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Hemp-Straw Composites: Thermal And Hygric Performances

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Abstract

The European ISOBIO project aims to develop new bio-based building insulating materials which contribute to reduce environmental impacts of buildings. The developed materials shall have low embodied energy and low carbon footprint and shall contribute to reduce energy needs of buildings and to ensure high hygrothermal comfort of users. This study investigates the valuation of agro resources as bio-based aggregates and as binding material to produce wholly bio-based composites. The developed composites are made of hemp shiv glued with wheat straw. After a feasibility study which investigates several ways to use wheat straw as a gluing material and several hemp to wheat straw ratio, three hemp-straw composites are selected. Specimens are produced to characterize thermal and hygric properties of developed composites. They show interesting thermal and hygric properties as they have low thermal conductivity (0.071 to 0.076 W/(m.K)) and they are excellent hygric regulators (MBV > 2 W/(m².%RH)).

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Keywords: Bio-based material, Conductivity, Moisture buffer value

1. Introduction

This study is part of the European ISOBIO project which aims to develop new bio-based building insulating materials. The aim is to reduce the embodied energy of materials while also reducing the total energy needs of buildings and allowing high hygrothermal comfort of users. Two kinds of products will be developed within ISOBIO project: insulating panels and bio-based insulating composites to be implemented on-site. The project focuses on the

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valuation of agro resources as bio-based aggregates or as binding material. Five agro resources are considered in ISOBIO project: wheat, rape, hemp, flax and corn cob. They are available as straw, fiber, shiv or dust.

This study investigates the development of bio-based composites to be used to produce insulating panels. This first investigation considers only one kind of bio-based aggregate (hemp shiv) and one kind of agro resource as binding material (wheat straw). The aim is to attest the feasibility of such composites and to qualify their hygrothermal performances, in link with the objectives in term of reduction of energy needs of buildings and in term of hygrothermal comfort of users.

2. Materials and methods

2.1. Developed materials

This study focuses on the valuation of agro resources as bio-based aggregates and as binding material to produce a wholly bio-based composite.

For this first investigation, hemp shiv are used as aggregates and wheat straw is considered as gluing material. Polysaccharide is also used as reference gluing material.

Actually, hemp shiv are commonly used to produce hemp composites with lime based binders or, more recently, with PLA (Polylactic acid) or with starch [1] [2] [3]. The aggregates used to produce the composites are commercial hemp shiv (Chanvribat from LCDA Les Chanvrières de l'Aube – France). Their bulk density is about 100 to 110 kg/m^3. Their particle size distribution, measured by sieving, are given fig. 1. The mean width of shiv (W50) is 4 mm for Chanvribat and the width/length ratio is about 4.

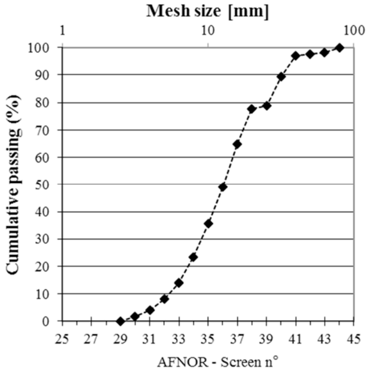

Fig. 1 Particle Size Distribution of Chanvribat hemp shiv

As mentioned in [4], the lignin within the straw and other herbaceous crops acts together with hemicellulose as a perfect natural adhesive for straw and any other cellulosic materials. Thus, wheat straw is expected to be convenient as binding material with hemp shiv. In this study, several ways to use wheat straw as a gluing material are tested, varying the hemp to wheat straw ratio and thermal activation step. Firstly, wheat straw is finely chopped and mixed with hemp shiv. The dry mix is then moistened and processed under pressure and heat. It is shown (fig. 2a) that to ensure good cohesion using the same thermal treatment, a minimum of 15% of wheat straw is required in the dry mix. Then, the selected mix proportioning consists in 80% of hemp shiv and 20% of straw powder.

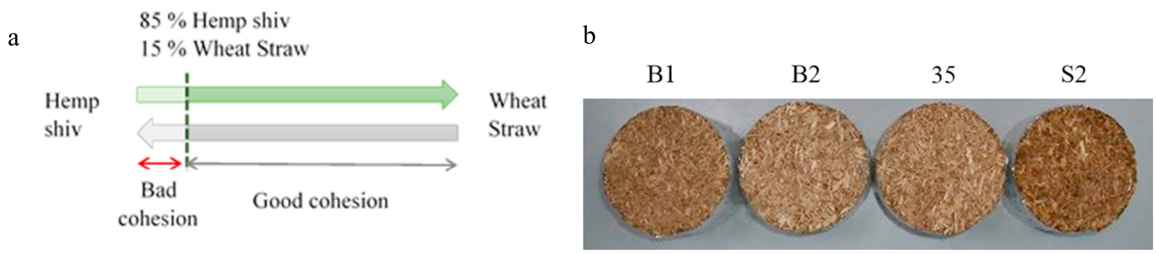

Fig. 2 : (a) Cohesion versus formulation of composites (b) Developed composites

Once the gluing effect of straw powder is attested, complementary tests are made using a wheat straw infusion. For confidentiality reasons, no more details are given on the production process. After production process optimization, composite specimens are produced. Four kinds of composites are considered: three hemp-straw composites and one hemp-polysaccharide composite (Table 1). For each composite, three specimens 10 centimeters in diameter and about 7 cm high are produced (fig. 2b). The developed composites show quite low density, ranging from 166 to 188 kg/m^3 (Table 1). For the same process, the composite with highest hemp content show lowest density (B2 vs B1).

Table 1. Formulation of composites (ratio of dry mix) and apparent density.

Ref.	Hemp shiv	Milled wheat straw	Infused Wheat straw	Polysaccharide	Apparent density		
					$\rho_{av.}$ (kg/m³)	σ_ρ (kg/m^3)	CV_ρ (%)
35	80 %	20 %	-	-	179.8	13.2	7.4
B1	80 %	-	20 %	-	187.9	3.6	1.9
B2	85 %	-	15 %	-	165.9	3.4	2.0
S2	90.5 %	-	-	9.5 %	181.6	2.8	1.5

2.2. Thermal characterization

The thermal characterization is based on the measurement of thermal conductivity after stabilization at 23°C, 50%RH in climate chamber. In order to limit water migration during the test, the measurement is performed with a transient method: Hot Wire (Fig. 3a). This method is based on the analysis of the temperature rise versus heating time (fig. 3b).

$$\Delta T = \frac{q}{4\,\pi\,k}(\ln(t) + C) \tag{1}$$

Where ΔT is the temperature rise (°C), q is the heat flow per meter (W/m) and k is the thermal conductivity (W/(m.K)), t is the heating time (s) and C is a constant including the thermal diffusivity of the material.

The measurement is performed with the sensor sandwiched between two specimens. The heat flow and heating time are chosen to reach high enough temperature rise (>10°C) and high correlation coefficient (R^2) between experimental data and fitting curve. In this study, the commercial CT Meter device is equipped with a five centimeters-long hot wire. The power used is 142 mW and the heating time is 120 seconds. These settings allow meeting the previous requirements (temperature increase higher than 10°C and high R^2 value). According to the manufacturer, the expected accuracy is thus better than 5%. For each formulation, three pairs of specimen are considered by combining differently the three specimens (A&B, A&C, and B&C). The thermal conductivity of a pair of specimens is the average of three values with a coefficient of variation (ratio of the standard deviation to the average value) lower than 5%. The thermal conductivity of a formulation is the average of the values of the three pairs of specimens.

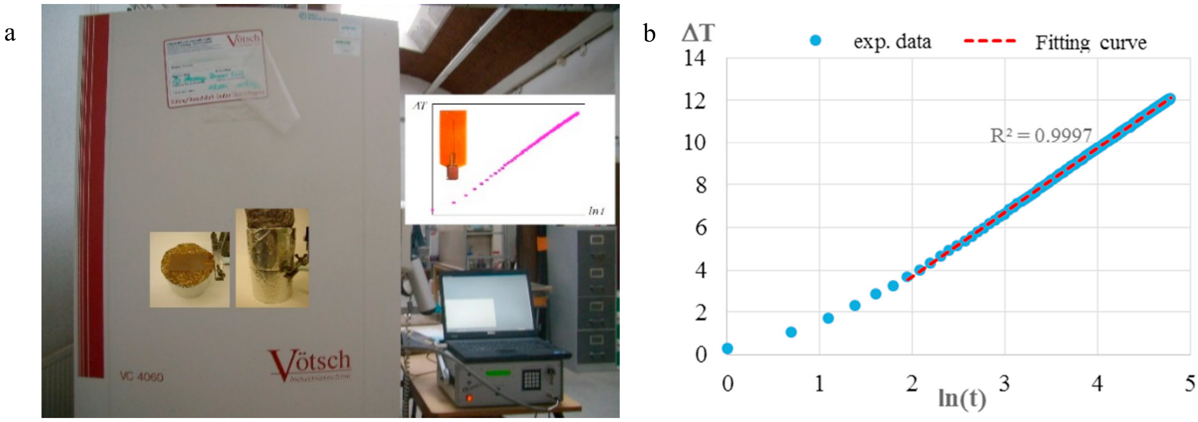

Fig. 3 : (a) Experimental device for the measurement of Thermal Conductivity.(b) Example of increase of temperature versus neperian logarithm of time

2.3. Hygric characterization

The hygric characterization is based on the measurement of the moisture buffer value (MBV) of materials which characterizes their ability to moderate the variations of indoor humidity in buildings.

The moisture buffer value is measured following the Nordtest protocol [5]. Specimens are sealed on all but one surfaces. After stabilization at 23°C, 50%RH, specimens are exposed to daily cyclic variation of ambient relative humidity (8 hours at 75%RH and 16 hours at 33 %RH) in a climate chamber (Vötsch VC4060). The moisture buffer value is then calculated from their moisture uptake and release with:

$$MBV = \frac{\Delta m}{A(RH_{high} - RH_{low})} \tag{2}$$

where MBV is the moisture buffer value (g/(m². %RH)), Δm is the moisture uptake/release during the period (g), A is the open surface area (m^2), $RH_{high/low}$ is the high/low relative humidity level (%).

Temperature and relative humidity are measured continuously with sensor SHT75 and with sensor of the climatic chamber; the air velocity in the surroundings of the specimens ranges from 0.1 to 0.4 m/s for horizontal velocity and is lower than 0.15 m/s for vertical one.

The specimens are weighed out of the climatic chamber five times during absorption period and two times during desorption one. The readability of the balance is 0.01 g, and its linearity is 0.01 g. The accuracy of the moisture buffer value is thus about 5%.

For each formulation, the MBV is measured on the three specimens and the MBV of the formulation is the average value of the three specimens.

3. Results

3.1. Thermal characterization

Fig. 3b gives an example of the increase of temperature versus neperian logarithm of heating time during the measurement with hot wire. Table 2 and fig. 4 provide the average value, the standard deviation and the coefficient of variation of thermal conductivity of studied composites.

For all tests, the correlation coefficient between experimental data and fitting curve is very close to one, higher than 0.9997. More, for each composite, experimental values are very close to each other. The coefficient of variation is lower than 3 % between the nine measurements (three pairs and three measurements by pair). This induces great confidence in thermal conductivity values.

Table 2. Thermal Conductivity of composites: average value (k_{av}), standard deviation (σ) and coefficient of variation (CV).

	35	B1	B2	S2
k_{av} (W/m/K)	0.0747	0.0759	0.0714	0.0736
σ (W/m/K)	0.0016	0.0019	0.0013	0.0020
CV (%)	2.09	2.56	1.82	2.70

The thermal conductivities of developed composites, after stabilization at 23°C, 50%RH, range from 0.071 to 0.076 W/(m.K). As shown on fig. 4, the thermal conductivity increases with density. Whatever the kind of composite (glued with straw or with polysaccharide), the thermal conductivity shows the same tendency. So, the way of gluing hemp shiv doesn't seem to much impact thermal conductivity.

Compared with thermal conductivity obtained with hemp-lime composites, these values are lower, mainly thanks to lower density. Actually, for hemp-lime composites, Collet and Prétot [6] found thermal conductivity of 0.093 and 0.120 W/(m.K) at 23°C, 50%RH, with respective density of 260 and 390 kg/m^3. De Bruijn and Johansson [7] studied the thermal conductivity of two lime-hemp mixes at 15%RH and 65%RH. At 65%RH, they give thermal conductivity values of 0.116 and 0.100 W/(m.K) when the densities are respectively 394.8 and 298.1 kg/m^3. For hemp-PLA composite, the thermal conductivity ranges from 0.085 W/(m.K) at 260 kg/m^3 to 0.120 W/(m.K) at 350 kg/m^3 [2]. These values meet the same trend curve as developed composites. Moreover, the developed composites show thermal conductivity close to the value obtained by Tran le [3] on hemp-starch composite. Actually, at dry state, he founds a thermal conductivity of 0.062 W/(m.K) with a density of 176 kg/m^3. Finally, the main impacting factor on thermal conductivity of hemp composites is thus the density of composite.

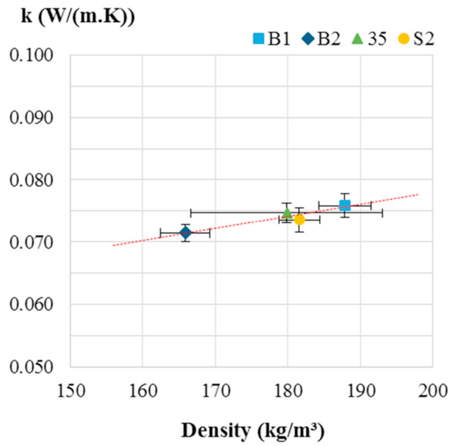

Figure 4 :Thermal conductivity of composites (W/(m.K)) versus density

3.2. Hygric characterization

The ambient relative humidity and temperature in the climate chamber is recorded during the test. The mean value of relative humidity (RH) is slightly lower than 75 % during absorption (about 72.9 %) and slightly higher than 33% during desorption (about 33.3%) because the door of the climate chamber is regularly open to weigh specimens.

Fig. 5a gives as example the moisture uptake and release of specimen S2-A. For all specimens, the change in mass shows less than 5 % of discrepancy for cycles 3 to 5. The moisture buffer value is thus calculated from cycles 3 to 5.

Table 3 and fig. 5b summarize the Moisture Buffer Values obtained in absorption, desorption and on average for the four kinds of composites. The standard deviations are very low, leading to coefficients of variation lower than 2% (and generally lower than 1 %).

Table 3. Moisture Buffer Value of composites in absorption, desorption and average: average value and standard deviation.

	35	B1	B2	S2
MBV abs (g/(m².%RH))	2.23 ±0.02	2.17 ±0.03	2.21 ±0.02	2.36 ±0.01
MBV des (g/(m².%RH))	2.30 ±0.02	2.23 ±0.02	2.24 ±0.01	2.47 ±0.02
MBV av. (g/(m².%RH))	2.27 ±0.02	2.20 ±0.03	2.22 ±0.02	2.42 ±0.01

The average MBV ranges from 2.20 to 2.42 g/(m².%RH). According the Nordtest classification [5], all these composites are thus excellent hygric regulators (MBV>2 g/(m².%RH)).

As shown on fig. 10, the Moisture Buffer Value is not impacted by the density of composite. On the opposite, the three composites glued with straw have similar MBV while the composite made with polysaccharide shows slightly higher MBV. Thus, the kind of binder slightly impacts MBV.

Compared with other hemp composites, the developed composites are in the high range of MBV. For hemp-lime composite MBV ranges from 1.94 to 2.24 g/(m².%RH) [8][2], while for hemp-PLA, the MBV is about 1.77 g/(m².%RH) [2].

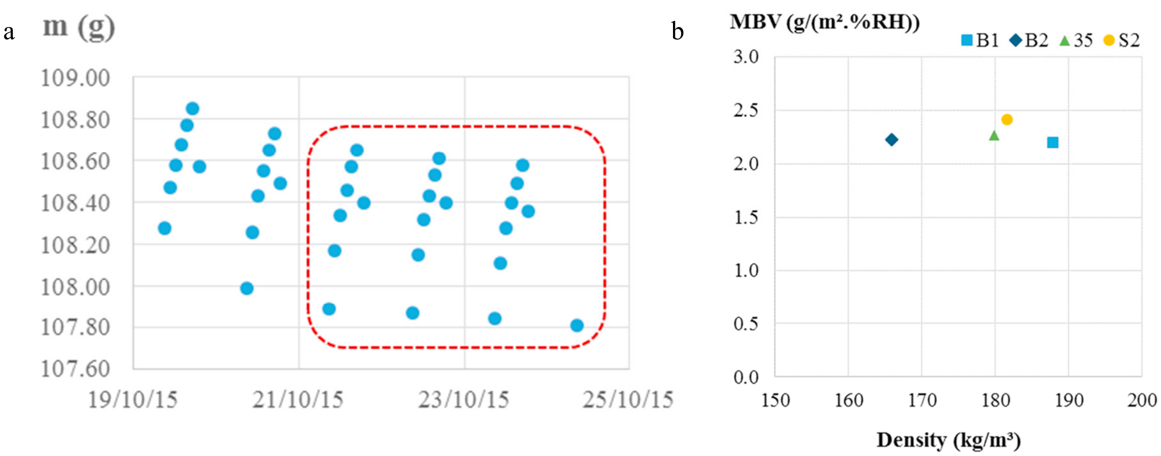

Figure 5 (a) Moisture uptake and release for specimen S2-A (b) Average Moisture Buffer Value of composites (g/(m².%RH)) versus density

4. Conclusion

This study shows that wheat straw can be used as gluing material to produce hemp-straw composites. To ensure good cohesion, the dry mix should include 15% at least of wheat straw (and 85 % of hemp shiv). The density of developed composites ranges from 165 to 190 kg/m^3. The thermal properties are interesting, as the thermal conductivity of developed composites is quite low (0.071 to 0.076 W/(m.K)). More, the developed composites are excellent hygric regulators, with MBV higher than 2.20 g/(m².%RH).

These results are thus encouraging. They meet the objectives of the project as the developed composites are fully bio-based and show thermal and hygric performances which contribute to reduce energy needs of building and to ensure hygrothermal comfort of users.

The mechanical characterization of composites will complete this study to show the full efficiency of the proposed solution.

5. Acknowledgments

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