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Microscopic hydric characterization of hemp concrete by X-ray microtomography and digital volume correlation

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HIGHLIGHTS

- 3D X-ray tomography reconstructions are performed at various voxel sizes.
- The microscopic characterization of hemp concrete and hemp shiv is performed.
- The material's hygrometry was considered during the tomographic scans.
- Digital Volume Correlation is used to measure the strain fields in the material.
- The swelling effect of hemp shiv on the internal morphology of hemp concrete is finely examined.

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ABSTRACT

Hemp concrete is a bio-based material used in buildings construction. It presents particularly interesting hygrothermal properties. This very heterogeneous material is constituted by hemp particles embedded in a mineral binder. This paper focuses on the microscopic and hygromorphic characterization of hemp concrete based on non-destructive imaging techniques. X-ray tomography scans with different voxel sizes were performed on this material. The reconstructed volumes had a mean voxel size between 2.3 μm and 31.8 μm. 3D reconstructions of the real material showed that hemp concrete has several scales of porosity which depends on the orientation and position of the plant particles. Then, a tomography scan and SEM observations were made on the vegetable particle. The latter presents a complex and very porous microstructure. The hygromorphic behavior of hemp concrete under hydric solicitations was then studied. The technique consists in using X-ray tomography coupled to the digital volume correlation (DVC) to determine the three-dimensional strain fields in the studied three-dimensional volume. The results show a change in the internal morphology of hemp concrete subjected to different hygrometries. The humidification of the material leads to the appearance of anisotropic strains in the 3D volume. The strains of the hemp particles are greater compared to those of binder. In addition, the swelling of the hemp shiv causes the reduction of the porous space between the binder and the plant aggregates called interparticle porosity.

1. Introduction

The building sector presents new issues with regard to the potentials of energy saving and reducing greenhouse gas emissions by 40% until 2030 compared to the 1990 level by building on the low-carbon strategy, as expected in the Paris Climate Agreement [1]. Consequently, a real and pressing determination to reduce greenhouse gas (GHG) emissions and energy costs of buildings is needed to improve the environmental conditions. Literature works [2,3] confirm that the use of materials with a low environmental impact in the building sector leads to limit considerably greenhouse gas emissions. This is the case of bio-based materials that are renewable, low embodied energy and sustainable construction materials with better occupant comfort quality [4]. Among these bio-based materials, hemp concrete is an essential solution in response to current environmental problems, and it is more often used in construction, renovation and thermal upgrading of

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building. It is composed of a binder (mainly based on lime) and hemp shiv [5–8].

Hemp concrete exhibits excellent thermal insulation capacity due to its low thermal conductivity which is about 0.1 W/m.K [9–12]. This property depends both on the formulation, and the material density [13,14]. On the other hand, hemp concrete is a natural moisture regulator because of its excellent moisture buffering capacity [15] and its high permeability to water vapor which allows it to significantly moderate the relative humidity variations of the surrounding air [16].

The hemp concrete thermo-physical and hydric properties have been widely studied in literature. Recent works focus principally on the quantification of the amount of water entering the hemp as a function of time, by Nuclear Magnetic Resonance measurements [17], the evolution of hemp concrete's functional properties (thermal and acoustical performances) under the influence of humidification and drying cycles [18]. Further, the 2D microstructure of hemp concrete has been observed in the work of Delannoy et al. [19], where scanning electron microscope images of the hemp concrete accompanying the characterization of thermal conductivity, acoustic performance and hygroscopic properties were presented.

In general, the researchers show interest in the macroscopic behavior of hemp concrete [12,14–16,20–24] and neglect small-scale interactions. However, the macroscopic behavior of building materials strongly depends on the mechanisms that act at the microscopic scale [25,26]. The macroscopic properties of materials are directly related to their morphology [25]. In addition, hemp concrete is a very heterogeneous material, composed of vegetal fiber and binder. These two constituents of this material present different behaviors under variations of environmental conditions, which can cause considerable dimensional changes in contact with the ambient relative humidity conditions. This is due to the fact that the hemp shiv is a hygroscopic material very sensitive to relative humidity variations, and it quickly absorbs large quantities of water (3.5–5 times its own weight) [27] thus causing local deformations at microscopic scale. These morphological changes, caused by the swelling or shrinkage of hemp, lead to the degradation of hygrothermal performance as well as the modification of physical properties, porosity and internal morphology of the material. Thus the necessity to master all these phenomena and take into consideration their interaction to better evaluate the durability of hygroscopic materials exposed to various environmental solicitations [28].

It is therefore essential to evaluate the microscopic behavior of hemp concrete under hydric solicitations to better apprehend the swelling induced by relative humidity variations and influenced by its multi-scale, anisotropic, and heterogeneous structure. The use of microscopic non-destructive methods like X-ray tomography and the DVC is considered as a reliable way to perform hygromechanical and morphological characterizations of the microscopic behavior of the material in general. On the other hand, the digital volume correlation is often used for purely mechanical loads applied to building materials [29–32]. It consists in determining the strains within the material under mechanical stress. The existing references that treat the evaluation of microscopic strain related to bio-based materials concerns wood [33]. In fact, the characterization of the earlywood and latewood structures' and their influence on the hygromechanical behavior of the material were performed. On the other hand, the quantification of swelling was performed by studying the interaction of the moisture and mechanical behavior of wood [28]. The variation of the cell structure through the growth ring is responsible for the anisotropy of swelling and stiffness [34]. Moreover, the swelling phenomenon induces an initial and final wood interaction [35]. These techniques start to be explored on bio-based materials. Concerning hemp concrete, few studies were interested by the evaluation of the microscopic strains caused by relative humidity solicitations.

The aim of this paper is to characterize the microstructure and evaluate the hygromorphic behavior of hemp concrete. To do so, two original nondestructive techniques have been used: X-ray tomography and 3D digital volume correlation. A scanning electron microscopy (SEM) analysis was also performed to better understand the local microstructure of the studied material, in complementarity to the tomographic scans. The material's hygrometry was considered during the scans through an original device which was designed and adapted to the tomograph. The procedure adopted leads to the identification of the strain fields at the microscopic scale under hydric solicitations. The material and methods are first described, then the results of X-ray tomography and SEM observation are presented. Finally, the strain fields of hemp concrete studied by Digital Volume Correlation (DVC) were quantified and analyzed.

2. Material and methods

In this section, the material's composition and the used formulation were proposed. Concerning the experimental procedure, X-ray tomography tests were carried out in order to observe and analyze the microstructure of hemp concrete. First, the tomographic scans were performed at a relative humidity of 50%. After that, the swelling analysis was achieved by taking into consideration two scans at various relative humidity: drying condition and a relative humidity of 85%. Subsequently, these scans will be treated using the Digital Volume Correlation (DVC) technique to determine the strain fields in the material caused by the hydric solicitations.

2.1. Material setting and formulation

The material used for this study is constituted of bio-aggregate of hemp shiv and binder. The hemp shiv is an aggregate of hemp concrete shuttered, it's referenced C020. Its bulk density is about 110 kg/m^3. The used lime-based binder is called Batichanvre. This binder is a mixture of: natural lime from St. Astier (Hydraulics: NHL and aerial: CL), cement CEM I 52.5, and various additives to improve the rheology and permeability of hemp concretes These products (hemp shiv and binder) are marketed by a manufacturer-distributor of hemp products and ecological insulation, called Technichanvre[1] (France).

Hemp-based concrete presents variability of structures depending on the used formulation. In this study, the wall application is retained. It is developed based on the professional rules of implementation of hemp concrete structures and corresponds to a composition of materials used on construction sites. The mass dosages of hemp shiv, binder and water are reported in Table 1.

2.2. X-ray tomography

X-ray tomography is a technique that allows non-destructive imaging and quantification of internal characteristics of 3D objects. This imaging technique presents certain assets for a better microstructural characterization at the local scale of materials. It was first developed in the medical field, then used in the materials sciences and proves its interest in different fields of geosciences. The basic principle of this technique consists to reconstruct the 3D volume of an object from a series of 2D radiographs recorded at several angular positions.

Tomographs are mainly composed of an X-ray source, digital detector and a turntable. The resolution of images depends on

[1] http://www.technichanvre.com