EFFECT OF COMPACTION ON THERMAL AND HYGRIC PROPERTIES OF HEMP COMPOSITES

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Abstract

This study is part of the European ISOBIO project which aims to develop new bio-based building materials, through the valuation of agro-resources as bio-based aggregates or as green binders. Previous studies investigated several types of aggregates and binders. They highlighted that the main impacting factor on thermal conductivity was the density of composite. The aim of this paper is to investigate the effect of density on hygric and thermal properties of composites, using the same formulation. The composites are made of hemp shiv and black liquor. Specimens are produced with the same hemp to black liquor ratio but different compaction stress. The effect of compaction on bulk density, thermal conductivity and moisture buffer value (MBV) is analyzed. More it is shown that it is possible to reach low enough thermal conductivity to be considered as building insulating material, regarding the AFNOR NF 75-101 French standard [AFNOR 1983]. Thanks to this study, target density, and thus compaction stress to be applied, can be identified regarding thermal conductivity and MBV.

Keywords:

Agricultural waste valuation, Thermal insulation materials, Bio-based composites, Hemp shiv, Black liquor, Moisture Buffer Value, Thermal conductivity

1 INTRODUCTION

The agricultural waste valuation is one of the current challenges [Fava 2015; Kretschmer 2012; Searle 2013] in the field of bio-based construction material. One way of waste valuation is the production of bio-based panels with high insulating properties, low embodied energy, low embodied carbon and high hygrothermal efficiency [Adamczyk 2017; Liu 2017]. As part of the ISOBIO project, the developed panels are ecofriendly composites made of bio-based aggregates coming from local agriculture and green binders [ISOBIO 2015]. The adhesion between the aggregates and the binder is obtained by using thermal and mechanical treatment.

A previous study, presented in [Viel 2017], was performed with two types of aggregates: hemp shiv and corn cob residues, and five types of green binders: corn cob extract, flax fines extract, black liquor, Lignin BioChoice and PLA. After mixing, the composites are produced by compacting and then heating. This study showed that the developed composites show low thermal conductivity (ranging from 0.067 to 0.148 W/(m.K)) and excellent moisture buffering ability (MBV > 2 g/(m².%RH)). More, the thermal conductivity increased linearly with density, whatever the kind of aggregate and of binder.

Others studies also showed similar results. Indeed, composites based on bamboo fibers and bio-glues developed by Nguyen et al have an interesting thermal conductivity (ranging from 0.055 to 0.88 W/(m.K)) and good moisture buffer value (MBV > 1.7 g/(m².%RH)) [Nguyen 2017]. The composites based on hemp shiv and starch developed by Maalouf et al or by Bourdot et al are also good insulating panels (λ ranging from 0.063 to 0.74 W/(m.K)) and excellent hygric regulators (MBV > 2.4 g/(m².%RH)) [Bourdot 2017; Maalouf 2014]. Whereas the composites based on lavender stalks and mineral pozzolanic binder developed by Ratiarisoa et al have mainly an excellent moisture buffer value MBV > 3.5 g/(m².%RH)) [Ratiarisoa 2016].

The density of composites is impacted by the compaction stress applied during their production, among other factors. The influence of compaction on physical properties of composites has been shown by [Balčiūnas 2016].

Thus, this study investigates the effect of compaction on density, thermal and hygric performances of hemp composites. The composites are made with the same hemp shiv to black liquor ratio but seven different compaction stresses.

2 MATERIALS AND METHOD

2.1 Raw materials

The composites are produced with Biofibat® hemp shiv (commercial hemp shiv) and black liquor.

The Biofibat® hemp shiv are provided by CAVAC (agricultural cooperative, France), they are from the 2016 year production.

The length of hemp shiv ranges from l_{10}=5.5 mm to l_{90} = 19.4 mm, with an average value l_{50} of 11.5 mm (Fig. 56). The width ranges from ranges from w_{10}=1.7 mm to w_{90} = 4.8 mm, with an average value w_{50} of 2.9 mm. The elongation ratio (length/width) ranges from 2.2 to 6.5.

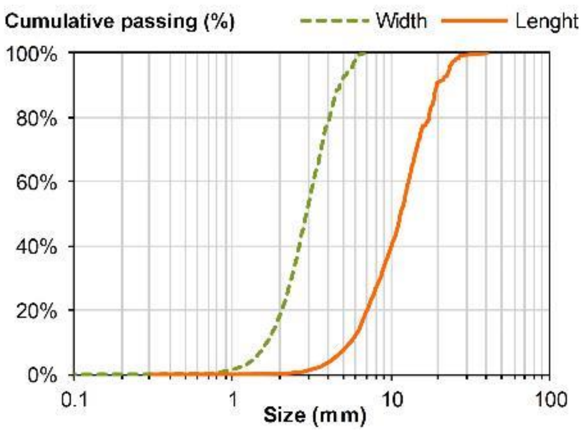

Fig. 56: Particle Size Distribution of hemp shiv.

The black liquor used here as binder, is a by-product from the kraft paper industry. It is composed of about 70 % dry matter. Its chemical composition mainly includes lignin and inorganic components which mainly come from the paper industry process. It also includes few polysaccharides and some aromatic and aliphatic components (Tab. 19). Thus, it has the advantage of having very interesting adhesive properties and protecting ligno-cellulosic resources from fungal development due to its composition [Durmaz 2015].

Tab. 19: Chemical composition of kraft black liquor.

Components	Content (%)
Alkali lignin	14.1
Carboxylic acid	1.1
Acetic acid	4.0
Formic acid	10.0
Hydroxide acid	2.8
Polysaccharides	5.4
Sulfate	3.4
Sulfur	8.3
Sodium	15.9
Other components	35.0

2.2 Composites

All the composites are made with a black liquor to hemp shiv dry mass ratio of 15%.

For preparation, the hemp shiv are mixed with the black liquor. Three specimens are produced from the same batch, by dividing into three equal parts (A, B and C) and each part is introduced in one of the three cells of a mold. Each part is compacted 5 times in the mold and then placed in an oven at 190 °C for 2 h. The three specimens of dimensions 100×100×50mm3 are demolded once they cool down to room temperature (Fig. 57).

To study the effect of compaction on multi-physical properties, seven compaction levels are considered: 15.6, 31.2, 62.5, 125, 250, 500 and 1000 kPa.

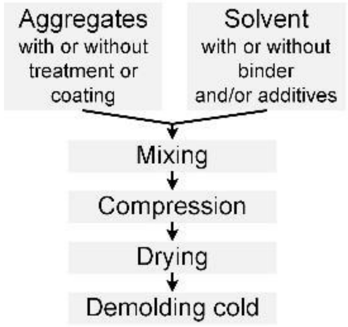

Fig. 57: Flow chart of composites production.

2.3 Characterization methods

Density

The density is calculated from size and weight of specimens. The three dimensions are measured with an electronic caliper (0.1 mm) and weight with an analytical balance (readability = 0.01 g, reproducibility = 0.01g, linearity = 0.02g). Each dimension is the average of four values.

Thermal characterization

The measurement of thermal conductivity is performed with a transient method: Hot Wire, following the method described by Collet and Pretot [Collet 2014]. The measurement is realized with the commercial CT Meter device equipped with a five-centimeter long hot wire. The power is 142 mW and the heating time is 120 seconds.

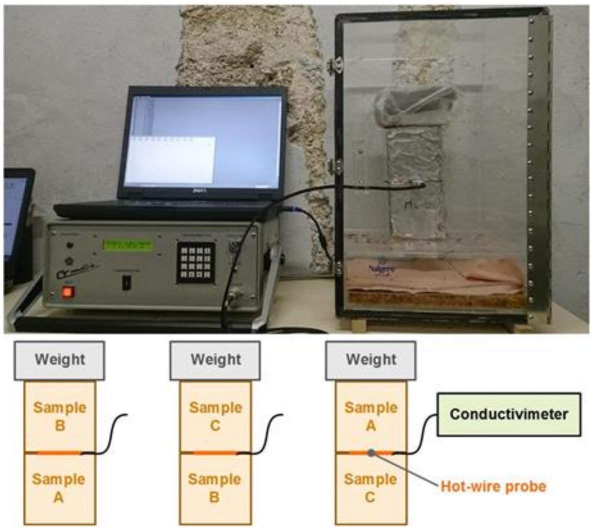

Fig. 58: Experimental thermal conductivity device.

Before taking the measurements, the specimens are first dried at 60°C in an oven. Then, the measurements are performed after weight stabilization at 23°C at dry state in desiccator and after weight stabilization at 23°C, 50 %RH in climate chamber. For each formulation, three pairs of specimens (A&B, A&C, and B&C) are measured. The thermal conductivity of a pair is the average of three values with a coefficient of variation lower than 5 %. The thermal conductivity of a composite is the average of the values obtained for the three pairs (Fig. 58).

Hygric characterization

The hygric performance is characterized by the measurement of the moisture buffer value (MBV) of composites. This value characterizes the ability of the materials to moderate the variations of indoor humidity in buildings.

The moisture buffer value is performed following the Nordtest protocol [Rode 2005]. After the stabilization of specimens 10 x 10 x 10 cm³ at 23°C, 50 %RH and their sealing on all their surfaces except one, specimens are exposed for 8 hours at 75 %RH and for 16 hours at 33 %RH during 5 days in a climate chamber (Vötsch VC4060). The specimens are regularly weighed: five times during the absorption period and two times during the desorption one. The air velocity in the climate chamber is consistent with the recommendations of the Nordtest protocol (lower than 0.15 m/s [Rode 2005]). Then, the moisture buffer value is determined according to the following equation:

$$MBV = \frac{\Delta m}{A.(RH_{high} - RH_{low})} \quad (1)$$

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 (m²), $RH_{high/low}$ is the high/low relative humidity level (%).

For each formulation, the MBV is the average of the values obtained for the three specimens.

3 RESULTS

3.1 Density

The apparent density of developed composites ranges from 128 to 247 kg/m³ (Tab. 20). It increases with the compaction pressure following the equation given on Fig. 59 with a high correlation coefficient. So, it is possible to identify the compaction pressure to apply for a target density.

Furthermore, the density of composites increases by 7 % between the dry point and the wet point (at 23°C, 50%RH).

Tab. 20: Effect of compaction on density of composites (average value and standard deviation).

σ_p kPa	$\rho_{23°C, dry}$ (kg/m³)	$\rho_{23°C, 50\%RH}$ (kg/m³)
15.6	127.6 ± 3.7	135.8 ± 3.7
31.2	135.3 ± 3.6	144.4 ± 3.8
62.5	144.9 ± 2.7	155.0 ± 2.8
125	160.3 ± 1.2	171.6 ± 1.2
250	180.7 ± 3.1	191.4 ± 0.9
500	213.7 ± 0.9	229.4 ± 3.3
1000	247.0 ± 1.6	265.9 ± 1.3

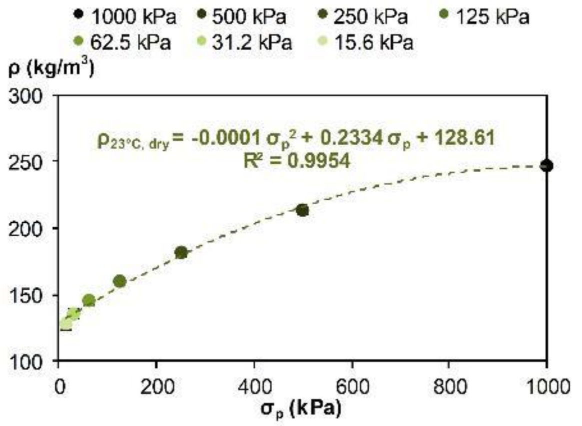

Fig. 59: Effect of compaction on density of composites.

3.2 Thermal conductivity

The thermal conductivity of developed composites ranges from 62.8 to 93.2 mW/(m.K) at dry state and from 71.0 to 101.5 mW/(m.K) at 23°C, 50%RH (Tab. 21). The composite with the lowest compaction pressure (15.6 kPa) meets the requirements to be classified as insulating building materials regarding the NF P 75-101 standard [AFNOR 1983]. Actually its thermal conductivity is lower than 65 mW/(m.K).

Tab. 21: Effect of compaction and humidity on thermal conductivity of composites (average value and standard deviation).

σ_p kPa	23°C, dry ρ kg/m³	23°C, dry λ mW/(m.K)	23°C, 50 %RH ρ kg/m³	23°C, 50 %RH λ mW/(m.K)
15.6	127.6 ± 3.7	62.8 ± 1.1	134.6 ± 3.4	71.0 ± 1.1
31.2	135.3 ± 3.6	65.7 ± 1.9	143.3 ± 3.9	73.1 ± 1.8
62.5	144.9 ± 2.7	65.6 ± 1.3	153.7 ± 2.7	72.7 ± 1.0
125	160.3 ± 1.2	68.9 ± 0.9	170.1 ± 1.1	77.8 ± 1.0
250	180.7 ± 3.1	71.1 ± 1.5	190.4 ± 1.0	78.2 ± 3.
500	213.7 ± 0.9	79.8 ± 2.8	225.4 ±3.4	91.0 ± 1.9
1000	247.0 ± 1.6	93.2 ± 1.9	258.8 ± 1.6	101.5 ± 1.8

As shown on Fig. 60, the thermal conductivity increases linearly with density with a high correlation coefficient. More, Fig. 60 also highlights that the slope is twice the slope obtained for agro-resources [Viel 2018]. This may be attributed to the addition of binder and the compaction which reduces inter-particular and maybe intra-particular porosity. Thanks to the linear regression, it is possible to identify the required density to reach a target thermal conductivity.

The thermal conductivity at wet state (23°C, 50%RH) is about 10 % higher than the thermal conductivity at dry state. The slope versus density remains the same.

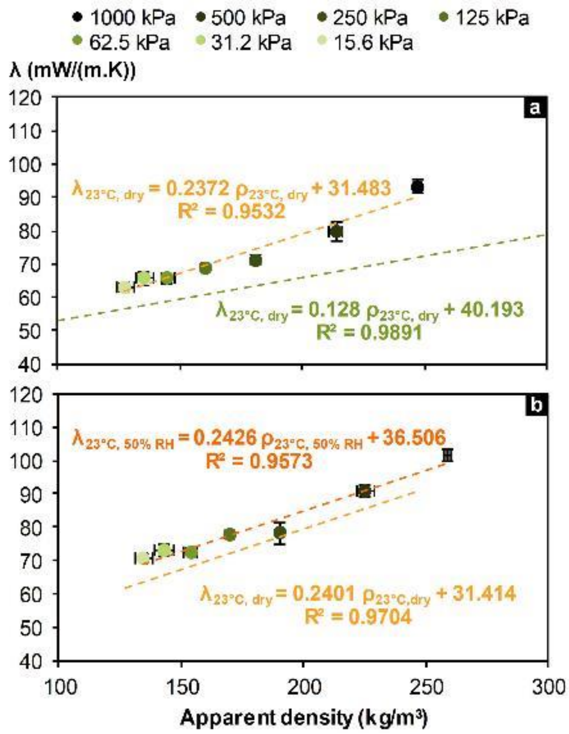

Fig. 60: Thermal conductivity of composites versus density at a) dry state and b) (23°C, 50%RH).

3.3 Moisture Buffer Value (MBV)

The MBV ranges from 2.40 to 2.94 g/(m².%RH). All the composites are excellent hygric regulator according the Nordtest classification (MBV > 2 g/(m².%RH)) [Rode 2005] .

The lowest MBV is obtained for the two composites with the highest densities (compacted at 500 and 1000 kPa). The highest MBV is obtained for the composite compacted at 62.5 kPa.

In a first time, the MBV increases up to 2.94 g/(m².%RH) for a density of 170 kg/m³. Then, it decreases down to 2.40 g/(m².%RH) for density of 200 kg/m³. Finally, the MBV remains constant. Such evolution may be explained:

- In a first time, by the increase in specific surface area with density which leads to higher sorption and thus higher MBV,
- Then, by the decrease in vapor permeability induced by lower inter-particular porosity which reduces the vapor penetration in the composite, and thus the MBV.

Tab. 22: Effect of compaction on MBV of composites (average value and standard deviation).

σ_p kPa	MBV_{abs} g/(m².%RH)	MBV_{des} g/(m².%RH)	MBV_{av} g/(m².%RH)
15.6	2.50 ± 0.03	2.77 ± 0.02	2.63 ± 0.02
31.2	2.60 ± 0.09	2.86 ± 0.09	2.73 ± 0.09
62.5	2.82 ± 0.11	3.06 ± 0.11	2.94 ± 0.11
125	2.63 ± 0.07	2.87 ± 0.06	2.75 ± 0.06
500	2.31 ± 0.01	2.49 ± 0.01	2.40 ± 0.01
1000	2.31 ± 0.12	2.49 ± 0.10	2.40 ± 0.11

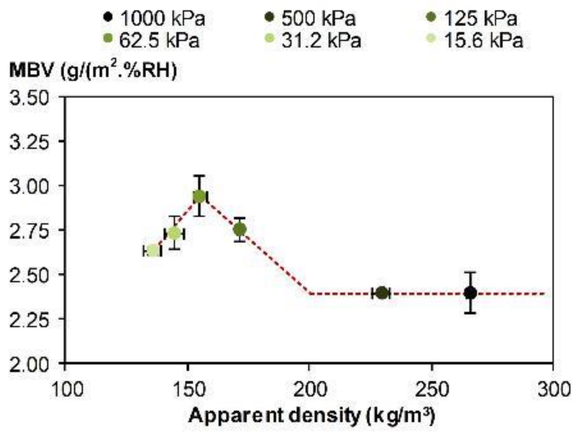

Fig. 61: Moisture buffer value of composites versus density.

The combination of these two parameters leads to identify an optimum value of density, and thus of compaction pressure. In order to validate these hypothesis, complementary investigations regarding vapor permeability and specific surface area are required.

4 SUMMARY

The developed composites are produced with hemp shiv and black liquor with several compaction pressure.

The composites density ranges from 128 to 347 kg/m³ at dry state. The density is correlated to the compaction pressure applied during the production.

The thermal conductivity increases linearly with density between 62.8 to 93.2 mW/(m.K) at dry state.

All the developed composites are excellent hygric regulators as their MBV ranges from 2.40 to 2.94 g/(m².%RH). The MBV evolves with density and shows an optimal value for density around 170 kg/m³.

Among developed composites, the composite with the lowest density shows high thermal and hygric performances. On the one hand, its thermal conductivity meets the requirements to make it considered as insulating building material. On the other hand, it is an excellent hygric regulator, with MBV of 2.77 g/(m².%RH).

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