First International Conference on
Bio-based Building Materials

June 22nd - 24th 2015
Clermont-Ferrand, France

IMPACT OF THE WATER CONTENT OF HEMP CONCRETES ON THEIR THERMAL AND ACOUSTICAL PROPERTIES

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Abstract

Hemp concrete is a multifunctional ecological material used in buildings which is obtained by mixing together a binder and hemp particles (the non-fibrous fraction of the hemp stem called “shiv” or “hurd”). Due to its high porosity (ranging from 60 to 90% in volume), it presents an “atypical” mechanical behavior and its hygrothermal and acoustical properties are particularly interesting. This paper focuses on the impact of the water content of hemp concretes on their acoustical and thermal properties. Four mixtures of hemp concrete were manufactured using a binder and two shives under two distinct stresses of compaction. It is shown that water content does not affect significantly the acoustical properties of hemp concretes altough a swelling effect can be detected by an increase of resistivity and a decrease of porosity and viscous characteristic length. Finally, thermal conductivity rises almost linearly with water content while evolutions of thermal diffusivity and specific heat capacity are different depending on the concrete.

Keywords:

Hemp concrete; Water content; Thermal conductivity; Sound absorption

1 INTRODUCTION

The building sector is the first post of energy consumption in France with 44.8% of overall consumption in 2013 [Dussud 2014]. Reducing this consumption is therefore a major challenge for France. However, the building materials generally used are responsible for significant emissions of greenhouse gases: thus, materials with a low environmental impact and excellent thermal insulation properties are now sought-after.

In this context, the solution of bio-based building materials is becoming increasingly relevant as they have very low or even positive impact on the environment (CO_2 storage [Ip 2012]). Some of them are also characterized by very good multi-physical properties (heat insulation, sound absorption, transmission loss) and are already well established on the building market. Hemp concrete (mixture of wood aggregates from hemp stem with a binder) is among these materials one of the most used in France.

Hemp concrete is characterized by a highly porous microstructure and has an open porosity ranging from 60 to 90% according to the mixture [Glé 2013]. Moreover, this porosity is multiscale, distributed as follows [Arnaud 2012]:

- Macropores (1 cm of diameter) due to the imperfect arrangement of hemp particles in the material.
- Mesopores (from 0.1 mm to 1 mm) within hemp shiv and binder (trapped air).
- Micropores between hydrates (lower than 0.01 µm) in the binder matrix.

Due to these characteristics, hemp concrete has a highly hygroscopic behavior, which is at the root of particularly interesting hygrothermal performances [Samri 2008, Gourlay 2014]. This also implies a very high sensitivity to water vapor and liquid water, much higher than for conventional building materials. Thus, the mass water content of hemp concrete can reach 10% at relative humidities commonly experienced in a building (50% RH) and exceed 25% in more extreme cases (RH>90%) [Cerezo 2005, Gourlay 2014]. However, the impact of the water content of hemp concretes on their thermal and acoustical properties has never been studied systematically. That is why it was decided in this work to study the evolution of acoustical and thermal performance of four different formulations of hemp concrete for various conditions of water content.

Tab. 1: Characteristics of the hemp concrete formulations.

Formulation	Shiv	Binder	B/S	W/B	Initial density (kg/m^3)	Stabilized density (kg/m^3)
Terrachanvre Light	Terrachanvre	PNC	2	1.3	578 ± 20	351 ± 9
Terrachanvre Heavy	Terrachanvre	PNC	2	1.3	688 ± 21	415 ± 13
Kanabat Light	Kanabat	PNC	2	1.3	573 ± 17	340 ± 11
Kanabat Heavy	Kanabat	PNC	2	1.3	700 ± 16	410 ± 7

2 MATERIALS AND METHODS

2.1 Manufacturing and curing conditions of hemp concrete cylinders

Hemp concrete specimens were manufactured from two different hemp shives (called “Terrachanvre” and “Kanabat”) and a Prompt Natural Cement (PNC) marketed by the Vicat group by using a concrete-mixer with rotary drum and fixed blades according to a clearly identified procedure [RP2C 2012]. For each batch of hemp concrete, two different stresses of compaction were used: consequently, four sets of “Wall” mixture cylinders were made (see Tab. 1).

For each set, two kinds of specimens were prepared: cylinders measuring 100 mm in diameter and 40 mm in height for measuring the acoustical and thermal properties and cylinders measuring 35 mm in diameter and 40 mm in height for determining the open porosity of hemp concretes. The various characterizations have been repeated on four different samples in each configuration in order to check the reproducibility of the experiment and the deviation between samples.

After their manufacture, the cylindrical specimens were preserved as follows:

- 7 days of curing in their molds with the ends covered by a plastic film.
- 83 days of curing in molds with their ends exposed to the open air.
- 10 days without their molds in a drying oven at 40°C.

The average characteristics of the specimens manufactured are shown in Tab. 1. The initial density is the one measured at the time of manufacture and the stabilized density corresponds to that observed after drying in an oven at 40°C (daily variation of specimen mass of less than 0.1%). It is observed from these data that the “Heavy” and “Light” sets are clearly distinct and that the various cylinders have homogeneous densities within a same set.

2.2 Method for determining hygroscopic sorption properties

The sorption isotherms at 20°C of the various hemp concretes were obtained by applying the procedure described in International Standard [ISO 12571:2013].

Tab. 2: Characteristics of the saturated salt solutions used.

Saturated salt solution	Relative humidity of the air at 20°C
Potassium acetate	23.11 ± 0.25
Potassium carbonate	43.16 ± 0.33
Sodium chloride	75.47 ± 0.14
Potassium sulfate	97.59 ± 0.53

Firstly, all the specimens were dried at 20°C in desiccators containing silica gel and their dry weights were determined.

Then, saturated salt solutions were prepared to place the hemp concretes in relative humidity atmospheres regularly spaced between 0 and 100% RH. These solutions, as well as the corresponding relative humidities, are shown in Tab. 2.

2.3 Acoustical characterization methods

In order to characterize a material from an acoustical point of view, it is generally interesting to know both its sound absorption coefficient α and its transmission loss *TL*, quantities that respectively allow to evaluate the performance of the material for acoustical correction or insulation [Glé 2013]. For this purpose, Kundt tube measurements at normal incidence with a Kundt tube AcoustiTube (Akustikforschung AFD1000 / AFD1200), presented Fig. 1 (a), were performed in the frequency range [100; 2000 Hz]. The choice of an inner diameter of 10 cm was made to minimize the edge effect (imperfect arrangement due to a substantial particle size of shiv relative to the tube). The measuring method used is based on the use of three microphones (two upstream the sample, and a third downstream), and is described in [Iwase 1998]. In order to seal the periphery of the samples, the specimens were surrounded by Teflon tape and a thin layer of vaseline.

Basic acoustical parameters including open and interparticle porosity Φ and Φ_{inter}, resistance to the passage of the air σ, tortuosity α_∞ and viscous characteristic length Λ were also characterized. Such parameters are more relevant to discuss the differences between materials from a microstructural point of view. The acoustical characterizations were based on the combination of two measuring equipments and a method of indirect characterization presented below:

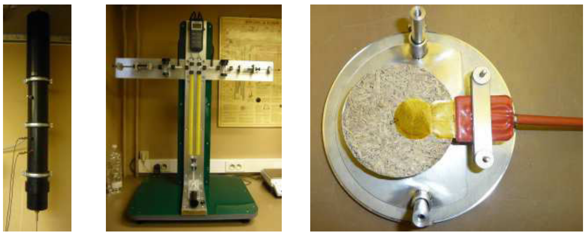
- To determine the open porosity Φ of materials, an air porosimeter based on the method described in [Leclaire 2003] was used (see Fig. 1 (b)). Volume V_s of the skeleton of the porous material is determined through the law of Boyle-Mariotte. Knowing the mass *m* of the test sample, the density of the skeleton ρ_s can be calculated, as well as the open porosity Φ according to the following equations, where ρ_v is the apparent density.

$$\rho_s = \frac{m}{V_s} \tag{1}$$

$$\phi = 1 - \frac{\rho_v}{\rho_s} \tag{2}$$

- Φ_{inter} was evaluated from the real part of the dynamic bulk modulus *K* and Zwikker & Kosten model.
- σ was evaluated by exploiting the low-frequency asymptotic behavior of the imaginary part of the dynamic density ρ.
- Ratio $\alpha_\infty/\Phi_{inter}$ and Λ were evaluated analytically from ρ [Panneton 2006].

More information about these methods can be found in [Glé 2012, Glé 2013].



(a) (b) (c)

Fig. 1: Equipment used for the experimental characterization: Kundt tube (a), Air porosimeter (b) and Hot Disk (c).

2.4 Thermal characterization method

In this study, the thermal characteristics of hemp concretes were also determined using a transient measurement technique based on the use of a heat shock probe: the Hot Disk method [Gustafsson 1991, Gustavsson 1994]. The basic principle of the system is to apply a constant power for a defined period of time to an initially isothermal specimen via the Hot Disk probe (see Fig. 1 (c)) and to follow the specimen temperature variation using the probe as a resistive thermometer.

This technique enables to measure the thermal conductivity λ and the thermal diffusivity *a* of the studied material. Its specific heat capacity *c* is then calculated with the following equation:

$$c = \frac{\lambda}{\rho a} \quad (3)$$

3 RESULTS AND DISCUSSION

3.1 Sorption isotherms

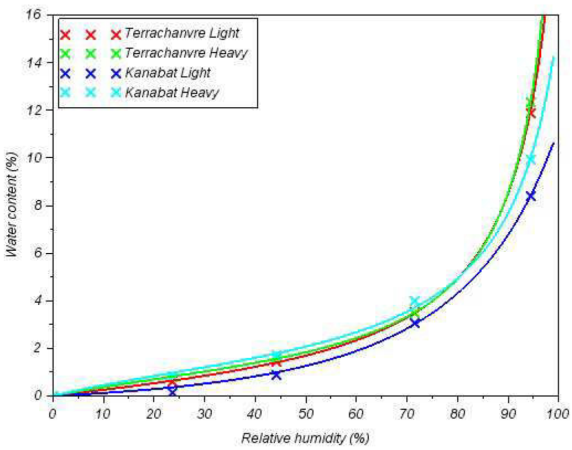


Fig. 2: Sorption isotherms at 20°C of the hemp concretes.

In Fig. 2, the sorption isotherms at 20°C of the hemp concretes are plotted. The various curves are smoothed according to the GAB model.

First, when relative humidities are very high, the hemp concretes based on “Terrachanvre” shiv have a larger water content due to the higher intraparticle porosity of the hemp shiv used [Glé 2015]. This result confirms the observations made in previous studies [Gourlay 2014].

Moreover, for a given shiv, the densest mixture (called “Heavy”) has a higher water content. This result is logical since the stresses of compaction applied during the manufacture of the cylinders change the interparticle porosity of hemp concretes but do not alter their intraparticle porosity.

3.2 Evolution of acoustical performance

Comparison of samples at the reference state (dry)

The acoustical properties of hemp concretes have initially been characterized in a reference state, after stabilization at 0% RH.

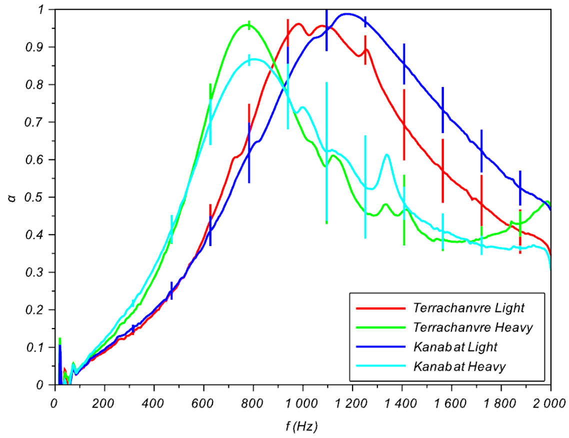


Fig. 3: Sound absorption of samples at 0% RH.

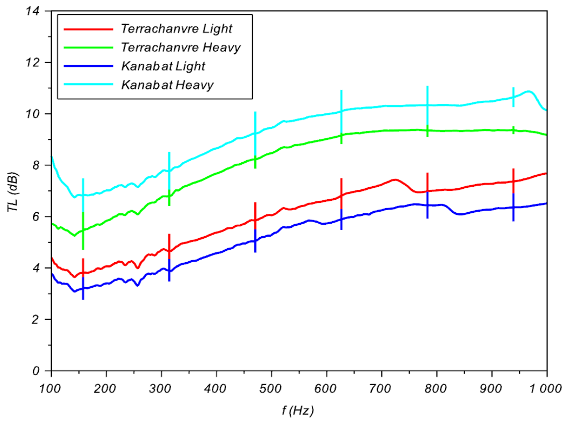


Fig. 4: Transmission loss of samples at 0% RH.

The results were averaged for the different samples of the same type (4 samples, 2 sides) and are shown in Fig. 3 and 4. Firstly, we can observe a significant effect of the density of hemp concrete, giving the heavier concrete a transmission loss greater from 2 to 4 dB, and a narrower peak for the absorption coefficient, moved from about 300 Hz to the lower frequencies. This is more visible for hemp concretes manufactured with “Kanabat” shiv, since they have a greater difference in density (see Tab. 1). These observations are consistent with the results published on the subject in the literature [Glé 2013]. Besides, there is little difference between the formulations with “Kanabat” and those with "Terrachanvre", this effect being generally erased by the binder in hemp concrete.

The acoustical parameters were also analyzed and are presented Fig. 5. Again, we can see that the density effect is the most visible, particularly resulting in lower porosities and increased resistivity and tortuosity for heavier samples.

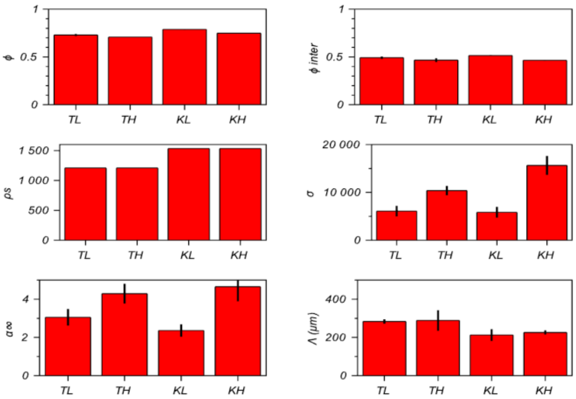


Fig. 5: Acoustical parameters of samples at 0% RH (TL: Terrachanvre Light, TH: Terrachanvre Heavy, KL: Kanabat Light, KH: Kanabat Heavy).

Evolution of the properties with water content

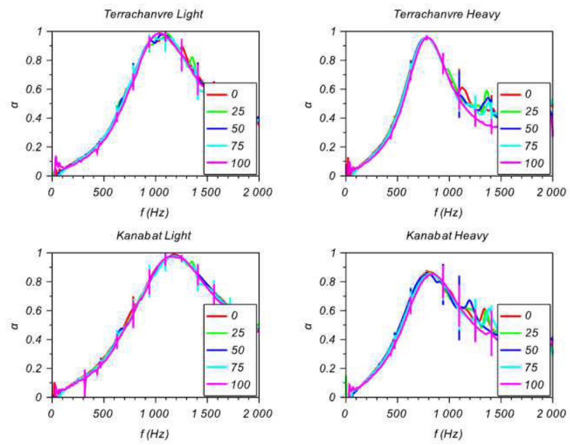


Fig. 6: Sound absorption of samples as a function of relative humidity.

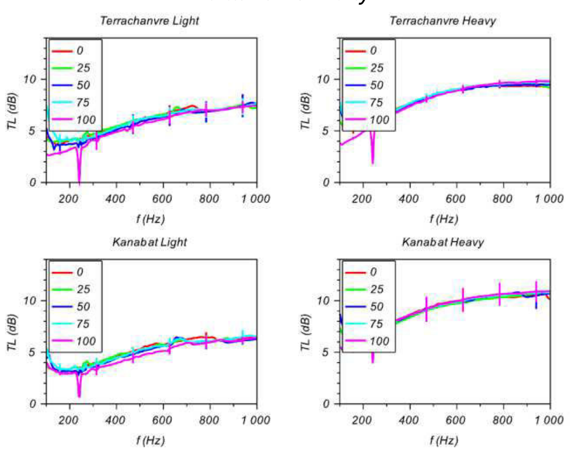


Fig. 7: Transmission loss of samples as a function of relative humidity.

Changes in acoustical properties according to the different levels of water content are highlighted in Fig. 6 and 7. For hemp concretes, the amplitude of the differences is of the same order of magnitude than the measurement uncertainties.

This result is not very surprising since liquid water settles preferably the pores of smaller dimension, that is to say the intraparticles and/or intrabinder pores, while acoustic dissipation is only related to interparticle pores of larger dimension [Glé 2012]. However, these characterizations constitute an additional experimental evidence of this original behavior.

The densities of skeleton determined on the materials are given in Fig. 8 and are characterized by a small decrease for large relative humidities. This evolution was compared to the theoretical evolution calculated assuming a basic superposition of liquid water and skeleton in the material, as described by the following equation where ω is the mass water content, ρ_s and ρ_{water} respectively the skeleton densities of the material and the density of water.

$$\rho_s(\omega) = \frac{1+\omega}{\dfrac{1}{\rho_s(0)} + \dfrac{\omega}{\rho_{water}}} \tag{4}$$

It appears on the figure below that the approach gives consistent results for the various hemp concretes.

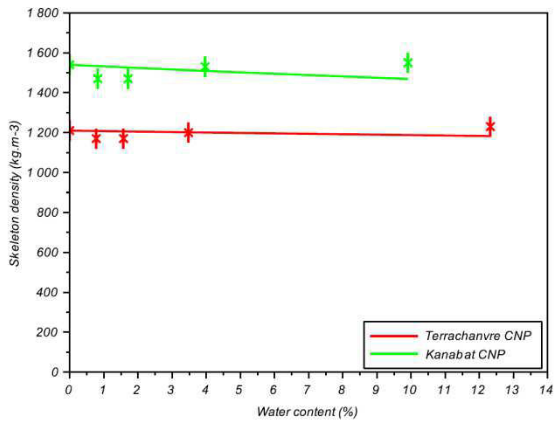


Fig. 8: Evolution of the skeleton density of the materials versus water content - Comparison with theoretical development based on a mixing law.

Regarding other acoustical parameters whose evolution is shown in Fig. 9, we can observe that porosity tends to decrease for the larger relative humidities, which is accompanied by an increase in resistivity and a decrease of the viscous characteristic length. These results show a slight swelling effect of the particles under the effect of moisture. This swelling causes a decrease in porosity due to a narrowing of the small section of interparticle pores, and therefore a rise in resistivity.

The relative humidity therefore has an effect on the acoustical properties and associated parameters. However, this effect remains small compared with axial compaction or clogging effects, which explains that the acoustical properties shown in Fig. 6 and 7 exhibit a relatively stable behavior depending on the relative humidity.

The recommendations which could be given on this basis, in order to overcome the biases related to this issues, is to systematically realize characterizations on samples stabilized at low relative humidity conditions.

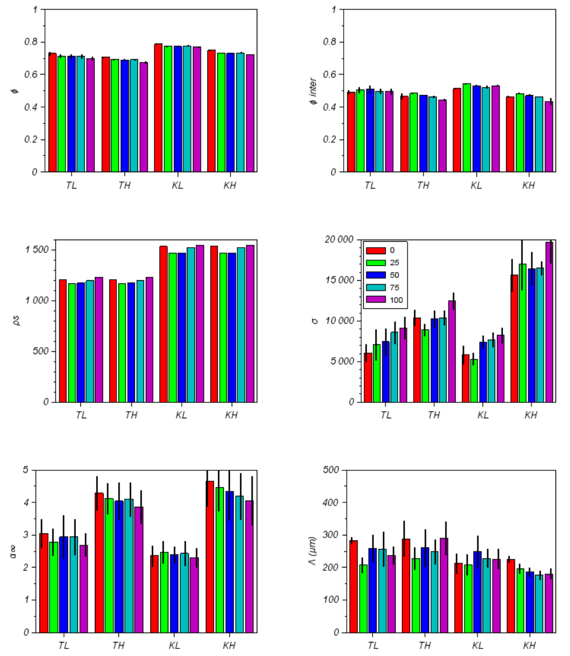


Fig. 9: Acoustical parameters of samples as a function of relative humidity (TL: Terrachanvre Light, TH: Terrachanvre Heavy, KL: Kanabat Light, KH: Kanabat Heavy).

Evolution of the microstructure of shiv after immersion in water

Following the previous observations concerning the evolution of skeleton density of hemp concretes, we extended the characterization in more severe conditions to check whether this parameter is stable or not. Thus, the skeleton density of shiv immersed for different periods in water was assessed.

For these measurements, the bulk particles were dried at 40°C, separated into different batches of the same mass (10 g), and placed in water using individual permeable bags. After fixed periods (ranging between 30 minutes and 100 days), particles were removed from water, and placed back at 40°C until stabilization of their masses. Their weights were then measured, as well as their skeleton densities. A summary of these results is presented in Fig. 10 and 11.

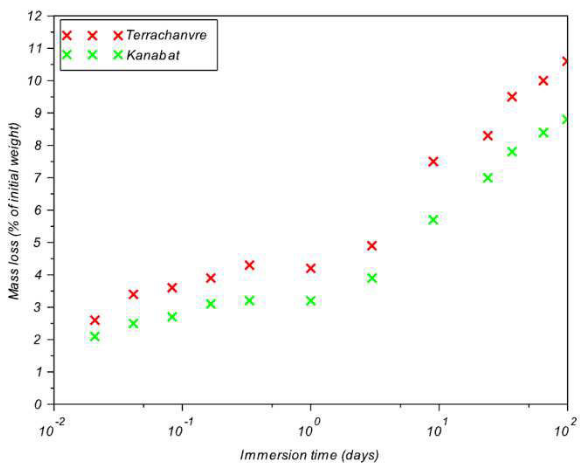


Fig. 10: Mass loss of shiv after immersion in water.

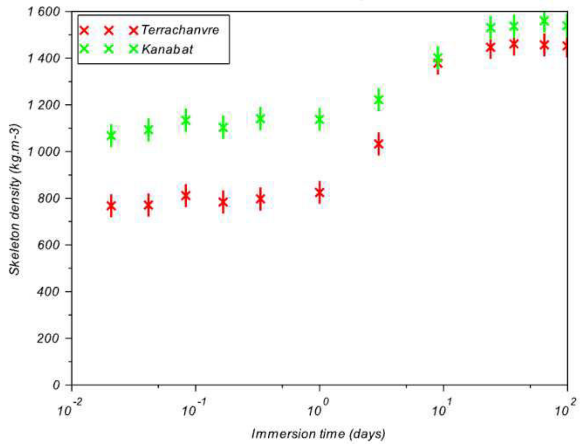


Fig. 11: Evolution of the skeleton density of shiv after immersion in water.

It is seen in these figures that shiv suffer a significant loss of mass during immersion, exceeding 8% after 8 days, which is important especially in comparison with pine wood whose mass loss is about 2% over the same period [Glé 2015]. This mass loss can be explained by a significant amount of water-soluble compounds in shiv [Diquélou 2015]. We notice also that this loss of material is characterized after 2 days by a logarithmic trend, which reflects a slowdown of the degradation process.

Concerning the skeleton density, an evolution is again very pronounced for shiv. Thus, “Terrachanvre” and “Kanabat” shives respectively pass from 800 and 1100 to about 1500 kg.m^{-3}, representing increases of 85 and 35%. It is also interesting to note that these skeleton densities converge to the same value, which could be related to the densities of skeleton of the main components of these particles (1580 kg.m^{-3} for cellulose, 1660 kg.m^{-3} for hemicellulose, and 1410 kg.m^{-3} for lignin [Hirsi 2015]). This point deserves to be explored in future studies. Finally, these measurements show that the skeleton density change occurs mainly in the period between 1 and 10 days, which corroborates previous observations on shiv, retted in water for periods of 10, 20, 30 and 40 days [Glé 2013].

Clearly, these tests demonstrate that immersion affects the microstructure of hemp particles. The fact that the density of skeleton increases indicates that the volume of the skeleton decreases, and therefore, that initially closed pores become open after immersion. This pore opening process could be attributed to a dissolution of material in the walls of the skeleton, or to a micro-cracking of the particles caused by their swelling (such hypothesis is also given in [Stevulova 2013]). However, the finer interpretation of these trends requires complementary analysis (microstructure analysis by 3D tomography or SEM) which is envisaged in future work.

3.3 Changes in thermal properties

Thermal conductivity, thermal diffusivity and specific heat capacity variations with water content were also determined (see Fig. 12, 13 and 14).

Initially, we note that for a given hemp shiv, the densest mixture has a higher thermal conductivity and a higher specific heat capacity. It is also observed that the nature of the shiv used to manufacture a hemp concrete has a significant effect on its specific heat capacity. However, the measured differences in specific heat capacity between “Light” and “Heavy” formulations seem low in light of their stabilized densities presented in Tab. 1.

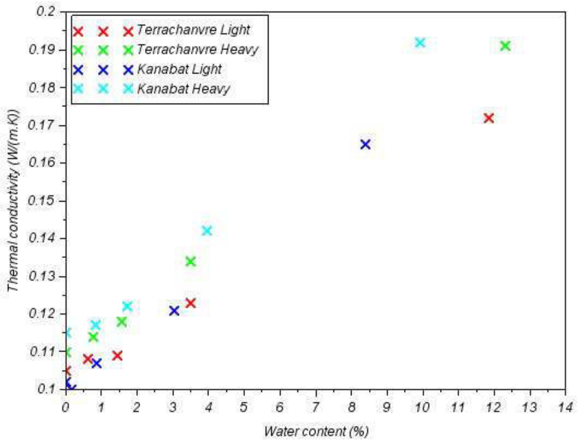


Fig. 12: Thermal conductivity of samples as a function of water content.

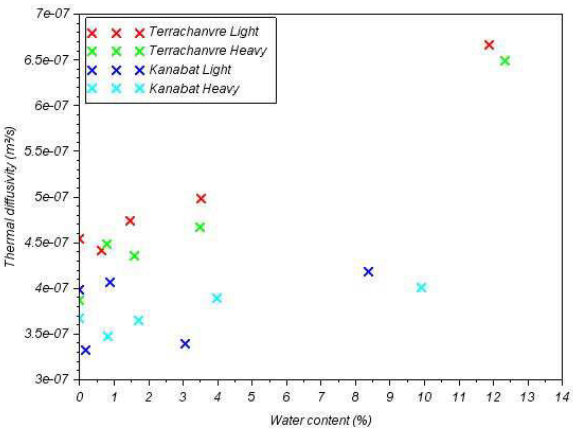


Fig. 13: Thermal diffusivity of samples as a function of water content.

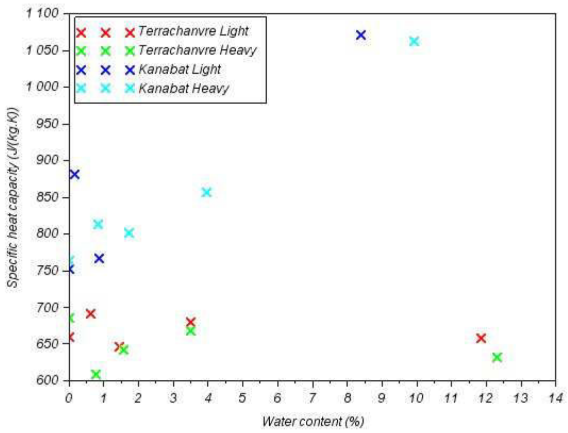


Fig. 14: Specific heat capacity of samples as a function of water content.

Then, as expected, the thermal conductivity of the various hemp concrete mixtures increases almost linearly with water content. In addition, we note that the thermal conductivity of the cylinders increases from 60 to 75% between the dry state and the saturated humidity atmosphere: these increases are slightly lower than those recorded in a similar study [Cerezo 2005] because the water contents of the samples used in this work are lower due to the lower sensitivity to water vapor of the two shives used to make the hemp concretes.

Nevertheless, the evolutions of the specific heat capacities observed are unexpected. Indeed, if the increase is effectively almost linear for the “Kanabat Heavy” formulation, it is observed that the specific heat capacities of hemp concretes based on “Terrachanvre” shiv hardly vary when water content increases. Further studies are underway to explain this phenomenon. It is especially planned to compare the results of this study with those obtained using other thermoanalytical techniques (such as the differential scanning calorimetry) in order to validate the use of such a measurement protocol for this kind of material.

4 CONCLUSION

Hemp concrete made up of plant particles (hemp shiv) and a binder meets a strong need for building materials which are both environmentally and technically efficient. It allows storing CO_2 by recovering a by-product of hemp farming which is thus renewable and easily recyclable. In this paper, four different formulations of hemp concrete were manufactured using a Prompt Natural Cement and two kinds of hemp shives under two different stresses of compaction and the impact of the water content of the specimens on their acoustical and thermal properties is assessed.

First, water content does not affect significantly the acoustical properties of hemp concretes as liquid water settles preferably the intraparticles and/or intrabinder pores, whereas acoustic dissipation is only related to interparticle pores of larger dimension. Still, moisture in the material yields to a light swelling of the particles, which is visible through a rise of resistivity of hemp concrete as well as a decrease of porosity and viscous characteristic length.

However, our results show that the behavior of hemp completely immersed in water is dramatically different than under moisture effect, resulting in a huge increase of skeleton density of shiv related to a microstructural transformation of the material.

Last, thermal conductivity of hemp concrete increases almost linearly with water content for all specimens whereas changes in specific heat capacity, and therefore in thermal diffusivity, differ according to the hemp concretes.

5 ACKNOWLEDGMENTS

The authors especially thank the Terrachanvre company for supplying one of the hemp shives used in this study.

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