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An iterative micromechanical modeling to estimate the thermal and mechanical properties of polydisperse composites with platy particles: Application to anisotropic hemp and lime concretes

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HIGHLIGHTS

- An iterative multiscale modeling technique including FE simulations is developed.
- It allows to account for the shape and spatial distribution of platy hemp shives.
- Thermal conductivity & mechanical properties of hempcretes (HLC) are estimated.
- Special attention is paid to the anisotropy of both hemp shives and compacted HLC.
- The evolution of HLC porosity throughout compaction process is also accounted for.

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ABSTRACT

This work aims at providing a multi-scale model to estimate the effective properties of hemp and lime concretes. The microstructures of such materials are characterized by a relatively high filling rate, platy orthotropic particles distributed on a wide range of spatial directions, and a high level of porosity at meso and micro scales. An iterative micromechanical modeling is here enhanced with some numerical features allowing to deal with the shape and orientation of the particles and with the resulting effective anisotropy of concretes. The model thus constructed is first put into practice to identify the properties of hemp shives and air-slaked lime for various compaction degrees. The results obtained are then used as input data to estimate the thermal and mechanical properties of both a collection of moderately compacted concretes, and a set of concretes with several compaction degrees. Simulations results are eventually confronted with experimental data from the literature.

1. Introduction

Over the past thirty years building materials reinforced with vegetal products, and more specifically vegetal concretes, have made a remarkable headway in the construction field due to their slight environmental impact. Hemp and lime concretes, also known as hempcretes, are one of the most commonly used bio-based construction material for walls since their outbreak in the late 1980s [46,21]. Not only are they made of sustainable resources usually considered as by-products of the fiber and oil industries, but their production has a very low carbon footprint. They have also proved to be particularly efficient as far as thermal insulation is concerned allowing thus some substantial energy savings [10,22,21,12]. On the other hand, their mechanical performances stay rather modest which explains why they are currently only used as filling materials for walls, roofs and floors, together with wooden load-bearing structures. Vegetable concrete manufacturers in association with project managers aim at improving the mechanical resistance of vegetable concretes while preserving the insulation properties of the latter. They also need the establishment of building norms that will enable a wide use of this new type of materials. Comprehensive constitutive models can provide valuable help to make this step easier. They allow indeed to perform collections of numerical simulations (so called "digital

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experiments") with varying parameters, such as the physical nature, shape or spatial arrangement of the constituents. In the framework of a large optimization and certification campaign, the purpose of this work is to predict the thermal and mechanical properties of hemp and lime concretes at the end of their manufacturing process by means of a numerical multi-scale modeling technique. Such technique allows to pay a special attention to the quite complex microstructures of this class of materials.

Hemp-lime concretes (HLC) are obtained by mixing hemp hurds commonly referred to as hemp shives with a lime based binder. The latter is an air-slaked lime produced in presence of pozzolans, and water. The mixture obtained is then processed and casted (which often includes a compaction stage) and is eventually dried. The very nature of the material and its manufacturing process make several modeling issues arise.

First of all the specific morphology and spatial distribution of hemp shives have to be taken into account. Hemp shives are indeed elongated platy particles cut in the wooden core of the plant stem. They have a rectangular parallelepipedic shape with a moderate slenderness Fig. 1(b). Hemp shives exhibit an orthotropic behavior as they are bored through by micro tubular ducts originally forming the sap distribution network. The spatial arrangement of shives together with their own behavior is at the origin of the material global anisotropy. The compaction phase of the manufacturing process tends moreover to align shives in several parallel planes or strata, increasing thus a potential initial anisotropy [29,39,44]. The architecture of the material also depends on the concrete formulation, i.e. on the quantities of shives and lime introduced. Some hemp and lime concretes may appear as an entanglement of hemp particles maintained together thanks to local lime bridges when the shives rate is high, whereas others have a more classical microstructure, i.e. hemp particles embedded in a lime matrix phase Fig. 1(a).

(a) Close up of a hemp and lime concrete sample

(b) Hemp shives covered with lime

Fig. 1. Hemp concrete sample and corresponding particles (hemp shives).

A related issue to deal with is the high porosity rate as it may represent up to 70% of the concretes volume [5,18], and sometimes nearly 80% [19,13]. Pores and voids are indeed present at both meso and microscales. Mesopores (i.e. whose size is close to the size of hemp shives) can be the result of the very architecture of the material when the lime rate is low. They appear as well in the matrix phase when the lime rate is high and the forming process lacks mixing. As noted earlier tubular microvoids can also be observed in shives. The porosity of hemp shives is indeed commonly considered as a little higher than 80% [25,33]. Some micropores may as well appear in the lime matrix as the result of chemical reactions during the drying phase. The presence of these two categories of voids (mesopores and micropores) and their potential closure during the compaction phase of the manufacturing process has to be taken into account in the constitutive modeling of the hemp concretes in use [15].

Scale transition modeling techniques including morphology features appear thus as an appropriate tool to account for all these complex morphological effects when trying to estimate the properties of hempcretes.

Micromechanical models have been developed over the past sixty years to determine the global behavior of heterogeneous materials depending on their local microstructures. A series of models can be found in the literature using analytical homogenization schemes, often based on the fundamental Eshelby's ellipsoidal inclusion model [17]. Very few are nevertheless dedicated to materials reinforced with rectangular parallelepipedic particles more or less randomly distributed in the material, for which analytical solutions are missing [6,23,24]. As computational resources increase numerical full-field finite element simulations on detailed Representative Volume Elements (RVE) could appear as a convenient solution to this problem. The RVE could either be numerically designed or digitally reconstructed from experimental imagery like computed tomography. In both cases, the generation of the RVE reveals itself quite complex when dealing with contacts between the particles and the size of the RVE as evidenced by several articles on fibrous media and especially wood-based ones [26,43,27,40,16] among others. As a consequence the filling rates of the materials numerically designed from scratch are generally below those of the category of concretes considered here. In the case of computed tomography, computer resources needed are high for both the reconstruction phase and the subsequent finite element solving procedure. But the most limitating fact in the use of this type of approach is that the meshing step entails some remodeling of the real microstructure in order to avoid distorted elements and mesh size problems. Some microstructural artefacts are therefore artificially added to RVE potentially with an effect on the identification of the global properties of the material.

As the materials at stake in this paper do not have a precisely controlled microstructure given their forming process it is here chosen, as several authors did previously [4,12,2], to focus on much more time efficient modeling methods.

More precisely this paper deals with an iterative multiscale modeling which has been developed to describe the behavior of highly-filled materials with polydispersed heterogeneities. The approach at stake is inspired by the differential scheme defined by McLaughlin [28], enhanced by Norris [31] and proposed for linear porous media by Zimmerman [47]. The modeling procedure follows the manufacturing process of granular composites materials in which heterogeneities are gradually introduced in a matrix phase whose properties evolve through the process. The creation of a given medium is thus achieved through the sequential production of intermediate partially-filled media. The effective