HYGROTHERMAL BEHAVIOR OF A HEMP-STARCH COMPOSITE FOR ROOF APPLICATIONS

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ABSTRACT

The paper presents preliminary results of the hygrothermal behavior of hemp-starch composites designed for building applications. These composites are produced by bonding hemp shiv with wheat starch as a binder. After presenting the material and its physical properties as sorption isotherm, water vapor permeability, thermal conductivity and heat capacity, we introduce the equations of coupled heat and moisture transfer within panels. These governing equations are applied on room level in order to assess the hygrothermal behaviour of the panels and its impact on building energy consumption and indoor comfort. Simulations are performed with the simulation environment SPARK suited for complex problems and for Nancy winter conditions.

INTRODUCTION

Nowadays, several European countries adopt regulations to increase building envelope performance with respect to heat loss and air permeability reductions, which can increase indoor relative humidity. Therefore, to ensure comfort and good health in buildings, indoor climate is an important factor to control air quality. The use of hygroscopic materials as hemp concrete appears as a good solution to reduce energy needs and maintain high indoor comfort ((Cerolini et al., 2009), (Simonson et al., 2004), (Simonson et al., 2004)). These materials absorbs and desorbs water vapor and can be used to moderate the amplitude of indoor relative humidity and therefore to participate in the improvement of the indoor quality and energy saving.

Hemp concrete is renowned for its hygrothermal performances related to the porous structure of hemp fibres and represents a low environmental impact. Classic hemp concrete composition is the result of hemp fibres mixed with a binder made from air lime with pozzolanic cementitious or hydraulic lime additions and some of the small amount of additives such as surfactants. It is used to form building envelopes by pre-fabrication of building blocks or panels, by casting or spraying and shuttering in situ (Shea et al., 2012).

This paper concerns the development of a new material made of hemp shives, the characterization of its hygrothermal properties and its application to building. First, the material is presented then its physical properties are measured, these include sorption isotherm curve, water vapor permeability, thermal conductivity and heat capacity. They are used in the simulation environment SPARK to assess material performance when used as a roof in hemp-lime constructions.

EXPERIMENTAL DETAILS

For this research, Chamtor Company (France) provided the native wheat starch used for the experimental study. The heating of starch granules in hot water results in a gelatinization process caused by irreversible swelling of granules and the mixture forms the binder.

Technical hemp hurds KANABAT were grown by la Chanvrière de l'Aube (France). They were subjected to surface treatment with 1% NaOH solution followed by a silane-coupling agent 1% (3-glycidyloxypropyl) trimethoxysilane solution to enhance the compatibility with wheat starch matrix (Umurigirwa et al., 2015). Chemical products were purchased from Sigma Aldrich Chemie Gmbh.

Fabrication of hemp-starch composites

The industrial hemp hurds are of size ranges from 5 to 20 mm, they are mixed with wheat starch binder with a hemp/starch ratio of 3.3 in weight. The specimens were compacted with 0.25 MPa pressure using a press. Two compositions are studied and they differ in hemp hurds properties: specimens without chemical treatment (HSU) and specimens with chemical treatment (HST). However, for the purpose of this study only the treated material is used. The final material has a density of 220 kg/m^3.

Water vapour permeability

Water vapor permeability tests are carried out with the cup method according to NF EN ISO standard 12571 (NF EN ISO, 2000). The cup method consists in sealing a vapor tight cup containing a desiccant or saturated salt solution, with the test material. Before measurements, samples were dried and stored at 50% relative humidity and 23°C until the stabilization of their weight. After that, specimens are insulated on all lateral sides with a waterproof adhesive and put into the cup and sealed with a gasket. The desiccant or saturated salt solution will ensure a constant relative humidity below the sample at constant temperature. Two tests were conducted under two different conditions: dry cup (0 %-50 %) and wet cup (50 %-93 %). The vapour flux goes from higher relative humidity to lower relative humidity through the sample of thickness d (m). Regular gravimetric measurements of the cup are used to determine the weight gain (or loss) of the cup and hence the moisture flux g ($kg.m^{-2}\ s^{-1}$) through the specimen. Water vapor permeability δ presented in equation (1) is determined by applying Fick's law at steady state.

$$\delta = \frac{g * d}{\nabla p_v} \quad (1)$$

$$\mu = \frac{\delta_a}{\delta} \quad (2)$$

Where μ is the material vapour diffusion resistance factor and δ_a ($kg.m^{-1}.s^{-1}.Pa^{-1}$) is the air vapour permeability.

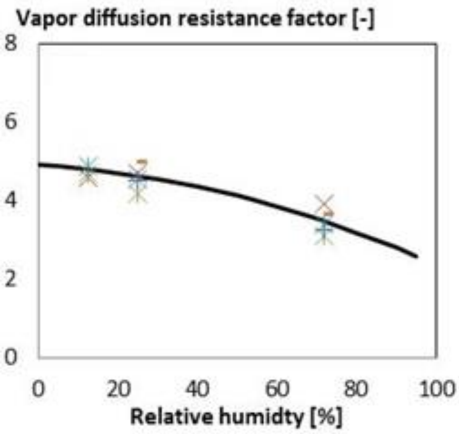


Figure 1 The vapour resistance factor for the hemp-starch composite.

The factor of vapour resistance was adjusted according to the proposed analytical form (Roels, 2010).

$$w = \frac{1}{0.192 + 0.0107 * e^{3.03*\varphi}} \quad (3)$$

Sorption isotherm curve

The sorption isotherm or hygroscopic curve describes the relation between moisture content and relative humidity for open porous materials. It is determined at successive stages of increasing relative humidity according to the discontinuous method with respect to NF EN ISO standard 12572 (NF EN ISO, 2001). The moisture content by mass w (kg / kg) is calculated according to the following equation:

$$w = \frac{m - m_0}{m_0} = \frac{m_w}{m_0} \quad (4)$$

where m (kg) is the mass of wet specimen, m_0 (kg) the mass of dry specimen at 0 % relative humidity and m_w (kg) the mass of water content.

Figure 2 shows the mean curve between sorption and desorption. It is adjusted using the following analytical expression (Merakeb, 2008):

$$ln\left(\frac{u}{0.222}\right) = 1.113 \ln(\varphi) \ln(1.055 * \varphi) \quad (5)$$

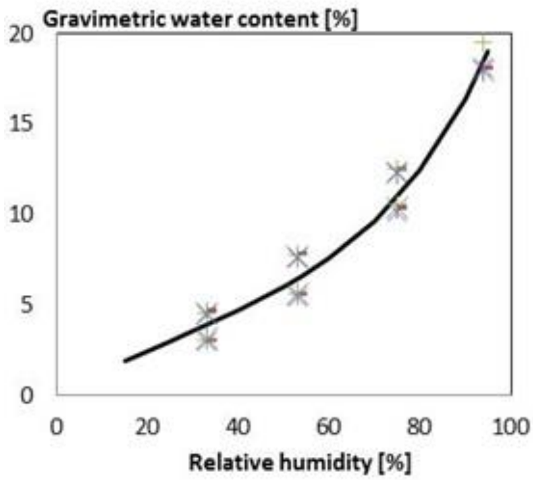


Figure 2 Sorption isotherm for the hemp-starch composite.

Thermal conductivity and heat capacity

Thermal conductivity of the hemp-starch is measured using the fluxmétrique method, by respecting the standard ISO 8301 (AFNOR, 1991). The principle of this technique is based on the relationship between the heat flux through the material and the generated temperature gradient, when the entire heat flux goes through the sample. One of the extremities of the sample is fixed at a cold finger (thermal bath) whose role is to evacuate the heat flux through the sample while the other end is fixed to a heater dissipating in the sample an electric power Q obtained by Joule effect, so as to produce a thermal gradient dT along the length L of the sample of area A. The thermal conductivity is thus computed by:

$$\lambda = \frac{Q\ L}{A\ dT} \quad (6)$$

Thermal conductivity in this paper was measured at a mean temperature of 23°C and samples at 50% relative humidity. A value of 0.08 W/m K was found. Additionnal measurements with the hot disk technique HOT DISK 2500 which uses the technique of the transient plane source, confirmed this value and allowed to measure the specific heat $Cp_0 = 1300$ J $Kg^{-1}°C^{-1}$

NUMERICAL STUDY

Mathematical models

Mechanisms of moisture transport in a single building material have been extensively studied by ((Künzel, 1995), (Perdesen, 1992), (Mendes et al., 1997)). Most of the models have nearly the same origin Philip and de Vries model (Philip and al., 1957). In this article, Umidus model (Mendes et al., 1997) is used, in which moisture is transported under liquid and vapour phases. The liquid phase is transported by capillarity whereas the vapour phase is due to the gradients of partial vapour pressure. The mass conservation equation is then:

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial}{\partial x}\left(D_T \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_\theta \frac{\partial \theta}{\partial x}\right) \quad (7)$$

With the boundary conditions (x = 0 and x = L)

$$\rho_l \left(D_T \frac{\partial T}{\partial X} + D_\theta \frac{\partial \theta}{\partial x}\right)\Big|_{x=0,e} = h_{M,e}\left(\rho_{ve,a,e} - \rho_{ve,s,e}\right) \quad (8)$$

$$\rho_l \left(D_T \frac{\partial T}{\partial X} + D_\theta \frac{\partial \theta}{\partial x}\right)\Big|_{x=L,i} = h_{M,i}\left(\rho_{ve,s,i} - \rho_{ve,a,i}\right) \quad (9)$$

One dimensional of the energy conservation equation with coupled temperature and moisture for a porous media is considered, and the effect of the absorption or desorption heat is added. This equation is written as:

$$\rho\ Cp_m \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda(T,\theta)\frac{\partial T}{\partial x}\right) + L_v \rho_l \left(\frac{\partial}{\partial x}\left(D_{T,v}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_{\theta,v}\frac{\partial \theta}{\partial x}\right)\right) \quad (10)$$

$$Cp_m = Cp_{0+} Cp_l \frac{\rho_l}{\rho_\theta} \quad (11)$$

Where Cp_m is the average specific which takes into account the dry material specific heat and the contribution of the specific heat of liquid phase. λ is the thermal conductivity depending on moisture content.

Boundary conditions take into account radiation, heat and phase change.

$$-\lambda \frac{\partial T}{\partial x}\Big)_{x=0,e} - L_v\ \rho_l\ \left(D_{T,v}\frac{\partial T}{\partial x}\right)_{x=0,e} = h_{T,e}\ \left(T_{a,e} - T_{s,e}\right) + L_v\, h_{M,e}\ \left(\rho_{ve,a,e} - \rho_{ve,s,e}\right) + \Phi_{ray,e} \quad (12)$$

Air model

The net heat transferred into the cell across its faces must equal the heat stored in the volume of air in the cell. That involves heat fluxes through the envelope (transmission, long and short-wave radiation input), additional thermal loads, air exchange due to natural convection or HVAC and thermal losses due to thermal heat bridges. The energy equation can be written as:

$$(\rho_i c_p V + I)\frac{\partial T}{\partial \tau} = \Phi_{West} - \Phi_{East} + \Phi_{South} - \Phi_{North} + \Phi_{Bottom} - \Phi_{Top} + \Phi_{Source} \quad (13)$$

where I is room thermal inertia.

The humidity condition in the room is due to moisture transfer from interior surfaces, moisture production rate and the gains or losses due to air infiltration, natural and mechanical ventilation as well as sources or sinks due to habitants of room. This yields to the following mass balance equation for room air:

$$V\frac{\partial \rho_i}{\partial \tau} = Q_{mWest} - Q_{mEast} + Q_{mSouth} - Q_{mNorth} + Q_{mBottom} - Q_{mTop} + Q_{mSource} \quad (14)$$

Radiation exchange in the room

In this work, the mean radiant temperature method is used to calculate long wave radiation exchange between walls. A linear equation expressing the radiative flow between a wall and all the other walls of the room is written as:

$$\Phi^{\text{int}}_{rad,LW} = h_r S\left(T - T_m\right) \quad (15)$$

The value of h_r is expressed by:

$$h_r = 4\varepsilon\sigma_0 T_m^3 \quad (16)$$

Where T_m is the mean radiant temperature of the walls and is given by:

$$T_m = \frac{\Sigma S_j T_{Sj}}{\Sigma S_j} \quad (17)$$

For the shorts-wave radiation, we assumed that radiant energy enters the room by pane window and is distributed by the quota of 0.6 for the floor and 0.1 for the other walls.

Simulation Environment SPARK

To solve this system of equations, the Simulation Problem Analysis and Research Kernel (SPARK) is used. The latter allows solving efficiently differential equation systems (Sowell et al., 2001). SPARK was developed by the Simulation Research Group at Lawrence Berkeley National Laboratory. Description of a problem for SPARK solution begins by breaking it down in an object-oriented way. This means thinking about the problem in terms of its components and represent it as a SPARK object. A model is than developed for this components. Since there may be several components of the same kind, SPARK object models, equations or group of equations, are defined in a generic manner called classes. Classes serve as templates for any number of objects required to formulate the whole problem. The problem model is then completed by linking objects together. Using graph theoretic techniques, SPARK reduce the size of the equation system and use a Newton-Raphson iterative method to solve the reduced system, and after convergence, solves for the remaining unknowns.

Simulations

In this study, two cases are presented and compared in terms of energy consumption. The vertical walls are made of hemp lime concrete with 2 cm of hemp lime mortar on internal side. The point of difference is in the ceiling composition. One is built using the hemp lime roof formulation (Cerezo 2005) and the other from hemp starch composites. The plan of study rooms is depicted in figure 3.

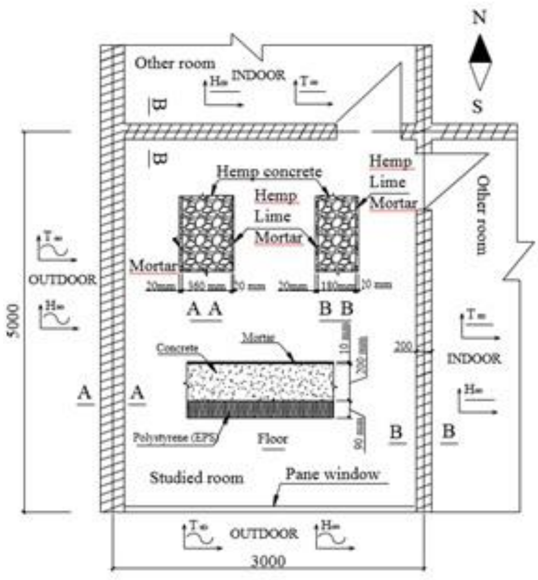
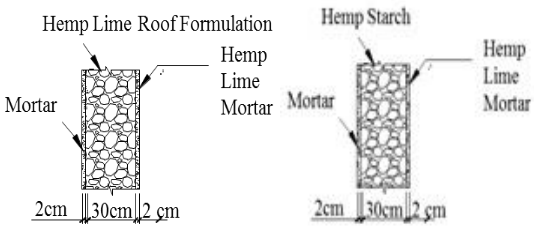


Figure 3: Plan of the studied room.

The room has a spacious area of 15 m^2 and a volume of 42,75 m^3 (Figure 3). Southern façade is made of double glazing with a solar heat gain coefficient of 0.55. The ceiling, the floor, the west and south facades are in contact with outdoor conditions while the other walls are considered as internal partitions and in contact with heated space at 19 °C temperature and 50 % relative humidity.

External walls have 40 cm thickness whereas partitions 24 cm (including internal and external mortars as shown in figure 3). In the room where the hemp concrete roof formulation is used, the ceiling encloses three layers of 30 cm of hemp concrete and 2 cm hemp lime mortar layer from inside and 2 cm of mortar from the outside (Figure 4). For the second, the ceiling presents also three layers; 30 cm of hemp starch and 2 cm of hemp lime mortar from the inside and 2 cm of mortar from the outside. (Figure 4).



(a) (b)

Figure 4 Ceiling Composition: (a) .HC; (b) HS

	Thermal conductivity at 50% RH (W/m K)	**Specific heat capacity (J/Kg K)**	**Density (Kg/m^3)**
Hemp-lime roof mixture	0.092	1100	258
Hemp starch	0.08	1300	220

Table 1: Materials physical properties

Table 1 summarizes the thermal properties of the hemp mixtures used for the roof. For the hemp lime mixture the data are based on the data of Cerezo (2005) and Collet (2014). For the hygrothermal properties of hemp lime mixtures the data given (Tran Le,2010) and (Maalouf 2014) are used. For the roof formulation, the same sorption curve is used as that of wall hemp concrete mixture.

The room is equipped with a heat sink and a PI controller that keeps the operative temperature around 19 °C during occupancy hours and 16 °C by night. Occupancy hours of the office are set from 8 am to 19 pm, with two permanent occupants. Air infiltration rate is taken to be 0.5 Vol/hr. Two ventilation systems are tested: the constant air flow rate ventilation system (with two air flow rates for occupancy and night periods) and the relative humidity sensitive ventilation. The first one provides 50 m^3/h during occupancy hours and 10 m^3/h at night; the second provides air flow rates between 10 and 60 m^3/h depending on indoor relative humidity (figure 5).

Heat transfer coefficients are $h_{T,e}$= 16 W/m^2.K for the outdoor surfaces and $h_{T,i}$= 3 W/m^2.K for indoor surfaces. Mass convection coefficients are respectively $h_{M,e}$= 0.005 m/s and $h_{M,i}$= 0.0025 m/s. The initial relative humidity and temperature in the walls and the studied room were respectively equal to 50 % and 20 °C. Simulations are run for five months and results are presented for the last three months corresponding to the period from November to late January for Nancy weather data (in France). The mortar layers are discretized in 5 nodes and the other layers are divided into 25 nodes. Time step is 300 s.

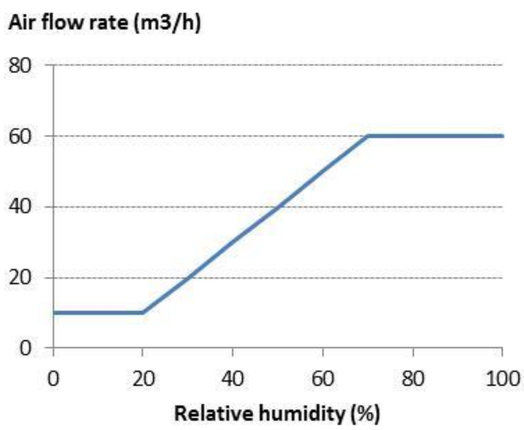


Figure 5: Air Flow rate variation in relative humidity sensitive ventilation system.

RESULTS

Constant flow rate ventilation strategy

Figure 6 shows the total energy consumption for the two ceiling formulations (hemp concrete roof formulation HC and hemp starch composites HS) using the constant airflow rate ventilation strategy (occupancy, vacation). For both cases, two cases are considered: interior surface coatings (for walls and roof) permeable to moisture (P) with mass convection values as shown in last section and internal surface coating (for walls and roof) has a moisture impermeable coating (I) with $h_{M,i}$= 0.0 m/s.

It is noticed that along the 92 days of simulation, heating energy consumption is always lower for the hemp starch roof than that for the hemp concrete roof. Though hemp starch thermal conductivity is 13% lower, energy consumption is 1% lower when using permeable coating and 0.5% lower with impermeable coating. This small difference is explained by the fact that the main heat losses are due to the double glazing façade and the ventilation.

Comparing impermeable coating to the moisture permeable one, energy consumption for the permeable case is always higher because of moisture desorption during vacancy period (by night) which slightly cools internal surfaces and required higher heating power as shown in figure 7. During occupancy period, the adsorption phenomenon tends to decrease heating power for the P case however its effect is small because air flow rate is higher in this period. An additional case is considered where the hemp starch roof is considered impermeable (HS-roof-I), in this case the heating consumption is still lower than the HC-I case (0.1%).

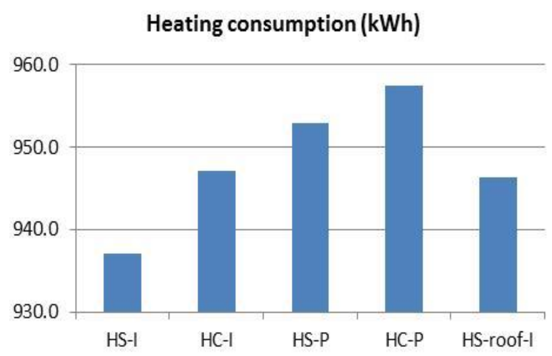


Figure 6: Heating energy consumption (kWh) for three months (92 days) in winter for different roof materials: hemp starch impermeable (HS-I; hemp concrete impermeable HC-I, hemp starch permeable HS-P, hemp starch impermeable HS-I, and hemp starch with only roof impermeable HS-roof-I).

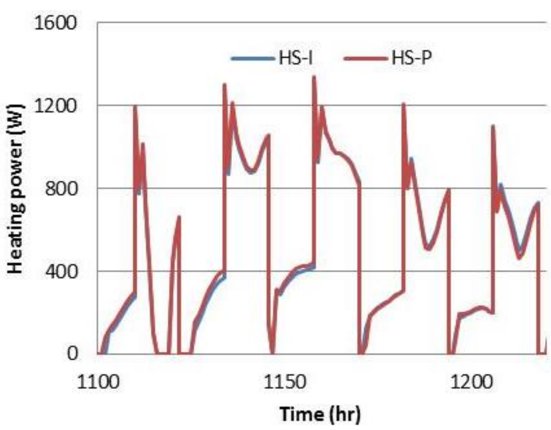


Figure 7: Pattern of heating supplied power for hemp starch composite roof with both moisture permeable

and impermeable internal coating for a typical week in December.

Relative humidity sensitive ventilation

Concerning the relative humidity variation in the studied office, Figure 8 presents indoor relative humidity pattern for the three hemp starch cases for a typical week in december: internal vapour permeable coating for all surfaces (P), impermeable coating (I) and roof only impermeable coating (roof-I).

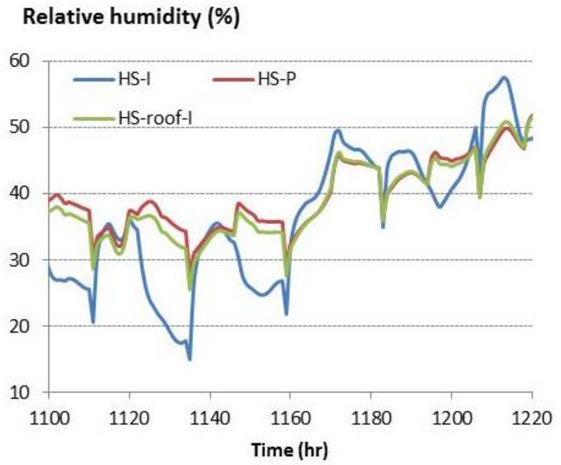


Figure 8: Variation of indoor air relative humidity during a typical week in December.

Details for indoor relative humidity minimum, maximum and mean values are also given in table 2 and for the five studied cases.

One can observe that using permeable coating dampens indoor relative humidity variation. When using impermeable coating indoor relative humidity varies between 13 and 69%, which is lower than 30% the lower limit of relative humidity for the comfort zone. Using permeable walls reduces drastically relative humidity amplitude to the range 24 -62% with few hours below 30% as shown in Figure 8.

	HS-I	HC-I	HS-P	HC-P	HS-roof-I
Mean RH (%)	38.28	38.22	42.02	41.15	41
Standard deviation	9.5	9.5	5.65	5.75	6.2
Minimum RH (%)	13.25	13.18	26.25	25.36	24
Maximum RH (%)	69.06	69.13	60.1	60.4	62

Table 2: Details about indoor relative humidity variation for the studied cases.

Table 2 also indicates that hemp starch roof has a higher dampening effect than hemp concrete roof mixture though the presence of the 2 cm of hemp lime mortar (amplitude of 33.85 for the HS and 35.05 for the HC). This is confirmed by the MBV value for the hemp starch composite which is about 3.4 g m^{-2} $\%HR^{-1}$ compared to 2.1-2.3 g m^{-2} $\%HR^{-1}$ for the hemp concrete mixtures (Maalouf;2015).

Figure 9 shows heating energy consumption for the 92 days period and for the five studied cases. As expected, the impermeable cases have lower energy consumption mainly due to the heating power during night which is lower because of the absence of desorption phenomenon though daily air ventilation rates can be higher some days. However in order to insure comfortable indoor conditions it is better to use moisture buffering coatings and only consider permeable walls with or without permeable roof coating.

Heating energy consumption for the HS-P case is 855 kWh compared to 856.1 kWh for the HC-P and 845.9 kWh for the HS-roof-I case. It is 11.88% lower than that of the HS-roof-I case with the constant flow rate strategy. These results suggest that if there is no restrictions on indoor relative humidity conditions, the coupling of moisture permeable vertical walls and impermeable roof coating is suited to obtain the best energy performance for the hemp starch roof mixture.

Comparing HS-P and HC-P cases, they almost have the same energy consumption though HS thermal conductivity is lower because of two factors: moisture desorption is higher during night for the HS case and relative humidity is more dampened giving higher indoor mean relative humidity during day with a slightly higher ventilation rate.

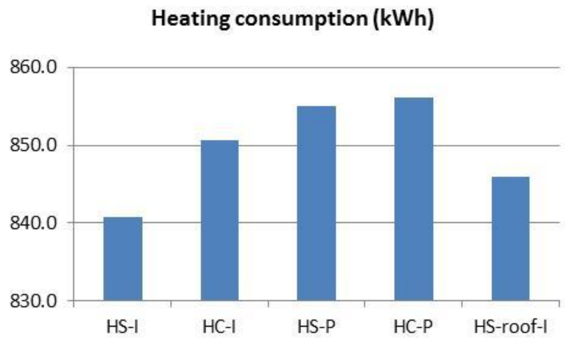


Figure 9: Heating energy consumption (kWh) for three months (92 days) in winter for the relative humidity sensitive ventilation and for different roof materials: hemp starch impermeable (HS-I; hemp concrete impermeable HC-I, hemp starch permeable HS-P, hemp starch impermeable HS-I, and hemp starch with only roof impermeable HS-roof-I).

CONCLUSION

In this paper, a vegetal fibre material made of treated hemp hurds with starch as binder for roof applications was presented. Preliminary results of material hygrothermal properties are shown and used in building simulation to assess the hygrothermal performance of a room used as an office under winter conditions. Our results suggest that for Nancy weather conditions, the effect of low thermal conductivity is counterbalanced by night desorption effect and in order to increase energy performance it is better to use a moisture impermeable coating for the roof. In this way, using a relative humidity sensitive ventilation results in an economy of 11.8% compared to the constant flow rate strategy.

NOMENCLATURE

Symbol	Definition	Unity
δ	Water vapour permeability	$kg.m^{-1}.s^{-1}$ Pa^{-1}
δ_a	Air vapour permeability in the air	$kg.m^{-1}.s^{-1}$ Pa^{-1}
∇P_v	Pressure gradient	Pa
μ	Material vapour resistance factor	
w	Moisture content by mass	Kg/kg
C	Specific heat	$J.kg^{-1}.K^{-1}$
C_0	Specific heat of dry material	$J.kg^{-1}.K^{-1}$
C_l	Specific heat of water	$J.kg^{-1}.K^{-1}$
D_T	Mass transport coefficient associated to a temperature gradient	$m^2.s^{-1}.K^{-1}$
$D_{T,v}$	Vapor transport coefficient associated to a temperature gradient	$m^2.s^{-1}.K^{-1}$
D_θ	Mass transport coefficient associated to a moisture content gradient	$m^2.s^{-1}$
$D_{\theta v}$	Vapor transport coefficient associated to a moisture content gradient	$m^2.s^{-1}$
g	Gravity acceleration	$m^2.s^{-1}$
h_M	Mass transfer convection coefficient	$kg.m^{-2}.s^{-1}$
h_T	Heat transfer convection coefficient	$W.K^{-1}.m^{-2}$
L_v	Heat of vaporization	$J.kg^{-1}$
R_v	Constant of water vapor	$J.kg^{-1}.K^{-1}$
T	Temperature	K
Ta	Indoor air temperature	K
T_m	mean radiant temperature of the walls	K
T_0	operative temperature	K
t	Time	s
x	Abscise	m
θ	Moisture content	$m^3.m^{-3}$
λ	Thermal conductivity	$W.m^{-1}.K^{-1}$
ρ_0	Mass density of dry material	$kg.m^{-3}$
ρ_l	Mass density of water	$kg.m^{-3}$
ρ_v	Mass density of vapor water	$kg.m^{-3}$
ψ	Capillary pressure	Pa
ψ_{tb}	Linear thermal bridge coefficient	$W.m^{-1}.K^{-1}$
ϕ	Relative humidity	%
ρ_i	Air density	$kg.m^{-3}$
Φ	Heat flux	W
Q_m	Air flow rate	$Kg.s^{-1}$
Φ_{source}	Heat source power	W
ε	Wall emissivity (long wave)	
σ_0	Stephan-Boltzmann constant	$W.m^{-2}.T^{-4}$

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