# MECHANICAL AND THERMAL PROPERTIES OF HEMP CONCRETES

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## ABSTRACT

Hemp concrete is a multifunctional ecological material used in buildings. This material composed of hemp chips (shiv) mixed with a binder is "atypical" due to its high porosity (about 70% in volume) with three main pore sizes (1 µm, 100 µm and 1 cm). This paper focuses on the impact of raw materials (hemp particles and binder) on the mechanical and thermal properties of the concrete. It is shown that a physico-chemical interaction at the interface binder / plant particles plays a significant role in the mechanical setting of the material. Moreover, the compressive strength of hemp concrete is correlated with the morphological characteristics of the hemp particles. Due to the hygrophilous character of plant chips, the phase change effects (water / vapour) result in increasing the global thermal insulating performances of the hemp concrete.

## KEYWORDS:

Hemp concrete; mechanical behaviour; hygrothermal transfers.

## INTRODUCTION

The hemp concrete is a composite material obtained by mixing together a binder and hemp particles which is the non-fibrous fraction of the hemp stem called "shiv". It is used in the building construction as filling material of a load-bearing structure or as ready-made units or also as coating of wall.

The advantages of this relatively new building material are its technical performances associated to its low environmental footprint. A Life-Cycle Analysis of material (Boutin, 2005) established that each square meter of hemp concrete implemented results in storing 35 kg of $CO_2$: its carbon footprint is negative.

This material composed of shiv mixed with a binder is "atypical" due to its high porosity (about 70% in volume) with three main pore sizes (1 µm, 100 µm and 1 cm, see Figure 1). Its technical performances come from a very high micro-porosity of the material. Hemp concretes are characterized by their lightness (dry bulk density of about 400 kg/m$^3$ for a "wall" mixture) but also by an important mechanical ductility (compressive strains higher than 10% are possible). They can reach outstanding levels of thermal and phonic isolation (dry thermal conductivity of 0.08 W/(m.K) (Cérezo, 2005) and acoustic absorption higher than 0.8 (Arnaud, 2006), (Glé, 2011). So, it is possible to define specific mix proportions depending on the use of hemp concretes: roof and floor insulations, wall infilling or insulating plasters and renders (Hustache, 2008).

Hemp concretes are prepared by mixing water, binder and shiv. Various types of binders and several qualities of hemp shiv, whose physical characteristics vary sharply, are available. In this work, the impact of three different shiv and several kinds of binder on the mechanical and thermal properties is assessed. The influence of heat and mass transfers on the hygrothermal control of a hemp concrete wall is also measured.

**Figure 1 – Photography of raw shiv particles (left) SEM micrograph showing shiv micro-porosity (right)**

## EXPERIMENTAL PROCEDURES

### Raw Materials

Three kinds of binders and three different shiv have been tested in this study. Binder A is a pre-formulated lime-based binder which is composed of air lime (75%, apparent density of powder 650kg/m$^3$), hydraulic lime (15%) and pozzolanic lime (10%). Binder B contains only hydraulic lime (apparent density of powder 700kg/m$^3$) and binder C is made up of Portland cement clinker (apparent density of powder 1700kg/m$^3$).

The three shiv have various geographical origins and result from very different methods of hemp harvesting and processing (crushing process for dried stalk). The bulk dry densities of shiv have been measured: 105 kg/m$^3$for HS no.1, 90 kg/m$^3$ for HS no.2 and 94kg/m$^3$ for HS no.3.

### Specimens

The specimens were manufactured by using a concrete-mixer with rotary drum and fixed blades according to a clearly identified procedure (RP2C, 2006). The name given to each mixture indicates the raw materials used: for example, "B-2" stands for a mix with binder B and shiv HS no.2. Water content was adjusted to take into account the water requirement of binder and shiv (Table 1).

**Table 1 – Mass and volume composition of freshly-mixed concretes**

| **Hemp concrete** | **Weight content %** | | | **Volume content %** | | |
|---|---|---|---|---|---|---|
| | *shiv* | *Binder* | *Water* | *Shiv* | *Binder* | *Water* |
| **A-1** | 17.0 | 34.1 | 48.9 | 61.6 | 19.9 | 18.5 |
| **A-2** | 18.2 | 36.4 | 45.4 | 66.6 | 18.4 | 15.0 |
| **A-3** | 18.6 | 37.1 | 44.3 | 66.1 | 19.1 | 14.8 |
| **B-1** | 17.2 | 34.5 | 48.3 | 62.7 | 18.8 | 18.5 |
| **B-2** | 18.0 | 36.0 | 46.0 | 67.2 | 17.3 | 15.5 |
| **B-3** | 18.8 | 37.7 | 43.5 | 67.3 | 18.1 | 14.6 |
| **C-1** | 16.8 | 33.6 | 49.6 | 69.8 | 8.6 | 21.6 |
| **C-2** | 19.3 | 38.6 | 42.1 | 76.8 | 8.1 | 15.1 |
| **C-3** | 19.8 | 39.6 | 40.6 | 76.7 | 8.5 | 14.8 |

For each mixture, 9 cylindrical specimens, measuring 160 mm in diameter and 320 mm in height, 3 square specimens, 270 mm long and 50 mm high, and a wall, measuring 1000 mm in length and 200 mm in height, were filled with 50 mm thick layers under a stress of compaction of 0.05 MPa. The specimens were preserved in their mould in a climatic room controlled at 20°C and 50% RH until the date of the test (RP2C, 2006).

## CHARACTERIZATION METHODS

### Mechanical properties

Before being tested, the cylinders were removed from their mould and placed during 48 hours in a drying oven at 50°C in order to prevent the saturation water from disrupting the mechanical properties measurements.

Compressive strength tests were made on specimens using a universal hydraulic servo-controlled compressive testing machine at a crosshead speed of 5 mm/min.

### Hygrothermal transfers

Porous materials are subjected to heat and mass transfers when they are submitted to temperature and relative humidity gradients as it is the case for building materials. An experimental device has been developed in the laboratory. Relative humidity and temperature on both sides of the sample are simultaneously controlled using a double climatic chamber. Measurements of temperature T and relative humidity RH are carried out using five sensors located in the chambers (sensors A and E), on the surface of both sides of the sample (sensors B and D) and in the middle of the wall (sensor C). The analysis is mainly based on the variations of this last sensor C.

### Dry thermal conductivity and effusivity

The square specimens were put in a drying oven at 50°C during 24 hours and then, the dry thermal conductivity of material was measured using an apparatus based on a transient hot-wire method. The dry thermal effusivity was determined using a transient hot plate method.

## RESULTS AND DISCUSSION

### Mechanical properties

Setting and hardening process are influenced by the water extracts of shiv (Diquelou, 2012).

The water extracts were prepared by mixing shiv and water with a shiv to water weight ratio of 0.1. After 24 h, the extracts were filtered (300µm) and analysed. Recent results show clearly that these extracts modify significantly the evolving mechanical properties of cement based matrix (Figure 2). Depending on the shiv considered, a fall in the compressive strength is noted and it can reach up to 50 % of the reference paste obtained with pure water. The same effect is also observed when a shiv particle is placed in a cement based matrix: just around the particle, the binder does not set. A new methodology enables a direct visualization and a precise following of the influence area of the products extracted from shiv by the alkaline cement paste. A shiv particle (or pellets of shiv powder) is placed on a glass and coated with cement paste. After setting, the device is turned upside down to observe the interface through the glass. It has been clearly shown that a full absence of setting occurs in a well define area, immediately surrounding the shiv particle (Diquelou, 2012).

Then, the influence of shiv is observed on the setting process of concrete. For each mixture, three cylindrical specimens were tested in compression after 28, 60 and 90 days. The typical stress-strain curves of hemp concretes manufactured using binder A are shown in Figure 3. Compressive strength and Young's modulus are deduced from the stress-strain curves, they are synthetised in Table 2.

Figure 3 proves particular behaviours of hemp concretes:

- the setting phenomenon for hemp concrete is relatively slow,
- hemp concretes present a very ductile behaviour which is characterized by a long post-peak plastic plateau on the curves.
- depending on the binder and shiv used, and on the curing conditions, the performances vary dramatically. This can be explained by the chemical interactions between shiv and binder in composite and physical influences of shiv morphology (Arnaud, 2011).

**Figure 2 – Time evolution (in log scale) of the compressive strength of cement matrix composed of cement mixed with water extracts and pure water (reference).**

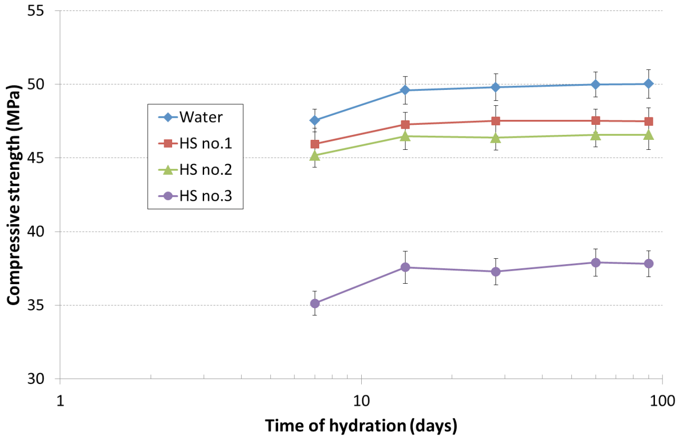


**Figure 3 – Stress – strain curves for compressive strength test performed on hemp concrete after 90 days, comparison of performances as function of the binder A, B and C.**

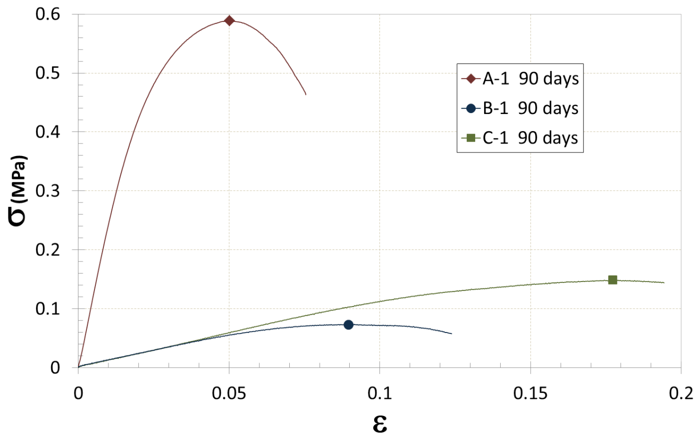


**Table 2 – Mean compressive strength and Young's modulus measured for each mixture after 28, 60 and 90 days**

| Hemp concrete | 28 days | | 60 days | | 90 days | |
|---|---|---|---|---|---|---|
| | *σmax (MPa)* | *E (MPa)* | *σmax (MPa)* | *E (MPa)* | *σmax (MPa)* | *E (MPa)* |
| A-1 | 0.34 | 17.9 | 0.51 | 28.0 | 0.59 | 24.8 |
| A-2 | 0.24 | 13.2 | 0.42 | 11.9 | 0.42 | 13.4 |
| A-3 | 0.37 | 17.6 | 0.42 | 22.4 | 0.52 | 18.8 |
| B-1 | 0.09 | 3.4 | 0.08 | 1.3 | 0.08 | 1.4 |
| B-2 | 0.07 | 1.7 | 0.09 | 1.0 | 0.10 | 1.2 |
| B-3 | 0.11 | 1.6 | 0.10 | 1.3 | 0.11 | 1.4 |
| C-1 | 0.06 | 1.8 | 0.09 | 2.4 | 0.11 | 1.3 |
| C-2 | 0.09 | 4.9 | 0.16 | 1.9 | 0.19 | 2.3 |
| C-3 | 0.09 | 4.4 | 0.21 | 2.6 | 0.25 | 3.1 |

The hemp concretes based on binder A have very good mechanical properties as compared to the limits of compressive strength (0.2 MPa) and Young's modulus (15 MPa) specified in (RP2C, 2006). In contrast, the specimens manufactured using binders B and C present very low mechanical properties, which is characteristic of a partial setting of the binder. This result is not surprising for the cylinders based on binder B since the specimens were preserved in an environment with low relative humidity (50% RH). These conditions slow down very sharply the setting of hydraulic binders. Nevertheless, the partial setting of the Portland cement binder can be explained sincewe noticed a full absence of setting all around the particle and for the considered mixes, the distance between two close particles is of the same order of magnitude as the unset area.

## Dry thermal conductivity and effusivity

**Table 3 – Dry thermal conductivity and effusivity of each hemp concrete**

| Hemp concrete | *A-1* | *A-2* | *A-3* | *B-1* | *B-2* | *B-3* | *C-1* | *C-2* | *C-3* |
|---|---|---|---|---|---|---|---|---|---|
| **λdry (W.m-1.K-1)** | 0.099 | 0.102 | 0.107 | 0.079 | 0.080 | 0.101 | 0.073 | 0.083 | 0.084 |
| **Edry (W.s1/2.K-1.m-2)** | 153 | 155 | 161 | 128 | 123 | 153 | 123 | 126 | 128 |

The dry thermal conductivities and effusivities measured are shown in Table 3. The hemp concretes based on binder A have higher dry thermal properties than the other concretes: this result can be related to the high dry thermal properties of the pure binder paste.

These measured quantities will be implemented in a numerical model of coupled heat and mass transfers in order to model the hygrothermal transfers inside a hemp concrete wall (Samri, 2005).

## Hygrothermal transfers

Hemp concrete as porous medium is sensible to heat and vapour transfers combining heat conduction, convection, diffusion of vapour and liquid water. For studying these phenomena, sample was subjected to temperature and relative humidity gradients in a new experimental device (Figure 4).

In order to identify precisely the effects of convective flows, a wall manufactured using binder C and hemp shiv HS no.1 has been covered with a fine tight layer of cellophane which is impermeable: thus, only the heat transfers by conduction take place through the material. Measurements are then compared with those performed on this same wall without the tight plastic film (Figure 5).

In the climatic chamber, the temperature and the relative humidity remains constant whereas the conditions in the second chamber are modified during stages of 24 hours as follows Stages 1 and 4: *20°C and RH 50%,* then

Stage 2: *10°C, RH 80%,* and finally, Stage 3: *40°C, RH 45%.* The changes in temperature and relative humidity are followed up in the middle of the wall (sensor C) and in the two chambers (sensors A and E). They are then compared during tests on Figure 5. During the second stage, the relative humidity decreases in C. This can be explained by the condensation of water vapour inside the wall. At the beginning of the third stage, relative humidity in C rises sharply before decreasing and then stabilizing. The noticeable temperature rise in A involves a vaporization of water within the specimen: the relative humidity in the middle of the wall then increases suddenly. Within the wall, a relative humidity gradient is created between the “hot” zone of the specimen where the water vaporizes and the “cold” zone where there is no phase change: the water vapour then migrates towards the “cold” zone, which explains the decrease in relative humidity measured in the middle of the wall. Finally, during the fourth stage, the relative humidity in C decreases strongly before rising slightly and then stabilizing. The temperature drop in A is responsible for the vapour condensation which implies a relative humidity decrease in C: it then creates a relative humidity gradient within the wall and the water vapour migrates within the specimen, thus explaining the relative humidity increase measured in the middle of the wall.

**Figure 4 – Temperature and relative humidity variation at the centre of hemp concrete wall submitted to sudden variations**

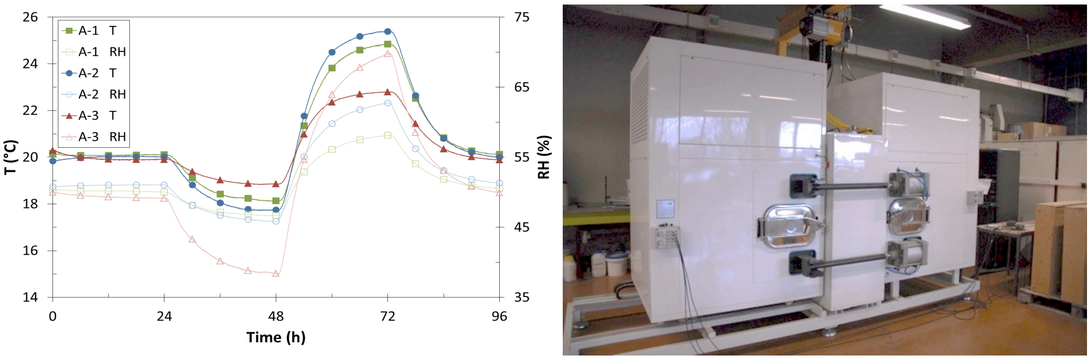
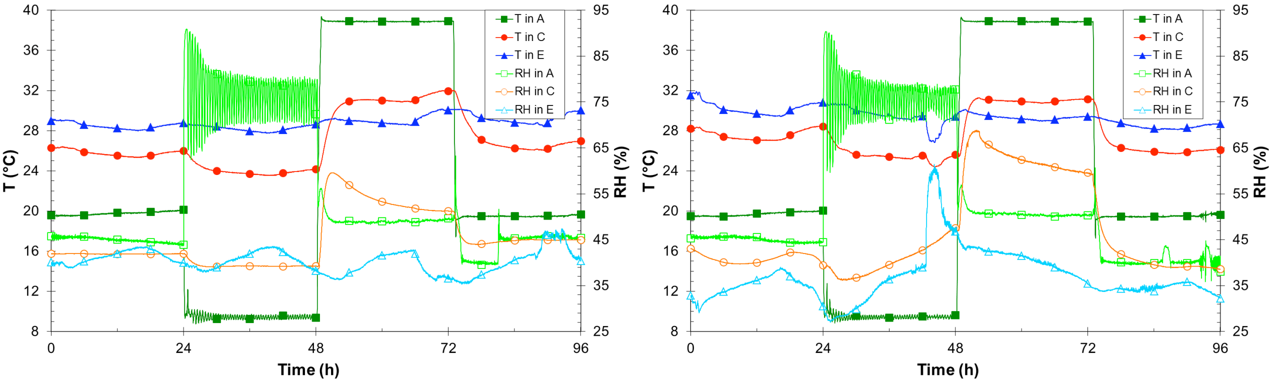


**Figure 5 – Evolution of temperature and relative humidity in points A, C and E for the wall, left side: wall covered with a tight cellophane film (i.e. without convective flow); right side: wall NOT covered i.e. with possible convective flows.**



By comparing graphs in Figure 5, it can be noticed that the amplitude of the temperature variation measured in the middle of the wall without convective effects between the second and the third stage, is about 7°C. It is larger than that measured in the middle of this wall without the tight plastic film (approximately 5.5°C). The cellophane prevents indeed the water vapour interchange between wall and outside. During the second stage, a part of the water vapour contained in the specimen condenses: the energy release induced by this phase change then makes it possible to slow down the drop in temperature in the wall. For the sample without cellophane, the RH decrease within the specimen induced by the condensation is offset by a water vapour stream coming from the outside, which promotes the phenomenon of condensation and the cushioning of the drop in temperature. It thus follows that the temperature drop in the middle of the wall during the second stage is less damped when the specimen is covered with cellophane. During the third stage, a part of the liquid water vaporizes: the energy absorption induced by this phase change allows cushioning the increase in temperature in the wall. During the second stage, thanks to the water vapour stream coming from the outside and because of the phase changes which occur within the material, the wall without cellophane was able to build up a larger reserve of liquid water: during the third stage, the phenomenon of vaporization is thus more significant in this wall, which enables a better cushioning of the rise in temperature in C. Finally, the increase in temperature in the middle of the specimen during the third stage is less attenuated when the wall is covered with the cellophane.

In conclusion, it that hemp concrete behaves as “natural material with phase changes”.

Finally, another prove of phase change effects is given Figure 4. It proposes a comparison of hemp concrete based on the three kinds of shiv (Mix formulation A-1, A-2, and A-3). For the same conditions (variation of temperature and relative humidity) the variations of temperature and relative humidity in the centre of the wall are dramatically different: the influence on temperature jump equals 2.5 °C at the pic between A-2 and A-3. Moreover, the correlated variations of relative humidity show once more that higher variation of relative humidity lead to smaller variation of temperature. These measurements are so consistent with the physical analysis proposed of natural phase change material since the quantity of water vaporization limits the increase of temperature.

## CONCLUSION

Hemp concrete is composed of shiv (hemp particles) and a binder. It is used as filling material in building construction and offers both environmentally and technically efficiencies. It allows storing $CO_2$ by recovering a by-product of hemp farming which is thus renewable and easily recyclable. The impact of three kinds of binders and three different hemp shives on the mechanical and thermal properties of concrete is assessed in this paper.

The specimens manufactured using a air lime-based binder have very good mechanical properties whereas the hemp concretes based on a Portland cement clinker and a hydraulic lime-based binder present very low mechanical properties, which is characteristic of a partial setting: a physico-chemical interaction between binder and shiv disrupts the mechanical setting of the hemp concrete. Moreover, the compressive strength of the material depends on the hemp shiv used: this may be correlated with the morphological characteristics of the shives (amount of fibers, size of hemp particles, etc.).

Finally, the hygrothermal transfers measurements carried out helped to highlight the important role played by the convective flows in the thermal control of a hemp concrete wall: the water vapour transfer coming from the outside promotes phase changes (condensation and vaporization) within the material and enables therefore to cushion significantly the temperature changes inside the wall. Due to these transfers, hemp concrete behaves as natural Material with Phase Changes.

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