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A novel methodology and new concept of structural dynamic moisture buffering for modeling building moisture dynamics

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Abstract

This paper presents a new methodology that takes a physical-statistical approach to dynamically model indoor air humidity and moisture transport in building structures. A new concept, structural dynamics moisture buffer capacity (SDMBC) is introduced that improves on the most commonly used moisture buffer measure. The paper proposes and experimentally proves several novel hypotheses regarding the linear relationship between model variables, great simplifying the

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derivation of the model equations. The resulting dynamic model is simple, efficient, and easy-to-implement. Furthermore, full-scale experiments using three identical wooden test houses were built to support the development of the dynamic model. Airflow rates were calibrated and verified by experiment. The results of this study establish the practicality of this new modeling methodology which can aid researchers in constructing improved simulation models and designers in selecting building materials to optimize indoor humidity, minimize energy consumption, and provide good indoor environmental quality.

Nomenclature

a,b,c	model parameter
AH	(absolute) moisture content [gm^{-3}]
C,C(0)	CO_2 concentration [ppm]
$G_{structure}$	moisture flow rate between indoor air and building structure [gh^{-1}]
I	air change rate [ls^{-1}]
Q	airflow rate [m^3h^{-1}]
t	time [s]
V	volume [m^3]

Subscripts

in	indoor
out	outdoor

Abbreviations

RH	relative humidity
MBC	moisture buffer capacity
MBV	moisture buffer value

SDMBC structural dynamic moisture buffer capacity

***Keywords**:* Moisture buffer; hygroscopic material; dynamic model; physical model; statistical model; multi identical test houses; plywood; gypsum plasterboard; massive timber

1. Introduction

The European Union (EU) is promoting sustainable buildings for the purpose of reducing their resource consumption and lifecycle environmental impacts [1]. In response to this imperative, hygroscopic materials, such as environmentally-friendly wood, are being promoted for use because of their moisture buffer capacity (MBC) [1]. The MBC in buildings offers a sustainable way to improve indoor air quality (IAQ), thermal comfort, and energy efficiency because it can dampen changes in humidity and save energy by reducing the system operating hours and the size of HVAC systems [2]. A critical review of the effects of moisture buffering on building energy consumption in different climates was conducted and the results show that moisture buffering has a great impact on building energy performance in a wide variety of climate zones (e.g. Paris and Madrid), with an energy reduction potential of up to 25–30% [3]. Based on measurements and simulation, Brauner et al. demonstrated how to efficiently use the moisture buffer effect of materials to target the selection of building materials based on their temperature and relative humidity performance [4]. Using hygroscopic materials, a desiccant coated air-to-air energy wheel, and a new type of ceiling panel with a vapour permeable surface, Fauchoux et al. presented a method for moderating indoor humidity and IAQ in buildings [5]. The passive hygrothermal performance of materials for controlling indoor thermal and humidity buffering capacity was investigated in [6]. Further, the adaptive evolution of the construction of the traditional Basque architectural model in terms of their passive hygrothermal behaviour and effects on indoor comfort was analysed based on measurement of hygrothermal data (indoor temperature and relative humidity) at 15 minute intervals using a SenNet DR-30-24 datalogger and two SenNet DL THL-I measuring devices [7]. Ojanen [8] used the commercial software WUFI plus to simulate indoor humidity in a log house with massive laminated logs as the wall structure. The results indicate that the moisture buffering effect of the log wall helps to maintain indoor conditions in a comfortable zone by reducing the incidence of high and very low relative humidity conditions. Similar simulations can be found in [9-11].

The literature clearly demonstrates that understanding the hygroscopic behaviour of building structures can result in the development of novel materials and controls for improved energy performance, IAQ, and the sustainability of buildings. This requires knowledge of moisture transfer inside and between materials (e.g. molecular vapor diffusion, capillary flow, evaporation and condensation) and hygrothermal properties (e.g. permeability, porosity, and sorption isotherm) [12]. Some of these parameters can only be determined by time-consuming experiments. The state-of-the-art methods used for this purpose focus on the material level or room/building level.

At material level, experiments are still dominant. The NORDTEST project [13] uses a test protocol to determine the moisture buffer values (MBVs) of materials of a variety of hygroscopic building such as spruce plywood, spruce board, concrete, gypsum, and laminated wood [14-15]. Similar to the MBV method, the effective moisture penetration depth (EMPD) model [16] has been developed and widely used due to its fast calculation times and reasonable accuracy. EMPD assumes two fictitious layers of material with uniform moisture content and the model calculates the moisture transfer between the air and the surface layer and between the two fictitious layers. The values of MBVs for materials, simple elements, and complex elements commonly applied to building interior surfaces can be found in [17]. A more complex model of Fick's second law was proposed in [18] to model one dimensional, unsteady-state, isothermal moisture transfer through a massive wooden wall. The Hailwood–Horrobin equation, a nonlinear relationship among temperature, relative humidity and equilibrium moisture content, was employed to compute the equilibrium moisture content for a wooden wall.

At room/building level, the operational indoor and outdoor environments are taken into consideration. To study the MBC of different building materials used for interior walls that are subject to variable internal moisture loads, ventilation rates, and exposed areas of materials to indoor air, most experiments focused on the internal moisture loads and artificially controlled the loads and outdoor climate conditions [14, 19-22]. This is convenient for analysis, but it does not represent the actual conditions. For example, in some instances, if mechanical ventilation is introduced into residential buildings, the amount of moisture brought into an empty place is significant and likely greater than the moisture generated by occupants. This condition is ignored in most room/building-level studies. As was previously described, there is a significant body of literature on detailed moisture flow simulations. The modeling methods typically use a holistic approach to the combined heat, air, and moisture flow in building structures. However, the underlying physical mechanism of structural moisture buffering remains obscure because the hygrothermal performance of buildings is very complex in terms of materials, ventilation, heating and cooling, airtightness, and other factors [4].

In this paper, we propose a novel modeling methodology to address these challenges. We introduce the concept of structural dynamic moisture buffer capacity (SDMBC) and formulate a new concept for building structural moisture buffering to simulate moisture buffering dynamics at building structural level combined with the actual indoor and outdoor environments. A new physical-statistical approach is applied to construct a simple dynamic model for injecting dynamic variations of operational indoor-outdoor environment into the static representation of structure's buffering dynamics. The developed method is easy to implement and the resulting dynamic model is computationally efficient, simple to use, and has good accuracy. Our second contribution is the full-scale experiments built for multiple identical test houses, a strategy rarely found in the literature.

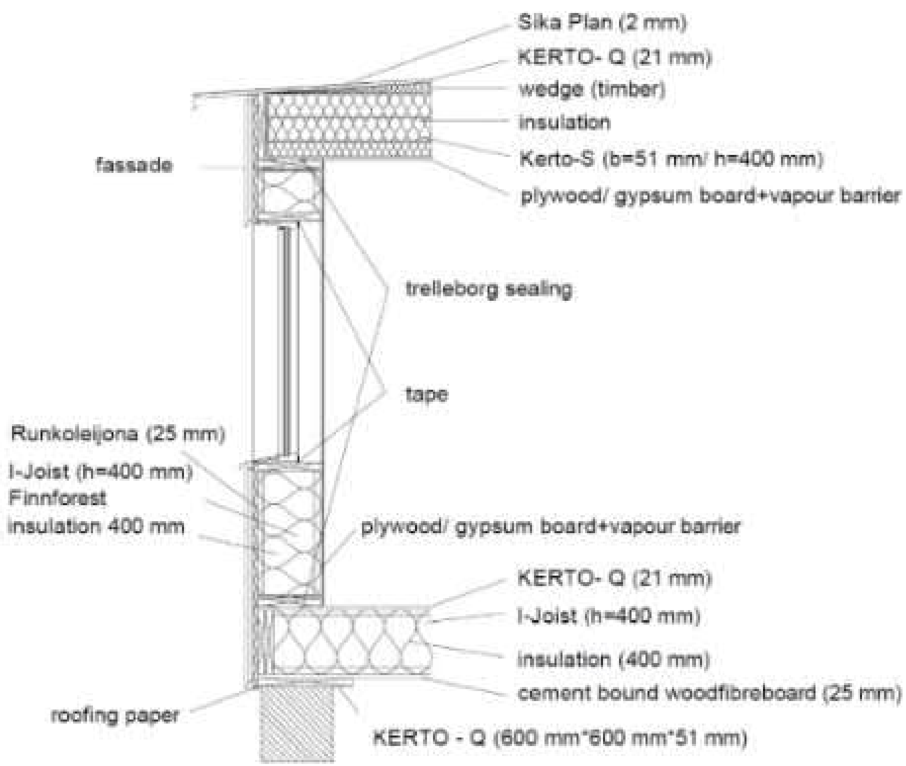
2. Well-controlled and full-scale experiments

Well-controlled and full-scale experiments of three identical houses were designed to specifically determine the dynamic mechanisms of moisture buffer at structural level under systematic variation of the related indoor and outdoor operational environments. As discussed in the Introduction, because internal moisture loads are the most important influencing variable, most experiments and simulations focus on investigating this factor. To rule out this important confounding variable, test houses were designed to be empty and without internal moisture load. Three virtually identical or twin wooden test houses were built on a university campus in Finland (Fig.1). The floor area is 10.2 m^2 and the height is 2.8 m with two windows (one 1.7 m x 1.5 m fixed triple glazed window facing the south and the other 0.8 m x 1.5 m operable box-type window facing the east). Detailed description of the three twin houses can be found in [23]. For the convenience of discussion, the three test houses are named based on their interior cladding materials: (1) Plywood house, (2) Gypsum house, and (3) Massive Timber house.

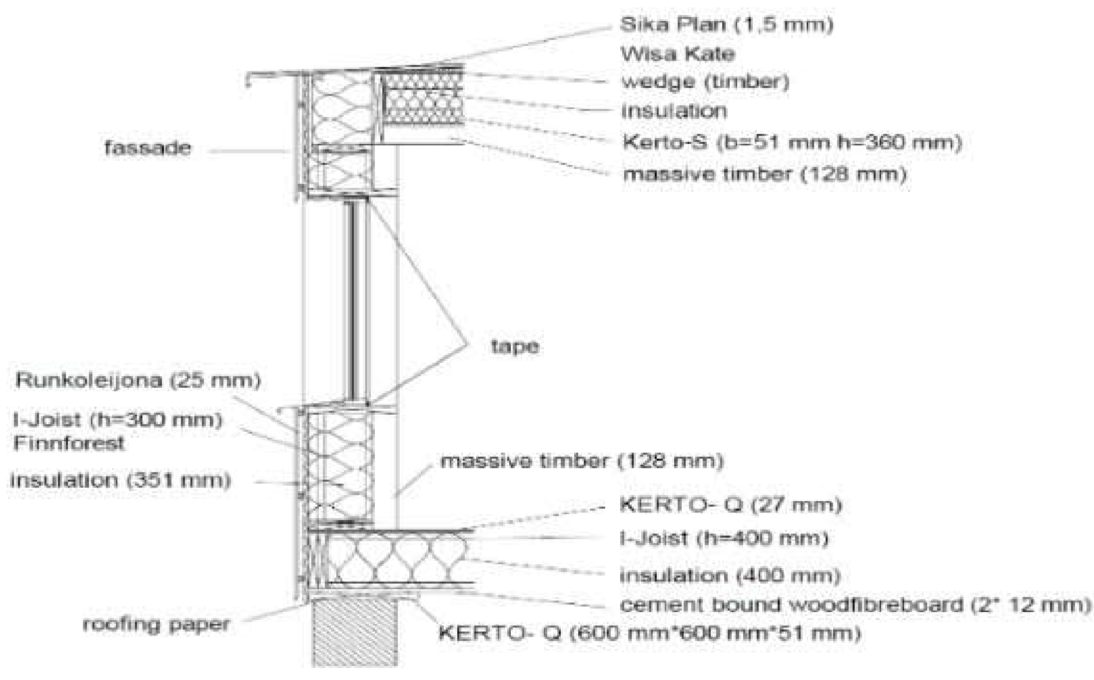
Fig.1. The three wooden test houses.

2.1. Structures and ventilation system

The Plywood house and the Gypsum house have “lightweight” timber structure while the Massive Timber house has “heavyweight” timber structure, as shown in Fig.2. All test houses have similar floor structures, built mainly with I-joists and laminated veneer lumber (LVL) panel as the interior cladding and cement-bound wood fiber board as the exterior cladding. The main difference among test houses is the interior cladding: the “lightweight” Plywood and Gypsum houses use 15 mm thick spruce plywood cladding and 15 mm thick gypsum plasterboard with an additional vapor barrier. The “heavyweight” Massive Timber house uses 128 mm cross laminated pine logs as the interior cladding, as shown in Fig. 3 [23].



(a)



(b)

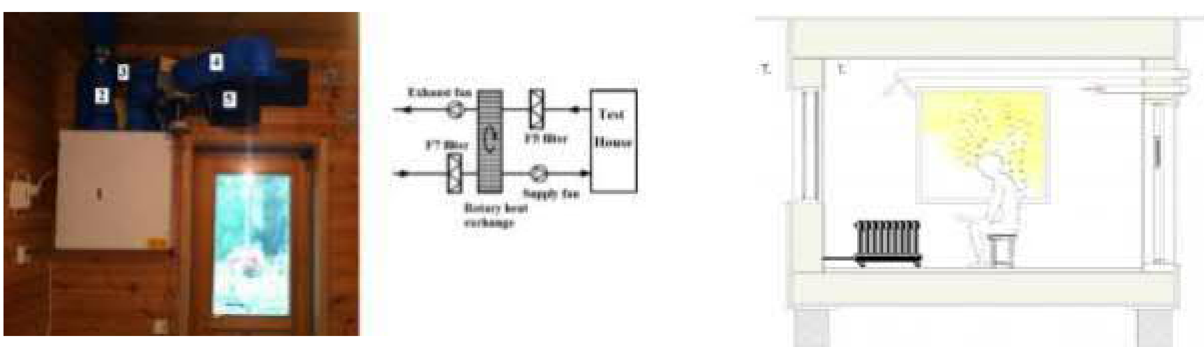
Fig.2. Cross sections of the lightweight (a) and the heavyweight (b) timber houses.

a) b) c)

Fig.3. Interior cladding: a) and b) Lightweight construction; c) Heavyweight construction.

The U-values were intentionally designed to be the same to allow comparison of the three different interior cladding materials and their impacts on indoor humidity. According to the state-of-the-art energy regulations in the Passive House standard, U-values were chosen as 0.1 W/m²K for walls and floors and 0.09 W/m²K for roofs. During a Blower-Door-Test, all test houses showed similar airtightness properties with q50 (EN 13829 standard of airtightness) values of about 0.6 1/h.

The same type of ventilation unit (Enervent Plaza eco EDE) was used in each house and consisted of a rotary heat recovery unit mounted to the wall (Fig.4). A 2000W oil-filled electric heater with 9 ribs and a thermostat was employed to heat test houses (Fig.4).



(a) (b)

Fig.4. (a) Ventilation unit and its diagram; (b) The electric heater.

2.2. Measurement and calibration setup

Three different outdoor air ventilation rates based on the floor area were utilized for all the test houses: 0.5 $(dm^3/s)/m^2$, 1 $(dm^3/s)/m^2$ and 2 $(dm^3/s)/m^2$, a total of nine experiments. Halton PRA-100 and Swema 3000 air flow measuring devices were used for calibration with a Swema 300 differential pressure gauge that was connected to the measurement taps (Fig. 5). Indoor temperature (accuracy±0.3°C), relative humidity (RH) (accuracy ±2-3%) and carbon dioxide (CO_2) concentrations (accuracy±50ppm) were measured using a Gray Wolf Sensing Solution system, which provides cloud-based logging, remote access and control of the WiFi-enabled AdvancedSense meter (Fig. 5).

(a) (b) (c)

Fig.5. (a) Halton PRA-100 air flow damper; (b) Swema 3000 device; (c) AdvancedSense Environmental Test Meter.

Corresponding outdoor temperature and relative humidity were obtained from the Finnish Meteorological Institute at Tapiola weather station, which is about two kilometers away from the experiment site. The outdoor data were collected at 10 minute intervals. In order to integrate two types of data, hourly average values were used for analysis.

3. Methodology

To model the structural dynamics of moisture buffer capacity, SDMBC, that produces the indoor humidity level AH_{in} in response to outdoor humidity AH_{out}, we introduce three components separating distinct hygroscopic moisture transport pathways (Fig. 6), and for each component we develop a model.

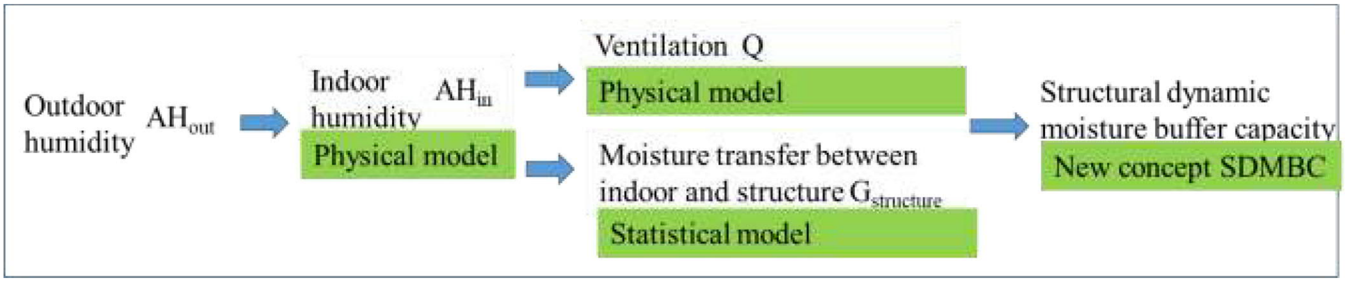


Fig.6. Block diagram for describing the new modeling method and defining the new concept SDMBC (structural dynamic moisture buffer capacity).

3.1. Indoor humidity and ventilation

Because the size of the test houses is small, indoor air is assumed well-mixed. The moisture mass balance shows [15]:

$$V.\frac{d(AH_{in})}{dt} = Q.(AH_{out} - AH_{in}) + G_{structures} \tag{1}$$

where $G_{structures}$ is the moisture flow between indoor air and building structures.

The CO_2 mass balance equation is:

$$V\frac{dC_{in}(t)}{dt} = Q(C_{out} - C_{in}(t)) \tag{2}$$

Eq. (2) is solved as

$$C_{in}(t) = C_{out} + (C(0) - C_{out})e^{-It} \tag{3}$$

where $C(0)$ is initial concentration of $C_{in}(t)$ and I = Q/V, air change rate (1/s). All houses experienced infiltration because exhaust airflow rates were slightly higher than supply airflow rates. Therefore, the exhaust airflow rate can be assumed to be the sum of the supply airflow rate and infiltration.

3.2. New hypotheses and statistical models

We propose original hypotheses and statistical models of linear regression tested by the experimental data: Both AH_{in} and $G_{structures}$ can be predicted linearly by using weather conditions:

$$AH_{in} = a.AH_{out} + b \quad (4)$$

$$G_{structures} = a_{structures}.AH_{out} + b_{structures} \quad (5)$$

where a , b, $a_{structures}$ and $b_{structures}$ are constant model parameters. Figs.7-8 illustrate experimental evidence for the hypotheses. As can be seen, high R-square model accuracies (Fig. 7 and Fig. 8a.) and relative high model accuracy (Fig. 8b) are obtained which confirm the proposed hypothesis.

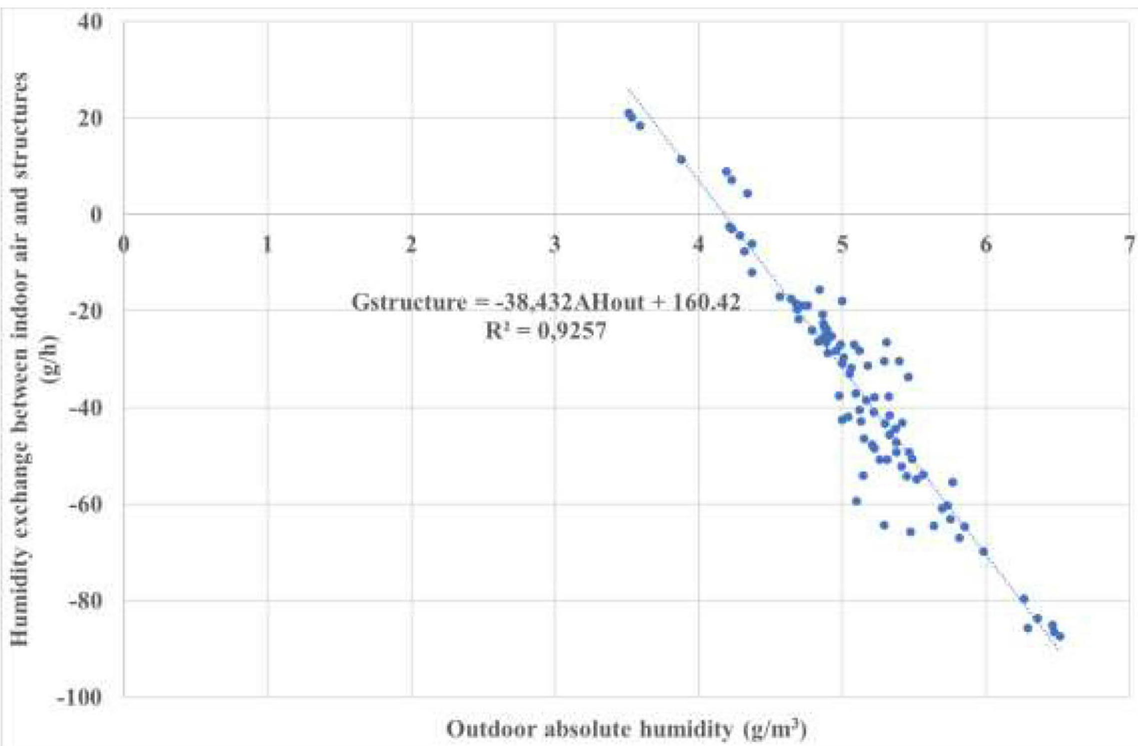
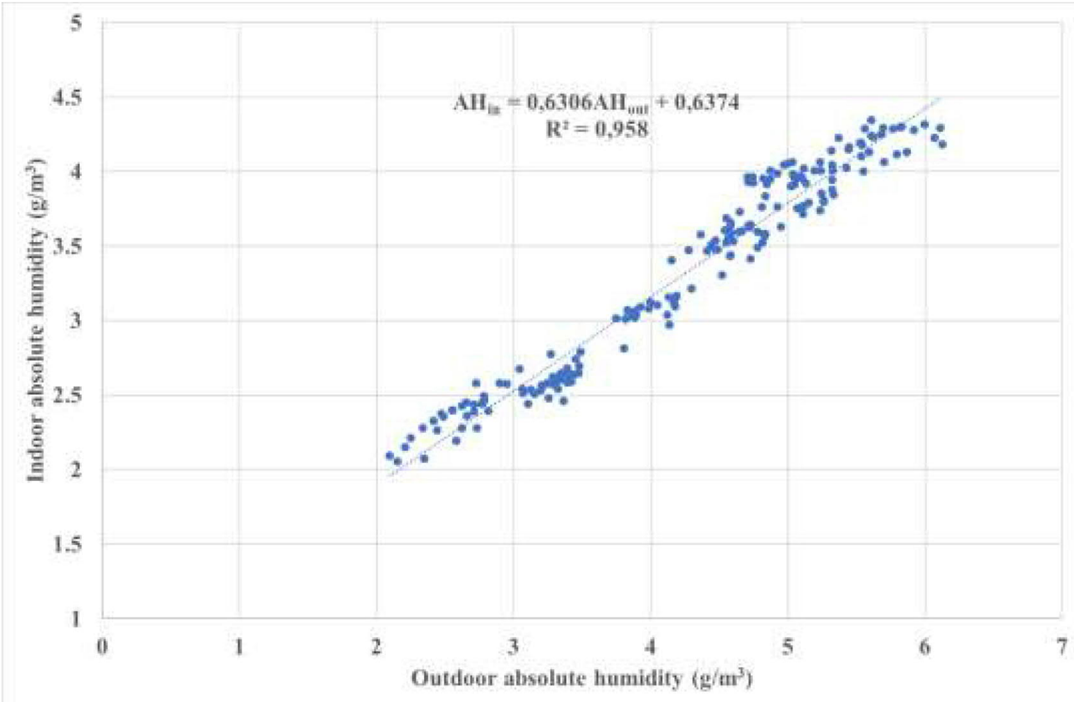
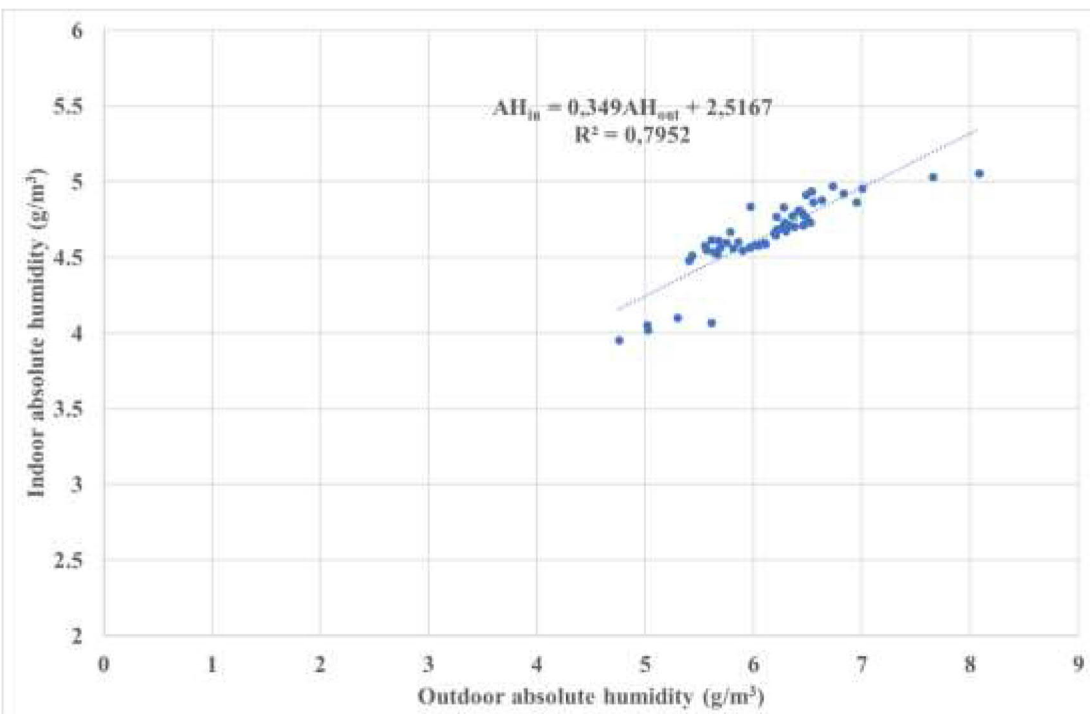


Fig.7. The hypothesis testing of $G_{structures}$ for Massive timber house at the airflow rate 1 $(dm^3/s)/m^2$.



(a)



(b)

Fig. 8. (a) The hypothesis testing of indoor humidity for Plywood house at airflow rate 2 $(dm^3/s)/m^2$**;** (b) The hypothesis testing of indoor humidity for Gypsum house at airflow rate 1 $(dm^3/s)/m^2$**.**

3.3. Novel hypothesis for moisture buffer concept SDMBC

Based on previous hypotheses/statistical models and the observation that the internal moisture excess change (AH_{in}-AH_{out}) is roughly proportional to the outdoor humidity change AH_{out}, we put forward a novel hypothesis: The "rough proportionality" between (AH_{in}-AH_{out}) and AH_{out} means the change speed is not constant but varies with the dynamic change of the structural dynamic moisture buffer, namely

$$(AH_{in} - AH_{out}) = SDMBC.AH_{out} + c \quad (6)$$

Here, we define the new concept, SDMBC or structural dynamic moisture buffer capacity, which is a function of the ventilation rate, Q, that is: SDMBC = SDMBC(Q). Fig. 9 shows the experimental evidence supporting the new concept of SDMBC modelled in Eq. (6).

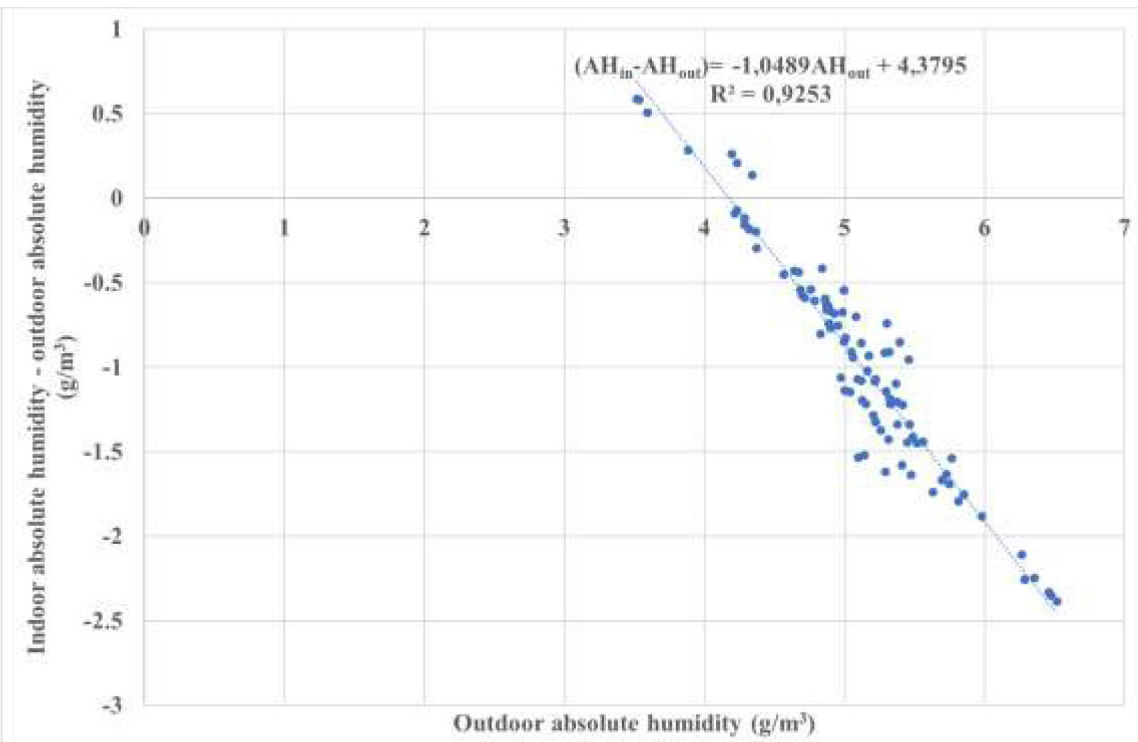


Fig.9. The hypothesis testing of the new concept illustrated in Massive timber house for airflow rate 1 ($(dm^3/s)/m^2$).

Eqs (1-6) provide novel methodology for modeling building indoor humidity, ventilation rate and building structures' moisture buffer dynamically. Model parameters are determined by minimizing the mean squared error between the measured and predicted data through measurements, as shown in Fig.7-Fig.9. Model performance is evaluated based on the commonly used R^2 metric. Half of the data were used for model development and the other half for model verification. Results indicate good-fitting models and confirm our hypotheses (R^2=0.7587). We demonstrate some of the results below.

4. Results

At the same outdoor test conditions, the moisture buffering capacities of the identical test houses under three different ventilation rates were measured, simulated and compared. The moisture buffering performance of each house with varying ventilation rates is investigated first. Then the moisture buffering capacities of the three identical test houses under the same ventilation rates are studied and compared. The predictive model for ventilation rate is also validated. The results are reported below.

4.1. Ventilation

Fig.10 shows comparison of measured and predicted indoor CO_2 concentrations in Gypsum house. Very good agreement was obtained as indicated from all the results listed in Table 1. For example, for the targeted ventilation rate 0.5 $(dm^3/s)/m^2$, the predicted values are 0.49, 0.53 and 0.51 $(dm^3/s)/m^2$ for the three test houses. As can be seen from the results, the predictions are precise.

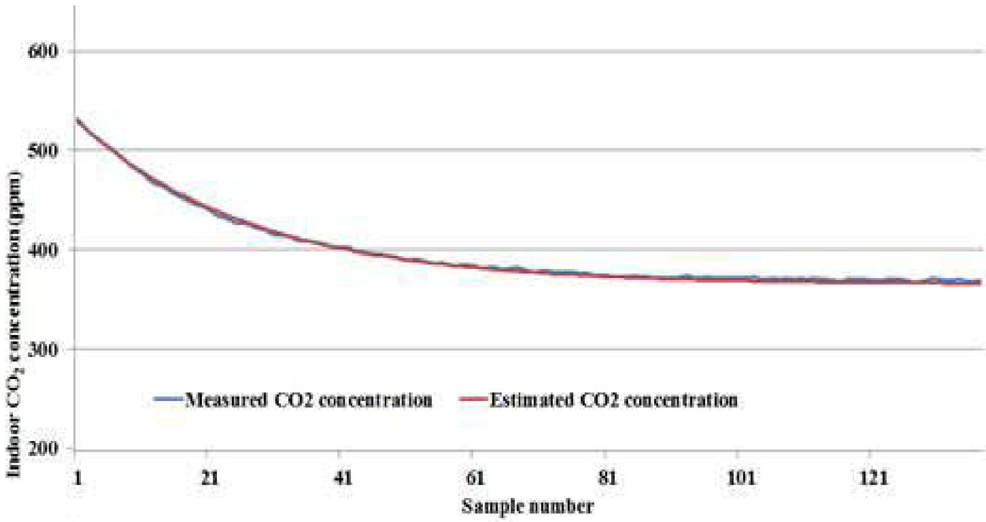


Fig.10. Measured and predicted CO_2 concentrations in Gypsum house (airflow rate 1.97 $(dm^3)/m^2$ with the target value 2 $(dm^3)/m^2$).

Table 1.

Airflow rate model results and corresponding outdoor CO_2 concentration. Three testing ventilation rates are separated by common. Predicted values are in bold and brackets.

Test house	**Three target and predicted airflow rate $(dm^3/s)/m^2$**	**Outdoor CO2 concentration (ppm)**	**Mean squared error**
Plywood house	0.5 (**0.49**) , 1 (**1.03**), 2 (**1.95**)	405, 400, 360	9.5, 7.3, 3.5
Gypsum house	0.5 (**0.53**) , 1 (**0.97**), 2 (**1.97**)	395, 375, 365	1.9, 4.0, 5.4
Massive timber house	0.5 (**0.51**) , 1 (**0.95**), 2 (**2.03**)	370, 375, 360	1.6, 1.1, 6.4

4.2. Comparisons within and between twin test houses

Figs.11-16 illustrate the comparisons of indoor humidity at different airflow rates within and between the test houses for a 24 hour period. Fig. 17 displays the corresponding outdoor temperature and relative humidity and Fig. 18 provides a statistical summary. It should be noted that values of outdoor temperature and RH from a local meteorological station were used in our analysis. Because the distance between the local meteorological station and the measurement site is only 2 (km), we considered that it was adequate to use local meteorological station data. Local microclimate data, for example RH, are more accurate, but the concept of microclimate depends largely on the question being addressed. One drawback of using local microclimate input is that it is complex and determined by the configuration of surrounding buildings, street layout, building density, and separation of buildings, etc [24]. Therefore, in terms of generality, microclimate data are less representative for investigating material hygrothermal response to climate conditions in this study. Furthermore, the data show microclimatic and climate gradients in humidity are the same despite a small discrepancy, see Figure of comparison of absolute humidity for climate and microclimate data in [24]. Hence sufficient generality is achieved without using microclimate data.

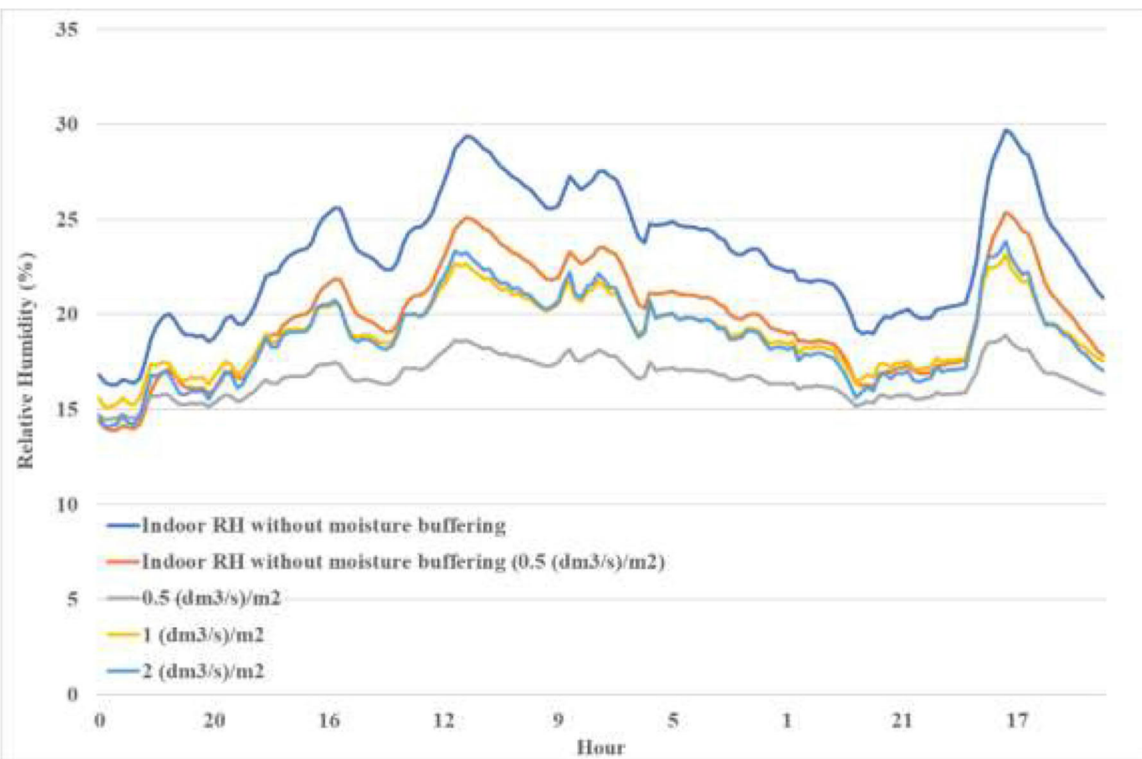


Fig.11. Comparisons of indoor humidity at different airflow rates in the Plywood house.

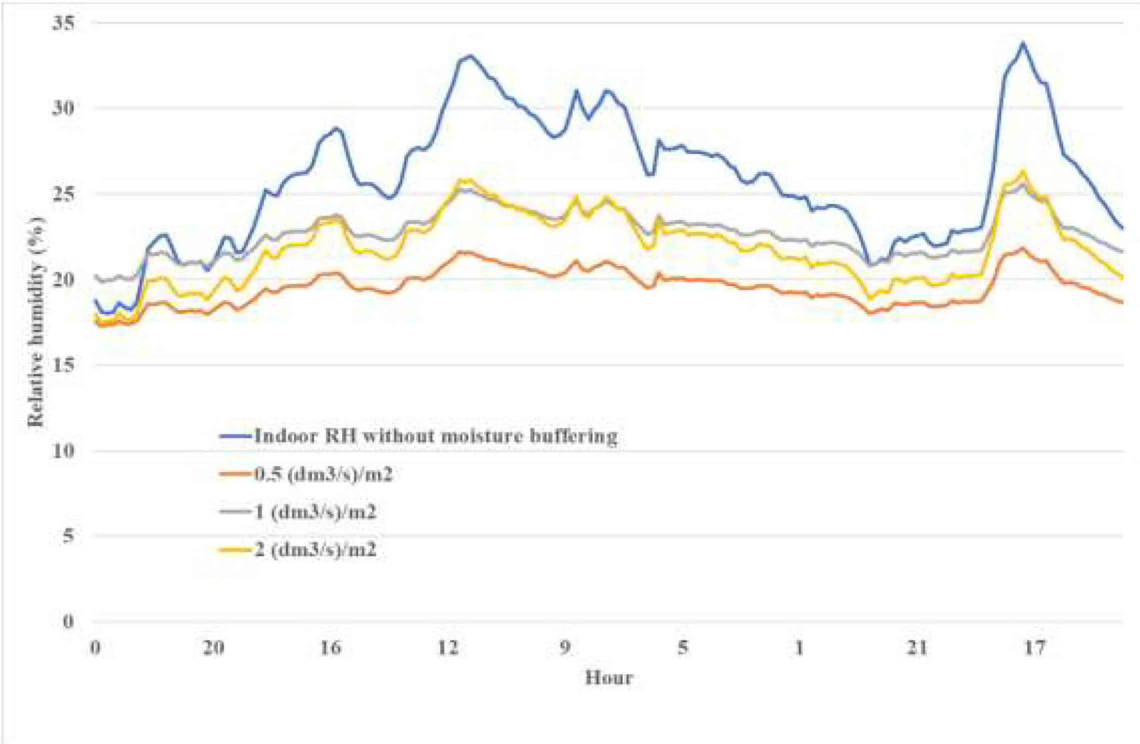


Fig.12. Comparisons of indoor humidity at different airflow rates in the Gypsum house.

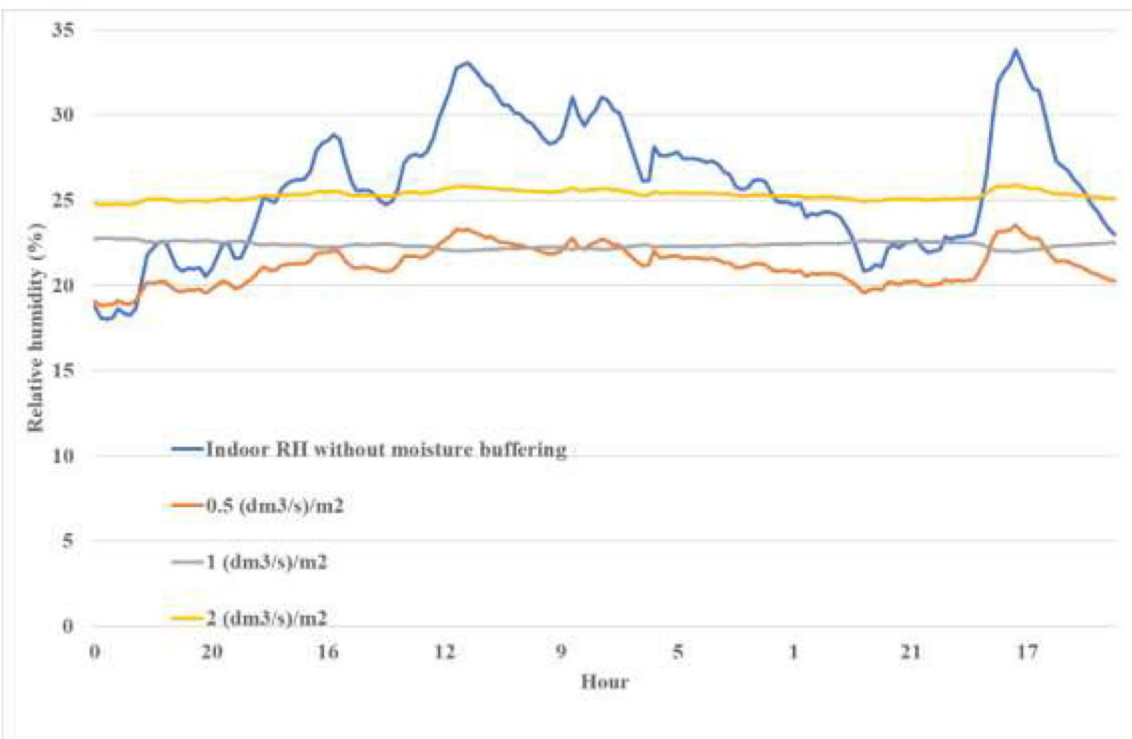


Fig.13. Comparisons of indoor humidity at different airflow rates in the Massive timber house.

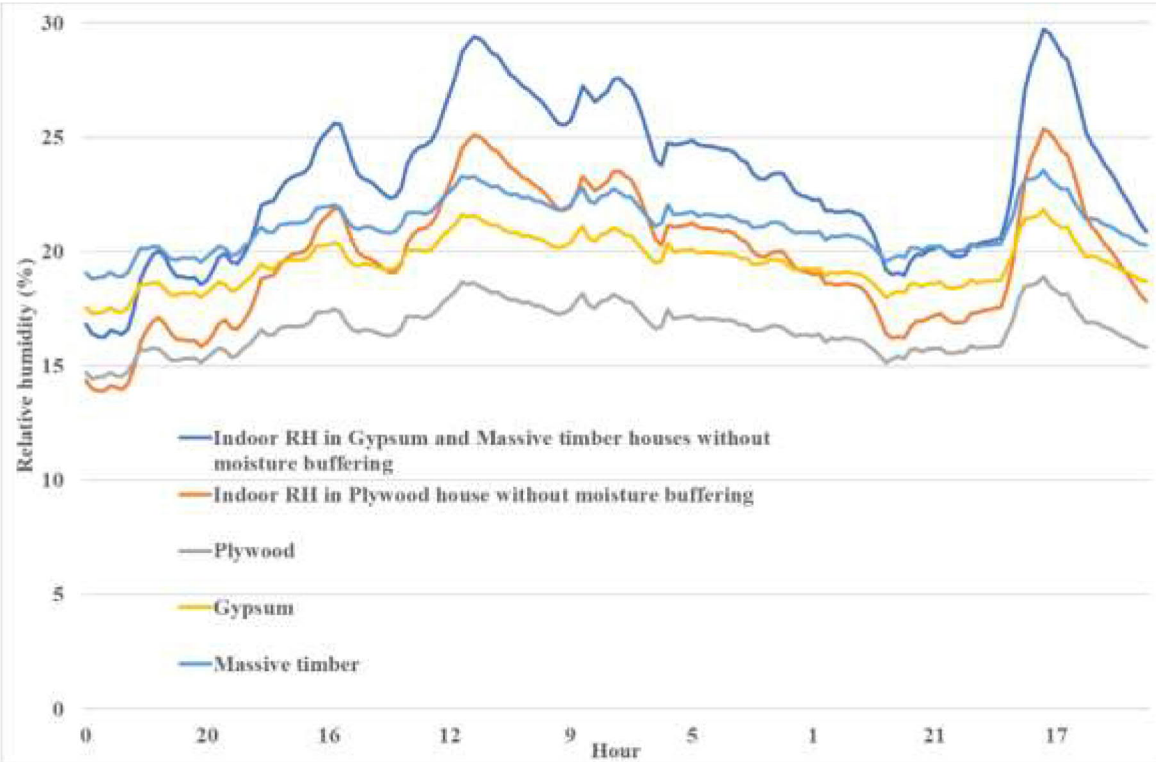


Fig.14. Comparisons of indoor humidity between test houses at ventilation rate 0.5 (dm^3/s)/m^2.

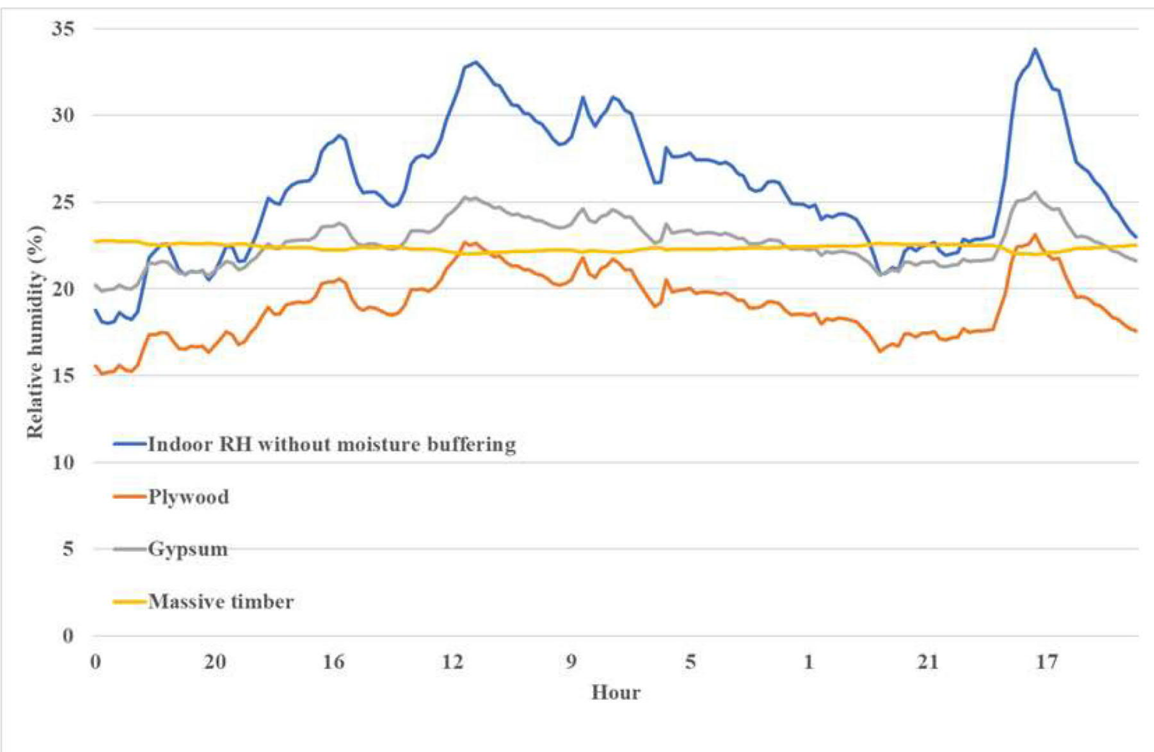


Fig.15. Comparisons of indoor humidity between test houses at ventilation rate 1 (dm^3/s)/m^2.

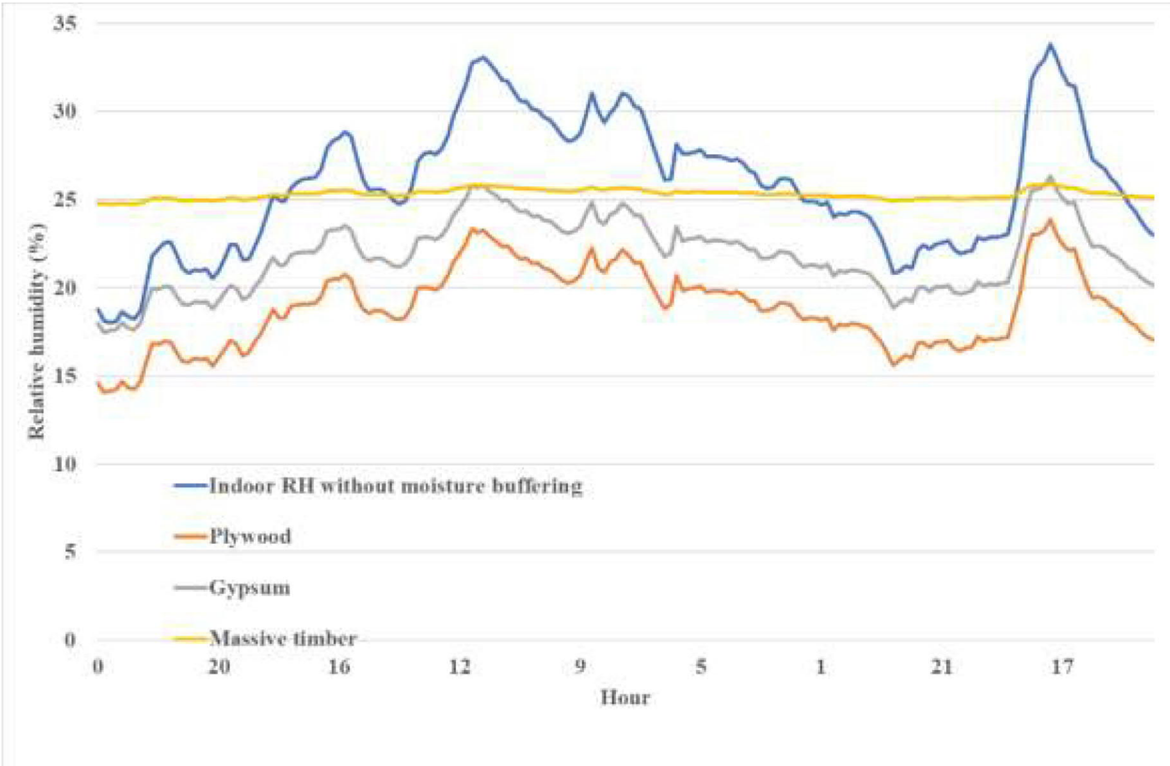


Fig.16. Comparisons of indoor humidity between test houses at ventilation rate 2 $(dm^3/s)/m^2$.

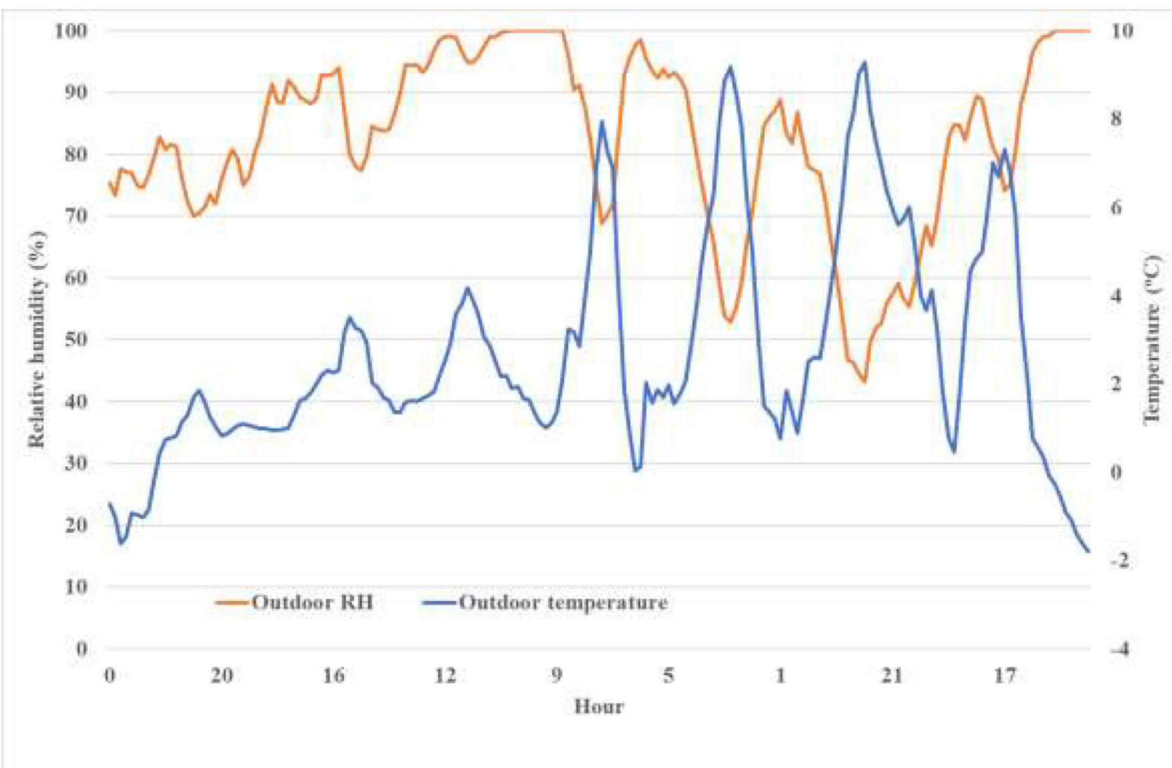


Fig.17. Corresponding outdoor temperature and humidity.

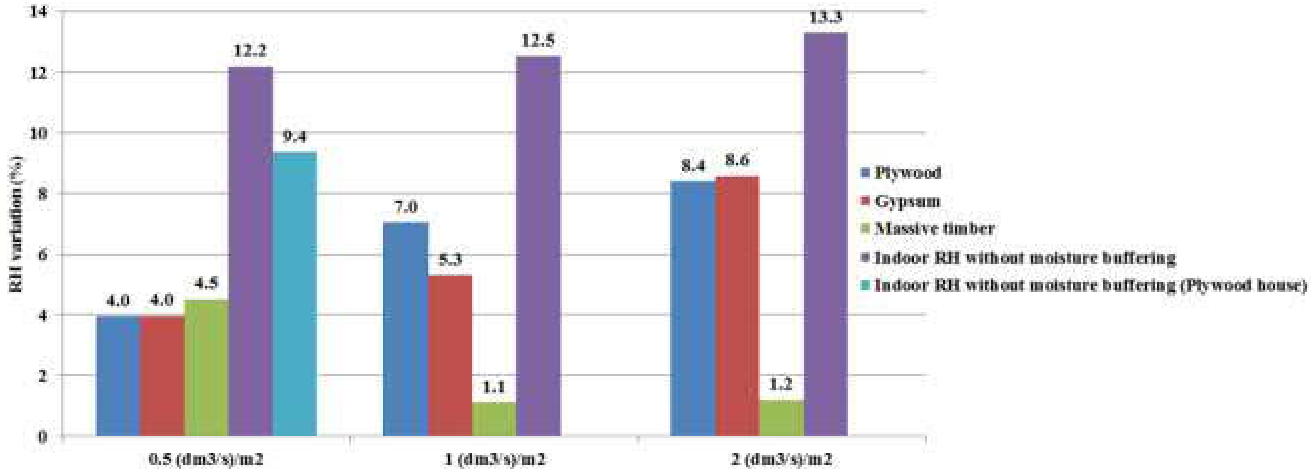


Fig.18. Comparisons of indoor humidity variation (Max RH–Min RH) among twin test houses.

In all the experiments, the indoor temperatures were controlled at 21.5±2.5°C. Moisture buffering can be observed in all cases. Among the identical test houses, the Massive Timber house demonstrates the strongest moisture buffering capability, particularly at higher airflow rates. As shown in Figs. 14-16, indoor RH in the Massive Timber house is almost constant. It is capable of not only reducing the maximum indoor RH but also increasing the minimum indoor RH. For instance, at ventilation rate 2 $(dm^3/s)/m^2$, the Massive Timber house increases the minimum indoor RH by 4.7% so that indoor RH (25.24% on average) presents the ideal RH for health and comfort range of 25- 45 % RH [25] during winter conditions. At a ventilation rate 0.5 $(dm^3/s)/m^2$, although the RH variation in the Massive Timber house is greater than those in the Plywood and Gypsum houses, it increases the minimum indoor RH by 1.6%. The strong moisture buffer ability of the Massive Timber house is consistent with the predicted SDMBS values.

For the Plywood and Gypsum houses, it is very difficult to differentiate between their moisture buffer effects based on Figs. (14-16). At the ventilation rate of 1 $(dm^3/s)/m^2$, the RH variation in

Gypsum house is smaller, but it is reversed at the ventilation rate 2 (dm^3/s)/m^2. At 0.5 (dm^3/s)/m^2, it seems the Gypsum house had slightly better moisture buffering effect because the RH variation without moisture buffering in the Gypsum house is bigger than that in the Plywood house (12.2% vs. 9.4%, their RH variation are almost same). But the indoor temperature in the Plywood house was about 3°C higher. In general, indoor humidity of the Gypsum house is higher. Finally, Table 2 shows the SDMBC results for three twin test houses at different airflow rates.

Table 2.

Structural dynamic moisture buffer capacity SDMBC for three test houses at different airflow rates.

.Test house	Airflow rate 0.5 (dm^3/s)/m^2	Airflow rate 1.0 (dm^3/s)/m^2	Airflow rate 2.0 (dm^3/s)/m^2
Plywood	0.6435	0.5085	0.3694
Gypsum	0.7032	0.651	0.4908
Massive timber	0.6742	1.0489	0.9292

Table 2 indicates that the higher the ventilation rate, the lower the SDMBC values. In other words, the moisture buffering is stronger at lower airflow rates, which is consistent with the literature [e.g. 26]. Starting from the minimum ventilation rate 0.5 (dm^3/s)/m^2, changes in SDMBC are stabilized at the ventilation rate 1 (dm^3/s)/m^2. It is interesting that the rate of SDMBC changes are the same for all the materials for the ventilation rate ≥ 1 (dm^3/s)/m^2. Hence if SDMBC values for ventilation range [0.5,1] (dm^3/s)/m^2 are known, SDMBC values outside of this range are predictable. Based on our limited experimental data, we obtain $SDMBC(Q)_{plywood}$ = [0.51, 0.64]; $SDMBC(Q)_{gypsum}$ = [0.65, 0.70]; $SDMBC(Q)_{massive\ timber}$ = [0.67, 1.05]. A larger SDMBC(Q) range indicates higher buffer capacity. Hence the moisture buffer effects of the three twin houses in increasing order are:

$$SDMBC(Q)_{massive\ timber} > SDMBC(Q)_{plywood} \geq SDMBC(Q)_{gypsum} \quad (7)$$

5. Discussion

The key findings of the results emerge as (1) The Massive Timber house demonstrates the strongest moisture buffering effects among the test houses; (2) Regarding moisture buffering, there is not much difference between the Plywood and Gypsum houses, but the indoor humidity is higher in the Gypsum house, and (3) Without an internal moisture source, indoor humidity is normally lower than outdoor humidity in winter conditions due to moisture buffering. Thus, moisture buffer is more effective at high airflow rates for the Massive Timber house, which is different from the Plywood and Gypsum houses and the cases with an internal moisture source.

This paper presents the new concept of the dynamic moisture buffer at structural level and several novel research ideas and our results are consistent with existing literature. Some illustrative examples are described below.

First, new SDMBC values are compared with existing literature of benchmarking values [14]. To facilitate comparison, SDMBC is converted in unit [g/m^2,%RH], as shown in Table 2. Take gypsum as an example, as indoor temperature 21.5^{o}C corresponds saturated vapor density 18.9 g/m^3 (1g moisture change corresponds to 18.9 % RH change), hence $SDMBC(Q)_{gypsum}$ = [0.26–0.38] in unit [g/m^2,%RH] at ventilation rates of 0.5-2 dm^3/s/m^2, which is consistent with benchmark values [0–0.7] [g/m^2,%RH] [14].

Second, in a separate study in the same wood test houses regarding SDMBC, the moisture content of various depths in wall structures were measured [23]. Indoor temperature and humidity were kept constant around 19^{o}C and 50%RH. Results showed, regarding moisture profiles in wall structures, there was no major difference between the Plywood and Gypsum test houses but there was significant difference between the Massive timber house and the others. The results provide further evidence supporting our findings that the Massive timber has better moisture buffer capability than Plywood and Gypsum houses.

Finally, this study advances our current modeling and knowledge regarding hygroscopic materials and buildings. For example, the following knowledge gaps and needs can be readily filled using our dynamic model and the new concept SDMBC : (1) lack of quantitative information about how exactly temperature affects moisture buffer [25]; (2) current knowledge gaps in estimating indoor RH in terms of varied ventilation conditions without internal moisture sources [17]. In such conditions, the moisture flow between indoor air and structures is dominantly driven by the outdoor moisture. Through ventilation, relatively humid outdoor air will bring excessive moisture into the test houses, causing an increase in indoor RH and absorption of moisture for structures. For example, the average ($AH_{out} - AH_{in}$) was 1.1 g/m^3 in our measurements. The ventilation leads to 20.196 g/h at 0.5 $(dm^3/s)/m^2$, 40.39 g/h at 1 $(dm^3/s)/m^2$ and 80.78 g/h at 2 $(dm^3/s)/m^2$ excessive moisture in test houses. This excessive moisture therefore can be absorbed and later released to the indoor air by the structure. As described in the Introduction, moisture transfer between indoor air and the structure is a very complicated process and is normally modeled using an instantaneous equilibrium assumption. This type of assumption certainly overestimates the true variations and penetrations of moisture inside the wall because the equilibrium moisture content does not strictly exist in the uncontrolled indoors [17], and (3) Based on [23] and Figs.(14-16), moisture buffer effects of plywood and gypsum are difficult to distinguish, as described previously. However, using our new concept of SDMBC, Eq. (7) gives $SDMBC_{plywood} \geq SDMBC_{gypsum}$, we can conclude that the Plywood house has better moisture buffer capacity, which proves why the indoor humidity of the Gypsum house is higher. Furthermore, the strong moisture buffer ability of the Massive Timber house is consistent with the predicted SDMBS values.

These issues can be easily resolved using our proposed physical-statistical model, which is free from restrictions on material thickness, surrounding temperature, ventilation rate, and internal moisture source, etc. We can use simple dynamic relationships to determine optimal input, for example, the thickness of the wall for an acceptable indoor humidity given the outdoor humidity. This is illustrated in Fig. 14-Fig. 16. As a result, our proposed methodology is robust and generalizable for solving more complicated situations and the models are useful for numerous applications including optimal building design by, for example, assessing a wide variety of indoor-outdoor environments.

6. Conclusions

Indoor humidity and temperature were continuously measured in three full-size (empty) identical test houses with various cladding materials at different airflow rates. Measurement data were used to develop a dynamic model for introducing a new moisture buffer mechanism and for modeling the dynamics of indoor air humidity. The new contributions can be summarized as: (1) Initiated the new moisture buffer concept for building structural level's moisture buffer dynamics; (2) Proposed hypotheses on the linear relationship between model variables supported by the experimental evidence which provides great simplification of the model so that a simple and efficient dynamic model was obtained; (3) Full-scale experiments were designed and executed. Except for the interior cladding, the remainder of the materials are virtually the same for the three twin test houses, including the U-values for envelopes, tightness, orientation, size, ventilation system, and so on. Furthermore, all the floors were elevated off the ground which totally eliminated moisture flow between the floor and the ground. This provided very natural qualitative conditions for controlling confounding variables for studying the moisture buffer effect of the building materials. Such full-scale and realistic experiments are rare in the literature; and (4) This study has been analytical in nature, which is efficient and easy to implement with wide practical uses.

Future work should collect more data in the test houses for broader scope studies including forecasts. Well-controlled internal moisture loads should also be included. For this purpose a humidifier system will be installed in each test house. The system will be able to be controlled to release a controlled quantity of moisture into the house to study the moisture buffering effects under these conditions.

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