CONSTRUCTIONS & BIORESSOURCES

Current State of Knowledge on the Hygrothermal Behaviour of Bio-based Materials

Technical Document C&B

First Edition February 2013

We want to give special thanks to Laurent Arnaud, Florence Collet, Julien Lamoulie and Mike Lawrence for their comments and close second-reading of this document.

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1. FORWARD

The hygrothermal behaviour of a given material is strongly related to its nature (the matter that constitutes it) and to its porosity. Consequently, all materials do not have the same characteristics in regards to hygrometric, hydric and thermal variations. Studies undertaken on the topic highlight the difficult nature of this issue. The physics linked to the transfers of water vapour and liquid water within a given material are indeed complex. However, it is important to adequately characterize the behaviour of a material when confronted to these events, in order to optimize the material's use.

On this subject, bio-based materials have been the focus of studies for several years, aimed at understanding and characterizing their hygrothermal behaviour. These studies show that bio-based materials demonstrate specific performances in regards to hygrothermal phenomena. These specific performances are important for the interior comfort of a building.

Certain scientific studies evaluate the capacity of bio-based materials to store and release water vapour. These studies also estimate how hygrothermal events influence the bio-based materials' characteristics and durability. Other studies are devoted to characterizing and modelling the hygrothermal behaviour of bio-based materials. These studies show that hygrothermal behaviour specifically influences the energetic performance of a building (energy consumption).

The purpose of this document is to present an inventory of the publications concerned with the hygrothermal behaviour of materials and bio-based construction products, as well as present, in a summarized form, the main results from these studies.

It is important to keep in mind that the authors of the present document are not undertaking a critical study of the results. All the studies presented here have been conducted by researchers on their own results.

We hope that this document will guide the work of researchers, and that it will help professionals in the field of bio-based construction materials to value these products' specific characteristics, using scientific and technical arguments.

This overview has been established based on scientific publications that were available when this document was written. We are aware that many research studies are currently being conducted; we therefore aim on updating the information at a later date.

2. Introduction

2.1. Bio-based Construction Materials and Products

2.1.1 Definition

A material or a construction product is considered bio-based if it is composed in part of biomass[1]. In this overview, we will be focusing on bio-based construction products. The bio-based materials most often used for construction include timber, wood building boards, rigid and semi-rigid insulation made with plant fibre, cellulose wadding, straw and hemp concrete.

2.1.2 Materials Being Studied

In terms of scientific research, the studies are mainly centred on three different types of bio-based materials and products: hemp concrete, solid wood and straw bale. This overview will focus on these three elements, but will also include bio-based loose-fill insulation as well as structural insulation boards and blanket insulation.

2.2. Defining Hygrothermal Behaviour

The term “hygrothermal” is generally used to define the indoor temperature and humidity level of ambient air. It has now become a frequent form of measurement in the construction industry, since the ideal hygrothermal comfort level is sought for the health of the inhabitants and to maintain the infrastructure’s durability.

More specifically, a material's hygrothermal behaviour represents the material's behaviour in an environment in which the temperature and the humidity levels vary.

When creating this overview, we were able to categorize the studies according to three scales:

- Material Scale
- System or Component Scale
- Building Scale

The term Hygrothermal Behaviour can be defined in several ways, depending on the scale used in the research studies:

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[1] Biomass: Organic matter, with the exception of geological and fossil matter.

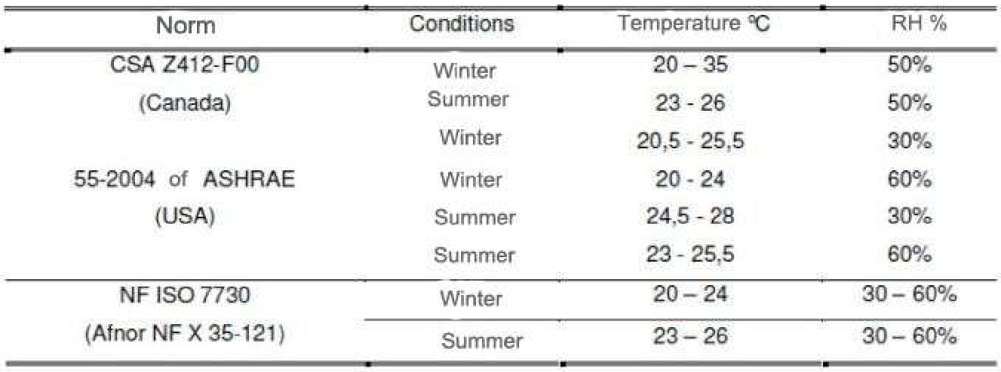
- At the Material scale, we discuss moisture and heat transfers and the values of the material's intrinsic characteristics.
- At the Component scale, we are interested in observing the variations in temperature and humidity on one side or in the middle of the component anytime there is a change in condition on its opposite side.
- At the scale of the Building, we study the variations in temperature and humidity inside the building as well as energy consumption under certain weather conditions.

The methods used to study the hygrothermal behaviour of bio-based materials are different according to the scale.

First of all, the *Material* level allows us to define a material's hygrothermal behaviour by conducting various tests at a macroscopic scale. At this level, we can therefore measure the material's intrinsic coefficients (porosity and pore morphology, thermal conductivity, sorption isotherm, moisture buffer value, etc.). We can also develop mathematical models in order to better understand the combined humidity and heat transfer inside the material. The models are based on differential equations of mass conservation and energy.

We can then move to the *System* scale, which is concerned with the building's envelope: the wall systems, roofs, etc. Simulations and experimentations are conducted at this scale. Most of the time, when hygrothermal variations occur in the environment (inside or outside), we observe variations in temperature and in humidity on the surface of the component or inside it. At this scale, several materials are generally associated and can interact during hygrothermal transfer events.

Finally, simulations and experiments can also be done at the level of the *Building*. The aim of these studies is to determine the hygrothermal comfort and energy consumption of buildings made with bio-based materials. Several norms exist to define the standards of hygrothermal comfort at this scale: the American standard 55 (ASHRAE, 1992), the Canadian standard SCA Z412-F00 and the international standard of the OIN 7730 (ISO, 1994). A comfort zone is defined as a zone where the relative temperature and humidity is hygrothermally satisfactory for 80% of the occupants in an interior room. [8]



Norm	Conditions	Temperature °C	RH %
CSA Z412-F00 (Canada)	Winter	20 – 35	50%
	Summer	23 - 26	50%
55-2004 of ASHRAE (USA)	Winter	20,5 - 25,5	30%
	Winter	20 - 24	60%
	Summer	24,5 - 28	30%
	Summer	23 - 25,5	60%
NF ISO 7730 (Afnor NF X 35-121)	Winter	20 – 24	30 – 60%
	Summer	23 – 26	30 – 60%

Figure 1: Comfort zones defined by various norms [8]

Certain simulations on the *System* and *Building* scales have been conducted using mathematical models that were established on the *Material* scale: using the models from the *Material* scale as a base, we then add boundary conditions that describe a physical model in detail at the *System* or *Building* scale. Therefore, by using simulation software, we can know the hygrothermal behaviour of a *System* or a *Building*. But most of the simulations stem from physical laws of conduction and use thermo-physical quantities related to the given materials.

In the first part of this overview, we will define and give values to the physical quantities needed to characterize the Material scale. We will then address studies that have been conducted on System and Building scales. This will allow us to draw a general conclusion on the hygrothermal behaviour of bio-based materials.

3. Characteristic Definitions and Quantities

In this chapter, we will review a number of definitions and will detail the intrinsic values needed to define the Material scale. Following these definitions, a summary table of these values will be drawn for each studied material. These definitions are partly based on the comparative study drafted by the CSTB and the FCBA concerning wood frame walls [1].

3.1. Relative Humidity

The air's relative humidity (also known as moisture content) is usually noted φ and corresponds to the ratio of the partial pressure of water vapour in the air to the saturation vapour pressure, at the same temperature. It is therefore a way of measuring the relation between the air's water vapour content and its maximum capacity to contain water vapour in these conditions.

For their comparative study on wood frame walls [1], the CSTB and the FCBA defined this concept more precisely:

The air's water vapour content is also called absolute air moisture and is noted W. It is expressed in kg/m^3 : $W = \frac{mv}{V}$

Where: V is the volume of the humid air sample and mv is the water vapour mass.

If the air is not saturated with moisture, then the absolute air moisture is lower than the one obtained at saturation. We can therefore define φ as the ratio between absolute air moisture and its maximum saturated value:

$$\varphi = 100.\frac{W}{Ws}(\%)$$

φ, which defines relative humidity, is also frequently known as RH.

3.2. Phase Change

When studying the hygrothermal behaviour of bio-based materials, the phase-change of water within these materials plays an important role. When this phase-change happens, absorption or release of energy occurs in the bio-based material. The energy released by the water's phase-change is up to 10 times higher than the energy released within a phase-change material[2] (since the energy needed for the phase-change of water is quite high, equal to 2257 kJ/kg).

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[2] Phase-change materials: The practical use of these materials lies in the fact that one or more phase transitions occur in their microstructure (the studied system's transformation being provoked by the variation of an external parameter).

For the time being, two approaches are being used to handle phase-change in the studies:

- One approach is qualitative: explaining certain events observed in the experiments through evaporation and condensation ;
- The other is quantitative: When used for the modelling of mass and energy transfers, the phase-change is regarded as a heat source.

This second approach is based on a method used for materials that are considered “porous”, and for which we can find a large number of scientific publications.

3.3 Moisture transfer

Moisture transfer within materials is a concept which has been extensively defined in many research studies:

The transport of humidity in porous environments stems from a mix of various events; these events are, in turn, at the source of the movement of each given phase (liquid and vapour phases).

The part played by each of these mechanisms on a given amount of water depends on the material’s properties (porosity, pore morphology, state of the pore surface, chemical nature of the compounds,…) as well as on the climatic conditions in which the material is placed (pressure and temperature) and finally on the nature of the aqueous phase (liquid or vapour).

Combined transfers of heat and humidity are largely known today. They stem from the simultaneous transport of the liquid and gas phases present in the porous environment.

3.4. Surrounding Environment

The definition of the surrounding environment is partly based on the paragraph entitled “Climates” written by the CSTB and the FCBA for their comparative study on wood frame walls [1].

A good understanding of the surrounding environment is necessary in order to evaluate the hygrothermal behaviour of a material in real conditions.

In the external environment, many parameters have a direct influence on a material's hygrothermal behaviour, such as relative humidity, temperature, pluviometry, wind and sunshine. Unfavourable metropolitan climates are then defined to characterize external environments: oceanic (Brest), continental (Nancy), mountainous (La Pesse) and humid Mediterranean (Nice) climates.

Concerning the interior environment, the relative humidity corresponds to the amount of water contained in the exterior air that enters the room, to which is added the amount of water produced inside the room (cooking, human production, etc…).

Vapour production is defined by:

$$\Delta v = \frac{G}{nV} = v_i\text{-}v_e = W/\ n$$

With :

- G: interior humidity production rate in kg/h
- N: air renewal rate per number of air changes/h

- V : interior volume of the building in m3
- W: Absolute humidity in kg/m3
- vx: Humidity excess (inside or outside) in kg/m3

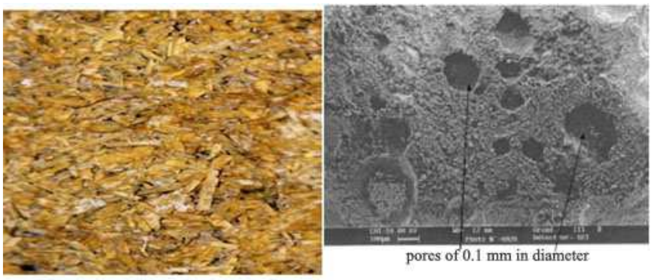
3.5. Porosity

The porosity of a material, ε, is the ratio of the pore space to the total volume. Porosity is an important characteristic in bio-based materials. Moisture and heat transfers in materials are linked to porosity and all the models for hygrothermal behaviour rely on this knowledge.

Concerning hemp concrete, SAMRI D. [4] has distinguished 3 classes of pores (see figure below):

- macroscopic pores (average size: 1mm), due to the imperfect arrangement of the particles in the solid matrix;
- mesoscopic pores (average size: 100µm) in the binder, due to the action of the air-entraining agent, and in the intra-particle capillaries, especially for hemp;
- microscopic pores (average size: 0.01µm), including inter-hydrate pores created during the calcium carbonate formation.

Total porosity in hemp concrete studied by SAMRI D. reached 72% - 79% depending on the binder dose. Methods to evaluate the porosity of hemp particles and hemp concrete have been developed based on air permeability measurements ([46] and [49]).



Macroscopic pores Mesoscopic pores

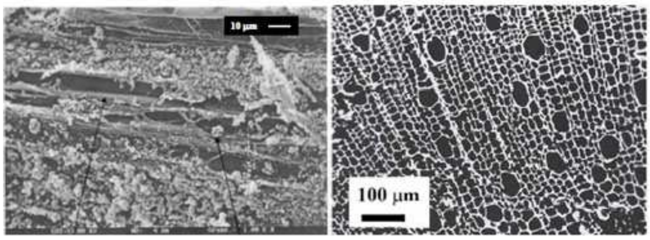


Figure 2 : Three Classes of Pores Observed in Hemp Concrete [4]

However, when it comes to other bio-based materials, very few scientific publications focus on porosity. We can nevertheless suppose that macro-porosity (fibre arrangements or fibre bundles in an insulator made from plant fibres, for example) and micro-porosity (porosity of the plant fibres themselves) exist. Beyond porosity value, there is even less information on pore morphology and pore surface (specific surface).

3.6. Thermal Conductivity

Thermal conductivity is defined by a material's capacity to transmit heat by conduction.

Concerning hemp concrete, thermal conductivity depends on the following parameters [5]:

- The nature of the raw material and the proportion of raw material used
- The sample's manufacturing process (compaction force, projection distance)
- The material's water content

Various studies have been undertaken to characterize thermal conductivity. Experimental measurements range from 0.06 W (mK) to 0.21 W (mK) [5].

A study from the CEBTP, in partnership with the FFB and ADEME [6], made it possible to find thermal conductivity values for straw:

- The bales of straw used for the infilling of the roof have a density of 80 kg/m3, and an effective thermal conductivity of: λ effective value = 0,07 W/m.K.
- Concerning the walls: because of the framework and the joints filled with a lime-hemp mixture, the equivalent thermal conductivity obtained by a thermal transmission test on a wall model is : λeq = 0,10 W/m.K, which is an average thermal transmission coefficient of U = 0,25 W/m ². K for the walls.

3.7. Thermal Capacity

Heat capacity is a quantity that allows us to quantify a body's capacity to absorb or restore energy through heat exchange. In other words, a material's heat capacity is the material's capacity to stock heat.

Specific heat capacity is expressed using the following formula:

$$c = \frac{\lambda}{\rho a}$$

With:

- λ : heat capacity
- c : specific heat capacity
- ρ : density
- a : diffusivity

3.8. Moisture Content

In the field of porous medium physics, when we talk about moisture content, we mean the amount of water contained in a matter sample; the amount being assessed using a weight or volumetric ratio.

Specific moisture content: u

A material's specific moisture content is the ratio of the water mass contained in the material to the mass of the dry material. It is expressed in kg/kg : $U = \frac{me}{ms}$

m_e being the water mass contained in the material and m_s the dry material mass.

Specific moisture content per volume: w

The specific moisture content per volume is the ratio of the water mass to the volume of dry material. It is expressed in kg/m³. A relation exists between specific moisture content and specific moisture content per volume: $w = \rho_0 . u$.

ρ_0 being dry bulk density.

Volumetric Moisture ratio: ψ

The volumetric moisture ratio is the ratio of the water volume to the volume of the dry material. It can be determined based on specific moisture content with this formula:

$$\Psi = \frac{\rho 0}{\rho w} . u$$

ρ_0 being dry bulk density and ρ_w being water's density (997,6 kg/m³ at 23 °C).

When the water content varies within a material, the other characteristics (such as thermal conductivity) can vary slightly.

Furthermore, when relative humidity varies, moisture content within a material varies also.

In the case of straw [6], for example: for relative humidity of 50%, moisture content is approximately 15 % in mass. It reaches 25% for RH= 90%.

3.9. Sorption-desorption Isotherm Curve

This curve reflects the increase of water content according to relative humidity, for a given material at a given temperature.

The sorption isotherm is often presented as a curve that shows a material's water content in balance with the surrounding relative humidity at a certain temperature. The general shape of the curve is shown on the figure below. If the variation of the material's water content stems from a state of water saturation, the curve is called a desorption isotherm. If the variation stems from a dry state, the curve is called an adsorption isotherm; [7] and [5] in the case of hemp chaff. Concerning porous materials, this phenomenon is also called the adsorption-desorption effect. It is important to mention that a hysteresis exists between these two curves, and is often neglected.

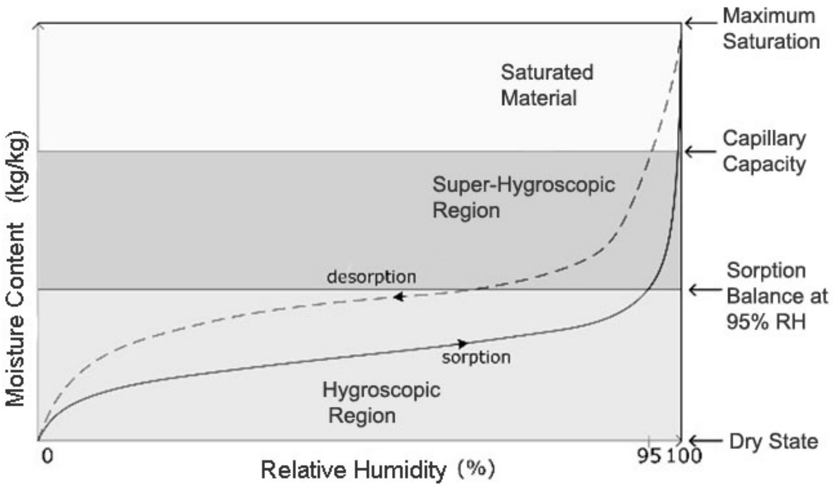


Figure 3 : Overall Shape of the Sorption Isotherm Curve [7]

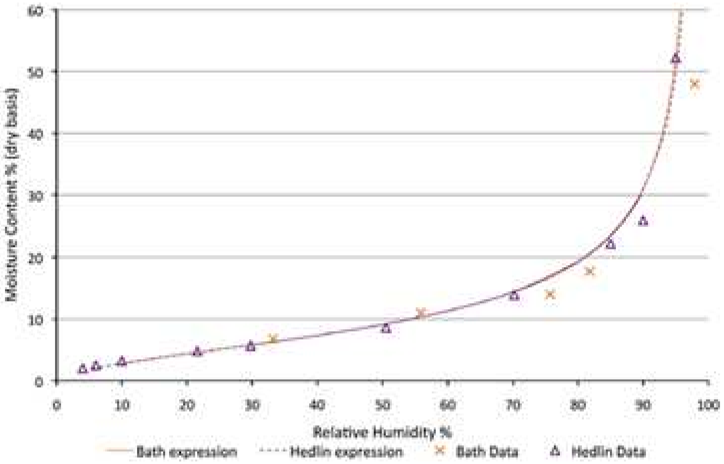


Figure 4 : Overall Shape of the Adsorption Isotherm Curve of Straw [44]

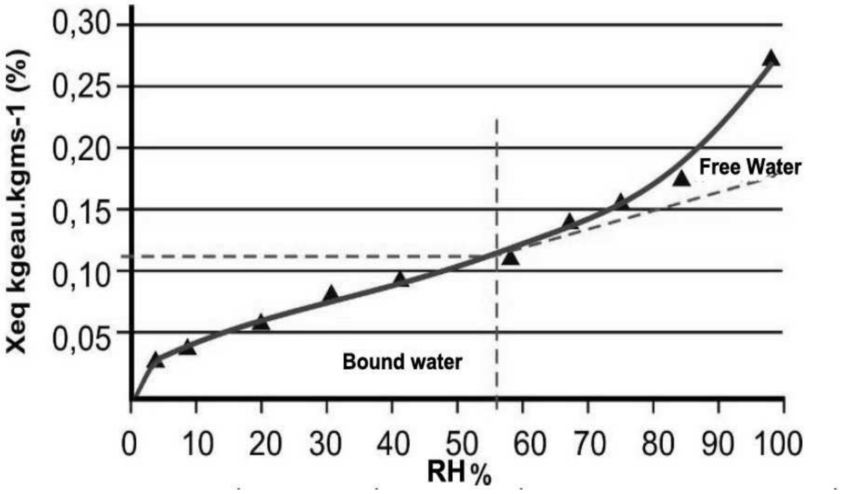


Figure 5 : Sorption Isotherm Simulation of the Nordic Pine at 20°C [8]

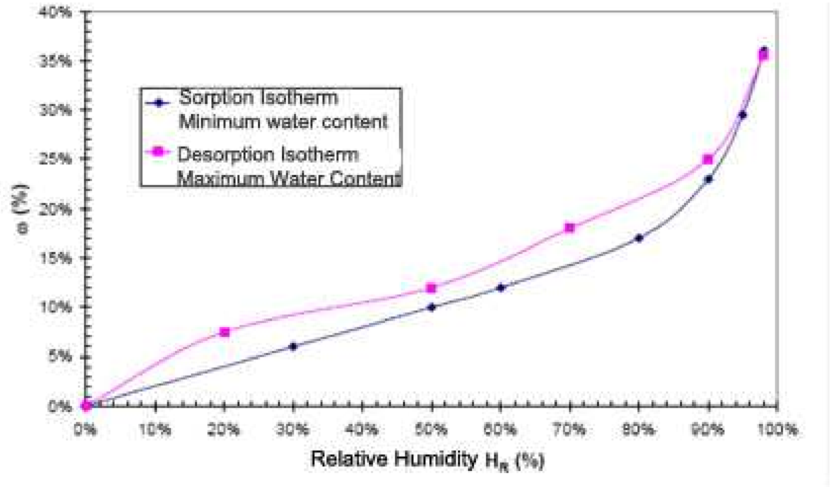


Figure 6 : Hemp Concrete Sorption-desorption Curves at T=20°C CEREZO V. (ENTPE) [5]

3.10. Moisture Buffer Value (MBV)

The notion of “Moisture Buffer value” is often encountered in studies. In his thesis, TRAN LE A.D. [2] offers the following definition:

The English expression « Moisture buffer value – MBV » indicates the amount of water that is adsorbed or desorbed when the material is subject to an exterior relative humidity variation over a given period of time. Its value is expressed in kg.m^{-2}.%HR^{-1}. The moisture buffer is the material’s capacity to moderate the relative humidity variations of the neighbouring air.

The NORDTEST [3] project was established to determine the moisture buffer value of materials. It defines a dynamic cycle, for a 24 hour time-period, in which relative humidity is set to 75% for 8 hours, then to 33% for the following 16 hours. The moisture buffer value is determined by the amount of adsorbed or desorbed humidity for one area unit, when the material is subject to a 1% change in relative humidity. When the thickness of the material exceeds the hydric depth of penetration under diurnal conditions, the MBV is not connected to the thickness of the material or to the variation amplitude of relative humidity.

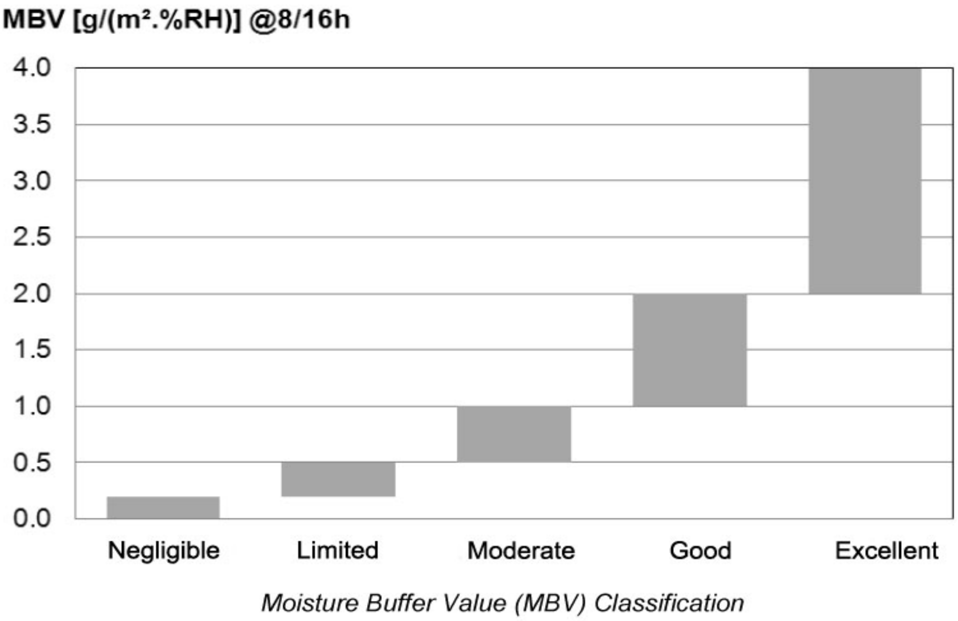


Figure 7: Moisture buffer value (MBV) classification [42]

In the context of the ANR project “Betonchanvre” (“Hempconcrete”), COLLET F. and PRETOT S. [42], checked the hygrothermal characteristics of the different hemp concrete formulas. For all the formulas, the average MBV values ranged from 1,99 to 2,53 g/(m².%RH), which ranks hemp concretes as good (1<MBV<2) to excellent (2<MBV) hydric regulators.

3.11. Permeability and Permeance to Water Vapour

3.11.1 Permeability to Water Vapour

A material’s permeability, δp, is the property that governs the flow of a fluid into the material, under a pressure exercised between the material’s two opposite faces. Permeability to water vapour thus designates the ratio of the amount of water vapour crossing a material per thickness unit, time unit, and per unit showing the difference in steam pressure on both sides of the material.

This quantity depends on the physical characteristics of the considered fluid (air, water vapour or water) and of the material’s characteristics, such as its pore diameter, air space geometry, thickness…

3.11.2 Permeance to Water Vapour

The permeance of a homogeneous material is the ratio between the material's permeability to water vapour and its thickness: Wp =$\frac{\delta p}{d}$ [kg/(m².s.Pa)]

We can also define a coefficient for water vapour permeance. The material's diffusion strength factor is the ratio between the air's permeability to water vapour and its own permeability.

Therefore : $\mu = \frac{\delta 0}{\delta p}$

The air's permeability to water vapour being: $\delta 0 = 2*10^{-7}.\frac{T^{0.81}}{P0}$ [kg/(m.s.Pa)]

Where P_0 is the atmospheric pressure in Pa.

3.11.3 Thickness of Air Layers of Equivalent Diffusion

By this, we mean the thickness of a layer of air, for it to have the same permeance as a layer of material of a given thickness (d).

Where : Sd = μ.d [m]

3.12. Summary Table of Characteristic Values

Table 1 : Characteristic Values for Each Class of Materials

	References	Density [kg/m3]	Porosity [%]	Thermal Conductivity [W/(m.K)]	Permeability to water vapour	Comments
Hemp Concrete	[5]		60 to 80 % (avg 70%)	0,06 to 0,21 (avg 0,13)		
					μ = 3-5	Hemp
Hemp Wool	ASIV website	25 to 80		0,038 to 0,042		
Wood Fibres	ASIV website	40 to 250		0,037 to 0,005		
	[1]	55	98%	0.045		
Solid Wood	[1]	600	72%	0.13		Fir
					μ = 5	
Straw	[6]	66 to 85		0,064 to 0,072		
					μ = 1	
Cellulose Wadding	ASIV website			0.04		
	[1]	50	95%	0.041		
Linen Wool	ASIV website	20 to 35		0,037 to 0,047		
					μ = 1	Linen

4. Models and Software Used for the Study

4.1. Most Often Encountered Models and Necessary Data

Water exists in two forms in the materials: as liquid water and as water vapour [8]. The transfer mechanisms of these two forms of water are different. Liquid water can transfer in the following ways:

Under the effect of a capillary pressure gradient: difference in pressure between the liquid phase and the gas phase in the material's pores, pressure difference caused by the pore's meniscus;

- Under the effect of adsorption-desorption;
- Under the effect of gravity;

In the case of water vapour, the migration is carried out by the gradients of the vapour's partial pressure. These gradients take two forms:

- Pressure gradient between the inside and the outside of a building;
- Concentration differences in a material involving partial pressure variations.

Therefore, by taking into account the dominant effects shown above, moisture conservation (or conservation of mass) can be modelled with differential equations.

As for heat transfer, it takes place in the materials through:

- Conduction
- Convection
- Thermal radiation
- Phase-change (evaporation/condensation)

In the same way, we can write the equation for heat conservation (or energy conservation) according to these different effects.

By focusing on transfer drivers, we notice that the heat and moisture transfers in materials are always coupled. Therefore, the two parts that relate to moisture and heat conservation are absolutely necessary.

As explained in the thesis by SAMRI D. [4] and in the presentation by COLLET F. et al. [9], the equations that govern those coupled transports of mass and energy are based on Künzel's model and can be written as follows:

- Mass conservation

$$\underbrace{\frac{\partial \mathrm{w}}{\partial \mathrm{HR}}.\frac{\partial \mathrm{HR}}{\partial t}}_{\text{Hydric Inertia}} = \frac{\partial}{\partial x}\left(\underbrace{D_{\varphi}.\frac{\partial \mathrm{HR}}{\partial x}}_{\text{Liquid Diffusion}} + \underbrace{\delta_{p}.\frac{\partial}{\partial x}(\mathrm{HR}.p_{sat})}_{\text{Vapour Diffusion}}\right)$$

- Heat conservation

$$\underbrace{\rho_0.c.\frac{\partial \mathrm{T}}{\partial t}}_{\text{Thermal Inertia}} = \underbrace{\frac{\partial}{\partial x}\left(\lambda.\frac{\partial \mathrm{T}}{\partial x}\right)}_{\text{Thermal Conduction}} + L_{v}.\frac{\partial}{\partial x}\left(\underbrace{\delta_{P}.\frac{\partial}{\partial x}(\mathrm{HR}.p_{sat})}_{\text{Liquid Convection and Vapour Convection}}\right)$$

With:

- HR : Relative Humidity
- ρ_0 : Dry bulk density [Kg.m^{-3}],
- c : Specific heat of the material [J.kg^{-1}.K^{-1}]
- w : Moisture content of the material [kg.m^{-3}]
- p_{sat} : Saturated vapour pressure [Pa],
- λ: Thermal conductivity of the material [W.m^{-1}.K^{-1}],
- D_ϕ : Liquid conductivity [kg.m^{-1}.s^{-1}] (= $\xi_w * D_w$, with D_w : Moisture diffusivity of the material [m^2.s^{-1}]),
- δ_p : permeability to water vapour of the material [kg.m^{-1}.s^{-1}.Pa^{-1}],
- L_v : Phase change latent heat [J.kg^{-1}].

In addition, the boundary conditions are needed to describe and simulate a specific hygrothermal problem. It is important to note that each situation has its own boundary conditions and that the applied conditions have a significant impact on the simulation.

The Glaser method, helpful to calculate the diffusion of water vapour, nevertheless neglects the hygroscopic properties of materials and is therefore not really adapted to bio-based materials. That is why it is better to prefer numerical simulation to experimentation at the Wall and Building scales.

4.2. Simulation Software

Simulation software tools are very important for hygrothermal research at the component and building scales. By using these types of software, we can not only predict temperature and moisture evolutions in the material and in the building under simple conditions or under real climatic conditions, but we can also predict energy consumption.

We can establish two groups among the software most commonly used:

The first group includes WUFI, hygIRC, DELPHIN and MOIST. These programs are based on a certain moisture and heat transfer model. The user then simply establishes a physical model (walls, roofs, ceilings etc.), applies the boundary conditions (the conditions are often climatic data: temperature, humidity outside the building...), and launches the calculation of the component’s or the building's hygrothermal response. The software program is simple to use and can be handled both by researchers and project managers.

The program COMSOL is separate from other types of software. It can simulate coupled phenomena by using the finite element method. In order to simulate the hygrothermal behaviour of a component or a building, the mathematical models established by the researchers must be set up in the software program. After that, the calculation method is the same as in the other software programs.

5. Reports on Already Completed Studies

In this chapter, we will report on the studies that have already been completed, at the component and the building scales. For each selected class of materials, we will first describe the studies that were undertaken at the component scale. We will then give an explanation of the studies conducted at the scale of the building. In the first part of this chapter and in order to better understand the studies chosen for this overview, we will give definitions regarding the elements being studied and the expected results at the component and building scales.

5.1. Definitions

5.1.1. Component Scale

The system scale represents the second level of research in regards to the hygrothermal behaviour of bio-based materials. The components that are studied are either simple walls or wall systems. The simple wall refers to a wall with no coating, whereas wall systems are walls covered with one or more layers, and are therefore complex systems. Examples of wall systems are shown as follows:

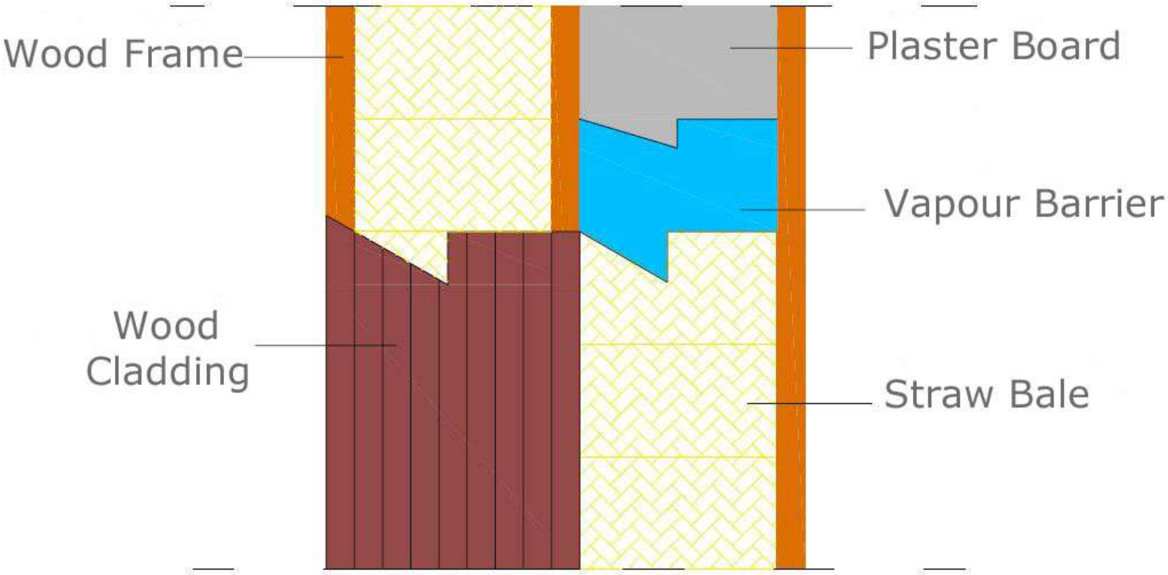


Figure 8: Superposition of Various Layers in a Straw Wall with a Wood Frame

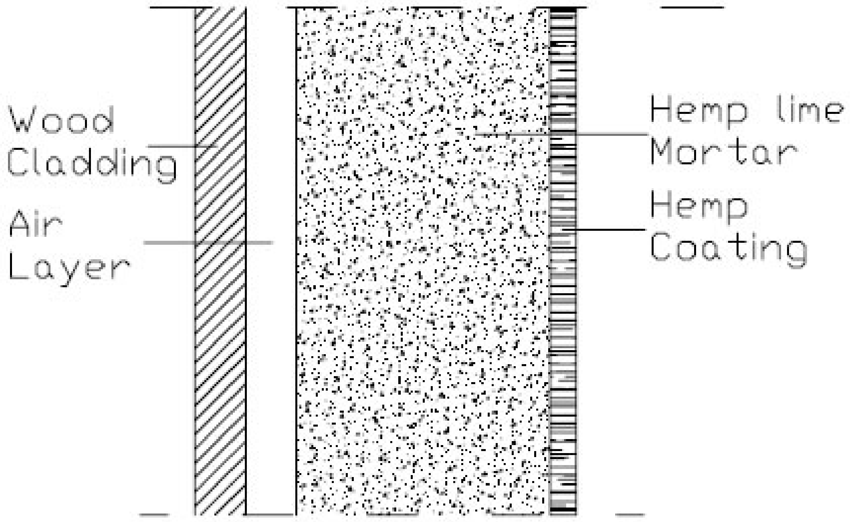


Figure 9 : Hemp Concrete Wall

The coating and other outer layers have an effect on the hygrothermal behaviour of bio-based walls since the outer layers restrict air flow and moisture, and they also impact heat conduction. There is therefore a significant difference in hygrothermal behaviour between simple walls and walls with outer layers.

There are, moreover, two types of research at this level of work: numerical simulation and experimentation. Experimentation is very important to understand the actual behaviour of a building component. Simulations are conducted by choosing a mathematical model associated to a simulation software program. The major advantage of simulation software programs is the fact that they save time.

We notice that, in many cases, the simulations and experiments are carried out simultaneously. This gives the possibility to compare results and thus validate the model on which the simulation is based. After having validated the model through experimentation, we can correctly predict the hygrothermal behaviour of a building component without having to do systematic experimental campaigns, but only if the physics of the phenomena is well preserved.

5.1.2. Building Scale

At the Building level, we can establish a link between the material's properties and a building's energy performance. Studies at this scale have a significant value, especially in order to develop the entire sector and implement the use of bio-based materials at a larger scale.

At this level, experiments and simulations can be performed in the same way as at the Component level. In regards to the simulations, the calculations are still based on models created at the Material scale. The boundary conditions are set at the interfaces between the building and the indoor or outdoor environment and some additional situations inside the building (air flow, heat sources, etc.). Concerning the experiments, they can be conducted in real occupied buildings or in units constructed specifically for research.

5.2. Vegetable Concrete

5.2.1 Component Scale

Many studies are available concerning vegetable concrete. There is a lot of documentation and research around hemp concrete and hygrothermal behaviour. A few research teams have studied these materials: the ENTPE, Rennes 1 University, Bath University in England, Louvain University in Belgium, Reims University…

5.2.1.1 Experimental devices

The majority of the studies that aim to define the hygrothermal behaviour of vegetable concretes have been conducted using an experimental device, represented below as a diagram:

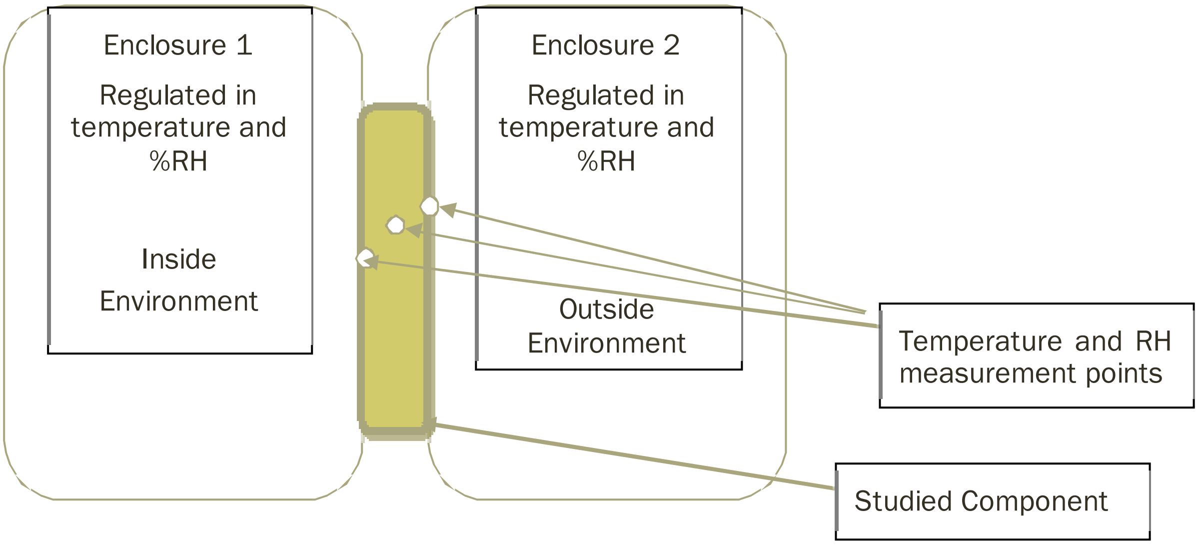


Figure 10: Schematic Representation of the Experimental Device Used to Study a Component's Hygrothermal Behaviour

The idea behind the tests done to study the hygrothermal behaviour of bio-based components is as follows: the component to be studied is positioned (test-tube) between two climatic enclosures where the temperature and the hygrometry are controlled to recreate the interior / exterior conditions of a home, including the temperature and hygrometry variations that can occur in real conditions. With sensors, we measure temperatures and relative humidity at the surface and inside the component, as well as in the climatic enclosures.

These tests are often compared to simulations.

5.2.1.2. Types of Tested Components

The component that is being tested is mainly hemp concrete with no coating, in the shape of masonry blocks or as poured concrete.

Some tests have nevertheless been made on coated hemp concrete [4], [37].

5.2.1.3. Climatic Stresses

In order to reproduce different climatic conditions, several climatic stresses were imposed. These stresses led to:

- A pressure gradient between the inside and the outside, constant temperature
- A temperature gradient between the inside and outside, constant vapour pressure.
- Temperature and vapour pressure gradients between the inside and the outside.

5.2.1.4. Identified Phenomena

In 2005, Arnaud L. et al. [36], [37] demonstrated the phenomena related to the evaporation-condensation of water in hemp concrete when subject to temperature gradients. When the temperature rose from 10°C to 40°C in the enclosure that matched outside climatic conditions, Arnaud L. et al. observed an increase in vapour pressure within the hemp concrete wall, illustrating the evaporation phenomenon. This evaporation phenomenon is accompanied by heat absorption, which leads to a reduction of temperature variations within a wall (see figure below).

Arnaud L. et al. also showed that these types of phenomena do not happen often in the case of brick or cellular concrete. Consequently, they do not significantly influence thermal transfers.

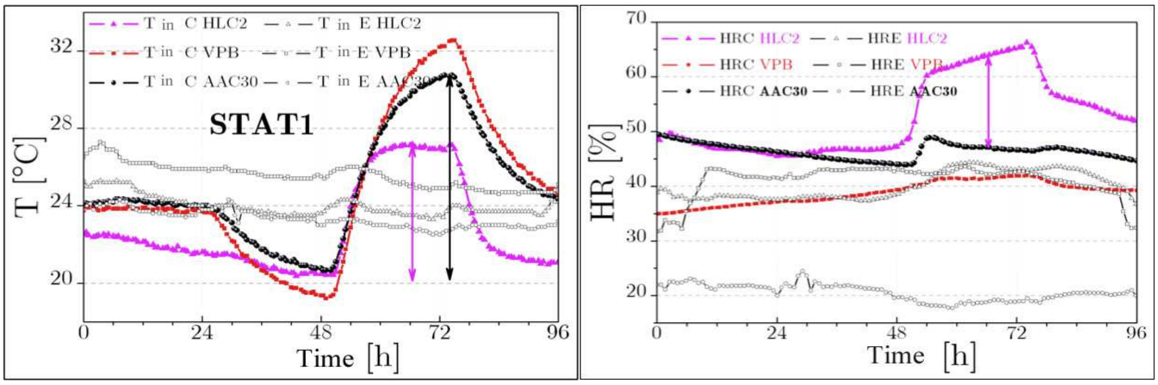


Figure 11: Evolution of the Temperature and Humidity Levels at the Centre of Hemp Lime Concrete Walls (HLC2), Vertically Perforated Brick (VPB) and Autocaved Areated Concrete (AAC30), Under Static Stress

The same types of phenomena were also noticed in a 30 cm concrete hemp wall by Collet F. et al. [15] . When the temperature in the outside environment varied from15°C to 28°C (with constant vapour pressure), Collet F. showed that there was, on the one hand, an inversion in the heat flow between the inside and the outside within the wall from the initial moment (t=0) to the final moment (t=10 days) of the test (see figure below, a). On the other hand, there was a vapour pressure peak, illustrating the evaporation-condensation phenomenon of water adsorbed in the wall (see figure below, b).

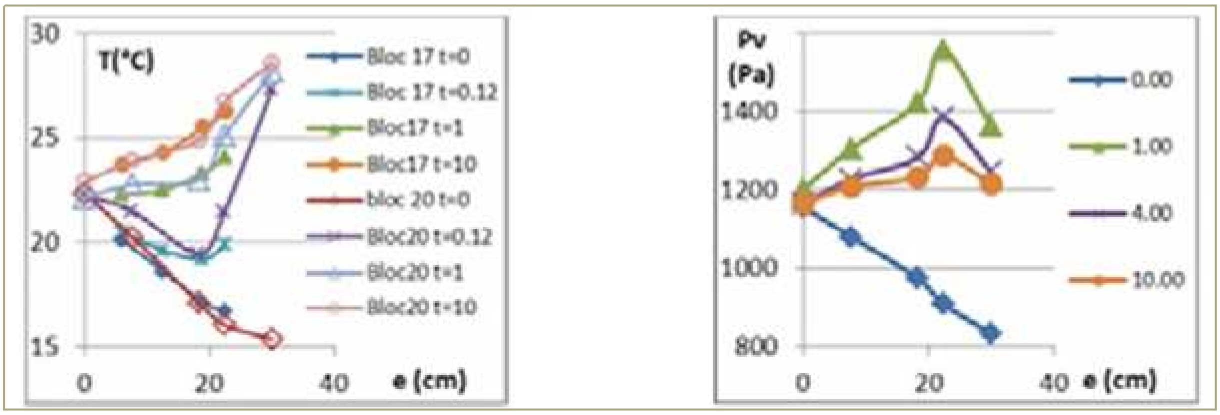


Figure 12 a and b : T and Vapour Pressure within a Hemp Concrete Wall, at Various Times (t), in Days.

In addition, COLLET F. et al. [15] showed, in the context of their work, that vapour diffusion occurred in a homogeneous way throughout the material's thickness, and that the wall's framework did not disrupt the wall's hygrothermal behaviour.

In the case of coated hemp concrete, SAMRI D. [4] showed that the coating modified water vapour transfers and acted as a hydric filter.

5.2.1.5. Simulation and Experimentation Comparison and the Models' Parameters of Influence

AIT OUMEZIANE Y. et al. [12] compared simulations and experiments on a hemp concrete wall. The experiments were conducted in a biclimatic enclosure as shown on § 5.2.1.1.

The wall's initial condition was stabilized to 40% of relative humidity and to a temperature of 23°C. The variation of the conditions on the wall's internal and external sides is represented on the figures below.

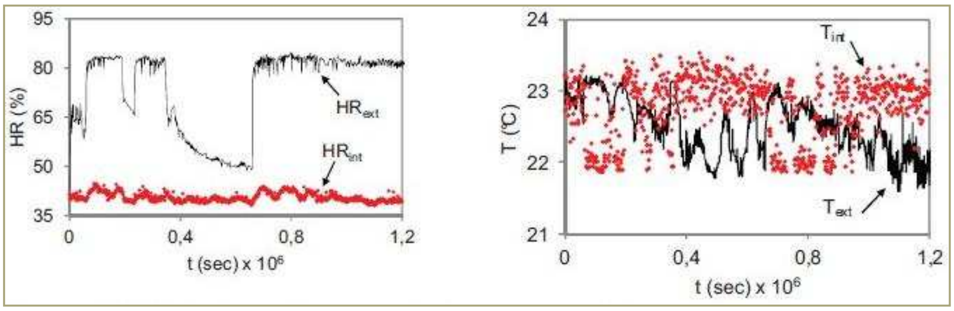


Figure 13: Interior (in red) and Exterior (in black) Climatic Stresses

The simulations are based on a unidimensional numerical mass and heat transfer model, based on the work by Künzel which takes the sorption isotherm hysteresis into account, as well as the air transfer that takes place at the centre of hemp concrete. The climatic data for the simulation was gathered based on the exterior conditions.

Initially, the simulations didn't take into account the air transfer inside the wall or the sorption-desorption isotherm hysteresis; only the sorption branch was taken into account.

The following figure shows the experimental and simulated results at various depths.

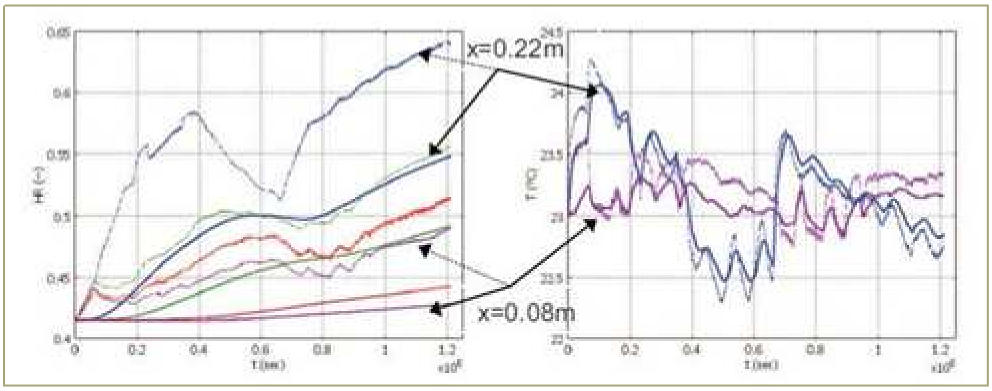


Figure 14: Experimental Results (dotted line) and Simulated Results (continuous line) for Relative Humidity (left) and Temperature (right) at Various Depths x = 0.08 m, 0.12 m, 0.18 m and 0.22 m

Concerning temperatures, the simulation and experimentation curves are similar (with the simulated curves always slightly higher than the experimental ones). However, when we look at the variations in relative humidity, there is an important gap between simulation and experimentation (the simulated curves are much higher than the experimental ones). The amplitudes of the variation in relative humidity are underestimated, with a difference reaching up to 10%.

AIT OUMEZIANE Y. et al. [12] as well as SAMRI D. [4] suggest taking into account air transfer, as it leads to better water vapour diffusion in hemp concrete. They also suggest taking into account the sorption-desorption hysteresis, as it improves the representation of humidity's effective storage in the material. In addition, phase change is also an important factor since it can alter the studied material's performances. Phase-change is taken into account in Künzel's equations, which are used in these two studies.

Depending on the simulation, a small difference in the total pressure between both sides of the wall becomes the driving force for the air transfer and considerably increases the distribution of humidity with a high absolute permeability. Moreover, the sorption branch doesn't exactly represent the real behaviour of the material's water content. Intermediate cycles[3] exist, which lead to a decrease in the material's storage capacity.

AIT OUMEZIANE Y. et al [12] show that the relative humidity variations obtained with simplified modelling are more satisfactory than the variations obtained with a simulation that doesn't take the sorption-desorption isotherm hysteresis into account.

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[3] Document [12] p 230 : "The sorption/desorption isotherms for hemp concrete […] are "extreme" curves that don't represent the real evolutions of water content in relation to relative humidity. This main cycle does nevertheless correctly frame the value of stocked humidity in the material. For hygroscopic materials that present a hysteresis, studies proved the existence of intermediate cycles ((Roels et al, 2008) for plaster, (Cameliet et al, 2005) for wood)."

5.1.2.6. Characterization Quantities

EVRARD A. and DE HERDE A. [14] did a simulation with the WUFI software to study the hygrothermal responses of different wall systems subject to temperature variations. They evaluated the different quantities that could characterize these responses (see tables below).

Table 2: Wall Systems Being Studied

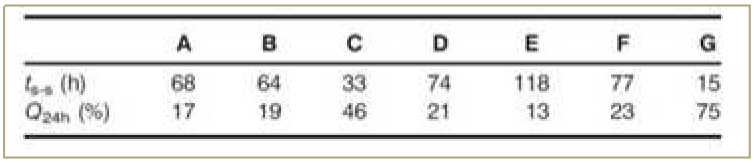
Wall System	Nature of the System
A	Hemp concrete with internal and external coating
B	Hemp concrete with internal coating and external cladding
C	Cellular concrete
D	Blocks, clay bricks and extruded polystyrene
E et F	Clay bricks
G	Mineral wool

Table 3 : Characteristic Quantities for Hygrothermal Behaviour

Characteristic Quantities	Definition
$t_{s\text{-}s}$	Time needed to reach 95% of the thermal flow at a stationary state (in hours)
Q_{24}	Ratio of the energy effectively transferred during 24 hours Shows the stress that must be applied to maintain the interior condition at a constant level during sudden changes in outside temperature
phs_{th}(h)	Corresponds to the thermal phase shift. It defines the time needed to reach extreme values on the inside surface while considering the same extreme values on the outside surface
dmp_{th}(%)	Corresponds to thermal damping. It is the difference in the temperature amplitude between the inside and outside surfaces, calculated with the data from the 3rd day.
MBV	The Moisture Buffer Value indicates the amount of adsorbed or desorbed water when the material is subject to a variation in outside relative humidity, and for a given time.

Concerning the $t_{s\text{-}s}$ and Q_{24} quantities, the results are presented in the table below.

Table 4: Calculated Values, $t_{s\text{-}s}$ and Q_{24}, for the Different Wall Systems

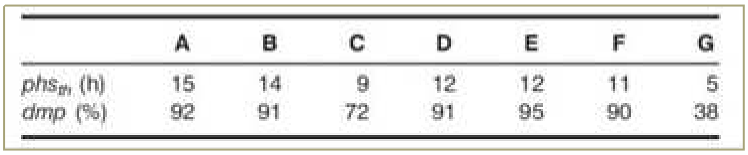


	A	B	C	D	E	F	G
$t_{s\text{-}s}$ (h)	68	64	33	74	118	77	15
Q_{24h} (%)	17	19	46	21	13	23	75

For hemp concrete walls, the stationary states appear 68 hours and 64 hours after the temperature drop. The fact that wall A's Q24 parameter is inferior to wall G shows that wall A has a better resistance to outside temperature variations.

The results of the phs_{th} and dmp_{th} quantities using WUFI are reported in the table below.

Table 5: Calculated Values, phs_{th} and dmp_{th}, for the 7 Wall Systems

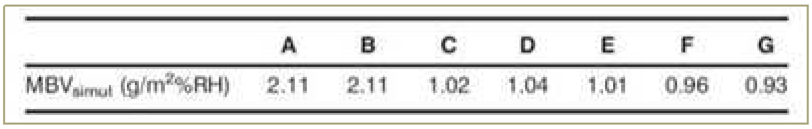


	A	B	C	D	E	F	G
phs_{th} (h)	15	14	9	12	12	11	5
dmp (%)	92	91	72	91	95	90	38

The results demonstrate a phase shift of approximately 15 hours and high thermal damping.

In regards to the MBV quantity (Moisture Buffer Value), the simulations to calculate it are based on the protocol presented by RODE et al. [17]. The results are represented in the table below for the different wall systems.

Table 6: The Simulated MBV of the Wall Systems

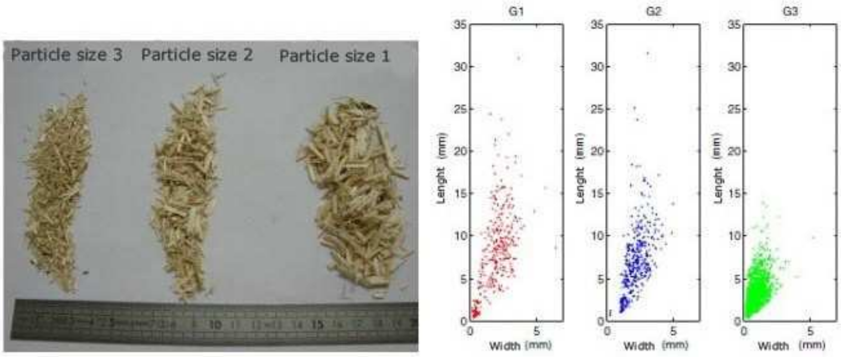


	A	B	C	D	E	F	G
MBV_{simul} (g/m²%RH)	2.11	2.11	1.02	1.04	1.01	0.96	0.93

The results show that the A and B hemp concrete walls present the best "moisture buffer" capacities. We can link this characteristic to thermal aspects, since the phase change of water is accompanied by a release or absorption of energy. EVRARD A. and DE HERDE A. calculated that hemp concrete walls could release energy – 43kWh/m2 – during night time.

5.2.1.7. Hygrothermal Behaviour Optimization

GOURLAY E. et al [16] worked on the optimization of hemp concrete's hygrothermal behaviour by focusing on the impact that the size of the aggregate had on hygrothermal transfers in the material. Three square walls were tested, each made with hemp concrete that was composed of aggregates that had differently sized particles. (See Table 7 and Fig. 15)



(a) (b)

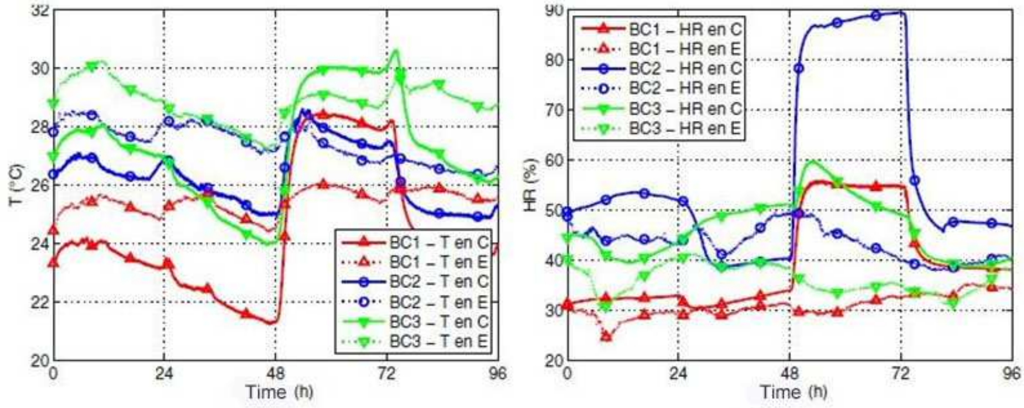
Figure 15: Picture (a) and dimension (b) of hemp particles in 3 particle sizes

On the internal side of the wall, GOURLAY E. et al imposed step-change stresses, where T and RH remain constant for 24 hours at each stage, the first stage being at 20°C and 50%, the second being at 10°C and 80% and the third being at 40°C and 45%.

Table 7: Average Length and Width of Hemp Particles

Name of the hemp particles	Average length	Average width
G1	8,9 mm	2,0 mm
G2	7,6 mm	1,8 mm
G3	3,1 mm	1,0 mm

Five probes were used to measure the temperature and the humidity inside the wall (A), outside the wall (E), on both surfaces (B and D) and in the middle of the wall (C). The results are presented in Fig.4.15.



(a) (b)

Figure 16 : Evolution of T and RH in C and E, relative to time for BC1, BC2 and BC3

GOURLAY E et al observed the following phenomena:

- At the centre of the BC2 wall, RH increases rapidly, T variation is low. The phase change buffers the variation of T, since the evaporation is endothermic.

- At the centre of the BC3 wall, the T increase is greater than the one in the BC2 wall and the RH increase is smaller. Since the porosity of the BC3 wall is smaller, the vaporization and the convective transfers are weaker. The temperature increase in the wall is therefore less curbed.
- At the centre of the BC1 wall, T and vapour pressure increases are greater than those in the BC2 wall, even though the high porosity is conducive to phase changes and also implies lower inertia.

These studies show that adopting an appropriate particle size makes it possible to optimize the material's hygrothermal behaviour and to mitigate the variations in outside temperature.

5.2.2. Building Scale

5.2.2.1 Variations in Temperature and Humidity– Hygrothermal Comfort

Through experimentation, SHEA A. et al [18] studied a unit with hemp concrete walls. The unit was composed of a single 27 m^2 room and was built for the experiment at the University of Bath in Great Britain. The material, components and parameters that were used to characterize the unit are listed in table 8 (below). The experiments took place once a balance between the humidity of the building and the exterior environment was reached, after the wall was dried and after having applied mortar to the wall.

Table 8 : Main Parameters of the Unit's Components

Component	Material(s)	Parameter(s)
Walls	Hemp concrete	Thickness = 200 mm Dry bulk density = 275 kg/m^3 Total thermal resistance = 3.20m^2 K/W Thermal transmission coefficient= 0.42 W/m^2K
Ceiling	Plaster board	Thickness = 9 mm
Ceiling insulation	Closed cell material	Thickness = 200 mm Thermal conductivity = 0.023 W/m·K
Floor	Particle board	Surface = 27 m^2
Floor insulation	Closed cell material	Thickness = 200 mm Thermal conductivity = 0.023 W/m·K
Door facing South	Wood frames with low emissivity triple pane glass, filled with argon.	U-value = 0.79 W/m^2K
Windows facing North		U-value = 0.97 W/m^2K
Windows facing South		U-value = 1.05 W/m^2K

The temperature sensors were placed on the internal and external surfaces of the walls. The sensors that measured relative humidity were placed at the centre of the walls. The inside and outside air temperature and relative humidity of were also measured. The evolution of the temperatures of the wall's internal and external surfaces for 11 days in May 2011 is shown on the figure below; the evolution of relative humidity of inside and outside air during the same time period is also shown below. Finally, another figure allows us to compare the inside air temperature and the temperature of the internal surfaces of the walls.

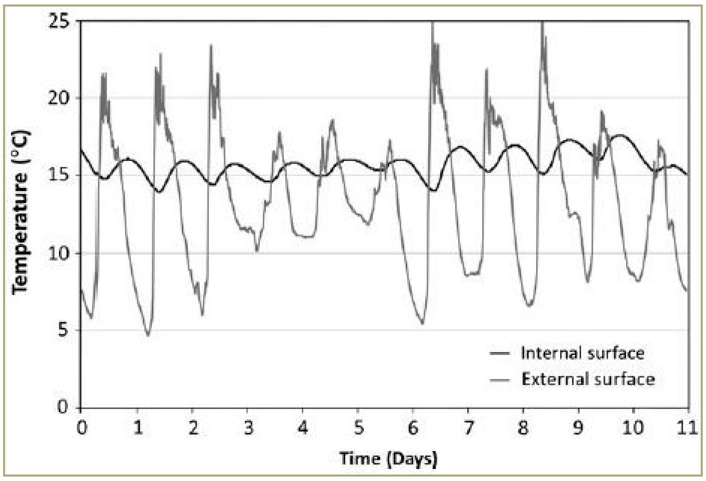


Figure 17 : Temperature Evolution of the Walls' Internal and External Surfaces

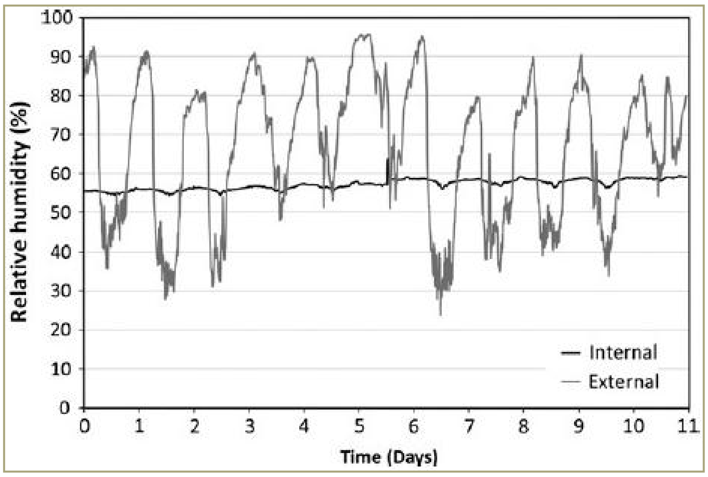


Figure 18 : Evolution of the Relative Humidity of Internal and External Air

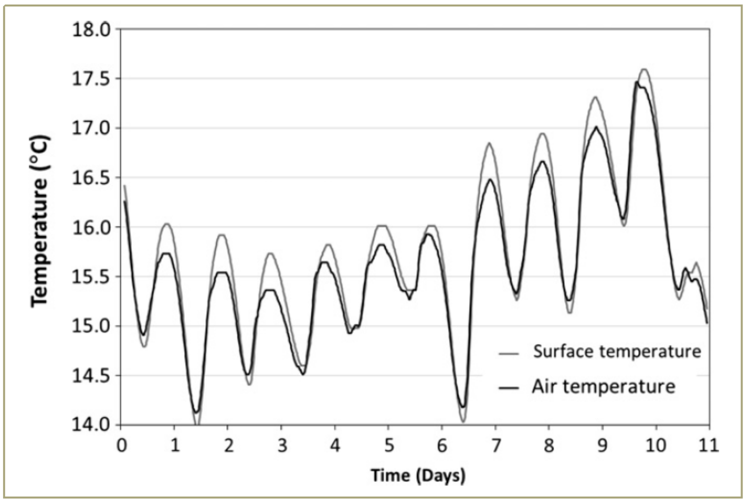


Figure 19 : Comparison of Inside Temperature and Temperature on the Wall's Internal Surface

The outside temperature variation during the month of May was of 6.5°C whereas the variation inside was of 0.9°C. Similarly, relative humidity inside was stable compared to the exterior conditions, which means that the unit has a high capacity to reduce temperature and relative humidity oscillations.

5.2.2.2. Variations in Temperature and Humidity – Hygrothermal comfort - Energy consumption

TRAN LE A.D. et al [11] simulated the hygrothermal behaviour of a building made with hemp concrete. A model based on the work of N. Mendes et al [50] was used in their study.

Most of the information is outlined in the table below. Humidity diffusion in the floor was not considered; a heat dissipator and a pressure controller were installed in the unit. For the simulation, the temperature and relative humidity measured in Nancy in January were applied to the South and West walls. For the North and East facing walls, temperature and relative humidity remained constant, at respectively 20°C and 60%.

Table 9: Main Information for the Unit Studied by Tran et al. [11]

Surface	15 m²
Volume	42.75m²
Exterior walls	Thickness = 30 cm
Interior walls	Thickness = 20 cm
Ceiling	Thickness = 30 cm
Ventilation	Air renewal rate= 0.5 air change per hour

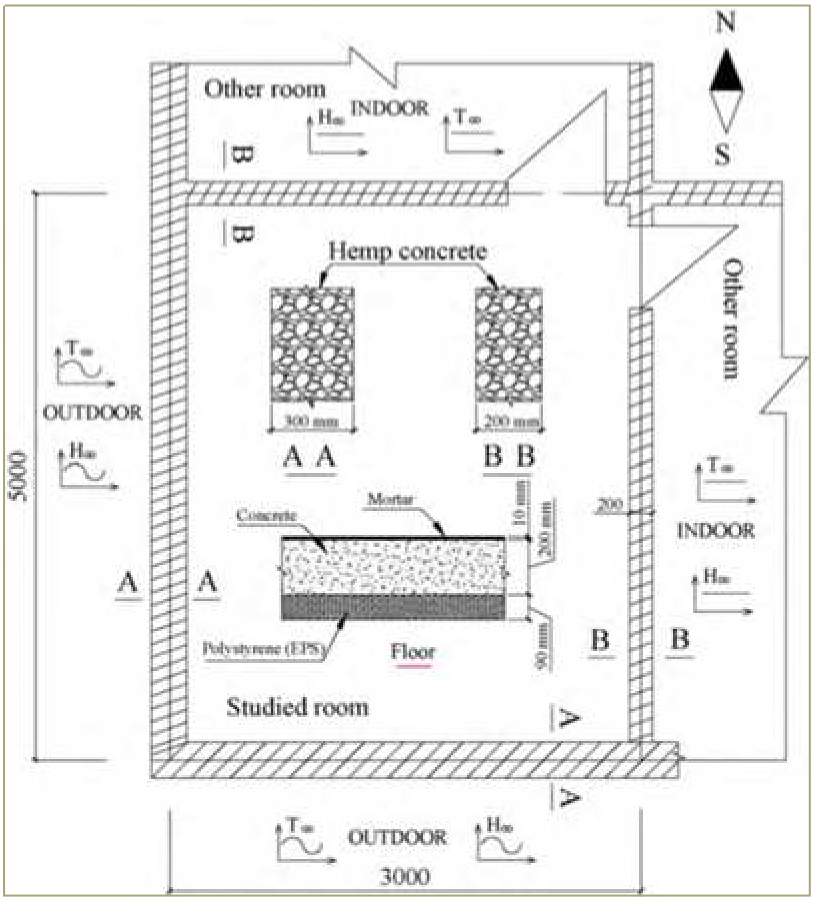


Figure 20 : Unit Studied by TRAN LE A.D et al.

Two models are used to simulate two different case studies. Both models and cases are explained in the following table.

Table 9: Details from the 2 Models and 2 Simulated Cases

Model Th	Model which doesn't take into account mass transfers throughout the building.
Model HAM	Model which takes into account mass and heat transfers throughout the building.
Case 0	Unoccupied unit
Case 1	Unit occupied between 10:00 pm and 8:00 am (Humidity and heat production increases)

The evolution of temperature and relative humidity inside the unit for both cases is shown on the figure below:

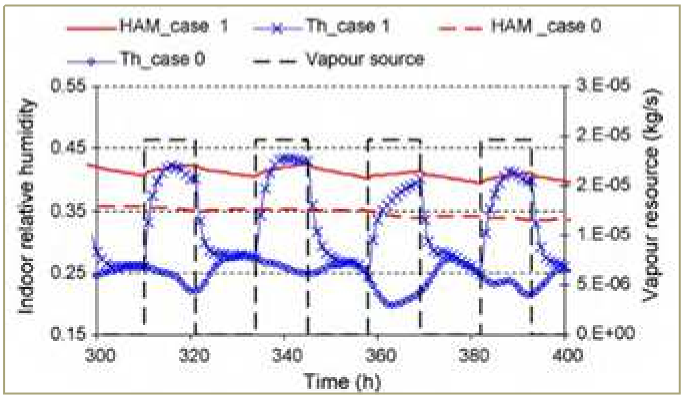


Figure 21 : Temperature and Reltive Humidity Variations in the units for both cases and models

We notice that hemp concrete's humidity absorption capacity moderates the humidity variations inside de room.

TRAN LE A.D. et al then conducted a sensitivity analysis for these results and noted that the sorption isotherm and thermal conductivity had a slight effect on the variation of relative humidity.

Furthermore, in regards to the energy consumption of the unit, TRAN LE A.D et al showed that a link existed between the unit's energy performance and the material's hygrothermal behaviour.

Through a sensitivity analysis, they found that:

- Mass transport properties had a slight effect on the variation of energy consumption ;
- The sorption isotherm had a slight effect on the variation of energy consumption ;
- The air change rate had a big effect on the variation of energy consumption ;

They also proved that a good ventilation strategy allied to the moisture buffer capacity of hemp concrete made it possible to decrease a building's energy consumption.

Finally, TRAN LE A.D et al wanted to compare the hygrothermal behaviour of a hemp concrete unit to that of a unit made in cellular concrete. The evolution of relative humidity is shown below, for both cases.

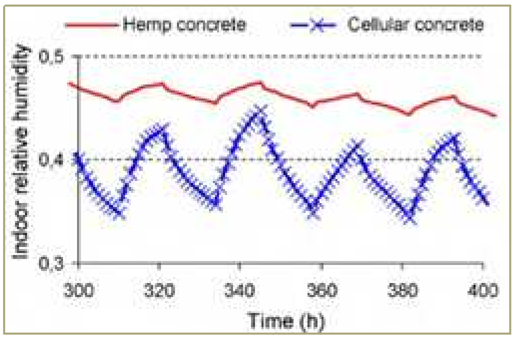


Figure 22: Evolution of Relative Humidity inside the hemp concrete Unit and in the cellular concrete Unit

It is clear that the hemp concrete unit has a better moisture buffer value than the cellular concrete unit.

Similarly, the researchers calculated that the hemp concrete unit consumed less energy than the cellular concrete unit (see next figure). These calculations are based on the energy consumption data from the month of January, based on winter weather conditions in Nancy.

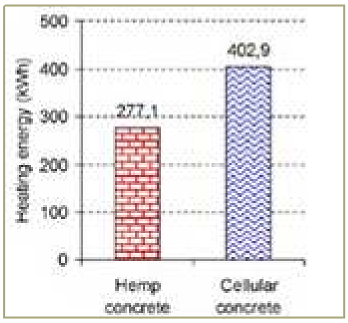


Figure 23: Heating Energy for the hemp concrete Unit and the cellular concrete Unit [11]

5.3. Straw Bale Construction

5.3.1. Component Scale

5.3.1.1. Wall System

WIHAN J. [13] simulated the hygrothermal behaviour of a straw-bale wall system by using the WUFI software. The simulation results were then compared to the results from real measurements.

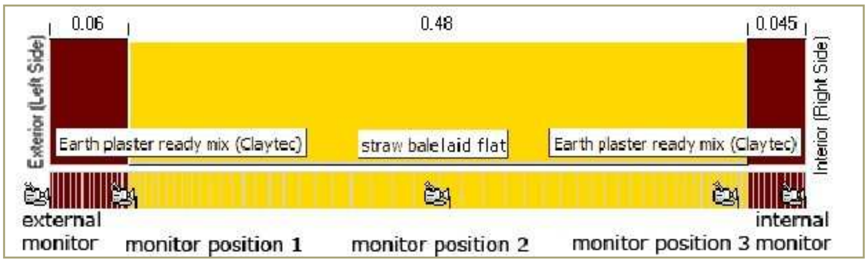


Figure 24: Straw bale wall system and sensor positions

The straw-bale wall system and the positions of the sensors are shown on the above figure.

The wall consists of a main part made in straw and covered in an earth-based plaster that is applied on the internal and external faces of the wall. Three sensors are implanted in the wall to measure the temperature and relative humidity. Two other sensors measure these values on the wall's internal and external surfaces.

The measurements were conducted over a period spanning from December 7th, 2005, to May 1st, 2006 (see figure below). The outside temperature and relative humidity were used as solicitations for the simulations with the WUFI software.

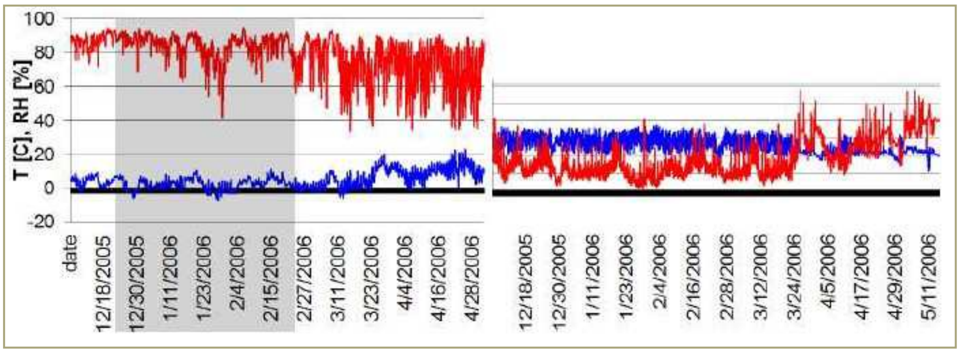


Figure 25: Temperature and Relative Humidity Evolution Outside (a) and Inside (b) from February 19, 2006 to March 12, 2006

The simulation's temperature and relative humidity evolution (red curves) and the real measurements (blue curves) are shown on the figure below:

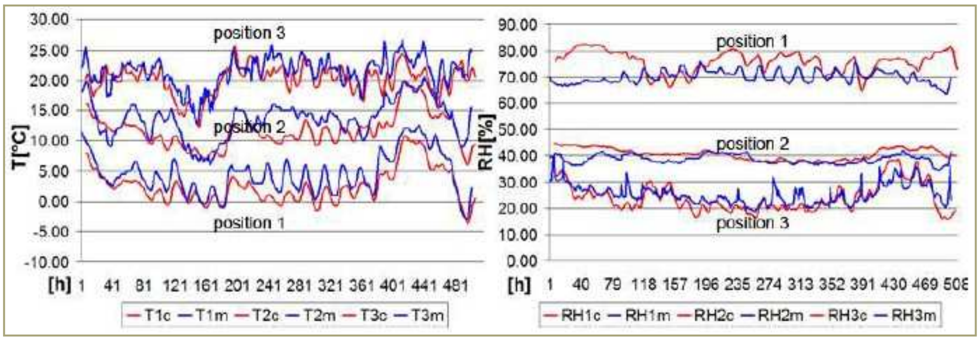


Figure 26 : Temperature and Relative Humidity Evolution for Simulations (red curves) and Measurements (blue curves) from February 19, 2006 to March 12, 2006

Generally, the simulated results on WUFI present the same tendencies and values as the measured results. The only substantial differences lie with the relative humidity values at point 1. The important difference in humidity between the simulated results and the real results at position 1 could be due to inaccurate input data. In reality, the exterior relative humidity was measured at a location that was far away from the studied wall, and was therefore probably overestimated.

This study allows us to conclude that, even though the air infiltration and the air flux convection are not taken into account in the modelling, the results are satisfactory since they correspond quite well to reality. In this study, the material's conductivity plays an important role in the simulation of the evolution of temperature and relative humidity.

5.3.2. Building Scale

5.3.2.1. Variations in Temperature and Humidity – Hygrothermal Comfort:

ASHOUR T. et al [19] measured the evolution of temperature and relative humidity within the walls of an existent two-story residential straw bale house, located in Germany (not inhabited when the measurements were taking place).

Various sensors were installed on the walls, as the next figure shows:

- On the outside plaster surface (T)
- Between the outside plaster and the straw wall (T)
- In the wall, 10 cm from the outside (T+RH)
- In the wall, 20 cm from the outside (T+RH)
- Between the straw wall and inside plaster (T)
- On the inside plaster surface (T).

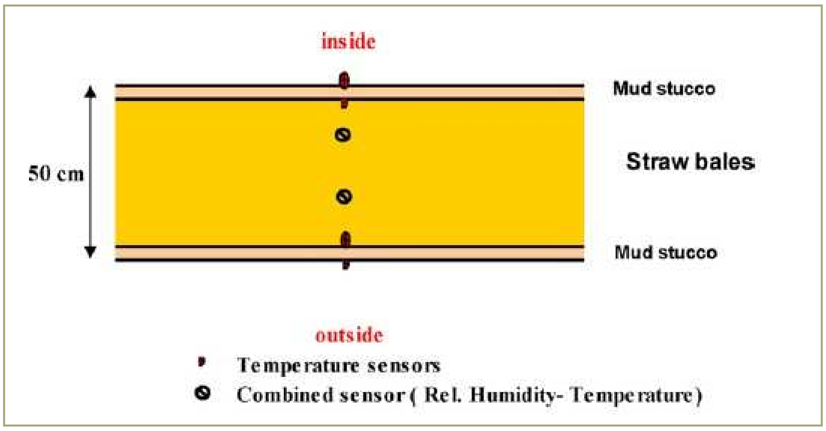
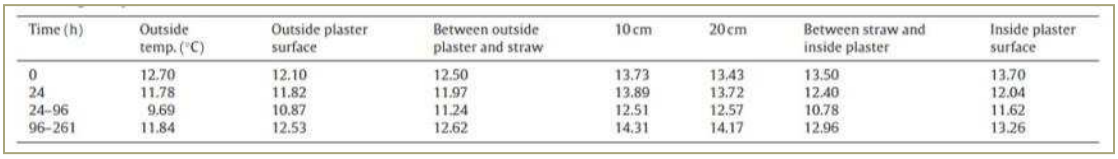


Figure 27: Temperature and relative humidty sensor positions

The evolution of the exterior environment temperatures was also measured. On the next table, the temperature variation is shown at various points.

Table 10 : Average Temperatures on Various Points



Time (h)	Outside temp. (°C)	Outside plaster surface	Between outside plaster and straw	10 cm	20 cm	Between straw and inside plaster	Inside plaster surface
0	12.70	12.10	12.50	13.73	13.43	13.50	13.70
24	11.78	11.82	11.97	13.89	13.72	12.40	12.04
24–96	9.69	10.87	11.24	12.51	12.57	10.78	11.62
96–261	11.84	12.53	12.62	14.31	14.17	12.96	13.26

The results show that the interior temperature remained stable despite strong outdoor temperature variations. The study also shows that the temperatures within the straw bale wall (at 10 cm and 20 cm from the outside) were most of the time higher than the plaster's temperature.

Table 11 : Average Relative Humidity on Various Points

Time (h)	Outside relative humidity (%)	10 cm from outside	20 cm from outside
0	78.77	71.76	68.82
24	61.58	70.25	67.94
24–96	62.33	69.72	67.50
96–261	67.39	71.26	69.16

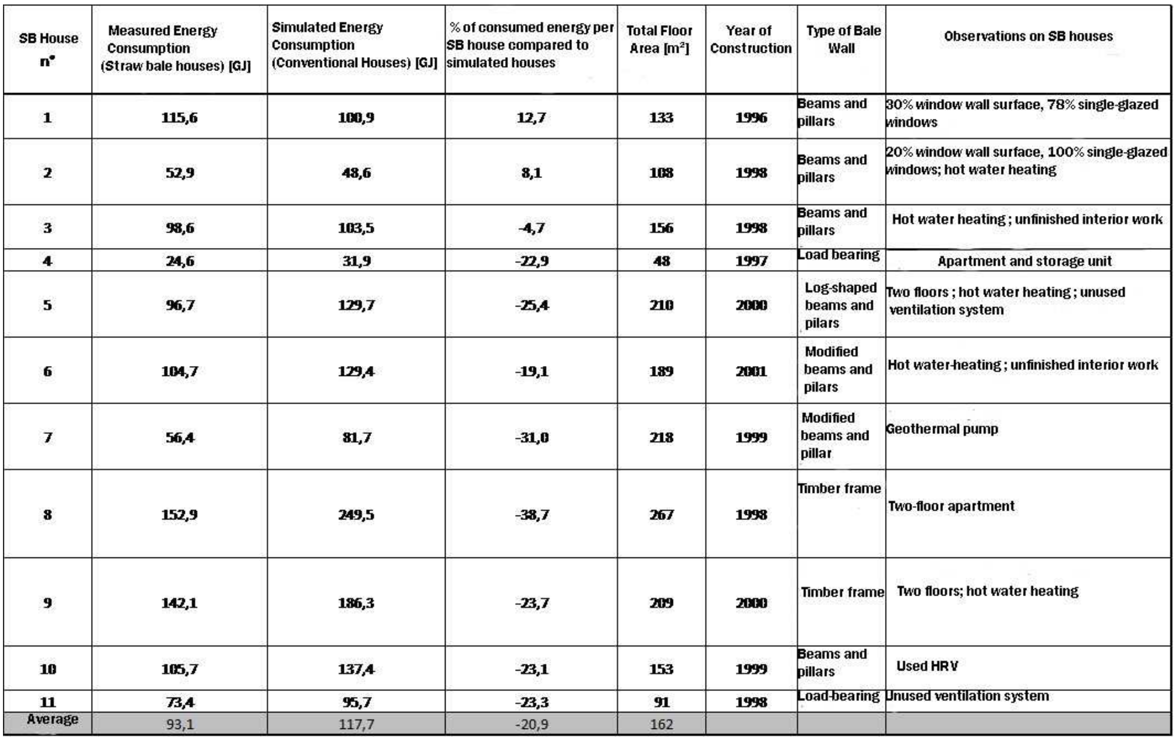
In the same way as for temperature, the study proves that relative humidity measured within the wall remained stable, even with high variations in outside relative humidity. ASHOUT T. et al also noticed that the moisture transfer in this straw bale wall was slow.

5.3.2.2. Energy Consumption:

The heat energy consumption in straw bale houses was measured by the SCHL [10] ("Société canadienne d'hypothèques et de logement" – CMHC "Canada Mortgage and Housing Corporation") and was compared to the consumption of conventional houses, estimated through simulation.

The 11 straw bale houses that were measured have walls that are approximately 450mm thick. The simulations were done with the HOT2000 software. Simulated houses were constructed in accordance to the British Columbia building code. The floor area, floor insulation, roof insulation, sun exposure were the same in the conventional simulated houses as in the straw bale houses. Furthermore, the simulated houses had double-glazed windows with reinforced PVC with air space and insulator sheets.

Table 12: Energy Consumption and Description of the 11 Houses



SB House n°	Measured Energy Consumption (Straw bale houses) [GJ]	Simulated Energy Consumption (Conventional Houses) [GJ]	% of consumed energy per SB house compared to simulated houses	Total Floor Area [m²]	Year of Construction	Type of Bale Wall	Observations on SB houses
1	115,6	100,9	12,7	133	1996	Beams and pillars	30% window wall surface, 78% single-glazed windows
2	52,9	48,6	8,1	108	1998	Beams and pillars	20% window wall surface, 100% single-glazed windows; hot water heating
3	98,6	103,5	-4,7	156	1998	Beams and pillars	Hot water heating ; unfinished interior work
4	24,6	31,9	-22,9	48	1997	Load bearing	Apartment and storage unit
5	96,7	129,7	-25,4	210	2000	Log-shaped beams and pilars	Two floors ; hot water heating ; unused ventilation system
6	104,7	129,4	-19,1	189	2001	Modified beams and pilars	Hot water-heating ; unfinished interior work
7	56,4	81,7	-31,0	218	1999	Modified beams and pillar	Geothermal pump
8	152,9	249,5	-38,7	267	1998	Timber frame	Two-floor apartment
9	142,1	186,3	-23,7	209	2000	Timber frame	Two floors; hot water heating
10	105,7	137,4	-23,1	153	1999	Beams and pillars	Used HRV
11	73,4	95,7	-23,3	91	1998	Load-bearing	Unused ventilation system
Average	93,1	117,7	-20,9	162			

These results show a definite improvement in straw-bale house energy efficiency compared to conventional houses. We can indeed see that the straw bale houses that were measured consumed 20% less energy for heating than in the modelled conventional houses. The author of the report partially explains this result by the fact that the houses for which energy consumption was measured were under-ventilated.

5.4. Solid Wood

5.4.1. Component Scale

5.4.1.1. Simple Wall

RAJI S. [8] detailed the thermal and hydric transfer characteristics of “vertically laminated solid wood” timber walls with felt joints between beams. He especially studied the effect of the glue joint on the hydric properties of the beams, as well as the effects of the felt joints between the beams on the wall’s total permeability.

The beams used for this study were vertically laminated solid wood with felt joints between beams. The wood used was pine imported from Finland. The felt joints were made in polypropylene, 90 mm in width and 8 mm thick. The wall’s profile is represented below:

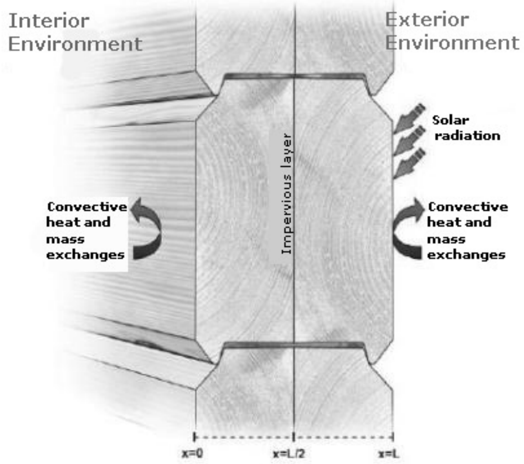


Figure 28: Laminated Wall with Felt Joints Made in Solid Wood

The model used to numerically simulate the wall’s hygrothermal behaviour is a simplified model. The impervious condition of the layer wasn’t always taken into account. It would be possible to add an impervious layer, therefore resistant to hydric transfers.

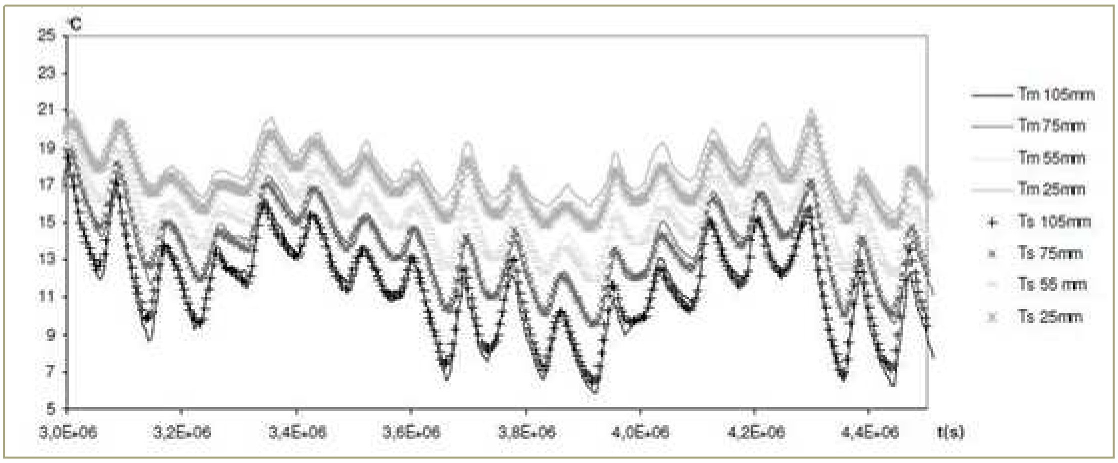


Figure 29: Evolution of the Temperature at the Points (x = 25mm, 55mm, 75mm and 105mm), Measurements (Tm) and Simulations (Ts) Over Time

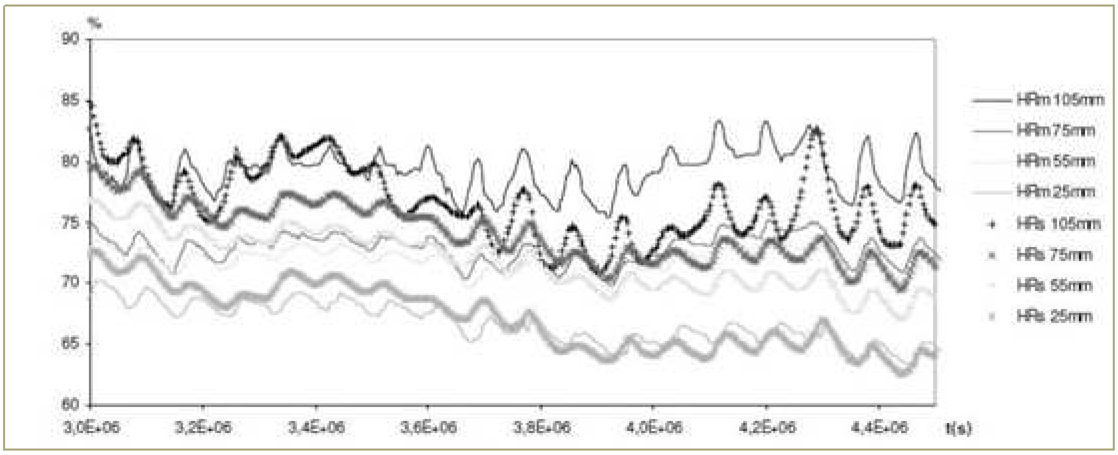


Figure 30: Evolution of the temperature at the points (x=25mm, 55mm, 75mm and 105mm), measurments (RHm) and simulations (RHs) over time

The boundary conditions on both sides are implemented in the COMSOL software thanks to the temperature and relative humidity measurements made on site. All the values for the wood's parameters used for the simulation were measured in a laboratory: thermal conductivity (λ), thermal diffusivity (a), thickness of the wall (e), permeability (k), density (ρ), effective diffusivity of water vapour in pore space (D_e), sorption isotherm.

The simulations' temperature and relative humidity evolutions are represented in figures 26 and 27 for various depths x=25mm, 55mm, 75 mm and 105 mm. The results for the real measurements are displayed on the same figures.

In regards to temperature, the measurements and the simulation are similar. The differences are contained within a measuring error of ±0.5°C.

The relative humidity simulations replicate the trend and the order of magnitude of the measurements correctly. But some substantial differences exist at the point x=105 mm. The study indicates that the difference is probably due to a watertightness issue in relation to the interior environment.

Through the simulation and measurements, it is shown that the wood's temperature is inferior to the temperature of the joints between the beams.

Experiments showed that the glue joint has a resistance to water vapour transfers in a steady state, whereas the resistance is less important in a variable state.

5.4.2. Building Scale

RAJI S. [8] undertook studies to characterize hygrothermal comfort in solid wood buildings. To do this, he measured the evolution of temperature and relative humidity in real buildings. Two studies were conducted in parallel:

- Comparison between a residential building and an office building : case n°1;
- More generally, the hygrothermal behaviour of 20 solid wood houses: case n°2.

5.4.2.1. Variations in Temperature and Humidity – Hygrothermal Comfort

Two solid wood buildings, one for residential use (known as B.RU) and one for office use (known as B. OU) were built in Juzagan, in France. The interior and exterior walls are made of vertically laminated solid wood balks. B. RU is a home for a family of 4 people with a 147 m² total surface (for a 303m³ volume). B. OU is a building that serves as an office for 7 people and also serves as a model home for the company *Confort Bois*. The building has a total surface of 110m² (for a 350m³ volume). The thickness of the walls is of 113 mm for the residential building, and of 134 mm for the office building.

The measured temperatures are air temperatures, obtained through sensors installed against the walls. A sensor placed in the living room of the B. RU is known as *Day Area* and another sensor in the bedroom is known as *Night Area*.

Temperatures and relative humidity have been measured during two time periods:

- The « Winter » period is the period when heating occurs: from October 1st to March 31st.
- The « Summer » period: from June 22nd to September 21st.

To characterize hygrothermal comfort, RAJI S chose a winter comfort zone that differed from the French norm and from the ASHRAE norm (the studied houses were equipped with room thermostats, allowing users to adapt the amount of emitted heat to instant needs). Therefore, the chosen zone had temperatures between 18°C and 23°C in the winter period and between 19°C and 27°C in the summer period. Relative humidity varied between 30% and 60%.

The analysis of the temperature and relative humidity measurements is detailed in the following paragraphs.

5.4.2.2. Measurements and Temperature Study

From the measurements, RAJI S identified two trends:

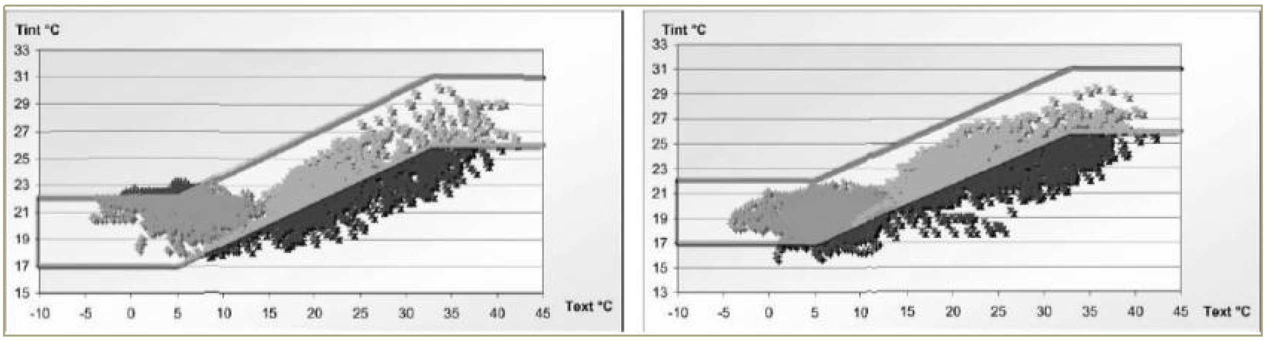
- Over the two periods, the minimal temperatures in the office building were always lower than the temperatures in the residential building.
- During the summer period, the average temperatures in the office building were higher than those in the residential building.

The sharp temperature variation in the office building is correlated to the use of the building. RAJI S notes that the temperature had been maintained at 16 °C at night; that the temperature had steadily increased to 21 °C at 7:00 am and that the arrival of 7 people in the building from 9:00 am led to a temperature increase going up to 24 °C and even sometimes 26 °C.

On the figure below, the inside temperatures in the residential building are given during the Winter and Summer periods with a thermal comfort zone.

During the winter period, 93% of the points are found between two limits; 3% of the points are above 22 °C for the day area and 5% below 17 °C for the night area.

During the summer period, 100% of the measured points are below the superior limit, and 50% of the measured points are below the lower limit.



(a) (b)

Figure 31: Thermal Comfort Zones in the House: (a) Day Area (b) Night Area

For the office building, the inside temperatures are shown on figure 29 for the Winter and Summer periods, and with a thermal comfort zone. We notice that 11% of the measured points are above the superior limit.

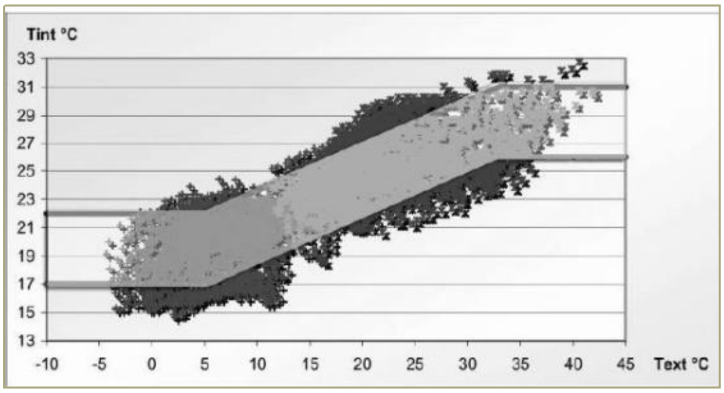


Figure 32: Thermal Comfort Zone in the Office Building

It is worth mentioning that the residential building has good thermal performance (temperatures in the comfort zone) whether it is during the summer or the winter periods. The office building results are not as good as the residential building results. But generally, the temperatures are always situated within the hygrothermal comfort zone.

5.4.2.3. Measurements and Relative Humidity Study

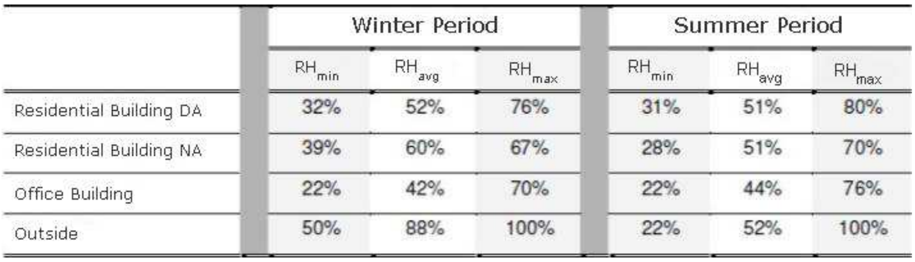
The average of the relative humidity measurements obtained in both buildings is shown in the next table.

We notice that:

- During the summer and winter periods, the residential building had an average relative humidity value that was higher than the office building's relative humidity value.
- During the winter period, the residential building had an average relative humidity value that was higher in the night area than in the day area.

By analysing the relative humidity values, RAJI S. concluded that the relative humidity levels were acceptable during the winter period and that the relative humidity was higher in the residential building than in the office building.

Table 13: Relative Humidity Measured Inside and Outside the 2 Buildings during the Winter and Summer Periods

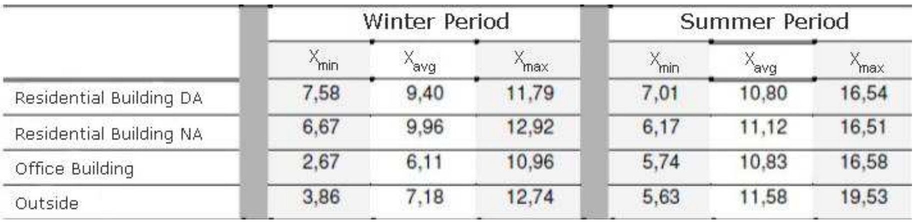


	Winter Period			Summer Period		
	RH_{min}	RH_{avg}	RH_{max}	RH_{min}	RH_{avg}	RH_{max}
Residential Building DA	32%	52%	76%	31%	51%	80%
Residential Building NA	39%	60%	67%	28%	51%	70%
Office Building	22%	42%	70%	22%	44%	76%
Outside	50%	88%	100%	22%	52%	100%

RAJI S. calculated and analysed absolute humidity inside both buildings and outside (see table below). Absolute humidity corresponds to the mass of water vapour contained in 1kg of dry air. It indicates the building's moisture content.

We can see that during the summer period, the moisture content was higher in the residential building than in the office building, even though fewer people occupied the residential building. This can be explained by the fact that the doors were frequently opened in the office building when it was occupied.

Table 14: Absolute Humidity [g/kg] Calculated Inside and Outside the 2 Buildings during the Winter and Summer Periods



	Winter Period			Summer Period		
	X_{min}	X_{avg}	X_{max}	X_{min}	X_{avg}	X_{max}
Residential Building DA	7,58	9,40	11,79	7,01	10,80	16,54
Residential Building NA	6,67	9,96	12,92	6,17	11,12	16,51
Office Building	2,67	6,11	10,96	5,74	10,83	16,58
Outside	3,86	7,18	12,74	5,63	11,58	19,53

By analysing the absolute humidity measurement results, we can see that:

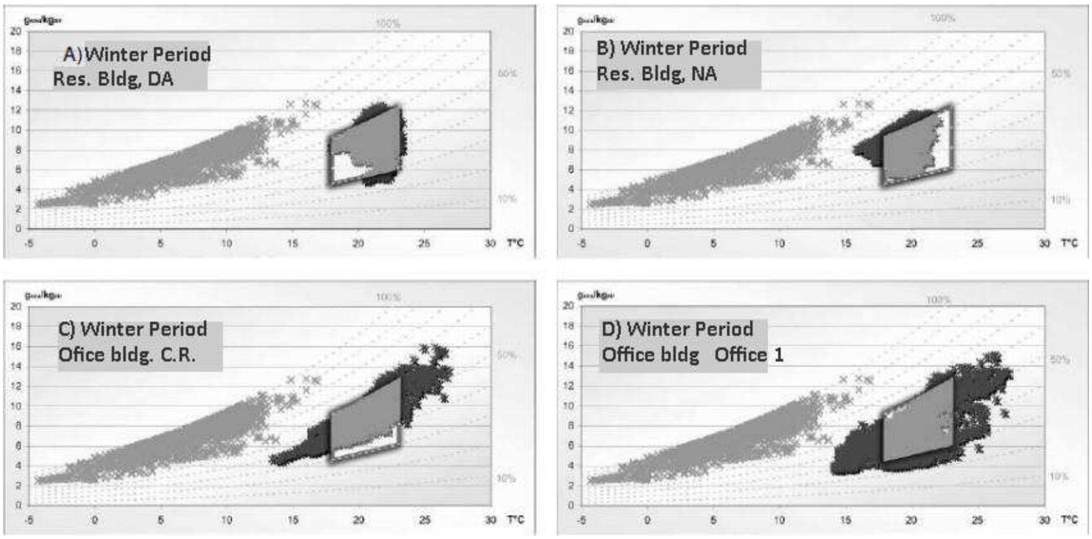
- The absolute humidity values in the office building were very close to the outside absolute humidity values in the winter time;
- Absolute humidity in both buildings was very close to the outside absolute humidity in the summer time;
- The moisture content in the residential building was higher in the night area than in the day area for both periods.

Finally, RAJI S. highlights the important role of human activity in regards to the evolution of hygrothermal behaviour inside the building.

5.4.2.4. Hygrothermal Comfort

Hygrothermal comfort in the residential building – day area and night area – as well as in the office building are shown below for the winter and summer periods.

On this graph, we can see the comfort zones for both buildings during the winter and summer periods, the measurement points having been placed in the comfort zones for the residential building. The C and D graphs confirm the comfort results obtained in the office building. The E and H graphs represent overheating and high humidity in the house, and high overheating in the office building.



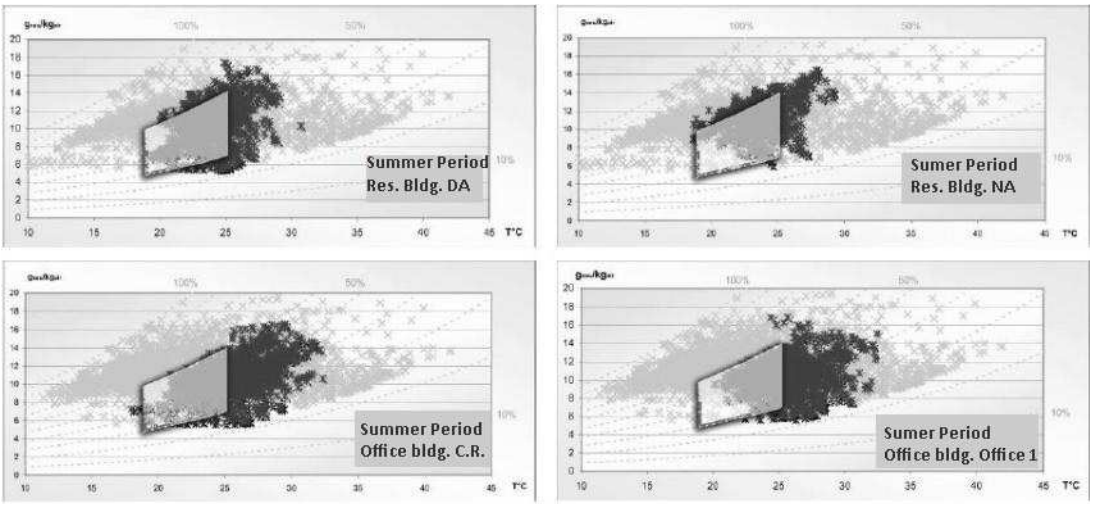


Figure 33 : Comfort Zones for the Residential Building (Day Area and Night Area) and for the Office Building (Conference Room and Office 1)

During the winter time, the residential building presents good hygrothermal comfort: only 17% of the T measurements are below 18 °C and 20% of the RH measurements are slightly high. The office building also presents relatively good hygrothermal comfort, but 25% of T measurements are below 18°C.

During the summer time, the temperature is very high in both buildings and there are high relative humidity measurements.

5.4.2.5. Temperature and Humidity Variation – Hygrothermal Comfort:

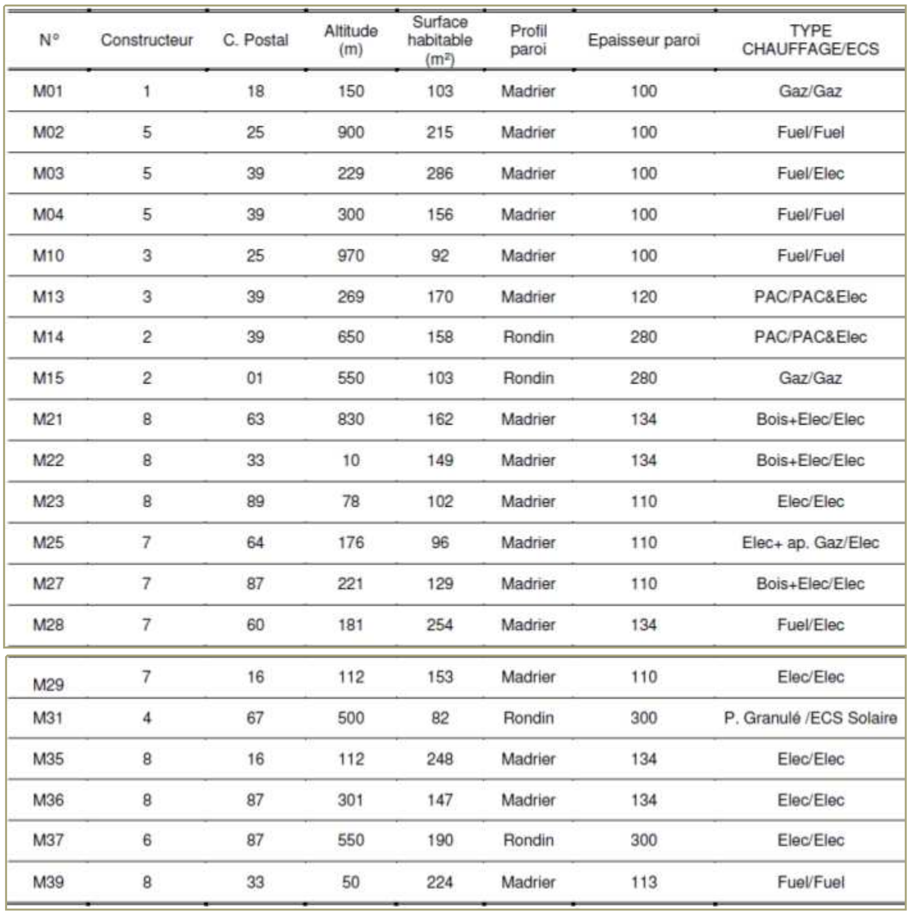
For the second case, RAJI S chose 20 solid wood houses with an average surface of 160 m² (minimum of 80m² and maximum of 280m²) and made temperature and relative humidity measurements. The houses are located in 12 different French departments.

The houses were built with different timber elements: with planks, (Madrier (M) in the figures), or with circular section logs, (Rondin (R) in the tables). These timber pieces had different dimensions depending on the houses.

In addition, an overview of the different heating systems was done by having the residents fill out a survey, therefore: 40 % of the heating was electric, 10% gas, 30% fuel and 20% wood. This survey also allowed the researcher to get another piece of essential information, as in the type of ventilation (natural, mechanically controlled ventilation, single flow or double flow…). But this information was not used in the next phases of the study.

The main characteristics of the solid wood houses are found in the table below.

Table 15 : Summary of Information Concerning Each House



N°	Constructeur	C. Postal	Altitude (m)	Surface habitable (m²)	Profil paroi	Epaisseur paroi	TYPE CHAUFFAGE/ECS
M01	1	18	150	103	Madrier	100	Gaz/Gaz
M02	5	25	900	215	Madrier	100	Fuel/Fuel
M03	5	39	229	286	Madrier	100	Fuel/Elec
M04	5	39	300	156	Madrier	100	Fuel/Fuel
M10	3	25	970	92	Madrier	100	Fuel/Fuel
M13	3	39	269	170	Madrier	120	PAC/PAC&Elec
M14	2	39	650	158	Rondin	280	PAC/PAC&Elec
M15	2	01	550	103	Rondin	280	Gaz/Gaz
M21	8	63	830	162	Madrier	134	Bois+Elec/Elec
M22	8	33	10	149	Madrier	134	Bois+Elec/Elec
M23	8	89	78	102	Madrier	110	Elec/Elec
M25	7	64	176	96	Madrier	110	Elec+ ap. Gaz/Elec
M27	7	87	221	129	Madrier	110	Bois+Elec/Elec
M28	7	60	181	254	Madrier	134	Fuel/Elec
M29	7	16	112	153	Madrier	110	Elec/Elec
M31	4	67	500	82	Rondin	300	P. Granulé /ECS Solaire
M35	8	16	112	248	Madrier	134	Elec/Elec
M36	8	87	301	147	Madrier	134	Elec/Elec
M37	6	87	550	190	Rondin	300	Elec/Elec
M39	8	33	50	224	Madrier	113	Fuel/Fuel

Two sensors were installed inside each house. The first sensor was in the living room, known as Day Area. The second sensor was in a bedroom, known as Night area. Both sensors were installed on a wall more than 1m50 above ground, in order to avoid direct solar rays. Another sensor was placed outside, under a shelter on the North facade.

The measurements took place during two time periods: from October 1 to April 20, known as Winter Period and from June 21 to September 20, known as Summer Period.

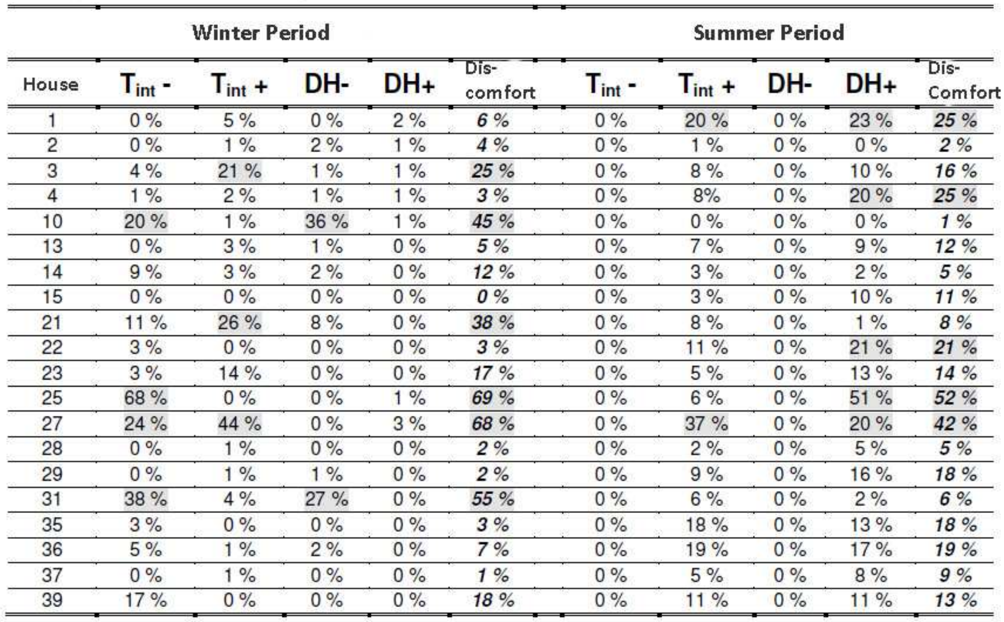
The measurements show that, during the winter period, the average temperature inside remained between 18 and 22 °C and the maximum temperature always remained below 25 °C for 65% of the houses.

Concerning the Summer Period, the average temperature was below 25 °C for 95% of the houses and the maximum temperature stayed below 28 °C for 85% of the houses.

RAJI S. used the same criteria as for case N° 1 to analyse the hygrothermal comfort level of the 20 houses. In his analysis, 4 discomfort situations are identified and respectively known as:

- Tint- for “under heating”
- Tint + for “overheating”
- DH- for “too dry”
- DH+ for “too humid”

Table 16: Discomfort Rates for the Winter and Summer Periods out of the 20 Houses



	Winter Period					Summer Period				
House	T_{int} -	T_{int} +	DH-	DH+	Dis-comfort	T_{int} -	T_{int} +	DH-	DH+	Dis-Comfort
1	0 %	5 %	0 %	2 %	*6 %*	0 %	20 %	0 %	23 %	*25 %*
2	0 %	1 %	2 %	1 %	*4 %*	0 %	1 %	0 %	0 %	*2 %*
3	4 %	21 %	1 %	1 %	*25 %*	0 %	8 %	0 %	10 %	*16 %*
4	1 %	2 %	1 %	1 %	*3 %*	0 %	8%	0 %	20 %	*25 %*
10	20 %	1 %	36 %	1 %	*45 %*	0 %	0 %	0 %	0 %	*1 %*
13	0 %	3 %	1 %	0 %	*5 %*	0 %	7 %	0 %	9 %	*12 %*
14	9 %	3 %	2 %	0 %	*12 %*	0 %	3 %	0 %	2 %	*5 %*
15	0 %	0 %	0 %	0 %	*0 %*	0 %	3 %	0 %	10 %	*11 %*
21	11 %	26 %	8 %	0 %	*38 %*	0 %	8 %	0 %	1 %	*8 %*
22	3 %	0 %	0 %	0 %	*3 %*	0 %	11 %	0 %	21 %	*21 %*
23	3 %	14 %	0 %	0 %	*17 %*	0 %	5 %	0 %	13 %	*14 %*
25	68 %	0 %	0 %	1 %	*69 %*	0 %	6 %	0 %	51 %	*52 %*
27	24 %	44 %	0 %	3 %	*68 %*	0 %	37 %	0 %	20 %	*42 %*
28	0 %	1 %	0 %	0 %	*2 %*	0 %	2 %	0 %	5 %	*5 %*
29	0 %	1 %	1 %	0 %	*2 %*	0 %	9 %	0 %	16 %	*18 %*
31	38 %	4 %	27 %	0 %	*55 %*	0 %	6 %	0 %	2 %	*6 %*
35	3 %	0 %	0 %	0 %	*3 %*	0 %	18 %	0 %	13 %	*18 %*
36	5 %	1 %	2 %	0 %	*7 %*	0 %	19 %	0 %	17 %	*19 %*
37	0 %	1 %	0 %	0 %	*1 %*	0 %	5 %	0 %	8 %	*9 %*
39	17 %	0 %	0 %	0 %	*18 %*	0 %	11 %	0 %	11 %	*13 %*

During the winter period, the under-heating level was less than 10% for 14 of the 20 houses, and the discomfort ratio was also less than 20% for 14 of the 20 homes.

During the summer period, the overheating level was also below 10% for 14 of the 20 houses.

Hygrothermal comfort for solid wood houses was therefore satisfactory, in the summer and in the winter.

5.4.2.6. Energy Consumption:

Raji S [8] furthered his study by measuring energy consumption related to the heating of these 20 solid wood houses. The measured energy consumption in relation to the calculated value is shown on the figure below:

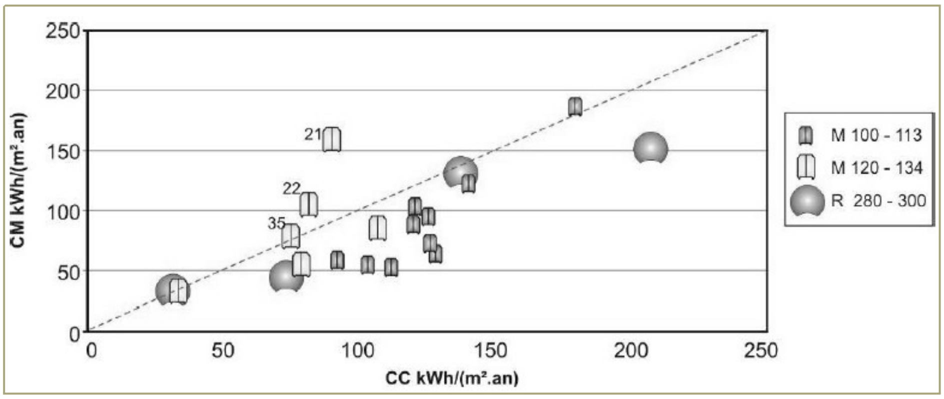


Figure 34: Measured Energy Consumption Compared to Calculated Consumption, According to RT2000

15 measured houses out of 20 presented heat energy consumption that was lower than the calculated value. The high energy consumption rate of the 5 other houses was due to heating or insulation issues.

On average, the measured energy consumption for heating was 85 kWh/(m^2·year), which is 18% less than the calculated value.

A relation between the wall's thickness and energy consumption is hard to determine.

The study conducted by RAJI S. shows that solid wood houses that are well insulated and with normal heating performance have a normal to low energy consumption.

Furthermore, the ratios of consumption and heating needs indicate that, in order to ensure low energy consumption, choosing a heating system and managing it are more important than the thickness of the wall.

5.5. Loose-fill Insulation or Structural Insulation Boards

5.5.1. Component Scale

The CSTB and the FCBA [1] led a study on hygrothermal transfers through walls in wood-frame houses. In the context of this study, the CSTB and the FCBA highlighted the importance of these transfers and their potential impact on the performance and durability of the products (corrosion, fungal growth,…).

This study's objective was to identify how certain parameters influenced hygrothermal transfers that go through wood frame walls.

The following parameters of influence were studied:

- Climate
- The vapour barrier's permeability to water vapour
- Type of insulation
- The barrier's permeability to water vapour
- The braced panel's permeability to water vapour

One of the most important parameters that can influence transfers is the type of thermal insulation used between vertical supports. Three types of insulation were used in the context of the study:

- Mineral wool
- Cellulose wadding
- Wood fibres

The outside environment climates used in the calculations were:

- Adverse plain climate
- Coastal climate
- Mountainous climate
- Mediterranean climate

The calculations were done for a vertical wall exposed North.

The transfers were studied by simulation using WUFI.

Some data on the products and materials that constitute the wall were necessary for the calculation models, such as:

- Resistance to water vapour diffusion
- Sorption curve
- Thermal conductivity
- Specific heat
- Porosity
- Density

As a result of all the different simulated configurations and given the variety of cases and wall configurations in the study, the CSTB and the FCBA decided that only the walls with the following specificities should be considered:

- The walls have acceptable[4] effects on the health of the occupants, limiting the amount of mould spores that enter the interior environment.
- They do not loose mechanical resistance over time, since such a defect would lead to security problems for the building's inhabitants.

Risk levels were therefore defined as follows:

Table 17 : Definition of Humidification and Condensation Risks [1]

The "no risk" level corresponds to cases where the wall's overall humidity does not increase over time, where the materials that are not involved in the stability of the building wall (insulation, plaster, struts…) never reach more than 23% humidity, and where the structural elements (jambs,sleepers, panels…) never reach more than 20% humidity. Additionally, these "no risk" cases do not present high surface humidity levels. High surface humidity can generate mould and impact the health of the people who use the building.
The "manageable risk" level corresponds to buildings that, initially, do not fulfill the "no risk" conditions but that can change categories if the calculation assumptions are adapted in relation to the use of the building. A calculation assumption that can be modified could be, for example, reducing the building's hygrothermial behaviour: from a W/n for 5 g/m^3 (initial calculation assumption), we would go to a W/n for 2,5 g/m^3. *One must note that the project manager would then need to commit to an air change rate that would respect the condition W/n ≤ 2,5* g/m^3.
The **"permanent risk"** level does not fulfill the conditions of neither the "no risk" or the "manageable risk" levels.

Wood has a property which also influences its behaviour towards humidity: its capacity to contain both free water and/or bound water. Water is known as bound, or hygroscopic, when it is chemically retained (hydrogen bonds) by the material. The water molecules are then joined to the material itself. In the case of wood, free or capillary water – therefore liquid – appears when the humidity rate (in mass %) exceeds the saturation point of the fibres. For most softwood species used in construction, the saturation point of fibres is reached when wood humidity exceeds 30% in mass.

When calculations attest to humidity that exceeds 30% in wood or in wood-based materials (insulating boards), the wall is not deemed fit to use, since liquid water in a closed wall is very difficult to evacuate.

The influence of the type of insulation used has been studied based on calculations done on configuration 2 and configuration 3 shown below.

Configuration 2 is a classical wall configuration, to which has been added insulation on the internal side. This insulation is therefore placed between the plaster board and the water vapour barrier.

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[4] [1] p14 : In regards to the effects on health and air quality, each calculated case study is considered individually. Those cases which present high surface humidity (higher than 30% in mass, over the course of several weeks) are discarded.

Configuration 3 resembles configuration 2, but this time with the braced sheathing panel placed on the internal side between two insulation layers and with added insulation on the external side.

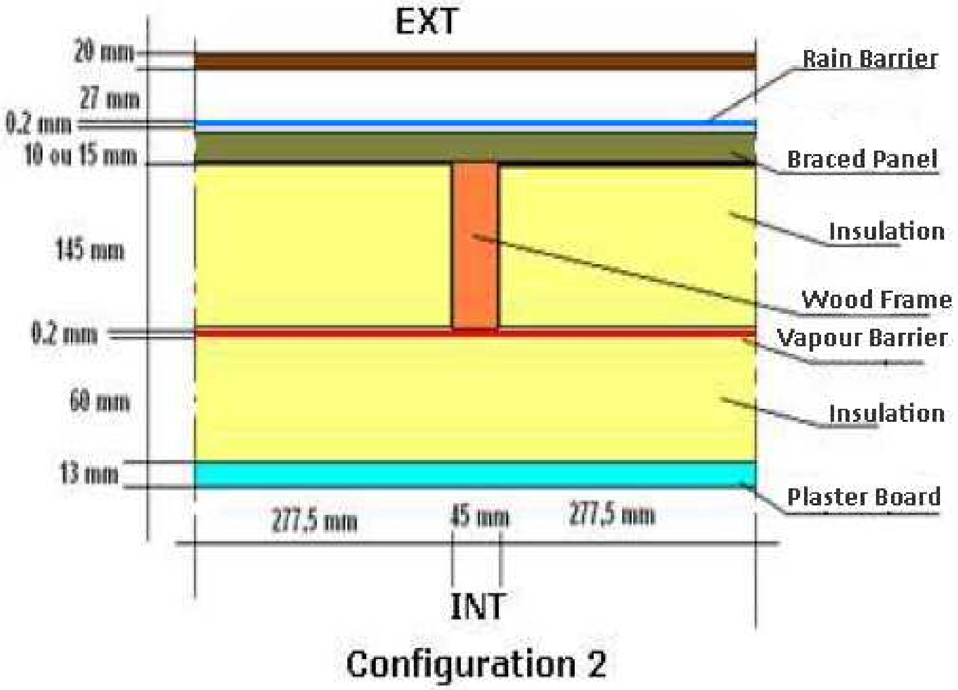


Figure 35 : Schematic Representation of the Wall - Configuration 2

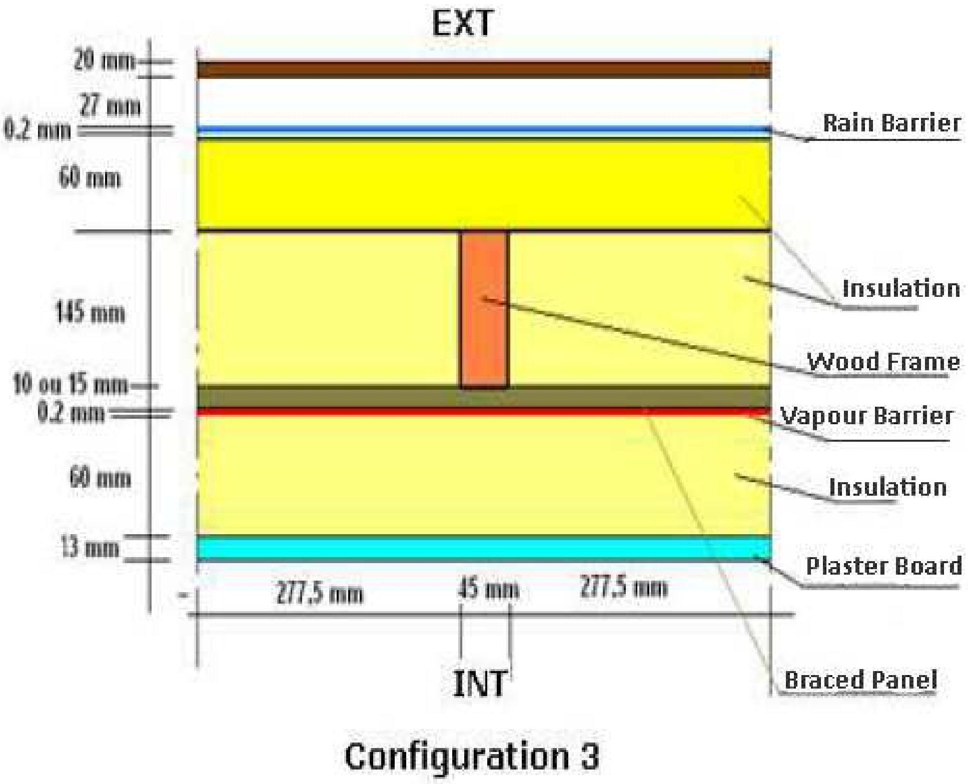
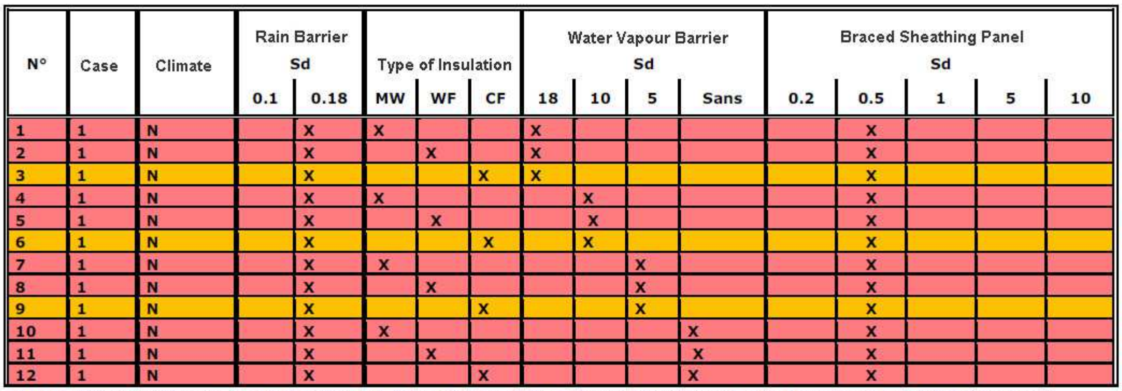


Figure 36: Schematic representation of the wall - Configuration 3

In Configuration 2, the first 12 cases (1 to 12) give us the opportunity to see the differences according to the different insulation types and water vapour barriers.

Table 18: Values of the Variables of the Walls' Characteristics for Configuration 2



N°	Case	Climate	Rain Barrier Sd		Type of Insulation			Water Vapour Barrier Sd				Braced Sheathing Panel Sd				
			0.1	0.18	MW	WF	CF	18	10	5	Sans	0.2	0.5	1	5	10
1	1	N		X	X			X					X			
2	1	N		X		X		X					X			
3	1	N		X			X	X					X			
4	1	N		X	X				X				X			
5	1	N		X		X			X				X			
6	1	N		X			X		X				X			
7	1	N		X	X					X			X			
8	1	N		X		X				X			X			
9	1	N		X			X			X			X			
10	1	N		X	X						X		X			
11	1	N		X		X					X		X			
12	1	N		X			X				X		X			

MW(Mineral Wool) ; WF (Wood Fibre) ; CF (Cellulose Wadding) ; N (Nancy) ; Sd (Sd Value)

Concerning the impact of the type of insulation used, the CSTB and the FCBA come to the following conclusions:

"Plant-based insulation (wood fibre, cellulose wadding, etc…) are insulants that are made out of water-absorbing material.

Therefore, when the moisture levels are close to the condensation limits, these insulants absorb humidity and can delay or even – in certain cases – prevent such condensation to happen.

For a product that is very absorbent, the phase shift will be greater.

The phase-shift mechanism also occurs during desorption. The product stays humid for a longer period.

In these conditions, the insulant's water content – specifically the insulant on the internal side tested in configurations 2 and 3 – can go up to 58 kg/m^3 for wood fibre, which corresponds to thermal conductivity of 0.43 W/(m.K), which would diminish the wall's thermal performance."

5.5.2. Building Scale

No published documents on this topic.

6. Conclusion

As it has been demonstrated in these various studies, the term “hygrothermal behaviour” actually represents several different phenomena. It is therefore important to agree on the definition of the term. This definition is related to the 3 scales that have been mentioned in this overview: the material scale, the component scale and the building scale.

At the Material scale, several of the material's intrinsic properties - especially porosity – are studied, as well as the modelling of mass and energy transfers inside the materials.

At the Component and Building scales, the case studies are experiments and simulations related to hygrothermal behaviour and energy consumption.

Most studies focus on the role played by phase change and the evaporation and condensation of water.

In certain studies, such phenomena are characterized through experiments or simulations, in order to evaluate the phenomena's effects on the durability of construction systems (effect on fungic growth, on the durability of mechanical properties…).

In other studies, these phenomena are characterized through experiments or simulations in order to evaluate their role in a wall's thermal performance. Since absorption or release of energy occurs with the phase changes of water inside the wall, phase changes can have an impact on a building's energy consumption.

We can point out that, concerning hemp concrete, phase change and its influence on a wall's thermal performance have already been well demonstrated. Similar studies could be undertaken for vegetable fibre insulants and straw construction.

It is therefore necessary to quantify the phase change happening inside the material and to make a connection between this phenomenon and energy consumption at the level of the building.

The energy consumption of bio-based materials is therefore a very interesting topic. Several studies have already led to measurements in real buildings. However, these studies do not establish the link between hygrothermal behaviour and energy consumption. Establishing such a link would allow for the integration of hygrothermal behaviour to the calculations that determine the energy consumption of a building.

In order to make better use of bio-based materials and to develop the entire industry, it is now necessary to quantify phase change in the material and to make links between phase changes within materials, hygrothermal comfort in a building and energy consumption.

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