INFLUENCE OF LIQUID WATER ON THERMAL AND ACOUSTICAL PROPERTIES OF HEMP CONCRETES

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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 influence of liquid water on thermal and acoustical properties of hemp concretes. It is shown that wetting and drying cycles do not appear to degrade the properties of the material. Moreover, the water added to the surface of hemp concrete does not saturate the surface layer before penetrating more deeply into the material. Nevertheless, when a large amount of water is added, the acoustical behavior of hemp concrete becomes analogous to that of a two-layer material insofar as most of the acoustic energy is reflected by the first layer of hemp concrete, which is completely wet. Finally, the thermal conductivity of the material seems to stabilize from a certain volume of added water.

Keywords:

Hemp concrete; Liquid water; Thermal conductivity; Sound absorption

1 INTRODUCTION

In developed countries, the global contribution from buildings towards energy consumption has risen sharply in recent decades and has even exceeded the other major sectors in EU and USA: industrial and transportation [Pérez-Lombard 2008]. In France, for example, energy consumption of buildings accounted for 44.8% of overall consumption in 2013 [Dussud 2014]. Reducing this consumption is therefore a major challenge for developed countries. However, the building materials generally used are responsible for significant emissions of greenhouse gases [Zabalza Bribián 2011, Van den Heede 2012]: thus, materials with a low environmental impact and excellent thermal insulation properties are now increasingly sought after [Kymäläinen 2008, Benfratello 2013, Nordby 2013, La Rosa 2014].

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 (CO2 storage, reduction of greenhouse gas emissions, etc.) [Pervaiz 2003, Ardente 2008, Ip 2012]. Some of them are also characterized by very good multi-physical properties (heat insulation, sound absorption, transmission loss) [Arnaud 2012, Mati-Baouche 2014] and are already well established on the building market. Hemp concrete (mixture of wood aggregates from hemp stem with a mineral binder) is among these materials one of the most used in EU.

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 and distributed as follows:

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

Furthermore, the vegetal aggregates are made from different hydrophilic macromolecules. Due to these characteristics, hemp concrete has a highly hygroscopic behavior, which is at the root of particularly interesting hygrothermal performances [Tran Le 2010, Shea 2012, Gourlay 2014]. This also implies a very high sensitivity to water vapor and liquid water, much higher than for conventional building materials [Samri 2008]. 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, in order to perpetuate the use of hemp concrete in the building industry, it is necessary to better understand the consequences of its high sensitivity to liquid water on its thermal and acoustical performances. Indeed, in the construction phase for example, before being covered with a plaster, the material can be exposed to rain. Moreover, during the life of the building, disorders can appear and bring a large amount of liquid water within hemp concrete. That is why it was decided in this work to study the impact of liquid water addition on thermal and acoustical properties of a formulation of hemp concrete.

2 MATERIALS AND METHODS

2.1 Manufacturing and curing conditions of hemp concrete specimens

Hemp concrete specimens were manufactured from 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]. Due to the quick setting of the binder, the use of a retarding agent was necessary.

Two kinds of specimens were prepared: cylinders measuring 100 mm in diameter and 40 mm in height for measuring the acoustical and thermal properties of the material and cylinders measuring 100 mm in diameter and 200 mm in height for determining the penetration depth of water into the hemp concrete. The density of the specimens at the time of manufacture was 578±20 kg/m^3.

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 density of the specimens after drying in the oven was 351±9 kg/m^3.

2.2 Specimens wetting protocol

An experimental protocol was developed in this study in order to wet the specimens homogeneously and consistently with a rainy weather.

The liquid water was added to the surface of the material by means of a graduated pipette (see Fig. 1). Thus, the volume of water injected could be controlled precisely. In addition, the specimen was weighed before and after each measurement in order to ensure the amount of water actually present in the material during the test.

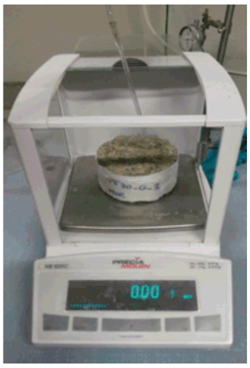

Fig. 1: Specimens wetting protocol.

2.3 Measurement of the penetration depth of water by gamma ray densitometry

The penetration depth of the liquid water into the hemp concrete was evaluated by gamma ray densitometry (see Fig. 2). This is an experimental method, which allows to obtain the density profile of a material. This method is non-destructive and is based on the absorption by the material of the gamma rays emitted by a radioactive source of Cesium 137. The specimen moves at a speed of 6 mm/min in the axis of its height below the gamma ray beam, allowing measurements to be made over the entire height of the material. The rotation of the specimen around its axis makes it possible to obtain also all the radial distributions.

Fig. 2: Gamma ray densitometer.

2.4 Sound absorption coefficient determination

In order to evaluate the sound absorption coefficient α of the material, Kundt tube measurements at normal incidence with a Kundt tube (Brüel & Kjær© Type 4106), presented Fig. 3, were performed in the frequency range [100; 2000 Hz]. The choice of an inner diameter of 100 mm 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.

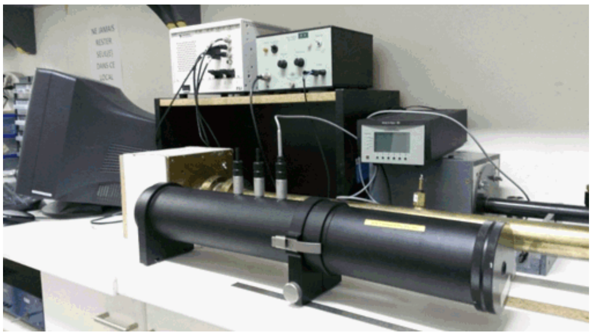

Fig. 3: Device for measuring the sound absorption coefficient.

2.5 Thermal conductivity measurement

The thermal conductivity λ of hemp concrete was 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 (Fig. 4) and to follow the specimen temperature variation using the probe as a resistive thermometer.

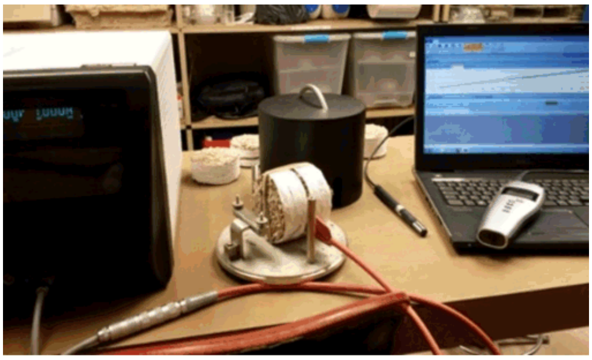

Fig. 4: Hot Disk device.

3 RESULTS AND DISCUSSION

3.1 Penetration of water into the material

In this work, the compactness profile (opposite of porosity profile) of a dry specimen measuring 100 mm in diameter and 200 mm in height was determined by gamma ray densitometry. 100 mL of water were then added to the surface of the hemp concrete and the compactness profile of the specimen was again evaluated in order to know the distribution of the liquid water in the material. This water volume corresponds to a rainfall depth of 12.7 mm at the surface of the hemp concrete. The compactness profile of the wetted material was determined twice by completely drying the specimen between the two measurements (see Fig. 5).

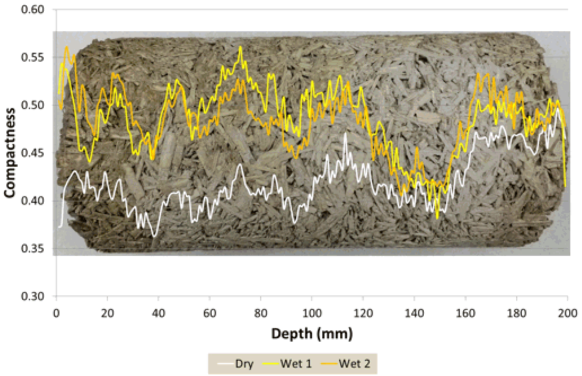

Fig. 5: Compactness profile of hemp concrete before and after wetting.

First, on the curve corresponding to the dry material, there are three regularly spaced minima due to the manufacturing process. Indeed, four layers of about 50 mm in height were compacted one after the other.

Besides, the two measurements carried out on wetted material give very close results, which indicates a good repeatability of the measurement as well as a distribution of the liquid water within the hemp concrete quite similar from one to the other. The two curves obtained meet that corresponding to the dry material at around 140 mm: this means that the 100 mL of water infiltrate up to 140 mm deep into the hemp concrete.

Furthermore, the measurements carried out make it possible to observe that the water does not saturate the surface layer before penetrating more deeply into the material. Water therefore infiltrates through the inter-particle pores into the hemp concrete and penetrates into a part of the intra-particle and intra-binder pores along its path through the material.

3.2 Evolution of acoustical performance

The sound absorption coefficient of hemp concrete was measured in the dry state and after addition of 2, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70 and 80 mL of liquid water, respectively (see Fig. 6).

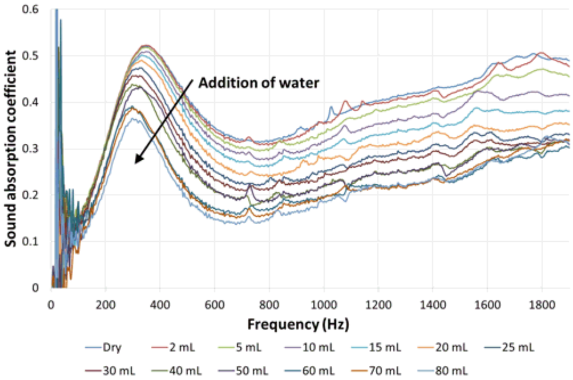

Fig. 6: Sound absorption coefficient of material as a function of added water volume.

If we do not take into account the experimental disturbances at low frequencies (below 100 Hz) due to low frequency limits of loudspeaker and small dimensions of Kundt tube, the curves are fairly regular and clearly illustrate the degradation of the acoustical performance of hemp concrete when liquid water is added to its surface.

The evolution of the sound absorption coefficient of a specimen was determined three times by completely drying it between two measurements. The results obtained show the repeatability of the experiment insofar as the observed differences are of the order of measurement uncertainty (see Fig. 7, 8 and 9). It is noteworthy that despite the very heterogeneous structure of the hemp concrete, the water seems to be distributed quite similarly inside the pores and thus affects the acoustical characteristics of the material in the same way. Moreover, the results obtained show that hemp concrete does not degrade after a wetting and drying cycle despite the addition of 80 mL of liquid water (equivalent to a rainfall depth of 10.2 mm), which is a large amount of water that completely wets the specimen.

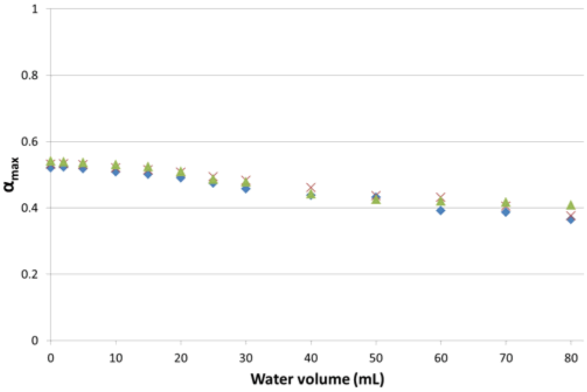

Fig. 7: Maximum of sound absorption coefficient.

There is a decrease in acoustical performance between the dry state and the addition of 80 mL of liquid water of approximately 30% for the maximum and about 50% for the average of sound absorption coefficient. The average is more affected than the frequency peak because, for frequencies above 800 Hz, the gap between the different curves widens: the sound absorption coefficient at these frequencies is therefore more impacted by the liquid water.

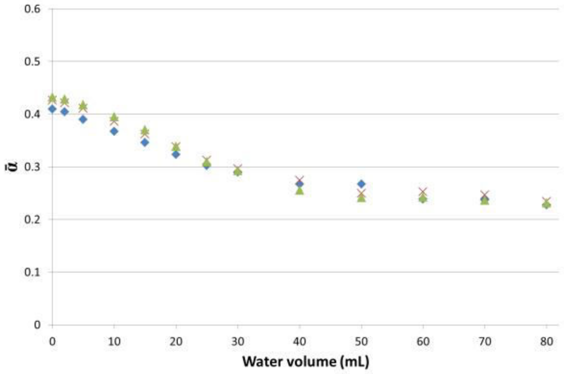

Fig. 8: Average of sound absorption coefficient.

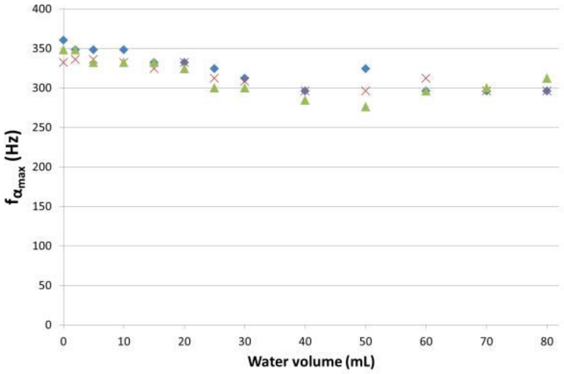

Fig. 9: Frequency of absorption peak.

In Fig. 8, the curve is divided into two parts: the average of sound absorption coefficient first evolves linearly up to 40 mL of added water (equivalent to a rainfall depth of 5.1 mm) and then the slope of the curve becomes smaller. Similarly, in Fig. 9, the frequency of absorption peak, which is mainly related to the value of the tortuosity in the material, stabilizes from 40 mL of added water. This change in behavior of hemp concrete can be explained by the fact that the measurement essentially takes into account the surface condition of the material, which gradually saturates with water up to 40 mL. Beyond this limit, water penetrates more deeply and the surface layer remains saturated. In other words, this is the behavior of a two-layer material whose limiting thickness of its first layer is reached for 40 mL of added water: beyond this thickness, most of the acoustic energy has already been reflected by the first layer of the material and the acoustical properties of hemp concrete stabilize.

3.3 Changes in thermal conductivity

The thermal conductivity of the material was measured in the dry state and after addition of 2, 3, 4, 5, 6, 10, 15, 30 and 50 mL of liquid water, respectively. For each water volume, three measurements were made (see Fig. 10). In each case, the three values obtained are very close to each other and demonstrate the good reproducibility of the measurement.

In Fig. 10, the curve is divided into two parts: the thermal conductivity of hemp concrete first increases linearly up to 5 mL of added water (equivalent to a rainfall depth of 0.6 mm) and then stabilizes at about 0.3 W/m.K. This plateau is due to the limits of the experimental device and to the water saturation of the surface layer. Indeed, the Hot Disk device measures the thermal conductivity only on the first millimeters of the material (up to 20 mm): as soon as the penetration depth of the liquid water into the hemp concrete becomes greater than the probing depth of the Hot Disk device, the measured thermal conductivity remains the same regardless of the amount of added water.

The use of a steady state thermal conductivity measurement device could eliminate this problem but would considerably increase the duration of the study. Furthermore, care should be taken to ensure that water does not evaporate from hemp concrete during the measurement.

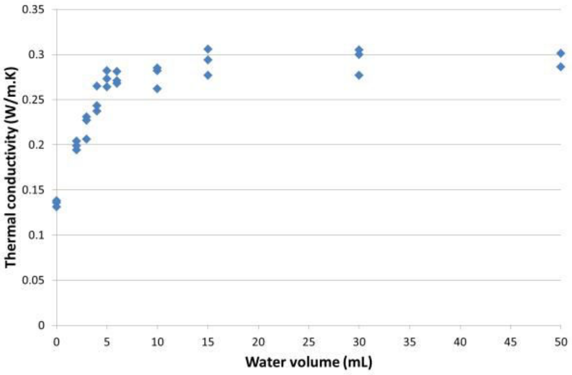

Fig. 10: Thermal conductivity of hemp concrete as a function of added water volume.

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, the influence of liquid water addition on acoustical and thermal properties of a formulation of hemp concrete is assessed.

First, although relatively large amounts of water have been added to the surface of the material, the wetting and drying cycles performed in this work do not affect the properties of hemp concrete.

Besides, it has been established by means of gamma ray densitometry measurements that the water does not saturate the surface layer before penetrating more deeply into the material. Water therefore infiltrates through the inter-particle pores into the hemp concrete and penetrates into a part of the intra-particle and intra-binder pores along its path through the material.

From a certain amount of added water (equivalent to a rainfall depth of 5.1 mm in this study), the acoustical properties of hemp concrete remain relatively constant. Indeed, its behavior becomes analogous to that of a two-layer material: most of the acoustic energy is reflected by the first layer of the hemp concrete, which is totally wet, and the acoustical properties of the material stabilize.

Last, the measured thermal conductivity also no longer changes from a given volume of added water due to the use of an experimental device which is not adapted to the characterization of heterogeneous materials (in this case, a partially wet and partially dry hemp concrete).

5 REFERENCES

[Ardente 2008] Ardente, F.; Beccali, M.; Cellura, M.; Mistretta, M.; Building energy performance: a LCA case study of kenaf-fibres insulation board. Energy and Buildings, 2008;40:1-10.

[Arnaud 2012] Arnaud, L.; Gourlay, E.; Experimental study of parameters influencing mechanical properties of hemp concretes. Construction and Building Materials, 2012;28:50-56.

[Benfratello 2013] Benfratello, S.; Capitano, C.; Peri, G.; Rizzo, G.; Scaccianoce, G.; Sorrentino, G.; Thermal and structural properties of a hemp-lime biocomposite. Construction and Building Materials, 2013;48:745-754.

[Cerezo 2005] Cerezo, V.; Propriétés mécaniques, thermiques et acoustiques d’un matériau à base de particules végétales : approche expérimentale et modélisation théorique. Ph.D. thesis, Vaulx-en-Velin: MEGA INSA de Lyon, 2005 (in French).

[Dussud 2014] Dussud, F.X.; Louati, S.; Mordant, G.; Rouquette, C.; Bilan énergétique de la France pour 2013. Commissariat général au développement durable – Service de l'observation et des statistiques, 2014 (in French).

[Glé 2013] Glé, P.; Acoustique des matériaux du bâtiment à base de fibres et particules végétales - Outils de caractérisation, modélisation et optimisation. Ph.D. thesis, Vaulx-en-Velin: MEGA ENTPE, 2013 (in French).

[Gourlay 2014] Gourlay, E.; Caractérisation expérimentale des propriétés mécaniques et hygrothermiques du béton de chanvre : détermination de l’impact des matières premières et de la méthode de mise en œuvre. Ph.D. thesis, Vaulx-en-Velin: MEGA ENTPE, 2014 (in French).

[Gustafsson 1991] Gustafsson, S.E.; Transient plane source techniques for thermal conductivity and thermal diffusivity measurements of solid materials. Review of Scientific Instruments, 1991;62(3):797–804.

[Gustavsson 1994] Gustavsson, M.; Karawacki, E.; Gustafsson, S.E.; Thermal conductivity, thermal diffusivity, and specific heat of thin samples from transient measurements with hot disk sensors. Review of Scientific Instruments, 1994;65(12):3856–3859.

[Ip 2012] Ip, K. ; Miller, A.; Life cycle greenhouse gas emissions of hemp-lime wall constructions in the UK. Resources, Conservation and Recycling, 2012;69:1-9.

[Iwase 1998] Iwase, T.; Izumi, Y.; Kawabata, R.; A new measuring method for sound propagation constant by using sound tube without any air spaces back of a test material. Internoise 98, Christchurch, New Zealand, 16-18 November 1998.

[Kymäläinen 2008] Kymäläinen, H.R.; Sjöberg, A.M.; Flax and hemp fibres as raw materials for thermal insulations. Building and Environment, 2008;43:1261-1269.

[La Rosa 2014] La Rosa, A.D.; Recca, A.; Gagliano, A.; Summerscales, J.; Latteri, A.; Cozzo, G.; Cicala, G.; Environmental impacts and thermal insulation performance of innovative composite solutions for building applications. Construction and Building Materials, 2014;55:406-414.

[Mati-Baouche 2014] Mati-Baouche, N.; De Baynast, H.; Lebert, A.; Sun, S.; Sacristan Lopez-Mingo, C.J.; Leclaire, P.; Michaud, P.; Mechanical, thermal and acoustical characterizations of an insulating bio-based composite made from sunflower stalks particles and chitosan. Industrial Crops and Products, 2014;58:244-250.

[Nordby 2013] Nordby, A.S.; Shea, A.D.; Building materials in the operational phase - Impacts of direct carbon exchanges and hygrothermal effects. Journal of Industrial Ecology, 2013;17:763-776.

[Pérez-Lombard 2008] Pérez-Lombard, L.; Ortiz, J.; Pout, C.; A review on buildings energy consumption information. Energy and Buildings, 2008;40:394-398.

[Pervaiz 2003] Pervaiz, M.; Sain, M.M.; Carbon storage potential in natural fiber composites. Resources, Conservation and Recycling, 2003;39:325-340.

[RP2C 2012] Règles professionnelles d’exécution d’ouvrages en béton de chanvre. Commission “Règles Professionnelles Construction Chanvre” RP2C, 2012 (in French).

[Samri 2008] Samri, D.; Analyse physique et caractérisation hygrothermique des matériaux de construction : approche expérimentale et modélisation numérique. Ph.D. thesis, Vaulx-en-Velin: MEGA Université de Lyon/ENTPE, 2008 (in French).

[Shea 2012] Shea, A.; Lawrence, M.; Walker, P.; Hygrothermal performance of an experimental hemp-lime building. Construction and Building Materials, 2012;36:270-275.

[Tran Le 2010] Tran Le, A.D.; Maalouf, C.; Mai, T.H.; Wurtz, E.; Collet, F.; Transient hygrothermal behaviour of a hemp concrete building envelope. Energy and Buildings, 2010;42:1797-1806.

[Van den Heede 2012] Van den Heede, P.; De Belie, N.; Environmental impact and life cycle assessment (LCA) of traditional and ‘green’ concretes: literature review and theoretical calculations. Cement and Concrete Composites, 2012;34:431-442.

[Zabalza Bribián 2011] Zabalza Bribián, I.; Valero Capilla, A.; Aranda Usón, A.; Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and Environment, 2011;46:1133-1140.