Hyro-thermal properties of flax fibers-raw earth building materials

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RESUME

L'objectif de cet article est d'explorer les propriétés hygrothermiques des matériaux composites terre crue-fibres de lin, en tenant compte de l'effet de différents paramètres tels que la teneur en eau, la teneur en fibres, la densité et l'arrangement des fibres. Ce matériau composite est destiné aux BTC (Briques de Terre Compactée). Des essais expérimentaux hygro-thermiques ont été réalisés sur les fibres de lin seules, la terre crue seule et les matériaux composites terre crue-fibres de lin. Les résultats montrent que la conductivité thermique et la capacité thermique des fibres de lin augmentent avec la densité et la teneur en humidité. De plus, quel que soit la densité et l'arrangement des fibres, des relations linéaires ont été trouvées pour la conductivité thermique, la capacité thermique et la perméabilité à la vapeur en fonction de la teneur en eau et la densité respectivement. De plus, l'ajout de fibres de lin a amélioré les propriétés hygrothermiques du matériau composite à base de terre crue.

Mots-clefs : Terre crue, fibres de lin, composite, hygro-thermique.

I. INTRODUCTION

In order to face the environmental and energy challenges, sustainable construction is one of the possible solutions. Sustainable construction requires the use of building materials with low environmental impact. Today, researchers are called upon to find solutions to reduce energy consumption in construction and to improve the hygrothermal comfort of buildings throughout their lifetime. Raw earth is considered as one of the materials to accomplish this challenge. It is an alternative building material that does not consume energy in terms of grey energy, with remarkable mechanical and hygrothermal performances. In this context, hygric and thermal transfers in raw earth materials have been evoked by several researchers. Simons et al (2015) measured the vapor resistance factor of a fiberless soil (0% fibers), with 3% and 6% barley straw. The samples are of densities 1990, 1520 and 1220 kg/m^3 respectively. The water vapour resistance factor of these three mixtures is 4.6 for 0% added fibres, 4.7 for 3% added fibres and 6.3 for 6% added fibres. It can be seen that the presence of fibers has a slight influence on the water vapor permeability of the earth-barley straw mix. Phung et al. (2019) evaluated the impact of water and fibers content on the thermal conductivity of different cob formulations. Straw fibers were incorporated into these soils in different amounts, ranging from 0 to 3%. The results revealed that, for both composite materials, the thermal conductivity decreased as the fibers and water contents increased. At 3% fibers content, the thermal conductivity was measured to be 0.65 ± 0.09 W/ (m. K) for the first soil and 0.59 ± 0.05 W/ (m. K) for the second one. Moreover, the water vapor permeability of the first composite raw earth material increased from 2.36×10^{-11} to 2.71×10^{-11} kg/ (m. s. Pa) as the straw content varied from 0 to 3%. Similarly, the second composite material exhibited an increase in water vapor permeability from 1.90×10^{-11} to 2.05×10^{-11} kg/ (m. s. Pa) when the straw content was varied from 0 to 3%. In addition, Mazhoud et al (2021) studied the effect of adding hemp fibers on the moisture and thermal properties of a clay material. The sorption isotherm, moisture buffering capacity and thermal conductivity were identified. According to their results, the composite material is classified as an excellent moisture and thermal regulator thanks to a range of moisture storage and thermal conductivity values from 2.07 to 2.33 g/ (m^2. %RH) and 0.089 to 0.12 W/ (m. K) respectively, depending on the hemp fibers content. Azil et al. (2022) conducted a study on the hygrothermal properties of cob and light-earth materials. From the results, the resistance factor to water vapor diffusion values for cob and light-earth are 12.9 and 8.2 respectively. Moreover, they assessed the impact of variations in temperature, relative humidity (RH), and wind velocity on thermal conductivity within a climatic chamber, simulating both winter and summer conditions. The study established a correlation between thermal conductivity, density, and water content. As the water content decreased, the thermal conductivity also decreased, ranging from 1.27 to 0.58 W/ (m. K) during winter and from 1.31 to 0.48 W/ (m. K) during summer for the cob and 0.4 to 0.13 W/ (m. K) during winter and from 0.5 to 0.13 W/ (m. K) during summer for the light-earth. From the results, the evolution of thermal conductivity as a function of density and water content are similar in summer and winter conditions. due to their high fibers content, soil-fibers mixtures present a lower thermal conductivity than Cob or earth bricks.

This study focuses on the hygro-thermal properties of raw earth-flax fibers composite building materials. This material is destined for BTC (Compressed Earth Bricks). First, experimental tests for measuring the thermal conductivity and the heat capacity of flax fibers alone were carried out showing the effect of water content and density on these parameters. Then, these same thermal properties were measured for the composite raw earth-flax fibers, considering separately the influence of the water content and the fibers content. Besides, this paper deals with the hygric characterization of fibers alone and of the composite raw earth-flax fibers. The results have shown that the raw earth-flax fibers composite material has an interesting heat and humidity regulating behavior.

II. Materials and methods

A. Materials

A.1 Flax fibers

The fibers used in this study are quintessential Normandy fibers, measuring 70mm in length. They are characterized by a Young's Modulus ranging from 40 to 80 MPa, an ultimate strain ε_u = 2.4 – 3.3 % and ultimate stress σu = 800 - 2000 MPa.

B. Silt

The silt used in this study is a local bio-based material from Gonfreville l'Orcher, Le Havre Normandy in France. It is composed of 67% of sand, 25% silt and 8% of gravel. It is classified as a silty sand SL (SM) soil according to the Unified Soil Classification System.

B. Methods

B.1 Samples preparation

B. 1. 1 Flax fibers samples

Flax fibers samples, measuring 40 mm in diameter and 70 mm in length, were putted in a cylindrical PVC tube with the same dimensions. The PVC tube is open at both ends to allow the flux diffusion. The density of flax fibers samples ranges from 100 to 400 kg/m³. This variation in density was investigated to assess its impact on the hygro-thermal properties of the flax fibers.

B. 1. 2 Silt-flax fibers samples

The samples have a diameter of 100 mm and thicknesses of 12 mm and 50 mm for the thermal and hygric tests, respectively. Silt, fibers and water were mixed and then placed in a Proctor mold to be compacted with a static press as shown in FIGURE 1. To investigate the effect of the water content on hygrothermal properties of the raw earth-flax fibers samples, all samples were compacted at γ_d = 17 kN/m³ and a water content of 14% which are values of the OPN (Normalized Proctor Optimum). Starting from this compaction state, the samples were wetted until full saturation (w_{sat}). Indeed, the fact that γ_d is constant for all the samples, results a constant ratio $\frac{G_s}{e}$ since $G_s = \frac{\gamma_s}{\gamma_w}$ and $e = \frac{\gamma_s}{\gamma_d} - 1$. This constant ratio is included in the equation $S_r = \frac{w \times G_s}{e}$ and it represents the slope of the curve $S_r = f(w)$ (as shown in FIGURE 2). Hence, considering $S_r = 1$, the saturation water content w_{sat} can be determined for a given γ_d. Then the samples were drained (they were placed in the oven at 50°C) until reaching the dry state (when the mass of the sample stabilizes) (FIGURE 3). Throughout these wetting and draining processes, at specific water content levels, the thermal properties of the raw earth-flax fibers samples were measured.

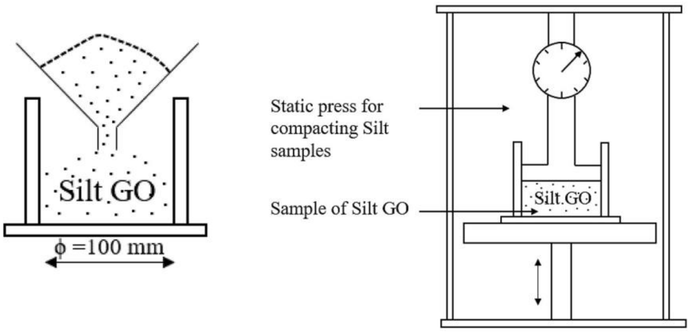


FIGURE 1: (a) Schema of mixed silt with water and versed in a Proctor mold, (b) Schema of sample compacting using a static press [Hamrouni et al., 2023]

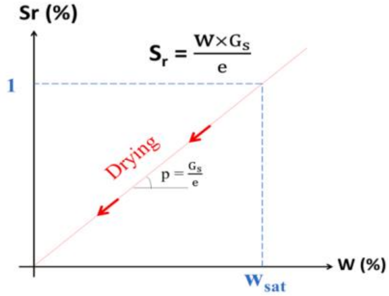


FIGURE 1 : Degree of saturation evolution versus water content [Hamrouni et al., 2024]

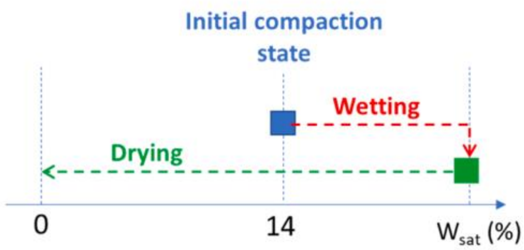


FIGURE 2 : Wetting/Drying processes for varying the water content of raw earth – flax fibers samples [Hamrouni et al., 2024]

B.2 Thermal method

To measure the thermal conductivity and heat capacity of flax fibers individually and raw earth–flax fibers composite samples, the thermal device “Tempos Meter” based on the unsteady state method was used according to the ISO 8894-2 standard. This method consists of introducing a heat source into the sample (either flax fibers or raw earth–flax fibers samples) and then the heat diffusion is recorded by the sensor is both source and sensor of heat. In fact, the temperature measured by the sensor is recorded as a function of time. Then, the thermal conductivity λ [W/ (m. K)] of the sample is calculated from the temperature variation in time and the heat flux**:**

$$\lambda = \frac{q}{4 \times \pi \times a} \quad \textbf{(1)}$$

- q : Heat flux [W/m]
- λ : Thermal conductivity [W/ (m. K)]
- a: slope of the curve of temperature evolution as a function of ln(t) [FIGURE 4]

The thermal conductivity is the slope of the temperature evolution as a function of time (FIGURE 3). The “Tempos Meter” device is presented in FIGURE 5.

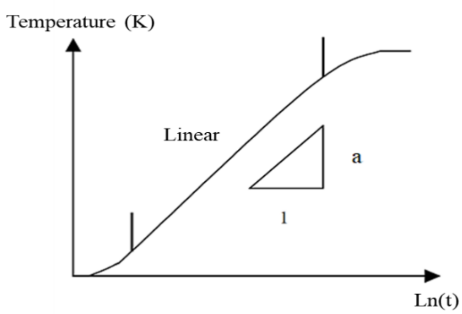


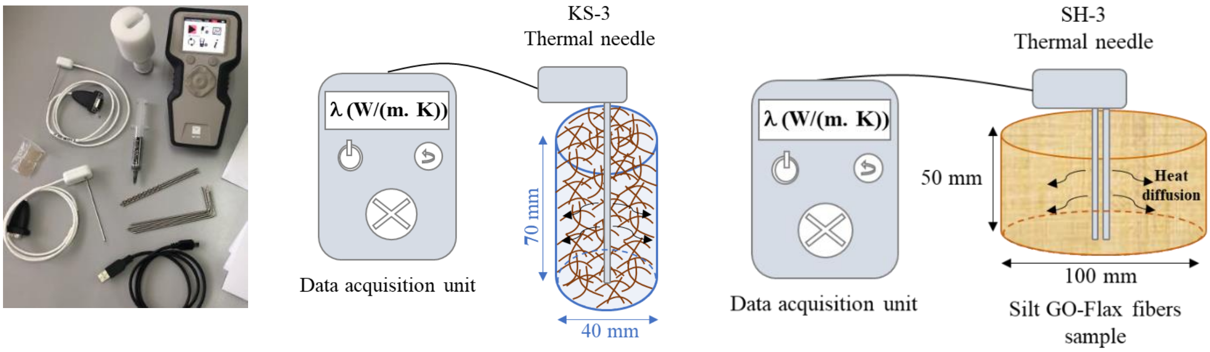
FIGURE 3 : Linear relationship between the temperature and ln(t)

After this, the thermal diffusivity D [m²/s] and the heat capacity c [MJ/ (m³. K)] can be deduced from the equations bellow:

$$\begin{cases} \Delta T = T - T_0 = \left(\frac{q}{4\,\pi\,\lambda}\right) \ln(t) + C \\ c = \frac{\lambda}{D} \end{cases} \quad \textbf{(2)}$$

- T : Temperature [K]

- T_0 : Initial temperature [K]
- t : Time [s]
- $C = -\left(\frac{q}{4\,\pi\,\lambda}\right)\left(\gamma + \ln\left(\frac{r^2}{4\,D}\right)\right)$: Constante [K]
- γ = 0.5772: Euler's constant
- r : Radial distance of heat diffusion [m]



(a) (b) (c)

FIGURE 4 : (a) Tempos Meter device, (b) measurement of thermal properties of flax fibers and (c) measurement of thermal properties of raw earth-flax fibers samples

B.3 Hygric method

To measure the water vapor permeability of the raw-earth samples, the Gravitest device were used. The Gravitest is an automated device for measuring water vapor permeability based on the cup method according to the NF EN ISO 12572 standard (FIGURE 6). The principle of this device involves imposing a unidirectional relative humidity gradient under isothermal conditions through a sample. The Gravitest has a capacity for nine cups and represents a climate-controlled chamber in terms of humidity and temperature, with a rotating platform containing the cups. A salt-saturated solution placed at the bottom of the cup allows for imposing a different relative humidity than that of the chamber, leading to a humidity gradient. The tests were carried out using wet cups. At predetermined time intervals, the cups rest on a scale with a precision of 10^{-4} g to measure the variation in vapor mass exchanged during the test. The sample size is 80 mm in diameter and 12 mm in thickness. Recording the curve of vapor mass variation over time allows deducing the vapor permeability δ_v [kg/ (m. s. Pa)] of the sample using Fick's law:

$$\delta_v = e\,\frac{j_v}{\Delta p_v} = e\,\frac{j_v}{p_{v2} - p_{v1}} \qquad (3)$$

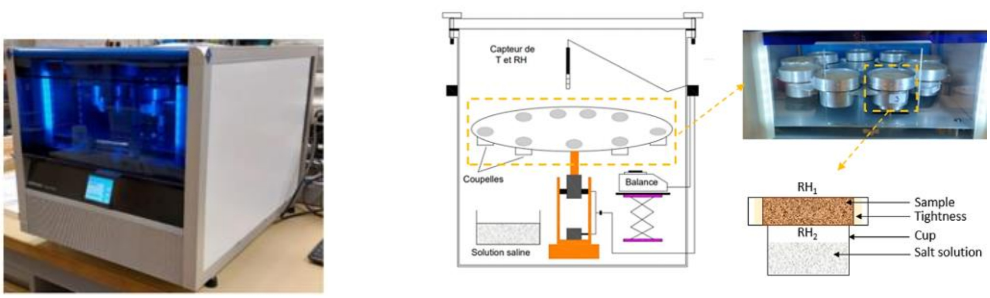


FIGURE 5: Gravitest device

e: sample's thickness [m]
j_v : water vaport flux densité [kg/ (m². s)]
p_v : water vapor pressure [MPa]

III. Results and discussions

A. Thermal results

A. 1 Flax fibers

The effect of water content and fibers density on the thermal conductivity λ [W/ (m. K)] and heat capacity c [MJ/ (m³. K)] of flax fibers was studied using the unsteady state method. For this, the fibers were firstly saturated with water, then, they were putted in centrifuge controlled in speed to vary the water content from saturation to the dry state. FIGURE 7 illustrates the results of thermal conductivity evolution as a function of water content for different densities. The thermal conductivity increases linearly with water content, regardless of the fibers density. As an example, for fibers with a density of 400 kg/m³, the thermal conductivity increases from 0.067 W/ (m. K) to 0.36 W/ (m. K). Indeed, the observed phenomenon can be due to the high heat-diffusing capacity of water, as highlighted by Kallel (2016). The more humid the fibers become, the greater their ability to conduct heat. Moreover, for a given water content, more the density increases, more the fibers conduct the heat. For w ≈ 60%, the thermal conductivity varies from 0.058 to 0.24 W/ (m. K). This phenomenon occurs because the increase in density leads to a reduction in the amount of air between the fibers. As air is a better insulator (λ = 0.025 W/ (m. K), Kallel, 2016) compared to flax fibers, the denser fibers become more efficient in conducting heat.

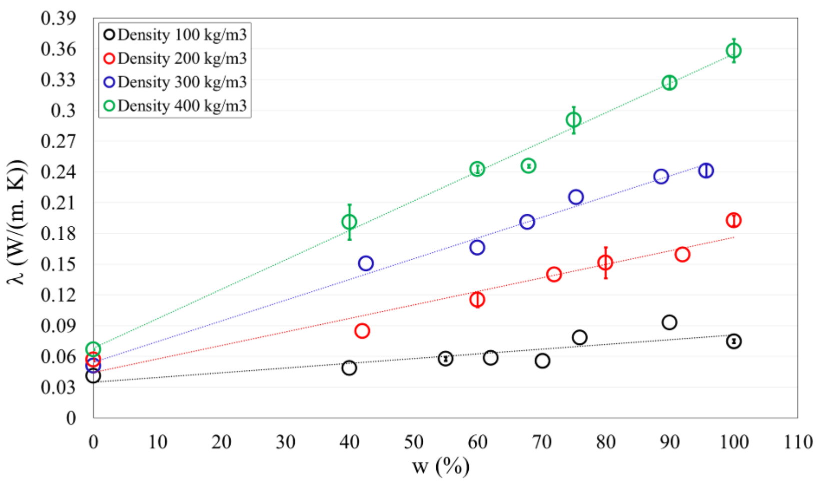


FIGURE 6 : Flax fibers thermal conductivity evolution as a function of water content

The same samples were used to measure their heat capacity using the Tempos Meter device. The results illustrated in FIGURE 8 A linear relationship between heat capacity and water content were observed. For a density of 400 kg/m³, the heat capacity rises from 0.57 to 3,63 MJ/ (m³. K) when water content increases from 0 to 100%. Furthermore, as the density of the samples increases, there is a proportional increase in heat capacity.

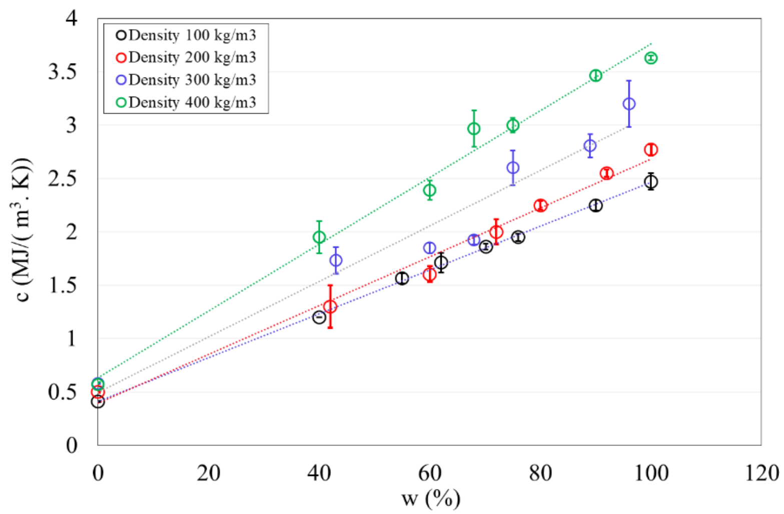


FIGURE 7 : Flax fibbers heat capacity evolution as a function of water content

A. 2 Silt-flax fibers composite material

In this section, the effect of the water content on the thermal conductivity of the composite silt-flax fibers were studied for 0%, 1% and 3% of fibers contents. The samples density increases from 17 to 15.6 kN/m³ when the fibers content in the raw earth samples increases from 0 to 3%. The increase of the thermal conductivity as a function of water content was observed, as shown in FIGURE 9. In the case of silt reinforced with 3% of flax fibers for example, the thermal conductivity increases from 0.6 W/ (m. K) to 1.85 W/ (m. K) when the water content increases from 0 to w_{sat} = 26%. This is explained by the significant difference between the thermal conductivities of water and of air. In fact, for water λ = 0.62 W/ (m. K) whereas the thermal conductivity of air is λ = 0.025 W/ (m. K) (Kallel, 2016).

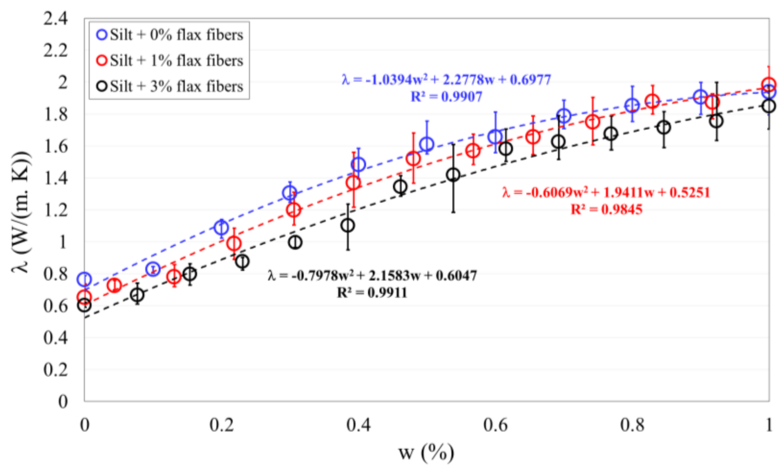


FIGURE 8 : Raw earth-flax fibers thermal conductivity evolution as a function of water content

FIGURE 10 shows the evolution of the heat capacity as a function of water content for fibers contents. Initially, it was anticipated that an increase in fibers content would lead to an improvement in heat storage capacity with an increase in saturation. However, based on the limited range of three considered fibers contents, the expected conclusion does not seem to be definitively supported. In fact, in the case of a 1% fibers content, the heat capacity increases from 1.47 to 3.08

MJ/ (m³. K) when the water content ranges from 0 to w_{sat} = 20%, whereas, when the fibers content is 3%, the heat capacity increases from 1.39 to 2.69 MJ/ (m³. K).

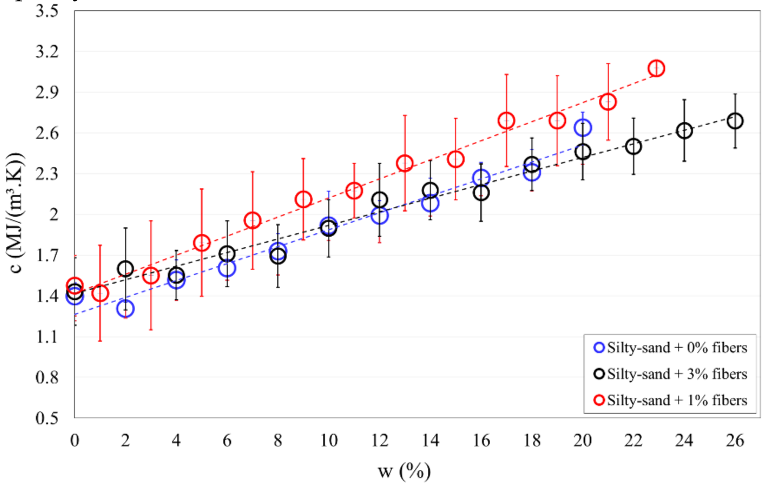


FIGURE 10 : Raw earth-flax fibers heat capacity evolution as a function of water content

B. Hygric results

B. 1 Flax fibers

In order to evaluate the anisotropy of the capacity of flax fibers to diffuse vapor, the water vapor permeability of flax fibres was evaluated for different directions (longitudinal, transversal and random) and densities (100, 200, 300, 400 and 700 kg/ m³). The results showed in FIGURE 11 reveal that as the density of fibers increases, the water vapor permeability decreases. In the case of longitudinal fibers (aligned with the direction of vapor flow), the permeability ranges from 1.11×10^{-10} to 6.4×10^{-11} kg/ (m. s. Pa) across a density range of 100 to 700 kg/m³. A more significant reduction is observed for transverse fibers (perpendicular to the direction of vapor flow), where permeability decreases from 6.83×10^{-11} to 3.9×10^{-11} kg/ (m. s. Pa). Regarding random fibers, vapor permeability varies from 1.06×10^{-10} to 4.95×10^{-11} kg/ (m. s. Pa) within the same density range. Additionally, the results underscore the influence of fibers orientation on their ability to allow the passage of water vapor. Fibers aligned with the vapor flow exhibit higher permeability to water vapor (Hamrouni et al., 2023).

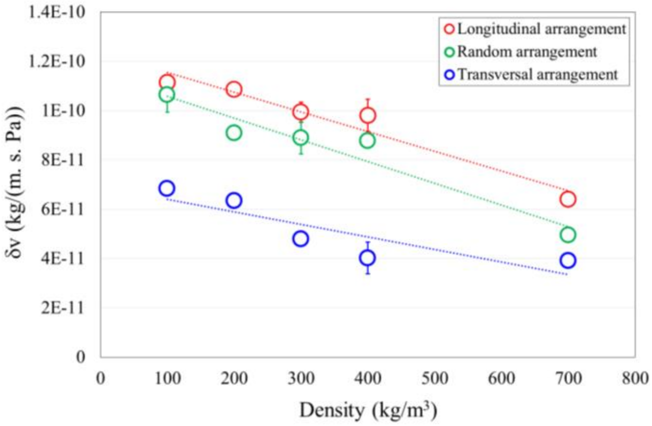


FIGURE 11 : Flax fibers water vapor permeability evolution as a function of density for different arrangements

B. 2 Silt-flax fibers composite material

The water vapor permeability of silt GO reinforced with random flax fibers is determined for different percentages of fibers and arrangements. FIGURE 12 illustrates the results and show that the water vapor permeability of raw earth-flax fibers composite materials increases with fibers content. It increases from 2.73×10^{-11} to 3.9×10^{-11} kg/ (m. s. Pa) when the fibers content ranges from 1 to 5%. These results can be explained by the decrease of the composite raw earth-flax fibers density with the increase of added fibers content which makes the composite more breathable regardless the water vapor.

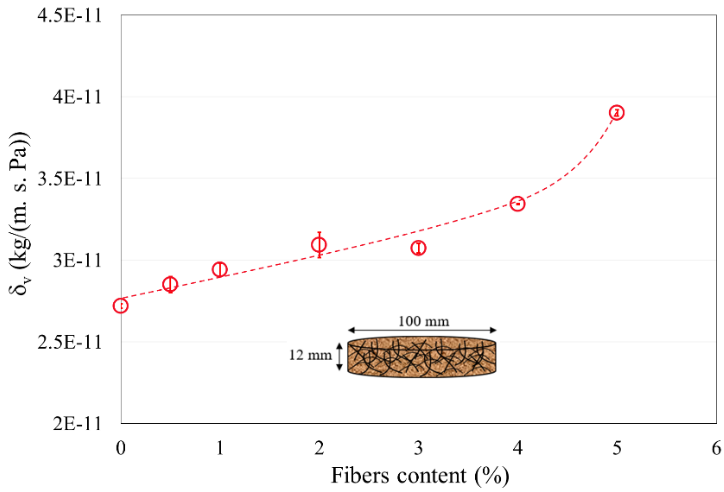


FIGURE 12 : Flax fibers water vapor permeability evolution as a function of density for different arrangements

IV. CONCLUSION

The results obtained in this study show that:

- The thermal conductivity and the heat capacity of flax fibers alone exhibit a linear relationship as a function of water content, regardless of sample density,
- The water vapor permeability of flax fibers decreases with increasing of density regardless of their arrangement (transversal, longitudinal or random). Besides, they highlighted the effect of the arrangement on the ability of fibers to diffuse the vapor.
- The thermal conductivity of the composite increases with the increase of the water content whatever the percentage of added fibers,
- The effect of flax fibers on the heat capacity of the raw earth-flax fibers is no significant,
- The addition of random flax fibers to the raw earth material improves the ability of the material to diffuse the water vapor. In fact, the water vapor permeability of the composite material silt-flax fibers increases with the increasing of fibers content,
- The hygrothermal properties of flax fibers are very interesting and allowing a good hygrothermal comfort,

- The composite of raw earth and flax fibers exhibits significant hygrothermal behavior due to its insulating and breathable properties.
- The mechanical behavior of the composite material remains to be studied in the future.

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