A MULTI-SCALE ANALYSIS OF HEMP-BASED INSULATION MATERIALS

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Abstract

Biobased materials are increasingly used for building insulation. Hemp concrete (mix of hemp aggregates and mineral binder) is an efficient thermal insulation material containing renewable resources. It provides also comfort in habitation thanks to its acoustical and hygrothermal properties. In this study, two hemp concrete “wall” formulations are manufactured with one type of hemp shiv and two commercial binders: a rapid setting natural cement and a formulated binder based on lime. 90 days of curing ensures the hardening of the materials. The influence of binders on the microstructure and its relation with functional properties is investigated in this paper. Similar behaviors in thermal conductivity, acoustical performances and hygroscopic properties are observed for the two binders. No differences are measured through porosity, which can explain the similar functional properties behaviors as they partly depend on porosity. Both formulations have low compressive strength compared with hemp concretes in literature. This could be due to the shiv extractible compounds that impact the hydration of the mineral binders.

Keywords:

Biobased materials, building insulation, hemp concrete, porosity, functional properties

1 INTRODUCTION

19% of the global greenhouse gas emissions are imputed to building sector [Lucon 2014]. For a large part, it is due to indirect CO_2 emission, and especially energy consumption. One third of this energy is used to heat and to cool spaces [Lucon 2014]. Better insulation of buildings is then needed to reduce energy consumption.

Environmental-friendly and efficient insulation biobased materials [La Rosa 2014] have increasingly been used for the past thirty years. Renewable resources, such as hemp shiv associated with mineral binders enable the production of “hemp concrete”, one of the most common biobased insulation material used. More than thermal insulation, hemp concretes ensure also a comfortable habitat with moisture management and acoustical properties [Cérézo 2005, Gourlay 2014, Glé 2013].

The high porosity of shiv [Glé 2013], the woody parts of the stalk, brings thermal, hygrothermal [Gourlay 2014], acoustical properties [Glé 2013] as well as lightness. A mineral binder mixed with water is added to ensure a minimal cohesion of the material. The mineral binder is often based on lime with possible addition of cement or pozzolanic materials [Cérézo 2005, Gourlay 2014]. Both aerial lime (hardening only by carbonation) and/or hydraulic lime (hardening mainly by hydration) are used. Natural cement is also used with hemp shiv to formulate hemp concrete [Marceau 2016]. The different mineral compositions may impact the porosity of the materials and their functional properties [Gourlay 2014, Glé 2013, Collet 2008]. For example, mechanical properties depend on the type of binder used and its hardening mechanisms (hydration and/or carbonation). In the case of mortars, hydraulic binders have higher compressive strength than lime [Silva 2015]. However, plant aggregates can have negative impact on hydration of hydraulic binders and reduce the strength of the material [Nozahic 2012, Magniont 2010, Diquelou 2015].

In this article, the authors present a large scope of microstructural and multifunctional properties of hemp concretes, focusing on the relation between the properties at different scales.

Two different binders commonly-used for hemp concretes are selected for the study: a binder based on lime and natural prompt cement.

Firstly, the evolution of the density during curing is measured. Secondly microstructure and porosity are analysed for the two formulations. Finally thermal, acoustical, hygroscopic and mechanical properties are presented. The influence of the binder’s nature on the properties is particularly studied.

2 MATERIALS AND METHODS

2.1 Materials

Two different binders commonly-used for hemp concretes are selected for this study:

- a formulated binder based on natural lime (70%) and hydraulic and pozzolanic binders (30%),

- a rapid setting natural cement (with 0.1% of retarding agent).

A commercial hemp for insulation is selected. Physical characteristics of hemp shiv are presented in Table 1 and Figure 1.

Tab. 7: Characteristics of hemp shiv measured according to RILEM recommendations [Amziane 2016]

	Hemp shiv
Apparent density (kg.m^{-3})	118 ± 3
Initial rate of water absorption (%)	IRA = 162 ± 8
Absorption coefficient (%/log(t))	K_1 = 27 ± 3
Fiber and dust content (%)	Fiber = 2.8 Dust = 0.3

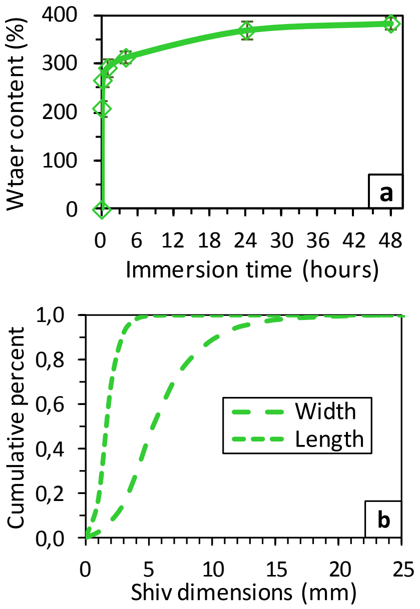

Fig. 41: a) Absorption of water by hemp shiv in immersion for 48 hours; b) Shiv size distribution obtained by image analysis

The same mixing proportions are used for both binders, with a water to binder mass ratio of 1 and a binder to shiv mass ratio of 2. Hemp shiv is introduced with half of the water in a mixer designed to produce 200L of hemp concrete. Then the binder (with retardant if needed) and the remaining water are added. The fresh concrete is filled and manually compacted in different molds to obtain a fresh density of 530 kg.m^{-3}.

Hemp concrete containing the binder formulated with lime is called FL-HC and the natural cement is NC-HC. Bulk hemp shiv is abbreviated as HS.

2.2 Methods

After manufacturing, 90 days of curing ensure hardening of hemp concretes by both hydration and carbonation of binders. Specimens are kept in their molds for 7 days. They are then demolded and stored for 81 days in a conditioned room (65% RH and 20°C). To control their water content, which impacts the functional properties [Gourlay 2016], specimens are finally dried at 40°C for 2 days before any measurement.

After curing, a large characterization of the two hemp concrete formulations is conducted. Microstructure is observed by Scanning Electron Microscopy (SEM) and quantification of the porosity of hemp concretes and hemp shiv is measured by several techniques:

- The open porosity, Φ, is measured with an air-porosimeter on 4 different specimens. It represents the volume fraction of the connected porosity.

- The interparticle porosity, Φ_{inter}, represents the voids between particles due to the imperfect arrangement of aggregates. The pore size is in millimeter range. Values are modeled from acoustical measurement conducted with a Kundt Tube for frequencies between 0 and 2 000 Hz [Glé 2012]. For this range of frequencies, micropores do not participate in acoustical dissipation. So the modeled porosity does not include the porosity inside the shiv and inside the binder [Glé 2012].

- Finally, the remaining intra porosity, Φ_{intra}, (shiv and binder porosities) can be calculated from the following equation:

$$\Phi_{intra} = (\Phi - \Phi_{inter})/(1 - \Phi_{inter}) \qquad (1)$$

Functional properties of hemp concretes are also measured:

- Thermal conductivity measurements commonly used to describe building insulation materials are conducted with a Hot Disk system. The probe is placed between two specimens and 6 measurements are realized by combination of 5 different specimens in a room at 24°C.

- Two acoustical properties are measured with the Kundt tube: the sound absorption coefficient α and the transmission loss TL. The sound absorption is the fraction of sound energy absorbed by a material. It is expressed as a value between 1 (perfect absorption, no reflection) and 0 (zero absorption, total reflection). Transmission loss (expressed in decibels), describes the sound insulation provided by a material. Acoustical measurements are realized on 3 specimens.

- Isotherms of sorption are plotted from a Dynamic Vapor Sorption system (DVS) at 25°C. They describe the moisture adsorption depending on relative humidity. Samples of hemp concrete of a few tens of µg are used for the measurements.

- Finally, the mechanical behavior of hemp concrete is investigated with compression tests on 3 specimens for each formulation.

3 RESULTS

3.1 Cure and density

The density of the two hemp concretes is following during the curing period (Figure 2).

After demolding, the main portion of water evaporating occurs during the first 30 days. Then densities are stable for the next 60 days. After 48h at 40°C, the dry density of NC-HC is 350 ± 14 kg.m^{-3} and 348 ± 10 kg.m^{-3} for FL-HC. Density of both concretes reaches the same value after the cure, pointing out that the nature of the binder does not induce any difference on this property. All the results presented below are focused on hemp concretes after this cure and drying.

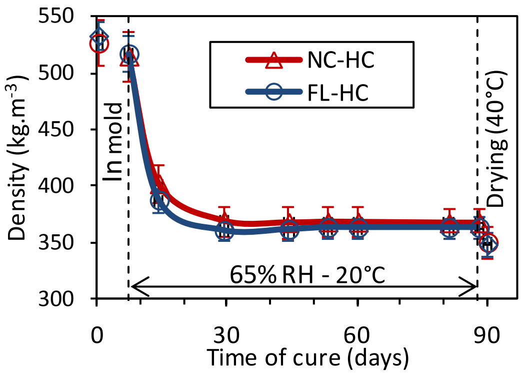

Fig. 42: Density of hemp concretes during the cure

3.2 Microstructure and porosity

SEM pictures presented in Figure 3-a and 3-b illustrate the microstructure for concretes based on FL-HC as no significant differences can be observed in the global microstructure between NC-HC and FL-HC.

Figure 3-a shows different shiv covered and linked by the binder as well as the interparticle porosity Φ_{inter}. Higher magnification allows better observations of Φ_{intra}, which is the sum of intra-binder and intra-shiv porosities (Figure 3-b). Xylem tubes, which compose the shiv, have various diameters (from 10 to 50 µm). Only the largest pores of the binder are visible on this figure, even if a nanometer-size porosity also exist (nanometer order) [Arandigoyen 2006].

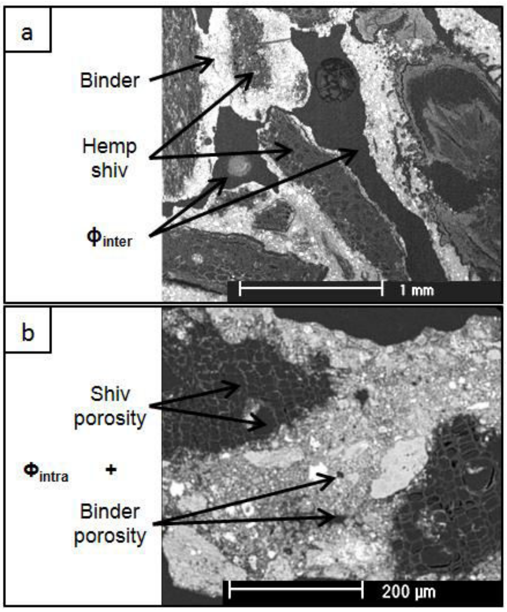

Fig. 43: a-b) Scanning Electron Microscopy of FL-HC at two different scales

Φ, Φ_{inter} and Φ_{intra} are measured and assessed using air porosimetry and acoustical characterizations as previously described. The results are presented in Table 3 for hemp concretes and hemp shiv in bulk.

Tab. 8: Open-air porosity, interparticle porosity and intraparticle porosity of NC-HC, FL-HC and hemp shiv

	Hemp shiv	**NC-HC**	**FL-HC**
Φ, %	0.87 ± 0.01	0.75 ± 0.02	0.76 ± 0.02
Φ_{inter}, %	0.79 ± 0.01	0.59 ± 0.01	0.65 ± 0.01
Φ_{intra}, %	0.40 ± 0.04	0.38 ± 0.04	0.33 ± 0.04

Hemp shiv Φ and Φ_{inter} are higher than both hemp concretes ones. That is partly explained by the fact that the binder covering shiv replaces the air volume initially present between particles. The comparison between the two hemp concretes reveals similar Φ values. Considering the variability of the results the slight differences of Φ_{inter} and Φ_{intra} are not significant.

3.3 Thermal conductivity

The results of thermal conductivity are presented in Table 3.

Tab. 9: Thermal conductivity of dry FL-HC and NC-HC

Formulations	**FL-HC**	**NC-HC**
Thermal conductivity ($W.m^{-1}.K^{-1}$)	0.103 ± 0.003	0.107 ± 0.005

The thermal conductivity of the two hemp concretes is about 0.1 $W.\ m^{-1}.K^{-1}$.

3.4 Acoustical performances

The sound absorption coefficient and the transmission loss are presented respectively in Figure 4-a and Figure 4-b.

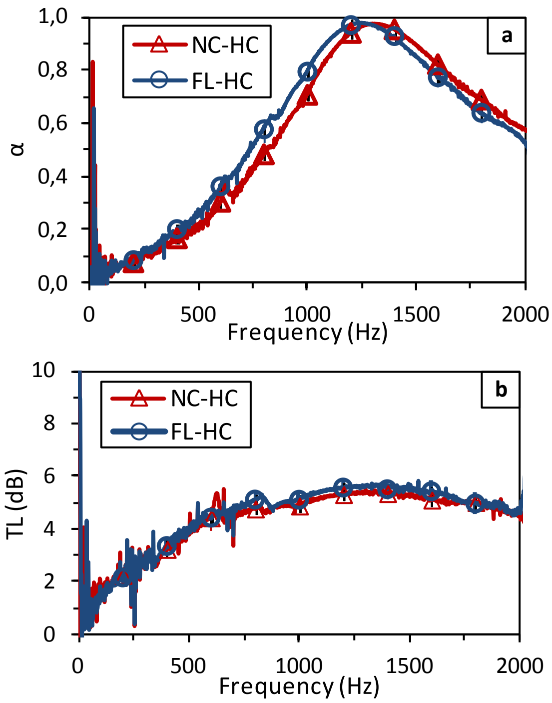

Fig. 4: a) Sound absorption of dry hemp concretes; b) Transmission loss of dry hemp concretes

α is in the range of 0.2 and 1 between 500 and 2 000 Hz, with a maximum around 1 250 Hz. So, hemp concretes have good level of sound absorption. TL is between 3 and 6 dB in the same range of frequency.

3.5 Hygroscopic properties

When immersed in water, hemp shiv can absorb almost 400% of its mass in water (Figure 1-a). In buildings, hemp concrete is not directly in contact with liquid water, but with moisture which can be adsorbed by hemp shiv through its porous structure [Collet 2008]. Figure 5 redraws the water sorption isotherms of FL-HC, NC-HC concretes and of bulk hemp shiv.

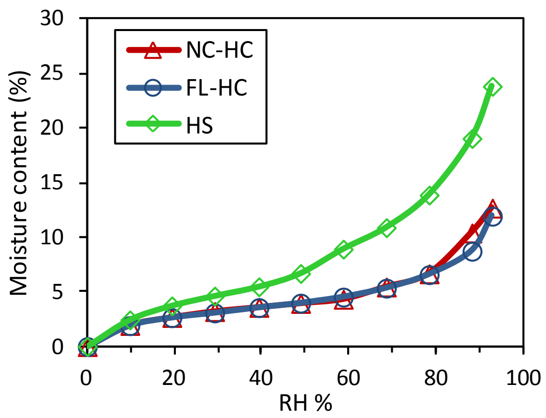

Fig. 5: Sorption isotherms of FL-HC, NC-HC and HS (25°C)

Shiv adsorbs 24 wt. % of moisture at 92% RH. For the same relative humidity, the two hemp concretes adsorb about 12 wt. % of water. The presence of binder reduces the adsorbed water in hemp concrete, because it reduces the weight fraction of hemp. The same trend is observed for both concrete formulations. For relative humidities higher than 80%, mass equilibrium takes longer to achieve, which complicates the interpretation of the observed differences.

3.6 Compressive strength

Strain-stress curves are plotted in Figure 6-a for NC-HC and in Figure 6-b for FL-HC.

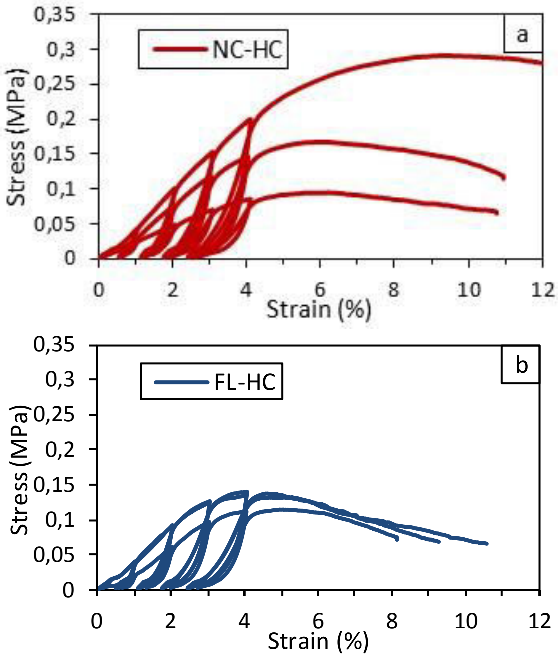

Fig. 6: Stress-strain curves for a) three specimens of FL-HC b) three specimens of NC-HC

The average of the maximal compressive strength (Rc) obtained are presented in Table 4.

Tab. 10: Compressive strength of NC-HC and FL-HC

Formulation	NC-HC	FL-HC
Rc (MPa)	**0.2**	**0.13**
Standard variation (MPa)	**0.1**	**0.01**
Coefficient of variation	**50 %**	**8 %**

On average, NC-HC has a slightly higher compressive strength than FL-HC. This is due to specimens with a significantly higher and lower Rc (Figure 6-a), explaining the high coefficient of variation for this formulation.

4 DISCUSSION

Qualitative observations of the microstructure of hemp concretes by SEM do not highlight any significant differences between the two formulations. The quantitative analysis of the different porosities (Φ, Φ_{inter} and Φ_{intra}) shows similar values. However, differences of porosity inside the binder may be obscured by the high shiv porosity as the binder/shiv volume ratio is only of 0.25. It can be concluded that no clear difference is observed in porosity between the two formulations.

Hemp concrete is used for its functional properties: thermal conductivity, acoustical performances and hygroscopic properties. The two materials studied show similar behaviors. This result is linked to the fact that the microstructure of the two concretes is equivalent.

Concerning the mechanical properties, NC-HC has higher compressive strength than FL-HC (respectively 0.29 MPa and 0.14 MPa for the maximal Rc). This can be due to the fact that a hydraulic binder like cement has a higher binding properties than a hydraulic or an aerial lime [Silva 2015].

However, the coefficient of variation of NC-HC results is higher than for FL-HC. In a large campaign of compression tests, 57 specimens of hemp concretes have been analyzed [Niyigena 2016], and the coefficient of variation of Rc obtained was 11%. Parameters like surface preparation [Cérézo 2005] or particle arrangement during compaction [Nguyen 2010] can explain variations between specimens. In our study, the coefficient of variation for FL-HC is in the same range of value. In the case of NC-HC, these arguments are not sufficient to justify the variability observed, and another assumption is needed to explain this result.

Mechanical performances of a composite material also depend on the interaction between its components. In our case, vegetal aggregates can affect the hydraulic reactions of the binder. Indeed, some components from the shiv are soluble in the water used during the manufacturing. Some of them can delay or even inhibit the hydraulic reactions [Nozahic 2012, Magniont 2010, Diquelou 2015]. Inhibition mechanisms have been studied in wood aggregate-concretes and in vegetal fibers-cement composites. For example, pectin can trap calcium ions which reduces the concentration of calcium available for hydration reactions [Sedan 2008]. Saccharides (sugars) can also be adsorbed at the surface of cement grain and either formed water diffusion barrier or poisoning precipitation sites of hydrates [Frybort 2008]. The shiv can randomly inhibit the hydraulic reactions, which could explain the high variability of NC-HC for the three specimens tested. This assumption can be confirmed by the lower Rc values measured than expected for hemp concretes of this density: NC-HC and FL-HC compressive strength results are compared in Figure 7, with compressive strength for hemp concretes formulated with hydraulic binders and with a formulated binder based on aerial lime (PF70) from literature.

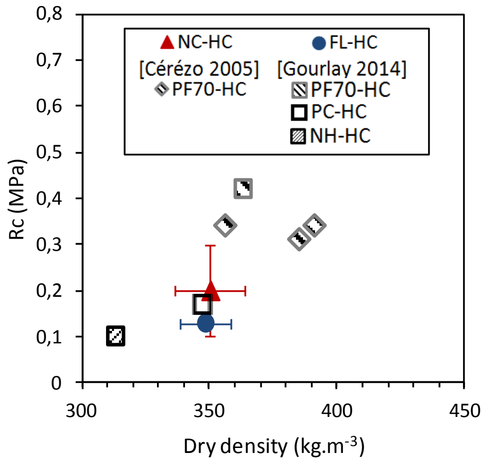

Fig. 7: Maximum compressive strength of NC-HC, FL-HC as a function of dry density. Comparison with hemp concretes formulated with PF70 [Cérézo 2005, Gourlay 2014]], with Portland cement [Gourlay 2014] and with hydraulic lime NHL3.5 [Gourlay 2014] (B/S ratio of 2, at 90 days after manufacturing)

All the formulations based on hydraulic binders, NC-HC and FL-HC included, have lower compressive strength than those using aerial lime. The shiv impacts only the hydraulic reactions, and not the carbonation of the aerial lime. In case of negative interactions between shiv and hydraulic binders, the hardening can be assured by the carbonation of aerial lime. Further studies are in progress to explain these results.

5 SUMMARY

In this study, two hemp concretes are formulated with one shiv and two different binders; the first one is based on lime, hydraulic and pozzolanic binders (FL-HC), and the other one is natural cement (NC-HC). After manual compaction with control of the density, specimens are unmolded after seven days, cured at 65% RH and 20°C for 81 days and dried for two days at 40°C. The same dry density (≈ 350 kg.m-3) is obtained for both formulations.

After the characterization of microstructural and functional properties, similar behaviors for both formulation are observed for thermal conductivity, acoustical performances, hygroscopic properties and compressive strength. The nature of the binder does not seem to influence the functional properties of the two hemp concretes. These results are mainly linked to porosity of the material, which is found to be similar for the two hemp concretes.

Possible negative effects of shiv on hydration for the two binders may explain the weak results observed in mechanical properties. Further studies are in progress to identify and to quantify the components present in the shiv, which are responsible of hydration inhibition.

The characterization of these two formulations is the first step in a larger study of the durability of hemp concretes. To observe and understand the behavior of properties with time, specimens are currently placed in different accelerated aging conditions: environmental aging, natural aging and biological aging.

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