Impact of raw materials on the mechanical and thermal properties of hemp concretes

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ABSTRACT: Hemp concrete is a multifunctional ecological material used in buildings. Due to its high porosity (about 80% in volume), it presents an “atypical” mechanical behavior and its thermal and acoustical properties are particularly interesting. It is today possible to design this material according to the required use. This paper focuses on the impact of raw materials (hemp particles and binder) on the mechanical and thermal properties of the hemp concrete. It is shown that a physico-chemical interaction between the binder and the vegetable particles may disrupt the mechanical hardening and setting of the material. Moreover, the hemp concrete compressive strength may be correlated with the morphological characteristics of the hemp particles. Finally, the water vapor transfers and the phase changes (condensation and vaporization) within the material allow cushioning significantly the changes in outside temperature.

1 INTRODUCTION

In order to preserve natural resources and to design building materials with lower environmental impact, the use of vegetable particles as building material aggregates becomes of particular interest nowadays.

The hemp concrete is a composite material obtained by mixing together a binder and hemp particles (the non-fibrous fraction of the hemp stem called “shiv”). It is used in the building field as filling material of a load-bearing structure or as ready-made units or also as coating of wall. Its carbon footprint is negative: indeed, a Life-Cycle Analysis of material [Boutin et al (2005)] established that each square meter of hemp concrete implemented results in storing 35 kg of CO₂.

This material has a very high porosity [Collet et al (2008)] (more than 80% in volume) from which come the physical performances, which are at the same time original and very interesting. Hemp concretes are characterized by their lightness (dry bulk density of about 400 kg/m³ for a “wall” mixture) but also by an important mechanical ductility (compressive strains higher than 10% are possible [Elfordy et al (2008)]). They can reach outstanding levels of thermal and phonic isolation (dry thermal conductivity of 0.08 W/(m.K) [Cerezo (2005)] and acoustic absorption higher than 0.8 [Arnaud et al (2006), Glé et al (2011)]). So, it is possible to define specific mix proportions depending on the use of hemp concrete: roof and floor insulation, wall infilling or insulating plasters and renders [Hustache and Arnaud (2008)].

To manufacture hemp concretes, various types of binders and several qualities of hemp shives, whose physical characteristics vary sharply, are available. In this work, the impact of different hemp shives 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.
2 EXPERIMENTAL PROCEDURES

2.1 Raw materials

Three kinds of binders and three different hemp shives were used to manufacture hemp concretes.

Binder A is a pre-formulated lime-based binder made up of air lime (75%), hydraulic lime (15%) and pozzolanic lime (10%). Binder B contains only hydraulic lime and binder C is made up of Portland cement with a high rate of clinker (CEM I). The apparent powder densities of the various binders are shown in Table 1.

Table 1. Apparent powder densities of the binders

<table>
<thead>
<tr>
<th>Binder</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent powder density (kg/m³)</td>
<td>650</td>
<td>700</td>
<td>1700</td>
</tr>
</tbody>
</table>

The three hemp shives have various geographical origins and result from very different methods of hemp harvesting and processing. The bulk densities of the hemp shives are given in Table 2.

Table 2. Bulk densities of the hemp shives

<table>
<thead>
<tr>
<th>Hemp shiv</th>
<th>HS no.1</th>
<th>HS no.2</th>
<th>HS no.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density (kg/m³)</td>
<td>105</td>
<td>90</td>
<td>94</td>
</tr>
</tbody>
</table>

2.2 Preparation of 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. The amount of water introduced into each mixture was adjusted in order to take into account the water requirement of binder and shiv (Table 3).

Table 3. Mass and volume composition of freshly-mixed concretes

<table>
<thead>
<tr>
<th>Hemp concrete</th>
<th>% Weight</th>
<th>% Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hemp shiv</td>
<td>Binder</td>
</tr>
<tr>
<td>A-1</td>
<td>17.0</td>
<td>34.1</td>
</tr>
<tr>
<td>A-2</td>
<td>18.2</td>
<td>36.4</td>
</tr>
<tr>
<td>A-3</td>
<td>18.6</td>
<td>37.1</td>
</tr>
<tr>
<td>B-1</td>
<td>17.2</td>
<td>34.5</td>
</tr>
<tr>
<td>B-2</td>
<td>18.0</td>
<td>36.0</td>
</tr>
<tr>
<td>B-3</td>
<td>18.8</td>
<td>37.7</td>
</tr>
<tr>
<td>C-1</td>
<td>16.8</td>
<td>33.6</td>
</tr>
<tr>
<td>C-2</td>
<td>19.3</td>
<td>38.6</td>
</tr>
<tr>
<td>C-3</td>
<td>19.8</td>
<td>39.6</td>
</tr>
</tbody>
</table>
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 600 mm in length and 100 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)].

2.3 Characterization methods

2.3.1 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 hemp concrete specimens using a universal hydraulic servo-controlled compressive testing machine at a crosshead speed of 5 mm/min.

2.3.2 Hygrothermal transfers

An experimental device was developed in the laboratory [Gourlay (2009)]. Relative humidity and temperature on one side of the specimen are simultaneously controlled using a climatic chamber: the hemp concrete specimen is thus subjected to temperature and relative humidity gradients between the inside of the climatic room and the laboratory. Measurements are carried out using five temperature and relative humidity probes put in the chamber (sensor A), in the laboratory (sensor E), on the surface of both sides of the specimen (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.

2.3.3 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.

3 RESULTS AND DISCUSSION

3.1 Mechanical properties

For each mixture, 3 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 1. The mean compressive strength and Young’s modulus measured for each material in compressive tests performed are presented in Table 4.

Figure 1 shows that the hardening kinetics of hemp concretes is relatively slow: therefore the mechanical behavior of hemp concrete is mainly linked to its age. At early ages, hemp concretes present a very ductile behavior (characterized by the presence of a long post-peak plastic plateau on the curve). The binder hydrates do not form a connected network yet, consequently, the behavior of the concrete is close to the one of shiv which can sustain very large strains. With time, the hydrates become connected together and gradually create a continuous skeleton enabling stresses transmission. The binder characteristics become little by little predominant in concrete that supports increasingly high stresses and its behavior becomes less and less ductile.
On Figure 1, it can be noticed that cylinders manufactured using shiv HS no.2 and, to a lesser extent, specimens based on shiv HS no.3 are more ductile than concretes based on shiv HS no.1. These differences in compressive strength may very likely be correlated with the shiv morphological characteristics (amount of fibers, size of hemp particles, etc.).

The hemp concretes based on binder A have very good mechanical properties taking into consideration 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 is unexpected: it seems that a physico-chemical interaction between the binder and the hemp shiv disrupts the mechanical setting of hemp concrete. Works in hand aim at studying the influence of shiv solubility on binder setting.

3.2 Hygrothermal transfers

A hemp concrete sample was subjected to temperature and relative humidity gradients. Several phenomena are superimposed: heat conduction, convection, diffusion of water vapor and liquid water within the material. In order to identify the role played by convective flows, a wall manufactured using binder C and hemp shiv HS no.1 has been covered with a fine tight layer of cellophane: 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.

In the climatic chamber, the temperature and the relative humidity are constant during stages of 24 hours. Outside conditions of temperature and relative humidity usually measured in spring in France are considered (Stages 1 and 4: 20°C, RH 50%), then in winter (Stage 2: 10°C, RH 80%) and finally, in summer (Stage 3: 40°C, RH 45%).

The changes in temperature and relative humidity in the climatic chamber (sensor A), in the middle of the specimen (sensor C) and in the laboratory (sensor E) are compared during tests on Figures 2 and 3.

Figure 2. Evolution of temperature and relative humidity in points A, C and E for the wall covered with a tight cellophane film (i.e. without convective flows).
Figure 3. Evolution of temperature and relative humidity in points A, C and E for the wall not covered with a tight layer (i.e. with convective flows).

Figure 2 shows during the second stage that the relative humidity decreases in C: this can be explained by the condensation of water vapor inside the wall. At the beginning of the third stage, the 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 vapor 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 vapor condensation which implies a relative humidity decrease in C: it then creates a relative humidity gradient within the wall and the water vapor migrates within the specimen, thus explaining the relative humidity increase measured in the middle of the wall.

By comparing graphs in Figures 2 and 3, 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 vapor interchange between wall and outside. During the second stage, a part of the water vapor 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 wall without cellophane, the relative humidity decrease within the specimen induced by the condensation is offset by a water vapor 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 vapor 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, hemp concrete behaves as natural Phase Change Material. Works in hand aim at studying the impact of different hemp shives and several kinds of binders on the hygrothermal transfers within the material.

3.3  Dry thermal conductivity and effusivity

The dry thermal conductivities and effusivities measured are shown in Table 5.

<table>
<thead>
<tr>
<th>Hemp concrete</th>
<th>A-1</th>
<th>A-2</th>
<th>A-3</th>
<th>B-1</th>
<th>B-2</th>
<th>B-3</th>
<th>C-1</th>
<th>C-2</th>
<th>C-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ_dry (W.m⁻¹.K⁻¹)</td>
<td>0.099</td>
<td>0.102</td>
<td>0.107</td>
<td>0.079</td>
<td>0.080</td>
<td>0.101</td>
<td>0.073</td>
<td>0.083</td>
<td>0.084</td>
</tr>
<tr>
<td>E_dry (W.s⁻¹/2.K⁻¹.m⁻²)</td>
<td>153</td>
<td>155</td>
<td>161</td>
<td>128</td>
<td>123</td>
<td>153</td>
<td>123</td>
<td>126</td>
<td>128</td>
</tr>
</tbody>
</table>

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 (2008)].

4  CONCLUSION

Hemp concrete made up of vegetable particles (hemp shiv) and a binder meets a strong need for building materials which are both environmentally and technically efficient. It allows storing CO₂ 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 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 vapor 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 Phase Change Material.
REFERENCES


