ABSTRACT

The purpose of this paper is to study heat and mass transfer in two vegetal fibre materials: flax and hemp concrete which are known to have a low environmental impact. After presenting each of these materials and their physical properties, we present equations of the coupled heat and moisture transfer within simple layer walls. In this model, moisture transport phenomenon is made through liquid and vapour phases. The liquid phase is supposed to move by capillarity whereas the vapour phase diffuses under vapour partial pressure gradient. Simulations are done with the simulation environment SPARK suited to complex problems. In this case, we investigate the impact of moisture transfer on heat diffusion within these two materials through the study of the damping effect, time lag and heat conduction loads and moisture transfer through a simple layer wall subjected to periodical variation of outdoor conditions.

1. INTRODUCTION

The sustainable world’s economic growth and people’s life improvement greatly depend on the use of alternative products in the architecture and construction, such as vegetal fibres conventionally called green materials. Among these materials, hemp and flax are widely used in building construction. Concerning the hemp concrete case (a lime-hemp fibres and water mixture), the researches done until this day ((Collet, 2004), (Cerezo, 2005), (Tran Le, 2010)) allowed us to determine its physical properties and its performances regarding the energy consumption and hygrothermal comfort in buildings. For the agro-composite based on flax-shaves (a mixture of the woody portion of the flax fibre stem and an agro-binder from casein and vinegar treated by microwave radiation), its mechanical, hygrothermal and acoustic properties have been recently studied by (El Hajj N, 2010).

In comparison with the agro-composite based on flax-shaves, the hemp concrete has lower thermal conductivity which is equal to 0.11 W/m.K compared to 0.145 W/m.K for the flax case. However, compared to other materials in construction as the normal concrete, the brick... they have lower thermal conductivity, which reduces heat diffusion, thus reducing winter heat losses and protecting from summer heat waves. Though they have a low mass density (415 and 570 kg/m\(^3\) for hemp and flax concretes respectively), which reduces their storage capacity, their density remains higher than classical insulation materials. Besides, both are hygroscopic materials, they have the capacity to store or to release moisture to ambient air so they can moderate daily or seasonal humidity variations of indoor environment.

Regarding all that, hemp concrete and flax-shaves can be considered as a good compromise between insulation, energy efficiency, buffering capacity purpose and green material. However the comparison of their hygrothermal behaviour based on their physical properties is difficult to quantify and we rarely find in literature studies comparing the use of these vegetable materials in construction.

The purpose of this paper is to study performance of hemp and flax-shaves concrete when they are used as building envelope.

2. MATHEMATICAL MODELS

In order to reduce the energy consumption and to increase the comfort in building, the study of heat and mass transfer through the wall is necessary because it is the main barrier that protects from the outside weather or other conditions, such as cold in winter, heat in summer, humidity, rain, wind and
Mechanisms of moisture transport in a single building material have been extensively studied ([Künzel, 1995], (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, we use the Umidus model (Mendes et al., 1997) in which moisture is transported under liquid and vapour phases. Forms of moisture transport depend on the pore structure as well as environmental condition. The liquid phase is transported by capillarity whereas the vapour phase is due to the gradients of partial vapour pressure. With these considerations, the mass conservation equation becomes:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left( D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x} \right)$$ (1)

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

$$-\rho_1 \left( D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x} \right)_{x=0,e} = h_{M,1} (\rho_{ve,1,e} - \rho_{ve,1,e})$$ (2)

$$-\rho_1 \left( D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x} \right)_{x=L,j} = h_{M,j} (\rho_{ve,1,j} - \rho_{ve,1,j})$$ (3)

The phase change occurring within porous materials acts as a heat source or sink, which results in the couple relationship between moisture and temperature. 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:

$$\rho_0 C_{pa} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} + L_0 \rho_1 \left( D_T \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial x} \left( D_\theta \frac{\partial \theta}{\partial x} \right) \right)$$

$$+ \frac{\partial}{\partial x} \left( D_\theta \frac{\partial \theta}{\partial x} \right)$$ (4)

$$C_{pm} = C_{pa} + C_{pl} \frac{\rho_L}{\rho_0}$$ (5)

Where $C_{pm}$ is the average specific heat which takes into account the dry material specific heat and the contribution of the specific heat of liquid phase. $\lambda$ is the thermal conductivity considered as a function of moisture content.

$$-\lambda \frac{\partial T}{\partial x} + L_0 \rho_1 \left( D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x} \right) = h_{T,e} (T_{ae} - T_{se})$$

$$+ L_0 h_{M,e} (\rho_{ve,e} - \rho_{ve,e}) + \Phi_{ry,e}$$ (6)

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

3. OBJECT – ORIENTED SIMULATION

3.1 Numerical resolution

In order to solve the previous equation system, the numerical solution is based on the finite difference technique with an implicit scheme. The numerical resolution is shown in (Tran Le et al, 2009).

3.2 Simulation Environment SPARK

To solve this system of equations we used the Simulation Problem Analysis and Research Kernel (SPARK), a simulation environment allowing to solve efficiently differential equation systems ((Sowell et al., 2001), (Mendonça et al., 2002). 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 component is represented by a SPARK object. A model is then developed for its component. 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 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.

We have just presented the physical model used in simulations, in the next part we present model validation for the simple hemp concrete wall.

3.3 Model validation

In order to validate the physical model presented above, the experiment has been done at laboratory of GRESPI/ LTM of Reims University. It considers two samples which surfaces are (10 cm x11 cm) and (12 cmx12 cm) and their thicknesses are 3 cm and 6 cm respectively. The test specimens are exposed to a periodical step change in ambient relative humidity chamber between 75% during 24 hours and 35% during 24 hours. The temperature is held constant at 20°C. In order to ensure one-dimensional water vapour transfer between the specimen and ambient air, five faces of samples were sealed with an aluminium tape.

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keeping only one face exposed to indoor environmental chamber conditions. The weight change of specimen was measured by a balance with a resolution of 0.01 g. Initially, the specimen are in equilibrium state at 20°C temperature and 35% relative humidity. The thermal and mass convection coefficients between the surface exposed and indoor air ambient of climate chamber are equal to \( h = 10 \text{ W/m}^2\text{K} \) and \( h = 0.008 \text{ m/s} \).

<table>
<thead>
<tr>
<th>Density</th>
<th>Thermal conductivity ( \lambda )</th>
<th>Heat capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg/m(^3)</td>
<td>W/m.K</td>
<td>J/kg.K</td>
</tr>
<tr>
<td>415</td>
<td>0.11</td>
<td>1000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \Theta )</th>
<th>( D_T ) and ( D_{fv} )</th>
<th>( D_{ov} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>m(^2)/s</td>
<td>m(^2)/(s.K)</td>
<td>m(^2)/s</td>
</tr>
<tr>
<td>1,2E-09</td>
<td>1E-12</td>
<td>1E-9</td>
</tr>
</tbody>
</table>

Table 1 Properties of hemp concrete for validation

The properties and the sorption isotherm of hemp concrete for validation are shown in the table 1 and figure 3. The comparison between the numerical results and the simulation results is presented in Figures 1 and 2.

One can see in these figures that predicted numerical results are in good agreement with experimental data. In order to appreciate the result we use the root-mean-square criterion. The average difference between the measured and predicted moisture content was expressed as a root-mean-square difference, so:

\[
\delta_{RMS} = \frac{1}{N} \sum_{i=1}^{N} (\Delta m_i)^2
\]

where \( \Delta m \) is the instantaneous difference sample weight between the measured and predicted values, and \( N \) is the number of values in the data set.

In our cases, the \( \delta_{RMS} \) values for specimen 1 and 2 are respectively 0.14 g and 0.15 g, which represent a very good agreement.

The physical model has been validated and will be used to investigate hygrothermal behaviour of hemp and flax shave concrete cases (other validation cases were run according to the exercises of the annex 41 of IEA).

3.4 Material properties

Material properties (density, thermal conductivity and specific heat) are given for the dry material and are shown in Table 2 (Collet, 2004; El Hajj, 2010). This table presents also the thermal diffusivity \( a (\text{m}^2/\text{s}) \) calculated by the ratio \( \lambda/(\rho C_p) \) and the thermal effusivity \( (\sqrt{k \rho C_p}) \) which indicates the aptitude of a material to absorb and to restore heat energy.

<table>
<thead>
<tr>
<th>Material</th>
<th>Flax shaves concrete</th>
<th>Hemp concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m(^3))</td>
<td>570</td>
<td>413</td>
</tr>
<tr>
<td>Thermal conductivity (W/m.K)</td>
<td>0.15</td>
<td>0.11</td>
</tr>
<tr>
<td>Specific heat (J/kg.K)</td>
<td>960</td>
<td>1000</td>
</tr>
<tr>
<td>Thermal diffusivity (*10(^{-7}) m(^2)/s)</td>
<td>2.64</td>
<td>2.66</td>
</tr>
<tr>
<td>Thermal effusivity (J/(m(^2).K.s(^{1/2})))</td>
<td>281.7</td>
<td>213.1</td>
</tr>
</tbody>
</table>

The sorption isotherm curves are shown in Figure 3. We have neglected hysteresis effect on the sorption isotherm curves due to the lack of data. The simulation is done by using the straight forward link between moisture content (expressed by volume %) and the
relative humidity. One can see in Figure 1 that when the relative humidity varies from 0 to 43%, the moisture content of the both materials are very close and apart from this value, the moisture content of flax-shaves case is much bigger than for the hemp concrete case.

**Figure 3** Sorption isotherms of studied materials (Collet, 2004; El Hajj, 2010).

The thermal conductivity of both materials as function of relative humidity is shown in Figure 4 in which one can see that the thermal conductivity of hemp concrete is smaller than that of flax-shaves concrete. Indeed when the relative humidity is bigger than 80%, the thermal conductivity in both cases increases dramatically due to their moisture sorption isotherm.

**Figure 4** Thermal conductivity of studied materials (Collet, 2004; El Hajj, 2010).

Concerning the mass transport coefficient associated to a moisture content gradient ($D_\theta$), for the same measurement condition ($25^\circ$C of temperature and 90% of relative humidity), its value for the flax-shaves concrete case is bigger than hemp concrete case and it is equal to 6.65*10^{-9} (m²/s) compared to 1.18*10^{-10} (m²/s) respectively. In the simulation, the mass transport coefficients for hemp concrete case ($D_\theta$, $D_{\theta v}$, $D_T$, $D_{\theta T}$) are functions of water content as presented in (Tran Le, 2010). Concerning the flax-shaves concrete case, only the coefficient associated to a moisture content gradient ($D_\theta$) is used because of lacking data (El Hajj, 2010).

### 4. NUMERICAL RESULTS

#### 4.1 Physical model

Firstly, we present the physical model in which we study the behaviour of a simple layer wall subjected to periodical outdoor temperature and relative humidity (Figure 5). Indoor conditions are given as (for $x=L$): $T_i=24^\circ$C and $T_i=20^\circ$C for summer and winter conditions respectively and the indoor relative humidity for both cases is 50%. External outdoor conditions are given by sinusoidal functions. External and internal thermal convection coefficients are equal to $h_{T,e}=16$ W/m²°C and $h_{T,i}=4$ W/m²°C.

**Figure 5** Physical model for the simple layer wall.

Indoor and outdoor mass transfer coefficients were calculated using the Lewis number relation for the air:

$$Le = \frac{h_{T,i}}{\frac{h_{T,e}}{\rho C_p}} = 1$$

(9)

Initial wall temperature and relative humidity were considered to be $20^\circ$C and 40% respectively through the wall. Wall thickness is 20 cm. The layer is discretized in 25 nodes and the time step is 240 s. The simulations are run for three months.

#### 4.2 Computed results for summer conditions

In this section, we study the behaviour of a simple layer wall subjected to extreme summer conditions. External outdoor temperature and relative humidity are given by sinusoidal functions:

$$T_{ext} = 30 - 4 \ast \cos (w * t)$$

$$HR_{ext} = 0.5 + 0.2 \ast \cos (w * t)$$

where $w=2\pi/T$ and $T=24$ hours.

Figure 6 shows the variation of internal surface temperature of the wall for the 60th day and the numerical results are shown in Table 3. One can see that internal surface temperature is dampened and phase shifted. We can notice that for the hemp concrete envelope, its temperature variation is slightly smaller than for the flax-shave case (about 0.12°C) and the average of internal surface temperature of both cases are extremely close (about 25.65 °C). Regarding the time lag which explains the
material capacity to dampen the outdoor temperature variation, it is 10.8 h for the flax shave concrete compared to 8.4 h for hemp concrete case. This is due to the thermal diffusivity which is slightly higher for the hemp concrete than that of flax shave concrete case (Maalouf et al., 2011).

Table 3 shows also the heat flux through the wall, it is positive when it is directed from outdoor to indoor air. Its values are always positive which explains that the wall protects the indoor from outdoor temperature variations. The average value is 2.62 W/m² for the flax shave concrete which is slightly higher than that of hemp concrete (2.54 W/m²).

![Figure 6 Variation of internal surface temperature of the wall for both cases.](image)

**Table 3**

<table>
<thead>
<tr>
<th></th>
<th>Flax_shaves concrete</th>
<th>Hemp concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time lag (h)</td>
<td>10.80</td>
<td>8.40</td>
</tr>
<tr>
<td>Minimal internal surface temperature (°C)</td>
<td>25.58</td>
<td>25.46</td>
</tr>
<tr>
<td>Maximal internal surface temperature (°C)</td>
<td>25.73</td>
<td>25.81</td>
</tr>
<tr>
<td>Average of internal surface temperature (°C)</td>
<td>25.65</td>
<td>25.64</td>
</tr>
<tr>
<td>Minimal heat flux (W/m²)</td>
<td>2.32</td>
<td>1.84</td>
</tr>
<tr>
<td>Maximal heat flux (W/m²)</td>
<td>2.92</td>
<td>3.24</td>
</tr>
<tr>
<td>Average heat flux (W/m²)</td>
<td>2.62</td>
<td>2.54</td>
</tr>
</tbody>
</table>

The variations of internal surface relative humidity of both cases are shown in Figure 7. We notice that its value is mostly influenced by the internal surface temperature variations caused by the outdoor temperature fluctuations (Figure 6). The internal surface relative humidity of the flax shave case is more dampened and phase shifted. Its average values are very close in both cases and they are 48.25 % for the hemp concrete and 48.45 % for the flax shave case.

In the next section, we will study wall behaviour under winter conditions.

**4.3 Computed results for winter conditions**

Outdoor temperature and relative humidity variations are described by the sinusoidal functions given by:

\[
T_{\text{ext}} = -5 \cdot \cos (w \cdot t)
\]

\[
HR_{\text{ext}} = 0.8 + 0.1 \cdot \cos (w \cdot t)
\]

(10)

We notice that indoor temperature and relative humidity are constant and equal to 20 °C and 50 % respectively.

**a. Effect of moisture transfer on thermal properties of materials**

Since both materials are porous, the effect of moisture content on their thermal conductivity and specific heat is important and thus will be extendly studied in this part. The moisture content in the middle layer of the wall is shown in Figure 8. One can see in this figure that the moisture content for the hemp concrete case is much smaller than that of flax shave case because of their sorption isotherm curves (Figure 3). When the moisture content tends to the equilibrium value, it is 11.3% and 2.82% for the flax concrete and the hemp concrete cases respectively. We notice also that the system needs three months to reach the equilibrium state, which means that moisture content through the wall depends strongly on initial moisture content (so initial relative humidity) and the simulation time (Maalouf et al., 2011).
The variation of the average thermal conductivity through the wall for both cases is shown in Figure 9. Due to the moisture transfer through the material, the thermal conductivity increases from 0.117 and 0.125 W/m K (6.8 %) for the hemp concrete and from 0.154 to 0.174 W/m K (13%) for the flax shaving concrete case. High moisture diffusion rate through the flax-shaves wall leads to higher variations in its thermal conductivity.

The variations of average specific heat for both moist materials are presented in Figure 10. We notice that the effect of mass transfer on the specific heat of flax concrete is much more significant than the hemp concrete case since its moisture content is higher. In the beginning of simulation (the initial relative humidity of the wall was set at 40%), the specific heat of hemp concrete is 5.8 % bigger than that of flax-shaves concrete and their values are respectively 1138 and 1072 (J/kg.K). However, flax concrete specific heat increases fastly and becomes higher after two days of simulation. It can be seen that to reach the equilibrium value of the average of specific heat, it takes approximately three months. Here, at the equilibrium state, a significant increase of 67% of average specific heat of flax concrete was obtained compared to 11.2 % for hemp concrete case.

b. Moisture transfer between the wall and the indoor air

Hygroscopic materials can be used to moderate the amplitude variation of indoor relative humidity in buildings thanks to their vapour sorption (absorption and desorption) capacity and thus they participate in the improvement of the indoor air quality and the reduction of energy consumption. Therefore, in this part we will study the moisture transfer between the envelope and the indoor air.

Figure 11 shows the water vapour flux exchange expressed in g/m²h between the inside wall surface and indoor air for a period of three months. A negative value means that water vapour flux is going from indoor air to the wall. The equilibrium state is considered when the difference of two successive maximum values of profile of water vapour flux is less than 1 %. For the studied cases, it takes 62 and 85 days for the hemp concrete and flax concrete respectively to obtain equilibrium state. This result shows that in hygroscopic region, materials with low moisture storage capacity are reaching faster their hygroscopic equilibrium.

In addition, the flux of the water vapour is always negative during the first 31 and 55 days for hemp concrete and flax concrete cases respectively. That
can be explained by the initial relative humidity which was set to 40% through the wall and is smaller than indoor relative humidity. The results suggest that initial conditions affect significantly materials sorption capacity.

Concerning the water vapour flux transfer between the indoor air and the wall when it reaches the equilibrium, the table 4 presents its minimal and maximal values at the 90th day. The maximal value of hemp concrete is 50% smaller than that of flax concrete case due its sorption isotherm curve.

**Table 4**

<table>
<thead>
<tr>
<th></th>
<th>Flax_shaves concrete</th>
<th>Hemp concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal water vapour flux (g/m²h)</td>
<td>-1</td>
<td>-0.5</td>
</tr>
<tr>
<td>Maximal water vapour flux (g/m²h)</td>
<td>0.94</td>
<td>0.48</td>
</tr>
</tbody>
</table>

### c. Heat exchange between internal wall surface and indoor air.

As shown in the boundary conditions, internally, the wall is exposed to thermal convection and phase change related to the water vapour transfer between the wall and indoor air. Regarding the heat loss due to the thermal convection, Figure 12 shows the variation of heat loss flux through the wall in the equilibrium state during five days of the third month. The heat loss flux through the hemp concrete wall is much smaller than that of flax concrete because it has a lower thermal conductivity. Hemps concrete mean heat loss flux value is 10.4 W/m² compared to 13.7 W/m² for the flax-shaves concrete showing a difference of 31.7%. Energy heat loss through the wall for the three months is 11.7 and 15.8 kWh/m² respectively for the hemp and flax concrete cases showing that the use of hemp concrete will reduce energy consumption about 35%.

![Figure 12: Heat loss flux from the wall during 5 days of the third month.](image)

In addition, the heat flux caused by phase change is small compared to heat loss due to thermal convection. For hemp concrete case, the maximal heat flux related to phase change is 0.38 W/m² and represents 3.3% of the maximal heat loss flux due to thermal convection which is 11.4 W/m². Concerning the flax concrete case, its value is 5%.

### CONCLUSION AND PERSPECTIVES

In this paper, the hygrothermal behaviour of hemp concrete and flax concrete is investigated at wall level. A one-dimension model for heat and moisture transfer through a simple layer wall was used in the simulation environment SPARK.

The computed results for summer conditions show that the internal surface temperature of the flax-shaves concrete wall is slightly more dampened and its time lag is higher than hemp concrete case due to its higher thermal inertia.

The results in winter conditions show that the thermal properties (thermal conductivity and specific heat) of flax concrete are much more affected by the moisture transfer in hygroscopic region compared to hemp concrete. Our results suggest that using hemp concrete may reduce conduction heat losses about 35% for winter conditions (at wall level). However, flax-shaves concrete material has a higher aptitude to interact with indoor conditions meaning it has a higher moisture buffering capacity that could affect its behaviour at building level.
For further work, we intend to study the hygrothermal behaviour of these materials for multi-layered walls as usual in construction design. In addition, the comparison of their performances should be done in the whole building level with different ventilation systems (sensitive relative humidity ventilation for example). In this way, it will be possible to quantify the effect of moisture buffering capacity of these materials on hygrothermal comfort.

**REFERENCES**


