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Microscopic estimation of swelling and shrinkage of hemp concrete in response to relative humidity variations

Aya Rima ¹, Kamilia Abahri ^{1*}, Fares Bennai ^{1,2}, Chady El Hachem ³, Marc Bonnet ¹

¹ Université Paris-Saclay, ENS Paris-Saclay, CNRS, LMT - Laboratoire de Mécanique et Technologie, 91190, Gif-sur-Yvette, France.

² Université de Lorraine, CNRS, Arts et Métiers ParisTech, LEM3, F-57000, Metz, France

³ ISSAE-Cnam Liban, Civil Engineering Department, Beirut, Lebanon

*Corresponding Author: Kamilia Abahri, e-mail address: kamilia.abahri@ens-paris-saclay.fr (phone: +33(0)1 81 87 50 85)

Abstract

The use of bio-based building materials such as hemp concrete has increased considerably in France in the last few years, due to its hygrothermal and acoustic advantages. Hemp concrete is hygroscopic and very sensitive to relative humidity. This property is responsible for dimensional variations and therefore the degradation of the material. To evaluate these dimensional variations, 2D and 3D imaging techniques can be used. For 3D tools, significant research and financial investments are required. This study is based on the analysis of the 2D microstructure of both hemp concrete and hemp shiv aggregates, in order to understand and estimate these dimensional variations for sorption and desorption cycles. First, the interaction between the different constituents of these bio-based materials was performed using scanning electron microscopy (SEM). Then, a new experimental optical setup was investigated to quantify the hemp shiv and hemp concrete swelling and shrinking by analyzing variations in their microstructure at different relative humidity levels. The quantification is calculated by 2D image analysis function of the fibers direction. Finally, digital image correlation (DIC) was performed to allow better estimation of the hemp concrete swelling. The findings of this study underline the real influence of relative humidity on the hemp concrete, that present a hysteretic swelling due to the porous structure and hygroscopic behavior of this material. The resulting dimensional variations should have to be seriously taken into account when modeling the hygrothermal behavior of this material.

Keywords: Bio-based material, Hemp shiv, Morphological behavior, Swelling/shrinkage, Digital image correlation (DIC), Microstructure.

1. Introduction:

The building construction sector becomes very attentive towards energy. It is the largest energy consumer in France. It currently consumes about 45% of total final energy [1–3] and generates around 26% of carbon dioxide emissions [4]. Unfortunately, this energy consumption in buildings continues to increase and generates a high level of pollution, either through the solid waste it produces or through the emission of CO₂ gases. Therefore, the preliminary choice of building materials can always lead toward the success of a high-performance building project in terms of reducing energy consumption, environmental impacts or even ensuring better occupant comfort. The choice of these materials will often be crucial, especially when environmental factors are key to solving pollution problems. Nowadays, and because of the high requirements for environmentally friendly building materials, a lot of research is being carried out in this field to provide answers to this problem.

In this context, the use of bio-based materials in construction is becoming more and more popular every year. In fact, they have emerged as an appropriate element in any project that meets environmental standards because of their positive impact on the project [5]. They reduce energy consumption while respecting environment [6,7]. The use of these materials is an essential element in meeting the requirements of sustainable development in the building sector.

Moreover, bio-based materials can perform several functions and offer various benefits in buildings. They can improve acoustic and hygrothermal characteristics because of their good properties: thermal insulation, sound absorption, high vapor permeability, excellent moisture buffer values [8–11]. Such characters again justify the interest of using these materials due to their qualities. For example, hemp concrete (mixture of hemp shiv with binder) is the most widespread bio-based material in the European Union; it is well known for its hygrothermal [8,12,13] and environmental performances [5,14]. It can also be an efficient material used in any modern construction applications. It was also demonstrated to be an excellent hygric regulator by quickly absorbing and releasing moisture when subjected to variable relative humidity conditions [15–18] to ensure the occupant comfort.

Despite all the major advantages that hemp concrete can offer, its use is still limited due to ignorance of its long-term behavior. Additionally, this material has a hygroscopic behavior and can be extensively sensitive to water vapor, liquid water and thermal variations [19]. These variations are constantly present in the building environment; they are principally caused by rainfall, wind or ventilation. Such behavior can lead to dimensional variations: swelling and shrinkage [20]. Indeed, the studied material is a multiphase and highly heterogeneous which presents several porosity scales. The interaction between its different constituents and its micro-anisotropic nature leads to a complex hygromorphic variations. Most of the works presented in the literature are on a macroscopic scale and focus especially on the characterization of the hemp concrete properties, its production methods and its chemical formulation [21–23]. Arnaud and Gourlay [9] have shown in their study that the mechanical properties of hemp concrete, conditioned from manufacture at different relative humidities, depend on the hygric state of the material. Samples conditioned at 50% relative humidity (RH) have a much higher compressive stress than those conditioned at 75% and 98%. These results justified that the swelling phenomenon and physicochemical interactions at high relative humidity disturb the evolution of the mechanical properties of hemp concrete. The age of the material also influences its mechanical properties. The hydration of binder improves the mechanical behavior of hemp concrete. Increases in mechanical strength have been observed up to 24 months after manufacture [9].

Only few works have studied the dimensional variations of the bio-based materials in general, and hemp concrete in particular, by examining their effects on the properties of these materials [24–31]. For example, Collet et al. [32,33] evaluated the hygroscopic behavior of hemp concrete and calculated the porosity of this material in order to determine the effect of the composition on the hygric properties. Walker and Pavia [34] studied the microstructure and pore size of hemp lime concrete using Scanning Electron Microscope (SEM). In fact, these works did not provide any estimates on the resultant dimensional variations for either hem shiv or hemp concrete. Also, the influence of high humidity on hemp concrete structure has not yet been studied in detail. It is therefore necessary to investigate the mechanisms on a microscopic scale especially under hydrothermal stress.

That's why, in this paper, the hygro micro-morphological behavior of hemp concrete is highlighted, since the macroscopic behavior is strictly dependent on the microscopic phenomena

according to the heterogeneity and anisotropy of its microstructure. In this context, a microscopic characterization was performed using scanning electron microscopy (SEM) to identify the hemp shiv structure and the interface between the fibers and the binders within hemp concrete. Then, an original experimental investigation was carried out to measure the swelling of hemp shiv, before studying the behavior in hemp concrete at different relative humidity values. The recourse to the digital image correlation (DIC) is essential to get more precisions of the dimensional variations caused by the hygric load. Studying the behavior of hemp shiv aggregates alone and then incorporating them into the cement matrix would allow to answer accurately if the presence of the binder really prevents the cracking of the concrete and quantify the resulting dimensional variations in each case.

2. Materials and methods

The bio-based material studied in this work is hemp concrete (Fig. 1a) obtained by mixing hemp shiv (Fig. 1b), binder and water. Hemp shiv is a vegetal particle made from the stem of the hemp plant. The bulk density of hemp shiv is 110 kg/m^3 . Due to high porosity and the lightness of this type of particle, hemp shiv are characterized by high thermal performance considered by a low thermal conductivity of about 0.05 W/m.K [35,36], which offers to hemp concrete very interesting insulation properties [8]. It is worth noting that this thermal conductivity is only valid in a dry state. A humid medium can drastically reduce the thermal resistance of hemp concrete.

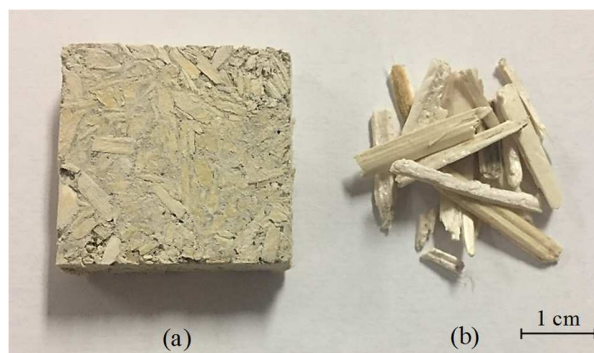


Fig. 1. Studied material (a) Hemp concrete (b) Hemp shiv

The used lime-based binder is called Batichanvre. This binder is a mixture of: natural lime from St. Astier in France (Hydraulics: NHL and aerial: CL), cement CEM I 52.5, and various additives to improve the rheology and permeability of hemp concrete. This binder should ensure easy mixing, including perfect coating of the constituents, and guarantee the mechanical

properties of the material [24]. It is specially formulated for the manufacture of hemp concrete. Its apparent density is 490 kg/m^3 which is within the range of values used for buildings walls in France [8].

The formulation of the hemp concrete used in this work is adapted for wall application. The chosen mass ratio of hemp concrete is 14.4% binder, 35.7% hemp shiv and 50% water.

The main objective of this study is to better investigate the microscopic behavior of hemp concrete against humidity variations. To do so, first, an imaging technique based on surface observations is used to characterize the hemp shiv and the hemp concrete morphology. It is the Scanning Electron Microscopy (SEM) which is able of producing high resolution images of the sample surface. This technique allows to observe the cell walls of the hemp shiv as well as the interface between the binder and the bioaggregates. The vacuum system consists of a high capacity 162 liter/min rotary pump and a 210 liter/sec. turbomolecular pump. The choice of SEM parameters is described in each image.

In order to measure the morphological variations of hemp concrete in response to changes in relative humidity, sample of dimensions $2.5 \times 2.5 \times 0.5 \text{ cm}^3$ were tested. The Keyence VHX-2000 microscope at LMT Laboratory was used to quantify the hemp concrete swelling/shrinkage and their variation over time. A specific device was manufactured for this purpose. It allows the conditioning of the hemp concrete sample and to maintain the relative humidity value constant during the test. This device has the shape of a Plexiglas box obtained using 3D printer (Fig. 2), where the salt solutions responsible for the regulation of the relative humidity are placed in a drawer located inside. Should be noted that, the hemp concrete sample is placed on the perforated tray above the salt solution. Then, the box is closed using a microscope slide to achieve the ideal sealing conditions and the best realistic results. In addition, the device was fixed on the Keyence microscope during all tests in order to guarantee reliable results with better accuracy.

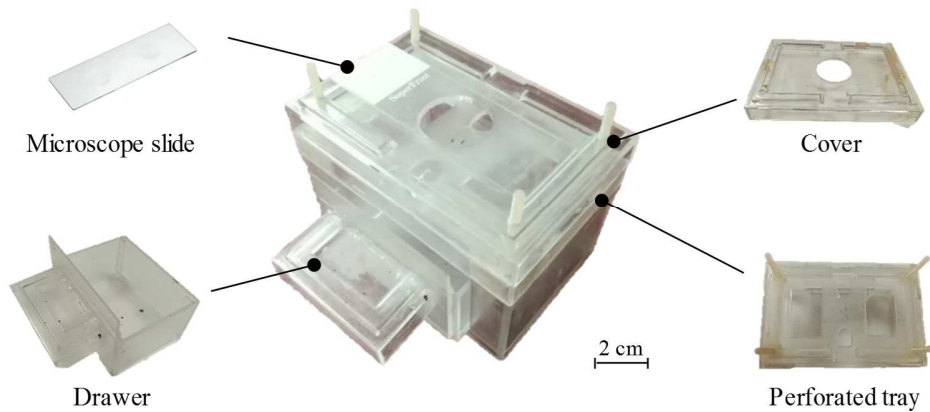


Fig. 2. Samples conditioning device for measuring swelling

The sample was initially dried in an oven at a temperature of 50 °C for 3 days to evaporate the entire amount of water and reach the equilibrium (dry point). Then, it was placed in the box above the salt solution to be exposed to different humidity levels for different durations at a constant temperature of 25 °C. The considered relative humidity levels, the exposure duration of the sample and the different salts used in the salt solutions are listed in Table 1.

After closing the box in order to keep the humidity constant, the device is fixed under a camera of the optical microscope Keyence VHX-2000 to be able to compare the dimensional variations from one humidity level to another. As a first observation, a picture of the dry state (reference state) of the sample is taken. Then, a solution of sodium bromide is poured in the drawer to ensure 57.7% relative humidity in the box. The weight of the sample was measured in “g” every 24h using a balance with a precision of 0.0001g. Once the sample reaches the mass equilibrium, the relative humidity is increased by changing the salt solutions. This step was repeated for every humidity level mentioned before (Table 1) for both sorption and desorption cycles.

Image processing was done after each relative humidity conditioning to predict the percentage of swelling and to plot the swelling curve of the separated hemp shiv and hemp shiv in the hemp concrete as a function of relative humidity. Data processing was investigated using the Keyence software.

Table 1. Humidity levels for swelling and shrinkage tests

Relative Humidity (%)	Duration (h)	Conditioning tools
0	72	Oven

57.70	72	Sodium bromide
75.28	48	Sodium chloride
84.26	72	Potassium chloride
97.30	72	Potassium sulphate
100	24	water

In a second step, and for reasons of repeatability, two hemp concrete samples of the same sizes (2.5 x 2.5 x 0.5 cm³), shape and composition were also tested for the same relative humidity stages. Finally, several dimensionless measurements in different directions of the sample were examined. Similarly, two specimens of hemp shiv of 0.2 x 0.25 x 1 cm³ were also tested for both morphological and swelling analysis.

In the continuation of this study, a new investigation was conducted using 2D digital image correlation (DIC) to better understand the hemp concrete swelling exposed to different hygric load. The study is done by exploiting the 2D images acquired by the Keyence microscope. The DIC consists in determining the field of displacement from the analysis of digital images comprising a set of pixels. It is undeniable that DIC is an important step in this research because it allows the measure of the displacement field of the material when the humidity changes; a comparison can be made between a referential image in a dry state and the images obtained at different humidities. The calculation code used for the digital image correlation is Correli-T3 (global code with mechanical regularization, elements T3). It is a software developed in LMT laboratory [29-31]. It uses multiscale procedures to facilitate the convergence of calculations. This DIC technique was applied on in our previous work for the estimation of the hygromorphic-mechanical deformation of spruce wood [32].

3. Results and discussions

3.1. Morphological analysis

SEM observations of hemp shiv and hemp concrete were performed to characterize the complex morphology of these bio-based materials. Fig. 3 and 4 represent the surface of a hemp shiv under two different resolutions. Fig. 3 shows the high porosity of hemp shiv which is characterized by different pore structures and geometries. The pores can be classified in three different types according to their sizes: vessels, wood fibers and parenchyma cells (Fig. 3). The

walls between the cells are mainly composed of cellulose (40 to 60%), hemicelluloses (10 to 20%) and lignin, which are the three most abundant polymers found in nature [37]. Fig. 3 and Fig. 4 show that the hemp shiv porosity is organized in capillaries parallel to the growth direction of the plant. This morphology of the pores is the main reason behind the increasing of hygrothermal transfers which are more important in the longitudinal direction. The exploitation of the different SEM images of the hemp shiv obtained allows the estimation of the pores sizes that presents different width varying between $2 \mu\text{m}$ to $45 \mu\text{m}$ (Fig.4). In other words, hemp shiv particles present meso-pores in intercommunication with offers the hygroscopic character of such material.

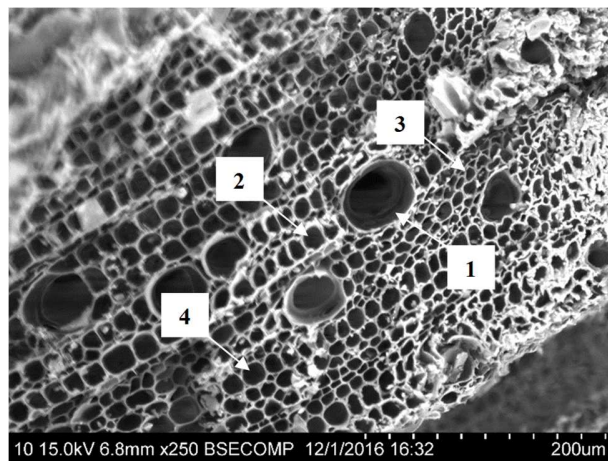


Fig. 3. SEM picture of hemp shiv ($200 \mu\text{m}$): (1) vessel (2) lumen fiber (3) parenchyma cell (4) fiber wall

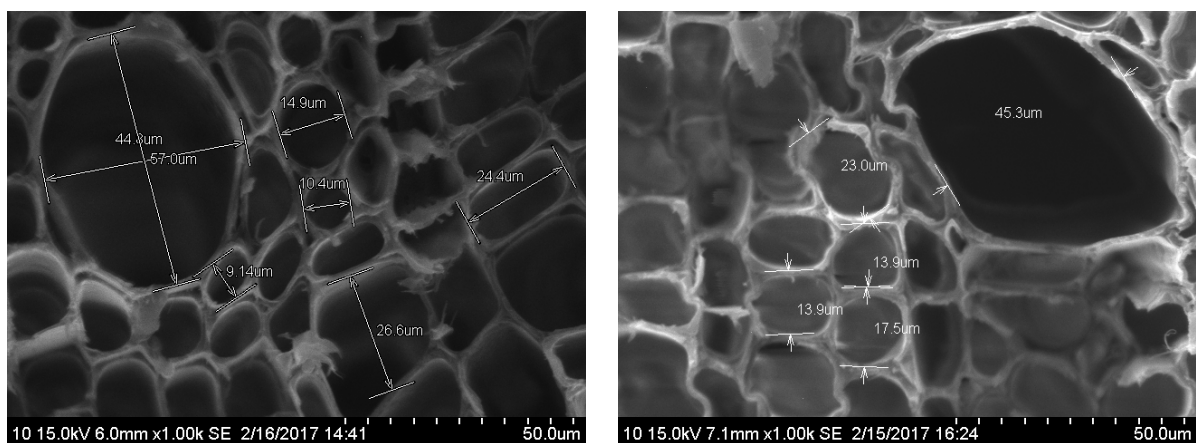


Fig. 4. SEM picture of hemp shiv ($50 \mu\text{m}$)

Further, hemp concrete morphology was also analyzed by SEM in this part of experimentation. Fig. 5 and 6 represent an example of the results obtained at two different magnifications (1.00 mm and 500 μm respectively). It can be seen that hemp concrete presents a multi-scales porous structure. In addition, there is intra-granular air (located within the particles) and inter-granular air (located between the particles). Fig.5 shows the three phases of hemp concrete: hemp shiv (1), air interface (2) and binder (3) and confirms the high porosity of this heterogeneous material.

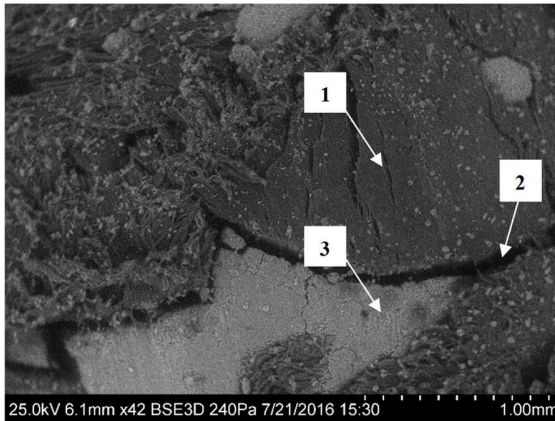


Fig. 5. SEM image of hemp concrete (1 mm): (1) Hemp shiv (2) Porosity (3) Binder

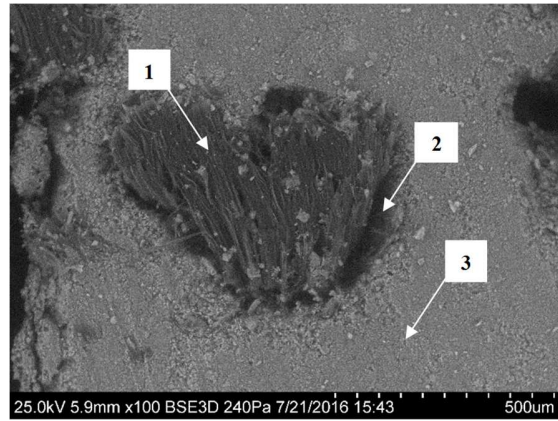


Fig. 6. SEM image of hemp concrete (500 μm): (1) Hemp shiv (2) Porosity (3) Binder

The different types of porosity can be easily identified: 1) The porosity between the hemp shiv and the binder (inter-particle porosity); the size of this category of pores can reach some millimeters. 2) In the binder matrix, the intra-binder porosity due to the arrangement of the binder components; it can also reach one hundred micrometers. 3) In the fibers phase, intra-shiv porosity, which can reach 50 μm .

3.2. Dimensional variations of hemp shiv and hemp concrete

In a first step, the dimensional variation of hemp shiv is presented, without cement binder, as a function of relative humidity. Then, their respective swelling percentage is calculated. As mentioned before, a sample of hemp shiv was submitted to different relative humidity values: 0%, 57.7%, 75.28%, 84.26% and saturated state. Then, the device presented in part 1 (Fig. 2) was used to measure the strains caused by moisture adsorption by our hygroscopic material. It allows to quantify the swelling and to better observe the morphological variations from one hydric state to another, using the microscope. By consequence, the obtained results will clarify if the hemp shiv present more dimensional variations than the hemp concrete.

Fig. 7 shows the evolution of hemp shiv size as a function of relative humidity. The results illustrate the significant effects of relative humidity on the swelling of the hemp shiv. In fact, the dimensional variations increase progressively with the relative humidity values especially from 57.7%. Otherwise, the microstructure of the hemp shiv was characterized by capillaries (SEM images) that allow water to easily penetrate in order to absorb a significant amount of water. Due to this characteristic, whenever the material is exposed to relative humidity variation, it begins to absorb bound water. This leads to the swelling of the wooden cell walls. An increase of the fiber thickness was observed from 1800 μm to 1978.2 μm between the dry and saturated states. Such variation corresponds to a swelling of 9.9% in of hemp shiv.

The second step focuses on the hygromorphic phenomenon and its effects on the behavior of the complex microstructure of hemp shiv in hemp concrete. The percentage of hemp shiv swelling when incorporated in the binder matrix was calculated by observing the same area of the hemp concrete sample for each relative humidity sollicitation. This percentage was calculated by taking several accurate and precise optical measurements in different directions.

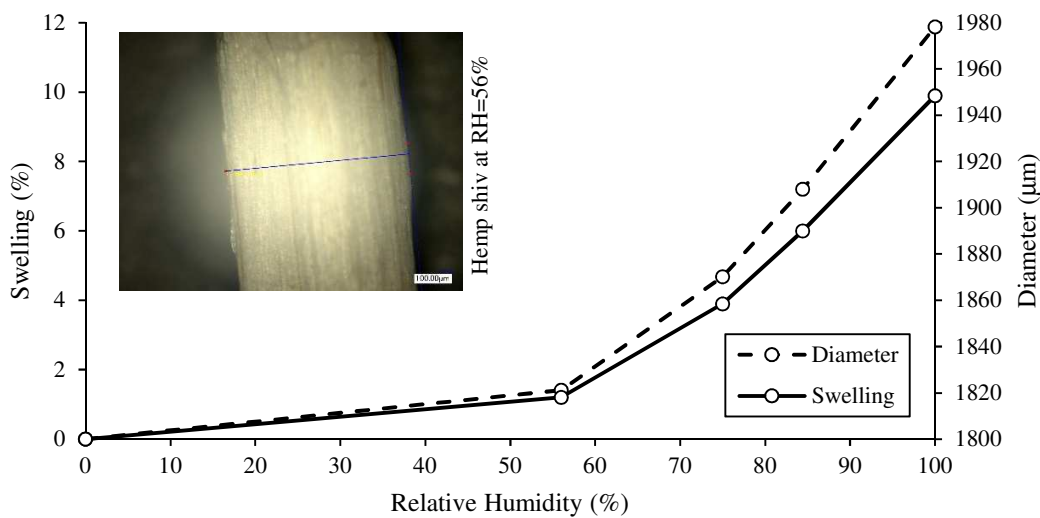


Fig. 7. Morphological Evolution of hemp shiv in function of relative humidity

According to the Keyence microscope observations, it is found that the dimensional variations resulting from swelling are much important in the fiber phase (hemp shiv alone) than in the binder. When the relative humidity in the box increases, the deformation of the binder is negligible compared to that of hemp shiv in hemp concrete. The reason for that is the high

porosity and the hygroscopicity of hemp shiv, which allow them to adsorb and store more amount of water than the binder phase.

Additionally, swelling was quantified in the longitudinal and tangential directions of hemp shiv. Results indicates that the swelling of the hemp shiv in longitudinal direction is greater than the tangential one (anisotropic strains). This is directly related to the porous structure of the hemp shiv organized in parallel capillaries in the longitudinal direction of the stem. The inter-particle porosity (located between binder and hemp shiv and due to the arrangement between the hemp shiv) that is already in the hemp concrete volume is gradually closed while increasing relative humidity due to the swelling of the hemp shiv. Fig. 8 shows the microscopic observations of the same surface of the hemp concrete sample for each considered relative humidity level. The purpose of this study is to investigate the response of this material under various hydric variations . It can be seen that the adjacent porous space between the hemp shiv and the blinder decreases with increasing relative humidity. This observation is due to the expansion of hemp shiv that contributes to the reduction of the pores in the material.

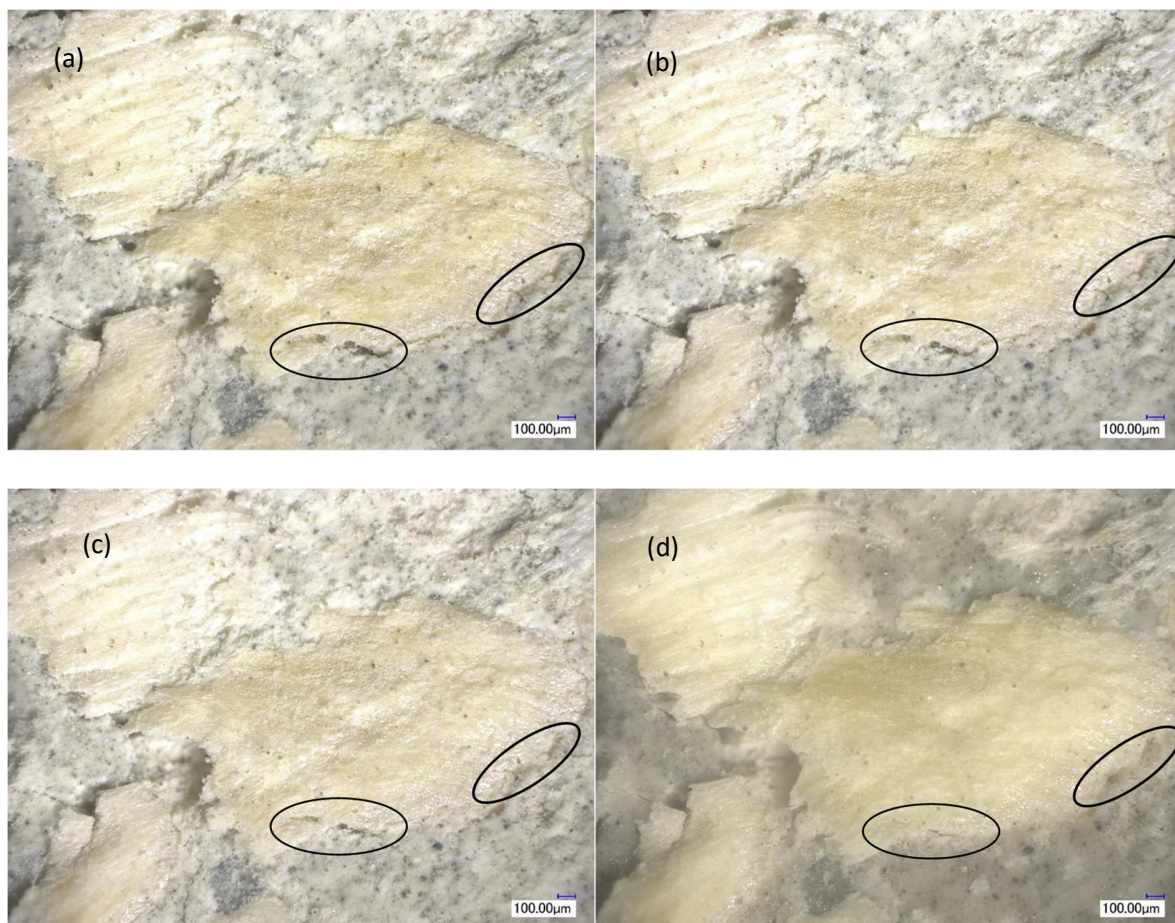


Fig. 8. Observation area of hemp concrete for different humidity: (a) dry state, (b) 57.7 % (c), 97.3 % and (d) saturated state.

To determine the percentage of swelling of the fiber phase (shiv) in hemp concrete, six measurements were taken as shown in Fig. 9. The swelling of hemp shiv in width and length is illustrated in Fig.10. These curves show that the behavior of the vegetal particle is slightly different in length and width. In each direction, the percentages of swelling are different for measurements by increasing relative humidity. In fact, this variation is caused by two important factors. First, the hemp fibers are characterized by anisotropic behavior which justifies the difference in swelling from one direction to another. In addition, the inter particle porosity at the fiber-matrix interface is arbitrarily located around the hemp shiv. Hence, this porosity distribution has a significant impact on the created swelling. Indeed, the variation is caused by locating the inter particle porosity around the hemp shiv

In general, the swelling evolution curves have the same shape in both x and y directions. In addition, the swelling in the width direction of the hemp shiv is greater than in the length direction due to the inter-particle porosities located along its length. For measurements 4-6, the swelling is blocked by the binder which prevents the free swelling of the hemp shiv. The results show that when the relative humidity increases, the hemp shiv occupies part of the free space, and shifts toward a direction parallel to the inter-particle porosity until reaching the fiber saturation point. In other words, the hemp shiv continues to absorb water as the relative humidity increases, causing them to swell.

The comparison between figure 7 and figure 10 shows that the hemp shiv alone swells more due to its hygroscopic nature. It can absorb large amounts of water quickly. Unlike hemp shiv included in the binder, the binder prevents and limits the swelling of the vegetable particles. This result is confirmed when a second sample of hemp concrete was tested, and the two results were almost identical regarding the percentage of swelling in both directions, as shown in Table 2. It can be seen that the difference between the swelling of the two hemp concrete samples is negligible.

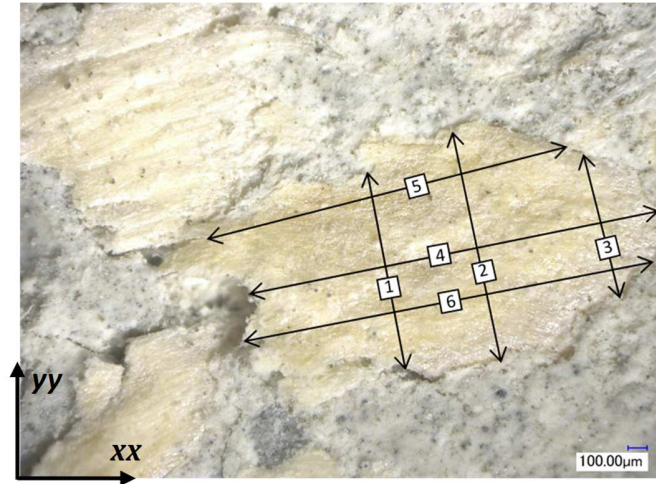


Fig. 9. Six measurements in different directions

Fig. 11 shows the average percent swelling (%) of two hemp concrete specimens as a function of relative humidity. when the initial dry samples are placed at 57.7% relative humidity, the deformation of the hemp phase in hemp concrete gradually increases with increasing the relative humidity to 1.09% and 0.23% in width and length, respectively. By increasing the humidity up to 75.28%, slight swelling of the hemp phase is observed. Above this value, in the super hygroscopic zone, and when the humidity is increased to 84.26%, the hemp swells rapidly to 2.52% and 0.46% in width and length, respectively. Then, it continues to swell to reach 3.35% in width and 0.65% in length at 97.3% relative humidity. When water is added to the samples, the hemp concrete becomes saturated and a sudden increase in the swelling of the hemp shiv is observed (6.4%in width and 1% in length).

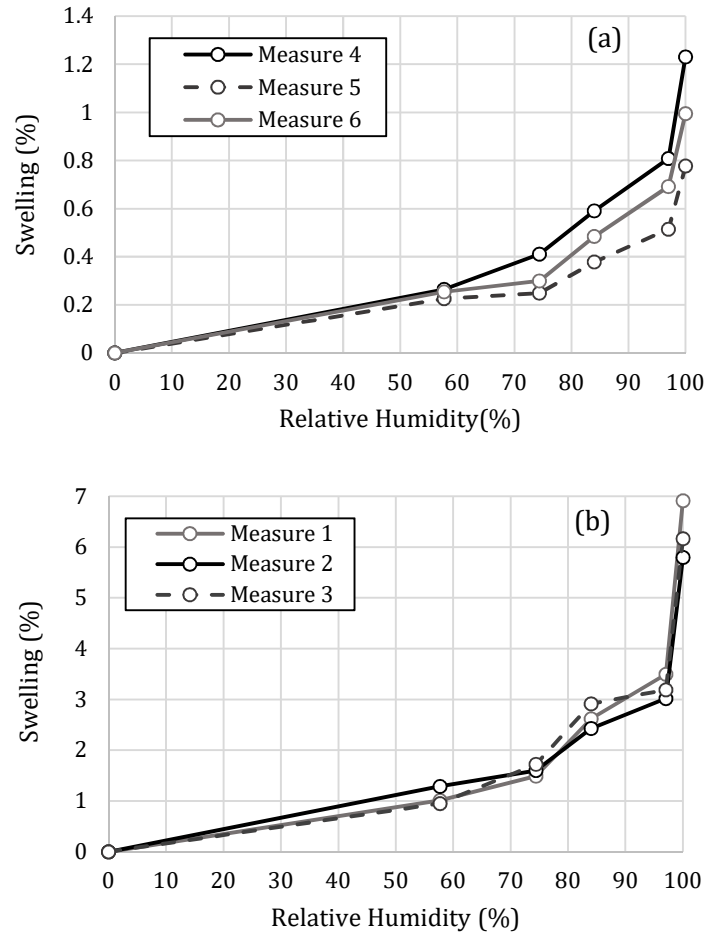


Fig. 10. Swelling of hemp shiv in hemp concrete (a) in width (b) in length as a function of relative humidity

Table 2. Percentage of swelling for two samples of hemp concrete

ϵ (%)	RH (%)	57.7	75.28	84.26	97.3	Saturated state
Sample 1		1.08	1.61	2.66	3.23	6.29
Sample 2		1.09	1.45	2.39	3.46	6.02
Variation (%)		0.92	9.93	10.15	7.12	4.29

To investigate the desorption behavior of hemp concrete, the relative humidity tested previously is gradually decreased. The percentage of swelling (relative to the initial dry state) of the hemp fiber in hemp concrete was different. It can be seen that the obtained swelling curves show a hysteresis loop between swelling and shrinkage during water adsorption and desorption. For a given relative humidity, the hemp fiber tends to a different swelling percentage for the

adsorption phase than for the desorption phase (the swelling in desorption compared to the initial dry state is greater than that in adsorption). This hysteresis behavior is due to the physical change of the material caused by the departure of water. It is attributed to the complex geometry of hemp concrete. Indeed, several phenomena prevent the evaporation of the water and leave a quantity of water trapped in the cell walls of the hemp shiv, i.e. the geometric non-uniformity of the pores (leading to the ink bottle effect), the changing of the contact angle, and the curvature of cell wall/pore interface. This behavior induces a different swelling between water adsorption and desorption. This hysteresis behavior is closely related to the hygroscopic character of this material and is presented by the desorption sorption isotherms that have been studied in previous work [8].

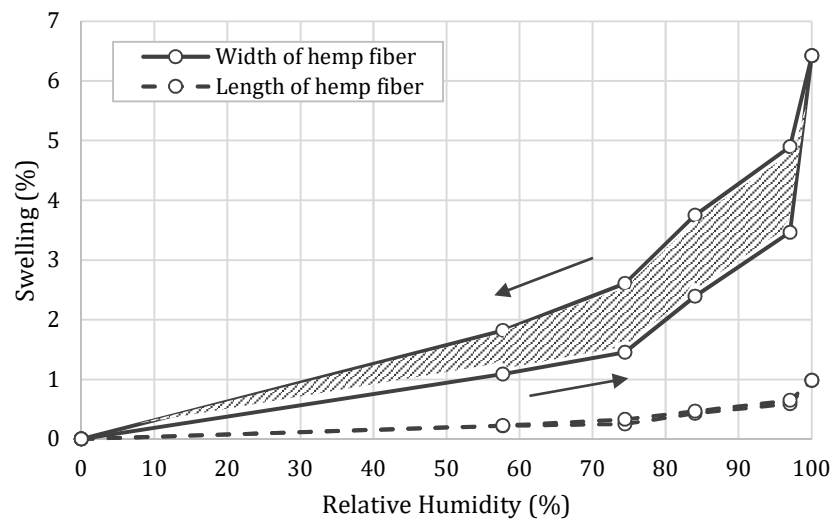


Fig. 11. Swelling of hemp concrete (%) as a function of relative humidity (%)

4. Digital Image Correlation DIC

The DIC study performed in this work was carried out on the hemp concrete images shown in Fig. 8 at different relative humidity levels. It was used to study the swelling process of hemp concrete and to quantify the different displacement fields in both directions of the sample surface (Fig. 9).

The study is done by exploiting the 2D images acquired by the Keyence microscope in part 3.2. From a reference image, the DIC consists in determining the displacement at each point

(displacement field) necessary to obtain the deformed image. In our case, the dry state image is used as a reference. Thus, for each RH (respectively 57.7%, 75.28%, 84.26%, and 97.3%) the displacement field is given, in pixel, on the xx direction and the yy direction with respect to the reference state. Each displacement corresponds to the local response of the material when subjected to higher relative humidity.

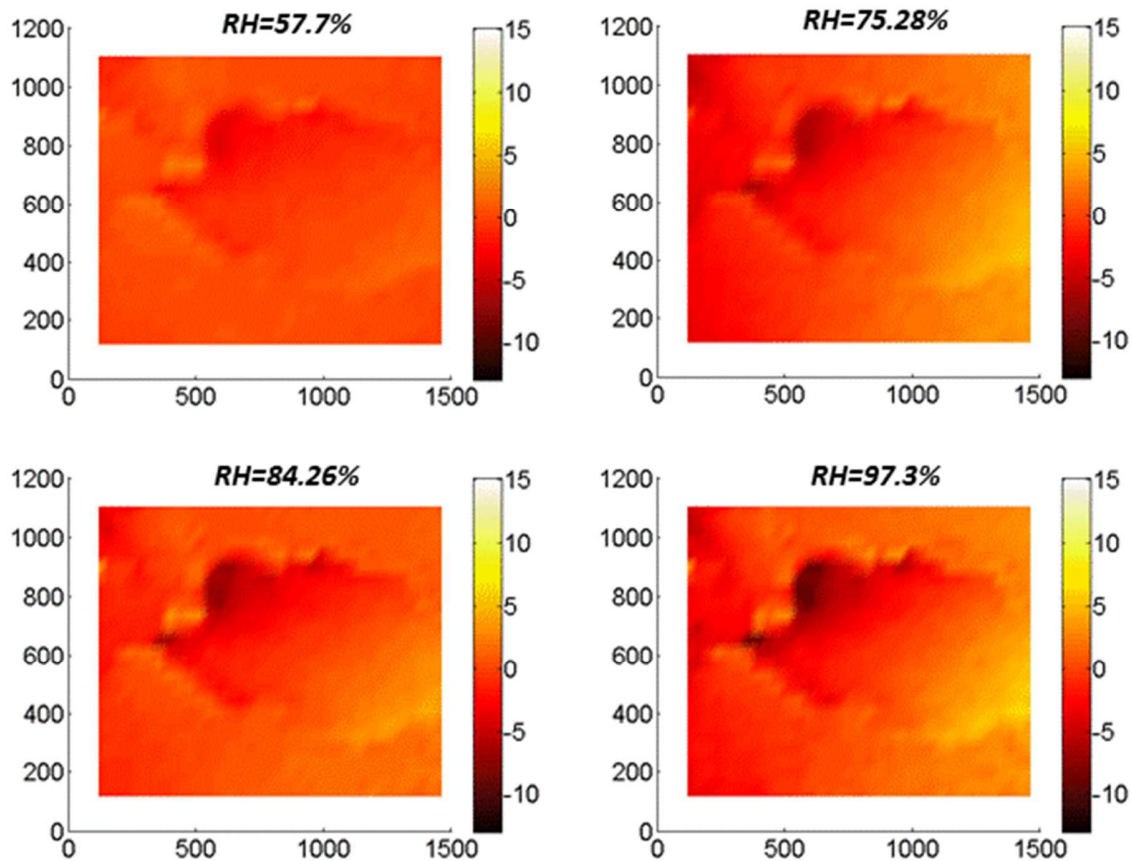


Fig. 12. Hemp concrete displacement fields (in pixels) in the xx direction for different RH levels

Fig. 12 and Fig. 13 illustrate the displacement fields on the surface of hemp concrete. The displacement is calculated in pixels in both directions and for four levels of relative humidity levels: 57.7%, 75.28%, 84.26%, and 97.3%.

These results correspond to the displacements of the section shown in Fig. 8. The digital image correlation results confirm the presence of swelling in hemp concrete. Furthermore, they show that the vegetable particles exhibit a much larger displacement (yellow color) than the binder. This is because the binder blocks the swelling of the hemp shiv. It should also be noted that the

displacement fields at the sample surface depend on the relative humidity level considered. Increasing the relative humidity stimulates the amount of water absorbed by this hygroscopic material which leads to its swelling. It concludes that the displacement is directly proportional to the considered relative humidity.

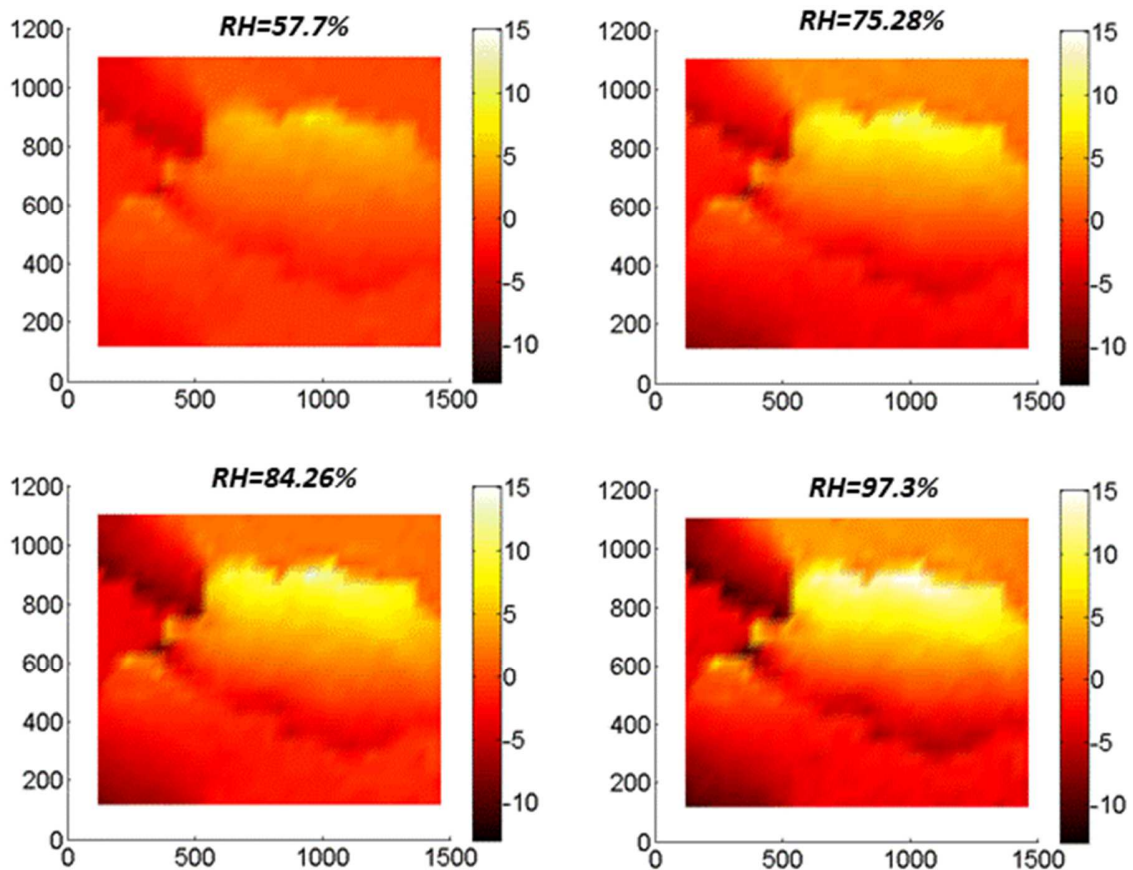


Fig. 13. Hemp concrete displacement fields (in pixels) in the yy direction for different RH levels

On the other hand, the comparison between the displacement obtained in each direction confirms and supports the results presented in Fig. 10 and Fig. 11. The swelling in the direction of the fiber width was more important than in the direction of the fiber length. Indeed, the swelling phenomenon of this anisotropic and very heterogeneous material is very complex. It strongly depends on the orientation of the hemp shiv in the material and its macro porosity distribution. The maximum displacement is 15 pixels, observed when the hemp concrete was conditioned at 97.3% relative humidity.

5. Conclusion

This study presents the swelling and shrinkage percentages of hemp concrete and the behavior of this material with respect to the relative humidity variations. Scanning electron microscopy observations show that the studied material is highly porous which ensures the lightweight of the hemp concrete. This high porosity is formed by very different pore geometries and is organized in parallel capillaries in the direction of the growth of the plant. These observations also show an interest in the complexity of the microstructure. The heterogeneity and anisotropy of hemp shiv and hemp concrete were highlighted. The effect of all these parameters on the morphological variations induced by the change of environmental conditions was also apprehended.

The designed experimental device is well adapted to study the hygromorphic behavior of hemp concrete when the relative humidity varies and to apprehend the morphological variations of a hemp concrete. It is shown that hemp shiv in hemp concrete is very sensitive to humidity variations. Indeed, this hygroscopic material presents swelling and shrinkage which can considerably impact the morphology of this bio-based material.

The obtained swelling percentage of hemp shiv in hemp concrete is about 6.5% (at 97.3% RH). This value is higher in the case of the hemp shiv alone (9.9% at 97.3% RH). Furthermore, the swelling of hemp shiv in hemp concrete is blocked by the binder which prevents the free swelling of the particles, although the binder is slightly affected by humidity variations. In addition, the neighboring inter-particle porosity of the vegetable particle is reduced as a result of the swelling of the hemp shiv, as shown by the displacement fields in the image correlation results.

The digital image correlation technique is used to quantify the displacement field of the hemp concrete for different relative humidity levels throughout the sorption cycle. The maximum displacement value is 15 pixels observed when hemp concrete was conditioned at 97.3% relative humidity.

Finally, the calculated swelling percentage of hemp shiv in hemp concrete can be used as input data for numerical modeling to study the coupled heat, moisture, and air transfers in hemp concrete. Therefore, it is necessary to consider these dimensional variations in the modeling to accurately predict the thermo-hydrromechanical behavior of materials used in the building envelope.

Compliance with Ethical Standards

- The authors declare that they have no conflict of interest.

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