Hygrothermal behaviour of hemp concrete

Experimental evidences and modelling

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Context

Lime

Water

Hemp shiv

Hemp concrete
Context

**Bio-based material**

- Low embodied energy

Material particularities:

Lime, Water, Hemp shiv

Hemp concrete
Context

Material particularities:
- Low embodied energy
- Vapor permeancy
Context

Material particularities:
- Low embodied energy
- Vapor permeancy
- Moisture buffering abilities
- Hygrothermal abilities
The old buildings are a major source of energy loss. The IBIS project aims to develop bio-sourced sustainable solutions, economical and low environmental impact, for the renovation and the thermal insulation of buildings which are constructed prior to 1950.

**Goals**

- To develop at an industrial scale and until its application, sustainable insulation composite bio-based mortars with accurate energy and acoustic performance
- To reduce the energy consumption and CO₂ emissions of old buildings, while improving the comfort of the inhabitants thanks to the properties of bio-based insulation
- To develop the theoretical tools and tests in order to properly assess the performance of these bio-based mortar.
The old buildings are a major source of energy loss. The IBIS project aims to develop bio-sourced sustainable solutions, economical and low environmental impact, for the renovation and the thermal insulation of buildings which are constructed prior to 1950.

**Goals**

- To develop at an industrial scale and until its application, sustainable insulation composite bio-based mortars with accurate energy and acoustic performance
- To reduce the energy consumption and CO₂ emissions of old buildings, while improving the comfort of the inhabitants thanks to the properties of bio-based insulation
- To develop the theoretical tools and tests in order to properly assess the performance of these bio-based mortar.
Outline

I. Experimental identification of HT processes

II. Modelling
   - Equilibrium model
   - Kinetic model

III. Conclusion
Experimental identification

- Double climatic chamber DUO

Samples: 90 x 90 x 10 [cm$^3$].

Instrumentation plan:

- $T_{left}, \Phi_{left}$
- $T_{right}, \Phi_{right}$
- $T_{middle}, \Phi_{middle}$
- Left heat flow meter
- Right heat flow meter
- $h = 6 \text{ W/m}^2\text{K}$
- $h = 7 \text{ W/m}^2\text{K}$
Experimental identification

Left climatic chamber

Right climatic chamber

$T = 30^\circ C$

$h = 6 \text{ W/m}^2/\text{K}$

$T = 40^\circ C$

$h = 7 \text{ W/m}^2/\text{K}$
Experimental identification

Left climatic chamber

Temperature

T = 30°C

Relative humidity

φ (%) 0% 20% 40% 60% 80% 100%

Time (days) 0 4 8 12 16 20

Right climatic chamber

Temperature

T = 40°C

Relative humidity

φ (%) 0% 20% 40% 60% 80% 100%

Time (days) 0 4 8 12 16 20

- Left climatic chamber: h = 6 W/m²/K
- Right climatic chamber: h = 7 W/m²/K
Experimental identification

2 tested walls:

**Hemp concrete**

**Pure hemp**

Same volume – Almost same porosity
Experimental identification

2 tested walls:

**Hemp concrete**

- Size = 0.9x0.9x0.1 [m³]
- Apparent density = 509 kg/m³
- Estimated porosity = 0.79

**Pure hemp**

- Size = 0.9x0.9x0.1 [m³]
- Apparent density = 160 kg/m³
- Estimated porosity = 0.84

Same volume – Almost same porosity
Hemp concrete results
Hemp concrete results

Temperature (°C)

Time (days)

Relative humidity (%)

Time (days)

Heat flow (W/m²)

Time (days)

Sorption stage

Desorption stage

Sorption stage

Desorption stage

Hemp concrete results
Hemp concrete results

Temperature (°C)

Time (days)

Relative humidity (%)

Time (days)

Heat flow (W/m²)

Time (days)

30.5°C  
39.5°C

sorption stage

desorption stage

sorption stage

desorption stage

Hemp concrete results
Hemp concrete results

Temperature (°C) vs. Time (days)

Relative humidity (%) vs. Time (days)

Heat flow (W/m²) vs. Time (days)

30.5°C to 39.5°C
Hemp concrete results

- Temperature (°C)
  - Right
  - Middle
  - Left

- Relative humidity (%)
  - Right
  - Middle
  - Left

- Heat flow (W/m²)
  - Right
  - Left

Time (days)

- Sorption stage
- Desorption stage

30.5°C → 39.5°C
Hemp concrete results

- **Sorption** = > Reduction of the incoming heat flow at the hot surface (=> reduction of the looses at the evening)

- **Desorption** => Reduction of the outgoing heat flow at the cold surface (=> keep the freshness during the day in summer)
Pure hemp results

- Temperature (°C)
- Relative humidity (%)
- Heat Flow (W/m²)

Sorption stage
Desorption stage

30.5°C
39°C
Pure hemp results

- Temperature (°C)
  - Right
  - Middle
  - Left

- Relative humidity (%)
  - Right
  - Middle
  - Left

- Heat Flow (W/m²)
  - Right
  - Middle
  - Left

- Time (days)

30.5°C 39°C
Enhanced hygrothermal properties while the porosity is almost the same.
HT Modelling

Physical principles

\[ - \langle \lambda \rangle \nabla T \]

\[ - \delta_p \nabla p_v \]

\[ - D_p (\nabla p_L - \rho_L g) \]

External liquid water supply
Physical principles

\[-<\lambda>\nabla T\]

\[-\delta_p \nabla p_v\]

\[-D_p (\nabla p_L - \rho_L g)\]

\(D_p \approx 0\) for hemp concrete in the hygroscopic regime

External liquid water supply
HT Modelling

Sorption curves of the tested material at several temperatures

Sorption / Desorption cycles at several temperatures

− δ_p V_p_v

WATER

Vapor

Sorption

Desorption

Liquid
Physical principles

\[ -\langle \lambda \rangle \nabla T \]

\[ -\delta_p \nabla p_v \]

\[ L_v \dot{m}_{\rightarrow v} \]

\[ p_v^{\text{sat}}(T) \]
Modelling

Physical principles

Vapor Heat

\[ L_v m_{\rightarrow v} \]

Condensation

\[ p_{v}^{\text{sat}}(T) \]

WATER

Vapor

Liquid

\[ L_{\text{v}} \text{MJ/kg} \]

\[ \varphi_{\text{eq}} [-] \]

\[ \text{Temperature [°C]} \]

\[ \text{Temperature [°C]} \]

\[ p_{v}^{\text{sat}} \text{[bar]} \]

\[ p_{v}^{\text{sat}} \text{[bar]} \]
HT Modelling

Continuity equations

Heat balance:
\[ < \rho C > \frac{\partial T}{\partial t} = \nabla \cdot ( < \lambda > \nabla T) - L_v \dot{m}_{\rightarrow v} \]

Vapor mass balance:
\[ m_{vs} \left( \frac{\partial \varphi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \nabla \cdot (\delta_p \nabla p_v) + \dot{m}_{\rightarrow v} \]

Water mass balance:
\[ \rho_d \frac{d\omega}{dt} + m_{vs} \left( \frac{\partial \varphi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \nabla \cdot (\delta_p \nabla p_v + D_p \nabla \varphi_L) \]

Notations:

\[ < \rho C > : \text{average heat capacity at constant pressure} \]

\[ < \lambda > : \text{average thermal conductivity} \]

\[ \delta_p : \text{vapor diffusivity transport coefficient} \]

\[ m_{vs} = \left( \phi - \frac{\rho_d}{\rho_l} \right) \frac{M_{w} p_{vs}}{R T} : \text{Mass of vapor at saturation with the RVE} \]

\[ \alpha_p = \varphi \left( \frac{1}{p_{vs}} \frac{dp_{vs}}{dT} - \frac{1}{T} \right) : \text{Apparent thermal dilatation of vapor at constant hygrometry} \]

\[ D_p = \rho_L \frac{\kappa}{\eta} : \text{Transport coefficient of liquid water} \approx 0 \text{ for hemp concrete} \]
HT Modelling : common assumptions

**Continuity equations**

Heat balance:
\[
< \rho C > \frac{\partial T}{\partial t} = \nabla \cdot (\langle \lambda \rangle \nabla T) - L_v \dot{m}_{\rightarrow v}
\]

Vapor mass balance:
\[
m_{vs} \left( \frac{\partial \phi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \nabla \cdot (\delta_p \nabla p_v) + \dot{m}_{\rightarrow v}
\]

Water mass balance:
\[
\rho_d \frac{d\omega}{dt} + m_{vs} \left( \frac{\partial \phi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \nabla \cdot (\delta_p \nabla p_v + D_p \nabla \omega)
\]

H1 : Variation of mass of vapor negligible
HT Modelling: common assumptions

Continuity equations

Heat balance:

\[ < \rho C > \frac{\partial T}{\partial t} = \nabla \cdot ( < \lambda > \nabla T) - L_v \dot{m}_{\text{v}} \]

Vapor mass balance:

\[ m_{\text{vs}} \left( \frac{\partial \varphi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \nabla \cdot (\delta_p \nabla p_v) + \dot{m}_{\text{v}} \]

Water mass balance:

\[ \rho_d \frac{d\omega}{dt} + m_{\text{vs}} \left( \frac{\partial \varphi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \nabla \cdot (\delta_p \nabla p_v + D_p \nabla \varphi) \]

\[ p_l = p_0 + \rho_l \frac{RT}{M_l} \ln \varphi \]

\[ \frac{\partial \omega}{\partial t} = \frac{\partial \omega}{\partial \varphi} \frac{\partial \varphi}{\partial t} + \frac{\partial \omega}{\partial T} \frac{\partial T}{\partial t} \]

H1: Variation of mass of vapor negligible

H2: Equilibrium between the liquid water and the vapor within the pores
HT Modelling: common assumptions

**Continuity equations**

**Heat balance:**
\[
< \rho C > \frac{\partial T}{\partial t} = \nabla \cdot (\langle \lambda > \nabla T) - L_v \dot{m}_{\rightarrow v}
\]

**Vapor mass balance:**
\[
m_{\nu s} \left( \frac{\partial \varphi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \nabla \cdot (\delta_p \nabla p_v) + \dot{m}_{\rightarrow v}
\]

**Water mass balance:**
\[
\rho_d \frac{d\omega}{dt} + m_{\nu s} \left( \frac{\partial \varphi}{\partial t} + \alpha_p \frac{\partial T}{\partial t} \right) = \nabla \cdot (\delta_p \nabla p_v + D_p \nabla p_l)
\]

\[
p_l = p_0 + \rho_l \frac{RT}{M_l} \ln \varphi
\]

\[
\frac{\partial \omega}{\partial t} = \frac{\partial \omega}{\partial \varphi} \frac{\partial \varphi}{\partial t} + \frac{\partial \omega}{\partial T} \frac{\partial T}{\partial t}
\]

**H1:** Variation of mass of vapor negligible

**H2:** Equilibrium between the liquid water and the vapor within the pores

**H3:** Influence of \( T \) on water content at constant \( \varphi \) negligible
HT Modelling: Equilibrium model

Final set of equations

\[
< \rho C > \frac{\partial T}{\partial t} = \nabla \cdot ( < \lambda > \nabla T) + L_v \nabla \cdot (\delta_p \nabla p_v)
\]

\[
\rho_d \frac{\partial \omega}{\partial t} = \frac{\partial \varphi}{\partial t} = \nabla \cdot (\delta_p \nabla p_v) \quad \text{where} \quad p_v = \varphi \ p_v^{\text{sat}}(T)
\]

Boundary conditions

\[
\left[ \begin{array}{c}
(q + L g_v) \cdot n \\
(g_v + g_l) \cdot n
\end{array} \right] = \left[ \begin{array}{c}
-(\lambda \nabla T + \delta_p \nabla p_v) \cdot n \\
-(\delta_p \nabla p_v + D_p \nabla p_l) \cdot n
\end{array} \right] = \left[ \begin{array}{c}
\alpha (T_a - T_s) + L_v \beta (p_v^{\text{sat}}(T_a) \varphi_a - p_v^{\text{sat}}(T_s) \varphi_S) \\
\beta (p_v^{\text{sat}}(T_a) \varphi_a - p_v^{\text{sat}}(T_s) \varphi_S)
\end{array} \right]
\]
HT Modelling: Equilibrium model

Final set of equations

\[
\langle \rho C \rangle \frac{\partial T}{\partial t} = \nabla \cdot (\langle \lambda \rangle \nabla T) + L_v \rho_\alpha \frac{\partial \omega}{\partial \varphi} \frac{\partial \varphi}{\partial t}
\]

\[
\rho_\alpha \frac{\partial \omega}{\partial \varphi} \frac{\partial \varphi}{\partial t} = \nabla \cdot (\delta_p \nabla p_v) \quad \text{where} \quad p_v = \varphi v_{v\text{sat}}(T)
\]

Boundary conditions

\[
\begin{bmatrix}
q \cdot n \\
g v \cdot n
\end{bmatrix} = \begin{bmatrix}
-(\lambda \nabla T) \cdot n \\
-(\delta_p \nabla p_v) \cdot n
\end{bmatrix} = \begin{bmatrix}
\alpha (T_a - T_s) \\
\beta (p_{v\text{sat}}(T_a) \varphi_a - p_{v\text{sat}}(T_s) \varphi_s)
\end{bmatrix}
\]
Model VS experiment: Pure Hemp

Temperature (°C)

Relative humidity (%)

Heat Flow (W/m²)

Time (days)
Model VS experiment: Pure Hemp

- **Temperature (°C)**
- **Relative humidity (%)**
- **Heat Flow (W/m²)**

- **Time (days):**
  - 0
  - 2
  - 4
  - 6
  - 8
  - 10
  - 12
  - 14
  - 16
Model VS experiment: Pure Hemp

- Temperature (°C) vs. Time (days)
- Relative humidity (%) vs. Time (days)
- Heat Flow (W/m²) vs. Time (days)
Model VS experiment: Pure Hemp

- Good agreement between experimental data and model in sorption
- Important differences in desorption => need to use the desorption curve
Model VS experiment: Hemp Concrete

Temperature (°C) vs Time (days)

Relative humidity (%) vs Time (days)

Heat Flow (W/m²) vs Time (days)
Model VS experiment: Hemp Concrete

- Temperature (°C)
  - Right
  - Middle
  - Left

- Relative humidity (%)
  - Right
  - Middle
  - Left

- Heat Flow (W/m²)
  - Right
  - Middle
  - Left

- Time (days)
Model VS experiment: Hemp Concrete

Temperature (°C)

Relative humidity (%)

Heat Flow (W/m²)

Time (days)

0 2 4 6 8 10 12 14 16 18 20

29 31 33 35 37 39

0 2 4 6 8 10 12 14 16 18 20

0 10 20 30

-25 -15 -5 5 15 25

0 2 4 6 8 10 12 14 16 18 20

-25 -15 -5 5 15 25

0 2 4 6 8 10 12 14 16 18 20

-10 -8 -6 -4 -2 0 2 4 6
Model VS experiment: Hemp Concrete

- Overestimation of the phase change effect on both heat and mass balances
- The «classic» HT-model needs to be improved to simulate the behavior of hemp concrete
HT Modelling: double porosity model

\[ \omega = \frac{m_{\text{hemp}}}{m_s} \tilde{\omega}_{\text{hemp}} + \omega_{\text{binder}} \]

Mass exchange between macropores and hemp particles

Mass exchange between macropores and binder

Flow of vapor
HT Modelling: double porosity model

\[ \frac{\partial \tilde{\omega}_{\text{hemp}}}{\partial t} = \frac{\partial \tilde{\omega}_{\text{hemp}}}{\partial \varphi} \frac{\partial \varphi}{\partial t} \]

**Instantaneous phase change**

**Mass exchange between macropores and hemp particles**

**Mass exchange between macropores and binder**

**Flow of vapor**

**Graph:**
- Water Content (%) vs. Relative humidity (%)
- Symbol representation:
  - \( \omega = \frac{m_{\text{hemp}}}{m_s} \tilde{\omega}_{\text{hemp}} + \omega_{\text{binder}} \)
HT Modelling: double porosity model

\[ \omega = \frac{m_{\text{hemp}}}{m_s} \tilde{\omega}_{\text{hemp}} + \omega_{\text{binder}} \]

\[ \approx 25\% \text{ by dry mass} \]

Flow of vapor

Mass exchange between macropores and hemp particles

Mass exchange between macropores and binder

Water Content (%) vs. Relative humidity (%) graph

- \( \omega \)
- \( \omega_{\text{binder}} \)
- \( \left( \frac{m_{\text{hemp}}}{m_s} \right) \tilde{\omega}_{\text{hemp}} \)
HT Modelling: double porosity model

Mass exchange law between the two porous systems

\[
\frac{\partial \omega_{\text{binder}}}{\partial t} = KS \rho_d (\mu_v - \mu_l) = -KS \frac{\rho_l RT}{M_w} \left( \ln \left( \frac{\varphi^*(\omega_{\text{binder}})}{\varphi} \right) \right) \approx -kS \ln \left( \frac{\varphi^*(\omega_{\text{binder}})}{\varphi} \right)
\]

where \( \varphi^*(\omega_{\text{binder}}) = \exp \left[ -\frac{\gamma}{f(\omega_{\text{binder}})} \frac{M_l}{\rho_l RT} \right] \) = Relative humidity in equilibrium with the in-pore water of the lime binder
HT Modelling: double porosity model

- RH = 23%
- RH = 43%
- RH = 59%
- RH = 75%

Water content (%) vs. Time (days)

- Data - total
- Data - without hemp
- Fit with kS = 0.0087 /days
- Fit with kS = 0.0008 /days
- Fit with kS = 0.0015 /days
The mass exchange law does not allow to reproduce the total mass increase of the sample.

The mass exchange law seems correct to model the mass increase within the binder.

\[ kS \approx 1 \times 10^{-3} \text{/days} \]
HT Modelling: double porosity model

Continuity equations with phase change kinetic

\[
<\rho C> \frac{\partial T}{\partial t} = \nabla \cdot (<\lambda> \nabla T) + L_v \nabla \cdot [\delta_p \nabla (\varphi p_v^{sat}(T))] \\
\rho_d \left( \frac{m_{hemp}}{m_s} \frac{\partial \tilde{\omega}_{hemp}}{\partial \varphi} \frac{\partial \varphi}{\partial t} + \frac{\partial \omega_{binder}}{\partial t} \right) = \nabla \cdot [\delta_p \nabla (\varphi p_v^{sat}(T))] \\
\text{with} \quad \frac{\partial \omega_{binder}}{\partial t} = -kS \ln \left( \frac{\varphi^*(\omega_{binder})}{\varphi} \right)
\]

Boundary conditions

\[
\begin{bmatrix}
(q + L g_v) \cdot n \\
g_v \cdot n \\
\end{bmatrix} = \begin{bmatrix}
-\left( \lambda \nabla T + \delta_p \nabla p_v \right) \cdot n \\
-\left( \delta_p \nabla p_v \right) \cdot n
\end{bmatrix} = \begin{bmatrix}
\alpha (T_a - T_s) + L_v \beta (p_v^{sat}(T_a) \varphi_a - p_v^{sat}(T_s)\varphi_S) \\
\beta (p_v^{sat}(T_a) \varphi_a - p_v^{sat}(T_s)\varphi_S)
\end{bmatrix}
\]
HT Modelling: Model VS Experiment

- Temperature (°C)
- Relative humidity (%)
- Heat Flow (W/m²)

--- Calculation with equilibrium model
HT Modelling: Model VS Experiment

- Calculation with equilibrium model
- Calculation with kinetic model
HT Modelling: Model VS Experiment

- Temperature (°C)
  - Right: Red
  - Middle: Green
  - Left: Blue

- Relative humidity (%)
  - Right: Red
  - Middle: Green
  - Left: Blue

- Heat Flow (W/m²)
  - Right: Red
  - Left: Blue

Graphs show data trends over time (days).
Calculation with kinetic model

HT Modelling: Model VS Experiment

- Better estimation than equilibrium model
- It remains some differences between model and experiments in desorption (effect of the hysteresis?)
Conclusions and perspectives

- **Experimental identification** of the hygrothermal behavior of hemp concrete

- This effect is non negligible and **is higher than 6W/m² for more than 1 day** in the experiment reported in this study

- A hygrothermal model that distinguish the effect of water in hemp particules and water in binder is developped

- This model leads to first promising results. It suggests that **all the water does not have the same impact on the hygrothermal behavior** of the material

- More studies on **effect of temperature** and **on sorption-desorption hysteresis** are in progress to improve the model

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