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Influence of the setting process and the formulation on the drying of hemp concrete

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ABSTRACT

Hemp concrete is a sustainable material that becomes successful in the field of building construction. It is made out of hemp shivs mixed with a lime based binder and water and manufactured through three processes: spraying, moulding or mechanical mixing and tamping. Experiments were performed under natural and forced convection on several instrumented blocks during the curing time. The instrumentation (thermocouples, humidity sensors, weight-scales) allows investigating the drying kinetics and the moisture diffusivity and apprehending the hygrothermal behaviour of the material. It is observed that manufacturing process influences the initial water content and the final density whereas the hygrothermal behaviour depends on the material formulation.

1. Introduction

The construction and building industries are two of the major and most active sector in Europe, but are also responsibles for the depletion of large amounts of nonrenewable resources and for 30% of eq. CO_2 emissions [1,2]. One way to achieve a more sustainable construction industry consists in reducing the raw materials consumption by adding by-products or recycled materials. Such a strategy offers the triple advantage of creating new opportunities for these by-products while preserving natural resources and without changing the conventional construction methods [3–5].

An other way consists in natural building [6,7]. It looks for alternative materials, technologies and methods of construction which significantly reduce resource and energy consumption, provide a better energy efficiency without causing pollution and damaging health and eco-systems. In this respect, vegetable aggregates could be used as a possible input to lighten concrete mixtures [8]. For example, the advantages and limitations of the cement-bonded composites made with lignocellulosic wastes are discussed in the review by Karade [9]. Not mentioned in this review, hemp shivs (or hemp hurds), that are the chopped remains of the woody stem of the plant, may offers large possibilities in the building construction [10–14] as indicated by its positive life cycle analysis [15]. Since the beginning of the nineties, hemp concrete (or Hempcrete) is a lightweight concrete that is often associated with a timber frame and allows a distributed insulation in a large number of buildings in France [12] and in UK [14]. In terms of research, hemp concrete have been analysed in different projects in France [16–19], in Belgium [20], in Switzerland [21], in England [22], in Sweden [23] or in Canada [24].

To form hemp concrete, cement has been first used as binder [23,24], but it was rapidly substituted by a mix of hydraulic lime, hydrated lime and pozzolanic admixtures [25,26]. With appropriate proportion of hemp and binder, hemp concrete can cover different use in a building [16]: *Roof insulation* (minimal coating of hemp shivs to fix them to each other), *wall* (good compromise between the thermal and mechanical properties) and *ground floor insulating slab* (the more proportion of lime, the greater mechanical properties).

Similarly to classical concrete, three different processes are developed for setting hemp concrete [11]: *Moulding of prefabricated blocks, mechanical mixing and tamping and Spraying*. Each of building techniques has its advantages and disadvantages. The first one is referred as dry method of building, since the blocks are dried before on production site. According to Bevan and Woolley [11], even though prefabrication and new dry forms of timber frame construction seem very efficient, they do involve a number of trades and it is easy for things to go wrong, like construction's failure or heterogeneities in the block's series. On the other hand, spraying and mechanical mixing and tamping, which are considered as wet processes, provide a more continuous homogenous mass. However, before the application of any plaster, hemp concrete should be allowed to dry. This critical step depends mainly on the amount of water added at construction and the ambient conditions experienced during the curing period. Nevertheless,

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Nomenclature

Roman		t	time (s)
D_w	effective moisture diffusion coefficient ($m^2\ s^{-1}$)	X	moisture content $g_{H_2O}\ g_{dry}^{-1}$
F_m	drying rate ($g\ h^{-1}\ m^{-2}$)		
L	thickness of the slab (m)	*Greek*	
T	temperature (°C)	p	density ($kg\ m^{-3}$)

drying time is supposed to be reduced with the spraying technique, but it was actually never measured [20].

Whatever the material formulation or the setting processes, the previous results pointed out that final product has a low bulk density ($300 < \rho < 600\ kg\ m^{-3}$) and an high porosity ($\varepsilon > 0.65$) [27]. Consequently, it shows the thermal conductivity (λ) at ambient conditions (23 °C, 50% rh) which lies between 0.07 and 0.2 $W\ m^{-1}\ K^{-1}$ [17] and its acoustical absorption factor of samples without coating is between 0.5 and 0.9 [16]. Nevertheless, the mechanical behaviour in both compression and tension is found to be too low (generally a few MPa) since it depends on the mechanical behaviour of binder paste. Consequently, hemp concrete cannot be used for structural purposes up to now, but only to fill or cover a structure with sufficient load capacity [6,25]. Furthermore, Arnaud [28] and Cerezo [16] pointed out that the mechanical properties reach rapidly an initial level and then evolve slowly during two years at least, which is typical of the setting kinetics of lime.

On the other hand, a very few works deal with hygric properties. Water vapour sorption isotherms and vapour permeability was measured by Collet [17] and Evrard [20], whereas the liquid absorption coefficient was determined by De Bruijn et al. [23] and Evrard [20]. Similarly, the hygrothermal behaviour of hemp concrete during the curing time or even in use is practically not investigated in terms of numerical simulations or of specific experiments. Up to now, drying experiments on hemp concrete have been carried only by Bütschi et al. [24] and Evrard [20], who studied the effect of the material formulation (in terms of water to binder mass ratio) or the mixing process. However, these results were not interpreted in terms of evaporation rate and of transport parameters.

In this work, a specific experimental set-up and methodology is developed in order to investigate the drying of different samples. The objective is to complete the previous set of results and to explore experimentally the significance of the setting process, of the initial composition and of the operating conditions on the drying of hemp concrete, but also on the hydric transfer within the material. In this view, the paper is divided as follow: Section 2 contains the samples preparation and the measurement methodology whereas Section 3 presents the method to determine moisture diffusivity using experimental data. In Section 4, results are presented and discussed before the conclusion.

2. Materials and methods

2.1. Material setting and formulation

In this work, the three following setting processes are investigated (see Table 1):

- *Process A (Moulding of prefabricated blocks)*: hemp, binder and water are first mixed at low speed for 5 min into a twin screw mixer and fills then the blocks by the top in a moulding unit. Vibrations are applied to ensure that air bubbles are not trapped in the fresh mixture and the excess is then removed by levelling. After 1 day, moulds are removed and blocks are dried in the storage unit.
- *Process B (Mechanical mixing and tamping)*: binder is first mixed with water into a mechanical mixer for around 5 min until an homogeneous past is obtained, and then hemp shivs are progressively added. The hemp concrete mixture fills then the mould (generally of large dimension). Last, the mixture is tamped to avoid large air voids in the material.
- *Process C (Spraying)*: spraying requires specialist equipment in order to project the mixture directly into block moulds located at a distance of about 1 m. Two spraying processes are specifically investigated: in the first one (*Process C1*), a dry premix of lime and hemp shivs is conducted by air through a hose, and pulverised water is added just before the hose outlet [29], in the second one (*Process C2*), only hemp shivs is conducted through a hose and a formulated binder paste (mix of water and lime) is pulverised at the hose outlet.

The comparison between these three processes is based on samples manufactured according to the *wall* formulation. Basically, the *wall* formulation is defined as follow [16]: 17%wt of Chanvribat® hemp shivs, 33%wt of Tradical pf70® lime binder and 50%wt of water. Among the numerous samples provided by different industrial partners, only the sprayed block (*Process C1*) respects this formulation. The other one may use shivs with higher fibres content (*Process B*) or a preformulated lime-binder specifically adapted to the process (*Processes A and C2*). Consequently, their proportion is lightly adapted, but remains in the same order of magnitude as the base definition.

Similarly, the influence of density is investigated through two series of blocks manufacturated according to the *Process A* and to two *ground floor* formulations. Compared to the *wall* formulation, the proportion of binder increases whereas the fractions of hemp shiv and water decrease. The two series of block have the same proportion and the difference comes from the type of binder. Last, the mass ratios of all mixtures are tabulated in Table 1.

Whatever the process or the formulation, all samples are realised in moulds made of bakelized plates with dimensions of $30 \times 30 \times 16\ cm^3$ (Fig. 1a). The sample thickness was set to 16 cm since it corresponds to the half thickness of a usual hemp concrete wall. The two other dimensions are adapted to the drying vein in order to conduct the experiment simultaneously on four blocks. Such dimensions are in the order of magnitude of prefabricated blocks, but smaller than wall panels. However, since the objective of the paper is to compare blocks manufacturated with different setting process and different formulation, such dimensions may be reasonable in term of experiment duration, and still remain much larger than the representative volume element defined by Collet [17].

After their fabrication by the industrial partners, the blocks were completely sealed during 2–5 days, where there are supposed having no significant weight variation during this early-age period. They are then transported to the laboratory in order to investigate their curing.

2.2. Experimental set-up

The purpose of the present experiments is to measure the evolution of temperatures, relative humidities and mean moisture content of different hemp concrete blocks as a function of time and of two different convective configurations. In the first one, blocks are subject to natural (or free) convection: they are placed in a room, wherein a sensor controls the temperature, the relative humidity and eventually the regulation accuracy. In the second configuration, blocks are dried under forced convection conditions in a special experimental apparatus that was specially developed and designed to measure 1-D heat and moisture transfer between a flowing air stream and a stationary porous material, as it is shown on Fig. 2. A laboratory-drying tunnel of square shape of dimension ($80\ cm \times 27\ cm$), supplied upstream by a convergent for a good velocity distribution and downstream by a divergent so as to avoid the removement in the drying vein, produces a steady, fully developed air flow above the material. The airflow is provided by a variable speed fan, which draws air with an average velocity varying between 1 and 4 $m\ s^{-1}$. Air is pumped from a climatic chamber wherein temperature and relative humidity is controlled. Temperature and air relative humidity measurements are performed in the vein inlet and outlet by two thermohygrometers, whereas drying air velocity is done by hot-wire anemometer.

Whatever the drying mode, the bottom and all sides of the samples are impermeable and only the top surface of $0.09\ m^2$ is in contact with air. The measurement method consists of fixing values of air temperature, relative humidity and of air velocity for every test and controlling as function of time the evolution of the following parameters in an instrumented block (Fig. 1b):

- Product mass measurement is done by a display digital weighing apparatus with an accuracy of 0.1 g.

Table 1
Overview of the sample's formulation and preparation.

Setting process	Material reference	Hemp shivs	Binder paste or {binder + water}
Process A	Wall	23% wt	Formulated binder A1: 40% wt Water: 37% wt
Process A	Floor 1	20% wt	Formulated binder A2: 47% wt Water: 33% wt
Process A	Floor 2	19% wt	Formulated binder A3: 48% wt Water: 33% wt
Process B	Wall	16% wt (With fibres)	Tradical PF 70: 36% wt Water: 48% wt
Process C1	Wall	17% wt	Tradical PF70: 35% wt Water: 48% wt
Process C2	Wall	20% wt	Formulated binder: 45% wt Water: 35%wt

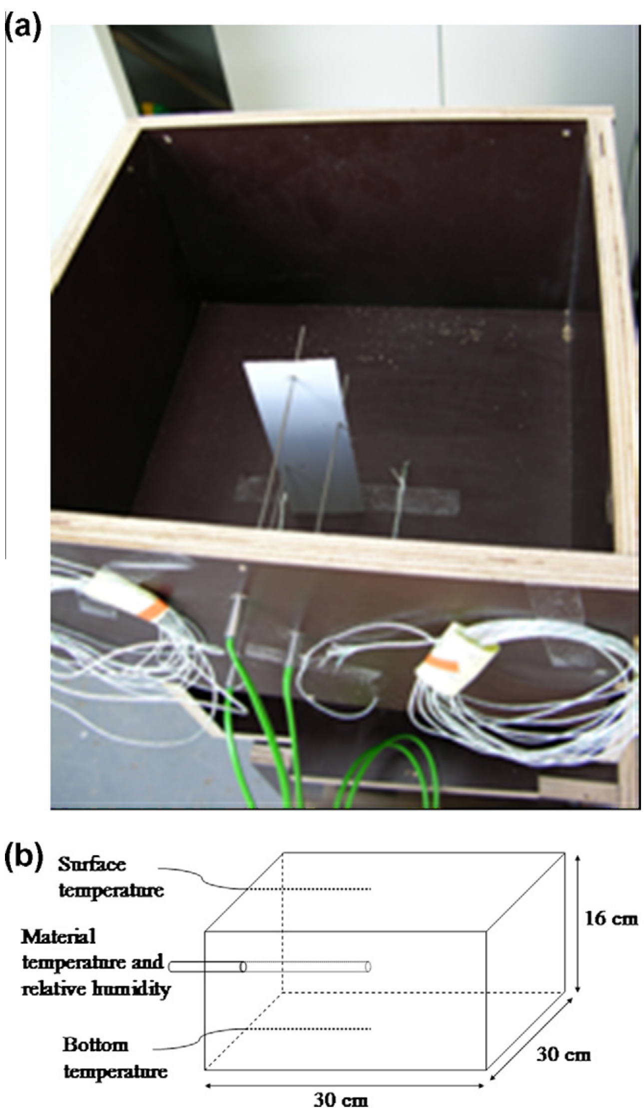

Fig. 1. Overview of a mould for hemp concrete block (a) and position of the instrumentation (b).

- Relative humidity and temperature measurement within the material (approximately at 8 cm from the drying surface) is done with a Sensirion SHT75 sensor of diameter d = 6 mm. This thermohygrometer have a maximal accuracy of 4% (resp. 0.5 K) in relative humidity measurement (resp. temperature measurement).
- Temperature measurement is performed at different positions (at 4, 8, 12 and 16 cm from the drying surface) by chromel/alumel thermocouples of diameter d = 1 mm and measurement accuracy of about 0.5 K.
- Surface temperature of the product is indicated by an optical pyrometer. Additional K-thermocouples allow measuring this value.

All temperature and relative humidity sensors and weight-scale are connected to an acquisition system and data are recorded every 10 min. The experiment is performed until the product mass is stabilized. According to the norm EN 772-13:2000 [30], constant mass is reached, if during the drying process in two subsequent weighings with a 24 h interval, the loss in mass between the two determinations is not more than 0.2% of the total mass. At the end of the experiment, the sample is dried in a ventilated oven at 60 °C until the complete dewatering of the product in order to get the dry mass.

3. Analysis of the experimental data

3.1. The role of water during the curing time

Water enters into the initial composition of hemp concrete in addition to the preformulated lime-binder and the hemp shivs and its initial amount depends on the setting process. During the setting and the curing of hemp concrete, water plays different roles:

- Water can be absorbed quickly by the hemp shivs during the mixing. Indeed, it was shown that hemp shivs can absorb a large amount of water in less than 5 min [16]. On the other hand, water can also be released if necessary. The hydrophilic behaviour of hemp shivs makes tough the water management during the manufacturing and setting time. Nguyen et al. [25] supposed that it is due to a lack of data concerning hemp shiv characteristics and the best granular size distribution for hemp concrete.
- Water is needed to ensure the hydration reaction: dicalcium silicate (C_2S), and tricalcium silicate (C_3S) contained in hydrated lime [31] react with water (H_2O) to form calcium silicate hydrate (C–S–H) and bulk calcium hydroxide ($Ca(OH)_2$) according to:

$$2(2CaO \cdot SiO_2) + 4H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + Ca(OH)_2 \qquad (1)$$

This reaction kinetic is fast in case of C_3S (few hours) and slower in case of C_2S (few days), which is the dominating phase in lime. Hydration is obviously enhanced under moist conditions.

- In opposition to hydration, the carbonation reaction form free water: bulk calcium hydroxide ($Ca(OH)_2$), which can be obtained from quicklime after hydration or other hydraulic lime, reacts with carbon dioxide (CO_2) to form calcium carbonate ($CaCO_3$) and water (H_2O) according to:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (2)$$

This reaction occurs over several years and is much slower in comparison to hydration reaction. Contrary to hydration, carbonation is promoted under dry conditions or in exposition to high level of CO_2

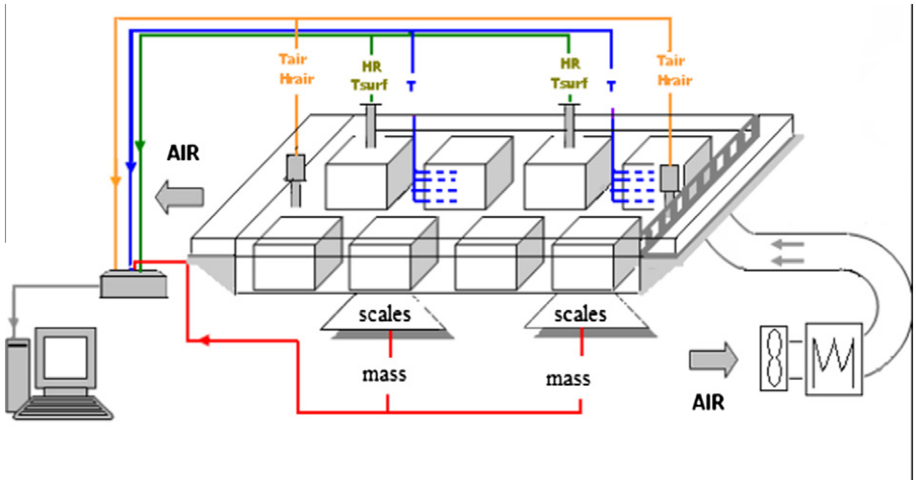

Fig. 2. Schematic view of the air flue.

since both diffusion and dissolution of the CO_2 is possible in the pore system.

- Last, water can also migrate from the centre to the surface through a diffusion pathway, evaporate at the surface and thus be transferred in the air layer close to the surface. This phenomenon is faster than the carbonation reaction and in competition with hydration reaction.

All these phenomena occur not simultaneously during the curing time. During the early-age period (between 2 and 5 days after fabrication), hemp concrete is either placed under moist conditions or completely isolated so that no water exchange can occur between the sample and the environment. Water may still be absorbed by the hemp shivs, but is more probably consumed by the hydration reaction, creating thus a first micro-porosity in the lime-binder and ensuring a sufficient strength development of the material.

After the early-age period, hemp concrete is stored in an air-conditioned room or in ambient condition: hydration reaction is in competition with water transfer. Water evolves through different states during dewatering [32]. At the beginning, water is in a funicular state: free water forms a saturating or non-saturating continuous liquid phase and can be transported to the surface and evaporates until the pendular state is reached. At this point, liquid water exists in disconnected separate islands and water can only be removed via a slow vapour transport until the residual water content is reached. This operation, generally referred to drying [20], results in a loss of mass through the open surface and takes some weeks depending on the sample size [33]. At the same time and after the end of the drying stage, the very slow carbonation reaction occurs: small amount of free water is released, mechanical properties are improved and pores size, water absorption surface and transport characteristics is reduced as it was shown by Lawrence et al. [34] in case of lime-mortar. If the curing conditions are too dry, carbonation occurs only the lime surface (skin effect) whereas the centre of the material has no consistency (powder aspect) [16] since the carbonation reaction prevails the hydration reactions and attacks the hydrated phases leading to their decalcification [35]. At the end, carbonation results in an increase of mass as molar mass of lime stone is 35% higher than hydrated lime. However, this reaction is very slow and mass increase occurs in several months. Thus, it can be supposed that the mass change during the drying time can be attributed only to water loss of the material.

Finally, two curves can be obtained from the weight's measurement of the samples:

- The drying curves, based on the variation of the water content (dry basis) in the product as a function of time,
- The drying rate curve, defined as the speed of mass loss per drying surface unit as a function of time.

These curves may also be interpreted in terms of water transport as it is explain in the next subsection.

3.2. Effective water diffusivity estimation

When drying processes take place during the falling rate period, Fick's second diffusion law (Eq. (3)) can be used to interpret the experimental drying data since unsteady-state moisture (liquid or vapour) diffusion to the surface of the porous media is one of the main transport phenomena that describes this drying period.

$$\frac{\partial X}{\partial t} = D_w \nabla^2 X \tag{3}$$

X is the dry-basis moisture content, t is the time and D_w the effective moisture diffusion coefficient in whole of the material. Here, the moisture diffusion represents all moisture gradient driven transfer mechanisms such as capillary flow (diffusion in liquid phase), migration in the adsorbed layer, vapo-condensation or true diffusion of vapour in air.

Crank [36] proposed analytical solutions of Eq. (3) for diffusion in plane sheets, cylinders and spheres. Solutions for plane sheets apply to samples so thin that effectively all the diffusing substance enters through the plane faces and a negligible amount through the edges, which is the case here. Assuming uniform initial moisture distribution, negligible external mass transfer resistance (i.e. constant concentration at the sample surface), constant slab thickness L and final equilibrium moisture content close to zero, the analytical solution of Fick's equation is written for a rectangular slab:

$$X_{red} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-\frac{(2n+1)^2 \pi^2 D_w}{4L^2} t\right] \tag{4}$$

where X_{red} is the dimensionless moisture content ratio, defined by:

$$X_{red} = \frac{\overline{X} - X_{eq}}{X_0 - X_{eq}} \tag{5}$$

with X is the moisture content, X_{eq} the equilibrium moisture content and X_0 the initial moisture content.

Eq. (4) can be simplified and linearised in two different ways, for two distinct time periods: at the beginning and at the end of the diffusion process. For short diffusion time, Eq. (4) becomes [37]:

$$X_{red} = 1 - 2\sqrt{\frac{D_w}{\pi L^2} t} \tag{6}$$

and can be transformed to a linear function of time as follow:

$$\frac{\pi L^2}{4}(X_{red} - 1)^2 = D_w t \tag{7}$$

Thus, the moisture diffusivity D_w can be calculated from the slope of the relative moisture content versus square root of time to square thickness ratio plot, this plot being expected to exhibit linearity within the considered moisture content domain.

For long diffusion time, Eq. (4) becomes [37]:

$$X_{red} = \frac{8}{\pi^2} \exp\left[-\frac{\pi^2 D_w}{4L^2} t\right] \tag{8}$$

and can be transformed to a linear function of time in the following way:

$$\frac{4L^2}{\pi^2}\left(\log\left(\frac{8}{\pi^2}\right) - \log(X_{red})\right) = D_w t \tag{9}$$

Thus, the moisture diffusivity D_w can be calculated from the slope of the natural logarithm of relative moisture content versus time, this plot being expected to exhibit linearity within the considered moisture content domain.

Even if the Fick's second law neglects the effects of gravity, temperature and pressure on mass transfer, as well as the hydration and carbonation reactions, and if the Crank's solution is valid for restrictive cases, Eqs. (7) and (9) can easily provide an order of magnitude of the effective moisture diffusion coefficient D_w.

4. Results and discussion

The drying results are first presented for a hemp concrete elaborated according to the *Process A* and to a *wall* formulation, for which the methodology is introduced and the influence of the drying mode is discussed. The influence of the formulation is also investigated. Then, this methodology is applied to blocks used in wet method of building (*Processes B, C1* and *C2*) Last, the influence of the manufacturing process is discussed.

4.1. Drying of prefabricated blocks (Process A)

4.1.1. Drying in forced convection

This part presents the results for block drying under forced convection conditions. Before analysing the experimental data, it should be noted that the experiment time is long (more than 4 months) and that the data acquisition was interrupted only three times (at the 15th, 30th and 110th day) due to power outage. Fig. 3a shows the evolution of temperature and relative humidity in the air flue. Air temperature is controlled at $T = 22$ °C during the drying period whereas the relative humidity oscillates between 30% and 60% around an average value of 45%. These conditions are consistent with the results of Arnaud and Gourlay [38], who found that a cure with 20 °C and 50% RH lead to the highest compressive strength for their material. Fig. 3b and c presents respectively the mean moisture content and the drying rate through the upper face of the sample as function of time. Both figures contains also the local measurements, i.e. the relative humidity measured within the material (see Fig. 3b) and the temperature differences between

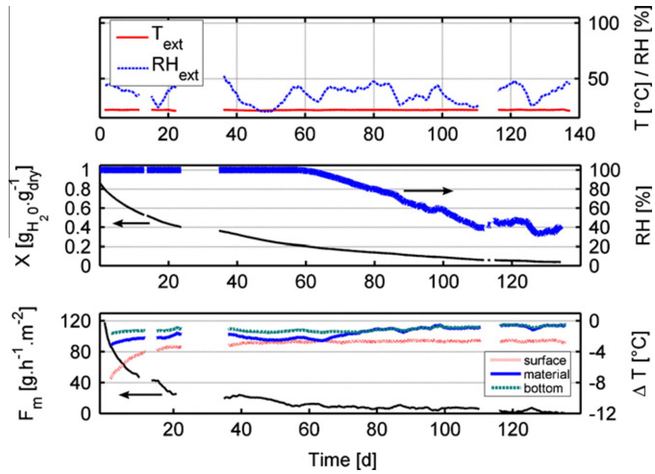

Fig. 3. Drying under forced convection of hemp concrete manufacturated according to the *Process A*. Time evolution of experimental drying conditions (a), of mean moisture content (black line) and of relative humidity within the material (bold blue line) (b), of drying rate (black line) and of temperature difference between the sample and the air. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the air flue and respectively the surface, the middle and the bottom of the material (see Fig. 3c).

For this formulation and this process, the initial moisture content is about 0.87 $g_{H_2O}\ g_{dry}^{-1}$. After drying begins, the mean moisture content starts to decrease immediately and continuously. The loss of water is more accentuated in the 25 first days and the drying rate reaches values from 40 to 120 $g_{H_2O}\ h^{-1}\ m^{-2}$. This corresponds to the period of high free water removal, in which the rate of water evaporation to the surface is lower than the rate of water migration. Since evaporation is an endothermal reaction, the surface temperature of the material is about 8–4 °C lower than the air. Temperature differences within the material are also lower and can be due to heat conduction from the bottom to the surface, not to evaporation since the relative humidity within the material is still at saturation. As the drying proceeds (after the 35th days), the mean moisture content evolves slowly and the drying rate reaches values lower than 20 $g_{H_2O}\ h^{-1}\ m^{-2}$. The evaporation is progressively completed from the interior of the material, and moisture is transported by diffusion to the surface. Particularly, contrary to the two other location, the temperature decreases in the middle of material between the 40th and 65th day, indicating that the evaporation front reaches this region of the material. This is confirmed by the fact that the relative humidity within the material starts to decrease from the 60th day. From this point, the temperature increase again within the material and the relative humidity decrease progressively until the drying is completed. According to the mass variation, drying seems to be completed after 80–100 days. However, it should be noted that at this time, the relative humidity within the material is not yet equilibrated with the environment. This is done around the 110th day: the relative humidity reaches values of about 40% (which are close to those in the air), whereas temperatures are stabilized within the material. Both are sensitive to ambient conditions variations. For example, a decrease in the air relative humidity around the 125th day induces a small increase in the drying rate and in the temperature differences and also a decrease in the relative humidity within the material. However, since the mean moisture content has almost reaches his equilibrium value, no significant changes can be observed. At the end of the process, the final moisture content is about 0.05 $g_{H_2O}\ g_{dry}^{-1}$, which is consistent with the one expected from the isothermal desorption curve [17], and the final density is about 420 kg m^{-3}.

4.1.2. Effective water diffusivity estimation

Fig. 4a presents the dimensionless moisture content ratio according to the Eq. (5) where the equilibrium moisture content X_{eq} and the initial moisture content X_0 are respectively set to 0.05 $g_{H_2O}\ g_{dry}^{-1}$ and 0.87$g_{H_2O}\ g_{dry}^{-1}$. Fig. 4b and c correspond respectively to the plot of the left term of Eqs. (7) and (9) as a function of time. As it can be expected, the two functions depend linearly on time. By using the *polyfit* function of Matlab, the effective moisture diffusivity can be calculated from the slopes of the dashed lines plotted in Fig. 4 for short and long diffusion time. The results are reported in Table 2. Both coefficients have the same order of magnitude and are respectively equal to 0.823×10^{-9} m^2 s^{-1} and 0.838×10^{-9} m^2 s^{-1}.

4.1.3. Influence of the drying mode

Fig. 5 presents the hemp concrete density as function of time for the two drying configurations: free convection and forced convection. Even if the manufacturing process and the material composition are the same, a small difference is observed in the initial density, which corresponds to a classical deviation of industrial processes. Nevertheless, as the drying proceeds until the 50th day, differences in density decreases since drying rate is higher in case of forced convection than for free convection. From the 50th day, almost no differences are observed between free and forced convection. At this point, it should be noted that air speed in the drying vein is equal approximately to 2 m s^{-1} for this experiment and the associated convective heat coefficient is approximately 10 W m^{-2} K^{-1}, which is in the same order of magnitude of free convection. An higher air speed could accelerate the drying stage, but also modify the hygrothermal conditions within the material, and thus influence the kinetic of hydration and carbonation reaction and finally the mechanical properties. This point is not investigated in this work.

Last, as it could be expected, the drying time for reaching a final density of 420 kg m^{-3} is about 15 days longer in case of free convection than of forced convection, although the effective moisture diffusion coefficients (for long diffusion time) are in the same order of magnitude.

4.1.4. Influence of the formulation

Fig. 5 presents also results for analysing the influence of the composition. In addition to the reference block, two blocks are fabricated according to two specific *ground floor* formulations. Both samples contain less hemp shivs than the reference one, and thus more binder (see Table 1). Consequently, as it can be observed on Fig. 5, the initial density increase with an increasing binder fraction. As the drying proceeds, the difference in density between the three samples remains the same. Indeed, the drying rates for every sample are similar, and the loss of water seems not to be influenced by the hemp concrete formulation. This last point is confirmed by the three identical values of the effective moisture diffusion coefficient (for long diffusion time). At the end, the density ranges from 420 to 580 kg m^{-3}, increasing with the binder fraction.

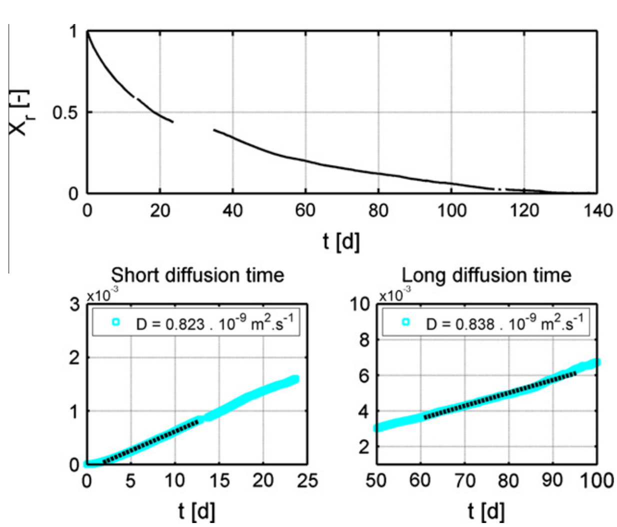

Fig. 4. Dimensionless moisture content as function of drying time and linear plots for short (Eq. (7)) and long diffusion time (Eq. (9)).

4.1.5. Intermediate conclusion

Whatever the formulation, the global mass of prefabricated blocks is stabilized after 80–115 days whereas the relative humidity is equilibrated with its environment around 10–15 days later. Moreover, almost no differences in drying time are observed between the two drying modes. Consequently, since they are produced on an industrial site, storage under ambient conditions could be sufficient to cure every kind of hemp concrete blocks. Furthermore, drying time could be reduced by subjecting all the faces to natural convection rather one.

4.2. Drying of blocks used in wet method of building

In the present part, the methodology developed in the Section 4.1 is applied for investigating the drying of blocks used in wet method of building. In this purpose, two others series of blocks were fabricated according to the *Process B* (mechanical mixing and tamping) and the *Processes C1* and *C2* (spraying).

4.2.1. Drying of mixed and tamped blocks (Process B)

The drying results of mixed and tamped blocks are presented in Fig. 6. Fig. 6a shows the evolution of temperature and relative humidity in the air flue inlet for blocks dried under forced convection conditions or in the ambience for the blocks dried under natural convection conditions. Once again, the conditions are around 22 °C and 50% RH.

On Fig. 6b, the evolutions of the mean moisture content and of the material relative humidity are plotted for a block dried under forced convection. Fig. 6c presents the evolution of density of two blocks dried under forced or free convection conditions. Similarly to the prefabricated blocks, water content of mixed and tamped blocks has an initial value of $\approx 0.85\ g_{H_2O}\ g_{dry}^{-1}$ (corresponding to an initial density of $\approx$ 850 kg m^{-3}) and decreases regardless of the drying mode as the drying proceeds. According to the definition of the drying time, the mass is stabilized and the drying proceeds in about 70 days, which is faster than for the prefabricated blocks. This is confirmed by the value of the effective diffusivity, which is 1.5 higher than for the prefabricated blocks. Nevertheless, even if the block is dried, the local relative humidity starts to decrease only after the 125th day, indicating that the evaporation front moves slowly within the material, but also resulting from more humid conditions than for the other experiments. At the end, whatever the drying mode, the density reaches a final value of $\approx$ 480 kg m^{-3} after 140 days.

4.2.2. Drying of sprayed blocks (Processes C1 and C2)

The results of sprayed blocks are displayed on Fig. 7 in the same manner as on Fig. 6, i.e. drying conditions on Fig. 7a, water content and material relative humidity on Fig. 7b and density of Fig. 7c. Moreover, Fig. 7 enable the comparison between the *Process C1* ({hemp shivs + binder} + water) and the *Process C2* (hemp shivs + binder paste).

In opposition to the prefabricated blocks or the tamped blocks, sprayed blocks have a low initial water content (in the order of

Table 2
Initial water content, final density, drying time and estimated effective moisture diffusion coefficients of the different samples.

	Material reference	Drying mode	T_{air} (°C) HR (%)	X_0 (g/g_{dry})	ρ (kg/m^3)	Drying time (day)	10^9 D_w (m^2 s^{-1}) (Eq. (5))	10^9 D_w (m^2 s^{-1}) (Eq. (7))
Process A	Wall	Forced	22 °C 30–60%	0.87	420	80–100	0.823	0.838
Process A	Wall	Free	–	–	420	95–115		1.1
Process A	Floor 1	Free	–	–	480	115		1.09
Process A	Floor 2	Free	–	–	580	115		1.09
Process B	Wall	Forced	20–23 °C 35–55%	0.85	470	75	1.183	1.265
Process B	Wall	Free	20–23 °C 35–55%	0.74	480	65	1.175	1.219
Process C1	Wall	Forced	22 °C 30–60%	0.41	420	40–70	0.868	0.883
Process C2	Wall	Forced	22–26 °C 40–50%	0.31	340	30	0.978	2.01
Process C2	Wall	Free	22–26 °C 40–50%	0.3	335	20	0.554	0.771

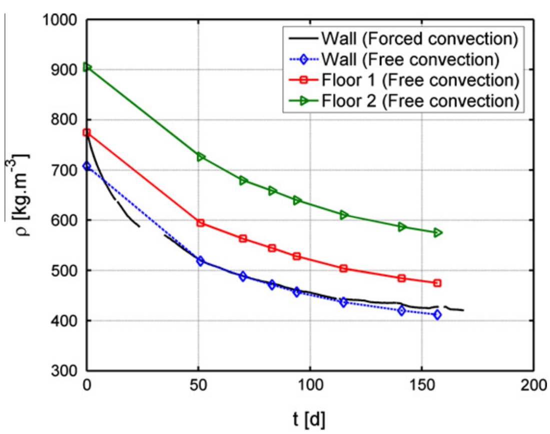

Fig. 5. Influence of the drying mode and of the formulation on the density.

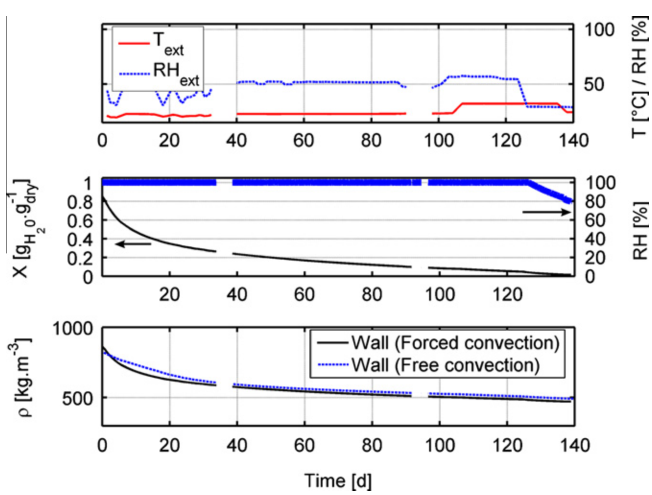

Fig. 6. Drying of hemp concrete manufacturated according to the *Process B*. Time evolution of experimental drying conditions (a), of mean moisture content (black line) and of relative humidity within the material (bold blue line) (b), of density (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

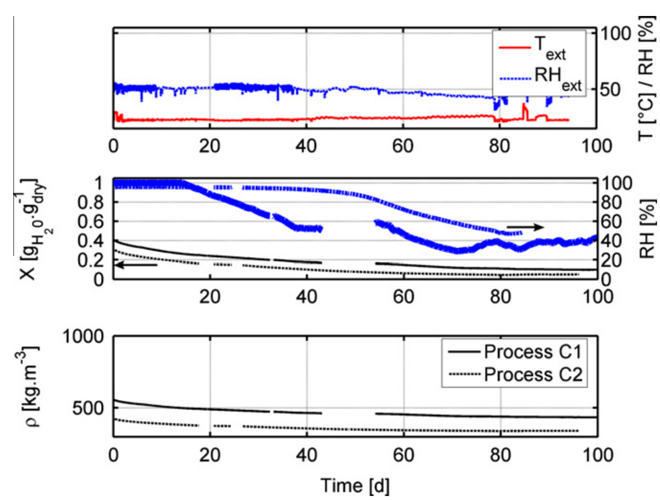

Fig. 7. Drying of hemp concrete manufacturated according to the *Processes C1* (solid lines) and *C2* (dashed lines). Time evolution of experimental drying conditions (a), of mean moisture content (black lines) and of relative humidity within the material (bold blue lines) (b), of density (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.4 g_{H_2O} g_{dry}^{-1}, corresponding to a density lower than ≈ 550 kg m^{-3}). Comparing the two spraying processes, it comes that *Process C2* leads to lower initial water content than *Process C1*. In case of *Process C1*, the operator adjusts the amount of water in order to completely wet the hemp shivs and the binder and to ensure a good cohesion between the particles. On the other hand, only the binder paste is added in case of *Process C2*, and a lower amount is required to coat the hemp shivs, thus leading to a lower initial density. As the drying proceeds, the decrease in the water content (see Fig. 7b) or in the density (see Fig. 7c) is similar whatever the spraying process. The drying proceeds in around 30 days for the *Process C2* and in 50 days for the *Process C1* until the mass is stabilized. Higher effective diffusivity and lower initial water content confirms that the drying should proceed more rapidly for the blocks manufactured by the *Process C2*. On the other hand, the relative humidity starts to decrease after the 40th day in the block manufactured by the *Process C2*, whereas it decreases only after the 20th day in the block manufactured by the *Process C1*. However, this last measurement may be uncertain since the sensor was not completely isolated from the ambient air. Nevertheless, the relative humidity within the material reaches values close to the air one after 80 days. Finally, the density reaches a final value of ≈ 430 kg m^{-3} in case of *Process C1* and of ≈ 340 kg m^{-3} in case of *Process C2*, indicating already that the setting process seems to have an impact on density.

4.2.3. Intermediate conclusion

The spraying processes leads to lower initial water content in comparison to the tamping process, and consequently to lower drying time in terms of mass stabilization or of relative humidity equilibrium. This is convenient since the render can be applied more rapidly once the wall is dried. On the other hand, the density is also decreased. Nevertheless, sprayed hemp concrete is nowadays associated with a timber frame that supports the mechanical solicitations, and thus could perform a function of distributed thermal insulation. However, this conclusion should be balanced by the facts that the results are obtained for small sample whereas tamping and spraying process are generally used for large scale samples and that the drying conditions are more favourable than outdoor conditions.

4.3. Influence of the manufacturing process

This part is devoted to the comparison between the different manufacturing *Processes A, B* and *C2*. For this, Fig. 8a presents the density and Fig. 8b the relative humidity measured within the three samples and the mean moisture content as function of time whereas Fig. 8c shows the drying rate and the temperature differences between the air flue and the surface of the samples as function of time.

On these three graphs, it can be noted that the mixed and tamped and the mould blocks presents a similar behaviour and their curves are almost overlayed: high initial density, high initial moisture content, high drying rate and high temperature difference between the air flue and the surface of the blocks at the beginning of the drying stage. As the drying proceeds, the mean moisture content decrease and the evaporation front moves slowly within the material. However, the local relative humidity is still at saturation level for long time and consequently, the drying time exceed 70 days. This similar behaviour is not surprising since the two processes are basically similar (step of mixing of ingredient and step for avoiding air bubble).

On the other hand, it can be clearly observed that the sprayed blocks have lower initial water content ($0.3 - 0.4\ g_{H_2O}\ g_{dry}^{-1}$) that the mould or mixed and tamped one ($\approx 0.85\ g_{H_2O}\ g_{dry}^{-1}$) as it was expected. Consequently, the drying rate at the beginning of drying, as well the temperature difference between the air and the sample's surface are also lower. Thus, the evaporation rate at the surface is lower and the evaporation front migrates toward the centre of the material. This is confirmed by the fact that the relative humidity within the sprayed sample decreases only after 40 days. The equilibrium with the environment is reached in less than 50 days, which is faster than for the mould and mixed and tamped blocks. This point is advantageous in the view of applying wall render.

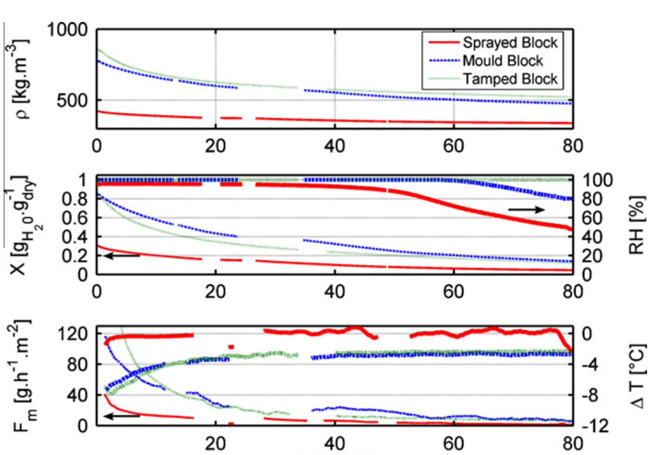

Fig. 8. Influence of the setting process on the density (a), on the moisture content and on the relative humidity within the material (bold lines) (b), and on the drying rate and on the temperature difference between the sample and the air (bold lines) (c). Sprayed block (resp. mould block and tamped block) is represented by solid line (resp. dashed and dotted line).

Moreover, spraying process leads to low density materials, which have a lower thermal conductivity [16,29].

By comparing the influence of the setting process on the effective moisture diffusion coefficients, mould block (resp. mixed and tamped) have the lowest (resp. highest) coefficient. However, the differences are very low and all coefficients can be considered in the order of magnitude of $1.10^{-9}\ m^2\ s^{-1}$.

Finally, Evrard [20] obtained similar results than ours even if its experiments are realised on thinner sample (3.5 cm in height, 19 cm in diameter). Particularly, he found that high initial water content decrease the final density of approximately 10% and slightly increases drying time. Additionally, it was observed that compaction, in opposition to the mixing procedure, appears to have a great influence on water release and density: the stronger the mixture was pressed, the heavier it gets and the slower it dries. Finally, lime and hemp type seems have no great influence on density and drying time, which indicates that the tamped block is representative.

Summarising the results of Evrard [20] and ours, it comes out that the process has a greater impact on the drying time than the initial formulation. The more the initial mixture is manipulated and tamped (or vibrated), the more the density and the drying time is.

5. Conclusion

In building construction, hemp concrete is currently used in a wall as a filling up material associated to a wooden frame. The preparation leads to a heterogeneous and anisotropic final structure, and considering an industrial's fabrication process to another, the quantity of initial water can be various. In the present work, the results show first that the drying is an important stage of the manufacture of hempcrete since it influence the setting of the porous, and thus of the mechanical, thermal and hydric properties. Then, it confirms the great influence of the setting process on the initial and final properties and on drying: spraying process leads to lower initial moisture content and lower density, and thus a faster drying time in comparison to the moulding or tamping process. Since this process is used in wet method of building, this result is advantageous in the view of applying render. On the other hand, it was shown that the initial hemp concrete formulation seems not to have an influence on the drying stage and thus on moisture diffusion. Last, it comes out that the block may be considered completely dried in terms of mass variation, whereas the relative humidity within the material is not equilibrated with its environment.

This work was also intended to evaluate the order of magnitude of effective moisture diffusivity coming from simple analytical processing of the experimental curves. However, the results are valid in a limited domain. The continuation of this work would consist in developing a numerical analysis on the blocks drying and estimating mathematical function with the objectives to predict the thermal and hydrous behaviour of the material.

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