	1
Light weight aggregate concrete	DTU	200 x 200	0.040	42	1
	LTH	200 x 201	0.035	42	1
	NBI	101x101, 100x101, 100x101	0.010	26	1
Cellular concrete	DTU	298 x 198	0.059	74	2
	VTT	198x302, 201x298, 198 x 295	0.060	74	1
	LTH	147 x 148	0.020	75	1
Brick	DTU	56 x 228	0.013	110	2
	VTT	56 x 226	0.013	110	1
	LTH	56 x 229, 109 x 229	0.011, 0.022	109, 56	1
Birch panels	VTT	95 x 350	0.033	15	1
	LTH	95 x 174	0.017	15	1
	NBI	95 x 250	0.024	15	1

Table 3-3: Some of the experimental conditions

	Sealing method	Temperature	air velocity
DTU	Alu-tape	23ºC	0.05 – 0.1 m/s
VTT	Alu-tape	22ºC	0.6 ± 0.3 m/s
LTH	Alu-tape	23ºC	0.5 – 0.59 m/s
NBI	Alu-tape	22ºC	0.1 – 0.3 m/s

3.1 Experimental setups

The purpose of the Round Robin Test was to see if it were possible to obtain similar and agreeable results of Moisture Buffer Value testing of all participating institutes. This was particularly relevant since the institutions did not have quite the same experimental equipment available. Also some of the experimental routines could differ somewhat, even though they were largely in accordance with the the test protocol that was under development. E.g., some institutes made manual weighing of the specimen, while it for others took place by automated logging of a balance.

3.1.1 Technical University of Denmark (DTU)

Figure 3-2 shows a drawing and photograph of one of the climatic chambers used at DTU. The humidity control of the chamber works by supplying it with either humid or dry air in an intermittent mode, such that the desired humidity in the chamber is achieved. In the beginning of the test series the switch in the chamber RH was done manually, but in the end this was done automatically. A single sample was measured at one time: it was attached to a hook connected to a balance, and the weight change of the sample was measured continuously. The samples were pre-conditioned at 50 %RH before the measurement series with step changes between 33 and 75 %RH.
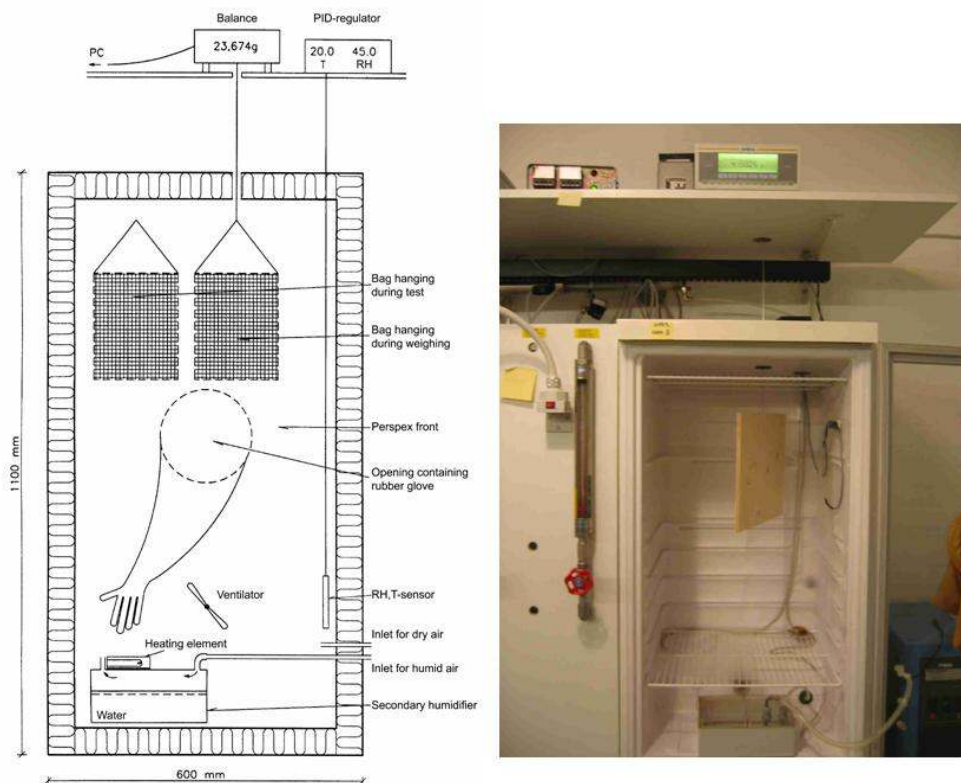

Figure 3-2: Drawing and picture of one of the climatic chambers used at DTU.

3.1.2 Technical Research Centre of Finland (VTT)

The experimental set-up at VTT consists of three small connected chambers designed particularly for this test purpose. The sample to be tested is placed in the middle chamber on a balance, which registers the weight change of the sample continuously. The RH of the two other chambers is maintained by saturated salt solutions, at 33 %RH and 75 %RH, respectively. The wall to the middle chamber is opened automatically in turns to expose the sample to the high and low RH according to the 8/16 hours scheme.

Figure 3-3:   *The experimental set-up at VTT. The sample is placed in the middle chamber and the low and high RHs are on each side.*

3.1.3   Lund University, Sweden (LTH)

The experimental set-up at LTH consists of two small climatic boxes both equipped with a cross-flow fan in the lid to accomplish mixing of the air inside the boxes. The relative humidity inside the boxes is generated through saturated salt solutions placed in a wide pan on the floor of the boxes, one box with NaCl (75% RH) and one box with $MgCl_2$ (33%). Over the pan a plastic lattice is placed to support the samples. The samples are placed in the appropriate box according to the 8/16 hour measurement schedule proposed in the method. The gravimetrical determination of the moisture absorption/desorption is made outside the climatic boxes on a balance with 0.01 g readability. The complete experimental set-up is placed in a climatic chamber with both temperature and relative humidity control.
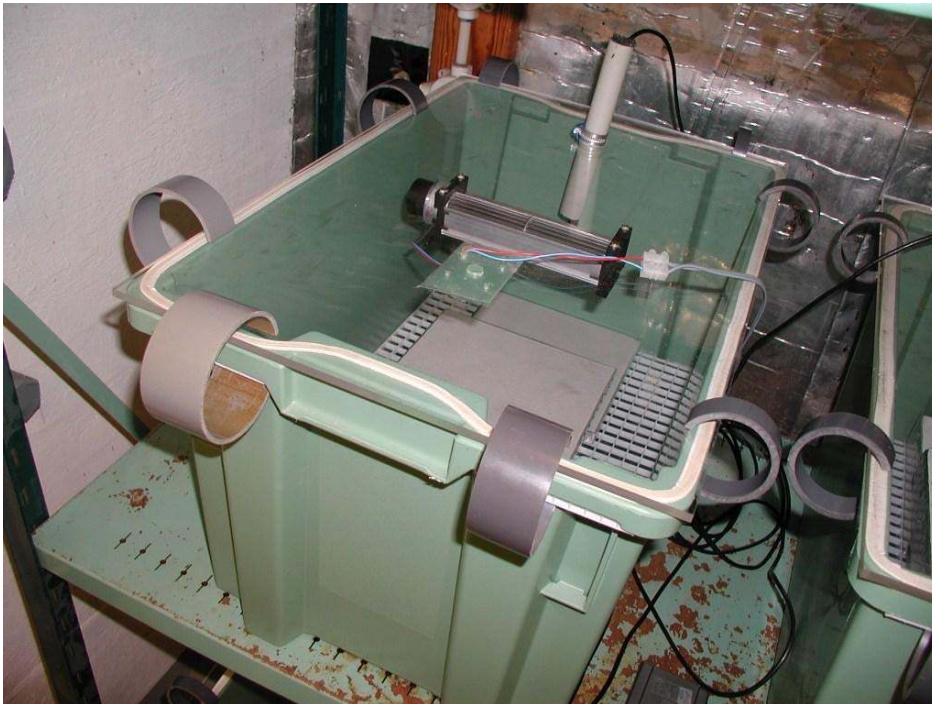

Figure 3-4: The experimental set-up at LTH.

3.1.4   The Norwegian Building Research Institute (NBI)

The climatic laboratory at NBI consists of 2 rooms of 17.56m^3: 2,4 x 3,05 x 2,4m. The temperature and relative humidity of the rooms can be controlled individually in the range +4 - +30° C (± 1° C) and 30 – 90 % RH (± 2 %RH). The air velocity is measured to be in the range 0,1 – 0,3 m/s. The samples are moved from one chamber with low RH to another with high RH according to the 8/16 hours scheme and weighed manually in the end of every RH level. For the final cycle the samples are weighed 5 times during the 8 hour wetting period.

Figure 3-5: The interior of one of the climatic rooms at NBI.

3.2   Initial Round Robin results with the spruce plywood

Before the actual Round Robin was executed, an initial round with a single material, spruce plywood, was tested by all the laboratories. The tests are not described here in detail, only the results are given in Figure 3-6 and Table 3-4.

University of Saskatoon also participated in this initial testing to give some comparison from an institution which did not participate in the project as such (Osanyintola et al., 2005).

The experience from this initial test was:
- Each laboratory had good agreement between their specimens, and the spread between the laboratories was not satisfactory. Reasons for deviations could be the initial conditioning or the first cycle starting either high or low.
- The time periods were not exactly like they should be (8/16 h) for everyone and that affects MBV$_{practical}$, but for the actual measurements there was corrected for the time.

- It is essential for compilation of the results that there is a uniform way of reporting the results from each laboratory, why a result template was created.

Table 3-4: Mean values for MBV$_{practical}$ for all cycles and all laboratories.

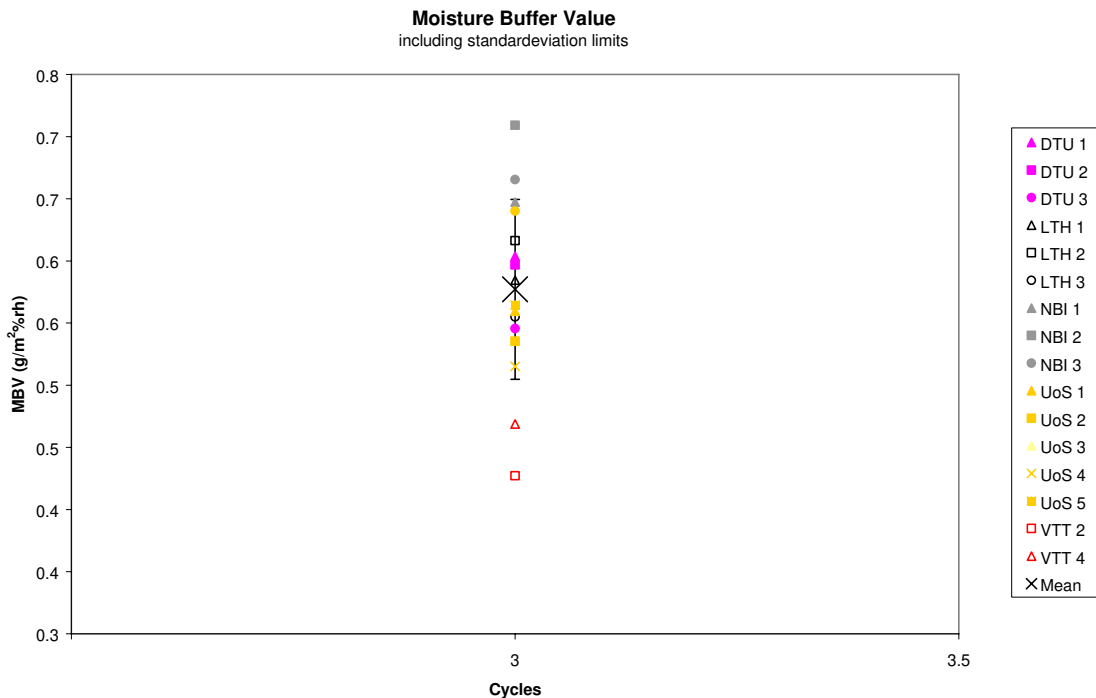|	DTU	LTH	NBI	UoS	VTT	Mean value
Mean of cycles (g/m^2%RH)	0.58	0.59	0.67	0.57	0.45	0.58
Stdv for cycle mean	0.03	0.03	0.03	0.06	-	0.07

Figure 3-6: The Moisture Buffer Value for the last of three quasi steady cycles and the overall mean value including a standard deviation bar for the overall mean value.

3.3 Measurement results for the Round Robin

Figure 3-7 shows an example of the measured weight change response of one of the specimens when it was subjected to cycles that varied the ambient humidity between 33% and 75 % RH for 16 and 8 hrs respectively. The choice of stable cycles and the moisture uptake is marked in the figure. A minimum of three stable cycles had to be carried out, and the weight amplitude must not vary by more than 5% from day to day. The stable cycles are also characterized by the fact that the daily amounts of moisture uptake and release are approaching each other as shown in Figure 3-8. The mass change is normalized as mass change ($m_{8\ hours}$-m_0) per m^2 and per ΔRH to give the practical MBV.

Figure 3-8 shows for three different specimens of the same type of material how the moisture uptake and moisture release varied from cycle to cycle until the three stable cycles were attained. Thus the results of measurements of one type of material give the following

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background for statistical analysis: Three specimens with results from three cycles of both moisture uptake and release - altogether 3x3x2 = 18 bids for the $MBV_{practical}$ result. The results are here represented with their mean value and standard deviation.
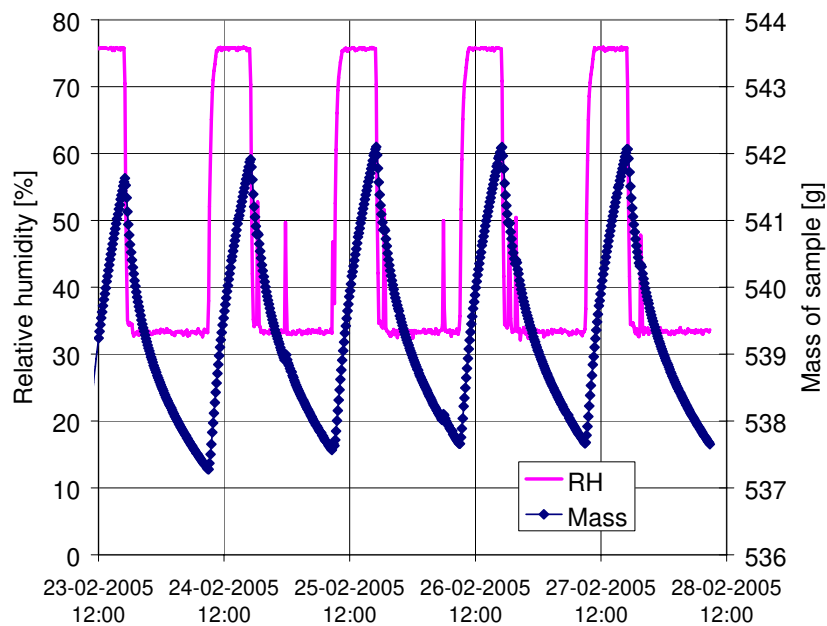
Figure 3-7:   Moisture uptake and release cycles for a sample. Exposure between 33 and 75% RH.
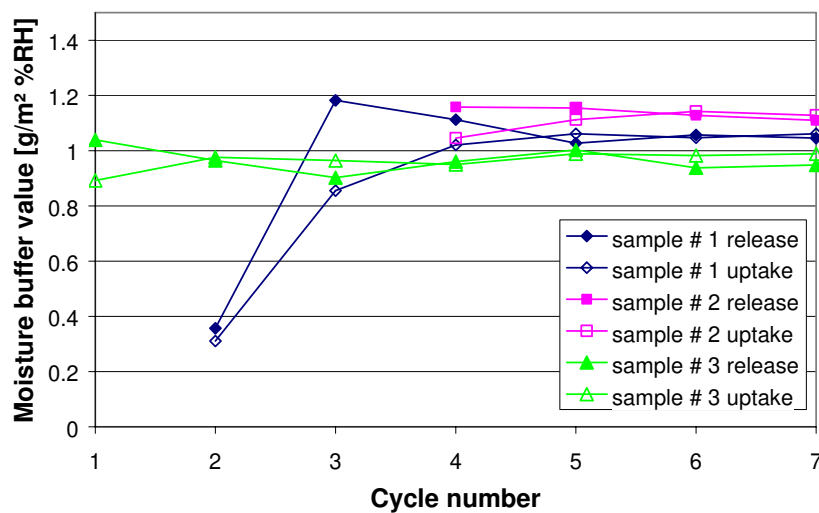
Figure 3-8: $MBV_{practical}$ of one material as a function of cycle number and uptake versus release. The last 3 cycles are the stable cycles (=quasi-steady)

Figure 3-9 shows the $MBV_{practical}$ for all the materials tested by the participating institutions. The bar diagrams indicate for each material and testing laboratory the average of the MBV-value and its standard deviation for the tested 3 samples. It seems that the order of magnitude for the tested materials is around 1 g/(m^2·%RH), and there may be approximately a factor 3 of a difference between the materials with the highest and lowest $MBV_{practical}$ among those tested. All the measurements are averaged in Figure 3-10 to give an overall picture of the materials tested.
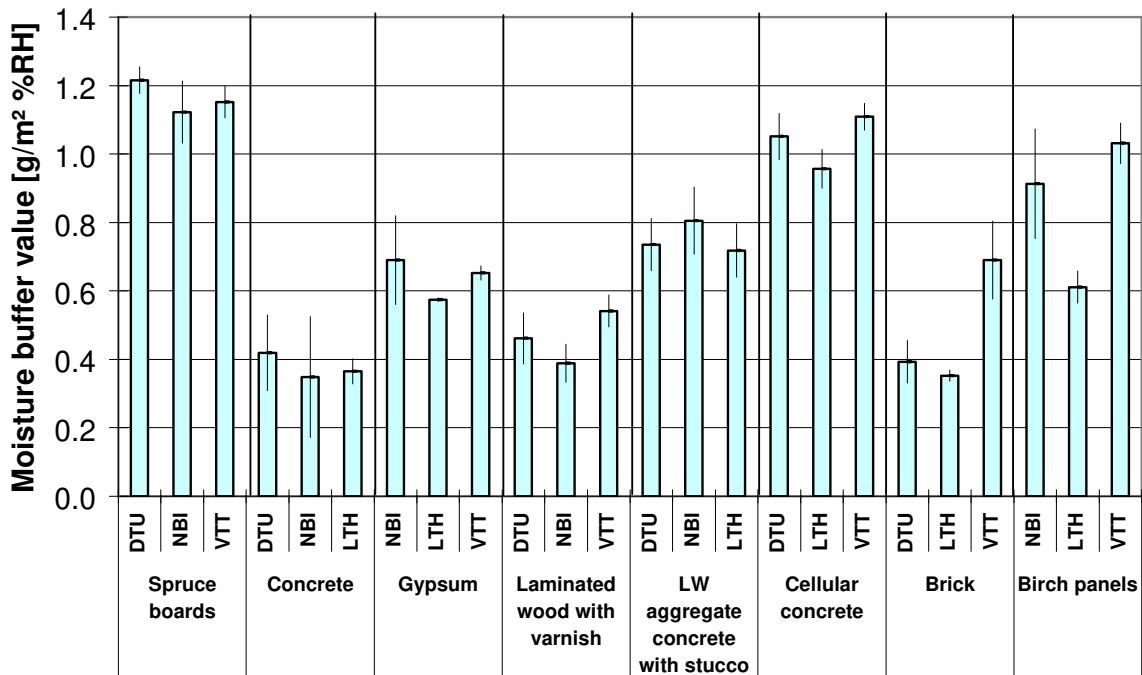
Figure 3-9: *Moisture Buffer Values (MBV$_{practical}$) found by different institutions for the different materials. Each bar indicates the average of three specimens over three stable cycles. The thin vertical line-bars indicate standard deviations.*

Figure 3-10: The Moisture Buffer Values (MBV$_{practical}$) as an average value for all the measurements: 3 laboratories, 3 samples, 3 stable cycles and both wetting and drying. The thin vertical line-bars indicate standard deviations.

Table 3-5: *Moisture Buffer Value (MBV$_{practical}$) for all the materials and every laboratory separately. The average value covers all 3 samples, 3 stable cycles and both moisture uptake and release for each material. Standard deviation is calculated for the same data.*

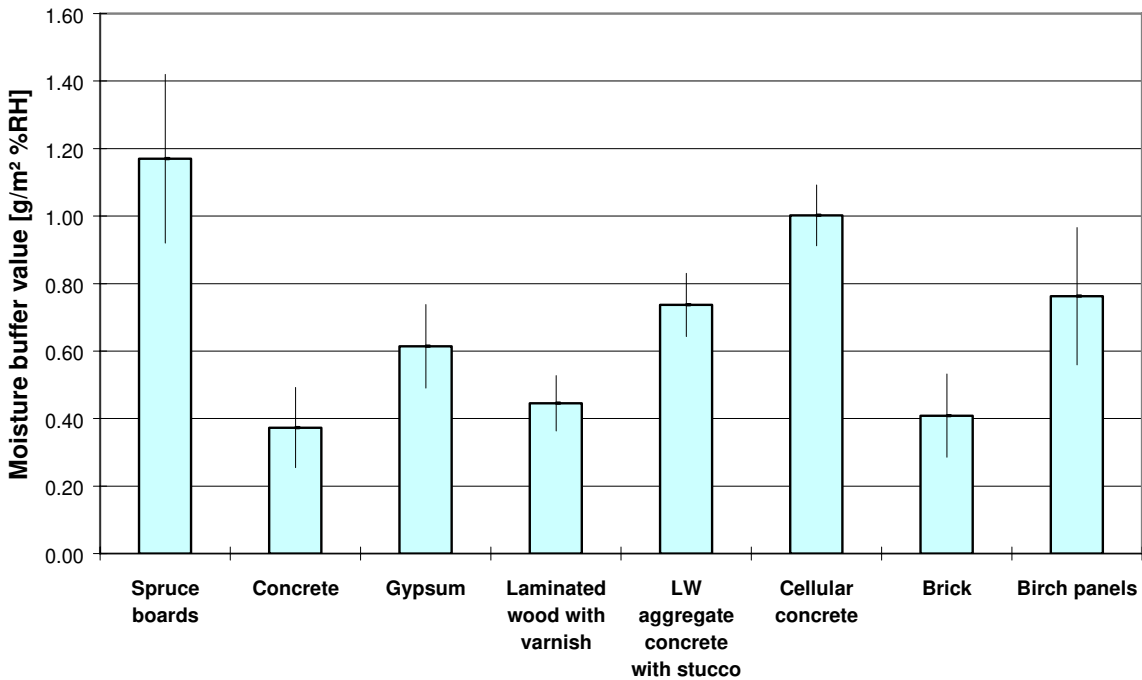|	LABORATORY	MBV$_{practical}$ [g/(m² %RH)]		
		AVERAGE	STANDARD DEVIATION	%-DEVIATION
Spruce boards	DTU	1.22	0.04	3
	NBI	1.12	0.09	8
	VTT	1.15	0.05	4
Concrete	DTU	0.42	0.11	26
	NBI	0.35	0.18	51
	LTH	0.37	0.04	10
Gypsum	NBI	0.69	0.13	19
	LTH	0.57	0.01	1
	VTT	0.65	0.02	3
Laminated wood with varnish	DTU	0.46	0.07	16
	NBI	0.39	0.06	14
	VTT	0.54	0.05	9
LW aggregate concrete with stucco	DTU	0.74	0.08	10
	NBI	0.81	0.10	12
	LTH	0.72	0.08	11
Cellular concrete	DTU	1.05	0.07	6
	LTH	0.96	0.06	6
	VTT	1.11	0.04	4
Brick	DTU	0.39	0.06	16
	LTH	0.35	0.02	5
	VTT	0.69	0.11	17
Birch panels	NBI	0.91	0.16	18
	LTH	0.61	0.05	8
	VTT	1.03	0.06	6

3.4 Discussion of the Round Robin results

The overall conclusion on the results of the Round Robin was encouraging: The determination of the practical Moisture Buffer Value with four very different laboratory equipments gave results that are comparable with each other. Also, consistent differences between the ability of different materials to buffer variations in RH of the ambient air were found: Materials like untreated spruce and birch boards and cellular concrete performed as best buffers while materials like brick and concrete were able to buffer under the half of the best buffers (Figure 3-10).

All samples were sealed on all but one or two sides with aluminium tape. Differences cannot therefore be explained with the sealing methods. But the thickness of the samples may be one of the most important parameters. An example is brick, which has a total thickness in the transport direction of 110 mm: Some institutions had a two-sided exposure of this material, while others used a single exposure. The double-sided exposure reduces the effective material thickness to only half of its value if it were single-sided. If this value is compared with a theoretically determined penetration depth, Equation (8), for a 1% criterion for periodic

variation, see Table 3-6, it is obvious that the effective thickness for double-sided exposure of brick is not enough. When studying other materials, most of them fulfil the criterion of penetration depth. Problematic samples were gypsum (the product is not thicker) and cellular concrete measured at DTU. However, the effect of thickness could not be seen for cellular concrete on the measured $MBV_{practical}$.

Temperature level under the tests was very uniform for all cases. Therefore no temperature effects were seen in this Round Robin.

Uncertainty is an unavoidable part of experimental work, but if using statistical analysis tools the quality of measurement results can be improved. In experimental methods, like the one proposed in this project, with a small number of specimens the determination of outliers is crucial. One effective statistical tool is the modified Dixon Q parameter test (Rorabacher, 1991) that can be used to determine if a grossly deviant measurement value is an outlier or not.

Table 3-6: *Calculated penetration depth compared with the thicknesses (for one sided exposure) used for the tests. The calculated values are based on literature material parameters and may therefore not be quite correct for the actual materials. Minimum thickness is the thinnest effective thickness used in this Round Robin. Values for LW aggregate concrete are for the stucco.*

Material/Product	Density	Water vapour permeability	Moisture capacity	D_w	d_p 1% for 24h	Minimum thickness
	kg/m³	10^{-9} kg/(Pa·m·s)	kg/kg	m²/s	mm	mm
Spruce boards	430	0.015	0.1905	$4.3 \cdot 10^{-10}$	16	15
Concrete	2250	0.005	0.0950	$5.5 \cdot 10^{-11}$	6	25
Gypsum	1000	0.025	0.0310	$1.9 \cdot 10^{-9}$	33	13
Laminated Wood	430	0.015	0.1905	$4.3 \cdot 10^{-10}$	16	15
Light weight aggregate concrete	1500	0.01	0.0950	$1.6 \cdot 10^{-10}$	10	26
Cellular concrete	500	0.07	0.0714	$4.6 \cdot 10^{-9}$	52	37
Brick	1600	0.03	0.0024	$1.8 \cdot 10^{-8}$	104	55
Birch panels	600	0.015	0.1667	$3.5 \cdot 10^{-10}$	14	15

4 Application issues

The purpose of this section is to demonstrate some practical use of the Moisture Buffer Value, e.g. when the impact of moisture buffering of building materials and systems is compared to other influences on the moisture balance of the indoor environment.

4.1   Moisture buffering performance of a room

4.1.1   The moisture balance of a room

There are different types of moisture variations in the indoor environment with different time periods. Seasonal variations represent a long (yearly) time period, and shorter periods of daily or hourly duration occur mostly due to occupancy, activity and diurnal variations in the outdoor climate. This test method's main focus is the short moisture variations.

The variations with time for the moisture conditions of a room, dv_i/dt [kg/(m^3 s)] , can be expressed by the following room moisture balance presented in Equation (9) (Svennberg, 2003).

$$\frac{dv_i}{dt} = \frac{G_{ms} - \sum_{j=1}^{n} g_{mbj} A_{sj} - q(v_i - v_e) - \beta_v (v_i - v_{ss}) A_c}{V} \qquad (9)$$

Where

A_c	Area of condensation	m^2
A_{sj}	Area of the surface material j	m^2
g_m	Sorbed moisture flux for material j	kg/(m^{2}s)
G	Moisture supply	kg/s
q	Ventilation rate	m^3/s
v_e	Exterior vapour content	kg/m^3
v_i	Interior vapour content	kg/m^3
v_s	Saturation vapour content	kg/m^3
v_{ss}	Saturation vapour content at the surface	kg/m^3
V	Volume of the room	m^3
β_v	Surface moisture transfer coefficient	m/s

From Equation (9) the conclusion can be drawn that knowledge about the moisture buffer capacity for a material or a set of materials is a necessary but not sufficient information to estimate the moisture buffer performance in a room or a building. Important factors that influence the moisture balance in a room are exposure area of the surface materials, the ventilation rate, vapour content of the indoor and outdoor air, the surface temperature and the surface moisture transfer coefficients of the surfaces.

It is also important to keep in mind that moisture buffering will never be able to alter the mean value of the moisture variations (diurnal or seasonal) but only dampen the peaks. To reduce the mean value of the moisture variations, increased ventilation is needed, or some

moisture sources have to be eliminated. The impact of the ventilation depends on the ventilation rate, and the vapour content of the indoor and outdoor air. If the ventilation rate is very high, it will control the RH of indoor air to a very high degree. If on the other hand the ventilation rate is low, the impact of moisture buffering in surface materials will be larger (Christoffersen, 1996). The main purpose of the ventilation is to supply the building and its inhabitants with the sufficient amount of fresh air, remove emissions from activities, people and materials and remove excess moisture, smells and hazardous substances.

4.1.2 Materials in the indoor environment

The materials in the indoor environment are a heterogeneous blend of materials, from heavy concrete used in the building construction to lightweight textiles found in furniture and furnishings. Several of the materials used indoors are polymers like wood, cotton and paper. The indoor materials often have a surface coating applied for aesthetical and cleaning reasons.

Field inventories have investigated which are the most prevalent materials found in Swedish dwellings and offices. See Figure 4-1 and Figure 4-2.
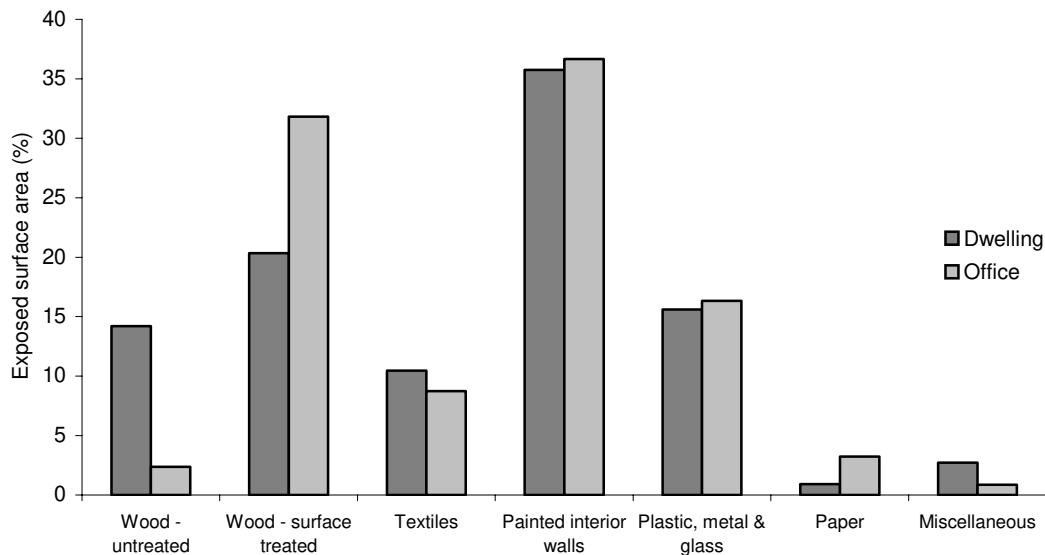

Figure 4-1   The exposed areas of different surface materials in a dwelling compared with an office (Berggren and Skoog, 2003).
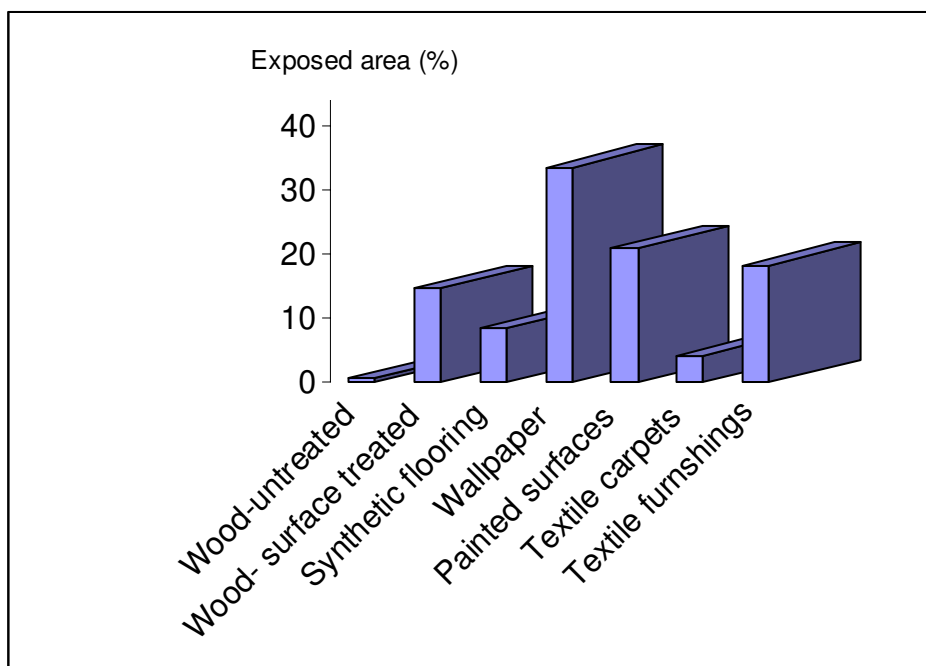
Figure 4-2   Results from "An inventory of surface materials exposed to the indoor air in 16 Swedish normally used rooms in dwellings" (Svennberg, 2005).

Wood and wood based materials are used in building constructions as well as in furniture. The surface coating used on wood can vary from none for a wooden ceiling to a hard varnish on parquet flooring.

Textiles are used in furniture and furnishings such as curtains, carpets and bedding. Compared with most traditional building materials textiles have a more mesh-like structure making them lighter and more permeable. The yarn can be made from a number of fibre types, e.g., wool, cotton, flax, viscose and nylon. The moisture properties of the fibre in combination with weaving technique give each fabric its unique moisture properties. The upholstery of furniture can be done with a variety of materials, e.g., foam plastic, cotton, down, wool, straw and horsehair. Textiles in furniture and furnishing are highly represented in the indoor environment and as they to some extent cover some more traditional materials, they play an important role in regulating the moisture variations of indoor air - especially for short time scales.

The paper found in the indoor environment can be of different types. Books, newspapers and magazines are one major part of the paper in the indoor environment exposed to the indoor air. Also wallpaper made from paper another, even if they usually have an additional surface coating such as paint or vinyl film. The manners the paper products are stored or exposed to indoor air will influence the impact of the moisture buffering from them.

Gypsum board in the indoor environment is used for interior walls and ceilings. Usually a surface coating of wallpaper or paint is used.

Concrete and various types of aerated and light-weight concrete is used for walls, floors and ceilings. The walls are usually surface coated in the same way as gypsum board and concrete ceilings are mostly painted. On concrete floors a layer of screed is usually applied, and after that a flooring material for example PVC-flooring, laminate flooring or ceramic tiles. Most

concrete is therefore not immediately exposed to the indoor air.

The composition of plasters and mortars can vary from lime mortar to cement mortar. Also gypsum based plasters are used for indoor purposes, especially in central and southern parts of Europe. Renderings of this type may play an important role as moisture buffers.

Surface coatings are often based on polymers, e.g., latex paint, wax and plastic films. In the indoor environment, surface coatings vary from sparse oil treatments to thick and almost impermeable enamel paints. The surface resistance of a surface coating is dependent on the material used and the application. If there is a "heavy" surface coating on the top surfaces of furniture, e.g., a wooden table, usually the side underneath will be untreated.

4.2 Moisture Buffer Value versus moisture production and ventilation rates

Moisture buffering of building materials may alleviate the high peaks of moisture concentration seen in indoor environments if there is a high intermittent moisture load. Likewise, moisture buffering may diminish peaks of low humidity. But these effects should be compared to other effects that can help to moderate the moisture excursions in indoor environments – mainly by ventilation and moisture production. This subsection has as a purpose to illustrate some possible relative importance of the phenomena.

4.2.1 Moisture Buffer Value, $MBV_{practical}$

The practical Moisture Buffer Value is presented using dimensions $g/(m^2 \% RH)$ @ 8/16h which indicates the change of the mass of moisture in the material per free surface area and the step change of relative humidity during 8/16 hour wetting/drying cycle. But it does not take into account other parameters that might influence the buffer performance, like moisture production and ventilation rates.

When trying to set some classification for the $MBV_{practical}$ values, these figures can be compared to typical moisture production rates and the ventilation of moisture out from the room. This analysis gives a relative approximation of the effect.

4.2.2 Moisture production and ventilation rates

Moisture production of a sleeping person can be approximated to be 30 g/h and in a case where two sleeping persons occupied a bedroom, the total moisture production is 60 g/h during the 8 h night period (Simonson et al. 2001). Based on this analysis, the case study seen in the frame on the next page was done.

A bedroom having 12 m^2 floor area (3 m x 4 m) and 30 m^3 volume and 0.5 1/h air change rate $\Rightarrow$ V_{air} = 4.17 dm^3/s. This 0.5 1/h is the minimum required air change for a living space. Assumption: Only the ceiling (12 m^2) has moisture buffering capacity.

The studied climate conditions are the following:

T_{in} = +23ºC,
T_{out} = +15ºC,
RH_{out} = 60 %,
$p_{v,out}$ = $p_{v,in}$ (min) = 1022 Pa,
RH_{in}(min) = 36.4 %.

A moisture increase in indoor air of +4 g/m^3 (compared to outdoor air) is a typical approximation for the internal loads used in moisture performance analysis of structures of dwellings.

Another approximation for the moisture load is 60 g/h moisture production that corresponds to two sleeping adults (8 hour period). Probably this load is not equal to the +4 g/m^3 indoor moisture increase during the occupation period and under such ventilation, but this approximation of the increase was used in this study.

Using the +4 g/m^3 moisture increase we get following indoor conditions during the occupation cycle:

In the beginning of occupation the indoor humidity corresponds to that in the outdoor air, RH_{in}(min) = 36.4 %. At the end of occupation, the moisture content has increased with 4 g/m^3. This corresponds to partial vapour pressure $p_{v,in}$(max) = 1598 Pa and relative humidity RH_{in}(max) = 56.9 %. Thus the difference of the maximum and minimum relative humidity of the indoor air during the occupation would be ΔRH_{in} = 20.5 %. This can be used as the RH difference causing moisture flow into hygroscopic building materials under constant temperature conditions. This ΔRH_{in} value can thus be used to estimate the possible and required moisture buffering effect and capacity.

Ventilated amount of moisture with 4.17 dm^3/s air flow rate:
q_m = $V_{air} \cdot dm$ = 0.00417*0.004 = $1.67 \cdot 10^{-5}$ kg/s = 60 g/h. This happens to correspond exactly to the moisture load caused by occupation of two sleeping adults.

Using the above solved approximations, we can solve the MBV$_{practical}$ for the ceiling area that corresponds to the ventilation effect or the moisture load of two sleeping persons during an 8 hour occupation period:

Total amount of additional moisture 60 g/h·8 h = 480 g.
Moisture per MBV area: 480 g/12 m^2 = 40 g/m^2

If all the ΔRH_{in} = 20.5 % range was used for buffering (not a valid assumption, when air change and moisture buffering are working together, but it gives an idea of the level of ventilation as a moisture buffering figure), the required MBV$_{practical}$ value would be = 40 g/m^2 / 20.5 %RH = 1.95 g/(m^2 %RH).

4.3 Classification of materials using practical Moisture Buffer Values

When the moisture buffering of material layer causes the same magnitude of average moisture flow rate as what the minimum required air change causes, the buffering effect can be considered to be quite significant for the moisture performance of a room space. It is obvious that the optimum moisture buffering response should be as high and fast as possible, but it has to be compared to the determined $MBV_{practical}$ values for different building materials in order to evaluate the realistic ranges. Most of the Round Robin test materials (measured without surface coating) had moisture buffering capacity in the range of 0.5 - 1.2 $g/(m^2 \% RH)$ @ 8/16h. Thus the $MBV_{practical}$ level 2 $g/(m^2 \% RH)$ @ 8/16h represents a very high efficiency moisture buffering material. On the other hand, if the $MBV_{practical}$ value corresponds to less than 10 % of that of the effect of the ventilation, it has (close to) negligible effect on the whole building performance aspect. Based on these approximations, the $MBV_{practical}$ values can be classified using five different categories. Table 4-1 and Figure 4-3 present the selected limits for the moisture buffering capacity values. These are the first approximations for classification of the moisture buffer performance of building materials and products and they can be adjusted and updated for different applications and with new research results.

Table 4-1 Ranges for practical Moisture Buffer Value classes.

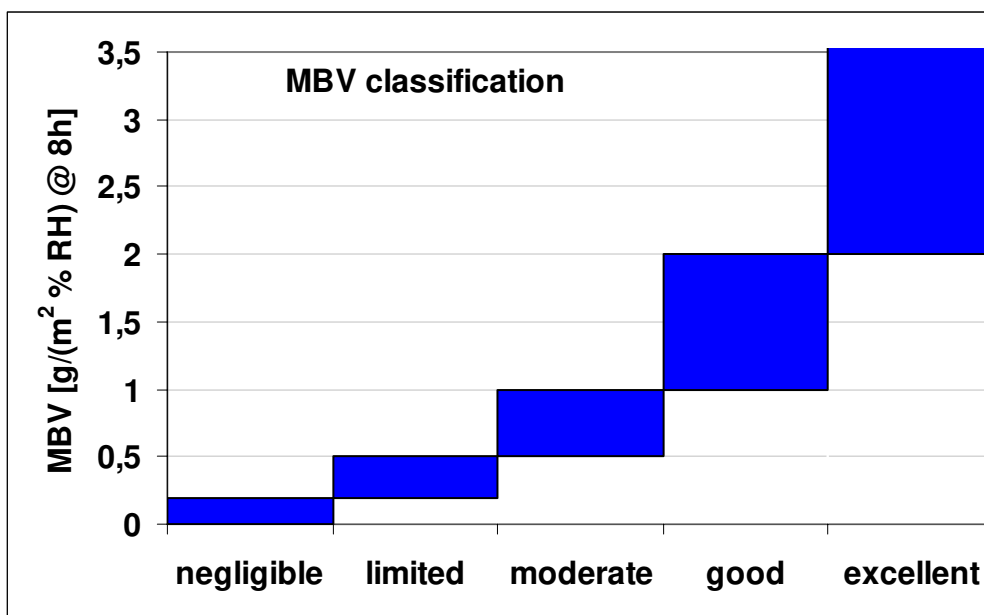| $MBV_{practical}$ class	Minimum MBV level	Maximum MBV level
	$[g/(m^2 \% RH)$ @ 8/16h]	
Negligible	0	0.2
Limited	0.2	0.5
Moderate	0.5	1.0
Good	1.0	2.0
Excellent	2.0	...

Figure 4-3. Graphic presentation about practical Moisture Buffer Value classes

4.4   *Effect of temperature on the MBV$_{practical}$ measurements*

The MBV$_{practical}$ is to be measured at 23°C according to the test protocol. Variation of temperature during the measurement may severely affect the MBV$_{practical}$ measurements. Temperature variations change the test conditions from those under constant temperature conditions. Due to delays in temperature field, there can be varying temperature and partial vapour pressure gradients in and around the test sample. Therefore the actual test conditions are unknown during the dynamic temperature conditions.

By far the moist important effect of temperature is the increase of saturation vapour pressure with temperature. Vapour pressures are roughly doubled every time the temperature is increased by 10°C. An experiment where the relative humidity is varied between two levels cannot be well defined in terms of vapour pressure if the temperature is not kept constant. Vapour pressure is the driving force for vapour diffusion, and therefore the results of moisture absorption will be strongly influenced by the conditions being non-isothermal. Even if the conditions in practice are seldom constant during occupation periods, the test method should be based on constant temperature conditions.

Temperature level also has an effect on the relative humidity level produced by salt solutions, but with the used magnesium chloride (MgCl$_2$) and sodium chloride (NaCl), this dependency is relatively low (Greenspan, 1977) and can be neglected if the temperature variations are moderate around normal indoor temperatures.
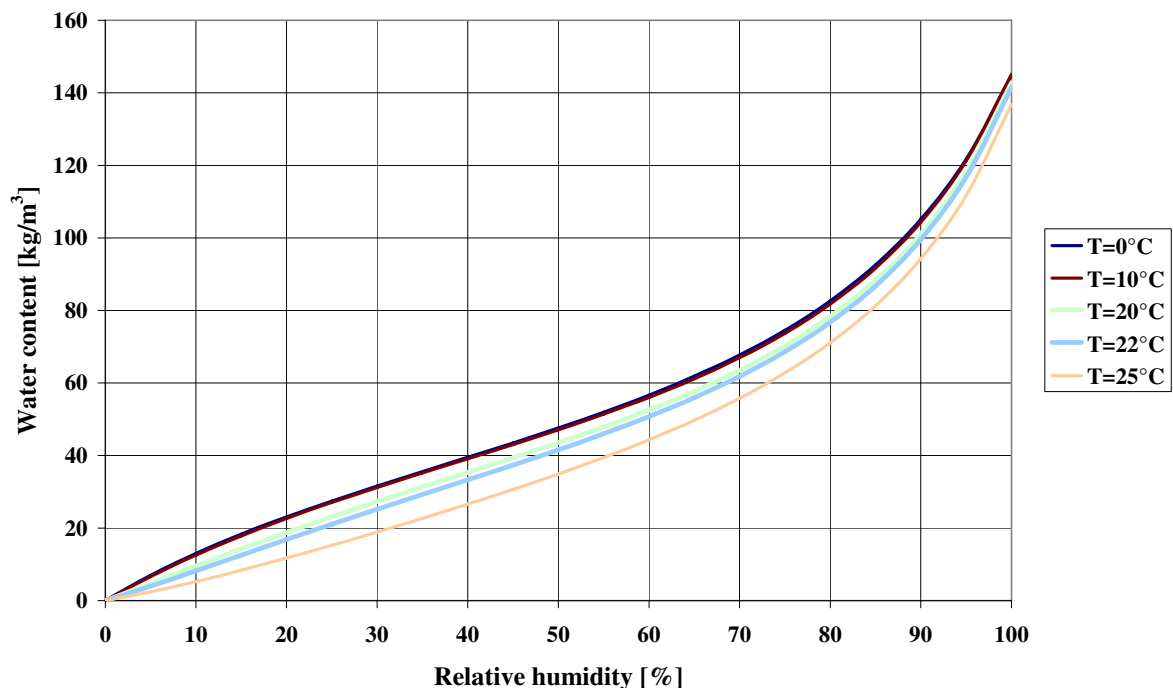

Figure 4-4   Sorption isotherm of wood in different temperatures (U.S. Department of Agriculture, 1999).

Temperature also has an effect on the sorption isotherms of the materials. The moisture capacity of materials can be read as the slope of their sorption isotherm. Figure 4-4 presents the sorption isotherm for wood at different temperatures.

The moisture buffer value is proportional to the moisture capacity, but since the moisture capacity changes only slightly with the temperature, the temperature effect on the sorption curve can seem insignificant. However if the temperature varies from one level to another, the transition from one sorption isotherm to another would mean that the equilibrium relative humidity would change, when the moisture content of the material is unchanged. Thus, an increasing temperature would result in higher equilibrium relative humidity. Conversely, if the surrounding relative humidity remains fixed, then the moisture content of the wood would vary even with small temperature differences. In this way temperature may also affect the $MBV_{practical}$-value.

4.4.1   Conclusions on the effect of temperature

Both temperature and relative humidity should be monitored during the tests to be able to check the conditions and also do some correction of the measurements, if required.

Special care should be taken when measuring the $MBV_{practical}$ value by using separate relative humidity jars that may have different temperatures between the jars or between the jars and the space used to weight the samples.

4.5   Sealing with paraffin and aluminium foil

Sealing of edges and back-sides are needed in the Moisture Buffer Value method to assure one-dimensional moisture flow and a defined exposure area for the specimens. There are on the market a vast variety of different sealing systems with various performance properties. The most common ones are wax-paraffin mixes, various rubber compounds and different tapes and films.

The main purpose of an edge sealing systems is to prevent moisture flow over the edges; it must therefore be water impermeable. To avoid error in the gravimetrical determination of the sorption process there is a need for a sealing system with an negligible hygroscopicity. The risk of hydrophobation due to solvents in the sealing system should as far as possible be avoided. Depending on the moisture related shrinkage and swelling of the material to be sealed, the flexibility of the sealing system needs to be taken into account. The workability of the sealing systems is also of great importance both for the over-all performance of the sealing system and the time consumption in preparation of the specimens.

Different sealing systems are suitable for various purposes; it can therefore be difficult to compare them. In a study to be presented at a conference in 2006 Svennberg & Segerholm reviews a number of different sealing systems. The conclusion from this study is that the best over-all performance seen in the "tape and film group" including aluminium tape, PVC-tape, butyl sticking strip and a thermoplastic laboratory film. The other sealing systems; epoxy adhesive, silicone rubber and beeswax-paraffin mix; fail to reach acceptable standard regarding flexibility and workability. These three sealing systems also show a higher risk for hydrophobation of the sample. The most important conclusion however is the most evident; sealing systems need to be chosen carefully with regard to a number of factors depending on the material that should be tested and the experimental set-up.

4.5.1 Sorption effect of paraffin and PE-foil

To study the magnitude of the sorption in sealing materials the following experiments were done at DTU:

- A sample of aluminium foil was prepared with a layer of paraffin such that the paraffin covered the foil on one side. The sample was exposed to about week-long conditions in the climate chamber at either 33% and 75% RH to note if there were any measurable change of weight of the aluminium/paraffin sample.
- A similar test was done with a sheet of 0.15 mm polyethylene cut to A4 size. This experiment lasted for 10 days.

The experiments concluded that the moisture absorption in paraffin, aluminium foil and polyethylene was insignificant compared to the weight changes caused by moisture in the materials that were otherwise tested.

5 Conclusion

The project has produced a definition of a quantity, the *Moisture Buffer Value (MBV)*, which can be used to describe the ability of building materials and systems of materials to exchange moisture with the indoor environment. The moisture buffer value indicates how much moisture is absorbed or released by a material when the humidity of air changes in the environment that surrounds the material. The property is dedicated for this purpose, and therefore constitutes a better choice as a property to express the moisture buffer property of building products than other standard hygrothermal properties, such as the sorption curve and sorption capacity, water vapour permeability, and penetration depth. Although the standard properties have a relation with the MBV, they do not precisely stipulate the flow of moisture being exchanged between a material and the surrounding air – and different relative rankings of materials result from the other parameters simply because they express some different properties. It is proposed therefore to use the Moisture Buffer Value concept when assessing the ability of materials and systems to moderate humidity variations in the environment that surrounds them.

The Moisture Buffer Value can be seen either as a pure material property or a practical performance property. The pure material property is valid only for a homogenous material layer, and it can be measured only under ideal surface transfer conditions. Under these ideal conditions the convective moisture transfer process at the material surface presents no resistance to the flow of moisture in or out of the material. This MBV_{ideal} has a close relationship with the so-called moisture effusivity, which is a parameter that can be derived purely from standard hygrothermal material properties. The relationships are given in the report.

However, in practice there is some degree of a convective surface resistance at surfaces – both in normal indoor environments and in climate chambers where the properties are tested. In addition, many building products are not homogenous and may have particular surface treatments. The project therefore has introduced the $MBV_{practical}$ definition. For $MBV_{practical}$ is assumed a surface resistance corresponding to normal air flow conditions seen in indoor environments (air velocity between 0.05 and 0.15 m/s), and an exposure with daily variations with 8 hours of high air humidity (75 % RH) and 16 hours with low humidity (33 % RH). Due to this $MBV_{practical}$ definition, this value can be determined also for other multilayer building components than just materials with surface coatings. In this case the result should be clearly separated from the pure material property. For example, the thickness of the material layer may have a significant effect on the practical performance value.

A test protocol has been developed to determine the practical Moisture Buffer Value. The test protocol constitutes the project's proposal for a NORDTEST method, and can be seen as Appendix 1 of this report.

A Round Robin test has been carried out as part of the project where eight different building materials and material systems were tested for their moisture buffer performance. Each material was tested by three different institutes, and the objective was to see that even if the equipment was not the same, it was possible to obtain reasonably similar results. In addition, the Round Robin was carried out while the test protocol was developed within the project, so it was possible to adjust the protocol according to the experiences. Finally, the Round Robin

has given some first results of MBV$_{practical}$ for those materials and systems which participated in the test.

A side-product from the project has been the development of a computer program which can be used to convert between standard moisture transport properties for building materials and the MBV value, and to display a comparison between measured results and the theoretical moisture uptake/release by a material.

One objective of this standardisation project was to define a practical performance value that is easy to comprehend and possible to compare with the moisture loads and effects of ventilation. The other objective was to represent a practical and easy to use method to determine this value. This practical approach was aimed to serve the needs of industry in their product development, and performance comparison, application assessment and marketing purposes. Connection of the Moisture Buffering Value to theory and standardised material property values is clear, but the presented method has a practical performance approach.

The MBV can be applied in design practices by comparing the moisture buffering properties of different materials and products used as indoor siding or furnishing purposes. In the first draft design level the choice of materials can already support the final realisation of the comfort of the indoor air space. Practical design tools can be developed to quantify the needed or possible MBV levels in different applications. One prospect could be to have an accepted and known MBV-classification of materials and products that could be used in marketing and to inform consumers about this performance property.

There has been a substantial interest in this project throughout its execution. This has resulted in quite some dissemination activities which have been carried out almost since the inception of the project. This has also had the significant result that a lot of feedback from other researchers and interested parties has been given to the project, e.g. Roels and Janssen (2005). A major group to whom the progress of the project has been presented and the developments have been discussed are the participants of the International Energy Agency's research project on *Whole Building Heat, Air and Moisture Response* – IEA ECBCS Annex 41. The complete list of passed and planned dissemination activities can be seen in Section 7.

6 Literature

Arfvidsson, J. 1999. Moisture Penetration for Periodically Varing Relative Humidity at the Boundary. Acta Physica Aedificiorum, Vol 2.

Berggren, T. and H, Skoog. 2003, Materials in the Indoor Environment – a preliminary study. *In Swedish* Department of Building Physics, Lund University, Unpublished report

Christoffersen, L. D. 1996. ZEPHYR Passive Climate Controlled Repositories. Department of Building Physics. Lund, Lund University, Sweden.

Greenspan, L. 1977, Humidity Fixed Points of Binary Aqueous Solutions. *Journal of Research of the National Bureau of Standards – A. Physics and Chemistry,* 81A (1), pp.89-96.

Hansen, E. de Place; K. K. Hansen. 2000. Lerstensprodukters fugttekniske og styrkemæssige egenskaber. Inst. for Bærende Konstruktioner og Materialer, Danmarks Tekniske Universitet, Series R No 71.

Japanese Standards Association. 2002. *Test method of adsorption/desorption efficiency for building materials to regulate an indoor humidity – Part 1: Response method of humidity.* JIS A 1470-1:2002.

Mitamura, T.; C. Rode and J. Schultz. 2001. Full Scale Testing of Indoor Humidity and Moisture Buffering in Building Materials". ASHRAE Conference, *IAQ 2001 – Moisture, Microbes and Health Effects: Indoor Air Quality and Moisture in Buildings*, November 4-7, 2001. San Francisco.

Mortensen, L. H., R. Peuhkuri, and C. Rode. 2005. Full scale tests of moisture buffer capacity of wall materials. In 7th Nordic Symposium on Building Physics, Reykjavík, pp. 662–669.

Osanyintola, O., C. Simonson and T. Ojanen, *Transient Moisture Buffering Capacity of Plywood.* Paper A41-T2-C-05-2 for IEA ECBCS Annex 41 presented at meeting at Concordia University, Montreal, May 16-18, 2005.

Padfield, T. 1999. *The Role of Absorbent Building Materials in Moderating Changes of Relative Humidity*. Ph.D. Thesis. Dept. of Structural Engineering and Materials, Technical University of Denmark, Series R No 54.

Peuhkuri, R., C. Rode, and K. K. Hansen. 2004. *Moisture buffer capacity of different insulation materials.* In Proceedings of Buildings IX, Clearwater, Florida.

Ramos, N. M. M. and V. P. de Freitas. 2004. *Hygroscopic inertia as a function of transient behaviour of covering materials*. In Proceedings of Buildings IX, Clearwater, Florida.

Rode C. (ed.). 2003a. *NORDTEST Workshop on Moisture Buffer Capacity - Collection of Abstracts*. August 21-22, 2003. Dept. of Civil Engineering, Technical University of Denmark.

Rode, C. (ed.). 2003b. *Workshop on Moisture Buffer Capacity – Summary Report,* August 21-22, 2003, Dept. of Civil Engineering, Technical University of Denmark, R-067, 2003.

Roels, S. and H. Janssen. 2005. Is the moisture buffer value a reliable material property to characterise the hygric buffering capacities of building materials? Working paper A41-T2-B-05-7 for IEA Annex 41 project, Whole Building Heat air and Moisture Response.

Rorabacher, D.B. 1991. Statistical Treatment for Rejection of Deviant Values: Critical Values of Dixon's "Q" Parameter and related Subrange Ratios at the 95% Confidence Level. *Analytical Chemistry* 63(2), pp.139-146.

Salonvaara, M., T. Ojanen, A. Holm, H. M. Künzel, and A. N. Karagiozis. 2004. Moisture buffering effects on indoor air quality - experimental and simulation results. In Proceedings of Buildings IX, Clearwater, Florida.

Sandberg, P.I. 1973. Byggnadsdelars fuktbalans i naturligt klimat. Institutionen för byggnadsateknik, Tekniska högskolan i Lund. Report 43.

Simonson, C., M. Salonvaara, T. Ojanen. 2002. *Humidity, Comfort and Air Quality in a Bedroom with Hygroscopic Wooden Structures*. Proceedings of the 6th Symposium "Building Physics in the Nordic Countries", Trondheim.

Svennberg, K. 2003. Determination of Moisture properties for Materials Exposed to the Indoor Air. Lund, Department of Building Physics, Lund University.

Svennberg, K., L. Hedegaard, and C. Rode. 2004. Moisture buffer performance of a fully furnished room. In Proceedings of Buildings IX, Clearwater, Florida.

Svennberg, K. 2005. An inventory of surface materials exposed to the indoor air in 16 Swedish normally used rooms in dwellings. TVBH-7232, Building Physics LTH, Lund University, Lund.

Time, B. 1998. *Hygroscopic Moisture Transport in Wood*. Dr. Ing. Thesis. Norwegian University of Science and Technology, 1998.

U.S. Department of Agriculture. 1999. *Wood Handbook - Wood as an Engineering Material*. http://www.knovel.com/knovel2/Toc.jsp?BookID=460

7 Dissemination activities and meetings

7.1 Previous Dissemination Activities

Carsten Rode, Berit Time, Tuomo Ojanen and Kaisa Svennberg. *Moisture Buffer Capacity - Initial Review of Definitions and Methods.* Paper A41-T2-DK-04-6 for IEA ECBCS Annex 41 presented at meeting at ETH Zürich, May 12-14, 2004.

Carsten Rode. *Status on NORDTEST project: Moisture Buffering of Building Materials.* Paper A41-T2-DK-04-5 for IEA ECBCS Annex 41 presented at meeting at Glasgow Caledonian University, October 27-29, 2004.

Carsten Rode, *NORDTEST project: Moisture Buffering of Building Materials.* FuktCentrum informationsdag, Lund University of Technology, November 22., 2004

Carsten Rode. *NORDTEST Moisture Buffer Project – Status, May 2005.* Presentation A41-T2-DK-05-2 for IEA ECBCS Annex 41 presented at meeting at Concordia University, Montreal, May 16-18, 2005.

Carsten Rode, Ruut Peuhkuri, Kurt K. Hansen, Berit Time, Kaisa Svennberg, Jesper Arfvidsson, and Tuomo Ojanen. *Moisture Buffer Value of Materials in Buildings.* 7th Symposium on Building Physics in the Nordic Countries, Reykjavik, June 13-15th, 2005.

Lars-Erik Harderup. *A PC-model to Predict Moisture Buffer Capacity in Building Materials According to a NordTest Method.* 7th Symposium on Building Physics in the Nordic Countries, Reykjavik, June 13-15th, 2005.

Carsten Rode, Ruut Peuhkuri, Kurt K. Hansen, Berit Time, Kaisa Svennberg, Jesper Arfvidsson, Tuomo Ojanen, *Nordtest Project on Moisture Buffer Value of Materials.* AIVC Conference "Ventilation in relation to the energy performance of buildings", Brussels, 21-23 September 2005.

7.2 Planned Dissemination Activities

Carsten Rode and Ruut Peuhkuri. *Modelling the Hygrothermal Interaction Between Materials and the Indoor Climate.* 22. internationales WTA-Kolloquium. Bauinstandsetzen + Bauphysik III. March 10, 2006. Hildesheim, Germany. (Submitted)

Carsten Rode, Ruut Peuhkuri, Kurt Kielsgaard Hansen, Berit Time, Kaisa Svennberg, Jesper Arfvidsson, Tuomo Ojanen and Jarkko Ahonen, *Moisture Buffer Value of Building Materials.* ASTM Symposium on Heat-Air-Moisture Transport: Measurements on Building Materials, Toronto April 23, 2006 (abstract accepted).

An article is planned for "Arkitekten" (Denmark). To be published in spring 2006.

7.3 Project Meetings

May 14, 2004. Open meeting for project partners and other interested parties (mainly from IEA ECBCS Annex 41). ETH Zürich.

August 16, 2004. Meeting for project partners. Norwegian Building Research Institute, Trondheim

June 11, 2005. Meeting for project partners. Icelandic Building Research Institute, Reykjavik.

December 5, 2005. Meeting for project partners. Lund University of Technology.

Appendix

A1   Test Protocol – Measuring *Moisture Buffer Value* for Homogenous Materials or Composite Systems Exposed to Indoor Air

A1.1 Scope

The scope of this NORDTEST method is to evaluate the moisture buffer value for materials exposed to indoor air, i.e. building materials, furniture, curtains etc. The test is intended to simulate daily variations.

A1.2 Field of application

The method is applicable to materials and composite systems intended for indoor use.

A1.3 Definitions

Moisture buffer value in this connection refers to the moisture uptake/release when the material is exposed to a square wave in relative humidity between 75 % RH (relative humidity) during 8 hours and 33 % RH during 16 hours. The value is normalized per exposed surface area and change in RH.

A1.4 Method of test

A1.4.1 Principle
A test specimen, partly sealed, is exposed to repeated step changes in ambient relative humidity. The temperature is held constant at 23°C. Because of the change in RH, the specimen will gain or loose weight. The weight change of the specimen is monitored continuously or by frequent weighing. The change in weight over certain durations of time can be considered as an expression of the moisture buffer value of the test specimen.

A1.4.2 Experimental equipment
A climate chamber/climate box where temperature and RH can be kept constant and where the proposed RH-step can be performed shall be used. Suitable sensors and a logging system to continuously record the temperature and the relative humidity within the test chamber shall

be used. The sensors shall be calibrated at regular intervals.

An analytical balance, capable of weighing the test specimens with the repeatability of 1 % shall be used. That means for example for a test sample with a change in mass of 1 g per 8 hours, a balance with a resolution of 0.01 g or better should be used, correspondingly for a test sample with a change in mass of 10 g per 8 hours, a resolution of 0.1 g or better can be used.

The air in the test chamber should circulate and the air velocity should be 0.10 ± 0.05 m/s like in a normal indoor environment. However, the air circulation must not disturb the balance, or it shall be switched off during weighing.

A1.4.3 Test specimens

A1.4.3.1 General
The test specimens shall be representative of the product.

A1.4.3.2 Exposed area
The shape and size of the test specimen is not fixed, but rectangular shapes are recommended. The minimum side length or diameter of the exposed area of the specimen is recommended to be 100 mm, and minimum exposed face area is 0.01 m^2. The area shall be determined within an accuracy of 1%. Representative smaller test specimens with homogeneous surfaces can be allowed given the total surface area is at least 0.03 m^2.

A1.4.4 Sealing of specimen
Box shaped test specimens shall normally be sealed on 5 out of 6 sides. Other test specimens should have as many sides exposed as in the intended use.

Sealing materials should not absorb moisture. An example of a good sealing material is aluminium tape. The sealing material must have a adherence to the substrate, and it must be ensured that moisture movement of the substrate does not cause loosening of the sealing material.

A1.4.5 Thickness of test specimens
The thickness of the specimen should be as in the intended use or at least the moisture penetration depth (1% definition) for daily moisture variation. This moisture penetration depth may be calculated according to material properties from literature for products similar to the one being tested.

For some products this may be beyond the largest thickness that is available commercially, in which case the largest possible marketed thickness should be used, or for loose fill products: The maximum thickness specified in official guidelines for normal construction with the material.

A1.4.6 Surface coating of test specimens
In some cases the test products may have surface coatings or they may consist of different material layers. The determined result is then not a material property but a system property.

A1.4.7 Number of test specimens

A minimum of 3 test specimens shall be tested.

A1.4.8 Conditioning of test specimens

Before testing, the test specimens shall be stored and initially be in equilibrium with air at 23±5°C and 50±5 % RH. The criterion for equilibrium is a period long enough for the weight of the sample to stabilise so that two successive daily determinations (24 hours between) of the weight agree to within 0.1 % of the mass of the test specimen.

A1.5 Procedure

A1.5.1 Test conditions

The test environments are given in Table 3. Test conditions can be maintained by saturated salt solutions, as given in Table 1-2, or it can be maintained by some other mechanism in a climatic chamber.

Table 1-1   Test conditions

Temperature (° C)	Low RH (%)	High RH (%)
23	33	75

Table 1-2   Salt solutions and performance characteristics (Greenspan 1977, Nyqvist 1983, Bertelsen 1984)

RH at 23°C [%]	Salt	Name	dRH/dT [%/°C]
32.9	$MgCl_2$	Magnesium chloride	-0.05
75.4	NaCl	Sodium chloride	-0.03

The high RH level should last for 8 hours (± 10 min.). The low RH level should last for 16 hours (± 10 min.). If the step changes of relative humidity cannot be achieved instantly, they shall be realized to an accuracy of ±3 % RH within at the most 30 minutes after the intended change. The intended temperature shall be maintained within ±0.5°C.

The cyclic exposure should continue until the change in mass, Δm [g], is less than 5 % between the last three cycles (days). In each cycle Δm should be determined as the average between the weight gain during the moisture uptake branch of the cycle, and the weight loss during drying. Also the difference between weight gain and weight loss within each cycle should be less than 5% of Δm.

If the weight gains and losses are not monitored continuously, at least 1 weighing has to be done by the turn of each exposure in the cycle. The specimen should be weighed a minimum of 5 times during the 8 hour absorption periods during the last three days.

A1.5.2 Preparation of specimen and test facility

Prepare test specimens. Measure the thickness and the exposed area before and after the sealing has been done.

A1.5.3 Test procedure

Place the test specimen in the test chamber.

Perform the weighing. The weight shall be determined in an environment with a temperature within +/- 2 °C of the test condition, wherever possible within the test chamber.
Movement to scale shall not influence the result by more than 1 % of the amplitude.

Plot a curve of the mass against time.

A1.6 Calculation and expression of results

The result shall be calculated as mass-change, Δm, per m^2 and per ΔRH. Two results of mass change shall be calculated for each cycle: One for the weight gain during absorption ($m_{8\ hours}$-m_0), and one for the weight loss ($m_{24\ hours}$-$m_{8\ hours}$) during drying. The average between the absorption and desorption weight changes is calculated in each cycle. The Moisture Buffer Value is the figure calculated on the basis of the mean of at least 3 cycles .

A1.7 Reporting of the result

The test report shall include:
♦ Reference to this method
♦ A concise description of the test specimen
  • type of product ;
  • product name, factory, manufacturer or supplier;
  • production code number or similar identifier;
  • the form in which the product arrived at the laboratory, including facings, if any;
  • the method of preparation of the specimen, including slicing where done, and details of any curing process, where necessary;
  • the thickness, exposed surface area, shape and sealing methods used. This shall include information on the number of exposed surfaces;
  • if the material is not homogenous, its composition shall be described;
  • other details of the product e.g. nominal thickness or nominal density.
♦ A description of the test conditions
  • test configuration used;
  • conditioning of the specimen carried out;
  • any deviation from this standard procedure and any incidents which may have influenced the results;
  • the dates of the test;
  • information concerning the operator and the apparatus used - it is mandatory that the information is available at the laboratory, but it should be included only if requested;
  • A picture of the sample and setup.

- ♦ The result as a Moisture Buffer Value
  - • the result shall be given as the average of all specimens, and either their standard deviation or the individual results of all tested specimens shall be given.
  - • All results shall be given as the average value of the last three stable cycles.

A1.8 References

Bertelsen, N.H., 1984, *Fugttransport målt med kopmetoder. Nordtest workshop, baggrund og udviklingsområder. (Moisture transport measured with cup methods, Nordtest workshop, background and further development issues).* Byggeteknik, Teknologisk Institut, Denmark, (In Danish).

Greenspan (1977), Humidity Fixed Points of Binary Aqueous Solutions. *Journal of Research of the National Bureau of Standards – A. Physics and Chemistry,* 81A (1), pp.89-96.

Nyqvist (1983), Saturated Salt Solutions for Maintaining Specified Relative Humidities, *International Journal of Pharmaceutical Technology and Product Manufacture,* 4(2), pp.47-48.

A2 MoistBuff - Theory and manual

- Informative

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A2.1 Nomenclature

Bi	Biot number	-
B_n	Coefficient	-
c	Specific heat capacity	J/(kg·K)
d	Relative thickness for the surface layer	m
d_s	Thickness of the surface layer	m
D_w	Moisture diffusivity	m²/s
g_v	Density of moisture flow rate	kg/(m²·s)
G'	Dimensionless accumulated flow	-
G_v	Accumulated moisture flow	kg/m²
L	Thickness of the slab	m
m	Mass	kg
M	molar weight	kg/kmole
p	Pressure	Pa
R	molar gas constant = 8314,3	J/(kmole·K)
t	Time	s
T	Temperature	°C; K
u	Dimensionless vapour concentration	-
v	Vapour concentration	kg/m³
v_s	Vapour concentration at saturation point	kg/m³
V	Volume	m³
w	Moisture content	kg/m³
Z	Water vapour resistivity (d/δ)	s/m
Z_s	Water vapour resistivity for the surface layer	s/m
α_{cv}	Convective surface heat transfer coefficient	W/(m²·K)
β	Surface coefficient of water vapour transfer $\beta = \alpha_{cv}/(\rho \cdot c)$	m/s
δ_s	Permeability to vapour for the surface layer	m²/s
δ_v	Permeability to vapour	m²/s
φ	Relative humidity	-
μ_n	Exponential factor	-
ρ	Density	kg/m³
τ	Dimensionless time	-
ξ	Moisture capacity	kg/m³, -

A2.2 Theory

If we assume that the vapour concentration is the only potential for moisture flow we can use the following equation:

$$\frac{\partial w}{\partial t} = -\frac{\partial}{\partial x}(g_v) \qquad 0 < x < L \tag{1}$$

$$g_v = -\delta_v \cdot \frac{\partial v}{\partial x} \qquad x = 0 \tag{2}$$

By writing

$$\frac{\partial w}{\partial t} = \frac{\partial w}{\partial v} \cdot \frac{\partial v}{\partial t} \tag{3}$$

and assuming that the water vapour permeability and the temperature are constant $(dw/dv = \text{constant})$ we get

$$\frac{dw}{dv} \cdot \frac{\partial v}{\partial t} = \delta_v \cdot \frac{\partial^2 v}{\partial x^2} \tag{4}$$

$$\frac{\partial v}{\partial t} = \frac{\delta_v}{\left(\dfrac{dw}{dv}\right)} \cdot \frac{\partial^2 v}{\partial x^2} = D_w \cdot \frac{\partial^2 v}{\partial x^2} \tag{5}$$

with

$$D_w = \frac{\delta_v}{\dfrac{dw}{dv}} = \frac{\delta_v}{\xi'} \quad (\text{m}^2/\text{s}) \tag{6}$$

Internally in the PC-program MoistBuff ξ' is used as the moisture capacity

Since

$$v = v_s(T) \cdot \varphi \quad (\text{kg/m}^3) \tag{7}$$

we can express D_w as

$$D_w = \frac{\delta_v \cdot v_s(T)}{\dfrac{dw}{d\varphi}} = \frac{\delta_v \cdot v_s(T)}{\xi} \tag{8}$$

where ξ is the moisture capacity (kg/m³).

$$\xi = \frac{dw}{d\varphi} \quad (\text{kg/m}^3)$$

In the next section this definition of moisture capacity is used. It should be noted that ξ is assumed to be constant for the given RH-interval.
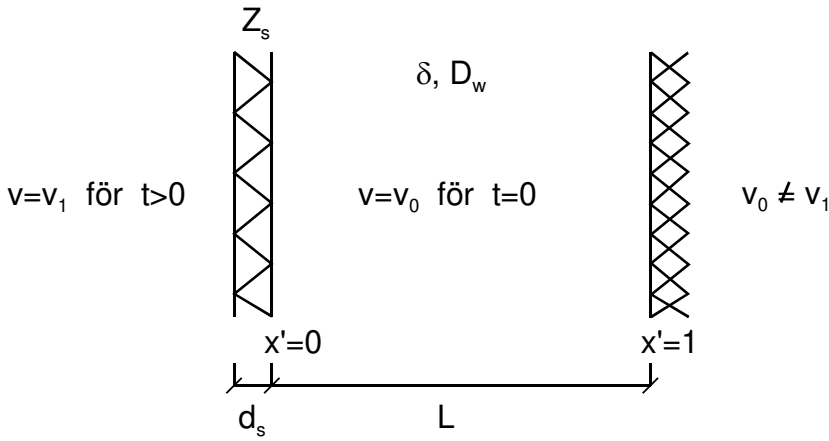
Figure 2-1   Slab with surface resistance.

With boundary- and initial conditions from Figure 2-1 we can write

$$\frac{\partial v}{\partial x} = 0 \qquad x = L \tag{9}$$

$$\frac{v_1 - v}{Z_s} = -\delta_v \cdot \frac{\partial v}{\partial x} \qquad x = 0 \tag{10}$$

$$v(x,0) = v_0 \qquad 0 < x < L \tag{11}$$

By rewriting equation (10) we have

$$v_1 = v - \delta_v \cdot Z_s \cdot \frac{\partial v}{\partial x} \qquad x = 0 \tag{12}$$

In a dimensionless form the vapour concentration can be written as

$$v(x,t) = v_0 + (v_1 - v_0) \cdot u(x',\tau) \tag{13}$$

where

$$x' = \frac{x}{L} \tag{14}$$

$$\tau = \frac{D_w \cdot t}{L^2} = \frac{\delta_v \cdot t}{\xi \cdot L^2} \tag{15}$$

$u(x',\tau)$ must fulfil the following conditions

$$\frac{\partial u}{\partial \tau} = \frac{\partial^2 u}{\partial x'^2} \qquad 0 < x' < 1, \quad \tau > 0 \tag{16}$$

$$\frac{\partial u}{\partial x'} = 0 \qquad x' = 1 \tag{17}$$

$$\frac{u_1 - u}{d_s} \cdot \delta_s = -\frac{\delta_v}{L} \cdot \frac{\partial u}{\partial x'} \qquad x' = 0 \tag{18}$$

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$$u(x',0) = 0 \quad 0 < x' < 1 \tag{19}$$

Equation (18) can be transformed to

$$1 = u - \frac{\delta_v \cdot Z_s}{L} \cdot \frac{\partial u}{\partial x'} = u - \frac{1}{Bi} \cdot \frac{\partial u}{\partial x'} \tag{20}$$

where

$$Bi = \frac{L}{\delta_v \cdot Z_s} = \frac{L}{d} \tag{21}$$

From equation (20) we can see that u only depends on one parameter, Bi the Biot number.

To calculate the accumulated moisture flow as a function of time, we have to integrate equation (23).

$$G_v = \int_0^t g_v \, dt' \tag{22}$$

$$g_v = -\delta_v \cdot \frac{\partial v}{\partial x} = -\frac{\delta_v \cdot (v_1 - v_0)}{L} \cdot \frac{\partial u}{\partial x'} \quad x = 0 \tag{23}$$

If we express equation (22) with a dimensionless integral we get

$$G_v = \frac{\delta_v \cdot (v_1 - v_0)}{L} \cdot \int_0^\tau (-) \cdot \frac{\partial u}{\partial x'}(0, \tau') \cdot \frac{L^2}{D_w} \cdot d\tau' \tag{24}$$

where

$$dt' = \frac{L^2}{D_w} \cdot d\tau' \tag{25}$$

Equation (24) can now be written

$$G_v = \frac{\delta_v \cdot L}{D_w}(v_1 - v_0) \cdot \int_0^\tau (-)\frac{\partial u}{\partial x'} \cdot (0, \tau') \cdot d\tau' = \xi \cdot L \cdot (v_1 - v_0) \cdot \int_0^\tau (-)\frac{\partial u}{\partial x'} \cdot (0, \tau') \cdot d\tau' \tag{26}$$

Now we can write
$$G_v = \xi \cdot L \cdot (v_1 - v_0) \cdot G' \quad (kg/m²) \tag{27}$$
where

$$G' = \int_0^\tau (-)\frac{\partial u}{\partial x'}(0, \tau) \cdot d\tau' \tag{28}$$

A2.3 Solution for dimensionless step response

According to Luikov (1968) the integral in equation (27) can be expressed as

$$G' = \int_0^\tau (-)\frac{\partial u}{\partial x'}(0, \tau) \cdot d\tau' = 1 - \sum_{n=1}^\infty B_n \cdot e^{-\mu_n^2 \cdot \tau} \tag{29}$$

The exponent factors, μ_n, in equation (29) are roots to

$$\cot(\mu_n) = \frac{1}{Bi} \cdot \mu_n \qquad (30)$$

which is equivalent to

$$\mu_n \cdot \tan(\mu_n) = Bi \qquad (31)$$

The B_n-coefficients can be calculated with equation (32).

$$B_n = \frac{2 \cdot Bi^2}{\mu_n^2 \cdot (Bi^2 + Bi + \mu_n^2)} \qquad n = 1, 2, \ldots\ldots \qquad (32)$$

With known B_n-coefficients we can solve equation (29) for arbitrary times, if thickness and material properties are known for the slab and the surface.

Further information about the theory and solutions for the special cases when $L = +\infty$ or the surface resistance Z_s is negligible can be found in Harderup (1983).

A2.4 Permeability to vapour

The density of moisture flow rate can be expressed with different potentials. If we use the gradient (dv/dx) the density of moisture flow rate can be written

$$g_v = -\delta_v \cdot \frac{dv}{dx} \quad (kg/(m^2 \cdot s)) \qquad (33)$$

where δ_v has the unit (m²/s).

As an alternative we can use the gradient (dp/dx) and write the density of moisture flow rate as

$$g_p = -\delta_p \cdot \frac{dp}{dx} \quad (kg/(m^2 \cdot s)) \qquad (34)$$

where δ_p has the unit (kg/(m·s·Pa)).

The ideal gas law can be written

$$p \cdot V = \frac{m}{M} \cdot R \cdot T \qquad (35)$$

where

p	pressure	Pa
V	volume	m³
m	mass	kg
M	molar weight	kg/kmole
R	molar gas constant = 8314,3	J/(kmole·K)
T	temperature	K

By rearranging equation (35)

$$\frac{m}{V} = v = p \frac{M}{R \cdot T} \quad (kg/m^3) \qquad (36)$$

and use equation (33) and (34) we can express a relationship between δ_v and δ_p by equation (37)

$$\delta_v = \frac{R}{M_v} \cdot T \cdot \delta_p = \frac{8314,3}{18,02} \cdot T \cdot \delta_p \approx 461,39 \cdot T \cdot \delta_p \quad \text{(m²/s)} \tag{37}$$

where

   M_v molar weight for water = 18,02   kg/kmole

A2.5 Overview of input

Figure 2-2   Start menu to MoistBuff.

When the program MoistBuff is initiated you will see the screen in Figure 2-2. Click the button at the top left Results from experiment to load results from experiment. The first row in the input file is reserved for information about the experiment. The first column in the file must contain the time with the format hh:mm:ss. The first time in the file is considered to be the start time, and set to zero.

The second column should contain the weights from the experiment (g/m²). The decimal point in the second column should be a comma (,). If you write a point (.) as the decimal point the program will change it internally to a comma.

The delimiter between the two columns have to be a TAB (ASCII=009).

The test specimen is supposed to be in equilibrium with the second RH-value, see Figure 2-2, when the experiment starts.

If you do not have any saved files with input information to the calculations, you have to fill in all the rows in the table in Figure 2-3.

Figure 2-3   Table from the screen with input data to the calculations.

<u>Material (e.g. Gypsum board – untreated:</u> General information about the material. The text is also displayed in the title in the graph.

<u>Thickness [mm]:</u> The total thickness of the material in mm.

<u>Exposure (single-sided or double-sided):</u> If the material is exposed to the surrounding climate from both sides it is considered as double-sided. If the backside of the material is protected with an impermeable layer it is considered as single-sided. You just have to write S, or s for single-sided and D, or d for double-sided.

<u>Cv-abs from experimental work [kg/m³]:</u> See equation (8).

<u>Cv-des from experimental work [kg/m³]:</u> See equation (8).

<u>Permeability to vapour [m²/s] (untreated material):</u> Permeability to vapour for the untreated material. If you have the permeability to vapour in (kg/(m·s·Pa)) you can calculate the equivalent value in (m²/s) by using the calculation procedure shown at the bottom of Figure 2-3. Before you click at the `Calculate` button you must give accurate numbers for both the permeability to vapour (kg/(m·s·Pa)) and the mean temperature (°C) from experiment.

<u>Temperature [°C]:</u> Temperature when the experiment was carried out.

<u>First RH-value[%]:</u> The initial RH-value when the experiment started. First and second RH-value is shown in the title in the graph.

<u>Second RH-value (conditioning) [%]:</u> Second RH-value, which is the same as the conditioning value.

<u>Surface moisture resistance (Z_s) [s/m]:</u> Surface moisture resistance. For an untreated material this is the same as the inverse of the surface coefficient of water vapour transfer $\beta = \alpha_{cv}/(\rho \cdot c)$ (m/s). For a material treated with paint etc. the surface moisture resistance is the total resistance for the paint and the air layer. The surface moisture resistance is shown to the right in the title in the graph.

<u>Hours per day with high RH-level [h]:</u> A number between 1 and 23. The default value is 8 hours.

<u>Number of cycles (max 5) [-]:</u> One cycle is equal to one day or 24 hours.

When you have answered all the questions in the table in Figure 2-3 you can save the file by clicking on the button `Save/Open` and choose `Save` from the drop-down list. If you already have saved a file you can reopen it by clicking at the `Save/Open` button and choose `Open`.

Above the table you can see the name of the file you have opened.

If you want to undo all the input in the second column in the table in Figure 2-3 you can click the button Clear. When you start the program this button is invisible.

If input is missing in one or more of the lines in the table in Figure 2-3, or if the input is wrong, the program will give you information about the error and which line/lines you have to correct.

When you have entered input information from a file about the results from the experiment and answered all the input questions to the calculation you can click on Start calculation button, see Figure 2-2. To the right of this button you can choose if you want a linear time-scale or the time scale as the square-root of time.
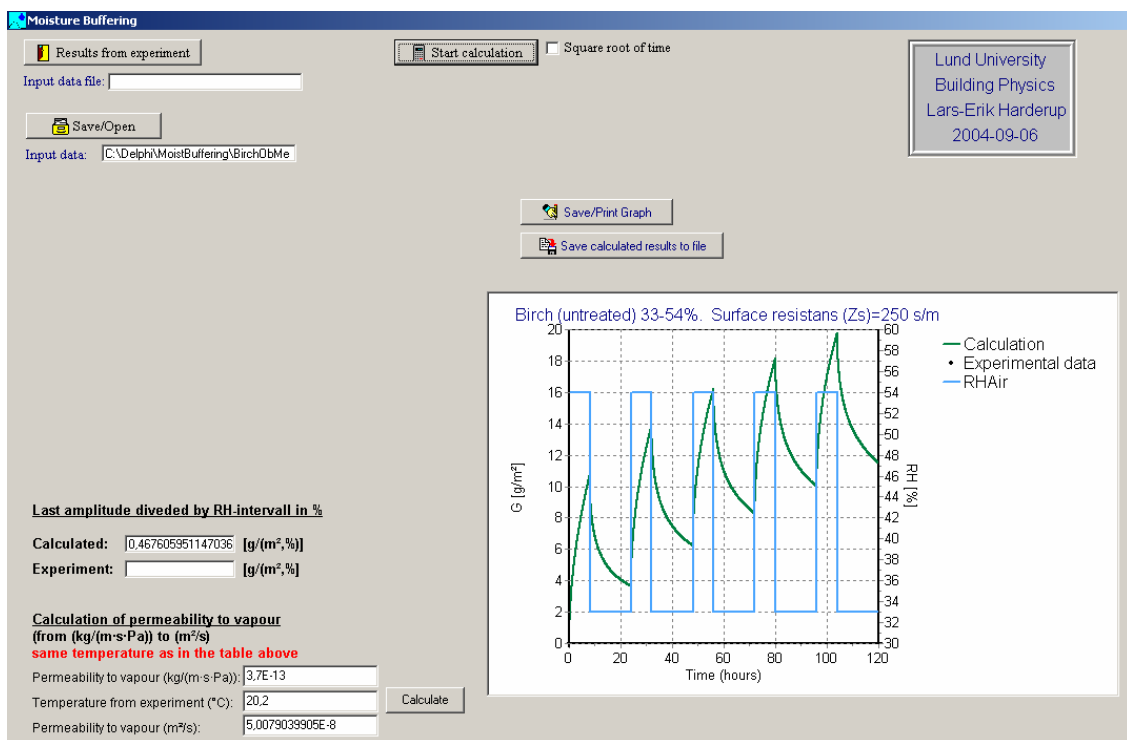
A2.6 Overview of output

Figure 2-4   Output from the program.

Figure 2-4 shows how the screen looks like when the calculations are finished. The light blue solid line in the graph shows the steps in relative humidity during the cycles. The scale to the right in the graph shows the relative humidity. The green solid line shows the results from the calculations according to the analytical model in the previous section. The circular dots in the graph show the results from the laboratory measurements.

A drop down menu will appear if you click on the button Save/Print Graph. If you click on Print in the drop down menu you can print the graph on your default printer. By clicking on the second alternative in the drop down menu you can save the graph as a metafile (*.wmf).

Above the graph in Figure 2-4 is another button named Save calculated results to file. If you click on this button you can save the calculated results to a separate file on your computer. The default file type is called (*.ber). This type of file has two columns separated

with a tab character. The decimal sign is a comma (,). In the first column is the time in hours and in the second column is the weight change from the start of the calculations and the experiment. Files with calculated results can easily be imported to Excel.

The last amplitude divided by RH-interval is shown to the left of the graph in Figure 2-4. Both the calculated result and result from the experiment are shown.
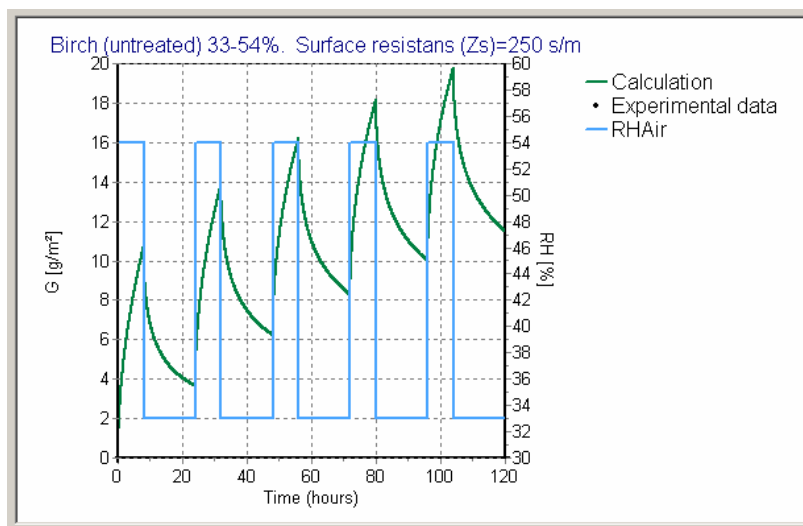

Figure 2-5   Last amplitude from calculations.

A2.7 References

Harderup, Lars-Erik, 1983. Luftfuktighet i bostäder. Lund University, Dept of Building Physics, TVBH-3009.

Nevander, Elmarsson, 1994. Fukthandbok – Praktik och teori. Svensk Byggtjänst, andra reviderade utgåvan, andra tryckningen. ISBN 91-7332-716-6.

A3   Penetration depth

- Informative

This Appendix presents a method to calculate the moisture penetration depth and the undisturbed moisture level, inside the region of periodic variation, in a porous material subjected to a periodic relative humidity variation at the boundary. The moisture properties for moisture transport and retention may be highly non-linear. The method is strictly valid for a semi-infinite material. The theory to determine the undisturbed moisture level is given in detail, and a calculation method to determine the penetration depth is presented.

A3.1 Introduction

Figure 3-1 illustrates the solution for a periodic variation at the boundary. The relative humidity varies between a maximum (75%) and a minimum value (33%) during the time period t_p (24hours). The curves in the figure are the moisture distribution at different times (t_p, $t_p/4$, $t_p/2$, $3t_p/4$) during the time period t_p. The dotted curves show the maximum and minimum values at different depths in the material. We see how the range of relative humidity variation (marked with arrows) decreases with the depth. Let x_p be the point where the relative humidity variation is equal to 1%. We define this point x_p as the *penetration depth*, see Figure 3-1.

In moisture calculations a complication is the non-linear behaviour. The mean value of the surrounding relative humidity is not the same as the value of the relative humidity in the material at the penetration depth and inwards. We define this value as the *undisturbed relative humidity*, φ_{und}. See Figure 3-1. Here the mean value for the surrounding relative humidity is 54% but the undisturbed value deep in the material becomes 59%. The variation of the relative humidity is, due to non-linearity, not symmetric.

The method presented below determines the moisture penetration depth and the undisturbed relative humidity in a material subjected to a variable surrounding relative humidity. The model determines a single value, which in a correct way represent a variable boundary condition in a material, taking non-linear effects into account. This value is valid from the penetration depth and further into the material. The method is strictly valid for a semi-infinite material

Much of the simplicity of the model presented here is obtained by the use of Kirchhoff's potential. It is originally introduced for heat transfer by Kirchhoff (Carslaw and Jaeger, 1959) and has been introduced and further developed to describe moisture transport during the past two decades (Arfvidsson and Claesson, 1989; Claesson, 1993; Arfvidsson, 1994; Claesson, 1997; Arfvidsson and Claesson, 1998). An important result is that the average value of the Kirchhoff potential in the material over a time period is equal to the average value of the Kirchhoff potential at the boundary. This is valid in a semi-infinite material.

A3.2 Calculation model

The model presented uses the Kirchhoff potentials to describe the moisture transport. This

simplifies the model considerably. A short description of the Kirchhoff potentials is given in the next section.

A3.3 Kirchhoff potential

Let g denote the moisture flow and ϕ any moisture flow potential. In the one-dimensional case we have, when temperature effects and hysteresis are neglected:

$$g = -D_\phi(\phi)\frac{\partial \phi}{\partial x} \tag{1}$$

Here the potential ϕ may denote relative humidity φ, absolute humidity v, water vapour pressure p in gas phases, pore water pressure $P_{p.w.}$ chemical potential μ_w for water, or moisture content w. The flow coefficient D_ϕ depends on ϕ. Kirchhoff originally introduced Kirchhoff's flow potential, when the flow coefficient is a function of the state (Carslaw & Jaeger, 1959). This potential is defined by:

$$\psi(\phi) = \psi_{ref} + \int_{\phi_{ref}}^{\phi} D_\phi(\phi)d\phi \tag{2}$$

It is a function of ϕ for each material: $\psi = \psi(\phi)$. The flow potential ψ is independent of which ϕ and D_ϕ one chooses to use. The reference values ϕ_{ref} and ψ_{ref} can be chosen arbitrarily for each material. We normally, by convenience, put the value of ψ to zero for a reference level ϕ_{ref} for the material: $\psi(\phi_{ref}) = 0$.

The moisture flow equation (1) becomes:

$$\vec{g} = -\nabla \psi \tag{3}$$

The formulation using Kirchhoff potentials are further investigated and explained in Arfvidsson and Claesson, 1998.
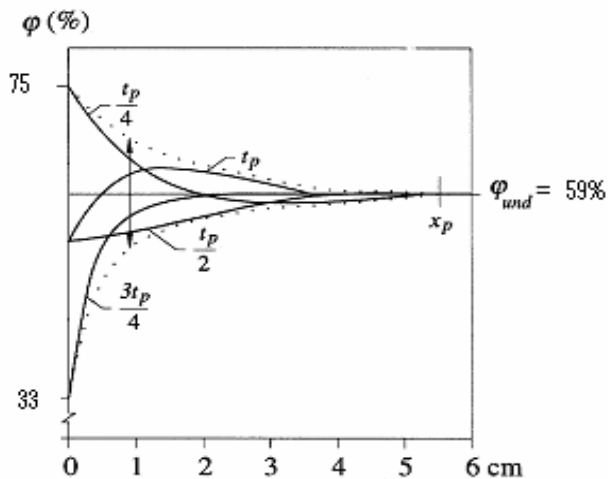
Figure 3-1   The moisture distribution at different times during the period time t_p due to a periodic boundary condition at the boundary. The amplitude of the variation (dotted lines) decreases with the depth. The penetration depth for the variation is marked x_p.

A3.4 Mathematical problem

We have the following mathematical problem. The moisture balance equation, using the Kirchhoff potential, is in the one-dimensional case:

$$\frac{\partial w}{\partial t} = \frac{\partial^2 \psi}{\partial x^2} \qquad w = w(\psi) \tag{4}$$

The boundary moisture state varies periodically:

$$w(0, t + t_p) = w(0, t) \tag{5}$$

We seek the truly periodic solution:

$$w(x, t + t_p) = w(x, t) \tag{6}$$

$$\psi(x, t + t_p) = \psi(x, t) \tag{7}$$

It is obtained for example by starting with a constant value for $w(x,0)$, $0<x<\infty$, and continuing the calculations for many periods until the above periodic conditions for $\psi(x,t)$ and $w(x,t)$ are attained.

A3.5 Theory for undisturbed moisture values during a periodic process

The undisturbed moisture level φ_{und}, ψ_{und} etc. of the periodic process at depth $x \geq x_p$ inside the material is of great interest. The convergence to truly periodic conditions is much more rapid if we start with this undisturbed value in the material. The technique to determine the undisturbed value is presented below.

Consider a periodic process with a period time t_p, and boundary condition according to (5). Then w and ψ vary periodically (6) and (7). The moisture balance equation is integrated in time over a whole period t_p. The left-hand side of the equation (4) then becomes zero:

$$\int_t^{t+t_p} \frac{\partial w(x,t)}{\partial t} dt = w(x, t+t_p) - w(x,t) = 0 \tag{8}$$

The right-hand side of the equation becomes:

$$0 = \int_t^{t+t_p} \frac{\partial \psi^2(x,t)}{\partial x^2} dt = \frac{\partial}{\partial x^2}\left(\int_t^{t+t_p} \psi(x,t)\, dt \right) \tag{9}$$

Let $\psi_m(x)$ be the mean value of ψ at the depth x during the period:

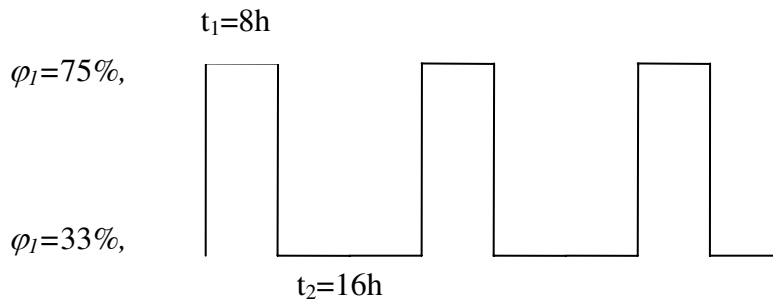$$\psi_m(x) = \frac{1}{t_p} \int_t^{t+t_p} \psi(x,t)\, dt \tag{10}$$

Figure 3-2   *Periodic variation of the boundary condition ($t_p = t_1 + t_2$)*

Then we have, according to equation (9) that $\psi_m(x)$ is linear in x:

$$\frac{d^2}{dx^2}(\psi_m(x)) = 0 \quad \Rightarrow \tag{11}$$

$$\Rightarrow \quad \psi_m(x) = A \cdot x + B \qquad 0 < x < \infty$$

In the limit $x \to \infty$, we have:

$$\psi_m(\infty) = A \cdot \infty + B \tag{12}$$

Because ψ_m is limited A=0. This means that ψ_m will be independent of x:

$$\psi_m(x) = B = \psi_m(0) \tag{13}$$

We have the result that the mean value of $\psi(x,t)$ over a time period is equal to the average value of ψ at the boundary $x=0$. By calculating $\psi_m(0)$ from the periodical boundary condition the mean value for all x is obtained. For large values of x, where the variation is completely reduced. We know the ψ-value. So we have:

$$\psi_{und} = \psi_m(x \geq x_p) = \psi_m(0) \tag{14}$$

From the material data relations we also know the corresponding relative humidity, φ, and the moisture content, w.

As an example let us consider a piece of concrete with material data according to Table 1 (Hedenblad, 1993). The boundary is subjected to periodic relative humidity on two levels. During the time t_1 the relative humidity is $\varphi_1=33\%$ and during time t_2 the relative humidity is $\varphi_2=33\%$ (Figure 3-2). We choose $t_1=8h$, $t_2.=16h$ The time period t_p is equal to $t_1 + t_2$. The relative humidity deep inside the material is to be calculated.

At first we get, from the material data, the Kirchhoff potential for the two levels of relative humidity.

$$\varphi_1 = 75\% \quad \Rightarrow \quad \psi_1 = 12.5 \cdot 10^{-10} \tag{15}$$

$$\varphi_2 = 33\% \quad \Rightarrow \quad \psi_2 = 3.0 \cdot 10^{-10} \tag{16}$$

The mean value of ψ becomes, (10):

$$\psi_m = \frac{t_1 \cdot \psi_1 + t_2 \cdot \psi_2}{t_1 + t_2} = \tag{17}$$

$$\frac{12.5 \cdot 10^{-10} \cdot 8 + 3.0 \cdot 10^{-10} \cdot 16}{24} \approx 6 \cdot 10^{-10}$$

From the material data (Table 3-1) we get the corresponding value of relative humidity to be around 60%. This means that the relative humidity deep into the material is 60%. The moisture content is 54 kg/m^3 (Table 3-1).

Table 3-1   Material data for concrete showing relation between relative humidity, φ, moisture content, w, and Kirchhoff potential, ψ (Hedenblad, 1993).

φ (%)	w (kg/m^3)	ψ (kg/ms)
0	0	0
33	28	$2 \cdot 10^{-10}$
50	42	$3 \cdot 10^{-10}$
60	54	$6 \cdot 10^{-10}$
70	68	$10 \cdot 10^{-10}$
75	74	$12.5 \cdot 10^{-10}$
80	84	$16 \cdot 10^{-10}$
85	96	$21 \cdot 10^{-10}$
90	110	$30 \cdot 10^{-10}$
93	120	$38 \cdot 10^{-10}$
95	130	$50 \cdot 10^{-10}$

A3.6 Determination of the penetration depth

When the undisturbed value for the relative humidity in the material is known for a specific periodical variation of the relative humidity on the boundary, the penetration depth can be calculated using a one-dimensional moisture calculation program.

We define the amplitude as the difference between the maximum and minimum value of the relative humidity in the material at each point x. The amplitude is the dotted line in Figure 3-1. This amplitude will decrease with the distance from the exposed boundary. Let x_p be the point where the relative humidity variation is equal to 1%. We define this point as the penetration depth, see Figure 3-1.

Consider a sufficiently thick piece of material. As initial relative humidity we put the undisturbed relative humidity φ_{und}, determined with the above shown technique. This relative humidity is also put as boundary condition on one side of the material. On the other side we have the periodical boundary condition. Then we calculate the moisture distribution in the material during that number of periods necessary to get identical solutions during one period and another. Normally five period times is sufficient.

The solution is found faster putting this undisturbed relative humidity φ_{und} as initial condition in the calculation. Any other value would require longer calculation time to obtain the right solution.

The working procedure is:
- The cyclic boundary condition is given as two levels of relative humidity φ_1 and φ_2, valid during the times t_1 and t_2, respectively.
- ψ_{und} is determined for the actual moisture variation at the boundary.
- The corresponding value φ_{und} (from material data) is given as initial condition in the calculation.
- The boundary condition φ_{und} is put on one side and the actual variable boundary condition on the other.
- A one-dimensional transient moisture flow calculation is made for five period times.

A3.7 References

Carslaw, H. and J.C. Jaeger, 1959. Conduction of Heat in Solids, pp. 8-13, 2:nd ed., Oxford University Press, Oxford.

Arfvidsson, J. 1998. Moisture Transport in Porous Media, Modelling Based on Kirchhoff Potentials. Doctoral Dissertation, Report TVBH-1010 Dept. of Building Physics Lund University.

Arfvidsson J. Hedenblad G. 1991. Calculations of Moisture Penetration Depth in Concrete. U91.06 Dept of Building Materials, Lund.

Arfvidsson, J. Moisture Penetration for Periodically Varing Relative Humidity at the Boundary. Acta Physica Aedificiorum, Vol 2, 1999.

Hedenblad, G. 1993. Moisture Permeability of Mature Concrete, Cement Mortar and Paste. LUTVDG/(TVBM-1014)/1-229/ (1993). Div. of Building Materials, Lund Institute of Technology, Lund, Sweden.

Hedenblad, G. 1996. Material data for Moisture Transport Calculation. (In Swedish) Byggforskningsrådet, Stockholm.

A4   Surface moisture transfer

- Informative

A4.1 Determination of surface moisture transfer coefficient

The convective moisture transfer coefficient, β_p $\left(\frac{kg}{Pa \cdot m^2 \cdot s}\right)$, and the surface resistance, $Z_{p,s}$ $\left(\frac{Pa \cdot m^2 \cdot s}{kg}\right)$, can be found using the Lewis relation, which is given in Equation (1) The exponent ¾ is recommended for interior surfaces in buildings (Sandberg, 1973).

$$Z_{p,s} = \frac{1}{\beta_p} = \frac{\rho \cdot c_p \cdot R_v \cdot T}{\alpha_c} \cdot Le^{\frac{3}{4}} \qquad (1)$$

where

$\rho =$ air density $\left(1.205 \frac{kg}{m^3} \text{ at } 20°C\right)$;

$c_p =$ heat capacity of air at constant pressure $\left(1005 \frac{J}{kg \cdot K}\right)$;

$R_v =$ gas constant for vapour $\left(461.5 \frac{J}{kg \cdot K}\right)$;

$T =$ temperature (K);

$\alpha_c =$ convective surface heat transfer coefficient $\left(\frac{W}{m^2 \cdot K}\right)$

$Le =$ Lewis number = ratio of thermal diffusivity to vapour diffusivity of air:

$\frac{a}{D} = \frac{2.1 \cdot 10^{-5} \text{ m}^2/\text{s}}{2.5 \cdot 10^{-5} \text{ m}^2/\text{s}} = 0.84$ at 20°C .

For the conditions at 20°C it gives

$$Z_{p,s} = \frac{1}{\beta_p} = \frac{1.44 \cdot 10^8}{\alpha_c} \qquad (2)$$

To estimate the convective heat transfer coefficient α_c, the following approach can be used. The flow over indoor surfaces is probably in the mixed regime between free and forced convection.

For *free convection* we have the relation:

$$\text{Nu} = \frac{\alpha_c \cdot L}{\lambda} = A \cdot (\text{Pr} \cdot \text{Gr})^n \qquad (3)$$

where
    Nu *is* the Nusselt number
    L is the characteristic length in the flow direction, m
    λ is the thermal conductivity of air, which is 0.0257 W/(m·K) at 20°C

Pr is the Prandtl number, which for air is 0.71

Gr is the Grashof number:

$$Gr = \frac{g \cdot \beta \cdot \Delta T \cdot L^3}{v^2}$$ (4)

where

g is the acceleration of gravity = 9.81 m/s^2

β is the volume expansion coefficient = $T^{-1} \approx (293 \text{ K})^{-1} = 3.41 \cdot 10^{-3} \text{ K}^{-1}$

ΔT is the temperature difference between air and surface, K

v is the kinematic viscosity, which for air at 20°C is $1.51 \cdot 10^{-5}$ m^2/s

In Equation (3) A, and n are constants which depend on the flow type and configuration.

For vertical plates, the flow is turbulent if $Pr \cdot Gr$ exceeds 10^9 – otherwise it is laminar This will be the case if $L^3 \cdot \Delta T$ exceeds the value 9.6 m^{3}K. Since interior building surfaces are normally at least a few meters in dimension, it means that the flow will be turbulent if ΔT is more than, say, 0.5 K. For example, for vertical surfaces in the turbulent regime A is 0.13, and n is 1/3. So in this case the heat transfer coefficient can be calculated as:

$$\alpha_c = 1.57 \cdot \Delta T^{\frac{1}{3}}$$ (5)

when all the above mentioned parameters are inserted. This means that for instance for $\Delta T =$ 1 K, α_c will be 1.57 W/(m^{2}K).

Likewise can be calculated for other configurations and flow conditions using the coefficients from Table 4-1.

Table 4-1   Coefficients for calculation of the Nu-*number for various types of free convection.*

Flow type and case	Laminar		Transition	Turbulent	
	A	n	$Pr \cdot Gr$	A	n
Vertical plane	0.59	1/4	10^9	0.13	1/3
Horizontal plane, heat flow upwards	0.54	1/4	$2 \cdot 10^9$	0.14	1/3
Horizontal plane, heat flow downwards	0.27	1/4	$3 \cdot 10^{10}$		

For **forced convection** the flow is laminar if the Re-number $\left(\dfrac{v \cdot L}{v} \right)$ is less than $\sim 3 \cdot 10^5$. In indoor climates we expect air velocities, v, significantly less than 1 m/s, and since L is expected to be within the 1-10 m range, it may be assumed that the indoor forced convection will be laminar. In this case, the average *Nu*-number for a surface will be:

$$\overline{Nu} = 0.664 \cdot Re_L^{\frac{1}{2}} \cdot Pr^{1/3} = 0.59 \cdot Re_L^{\frac{1}{2}}$$ (6)

and the heat transfer coefficient:

$$\alpha_c = \frac{\overline{Nu} \cdot \lambda}{L} = 3.9 \cdot \sqrt{\frac{v}{L}}$$ (7)

If v is 0.1 m/s and L is 3 m, then the heat transfer coefficient becomes $\alpha_c = 0.71$ W/(m^{2}K).

It is not clear, or at least very complicated, how to handle the ***mixed free and forced*** flows. One suggestion is to calculate the heat transfer coefficients for both cases, and then use the larger of the two. In indoor environments there can be surfaces where ΔT is 0 K, and we can expect air velocities in the order of magnitude around 0.1 m/s.

Calculations like the above ones, and general assumptions will lead to an assumption that the convective heat transfer coefficient for indoor surfaces is probably around 2.0 - 3.0 W/(m^{2}K). The surface moisture transfer resistance can generally be assumed to be $5 \cdot 10^7$ m^{2}s·Pa/kg.

A4.2 Moisture Biot-number

The Biot number (Bi) is a dimensionless number used in unsteady-state transfer calculations. It relates the transfer resistance inside and at the surface of a body. When heat transfer calculations are considered the Biot number is proportional to (thermal internal resistance) / (surface film resistance) and is used both in heat transfer calculations in general and unsteady state calculations in particular.

In unsteady-state moisture experiments, such as the proposed NORDTEST method, the approach of the dimensionless Biot number can be useful in designing advantageous and comparable experimental conditions. To prevent confusion the term Moisture Biot number is used to define the dimensionless number describing the proportionality between the moisture conductivity and the moisture surface film resistance.

The NORDTEST Moisture Buffer method is theoretically based on a semi-infinite approach. This gives the following constrictions: if a one-sided exposure is considered the moisture penetration will not reach the backside of the sample, see Figure 4-1.
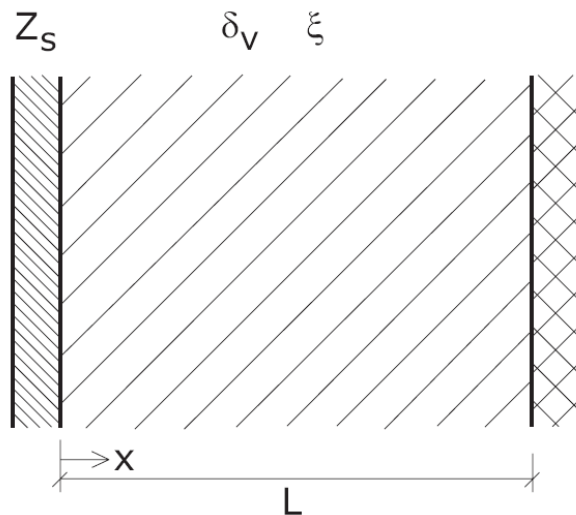

Figure 4-1   A sample with single sided exposure.

The moisture Biot number can be defined as :

$$Bi = \frac{L}{\delta_v \cdot Z_{s,v}} \tag{8}$$

Where L is the thickness of a one sided sample or half the thickness of a two sided sample (m), δ_v is the water vapour permeability (m^2/s) of the sample and $Z_{s,v}$ is the moisture surface resistance (s/m) which includes both the surface resistance of the material and the surface film resistance due to boundary air layer.

The relation between the moisture conductivity and the surface resistance will govern the mass transfer rate in the experiment. This is shown in Figure 4-2 where a decreasing Biot number shows a lower moisture transfer rate.
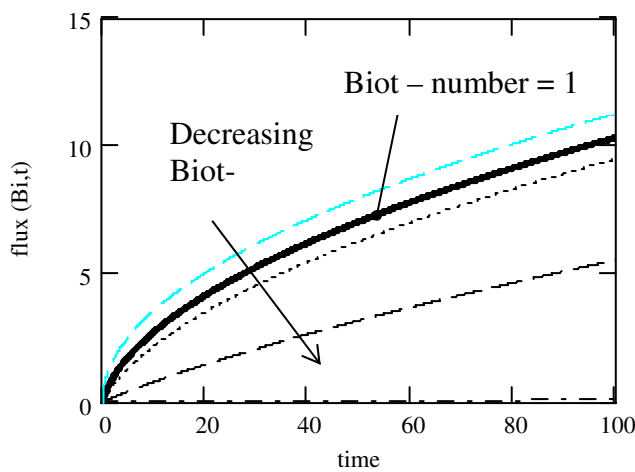

Figure 4-2   The Moisture uptake as a function of time (t) and the Moisture Biot number. The figure shows that a lower Biot number gives a slower moisture uptake.

To fulfil the theoretical basis for the NORDTEST method it is essential to estimate the moisture penetration deep for the experiment in question. The moisture Biot number could provide an evaluation base for the relation between sample resistance and the surface resistance.