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# An innovative forced convection method for drying geosourced and biosourced construction materials at wall scale

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**Abstract.** As global temperatures continue to rise, climate change impacts are now being observed in all aspects of life, driving the need to transition to a low-carbon economy. In the building sector and as a construction material, Earth-Hemp composites present a sustainable solution due to their low embodied energy and low environmental impact. However, at the construction site, and as with any other material, the drying process of Earth-Hemp can be very slow, which can lead to costly delays for building work and even serious problems in term of mold growth affecting their durability. The objective of this work is to develop an innovative drying method to reduce drying time of construction materials and speed up the completion of a project. In this paper, a comparative study of natural convection drying with innovative forced convection drying is carried out on sprayed Earth-Hemp-Lime "ELH" prototypes. The results show that the innovative forced convection method is very effective for drying ELH materials at an accelerated rate, where the drying period has been reduced by a factor of 2, compared to the drying time required when using the natural convection method.

## 1. Introduction

Human-induced climate change is one of the major challenges facing the world today. It poses a fundamental threat to human wellbeing and causes dangerous disruptions in nature, despite ambitious efforts taken to meet the goals set by the Paris climate agreement for more resilient economies.

According to the report published by the United Nations Environment Program in 2021, the building sector is one of the main contributors to global climate change, accounting for 36% of global final energy consumption and 37% of energy-related CO<sub>2</sub> emissions, where 10% of these carbon emissions come from the manufacture of construction materials [1].

The use of earth-based construction presents a way to reduce the building sector's emissions. Indeed, earth challenges the conventional building materials as being more environmentally sustainable, with a low embodied energy of 5-10 kWh/m<sup>3</sup>, compared to cement for example, of 590 kWh/m<sup>3</sup> embodied energy [2]-[3].

The mixture of earth and water can be processed using different manufacturing techniques which depend on the different compositions of the earth used, the local traditions, the drying process, and varying climates [4]-[5]. Some most common techniques are "adobe" or "compressed earth blocks" and "rammed earth" [6].

Earth walls are known to be excellent regulators of indoor air humidity. It has been shown that condensation/evaporation and sorption/desorption phenomena provide interesting qualities, allowing moisture exchanges between the earthen material and the environment, thus promoting an optimal



indoor climate for occupant's comfort and health [7]-[8]-[9]. Earth-based materials also present a particular role of energy storage due to their high density that can varies between 1610 and 2194 kg/m<sup>3</sup> [10]-[11]. With their significant thermal mass, earth constructions provide high thermal inertia but does not provide good insulation of the building [12].

In terms of the environment burden, building insulation requirements are constantly increasing, leading to improve the hygrothermal performances of construction materials. In order to reduce their thermal conductivity, earth-based construction can be lightened with several kinds of additions. Several studies have been conducted to investigate the influence of vegetable additions with raw earth on the hygrothermal performances of the lightened composites [13]-[14]-[15]-[16]-[17]-[18]-[19]. All these studies have highlighted that the incorporation of biobased additives lightened the earthen materials, leading to a decrease in their density and therefore their thermal conductivity, depending on the type of the biobased aggregate added, such as hemp shiv, and its dosage.

In this sense, the use of this technique is on the rise by meeting the requirements of the building energy efficiency and indoor comfort and health. However, at the construction site, and as with any other material, the drying process of Earth-Hemp can be very slow, which can lead to costly delays for building work and even serious problems in terms of mold growth affecting their durability. To avoid such damage, accelerated drying of building materials, for prefabricated elements or on the job site, is a need expressed by the construction industry to optimize manufacturing processes.

During the drying of porous building materials, the kinetics of this process are influenced by many external and internal factors [20]. External factors include numerous environmental parameters such as temperature, relative humidity and the velocity of the air surrounding the material to be dried, as well as the solar radiation intensity based on the orientation of the material to solar exposure. In general, high temperature and low humidity of the air accelerate the drying rate of any porous material and the equilibrium moisture content reached at the end of the process depends on the ambient humidity conditions [21]. Internal parameters mainly include the properties of the material itself, such as its pore structure [22] and its hygrothermal properties that are related to the composition and manufacture of the material.

Several studies have been conducted to investigate the drying of building materials and the influence of some of the aforementioned parameters on the process. At the wall scale, a study of the drying kinetics of a prototype building constructed with a double-wall system (cob on the interior side and light earth on the exterior side) was conducted [23]. It has been shown that the drying rate of the cob layers on the south and west walls was higher than that of the north wall and that the drying of the light earth layers reaches equilibrium faster than the cob layers because they are more exposed to environmental conditions and because of their lower initial moisture content. At the material scale, the influence of the manufacture technique on the drying process of building materials under forced convection test was investigated [24]. Hemp concrete samples produced by the spraying technique have been shown to require significantly less time to dry than samples produced by a conventional procedure that consists of pouring and compacting the mixture in moulds. This improvement in drying time is due to a lower water/binder ratio and to the porous material's microstructure which is more important in case of spraying method. Another study at the material scale highlighted the influence of the air velocity on the drying of ceramic bricks [25]. The bricks were dried in a wind tunnel with only the top surface exposed to air flow at different velocities. It has been shown that the higher the air flow over the exchange surface, the faster the evaporation with higher drying rates. Thus, the use of forced convection can be a solution to meet the need to speed up the drying process of building materials. Since rapid drying can affect the cohesion of the material, the definition of optimal drying conditions remains an open research topic.

The present work aims to investigate experimentally the influence of the surface air velocity on the drying of Earth-Lime-Hemp "ELH" composites at the wall scale. The hygrothermal behavior of two prototypes of ELH composites is analyzed during their drying period. Two different drying methods are compared: a natural convection drying applied to one prototype, and an innovative forced convection drying method applied to the second prototype.

## 2. Materials and methods

### 2.1. Formulation and manufacturing

The studied material is composed of raw earth, hemp shiv and Natural hydraulic Lime 3.5 as a binder to stabilize the fines.

The clayey matrix is a soil obtained from a quarry near Montreuil-Poulay in north-western France exploited by the PIGEON Group and characterized at the CBTP laboratory within the framework of their valorization in raw earth constructions.

The hemp shiv used for the manufacture of ELH prototypes is a product labelled "chanvre – bâtiment CenC" and marketed in 18 kg bags. Their physical characterization is investigated based on the recommendations of the Rilem Technical Committee 236 BBM (Bio-aggregate based Building materials) [26]. The results are summarized in Table 1.

Table 1. Physical properties of hemp shives at dry state.

Bulk density [kg/m <sup>3</sup> ]	Skeleton density [kg/m <sup>3</sup> ]	Total porosity [%]	Thermal conductivity [W/(m.K)]	Initial rate of water absorption [%]	Particle size distribution			
					Width		Length	
					Mean	Max	Mean	Max
120±1	1529±17	92	0.0566±0.0006	171	[mm]			
					2	6	8	24

The two ELH prototypes of dimensions 80x80x27 cm<sup>3</sup> are produced using the spraying technique on a building site in Saffré by LB Ecohabitat in partnership with the PIGEON Group. For this purpose, two Bakelite moulds of 80x100x27 cm<sup>3</sup> in size are used. Each mold is composed of a back face that serves as a support for spraying and a front face that is screwed on at the end of the manufacturing process to transport the prototypes to the laboratory.

The spraying technique consists of mixing the matrix paste and hemp shiv at the spray nozzle (Figure 1). The matrix paste is prepared by mixing raw earth, lime and water together.

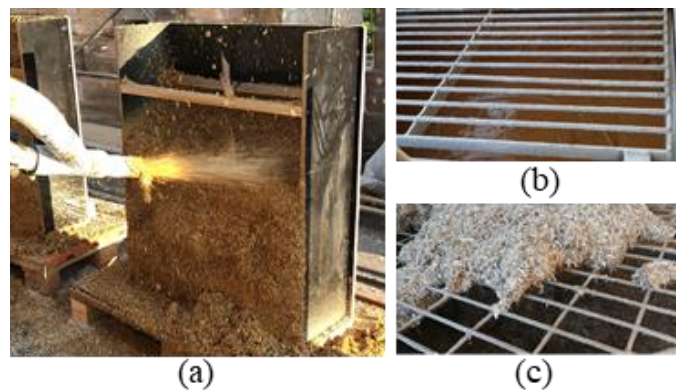


Figure 1. Spraying technique (a) and preparation of the matrix paste (b) and the hemp shiv (c).

### 2.2. Metrology and instrumentation

The monitoring of the drying of ELH prototypes is carried out by implementing temperature and relative humidity SHT35 sensors, designed by Sensirion and marketed by Step AT, at several depths in their thickness, on exchange surfaces and in ambient air. The accuracy of these sensors is 1.5% for a relative humidity range from 0 to 80% and 0.1 °C for a temperature range from 20 to 60 °C. The sensitive element of each sensor is protected with a filtering cap.

The measurement chain, used for the monitoring of the drying, including the SHT35 sensors and the acquisition unit is calibrated prior the instrumentation using the saline solution method in a temperature-controlled room at 23 °C.

The instrumentation of each ELH prototype in its thickness is ensured by a wooden fixing system shown in Figure 2. The wooden support is drilled at different positions to introduce wooden rods used to maintain 5 sensors in the layer of the ELH composite. The positions of the sensors in the thickness are schematized in Figure 2, with the origin 0 on the exterior surface. For surface instrumentation, one sensor is placed on each exchange surface for each prototype using a clamp. For ambience monitoring, one sensor is placed in an anti-radiation tube on each side for each prototype.

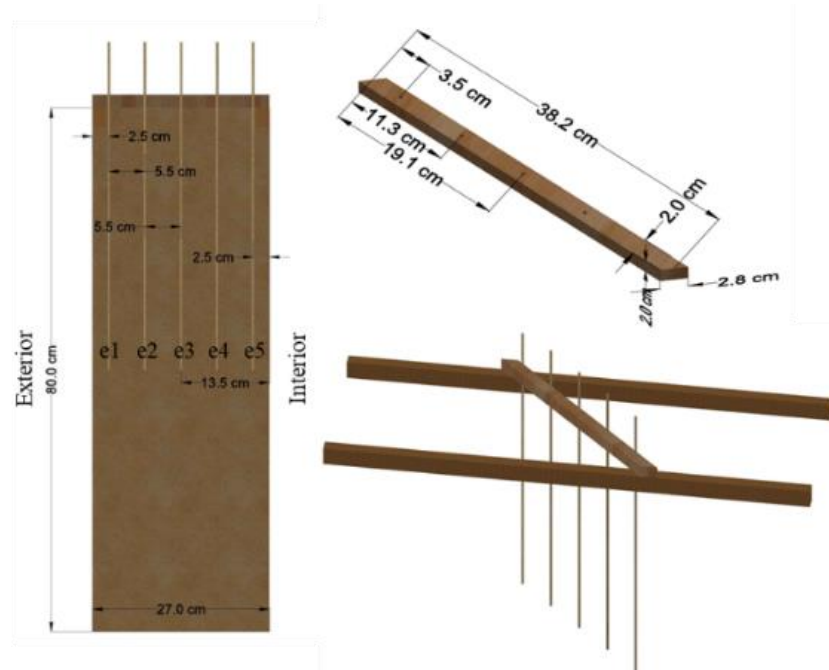


Figure 2. Wooden fixing system for thickness instrumentation.

### 2.3. Boundary conditions and drying set up

Two prototypes are intended for this study, one with natural convection drying symbolized by prototype N and the other with forced convection drying symbolized by prototype F (Figure 3).

Once they are installed side by side in the ambient air conditions of the laboratory, the front and the back faces are demolded and the side faces remain screwed on to limit lateral transfers. We note that the exchange conditions between the ambience and the exchange surfaces on each side of the prototypes are not the same. The exterior surface of the two prototypes is exposed to a large hall, while the interior surface of the two prototypes is exposed to a smaller volume limited by a wall (a distance of 2 m between the interior surface and the wall).

The two prototypes N and F are left to dry naturally for 11 days, then the innovative forced convection drying method is applied to the prototype F.

The forced convection drying method is applied on the whole exterior exchange surface of the prototype F by setting up a parietal exchanger. This one consists of a metal cladding with round perforations, originally developed as an air diffusion terminal unit for HVAC [27] and diverted here for a drying application. The perforated cladding has a dimension of  $80 \times 80 \times 0.15 \text{ cm}^3$  and 2793 round orifices with a diameter of 5 mm per hole. The cladding is positioned on a wooden frame having the dimensions of  $80 \times 80 \times 15 \text{ cm}^3$  and placed at 15 cm from the exterior side of the prototype F, creating an air cavity between them (Figure 3 - right). A fan extracts the air from the cavity, allowing the inflow of ambient air through the holes and the outflow of humid air from the top of the cavity. The flow rate of  $300 \text{ m}^3/\text{h}$  is measured at the outlet of the jet using a balometer from ACIN (Flowfinder mk2) with an accuracy of  $\pm 3\%$ . This flow rate induces a mean air velocity of  $0.7 \text{ m.s}^{-1}$  in the cavity.





Figure 3. Installation of the prototypes: N (left) and F (right).

### 3. Results and discussion

#### 3.1. Drying kinetics

The drying of the ELH prototypes was followed during 102 days and the acquisition time step is 3 minutes. Figure 4 shows the kinetics of 24 hours average relative humidity of the two prototypes at the ambient air conditions and at several positions within the ELH composites presented in Section 2.2. The ambient conditions on both sides of the two prototypes are the same in terms of temperature and humidity.

During the manufacturing, the pressure of the spraying causes the sensors to move. The positions of the sensors are therefore checked during spraying with a ruler and are given in Table 2 (origin 0 on the exterior surface).

Table 2. Positions of the sensors after the manufacturing.

Positions [cm]	e1	e2	e3	e4	e5
Prototype N	3.3	7.5	12.6	18.3	23.0
Prototype F	2.5	8.0	12.5	18.5	23.5

The manufacture of the ELH prototypes by the spraying technique requires less water than by casting, nevertheless the fresh composite contains a lot of free water, leading to high initial relative humidity of 100% within the material.

For the prototype N, the drying process began on the exchange surfaces, after 17 and 23 days since manufacture on the exterior and interior surfaces respectively. This difference may be due to the more limited volume exposed for the interior surface (see Section 2.3. ). The drying process continues from the exchange surfaces towards the core of the ELH composite until it reaches equilibrium with ambient air conditions after 71 days since its manufacturing.

The forced convection drying technique is applied to the prototype F on the 12<sup>th</sup> day following its manufacture. We can observe from the curves of the position e5 that the drying process started on the interior exchange surface only one hour after the installation of the equipment necessary for this technique. This immediate decrease in relative humidity highlights the instantaneous influence of the forced drying technique. After 39 days following its manufacturing, the relative humidity within the material was stabilized at ambient conditions indicating that the drying period is complete.

Comparing the drying rates of the two prototypes, it can be seen that they are much higher (slope bigger) for the prototype F than the prototype N. These results confirm the importance of the forced convection method: the drying of the prototype F is much faster than that of the prototype N. This innovative forced technique saves about half of the drying time required by the natural convection.

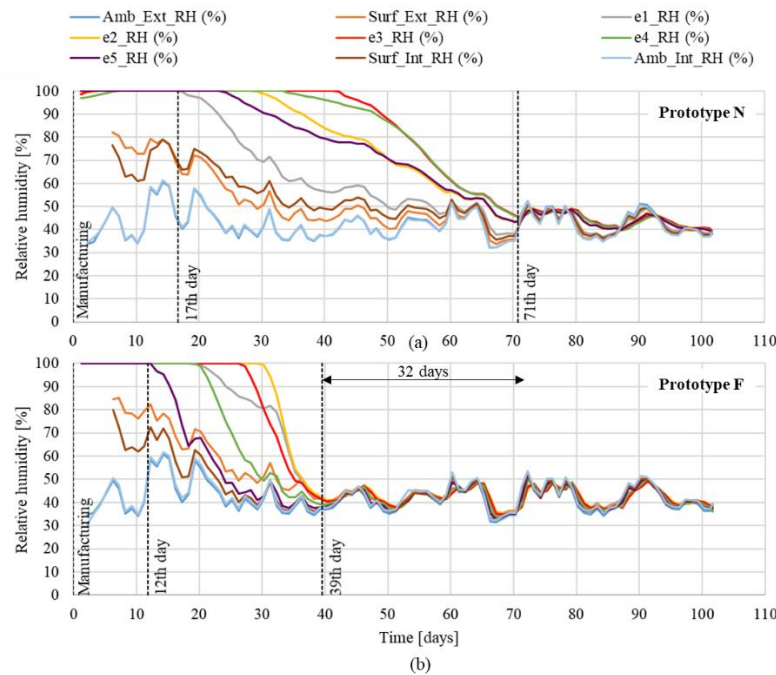


Figure 4. Evolution of 24 hours average relative humidity with time for prototypes N (a) and F (b).

Figure 5 shows the evolution of 24 hours average temperature versus time for the two prototypes. We can observe that the temperature within the ELH composite is lower than the ambient air temperature during the drying period (about 4 °C for prototype N). Indeed, during the evaporation, the energy removed will reduce the temperature inside the material. This difference in temperature is higher for prototype F (about 6 °C) since the evaporation rate is more important in the case of forced convection drying. We note that for both prototypes, the temperature within the ELH composite follows the evolution of the temperature of ambient air when the drying period is completed.

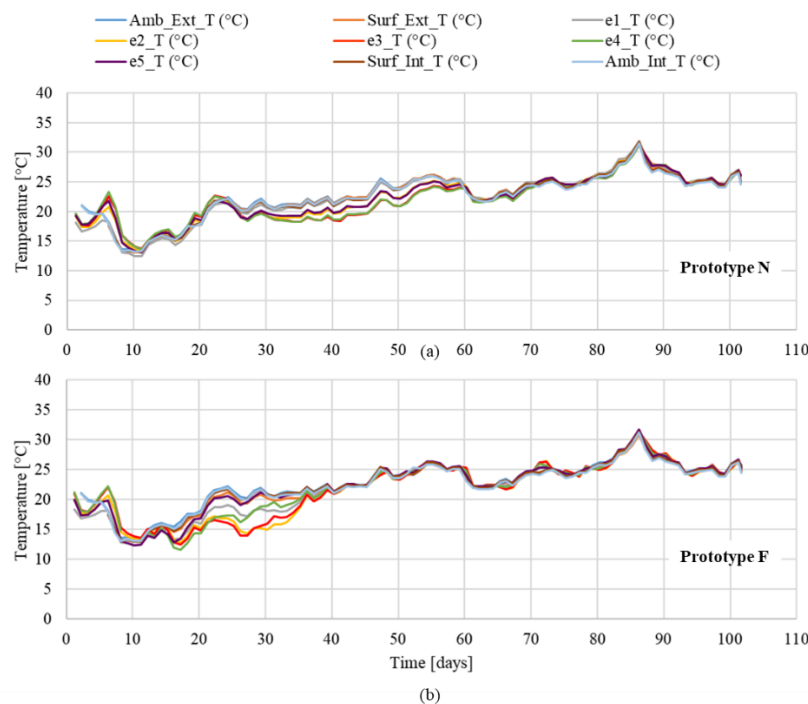


Figure 5. Evolution of 24 hours average temperature with time for prototypes N (a) and F (b).



### 3.2. Drying profiles

The relative humidity profiles at different times during the drying period of both prototypes are shown in Figure 6.

The evaporation front is defined as the interface between the saturated and unsaturated regions within the material. During the drying process of the prototype N, an evaporative front appears near each exchange surface once drying begins and moves towards the core of the prototype as drying proceeds. For the prototype F, drying began at the interior exchange surface and the evaporation front recedes into the porous ELH composite towards the exterior exchange surface, that is subjected to forced convection. Hence, the forced flow acts as a humidity pump.

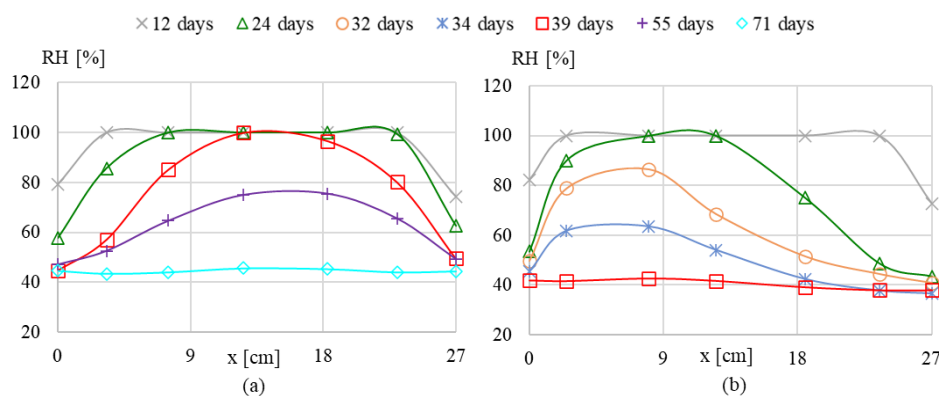


Figure 6. Drying profiles at different times for prototypes N (a) and F (b).

## 4. Conclusion

In this communication, an experimental study of the drying of Earth-Lime-Hemp composites is presented. Two prototypes of dimensions of 80x80x27 cm<sup>3</sup> are produced by the spraying technique and each is subjected to a drying method: a natural convection method for a prototype and an innovative forced convection method for the other. The forced convection method investigates the influence of the air velocity on the drying process of ELH prototypes.

The drying kinetics and profiles revealed two different behaviors of the ELH composites during their drying period depending on the method used. The results show that the drying rate of the ELH prototype is higher in case of forced convection drying. Therefore, the drying time is of course reduced in this case. In this study it is reduced by a factor of 2.

These results show that the innovative forced convection drying method is very efficient for drying porous building materials at an accelerated rate. In the construction industry, this method can be used either on site to dry the building walls, or in the factory to produce prefabricated components.

A continuation of this work is done to further reduce the drying time of ELH composites by testing other experimental configurations of the cladding with a constant flow rate. Some complementary experimental investigations can be performed to evaluate the applicability of this drying technique on a larger scale and on other materials. When considered for precast materials, it could be interesting to compare the corresponding energy consumption to the one of usual drying techniques.

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