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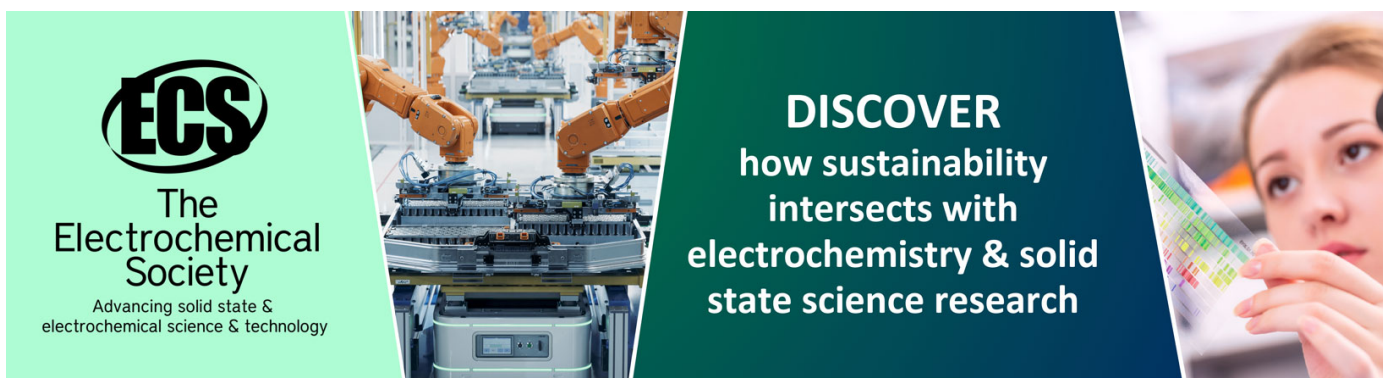
## Decisive Use of Building Materials Based on Hygrothermal Analysis

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# Decisive Use of Building Materials Based on Hygrothermal Analysis

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**Abstract.** Sustainable buildings, planning and construction process in the 21st century require an interdisciplinary approach by which the use of materials and products has to be a result of a complex decision procedure. Every building in its life span has an immense impact on the environment. This study shows that even small changes in material specification can engender a significant influence on indoor air quality and the whole ecosystem. This paper represents the second part of a research study described and presented by the CESB16 conference. An experimental and numerical study on real houses delivers new data which demonstrate the importance of material determination during the design process. Four different scenarios have been tested in two houses while introducing water vapour into a room to simulate occupancy. Indoor relative humidity, temperature and absolute humidity in the same room (size, position in the house, orientation) have been monitored while introducing various materials with a divergent moisture buffering capacity. This research has been based on real measurements assessed the data and compared with the hygrothermal performance of the original construction. The study further used a hygrothermal simulation to demonstrate the possibility of early materials assessment and allowance for the targeted specification of building materials. The information on how to efficiently use the hygrothermal qualities of materials in a build environment is a contribution to the goal of designing and constructing sustainable buildings.

## 1. Introduction

Housing in New Zealand is affected by high relative humidity (RH). This fact combined with the mostly poor quality of houses leads to many issues connected with dampness, mould, and rotting of structural timber. In addition to that this study is dedicated to the improvement of hygrothermal performance of buildings. Hygrothermal analysis constitutes a part of the science known as Building Physics in Europe or Building Science in North America. Building physics is a relatively young science (since 1930's) based mainly on experimental studies and empirical experience in building industry [1].

The fact is that little, or no building physics has been taught to architectural students at the universities in New Zealand and the progress in construction achieved by consultants was mainly based on the know-how from experience and new products and technologies coming from overseas. The consequence of this situation is that even newly built houses are often not performing well. Although numeric calculation in the field of statics, construction and energy engineering are standard the evaluation of hygrothermal processes of building constructions is not common. This research brings new knowledge into the field of construction in New Zealand whose intention is to encourage not only building science but the whole building industry to use hygrothermal assessment appropriately wherever technical decisions are made about buildings.



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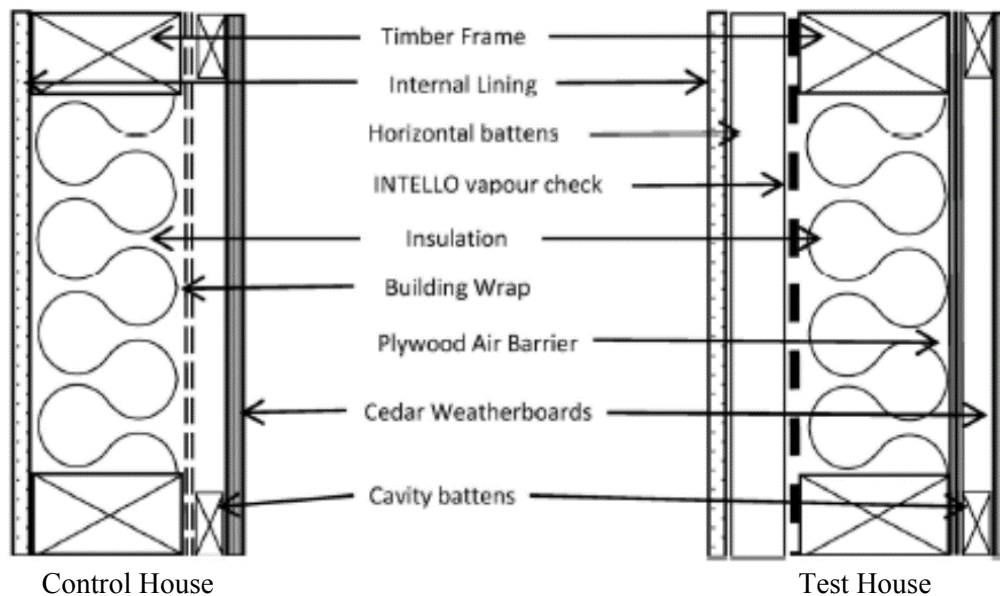
## 2. Quasi-Experiment

This research utilises a combined model of design using a combination of experimental and simulation design. With this combination of methods, the research demonstrates the benefits of using simulation during the design process to enhance the hygrothermal performance of houses. For the testing this study chooses RH, dew point, and temperature as parameters measured in one-hour intervals for consecutive 5 days (120 measurements in total) for each scenario. Independent variables represent weather conditions, different materials with different hygrothermal qualities, amount of daily released water vapour, and different type of exterior walls. The study compares the measured data with data from a hygrothermal simulation using WUFI Plus, Fraunhofer Institute, Germany.

For an understanding of this research, it is important to emphasize that RH represents the characteristic of the interest. Generally, under atmospheric conditions RH is influenced by two major factors: the absolute amount of water vapour in the air and temperature [2]. This fact is demonstrated in scenario 1 where RH is periodically changing although there is no additional moisture introduced to the room. However, as the exterior walls are not completely sealed the researcher notices some influence of the exterior level of humidity and temperature too.

### 2.1. Settings of the Experiment

The experimental set-up is situated in two test buildings located at Unitec Institute of Technology, Auckland, New Zealand (-36.882533, 174.707651). The houses are single storied, relocatable, complete with electrical and plumbing fittings, without floor coverings or wall finishes. They are identical in size, orientation, and layout but different in the exterior wall construction as shown in Figure 1.



**Figure 1.** Comparison of wall construction in Test and Control house [3]

For the testing is chosen a compartment consisting of a master bedroom with enclosed bathroom with 19.46 m<sup>2</sup> total floor area. The orientation of the compartment is North (Azimuth 340°) with the longer exterior wall (6.16 m) and West (Azimuth 250°) with the shorter exterior wall (3.78 m). The interior of the compartment with the total surface wall area of 43.8 m<sup>2</sup> and ceiling area of 19.46 m<sup>2</sup> is provided with unpainted plasterboard (10 mm). The basic configuration of exterior walls in both houses consists of 90 mm timber frame with polyester insulation (90 mm) in between. From outside, the construction is sheathed with a building wrap on the Control house (CH) and with 7 mm thick plywood air barrier on the Test house (TH). External wall cladding of both houses consists of cedar horizontal weatherboards fitted to cavity battens. As there is no opening on the top of the wall cladding the cavity (from building

physics' point of view), it is described as not vented. The inside of CH's exterior walls comprises plasterboard fixed directly to the frame. The inside of TH's exterior walls comprises an airtightness membrane fixed directly to the frame, followed by an installation cavity and plasterboard.

The RH, dew point, and temperature are measured every hour using 'EasyLog' Lascar EL-USB-2 data loggers. Multiple sensors in each house identical positions are installed. Sensors are fixed to the ceiling by a builders twine at 1500 mm high above the floor level as outlined by Barley, Deru, Pless, Torcellini and Hayter [4]. The sensors used by the experiment are calibrated by placing them in the same room one to each other and providing measurements for 2445 hours. Statistical analysis of the results shows that sensors deviate in their measurements in temperature with an absolute average deviation of 0.44 °C and RH with an absolute average deviation of 2.55 % RH. The arithmetic mean of deviation of temperature is -0.19 °C and RH -1.48 % RH. The results of the calibration are well within the accuracy stated for the sensors to be  $\pm 0.5$  °C [3]. The relatively high measurement uncertainties of the RH are common issues not only by field testing but by laboratory testing as well. In long-term measurements taken in uncontrolled and dynamic conditions the response time of sensors has to be taken into account as well. Therefore, the uncertainty of  $\pm 5\%$  RH and  $\pm 0.8$  °C in field studies seems realistic [5].

Additional humidity to simulate inhabitancy is provided by humiDisk10 with the maximal production of around 1 kg/h of atomised water. Required evaporation is controlled by a relay operating a switching on and off mode. To set up a correct amount of cycles a calibration method based on the trial of different relay's settings is employed. The closest possible setting with given technical equipment is to run the HumiDisk daily for a period of 12 hours from 7 pm till 7 am in a mode of 3min on and 7min off. This allows for a simulation of occupancy of two people based on Straube [6]. The only disadvantage of this type of evaporation is in an inaccuracy of released water. The amount of daily evaporation varies between 3.18 and 3.32 litres/24 hours with an average of 3.28 l/24h and variance of 0.0227 as shown in Table 1. Variational span is 0.14 l. Although the actual amount of evaporated water is slightly fluctuating, the results are suitable for analyses as this research intention is to demonstrate a tendential influence of different materials on the RH in real houses.

**Table 1.** Daily evaporated water (litre/24 hours) during individual tests.

|               | Scenario 2 | Scenario 3 | Scenario 4 |
|---------------|------------|------------|------------|
| Test House    | 3.32       | 3.18       | 3.30       |
| Control House | 3.32       | 3.30       | 3.28       |

The 5 days testing is applied for the following scenarios:

- Scenario 1: Existing plaster board lining (unpainted) on the walls and ceiling without any additional humidification.
- Scenario 2: Existing plaster board lining (unpainted) on the walls and ceiling with additional humidification as described above.
- Scenario 3: Three sheets of MgO (magnesium oxide) board additionally installed (fixed with stainless steel screws) to some of the walls in the room. The area of the MgO board is 8.28 m<sup>2</sup> which covers 18.9 % of the wall area in the room.
- Scenario 4: Earth plaster in a thickness of 2 mm approximately is applied to MgO board sheets as a wall finish. All residual walls remain unpainted.

Prior to the application of the plaster, MgO boards have been primed with a diluted (1:5) water-based co-polymer resin to assure bonding as per manufacturer's specification. In this application, the barrier properties of the resin represent key performance determining factors. Although this study does not include testing of any products the researcher notices that the polymer has an effect on permeability. This effect of polymer coatings has been described by Thomas [7] who outlined the theory of diffusion of small molecules through polymer films and demonstrated the effect of such coatings. The study intention of the fourth scenario is to show that finishing materials have an influence on interior RH levels.

Both buildings' airtightness has been tested with Blower door test. The test results are summarized in Table 2.

**Table 2.** Blower door test results summary and air infiltration rate calculation.

|                                 | Test House | Control House |
|---------------------------------|------------|---------------|
| ACH <sub>50</sub> pressurised   | 1.93       | 8.20          |
| ACH <sub>50</sub> depressurised | 2.37       | 8.28          |
| ACH <sub>nat</sub> estimation   | 0.1        | 0.4           |

During the experiment, no active ventilation is running. The mechanical ventilation is switched off, and all ventilation outlets are sealed with a plastic foil cover. The entry door to the master bedroom is shut during the testing. However, the gaps around the door are not segregated because this test intends to simulate a situation in one compartment in an occupied house without any mechanical ventilation. This fact is included in the simulation under 'interzone ventilation'.

The testing is done in a switching mode. This means that the testing of one scenario in one house is followed by the testing in the other house. The switching mode allows for drying of the structure in the first house and vice versa. Besides indoor measurements of temperature, RH, and dew point the same exterior values are constantly monitored. This enables the research to provide an analysis of covariance. The experiment ran from January 9th, 2018 till February 19th, 2018.

## 2.2. Results and Analysis

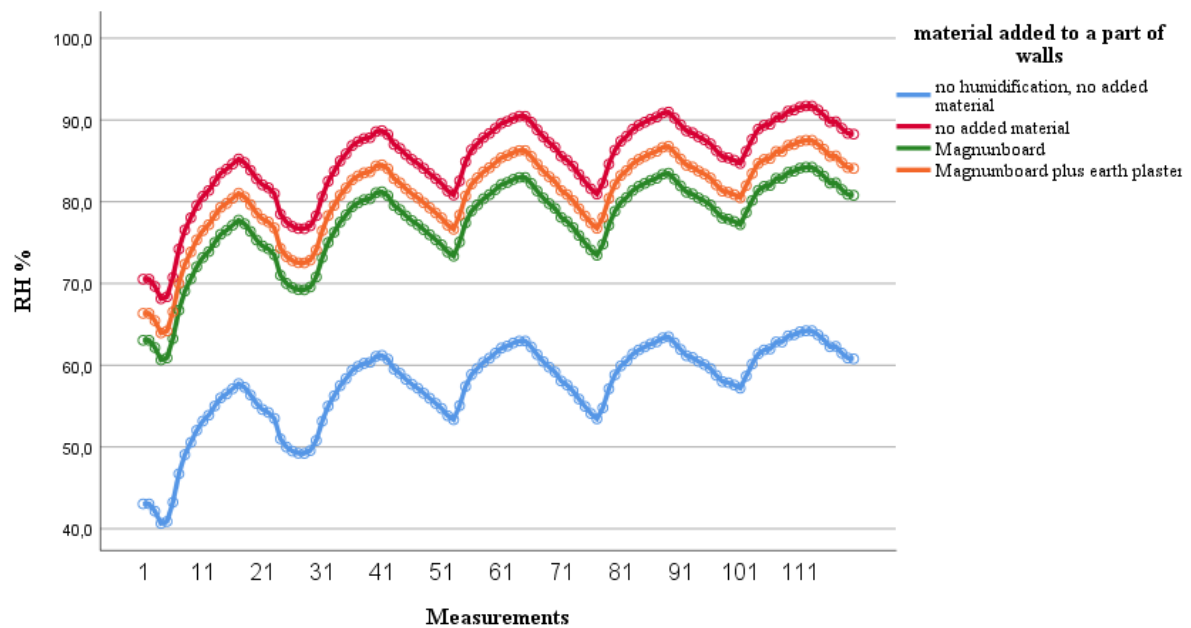
The analysis of the measured RH shows that the maximum reached RH level in the TH by each scenario is higher than in the CH although the initial RH levels in the TH are lower than in the CH as shown in Table 3. This fact might be influenced by different exterior conditions. To eliminate the influence of exterior RH the study implements analysis of covariance (ANCOVA). The results of ANCOVA are shown in Figure 2 and 3.

**Table 3.** Relative humidity levels by humidification and different materials added.

|                    | Scenario 2 RH % |      |      | Scenario 3 RH % |      |      | Scenario 4 RH % |      |      |
|--------------------|-----------------|------|------|-----------------|------|------|-----------------|------|------|
|                    | Initial         | Min. | Max. | Initial         | Min. | Max. | Initial         | Min. | Max. |
| Test House (TH)    | 67.0            | 66.5 | 92.0 | 56.0            | 55.5 | 87.0 | 61.5            | 55.0 | 90.0 |
| Control House (CH) | 76.0            | 70.5 | 82.0 | 62.5            | 61.5 | 85.5 | 74.5            | 73.5 | 87.0 |

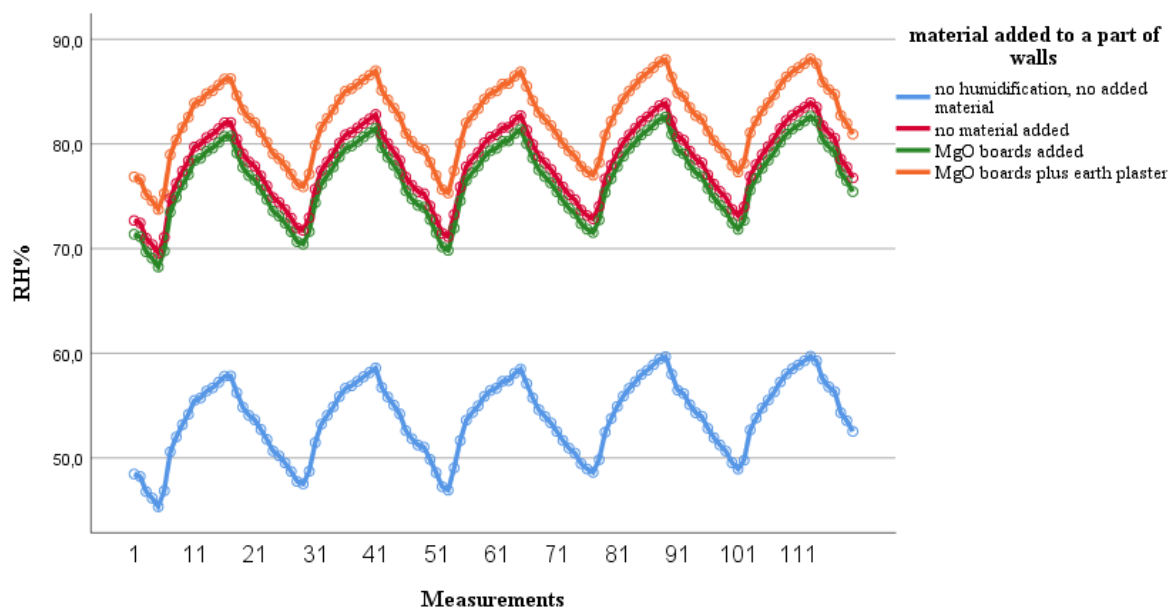
This study tests what material minimises the increase of the interior RH the most. In both houses, the most effective material seems to be MgO board. The highest levels of RH are measured by no adding any materials in the TH and by MgO board with Earth plaster in the CH. However, these absolute values might be partly influenced by the initial levels of RH, temperature, and outside weather conditions.

From the comparison of the Figures 2 and 3 the different development of RH by added humidity in both houses is evident. In the CH the estimated marginal means of inside RH are following a stable pattern, and the RH increases less than in the TH. Comparing the analysis of measured data and the analysis of covariance the ranking of materials' effectiveness stays the same. However, for the first scenario this study prefers to use the original data as the measurements are done in the same period with the same exterior conditions. The average RH in the first scenario in the CH is lower (2.2 percentage points) than in the TH. The initial RH level in both houses is identical. However, the initial temperature in the CH is 1.5 lower than in the TH. This means that the initial absolute humidity in the TH is slightly higher than in the CH.



Note: The covariants in the model have been calculated by exterior RH = 77.363%

**Figure 2.** Test house estimated marginal means of inside RH by the elimination of exterior RH



Note: The covariants in the model have been calculated by exterior RH = 69.929%

**Figure 3.** Control house estimated marginal means of inside RH by the elimination of exterior RH

The development of RH during the test is analysed by the introduction of interpolation functions. For the relatively short time period of each testing (5 days) this research finds a lineal interpolation to be sufficient. Linear interpolation functions although being very simple, demonstrate recorded differences between tested scenarios. Nevertheless, many times it has been proven [4] that the air saturation process is nonlinear, therefore, this research introduces exponential functions as well.

The lower slope of the interpolation function by the CH data is a depictive representation of high hygroscopic capacity of materials installed in the house and higher air exchange rate due to infiltration. As the first layers of materials from inside of the houses are identical the difference is assumed to be influenced by absorption capacity of in-wall construction materials, the level of diffusion openness of used materials, and by the natural air movement (infiltration rate). In-wall materials in the TH are partly blocked, and the infiltration rate is low due to the air tightness membrane. This would explain the higher level of reached RH (Table 3) and significantly higher slope of interpolation functions in the TH compared with the CH by each scenario (Table 4).

**Table 4.** Interpolation functions by humidification in Test and Control house as measured.

| Scenario No. | Linear Interpolation   |                        | Exponential Interpolation |                         |
|--------------|------------------------|------------------------|---------------------------|-------------------------|
|              | Test House             | Control House          | Test House                | Control House           |
| 2            | $y = 0.1299x + 77.192$ | $y = 0.0255x + 76.576$ | $y = 77.043e^{0.0016x}$   | $y = 76.493e^{0.0003x}$ |
| 3            | $y = 0.1415x + 68.931$ | $y = 0.0721x + 72.383$ | $y = 68.703e^{0.0019x}$   | $y = 72.183e^{0.001x}$  |
| 4            | $y = 0.1721x + 70.331$ | $y = 0.0467x + 79.031$ | $y = 70.142e^{0.0022x}$   | $y = 78.972e^{0.0006x}$ |

However, it is important to emphasize that the linear interpolation is not suitable for an extrapolation of the saturation process as this process represents exponential growth. The y-intercept in the linear interpolation specifies the level of humidity at the beginning of the testing. This factor might be influenced by exterior conditions, initial interior conditions, and by the immediate effect of moisture buffering.

### 3. Hygrothermal Simulation

The simulation set-up is mirroring the real situation. The simulation with WUFI Plus enables diverse visualisations of the experiment. The experimental setting might be specified as a zone in the whole building or as the compartment only with specifying of the remaining interior space as not visualised attached zone. After careful evaluation of the advantages and disadvantages of these options, the researcher decided to visualise the compartment only. This option allows for an exact specification of the location, area, wall properties, ventilation, solar radiation into the room, and initial conditions.

The simulation process contains eight cases where for each of the two houses, four scenarios are calculated. Each case consists of two simulated zones. The visualised zone represents the tested compartment with a user-defined net volume of 46.7 m<sup>3</sup> and floor area of 19.46 m<sup>2</sup>. The not visualised zone represents the remaining interior space of the house with the net volume of 226 m<sup>3</sup> and floor area of 94.85 m<sup>2</sup>. The simulation by each case runs simultaneously for the tested compartment and for the remaining interior space as a 'not visualized' zone. This way the whole building hygrothermal and thermal performance is calculated.

All building components are specified in detail as an assembly of homogenous layers. Exterior walls in the TH have thermal resistance 3.272 m<sup>2</sup>K/W and heat transfer coefficient (U-value) 0.291 W/m<sup>2</sup>K. Exterior walls in the CH have thermal resistance 2.973 m<sup>2</sup>K/W and U-value 0.318 W/m<sup>2</sup>K. As no hygroscopic data of the primer nor the earth plaster are available, some adjusting decisions have to be made. This study uses for simulation available data from reviewed papers for similar materials such as published results of testing of water-based acrylic paints [8] and WUFI material data for earth plaster. The infiltration values as an air exchange rate have been estimated from the results of the Blower Door Test (Table 2). According to the recommendation of BRANZ the natural air change rate is possible to calculate using a formula:  $ACH_{nat} = ACH_{50} / 20$  [9].

The results of the simulation confirmed the results of the experiment. Therefore, the hygrothermal simulation is a suitable tool for an early materials assessment and for the targeted specification of building materials.



#### 4. Discussion

The quasi-experiment and simulation results and their analysis manifest how the level of RH changes even with relatively minor alterations to interior materials (less than 1/5 of the total wall area). For example, by additionally covering an area of 8.28 m<sup>2</sup> with MgO boards representing 18.9 % of the total wall area the level of average RH by eliminated exterior RH drops at 7.56 percentage points by the TH and 1.37 points by the CH. The situation changes markedly by the application of an interior finish in the form of an acrylic primer and earth plaster on the same area. In the TH, RH still drops at 4.30 percentage points, and in the CH the level of average RH compared to scenario 2 increases at 3.74 percentage points. This is new knowledge of this research.

A question remains why such differences occur? One possible answer would be that the higher infiltration rate (natural air exchange caused by air leakages) by the house without airtightness features is responsible for faster removal of humidity from interior space than by the house with airtightness membrane. This still does not clarify where the water vapour goes. It is known that the air flow carries the moisture into walls [10]. As the situation inside of the walls has not been assessed by this experiment, the research makes no conclusions regarding airtightness or drying process inside of the walls. However, the reality has proven that persisting high humidity affects the wall structure and causes serious damage in the construction such as rust of metal parts or rotting of the structural timber [11, 12]. Missing airtightness layer has an impact on insulation quality, thermal transmittance, transient thermal response, and moisture tolerance of the construction [13].

Despite of the sorption-active thickness theory [2] structures without airtightness membrane are prone to be impacted by moist air due to the accessibility of materials inside of the wall's structure. This would explain why by addition of acrylic primer and clay plaster the RH develops differently. In the airtight house where the air movement through the building envelope is reduced the priming and plastering of the MgO boards seems not to have such a remarkable influence. In the house, without airtightness, the increase of RH in the same scenario indicates that vapour resistance of interior materials influences significantly the accessibility of in-wall materials for water vapour. The deeper layers are therefore not freely available for sorption and the overall RH increases.

#### 5. Conclusions and recommendations

Every building during its life span has an immense impact on the environment. This study shows that even small changes in the material specification can engender a significant influence on indoor air quality and therefore, on the whole ecosystem. The numerical analyses proved that the level of reached RH in houses is very much influenced by used materials especially by the first layer from inside of the room. RH levels at the end of each testing period in the TH have been higher than in the CH although by each testing initial RH levels have been lower. This is a new finding of this research.

Inside RH by the elimination of the influence of exterior RH reached by simulation of the habituated house the lowest level by adding MgO boards. The highest level of RH was reached in the TH with the original construction and in the CH by addition of MgO boards with earth plaster. These results might be influenced by the different exterior wall structure and by the different infiltration rate. Airtightness membrane prevents direct water vapour transport into the exterior wall. This means that for the moisture buffering the most available layers are the materials in direct contact with the interior air. These facts would explain the generally higher levels of maximum reached RH in the TH in each scenario. However, without a complete assessment of the hygrothermal house performance, no conclusions about the airtightness are feasible. This study has not done any testing of the drying/wetting process inside of the walls. Therefore, the evaluation of the airtightness membrane is not a part of this research.

From the visual analysis of the development of RH, the conclusion might be drawn that the span between maximal reached RH each day by different scenarios is higher in the TH than in the CH. This fact emphasises the need for a careful hygrothermal assessment of the construction, especially of the first layer from inside. Air open structures need more energy for heating and cooling the interior due to the infiltration. This is not viable because of the general need for saving energy. The solution would be a holistic approach to the combined heat, air, and moisture flow. As the hygrothermal performance of



buildings is very complex this research evaluates assessment of the first layer from inside as a part of holistic decision series which include but are not limited to materials assessment, suitable ventilation, the orientation of the house, use of passive solar energy, shading, airtightness, and thermal insulation.

For further research this study recommends repeating the experiment with more precise humidifiers allowing for simultaneous tests of each scenario in both houses to eliminate different weather conditions in the same scenario. The industry would also benefit from knowledge about long-term complete hygrothermal performance inclusive in-wall processes and wetting-drying cycles.

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