Innovative bio-based construction materials with improved moisture buffering and heat transfer properties

Housing and buildings in general are the EU's most important energy consumers and polluters. Improvements in this field are expected to contribute to meeting the EU climate-neutral objective of net-zero greenhouse gas emissions by 2050. In this regard, the use of bio-based construction materials for construction or renovation is currently growing as these materials are recognized as a means to **reduce carbon dioxide emissions from construction** through: (i) their sustainable production as crops grown annually or as longer harvest-cycle foresting, including secondary products from food growth, (ii) their contribution to air quality, (iii) the reduction of energy consumption for heating or cooling which they induce, (iv) their partial or full recyclability, and (v) their long term use in construction acting as a carbon sink. Such materials include pilings of natural fibers (or bio-elements) derived from wood, wheat, jute, flax, bamboo, straw, coir, cotton, pulp, etc., mainly used for insulation, or dispersions of plant materials (wood, hemp, cellulose wadding, straw, etc.), coated by a mineral matrix (lime, cement, earth, plaster, clay, etc.) generally used as filling for walls or for insulation: hemp concrete, wood concrete, flax concrete, adobe, cob, etc.

One important characteristic of bio-based construction materials is that they **are hygroscopic**, i.e., they can absorb (resp. release) a significant fraction of vapor as (resp. from) "bound water" inside the solid bio-components of the structure thanks to the presence of hydroxyl groups associated with the cell-wall macromolecules. This bound water plays several important roles. It favors the comfort of building occupants by ensuring a "**moisture buffering**" effect, in the sense that it reduces the daily variations of moisture, or more precisely the relative humidity (RH) in the air; in particular, this reduces ventilation requirements and thus curbs energy consumption. Also, due to the large latent heat (close to that associated with the liquid-vapor transition) associated with sorption or desorption processes, bio-based elements behave as **phase-change materials**, releasing heat as a result of sorption when the ambient temperature decreases. These coupled heat and moisture transfers in building envelopes have a significant impact on the annual cooling and heating energy consumption and the indoor thermal and humidity environment, but moisture transfer processes in building envelopes are not generally taken into account in current conventional thermal calculations and **energy consumption analyses**. This in particular precludes a correct estimation of a building's performance with respect to thermal regulations. In order to develop and optimize the use of such materials it is crucial to be able: (i) to quantify and predict their physical properties, (ii) to properly predict and thus control the hygrothermal behavior of buildings in use, and (iii) to develop innovative products with higher efficiency. This requires an in-depth understanding of the processes.

The major problem hindering progress is the lack of information and proper description of water transport and phase changes inside the porous structure. Measurements remain challenging, in particular considering that the materials are non-transparent and different states of water (free liquid water, bound water, vapor) can coexist.

The Navier Laboratory has a Magnetic Resonance Imager (MRI) and several NMR Spectrometers dedicated to applications in civil engineering. We recently achieved a world first by demonstrating the possibility to measure the evolution of the distribution of free and bound water in wood, with the help of appropriate NMR and MRI sequences (T_2 distribution in time, multi-echo alternating with Single-Point-Imaging) [1-2]. We were also able to measure the spatial distribution over time in cellulose fiber pilings, and fully model the vapor-bound water exchanges and transport through this structure [3].

The present thesis project will focus on typical bio-based insulation materials made by aggregation of of wood, flax, or wheat fibers. The aim will be to fully characterize moisture transport and exchanges in such materials types under various conditions of external air flux, through experimental and modelling approaches. The fiber size, the particle orientations, and the porosity of the materials will be varied. Depending on time heat transfers will also be studied, with the help of home-made systems under development.

Moreover, complementary in-situ X-ray imaging and X-ray wide- and small-angle X-ray scattering (SAXS/WAXS) are planned in a collaboration with P. Huber to correlate the NMR data with spatio-temporally resolved water distributions in pore space. These goals shall particularly profit from a 6 months visit in P.Huber's lab in Hamburg as well as joined experiments at synchrotron-based X-ray beamlines at PETRA III (Hamburg), or at ESRF (Grenoble) and Soleil (Paris).

The different techniques used will allow to get a complete set of data concerning the hygrothermal evolution of these controlled systems under controlled boundary conditions. This will allow us to develop models taking into account the different transport and transfers between phases and fully validate it by comparison with data at a local scale, which is a unique situation in the field of construction materials.

This work should lead to a clarification of the physical processes at work in various insulation and bio-based construction materials, provide some relevant means for their characterization, offer some practical recommendations on the most appropriate characteristics, and open the way to the development of new high performance materials.

This work will be mainly carried out within Laboratoire Navier, Physics and Porous Media Team, with P. Coussot (http://philippecoussot.com) as official supervisor, and in collaboration with R. Sidi-Boulenouar and B. Maillet from the NMR Team, and with Patrick Huber group (https://huberlab.wp.tuhh.de) in Hamburg.

The candidate is expected to have a strong motivation for research and a background in physics, fluid mechanics, or physicochemistry.

Application: https://clear-doc.univ-gustave-eiffel.fr/how-to-apply/list-of-phd-topics/

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Some references of our research groups

[1] Penvern et al, How bound water regulates wood drying, *Physical Review Applied*, 14, 054051 (2020) - Editor's suggestion – Featured in Physics: https://physics.aps.org/articles/v13/182 - Paper in CNRS News

[2] Cocusse et al, Two-step diffusion in cellular hygroscopic (vascular plant-like) materials, *Science Advances*, 8, eabm7830 (2022)

[3] Ma et al, Vapor-sorption coupled diffusion in clothes revealed by MRI, *Physical Review Applied*, 17, 024048 (2022) Featured in Physics: https://physics.aps.org/articles/v15/s22 - Paper in CNRS News