A review of moisture buffering capacity: from laboratory testing to full-scale measurement

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Abstract

It is important to control indoor humidity level in buildings as it influences occupant's health and comfort. Hygroscopic building materials present great potential to passively regulate air humidity due to their ability to adsorb and desorb moisture. In recent years researchers have focused on this capacity, referred to as Moisture Buffering, as it has the potential to improve indoor thermal comfort and reduce HVAC usage and their consequent energy consumption. However, building designers generally do not consider this property an important factor, due to its unclear influence and difficulty in the quantification of its effects in real buildings. Therefore, it is complicated to develop an appropriate laboratory scale testing. The aim of this paper is to investigate the challenges related to moisture buffering measurement and to examine the approaches adopted by researchers. The significance of this study is to identify discrepancies between existing methods in the evaluation of the dynamic adsorption properties and presents areas for further development in testing.

Keywords: moisture buffering, full-scale measurement, dynamic hygrothermal properties, finishing materials, indoor hygrothermal comfort

Nomenclature

α Time factor [-]

β Correction factor [-]

Δw_{max} Average humidity ratio increase $[g/kg]$

δ_p Water Vapour Permeability $[kg/m \cdot Pa]$

$\dot{M}_{diff}$ Water vapour diffusion through walls per hour [kg/h]

$\dot{M}_{HVAC}$ Water vapour removed/gained by HVAC per hour $[kg/h]$

$\dot{M}_{Vent}$ Water vapour removed/gained by ventilation per hour $[kg/h]$

ϕ Relative Humidity $[-]$

ρ Dry bulk density $[kg/m^3]$

ξ_u Moisture Capacity $[kg/kg]$

ξ_w Moisture Capacity $[kg/m^3]$

A Adsorption coefficient $[kg/m^2 \cdot h^{0.5}]$

b_{mexp} Experimental moisture effusivity $[kg/m_2 \cdot Pa \cdot s^{0.5}]$

b_{mthr} Theoretical moisture effusivity $[kg/m_2 \cdot Pa \cdot s^{0.5}]$

b_m Moisture effusivity $[kg/m_2 \cdot Pa \cdot s^{0.5}]$

C_r Imperfect mixing reduction coefficient $[-]$

D_ϕ Liquid conduction coefficient $[kg/msPa]$

G Moisture production [g]

HIR^* Production interval adapted hygroscopic inertia $[kg/m^3 \cdot \%RH]$

$I_{h,d}$ Hygroscopic inertia $[g/m^3 \cdot \%RH]$

M_a Moisture change in the room [g]

M_{diff} Water vapour diffusion through walls [g]

M_{mat} Accumulated moisture in walls [g]

$M_{vent-inf}$ Water vapour removed by ventilation/infiltration [g]

MBE_a Moisture Adsorption Effects) $[kg/kg]$

MBE_d Moisture Desorption Effects) $[kg/kg]$

MBV^* Production interval Adapted MBV $[kg/m^2 \cdot \%RH]$

MBV_{8h} MBV with 1 hour high humidity $[kg/m^2 \cdot \%RH]$

MBV_{8h} MBV with 8 hours high humidity $[kg/m^2 \cdot \%RH]$

MBV_{basic} Moisture Buffering Value Basic $[kg/m^2 \cdot \%RH]$

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$MBV_{practical}$ Practical Moisture Buffering Value $[kg/m^2 \cdot \%RH]$

$MBV_{theoretical}$ Theoretical Moisture Buffering Value $[kg/m^2 \cdot \%RH]$

p_s Saturation pressure [Pa]

p_t Barometric pressure [Pa]

Q_{inf} Infiltration rate$[kg/h]$

t_p Time interval [s]

$UMBV$ Ultimate MBV $[kg/m^2 \cdot \%RH]$

w' humidity ratio with hygroscopic materials $[kg/kg]$

w_a outdoor absolute moisture ratio [s]

w_i indoor absolute moisture ratio [s]

w_0 humidity ratio with no hygroscopic materials $[kg/kg]$

w_h Humidity ratio injected by the air conditioning system $[g/kg]$

w_l Humidity ratio in the room $[g/kg]$

Z_p Moisture surface resistance $[m^2 \cdot \%RH/kg]$

C Condensed water [g]

EDRH Effective damped RH $[kg/h]$

N Air change rate $[h^{-1}]$

RH Relative Humidity [%]

S Surface $[m^2]$

t Time $[s]$

TG Vapour production period [h]

V Volume $[m^3]$

w Moisture content $[kg/m^3]$

$\dot{g}$ Moisture production per hour [kg/h]

1. Introduction

Hygrothermal comfort has gained significant importance in building design, as humidity and temperature influence occupant's well-being and health in the indoor environment [1, 2]. Relative Humidity (RH) beneath 40% increases concentration of noxious chemicals in the air, which exposes people to respiratory infections and skin diseases. In contrast, RH above 60% alter the temperature perception in the room and provide conditions for the proliferation of viruses and mould spores.

Heating, ventilation, and air conditioning (HVAC) systems and moisture control devices [3, 4] were developed to provide optimal thermal comfort and maintain RH at ideal levels, but they require additional energy [5, 6]. Some materials, described as hygroscopic, have the ability to passively control the indoor climate, reducing operational energy. Timber [7], clay [8] and other novel materials, such as zeolite [9] and mineral based plasters [10] reduce the peaks and valleys of internal Relative Humidity, due to their ability to adsorb and desorb moisture, a process referred to as moisture buffering [11].

Indoor air quality and hygrothermal comfort significantly improve, when permeable and hygroscopic materials are applied on the indoor surface. Simonson et al. [12] demonstrated that when the internal surface of a building was permeable, the maximum RH was lower compared to impermeable case, and overall, RH dropped to 20%. Salanvaara et al. [13] showed that wood maintains the mean RH around 40%, which is between the optimal RH interval for the health and comfort of building occupants [14].

As Osanyintola & Simonson [6] indicated, moisture buffering has also direct and indirect effects on the energy use in buildings. As direct effect, in winter it may reduce heating energy consumption, due to the latent heat generated by hygroscopic materials, when adsorb moisture from the air [15]. In the cooling season hygroscopic material reduce the use of energy to cool the room, as they keep humidity lower and decrease the room entalphy [6]. Indirect energy saving are also possible, thanks to the indoor air quality and hygrothermal comfort improvement. It means that with lower ventilation rate and lower and higher indoor temperature respectively in winter and summer, it is still possible to guarantee a good air quality and comfort. This allows to minimise heat losses through ventilation and infiltration, and reduces heating/cooling energy waste, turning down total energy consumption in buildings [16, 17]. However, [6, 17, 18] highlight, that results can be improved, if good temperature and ventilation control strategies are applied.

Even though an increased interest in this property has been showed, as yet there is not an agreed interpretation of moisture buffering, due to the complexity of moisture exchange between materials and the environment, and because of its definition itself. Moisture buffering is a physical quantity, which reefers to a material property and building space characteristic at the same time. Moisture transport through walls has been always related to the differential temperature, vapour pressure and RH between the indoor and outdoor [19]. However, in 1960 Künzel [20] started considering the exclusive time-dependant moisture sorption process between finishing material and indoor RH regulation. This property involves only indoor surfaces and it is not directly linked to outdoor/indoor humidity and temperature correlation. Künzel [20] defined this property as moisture adsorption, which reefers only to a material property, but only 40 years later Padfield[11] used the word "moisture buffering", in order to describe the consequent effect of porosity and adsorption on the indoor moisture balance. The dynamic adsorption capacity has been consequentially gained interest and it has been studied in terms of theory, experiments and numerical simulation [16, 21, 22], looking for a connection between moisture transport mechanism in hygroscopic materials and the effects on the indoor hygrothermal comfort.

NORDTEST protocol [14] and other standards [23, 24] were introduced to quantify the cyclic amount of water adsorbed and desorbed. However, it is not clear how these methods can represent the moisture buffering behaviour of materials in real buildings, as tests are run in a controlled environment, where temperature and humidity variation are measured. Other studies [11, 25] developed different methods, but still the connection between experimental results and the effective impact of hygroscopic materials in buildings has not been found.

This paper aims to review theoretical models and laboratory-scale tests, highlighting the unsuitability of current methods to represent the actual performance of hygroscopic materials in real buildings. A particular focus is given on the uncertainty to validate material scale experimentation, due to the lack of a standard full-scale test and to the difficulty to quantify the impact of factors, such as solar radiation and ventilation, on the indoor moisture balance. In conclusion, difficulties to correlate laboratory-scale and in-situ measurement are considered, highlighting the importance to find a relationship between material properties and full-scale testing, to better understand moisture buffering.

2. Theoretical models

According to the definition given by the NORDTEST [14], moisture buffering can be evaluated by the Moisture Buffering Value (MBV), which can be estimated by direct experimental measures or by an approximate model, based on Fick's principle on the diffusion of water vapour in a porous material. The theoretical Moisture Buffering Value ($MBV_{\text{theoretical}}$) is defined as the amount of water adsorbed and desorbed from materials through 1 m^2 surface exposed to certain RH variation, over a defined period of time:

$$MBV_{\text{theoretical}} \approx 0.00568 p_{\text{s}} b_{\text{m}} \sqrt{t_{\text{p}}} \tag{2.1}$$

$MBV_{\text{theoretical}}$ is a function of the saturation vapour pressure p_{s} [Pa] and time period t_{p}[s] and moisture effusivity, $b_{\text{m thr}}$ $[kg/(m^2 \cdot Pa \cdot s^{1/2})]$:

$$b_{mthr} = \sqrt{\frac{\delta_{\text{p}} \xi_w}{p_{\text{s}}}} \tag{2.2}$$

Where δ_{p} is the water vapour permeability and ξ_w is the moisture capacity $[kg/m^3]$.

$MBV_{\text{theoretical}}$ does not represent the real capacity of materials, because it mixes steady-state properties, defined under steady state and equilibrium conditions with the dynamic buffering behaviour. Peuhkuri and Rode [26] demonstrated the dissimilarity of MBV, when b_{m} is calculated through Eq. 2.2 and when it is experimentally determined from adsorption and desoprtion cycles, based on 8/16 h square wave humidity steps between 33 and 75 %RH (Fig. 1). The measured effusivity ($b_{\text{m exp}}$) is determined from the measured MBV and derived from Eq. 2.1. As shown in Table 1, $b_{\text{m exp}}$ is lower than the theoretical ($b_{\text{m thr}}$) one, as $b_{\text{m thr}}$ does not consider the dynamic rate and amount of moisture flowing between materials and the environment. However, experimental results may be not representative of the real dynamic behaviour of materials, either because they are only related to a specific humidity variation function. It is clear that $b_{\text{m thr}}$ indicates only the specific moisture capacity for equilibrium conditions.

Similarly, the theoretical definition of penetration depth is also based on steady-state properties. The penetration depth is an essential property to determine the thickness of hygroscopic materials and make

Table 1: Determination of Moisture Effussivity for Autoclaved cellular concrete (ACC) [26]

Method	b_m $[kg/(m^2 \cdot Pa \cdot s^{0.5}]$
Theoretical	$2.66 \cdot 10^{-7}$
Experimental	$1.96 \cdot 10^{-7}$

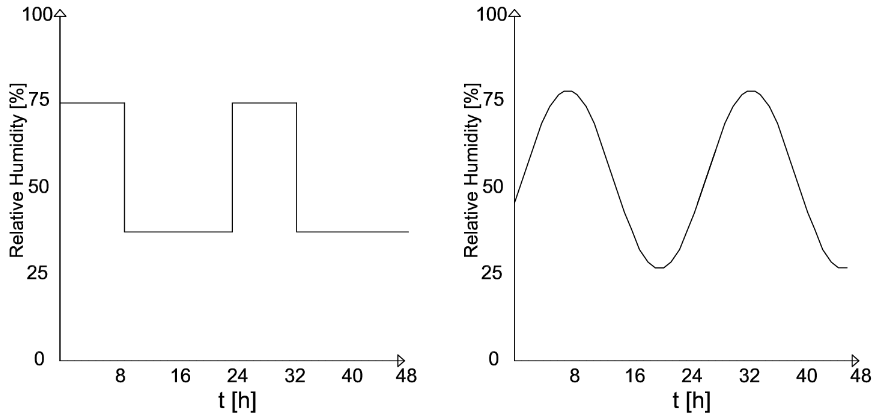

Figure 1: Square waves humidity cycles and Sinusoidal humidity variation

the most of moisture buffering potential ([14]). It defines how deep moisture infiltrates from the indoor air into the material for a given time period. However, Maskell et al. [27] underlined the theoretical models overestimate the moisture penetration depth, as these methods are also based on numerical approximations. Maskell et al. pointed out the necessity to quantify the penetration depth through direct measurement.

To reduce the gap between the theoretical models and experimental tests Zhang et al. [16] developed a new mathematical expression for MBV. Moisture Buffering Value Basic (MBV $_{\text{basic}}$) is applicable either with harmonic or square waves function of humidity (Fig. 1). The MBV $_{\text{basic}}$ function is variable not only of the time period, but also of time variation of the indoor condition, when high humidity is kept for αt_{p} hours and low humidity is maintained to $(1-\alpha)t_{\text{p}}$ hours, as shown in the Eq. 2.3:

$$MBV_{\text{basic}} = 1.27[\alpha(1-\alpha)]^{0.535}\sqrt{\delta_{\text{p}} \cdot \rho \cdot \xi_u}\sqrt{t_{\text{p}}} \tag{2.3}$$

Where: δ_{p} is water vapour permeability $[kg/m \cdot s \cdot Pa]$, ξ_u is moisture capacity $[kg/kg]$ and ρ is density $[kg/m^3]$. Eq. 2.3 is applicable only for square wave moisture variation. However, it can be indirectly used for harmonic function of humidity, if multiplied by a correction factor β, which is derived from quasi-harmonic humidity variation equations.

Roels and Janssen [28] highlighted there are other discrepancies between the theoretical model and experimental results, as the effect of the moisture surface resistance, Z_{p}, in the moisture exchange process with the air is not considered. The $MBV_{\text{theoretical}}$ supposes the moisture exchange happens on the material surface, but in reality it takes place on a thin air layer above the surface, where either convective moisture flows in the air and the intrinsic materials resistance are present. As Rode et al. [29] showed, $MBV_{\text{theoretical}}$ is comparable to the practical verification only if Z_{p} is zero, materials are homogeneous and their thickness is at least equal to their penetration depth.

Besides $MBV_{\text{theoretical}}$, other theoretical models have been developed to define the moisture buffering capacity in a dynamic context. Tsuchiya [30]'s model considered moisture buffering as average moisture content of a thin indoor surface layer, which instantaneously reaches equilibrium. The storage capacity is limited to a few millimetres of the surface and calculated only as a function of the dry mass of the surface material. Another method is the Effective Capacitance (EC) [21], which links both the capacity of the finishing material and the room air to store moisture: moisture buffering is so considered as an increment of the air capacitance of the room. It is a simplified model, which does not require many input data but it does not give any information about the moisture distribution into the materials. Later Cunningham [31, 32] developed the Effective Moisture Penetration Depth (EMPD) model, which represents the moisture buffering as mass transfer resistance between the air and the surface and the diffusion resistance into the material.

The EMPD is more realistic than $MBV_{\text{theoretical}}$ but coupled Heat, Air and Moisture transfer (HAMT) models, such as Künzel [33]'s and Janssen and Roels [34]'s, give a better interpretation of the moisture storage capability. Due to the link between simultaneous heat and moisture transport through the building envelopes and the simulated hygrothermal condition in the room model, moisture buffering is considered as part of the heat and moisture transfer between the surface and the indoors. An example of HAMT software is WUFI® Plus [35], which combines Künzel's equation (Eq. 2.4) to the indoor absolute moisture ratio (w_i $[kg/m^3]$) in Eq. 2.5.

$$\frac{dw}{d\phi} \cdot \frac{d\phi}{dt} = \bigtriangledown \cdot (D_\phi \cdot \bigtriangledown \phi) + \delta_p \cdot \bigtriangledown (\phi p_s)) \tag{2.4}$$

where: ϕ is the relative humidity (-), t is time (s), w is the moisture content (kg/m^3), p_s is the saturation vapour pressure (Pa), D_ϕ is the liquid conduction coefficient (kg/ms), δ_p is the vapour permeability (kg/msPa).

w_i $[kg/m^3]$) is calculated from the following water vapour mass balance equation:

$$V\frac{dw_i}{dt} = \sum_f S \cdot \dot{M}_{diff} + NV(w_a - w_i) + \dot{g} + \dot{M}_{Vent} + \dot{M}_{HVAC} \tag{2.5}$$

Where: w_a and w_i are respectively the absolute moisture ratio of the exterior and interior air (kg/m^3), $\dot{M}_{diff}$ is the moisture flux from the interior surface into the room (kg/sm^2), N is the air change per hour (h^{-1}), $\dot{g}$ is the moisture production (kg/h), $\dot{M}_{Vent}$ and $\dot{M}_{HVAC}$ are respectively the moisture gains or losses due to ventilation and HVAC systems (kg/h).

Moisture buffering is represented by $\dot{M}_{diff}$ in Eq. 2.5, and it is also indirectly included in Eq. 2.4, as the equation consider several moisture transport mechanisms, as moisture adsorption, distribution and surface diffusion.

Although several models have been developed, there is not yet a clear link between theory and the dynamic sorption process. Calculation methods may not represent moisture buffering in real buildings because they are only based on a few case studies and very specific full-scale test set-ups. Due to the complexity of the moisture transport mechanisms, a standard experimental validation technique does not exist and consequently it leads to different results and evaluations.

3. Laboratory scale experimentation

This section presents some laboratory methods used to characterise the dynamic water sorption properties of building materials. There have been various laboratory protocols to determine moisture buffering [36, 11, 14], but they can be generally divided into two groups: tests performed through step-response method and ones performed in a flux chamber. However, this simple distinction may prove to be restrictive, as some experimentation are the combination of the two. The main difference between the two is the humidity variation function (square waves and harmonic).

3.1. Step-response method

The simplest laboratory-based experimental method for the moisture buffering capacity is the "step-response" method, developed by Künzel [36]. It measures the weight variation of samples, when they are subjected to an adsorption phase for a set time, followed by a desorption step (Fig. 2).

Moisture buffering was defined by Künzel [36] as function of time through an adsorption coefficient A $[kg/m^2\sqrt{h}]$, which links the moisture uptake (kg/m^2) and the square root of time ($\sqrt{h}$). However, as Svennberg et al. [37] discussed, in this first configuration of the "step-response", air movement, sample size and experiment set-up were not standardized and the humidity generation interval to define RH-steps were

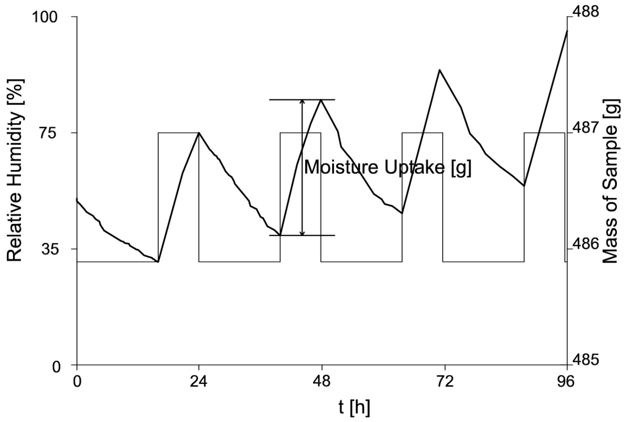

Figure 2: Cyclical moisture uptake and release of hygroscopic materials as function of RH in isothermal conditions [14]

always variable. RH intervals length is strictly dependent on the vapour diffusion resistance of materials, size of the chamber and the way to determine the moisture equilibrium. In particular, equilibrium was considered to have been reached, either after a predetermined time frame or if the weight variation were small [37]. Both methods might deviate from the true equilibrium and led to errors [38]. Furthermore, the method supposed that the material reached again the hygric equilibrium in the chamber before another cycle started, which never happens in reality. As a consequence, the test results were not comparable to each other and did not represent a realistic situation in a whole building.

The NORDTEST project [14] improved and standardised step-response test introducing the Practical Moisture Buffering Value ($\mathrm{MBV_{practical}}$), described as $[kg/m^2 \cdot \%RH]$. It is based on the Künzel's method, varying cyclically the RH from 33% to 75%. This method tries to replicate periodically the daily humidity exposure in a building, assuming 8 h of high humidity and 16 h of low RH in an ambient with air velocity around 0.1 m/s and constant temperature. The difference with the previous methods is in the definition of moisture buffering, which is not a function of the square root of time but a function of RH variation, and it requires a controlled environment for precise test performance.

Together with NORDTEST [14], other standards were introduced, such as the JIS A 1470 [23] and ISO 24353 [24], which present similar experimental procedure but use different time-steps and propose three RH levels. McGregor et al. [39] and Roels and Janssen [28] highlighted how those differences influence the adsorption curves, as shown in Fig. 3. Janssen and Roels [40] recognised that the NORTEST does not fully characterised moisture buffering in real buildings, due to the single time-steps interval. So Janssen and Roels proposed the Production-Adapted MBV (MBV*), which introduces another time-interval other than the one presented by the NORDTEST [40]:

$$MBV^* = \alpha MBV_{\mathrm{8h}} + (1-\alpha) MBV_{\mathrm{1h}} \tag{3.1}$$

where α is a weighting factor and 1h and 8h are the moisture generation time.

Further development were introduced by Wu et al. [41], who transformed the MBV in the Ultimate Moisture Buffering Value (UMBV). It is defined as:

$$UMBV = \sum_{k=I}^{III} \alpha_{\mathrm{i}} MBV_{\mathrm{i}} \tag{3.2}$$

Where α_{i} is the time coefficient defined as $t_{\mathrm{i}}/24$ and I, II and III are the time intervals of the test. Each phase simulates respectively sample pre-conditioning (23°C, 50% RH) summer (40°C, 98% RH) and extreme winter (18°, 3% RH) conditions. This method measures the behaviour of a material not on daily basis, but yearly because it considers only seasonal outdoor weather variation.

In addition, RH varies together with the temperature, which is still not clear how it influences moisture

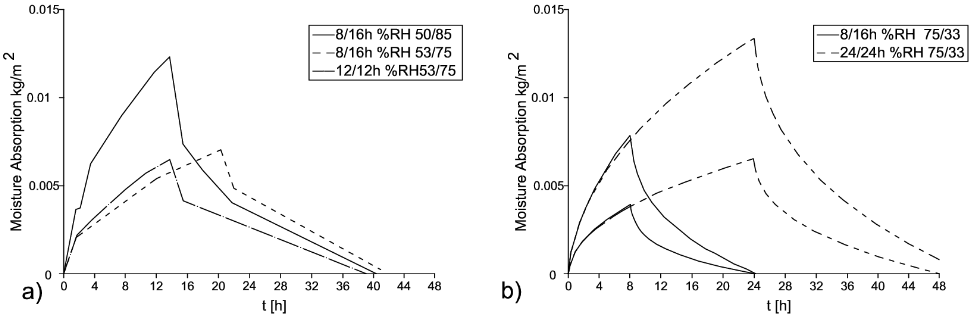

Figure 3: Comparisons between different moisture buffering tests:a)ISO and NORDTEST [39]; b)JPN and NORDTEST [28]

buffering. Rode et al. [14] explained that temperature affects the water vapour transport, due to its influence on vapour pressure and the unknown transitory effects during temperature variation. However, it is important to better understand the role of temperature in the dynamic vapour sorpion, as temperature in indoor environment is always variable.

Even though a lot of improvement has been given to the test-response method, air movement, air speed, temperature and the surface resistance coefficient inside the climatic chamber are assumed constant. For this reason, Gómez et al. [42] built another test facility, which reproduced the effect of the air movement for natural and forced convection on a surface. The specimen was placed in an air tunnel (Fig. 4), which had an adjustable speed fan. The produced air flow passed first through a stagnation chamber and a flow guide, before reaching specimen, in order to obtain a laminar flow. The instrumentation was then placed in a sealed box, where humidity was controlled by salt solutions. By following the NORDTEST protocol, they checked the influence of the coefficient of surface resistance on the sorption process through Lewis's correlation [14] and air speed, showing the strong correlation between convective moisture flows and MBV. As also Allinson & Hall [43] highlighted, results showed, that MBV decreases, if ventilation increases and vice-versa. The developed testing facility brought an effective improvement of the step-response method, as it demonstrated the importance of accurately measure the air velocity. Gómez et al. found an effective solution to this problem, but the instrument is an high accuracy apparatus, which might not be easy to replicate and it does not consider the effects on results of different time period and humidity levels, together with the air velocity. Furthermore, Gómez et al. [42]'s apparatus controlled the air speed in a laminar environment, while common environmental chambers cannot control the air velocity and the air distribution. Consequently, different results are obtained within the same chamber depending on the location of the sample inside the unit [44].

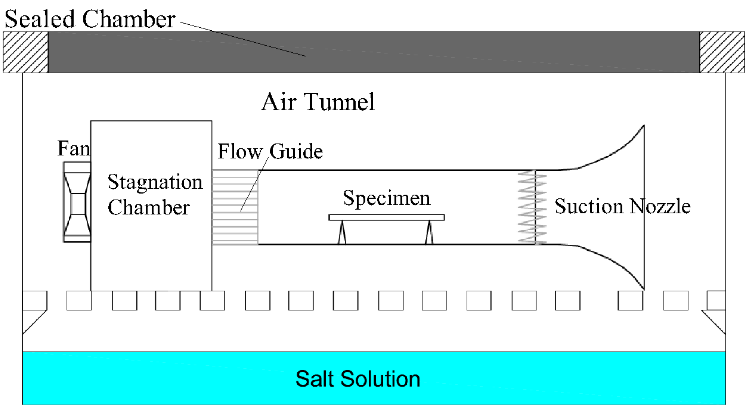

Figure 4: Test configuration of Gómez et al. [42] and 58 x 126 x 4 mm sample

3.2. Flux chamber

Step-response tests are carried out by varying humidity from high level to low, following a square-wave function. However, in real buildings Relative Humidity changes are more complex [12]. Padfield [11] developed a different experimental facility, which recreated human moisture production though a 'harmonically changing Relative Humidity'. The so-called flux chamber did not measure directly the moisture adsorption capacity of materials but it measured the RH variation in the cell and calculates the difference between a known amount of water introduced in the cell though humidification and the moisture recollected in a water tank during the dehumidification. This method is more suited to the comparison of the influence of materials on the indoor environment, but it does not allow analysis of the impact of moisture on the material sorption process.

Ramos and de Freitas [45] developed similar equipment in which the room ventilation is replicable. Their facility is placed in a climatic chamber, where it is possible to control the temperature and RH of the air injected in the flux chamber and the humidity generation is strictly controlled. Ramos and de Freitas [45] ran a step-response method but they found a correlation between the daily RH variation and the "hygroscopicity" level of the room. Those two factors are represented respectively by relative daily average amplitude of a RH variation and Hygroscopic Inertia $I_{\mathrm{h,d}}$, defined as:

$$I_{\mathrm{h,d}} = \frac{\sum_{k=i}^{n} C_{\mathrm{r,i}} \cdot MBV_{\mathrm{i}} \cdot S_{\mathrm{i}} + \sum_{k=j}^{m} C_{\mathrm{r,j}} \cdot MBV_{\mathrm{obj,j}}}{N \cdot V \cdot TG} \tag{3.3}$$

Where: $\mathrm{MBV_i}$ is the moisture buffer value of element i $(g/m^2 \cdot \%RH)$, $\mathrm{S_i}$ is the surface of element i (m^2), $\mathrm{MBV_{obj,j}}$ is the Moisture buffer value of complex element j $(g/\%RH)$, $\mathrm{C_r}$ is Imperfect mixing reduction coefficient (-). N, V and TG are respectively the air exchange rate (h^{-1}), the room volume (m^3) and the Vapour production period (h). MBV is measured through the NORDTEST protocol ([14]) and it is applied also to complex interior finishes or objects ($\mathrm{MBV_{obj,j}}$).

The flux chamber reproduces a small scale room condition (0.40 m^3), but needs more verification with full-scale testing, because there are other factors of influence in a room which are not considered or are assumed constant, such as the moisture transport through the wall, the outdoor weather condition and air speed. In Table 2 laboratory scale methods have been summarised.

Table 2: Comparison of laboratory methods

Author	Definition	Unit	Facility	Temperature
Künzel [36]	Absorption Coefficient	$[kg/m^3\sqrt{h}]$	Climatic Chamber and Jar	20°C
NORDTEST [14]	MBV	$[kg/m^2 \cdot \%RH]$	Climatic Chamber	23°C
Janssen & Roels [40]	Production-Adapted MBV	$[kg/m^2 \cdot \%RH]$	Climatic Chamber	23°C
Wu et al. [41]	Ultime MBV	$[g/m^2\%RH@12/8/4h)]$	Climatic Chamber	variable
Padfield et al. [11]	Water Vapour in the air	$[g/m^3]$	Flux Chamber	20°C
Ramos & De Freitas [45]	Hygroscopic Inertia	$[g/m^3 \cdot \%RH]$	Flux Chamber	23°C

4. Full-scale test

Full-scale investigations are necessary for experimental validation of hygrothermal simulations and laboratory scale tests, but there are no standard methods for moisture buffering verification testing. Several test configuration and test facilities for the moisture buffering validation process were developed in different ways. Some researchers [46, 47, 48] replicated a full-size room in a climatic chamber, which ensures to have a better control on the boundary environmental conditions. Others [49, 50, 12] built experimental spaces in direct contact with the indoor environment or tested existing dwellings, to have a complete picture of all phenomena, which may influence the moisture buffering. These approaches are reviewed below.

4.1. Room in a climatic chamber

Mitamura et al. [46] placed a 4.62 m^3 room in an environmental chamber, in which temperature and RH are kept constant. The purpose of the test was to measure the RH variation, by changing the ventilation rate through a forced ventilation system and changing the location of the tested hygroscopic materials on the surrounding walls. At the same time a small sample of the surface material was weighed on a scale inside the room, to compare the mass change of the material and RH fluctuation in the room. Although it is not clear if infiltration and moisture gain/losses through the ventilation system were considered, Mitamura et al. [46] were among the first to design this kind of facility.

Yang et al. [47] built a two storey structure placed in a climatic chamber, which simulated typical Canadian outdoor conditions. They calculated the accumulated moisture value into the surface (M_{mat}) through the Moisture Balance equation (Eq. 4.1), where not only the air infiltration and moisture diffusion through the envelope, but also the moisture removal through ventilation were evaluated.

$$M_{mat}(t) = (-M_a(t) - M_{diff}(t) - M_{vent-inf}(t) + G(t)) \tag{4.1}$$

Where M_a is the moisture change in the room, M_{diff} is the vapour diffusion through the walls, $M_{vent-inf}$ is the water mass removed by ventilation and infiltration and G is the moisture source.

The accumulated moisture removal ($M_{\text{vent-inf}}$) is defined through the Condensed Water Method:

$$M_{\text{vent-inf}}(t) = C(t) + Q_{\text{inf}}(w_{\text{h}} - w_{\text{l}})t \tag{4.2}$$

Where C is the condensed water, Q_{inf} is the infiltration rate calculated through T and RH sensors and w_h and w_l are respectively are humidity ration injected by the Air Handling Unit (AHU) and the one in the environmental chamber. This method is dependent on the design of AHU (Fig. 5), which weighs the condensed water and controls all psychometric parameters.

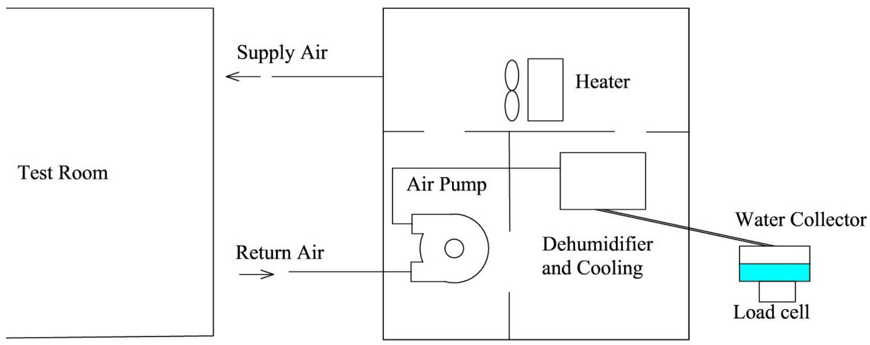

Figure 5: Test configuration of Yang et al. [51]

Later on, Li et al. [52] refined the test procedure in the same facility measuring directly infiltrations though moisture decay in the air after humidity generation stops and the room is not ventilated. They also developed another moisture buffering index, the Effective Damped Relative Humidity (EDRH):

$$EDRH = \frac{P_t \Delta w_{max}}{P_s(0.622 + \Delta w_{max})} \tag{4.3}$$

Where P_t is the barometric pressure, P_s is the saturation pressure at 21°C, Δw_{max} is the difference of average humidity ratio increases, comparing the RH level during the test with the one measured with the same experimental condition but in a non hygroscopic room. Eq. 4.3 also introduced a numerical factor, which includes measurement uncertainty and moisture losses through air leakages.

Meissner et al. [48] developed another set-up to apply the same principles of NORDTEST to a full scale facility. This is comprised of a timber structure mounted on four load cells, which measured the weight variation of the specimen, supported by a wood frame. The 8 m^3 'built-in test-cell' was supplied with an air tunnel (Figure 6), which provided specific hygrothermal conditions inside the structure. However, problems related to the step-response test are not solved and infiltration rates and mass transfer through the structure are not measured. Table 3 compared the previous methods.

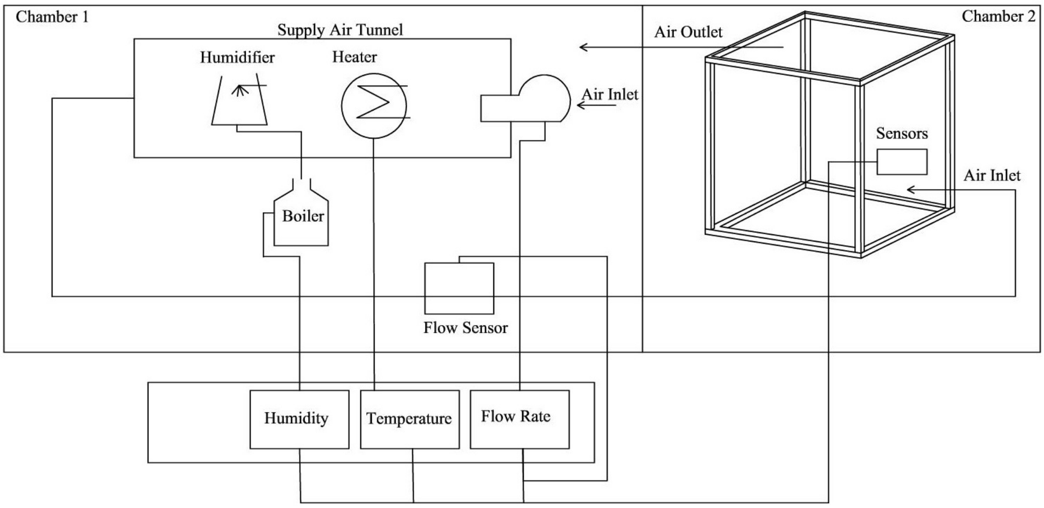

Figure 6: Test configuration of Meissner et al. [53]

Table 3: comparison of methods for test facilities in climatic chambers

Author	Method	Moisture exchange		Chamber T and RH	Room T
		Infiltration	Ventilation		
Mitamura et al.[46]	RH variation	Not measured	Not measured	20°C,50 % RH	20°C
Yang et al. [47]	Moisture Balance	Not specified	Condensed water	-10 °C, 45 %RH	20-21°C
Li et al.[52]	Moisture Balance	Moisture decay	Condensed water	-5 °C, 68 %RH	20°C
Meissner et al. [48]	NORDTEST	Not measured	Not measured	outdoor condition	23°C

4.2. Experimental Room in the outdoors

Another typology of test facility is the one in direct contact with the outdoor environment. An example is Rode et al. [49], who used an insulated steel box equipped with a condensation/evaporation supply, inspired by Padfield [11] (Fig. 7), which simulated the effect of ventilation in the mass balance. They measured the RH variation inside the room, comparing the mass change of specimen boards, placed on a scale, and RH variation. This method does not consider the influence of the mass transfer through the wall and the effects of infiltration and ventilation on the mass transfer surface resistance, due to the absence of a ventilation system.

Künzel et al. [54] set up a test room, where samples were directly applied on the wall but separated by an aluminium foil from the enclosure, to exclude any mass transfer from or to the outdoor. Infiltrations are measured through Blower Door test [55] and a ventilation system is designed to control the air flow. Inside the test room the temperature is kept constant and the RH is free to vary, depending on the moisture buffering effects and the influence of moisture injected from the humidifier and the ventilation system. Künzel et al. [54] consider the dynamic weather conditions an important factor for moisture buffering determination, due to the influence of outdoor temperature and RH through ventilation in the mass balance.

Recently Nghana & Tariku [56] did a similar study, where two 17.8 m^2 test cells were used. Two different materials were tested in each room, which was provided of HVAC system and humidifier, that simulated human moisture production. Differently from Künzel et al. [54], their facilities were provided of an HVAC system, which allows a better control of the ventilation rate and RH. However, Nghana & Tariku only

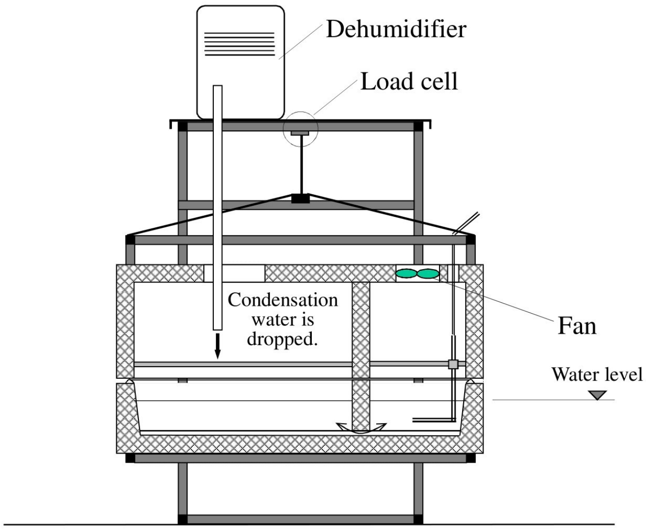

Figure 7: Test humidifier/dehumidifier developed by Rode et al. [49]

focused on the correlation between RH variation in the indoor, moisture production and ventilation rate, not considering the moisture exchange through ventilation, building infiltration and walls moisture diffusion.

4.3. Existing building testing

The evaluation of moisture buffering potential on existing building gives a better comparison for empirical models and more information about the real behaviour of hygroscopic materials, but it is harder to isolate moisture buffering effects of all phenomena in inhabited buildings, and evaluating results is more complex with higher levels of uncertainty. Kalamees et al. [57] showed that moisture buffering effects in inhabited houses is negligible, because it depends on occupant behaviour, ventilation rate and not-fully hygroscopic enclosures.

In contrast, Simonson et al. [12] demonstrated how a well-designed hygroscopic walls improve air quality and thermal comfort and reduce the necessity of ventilation. Simonson et al. [12] focused not only on the moisture buffering properties of the enclosure but also on the diffusion of CO_2, SF_6 and water vapour through walls. They compared building reaction to moisture and gas injection, testing the house, first covering walls with plastic, and then removing it. It was demonstrated that the permeability of the envelope increases the effective ventilation, reduces the concentration of noxious gases in the indoor and reduced the humidity peaks. However, there is uncertainty and discrepancy in the study due to measurement errors when outdoor RH became higher than the indoor, and because solar radiation, mass transfer effects on moisture buffering through walls and air distribution were not known.

Zhang et al. [16] also highlighted the role of hygroscopic material in a real house. They compared moisture buffering tests in a test room inside a climatic chamber and in an existing building, where they compared the humidity ratio between a non-hygroscopic reference room and an hygroscopic one. From this comparison Zhang et al. [16] proposed the Moisture Buffering Effect, a new evaluation method expressed as Moisture Adsorption/Desorption Effect ($\mathrm{MBE_a}/\mathrm{MBE_d}$), where:

$$MBE_{\mathrm{a}} = \frac{\sum_{k=0}^{t} (w'(t) - w_0(t))dt}{\sum_{k=0}^{t} (w'(t) - w_0(0))} \tag{4.4}$$

and

$$MBE_{\mathrm{d}} = \frac{\sum_{k=0}^{t} (w_0(t) - w'(t))dt}{\sum_{k=0}^{t} (w_0(0) - w'(t))} \tag{4.5}$$

where w' and w are respectively the indoor humidity ratio when there is moisture buffering and when there are no hygroscopic materials in the room. The moisture concentration is obtained by a simplified moisture balance where the contribution of ventilation and moisture diffusion through walls are not included. Zhang et al. [16] demonstrated that increasing the hygroscopic surface ratio in houses and decreasing the ventilation rate, moisture buffering has an important impact in the hygrothermal performance of the house, but it is hard to quantify the effects of such materials.

Altogether, full-scale testing does not have a standard procedure, which ensures comparable results and the isolation of moisture buffering from other moisture exchange processes. Testing in a climatic chamber simplifies moisture buffering evaluation, but it does not consider secondary effects, such moisture transfer though walls and variable climatic conditions, on the adsorption process of finishing materials. On the contrary, testing in real buildings have too many variables to consider and there still not a complete understanding of all factors, which may influence moisture balance and transport.

5. Scaling from laboratory to in-situ experimentation

It is clear that moisture buffering still needs to be explored and explained at all scales. It is important to understand the correlation between material characteristics and the indoor environment. Some researchers [9, 7, 58, 59] have noticed the importance to combine and compare laboratory scale and full-scale tests results, in order to better understand the physical principles which regulate the connection between material properties and their influence in a building.

One example is Sagae et al. [9], who analysed zeolite panels at three test scales: in a climatic chamber; in a steel box placed in the outdoors and in a storage room of a museum. Their research considered each test scale independent of each other, in order to evaluate different properties, such as the maximum water amount adsorbed in 24 hours, the damping effects and the humidity control ability of the material. These parameters correlated but were not complementary in the definition of the moisture buffering effects at different scales.

Hameury [60] linked directly moisture distribution in materials, observed through the Magnetic Resonance Imaging (MRI), to step-response humidity cycles developing an alternative method to NORDEST. The cyclically adsorbed and desorbed moisture was estimated, but it is limited to few millimetres of the surface and it is applicable only to small specimens. Hameury also tried to quantify the moisture buffering capacity of walls in a real building, recording the moisture content with $\pm 0.5\%$ accuracy Pin-Type moisture meters, applied in the first 3 mm of the surface. Difficulty to apply sensors at the same width and the impossibility to insert them deeper make it impossible to measure the direct quantification of the moisture buffering process.

Vereecken et al. [58] verified the applicability of a new definition of moisture buffering (HIR*), which combine the MBV* (Eq. 3.1) to the Hygroscopic Inertia (Eq. 3.3) , to full-scale simulation. The HIR* value is measured in a laboratory and then implemented in the Effective Moisture Penetration Depth Model (EMPD).

$$HIR^* = \frac{\sum_{k=i}^{n} (S_{\mathrm{i}} \cdot MBV^*{}_{\mathrm{i}}) + \sum_{k=j}^{m} MBV^*{}_{\mathrm{obj,j}}}{V} \tag{5.1}$$

The methodology validation is carried out either in a test room or in a real building, where NORDTEST protocol is followed. There is a good agreement with the empirical model, but the validation is limited only

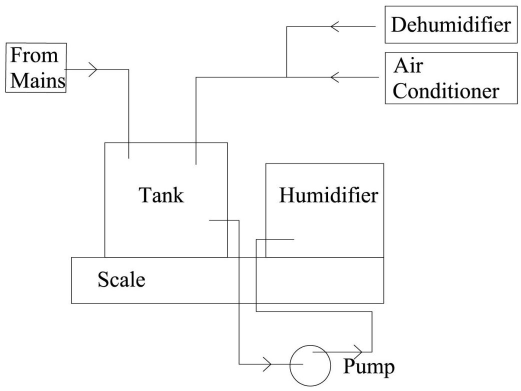

Figure 8: HVAC system developed by Woods et al. [59]

to a single case where ventilation and infiltration moisture gains are not measured and infiltration rate and indoor humidity are assumed constant.

Similarly to Vereecken et al., Woods et al. [59, 32] verified the applicability of the existing EMPD simulation model, which is based on standard material properties, like permeability and moisture sorption curve, to predict the moisture buffering capacity of hygroscopic materials in a house. They also developed a new experimental set-up, which is applicable both in the laboratory and in real buildings. The main component is the HVAC system, which controls the moisture removal and addition to a water tank placed on a scale and keeps the temperature constant in the house (Fig. 8). Moisture buffering is calculated from the mass balance, which includes measured moisture gains and losses through infiltration and the HVAC system, and compare results with the classical step-response method. The good agreement between the two methods in a climatic chamber led Woods et al. to conduct their new method in an existing house. From the results obtained by their experimental set-up they derived inputs for building simulations from house testing, improve the correlation between properties materials and the indoor humidity variation in the dwelling. In Table 4 all previous methods are summarised.

Table 4: comparison of outdoor test facilities

Author	Method	Moisture exchange		Wall assembly	Room T	Location
		Infiltration	Ventilation			
Rode et al. [49]	RH/Weight variation	Gas decay	No ventilation	Insulated steel	20°C	Denmark
Künzel et al. [54]	RH variation	Not specified	Not specified	Bricks	20°C	Germany
Nghana & Tariku [56]	RH variation	Not measured	Not measured	Steel frame	21°C	Canada
Kalamess et al. [57]	RH variation	Not measured	Not measured	170 assembly	variable	Netherlands
Simonson et al. [12]	RH variation	Gas decay	Condensed water	Timber frame	Variable	Finland
Zhang et al. [16]	RH variation	Not measured	Not measured	Timber frame	20°C	Not specified
Sagae et al. [9]	RH variation	Not measured	Not measured	Not specified	Not specified	Japan
Hamaury et al.[7]	Water content	Not measured	Not measured	Massive Wood	Variable	Sweden
Vereecken et al.[58]	RH variation	Not specified	No ventilation	AAC	Not specified	Belgium
Woods et al.[59]	Moisture Balance	Gas decay	Condensed water	Tmber frame	21-25°C	USA

Overall, in full-scale testing there are still some aspects to improve and consider as the moisture diffusion through the walls, the effects on the model of less accurate HVAC and ventilation systems, the influence of temperature fluctuation, the effect of different weather conditions and different enclosures.

6. Conclusion

Moisture Buffering is a tangible property, which influences the hygric balance of indoor environments and improve hygrothermal comfort. From the review of papers the lack of a globally agreed method to measure transient moisture transport and accumulation properties of hygroscopic materials is evident. Simulation tools were developed from steady-state material properties, which do not sufficiently represent dynamic material behaviour, while laboratory scale investigations were performed with various test conditions and test arrangements, making comparisons between different experimentation unclear. Consequently, moisture buffering measurements vary depending on the test set-up and the different interpretations of moisture exchange phenomenon.

It is important to use full-scale testing, to improve laboratory scale tests. A direct comparison between the two scales can bring improvement to moisture buffering material experimentation, as it is possible to modify existing testing, depending on the real behaviour of hygroscipic materials in buildings. Nevertheless, it is already clear, that the step response method is not representative of real indoor RH variation. It is probably necessary to adopt another kind of profile (like the sinusoidal one). Furthermore, existing methods mention the importance to control the air speed in moisture buffering testing. Wind tunnel can be a solution, but it is also comprehensible, that it is not always possible to reproduce it. However, it is more realistic, to understand what are the air movement and distribution inside climate chambers, and adjusting the final MBV, depending on air velocity. In this way, it is possible to have homogeneous results, independently on the facility, which is used.

However, there are uncertainties on the full-scale experimentation, which is essential to validate material scale testing and simulation. Moisture buffering in real dwelling is influenced by other moisture transport mechanisms, which make more difficult to isolate the dynamic water sorption process and to quantify its impact in the environment. It is also important to notice that climatic chamber air distribution and step response combined in climatic chamber with modifying factors

There are also uncertainties on the full-scale experimentation, which are essential to validate material scale testing and simulation. Moisture buffering in real building is influenced by other moisture transport mechanisms, which make it more difficult to isolate the dynamic water sorption process and quantify its impact on the environment. However, it is possible to improve existing methods, identifying the main factors, that contributes to the moisture balance in indoors and analysing them one by one. The first factors to consider are infiltration and ventilation. Authors have always considered ventilation rate a strong influencing phenomena on moisture buffering, but the relationship between ventilation and moisture buffering has never been really established. Ventilation might be analysed in two different ways: as contribute to indoors moisture balance and as air movement on the wall surface. It has been demonstrated, that increasing the ventilation rate, moisture buffering performances decrease.

Another consideration is related to moisture transport mechanism in walls. Moisture moves through enclosure, due to water vapour pressure or RH differential between the indoor and the outdoor. However, moisture buffering is always considered as an independent variable, which is not included in the moisture transport. Probably, this is not completely true and probably an accurate design of the whole enclosure could amplified moisture buffering effect.

For all these reasons, it is necessary to have more full scale testing and develop a standard procedure to evaluate moisture buffering performance of a building, to allow systematic and replicable verification methods.

Overall, there is a need to better understand the impact of hygroscopic materials on the indoor climate control and how they may play an important role in ventilation and conditioning design. It is important to help designers estimate and quantify the influence of exposed surfaces in the indoor on the Relative Humidity. This will stimulate development and improvement of new moisture control materials and promote their use to improve indoor hygrothermal comfort and reduce conditioning energy consumption.

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