Experimental Investigation of the Hygric Properties of Bio-based Building Insulation Materials with Novel Apparatus and Procedure

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HIGHLIGHTS

Heat and moisture transfer, bio-based materials, experimental investigation, novel apparatus, moisture storage, diffusion coefficient

ABSTRACT

The focus of this report is the investigation of hygric properties of bio-based insulation materials using novel experimental methods. The water vapor sorption isotherms were obtained with the Vapor Sorption Analyzer (VSA), an instrument developed for a novel method which can provide dynamic sorption isotherm curves. The water vapor diffusion was measured by another novel method by using The Oxygen Diffusion Apparatus 2020 (ODA 20). Both are more time-efficient methods then the standard methods commonly used. This could be a great improvement, since the development of less time-consuming methods would lead to more materials being able to get tested by the researchers. Determination of correct hygrothermal material properties is needed for conduction of various heat and moisture simulations. They could show important predictions of heat and moisture transport inside the materials, the material behaviour through time under different circumstances, for the determination of possible moisture problems in buildings or building materials, for simulation of indoor environmental conditions or energy consumptions with the use of different materials in buildings, etc. This is very important for the introduction of new materials in building constructions, especially for bio-based materials which have a great environmental impact but could also have great hygrothermal properties or maybe be more sustainable in production. The materials investigated in this report are the wood fibre board insulation and the loose fill paper wool and loose fill wood fibre. For the loose fill materials, the measurements were done for different densities. Due to the material physical structures, the determination of dry weight values was done for different temperatures in the oven. All values gained with the novel methods were compared to the values from the standard methods. The heat and

moisture transport simulations using Comsol were conducted with for both standard and experimental data.

Nomenclature

 g_v , g_l is vapour and liquid moisture flux [kg/m²s] c is the specific heat capacity [J/kg K] ρ C_{peff} is the effective volumetric heat capacity at constant pressure, SI unit: J/(m3·K) T is the temperature, [K] k_{eff} is the effective thermal conductivity [W/mK] L_v , h_e is the latent heat of evaporation [J/kg] ϕ is the relative humidity (dimensionless) p_{sat} is the vapor saturation pressure [Pa] Q is the heat source $[W/m^3 s]$ D_w is the moisture diffusivity $[m^2/s]$ K₁ is liquid transport coefficient [m²/s] G is the moisture source $[kg/m^3s]$ m_{measured} normal mass of material [g] m_{dry} dry mass of material [g] *k* is the thermal conductivity [W/mK] ρ is the density of the material [kg/m³] μ is the water vapor resistance factor [-] δ_{p} is the vapor permeability [s] ξ is the moisture storage capacity [kg/m³]

1. Introduction

In recent years, need for energy reduction is one of the essential aspects of all sectors across any industry. Together with energy reduction, another vital aspect is energy efficiency, especially in buildings. This aspects and approach are recognized not just inside the industry, but as well in government structures across many sectors. EU Commission's bioeconomy strategy of 2012 (1) proposed key features of implementing bio-based resources in innovative products, opening doors for increase in construction sustainability. Context of bio-based resources can be described as plant-, tree- and animal-derived materials, either in their sourced format modified within treatment or incorporate into other materials (2). There are numerous advantages of bio-based materials such; easily sourced; hygroscopic; recyclable; porous; nonabrasive etc. (3) Building and construction sector accounts for 30% to 40% of worldwide energy consumption (4), and 40% to 45% in Europe. A big part of that consumption belongs to heating and cooling, and because of that, there is a prominent ability to improve energy efficiency with better insulation materials and technologies applied to the building envelope (5). Combining this numbers with bio-based material properties and growing concern about climate changes leads to significant improvement in international building regulations regarding performance of the buildings. Benefits of biobased materials are; low mass densities, low thermal conductivity, high sound-absorption properties, no harmful effects on health, large availability and sustainability (low embodied energy and low-greenhouse-gas emissions for the production of the material and also the fact that they are often agriculture wastes or by-products. (6) (7) Therefore, natural materials, especially insulation, represent promising solution for building sustainability. To be able to successfully implement insulation in wall construction to comply with standard and provide satisfactory indoor conditions, hygrothermal properties are important to investigate. Reason is that with good hygrothermal characterisation of material it is easier to predict impact of the moisture on the material nature. Moisture is important because it has big impact on physic properties such as thermal conductivity (higher λ), larger heat flow (because of latent heat transfer), while some of visible damages are decrease of strength and rigidity and swelling (common with wood-based materials) (8).

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Most occurring risk in bio-based materials, especially wood is risk of the mould growth on higher relative humidity's caused by capillary transport and vapour convection due pore structure. (9) (10) Least damaging is vapour diffusion, but if there is significant amount of vapour it can be absorbed on the surface of pore walls. Nevertheless, this report will focus on defining hygric properties of three bio-based insulations. Two are loose fill insulations, of blow-in, and those are wood and paper-wool, while third investigated insulation is wood-fibre board. Imperative of this report is on laboratory work done to define moisture storage and vapour diffusion properties but using novel equipment. Two equipment, VSA analyser for sorption isotherms and ODA are presented and used to obtain hygric properties of materials, where ODA is apparatus developed on Aalborg University. Importance of this equipment is in reducing time needed to run experiment, especially one for obtaining diffusion coefficient.

2. Research objective

Bio-based insulation materials used in this report (wood-fibre and paper-wool) are defined as porous materials. As such they are sensitive to different moisture actions, drying and wetting. Conventional and standardise methods are often time-consuming and at the end, not always very precise and accurate, so to develop better understanding between new technology solutions and hygric properties of this materials this report works towards three major objectives:

- To characterise sorption isotherms for wood-fibre (loose and board) and paper wool insulation with humidity generating instrument, capturing their response on drying and wetting cycles
- With oxygen diffusion apparatus evaluate water vapour diffusion coefficients for different densities for each material
- To simulate one dimensional numerical model that can be used to study coupled heat and moisture effect on wall construction

Due to the nature of bio-based materials, to determinate hygric properties, more complex analysis is required, compared to conventional building materials. This complexity is even bigger when coupled heat and moisture analysis is included. Therefore, it is necessary to develop and use new technology in both aspect of determination – as laboratory equipment and as software tool.

3. Methodology

First section in this report is determination of physics parameters and dependence on one another. This step is defined and evaluated in the following section, where heat and moisture equations are governed based on assumptions. More detailed theory on heat and mass transfer can be found in Appendix A.

Second section is the description of the material samples obtained from manufactures, together with their properties defined by standardise methods, coming from product datasheets. More details on literature overview and general thermal and moisture properties of samples used in this study can be found in Appendix B.

Third section is the description of equipment and experimental set up made in the laboratory to investigate moisture storage capacity for each tested insulation and water vapour diffusion coefficient. Additional information describing experimental set up is in Appendix C.

3.1. Heat and moisture transfer in porous materials

Fundamental description of different nature effects needs to be explained and it is done by the First and Second Law of thermodynamics. In the heat and moisture transfer in porous materials, these two laws are well known as Second Fick's law for mass transport and Second Fourier's law for heat conduction. They represent energy and mass balance of the material exposed to different conditions. Focus in this report will be on Fick's law, but to understand the complete heat and moisture transport in the porous media, Fourier law will be explained in this section as well, together with Darcy's law. It is important to have overview of all transport mechanisms to get bigger picture of the experimental research described later in the report. (10)

Usually, moisture transport is multi-phase transfer of water which is accompanied by heat flow. (8) Main transports of moisture under different mechanisms are (8) (11):

- 1. Vapor diffusion within some porous materials;
- 2. Vapor convection;
- 3. Liquid water capillarity through porous materials;
- 4. Liquid gravity flow (hydraulic flow) through cracks, openings.

When investigating moisture or mass transfer in porous materials it is common to investigate water vapour or liquid water transport in building structure. (8) Water vapour is mixture of dry air and water vapour. (12) Another important effect that is occurring during moisture transfer is parallel transfer of sensible and latent heat that will be discussed as well.

Based on the standard BS-EN-15026 (13) and literature (15) (15) (16) (17) (13) (18) (19) (20): physical phenomena is presented under following assumptions (13) (18):

- Geometry of material is constant and continuous, non-deformable (no shrinkage or swelling) and no chemical reactions (stabilized);
- 2. Thermodynamic balance is assumed at every point of the material; for example, latent heat of sorption is equal to latent heat of condensation/evaporation;
- 3. The effect of gravity is negligible and total gas pressure is constant and air pressure is constant inside the material;
- 4. No air transfer occurs;
- 5. Temperature conditions are not exceeding 50°C
- 6. Moisture storage function is not dependent on temperature, just on pressure difference (relative humidity);
- Temperature and barometric pressure gradients do not affect vapour diffusion. (Soret effect; thermodiffusion neglected (19))

All these assumptions are defined by 1D domain, x and the time, t. Therefore, to conclude; vapour diffusion is described by Fick's Law, while capillary migration is defined by Darcy's Law. The heat transfer is described by Fourier Law and it is governed by heat diffusion (or sensible heat flux) and latent heat flux. (21)

Mass balance depends on the moisture flow in two phases; liquid and vapour, so based on the first law on thermodynamic, mass balance equation (Fick's second law) can be expressed as:

$$\frac{\partial w}{\partial t} = -\frac{\partial (g_v + g_l)}{\partial x}$$
 1

Under assumption that air pressure is constant inside the material, vapour transfer depends on the pressure gradient (Fick's First Law):

$$g_v = -\delta_v(w) \frac{\partial p}{\partial x}$$
 2

Liquid transport, or capillary transport can be expressed by Darcy's law:

$$g_l = K_l(w) \frac{\partial p_c}{\partial x}$$
³

Main difference between Fick's and Darcy's Law are signs because water vapour flows in opposite direction of the pressure gradient, while capillary water flows in the same direction of the pressure gradient (suction pressure). (11)

Substituting Fick's fist law for the flux, final equation with moisture balance can be expressed:

$$\frac{\partial w}{\partial t} = \frac{\partial \left(\delta_v(w)\partial p + K_l(w)\partial p_c\right)}{\partial x}$$

$$4$$

Since temperature variation on moisture content (22) is neglected and content is temperature independent; introducing moisture storage function ($\xi = \frac{\partial w}{\partial p}$) equation above can be rewritten:

$$\xi \frac{\partial p}{\partial t} = \frac{\partial (\delta_v(w)\partial p + K_l(w)\partial p_c)}{\partial x}$$
 5

Moisture storage function, sorption isotherm in this case, is expressed by the relation of the partial vapour pressure, which is connected to relative humidity as:

$$\Phi = \frac{p_v}{p_{sat}(T)}$$

where saturated vapour pressure is dependent on the temperature.

Energy balance equation and can be expressed as:

$$\frac{\partial E}{\partial t} = -\frac{\partial (q_{cond} + q_{conv})}{\partial x}$$
 7

If heat storage capacity ($E = \rho cT$) for gas phase in the material is neglected, then internal energy of material consists of energy of dry material and liquid water (21):

Derivation of internal energy in time gives (21):

In the literature (21) and the standard (13) simulation is done in the hygroscopic range of material, so last term in the equation above $(c_w T \frac{\partial w}{\partial t})$ is neglected. Therefore, energy balance is:

$$(c_m \rho_m + c_w w) \frac{\partial T}{\partial t} = -\frac{\partial (q_{cond} + q_{conv})}{x}$$
 10

Conductive heat flux is described with Fourier law as sensible heat transport depending on thermal conductivity of material based on the equivalent moisture content:

$$q_{cond} = -\lambda(w)\frac{\partial T}{\partial x}$$
¹¹

Latent heat is described by vaporisation-condensation process as consequence of moisture transport. (8) Therefore, convective heat flow is described as flow of each fluid phase (liquid and vapour):

$$q_{conv} = c_l T g_l + (c_v T + h_e) * g_v$$
 12

Based on energy conservation and Second Law of thermodynamic, and assumptions above, when water evaporates it absorbs sensitive heat equal to its latent heat of evaporisation. (9) In the standard (13) only latent and sensible heat flux are considered, therefore final heat conservation equation can be expressed as:

$$(c_m \rho_m + c_w w) \frac{\partial T}{\partial t} = -\frac{\partial}{x} (\lambda \nabla T + h_e \delta_v \nabla p)$$
¹³

After expressing both equations for mass and energy balance, coupled effect can be described as following:

$$\left(\rho C_p\right)_{eff} \frac{\partial T}{\partial t} - \nabla * \left(k_{eff} \nabla T + L_V \delta_p \nabla (\phi p_{sat})\right) = Q \qquad 14$$

$$\xi \frac{\partial \phi}{\partial t} - \nabla * \left(\xi D_w \nabla \phi + \delta_p \nabla (\phi p_{sat}) \right) = G$$
¹⁵

3.2. Materials

Wood fibre loose and Wood fibre board

The investigated wood fibre insulation materials in this research are materials manufactured by Hunton. The WFIL is "*Hunton Nativo Wood Fibre Blow-in Insulation*",

while the WFIB is "*Hunton Nativo Wood Fibre Insulation Board*". According to the Hunton product datasheet (38) which is based on different procedures done by the manufacturer using standard methods. both insulations are showing excellent moisture properties. For example, the use of a vapour barrier with these materials is not needed; internal convection is lower than in mineral wool (which was validated in the paper (39) as well). Both WFIL and WFIB have very similar thermal properties, with heat conductivities (λ) of 0.039 W/mK and 0.038 W/mK respectively, and with the same specific heat capacities of 2100 J/kgK for both, which is providing an amplitude attenuation of 7 (for $\Delta T=21^{\circ}$ C, $Ti = \pm 3^{\circ}$ C).

Paper wool loose

The investigated PWL material is manufactured by Papiruld, a Danish company specialized for paper wool insulation materials. The specific product used is *"Papiruld Iso-Let"*, and it mostly (84% of the material) consists of recycled newspapers. Thermal properties of PWL provided by the manufacturer are the same as the thermal properties for WFIL.

The summarized properties provided by the manufacturers for all 3 used materials are presented in table xx.

Manufactures properties					
Material	λ	ρ	μ	С	δ
	[W/mK]	[kg/m ³]	[-]	[J/kg K]	[kg/msPa]
PWL	0.039	30-45 ¹	1-2	2100	(1-2)E-10
WFIL	0.039	32-45 ²	1-2	2100	(1-2)E-10

Table 1. Summary of properties by manufactures for the investigated insulation materials

 $^{^{\}rm 1}$ Depending on the place of the installation (roof, cavities etc)

² Depending on the place of the installation (roof, cavities etc)

WFIB	0.038	50	5.3	2100	3,77E-11
					1

According to the specification sheet provided by Papiruld (27), blow-in PWL absorbs and releases moisture like ordinary wood, therefore due to its hygroscopic nature it has good moisture properties which are providing stable and comfortable indoor climate conditions when using paper wool in building constructions.

3.3. Experimental set-up

3.3.1 Dry weight

The method used in this report for obtaining the dry weight values of the specimens was the oven drying method. Samples were kept in an oven at fixed temperatures for several days and then weighed at intervals of one or two days. The dry mass of the samples was obtained by comparing the results of one/two days intervals, weighting until non-monotonous relative deviations between at least three consecutive weighing was below 0.1%. The Sartorius digital scale is used to weigh the samples has a precision up to 0,0001 g. To see how much exactly the values differ when using 70 °C and 105 °C as oven drying temperatures, the dry weights values for the tested samples were obtained for both temperatures.

3.3.2. Moisture sorption isotherms

To obtain the moisture sorption isotherms for the investigated materials, the Vapor Sorption Analyzer (VSA) was used (Figure 1). It is an instrument developed by Decagon Devices, designed for measuring moisture sorption isotherms in a much shorter time period then with the standard desiccator and climatic chamber methods presented in DS EN ISO 12571.



Figure 1. Vapor sorption analyser (28)

In this research, the DDI ("*Dynamic Dew Point*

Isotherm") method using VSA was chosen to measure the sorption isotherms. The temperature was set to 23 °C, the RH start point at 10% and the end point at 90%. The

loop option was turned ON, meaning that after the end point RH is reached, the test continues to run from the end point back to the start point, so both adsorption and desorption curves can be obtained. Several measurement cycles were done with the same settings on the same specimen without removing it from the VSA chamber. For the PWL 8 cycles were repeated and for the WFIL it was 6 cycles. After running the VSA DDI test, the measurement data was collected and exported to a Microsoft Excel workbook where the MC ("*moisture content*") was calculated for each noted RH level during the testing cycles, and the adsorption – desorption curves were plotted. To calculate MC in % by mass, equation $MC = \frac{m_{measured} - m_{dry}}{m_{dry}} * 100$ 16 (29) (15) was used.

$$MC = \frac{m_{measured} - m_{dry}}{m_{dry}} * 100$$
16

3.3.3. Water vapor diffusivity

The standard way of calculating the water vapor diffusivity through building materials is by translating it from its water vapor permeability by Fick's law (15) where the water vapor permeability is measured and calculated using the wet cup/dry cup methods presented in standard (28), which are time-consuming methods to conduct but also can be hard to prepare.

The method used to determine the water vapor diffusivity in this research is a method presented in (30) which is a method commonly used in soil physics investigation but is a novel experimental method for determining moisture diffusivity in building materials. The principle of the method is to calculate the oxygen diffusion coefficient ($D_{p,02}$), which is then translated into water vapor diffusion coefficient ($D_{p,H20}$) using the relative gas diffusivity (D_p/D_0), where D_0 is the gaseous coefficient of a gas in air. The D_0 values for O_2 and H_2O in air taken from literature can be seen in Table 2 below.

Gas system	Diffusion coefficient $D_0 [cm^2 s^{-1}]$
O_2 in air	0.205

Table 2. Diffusion coefficient of a gas system through ai

 H_2O in air 0.248

Therefore, the oxygen diffusion coefficient is translated into water vapor diffusion coefficient using equation 17.

$$D_{p,H_2O} = \frac{D_{p,O_2}}{D_{O,O_2 \text{ in air}}} \cdot D_{O,H_2O \text{ in air}}$$
 17

The oxygen diffusion coefficient was obtained using The Oxygen Diffusion Apparatus 2020 (ODA 20), an instrument that has been developed at BUILD, Aalborg University (14). (Lecture 6 Hygrothermal…) Figure 2 a) shows the schematic preview of ODA 20 and b) the picture of ODA 20.



Figure 2. a)ODA Schematic preview and b) ODA 20 picture (32)

The main part of the apparatus is an air-tight chamber (Diffusion vessel in the schematic preview) which has a built-in oxygen sensor inside it. The tested sample is sealed on top of the chamber, which is flushed using N_2 to remove all oxygen present in the chamber. Then the oxygen sensor in the chamber measures the oxygen diffusing through the sample into the chamber until the oxygen level inside the chamber is the same as in the ambient air (20.9%). The typical measurement using ODA 20 takes 1-3 hours, which is a

much more time-efficient method then the standard Dry cup/Wet cup method (28) More details about ODA 20 and the experimental method can be seen in Appendix C2,

It is important to note that the standard water vapor diffusivity values gained through the Wet cup/Dry cup methods, also include other moisture transport mechanisms besides diffusivity, such as condensation, surface diffusion, capillary condensation and liquid transfer, while the water vapor diffusivity values gained using the novel method mentioned above, represents the vapor diffusion mechanism alone. The usage of oxygen as a non-reactive gas in this method, neglects the liquid transport through pores and the condensation or evaporation at water-air interfaces (30). Therefore, the values gained with the standard methods will be noted as *Effective*, while the values from the novel experimental method will be noted as *Specific* in this report.

2.3.4. Water vapour permeability and water vapor resistance factor

The water vapour permeabilities and water vapor resistance factors were calculated with equation 18, which is a re-written equation for water vapor diffusivity calculation based on Fick-s Law.

$$\delta_{\rm v} = \frac{{\rm D}_{\rm w} \rho \frac{\partial {\rm w}}{\partial \varphi}}{{\rm p}_{\rm sat}}$$
 18

From water vapor permeability, the water vapor resistance factor was calculated using equation 19. (28)

$$\mu = \frac{\delta_a}{\delta}$$
 19

The water vapor permeability of air, δ_a at 23 °C is 1,98*10⁻¹⁰ kg/(m·s·Pa)(28)

The complete method used for calculation is explained, with step by step of re-writing of the used equations, in Appendix C.

As mentioned, the values for the hygric properties of the materials translated from the water vapor diffusivity values gained with the novel experimental method will be noted as *Specific* in this report.

2.3.5. Rockwool insulation

For the comparison of large moisture dynamics in the investigated bio-based materials, with the small (or none) moisture dynamics in the conventional hydrophobic insulation materials, the Rockwool mineral wool was used. The raw measurement data for sorption isotherms with the DDI method by using VSA, and the oxygen diffusion coefficient measured by ODA20 for RW, are provided by the authors (33), where the data was originally used. The dry weight value of RW in the paper is gained by the oven drying method, but only at 105 °C, so the results presented for RW are only for that dry weight. The tested RW has a density of 40 kg/m³ and a thermal conductivity of 37 mW/m*K.

3. Results

In this section results from measurements and investigation described in the previous section are going to be presented in the form of the tables and graphs mostly. More tables, graphs and figures can be found in Appendix D.

3.1. Results for dry weight

Final summary of all dry weights values for the tested materials is presented in the Table 3:

Material	Weight at 23.5°C & 34% RH [g]	Dry weight at 70 °C [g]	Dry weight at 105 °C [g]
PWL	0.652	0.593	0.577
WFIL	0.116	0.103	0.097
WFIB	/	/	0.324
RW	/	/	0.205

Table 3.	The dry	weights of	f the tested	l specimens	obtained	with	the oven	drying	method	at diffe	erent
				tempe	ratures						

In Figure 3 the pictures of tested WFIL specimen are presented, where the picture to the left shows the specimen before oven drying at 105 °C, while the picture to the right shows the specimen after oven drying at 105 °C.

Clearly, the damage on the material after drying at 105 °C is visible, which supports the proposal that for this kind of materials, drying at 70 °C should be a more adequate method then at 105 °C. Therefore, the moisture content values used in the material properties in hygrothermal simulations for the tested bio-based materials are obtained through dry weights at 70 °C.



Figure 3. Wood fibre tested specimen before and after oven drying at 105 $^{\circ}\mathrm{C}$

3.2. Isotherms results

For the calculation of the water vapor isotherms, the dry weight values from oven drying on both 70 °C and 105 °C were used to show how the moisture content could be different for this kind of materials, when using dry weight values gained by oven drying on different temperatures.

Figure 4 shows the lowest adsorption curve and the highest desorption curve out of all repeated cycles, without the results from the first cycle since the values from the 1st cycle deviate when comparing them to values from other cycles. The first two cycles for the WFI board were giving results which were not agreeable, so for that material, the first two cycles were neglected. Since the RW is a hydrophobic material, it has very little (or almost none) moisture dynamics, so there is no clear difference between adsorption and desorption curves. Therefore, in figure 4 d) the isotherm curves for RW are presented from a cycle giving the widest range of isotherms.



Figure 4 The lowest adsorption curve and the highest desorption curves for a) PWL, b) WFIL, c) WFIB and the curves from one cycle for d) RW

Curves from all VSA cycles are presented in figure 5, where the curves for the 1st cycle are presented with a dark colour, and for each consecutive cycle a lighter colour gradient was used.



Figure 5. Sorption isotherm curves from all measured VSA cycles with different dry weight values for a) PWL at 70°C, b) WFIL at 70°C, c) PWL at 105°C, d) WFIL at 105°C, e) WFIB at 105°C and RW 105°C

3.3. Result of calculations for the water vapour diffusion, specific

Experiments were conducted in the laboratory where the relative humidity was kept between 33.2% and 34% and the temperature was 23.5 °C. As mentioned in the Methodology section above, the measurement of the water vapor diffusion coefficient was done with the novel method using the ODA 20 apparatus.

The measurements with ODA for the loose fill materials (PWL and WFIL were done for different densities of the materials, because the densities of these materials in building constructions in real life depend on how they are installed by the construction worker, which could in some occasions end up with the density being slightly different then the suggested density ranges from the manufacturer, which were presented earlier in Table 1. Summary of properties by manufactures for the investigated insulation materials The measurement was done for densities just below the recommended density range, for the recommended range and also for the density above the range. The measurements were repeated 5 times, using a different sample of the same tested material, packed to a same density, each time. The complete range of the calculated water vapor diffusion coefficients for the tested materials and their different densities are presented in Figure 6, where the gradient of blue colour is for WFIL, red gradient for PWL and green is for the WFIB.



Figure 6. Range of Specific diffusion coefficients from ODA20

3.4. Results for Specific Water vapour permeabilities and Specific Water vapour resistance factors

In Table 4, the values of specific water vapor permeabilities and the specific water vapor resistance factors for the investigated materials are presented. They were calculated through Fick's law as explained in the Methodology section. All the material properties values shown in Table 5 are measured or calculated for 23 °C and 34% RH.

 Table 4. Results obtained from ODA translated into Specific water vapor diffusivity, permeability, and

 resistance factor values

Material	ρ	Dp, _{H20}	$\delta_{ ext{, Spec}}$	$\boldsymbol{\mu}_{\text{, Spec}}$
	[kg/m³]	[m²/s]	[kg/Pams]	[-]
PWL	30	1.36E-05	5.48E-08	3.61E-03
PWL	60	1.15E-05	9.27E-08	2.14E-03
PWL	70	1.12E-05	1.05E-07	1.88E-03
WFIL	30	1.38E-05	3.98E-08	4.97E-03
WFIL	45	1.27E-05	5.50E-08	3.60E-03
WFIL	60	1.22E-05	7.04E-08	2.81E-03
WFIB	50	1.23E-05	2.99E-08	6.62E-03

3.5. Comparison of the Specific and Effective Water vapour permeabilities and Water vapour resistance factors

The comparison of the Specific Water vapour permeabilities and Water vapour resistance factors obtained with the novel methods, to the Effective Water vapour permeabilities and Water vapour resistance factors gained using standard methods by the manufacturers, (27) (34) is presented in table 5.

Material	$\delta_{, \text{ Spec}}$	$\mu_{,{ t Spec}}$	$\delta_{, Eff}$	$\mu_{\text{, Eff}}$
	[kg/Pams]	[-]	[kg/Pams]	[-]
PWL	9.27E-08	2.14E-03	(1-2)E-10	1-2
WFIL	5.50E-08	3.60E-03	(1-2)E-10	1-2
WFIB	2.99E-08	6.62E-03	3.77E-11	5.88

Table 5 Comparison of the Specific and Effective Water vapour permeabilities and Water vapour resistance factors

5. Simulation

In reality, undesired liquid water inside the components can damage the construction and lead to degradation, depending on material propertis and conditions. (30) Therefore, in this section interstital condensation will be investigated using COMSOL Multyphiscs software. Before time-dependant simulation of investigated material properties in the section above, difference between two standardise methods will be presented. All studies are one-dimensional, and based on assumptions defined in section 3.1. Heat and moisture transfer in porous materials Because of the similarity between materials and their properties, all simulations are done for paper-wool.

5.1. Case study

Simulated wall consist od 4 layers, with concrete facing outdoor and gypsum as finishing layer. On the Figure 7 wall construction is presented. Material properties used for simulation are defined in the Table 64 and 5 and presented in Table 6**Error! Reference source not found.** U-value of wall is 0.18 W/m²K.



Figure 7. Wall construction with layers

Layer name	Thermal conductivity λ [W/mK]	Gross density ρ [kg/m³]	Spec. heat capacity c [J/kgK]	Layer thickness d [m]	R [m ² K/W]
R _{si}					0,13
Concrete, 1	max(0.14*(1+3*wc(phi)/6 00),0)	2000	1000	0,100	0,074
Paperwool, 2	(0.04743- 0.0420)/30*max(0,T- 263.15)+0.0420	45	2100	0,200	5,128
Masonry brick, 3	max(0.9*(1+8*wc(phi)/18 00),0)	1100	1000	0,080	0,167
Gypsum wall board, 4	0,19-0.6	600	1000	0,020	0,105
R _{se}					0,04

Table 6. Material properties defined in COMSOL (36)

5.2. Study 1

In the first study, difference between two standardise methods, Glaser (EN ISO 13788 (2002)) and one in BS-EN-15026 (14) will be presented. Glaser method is most common method for quick calculation for developing temperature and moisture profiles through envelope (also known as graphical stationary method). This method does not account for heat and moisture storage, latent heat effect, and capillary transport of liquid moisture. Therefore, the following equations are obtained for heat and moisture transport:

$$-\nabla(\lambda eff\nabla T) = Q \qquad 20$$
$$-\nabla(\delta\nabla(RH \ psat)) = G \qquad 21$$

Today with more advance simulation platforms and software's we can predict and simulate dynamic models more accurately, taking coupled activity between heat and moisture into account. Impact of coupled method and difference between simpler Glaser

is simulated. Boundary conditions and material properties used for this study are presented in the **Error! Reference source not found.**

Boundary conditions	Unit	Glaser	Stationary coupled
External temperature	°C	0	0
Internal temperature	°C	22	22
Initial conditions temp	°C	22	22
Initial conditions RH	1	0.5	0.5
External relative humidity	1	0.9	0.9
Internal relative humidity	1	0.5	0.5
Moisture storage function	kg/m³	Disabled	Enabled
Water vapour resistance	_	ODA	ODA
Liquid diffusion coefficient	m²/s	Disabled	Enabled

Table 7. Boundary conditions and set-up for study 1

Moisture storage function for stationary coupled method defined in the previous chapter, using VSA apparatus. Liquid diffusion coefficient in this case is used from COMSOL library, defined for the loose cellulose material. On the Figure 9 temperature profile and relative humidity through wall is presented. Dotted line is for stationary coupled method, while solid line is describing Glaser method. From temperature profile graph there is visible difference because thermal conductivity for each material is dependent on temperature change. This change is considered in coupled method but neglected in Glaser. For relative humidity profile (Figure 8) it is easy to conclude that moisture storage capacity of each material, together with liquid transport coefficient have big part in material behaviour. Glaser method often can overestimate relative humidity values because its neglecting liquid transport, so false conclusions can be made.



Glaser and stationary coupled method comparison: Relative humidity (%)





Glaser and stationary coupled method comparison; Temperature (degC)

Figure 9. Temperature profile comparison between Glaser and coupled method

5.3. Study 2

In the second investigation, time-dependant study is simulated, based on the boundary conditions as described in the standard BS-EN-15026 (14). Study is done for paper-wool insulation material and impact of different densities on relative humidity profile. Experimentally determinate properties are compared with manufactures datasheets. For time period, step function is introduced $(T_int + step1(t[1/s])*(T_ext-T_int))$ for temperature and $(phi_int+step1(t[1/s])*(phi_ext-phi_int))$ for relative humidity). Boundary conditions are presented in the Table 8.

Boundary conditions	Unit	Time-dependant study
External temperature	°C	30
Internal temperature	°C	20
Initial conditions temp	°C	22
Initial conditions RH	1	0.5
External relative humidity	1	0.95
Internal relative humidity	1	0.5
Moisture storage function	kg/m³	VSA
Water vapour resistance	-	ODA
Liquid diffusion coefficient	m²/s	Enabled

Table 8. Boundary conditions for time-dependant study

Simulation is run for 365 days, and on Figure 10 comparison between manufacture data and experimental data for different densities is presented. Very small differences, less than 1% between different densities for the same paper-wool materials is visible, therefore it can be neglected. Significant difference is between experimentally determinate (ODA) and manufactures data, meaning that retardation factor should be introduced to obtain more realistic behaviour. Based on this simulation, possible condensation can occur, but as stated it is mostly connected due very low vapour resistance factor obtained from ODA.



Figure 10. Time-dependant study for different material densities from ODA and comparison with manufactures data

On the Figure 11. moisture vapour storage function is presented for paper-wool insulation with densities of 30 kg/m3 and compared with manufactures profile.

Time-dependant; Moisture vapour storage function (kg/m3)



Figure 11. Moisture vapour storage function for manufactures data and experimental

6. Conclusion

This report presents an overview of novel apparatus used on biobased materials to obtain hygric properties and determinate moisture transfer in them. That overview demonstrated that VSA apparatus and non-equilibrium method for DDI is cutting time needed for determination of sorption isotherms and it can provide more in-depth view of the sorption isotherms then the equilibrium method. Since the method which is using ODA20 to obtain water vapour diffusion coefficient is not considering all moisture transport mechanism, which are included in the diffusivity from the standard method. Also, hygrothermal simulation have different complexity levels, but with technology regarding laboratory equipment, similar approach should be used when simulating those properties. Since the results from a steady state conditions modelling can sometimes be from realistic ones, the dynamic modelling should be introduced. The case is divided on two studies that are investigating this statement. In the first study difference between coupled and uncoupled (Glaser method) are presented, showing significant discrepancies between temperature and relative humidity profiles. Second study is a time-dependant study, which is simulated with applying different experimental diffusivities for different densities of paper-wool insulation, which are measured with

ODA20. The study is showing that there is small difference when using different properties for different densities of same materials gained with the experimental method. The experimental data was also compared to the standard manufacturer data. From that it can be seen that simulating with the water vapor permeability (or resistance factor) from the experimental method can result in differences and in accuracies when compared to data from standard methods.

7. Discussion

The novel methods for determination of hygric properties in building materials used in this report give a great advantage due to much shorter time then the standard methods. The method for sorption isotherms provides agreeable results to standard method results, but the method for oxygen diffusion coefficient can result in a big difference compared to values by standard methods. This is because not all same moisture transport mechanisms are included in the two compared methods. Therefore, additional research in the field of this experimental method must be conducted in future research in order to provide more accurate results. One thing which can be done is introducing a retardation factor which would stand for the neglected transport mechanisms in the experimental method. For good implementation of the retardation factor, the measurements should be conducted for different RH levels, so the normalization of data is done for several different values where the retardation used would be the one giving best fit compared to all values. While normalizing only for one value, it would give us the same number to which it would be compared. The retardation factor should be investigated for different materials with similar physical structures, where the implementation of one universal R factor for several different materials would be a great improvement. Another thing which could be done, is separating the other moisture mechanisms and investigating their effect in the moisture transport.

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