Joint ELytMaX[1] PhD subject 2024-2027

Double degree PhD INSA Lyon (Lyon, France) – Tohoku University (Sendai, Japan)

PhD's title: Understanding long term aging mechanisms of fiber dense media in superinsulation materials: coupled mechanical and thermal characterization and modelling

Start of the PhD thesis: October 2024

PhD's candidate profile and skills sought
Master 2 degree or Engineer degree in Mechanics of Materials, Physics, Materials Science, Mechanical Engineering, Numerical Mechanics

Deadline for applications: 26 April 2024

PhD's Keywords
Superinsulation materials, Fiber Networks, Ageing, X-ray microtomography, In situ mechanical experiments, Creep, Advanced experiment, Thermal conductivity

Summary of the PhD's subject
Energy efficiency in buildings is one of the significant challenges that need to be addressed for reducing their impact on climate and reaching the emission targets as agreed in the Paris agreement. In the EU, buildings approximately consume 40% of energy and are responsible for 36% of CO2 emissions. Insulating the building envelope is key to achieving savings on building space heat energy and reducing carbon emissions (Brunner and Simmler 2008, Karami et al. 2015). As noticed by the European Commission, "about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient. The renovation of existing buildings has the potential to lead to significant energy savings, possibly reducing the EU's total energy consumption by 5-6% and lowering CO_2 emissions by about 5%", thus leading to a reduction of approx. 150-200 Mt eq. CO_2 a year. In addition, in the domestic, refrigerators accounted for a very large amount of residential electric energy consumption (up to 20%) in some countries and taking a larger view on the cold chain shows that the potentials energy saving equals 10 000 GWh/y or 665 Mt eq. CO_2 a year worldwide (Gao 2018).

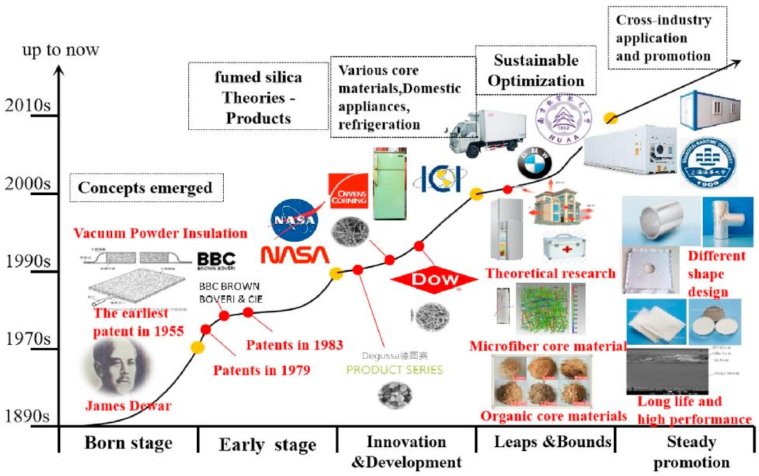

Figure 1. Development of VIP's (Kan et al., 2022)

[1] https://www.elyt-lab.com/en/content/elytmax-umi-3757

In this context, **vacuum insulation panels (VIP)** are increasingly used for the thermal insulation of buildings, cold chain chambers and refrigerators, medical transportation systems (Figure 1). They offer a unique way of reducing the transmission losses with minimal insulation thicknesses. So, it is possible for buildings to save valuable living space areas, whereas it is possible to enhance the useful volume of the compartments of refrigerators without changing their external dimensions (Verma and Singh 2019, Kan et al., 2022).

VIP's exhibit thermal conductivity down to 1-2 mW m^{-1} K^{-1} that are five times lower than that of the best polyurethane foams (20-29 mW m^{-1} K^{-1}) used for domestic appliances or eight times lower thermal conductivity than conventional thermal insulation materials (glass wool) used in the building domains.

VIP's consist of a sealing envelope 400x400 mm² (Figure 1a) with a thickness of approx. 100 µm in the form of a polymer-metal multilayer, e.g. a polyethylene (PET) layer coated with aluminum assembled with a low-density polyethylene (LDPE) layer by an adhesive (Planes et al. 2011).

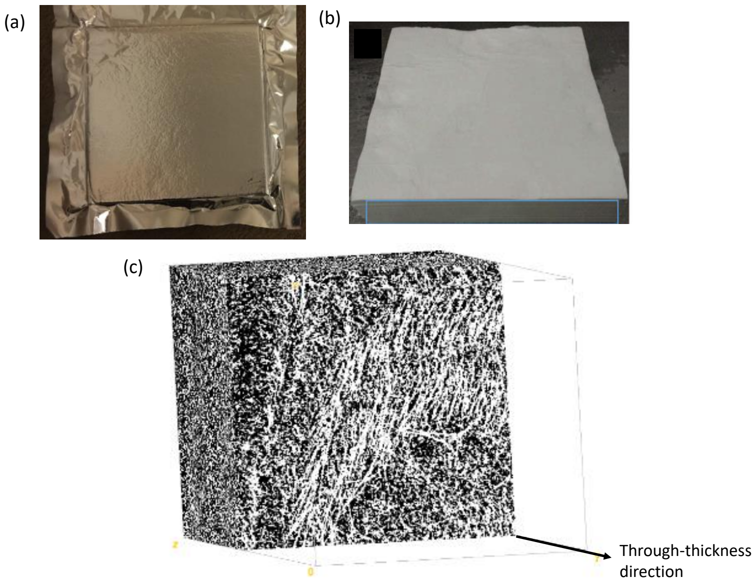

Figure 2. (a) Top view of a VIP with its envelope (In-plane dimensions 400x400 mm². (b) View of the corresponding fibrous core material inside the envelope under vacuum. Adapted from Chen et al., Energy, 2015. (c) 3D image of a fibrous core material of a VIP (30-µm resolution, in-plane dimensions 2x2 mm²).

VIPS' also consist of a highly porous bearing core material that is usually made of an anisotropic network of glass fibers (Figure 2). Natural fibers (Kan et al., 2023) are emerging materials in this domain as well as polymer-based fibers. These new fibers are scrutinized because they offer the possibility to adapt the VIP's concept to e.g. food packaging applications that require a shorter life-time than in the traditional domains of VIP's for a lower cost and an expected better environmental impact and also using local resources (for natural fibers).

The bearing core fibrous materials, assemblies of fiber stacks (Figure 2c), are subjected to various **coupled thermo-mechanical loadings** during their manufacturing and their use. During manufacturing, the sealing envelope exerts compressive loading on the fibrous material because of the vacuum (< 0.1 mbar) that is applied to lower the thermal conductivity of VIP's, which results in an initial compressive stress state applied on the fibrous network. During their use, VIP's are also subjected to varying environmental conditions (varying temperature and relative humidity conditions). Varying temperature conditions can induce cycling loading conditions on VIP's which is known to induce in fibrous materials a structural evolution (Ghafour et al., 2021): *cf.* Figure 3. These couplings between the thermal properties and the mechanical behavior of the VIP's and more especially the VIP's core materials are not taken into account in the current approaches for the modeling of the effective thermal conductivities of these structures (Zhang et al., 2024). Varying relative humidity conditions can result in dry gas and moisture permeation through the polymer-metal envelope and the absorption of water in the core materials of VIP's.

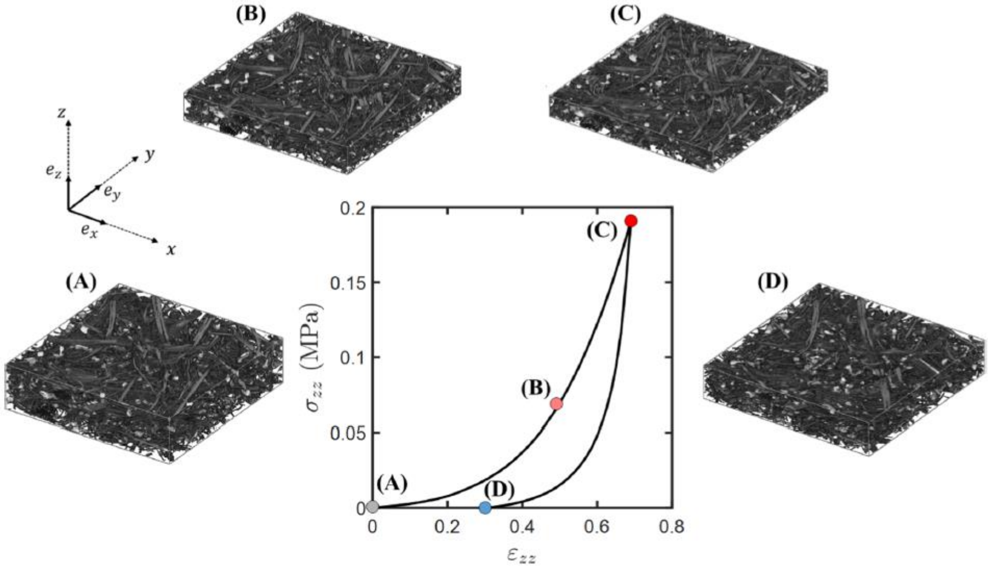

Figure 3. 3D cropped views of a fibre network made of natural fibres during in situ compression test and corresponding stress–strain compression curves, revealing the hysteresis during the loading and unloading (adapted from Ghafour et al., 2021).

These mechanisms can affect the overall thermal conductivity of the VIP's that depends on residual gas conductivity, fibrous material conductivity, envelope conductivity and result in their aging, i.e., a progressive increase in their thermal conductivity (Figure 4). This figure also shows the VIP's that were produced more than twenty years ago exhibit a drastic decrease in their thermal performances, thereby raising the question of their recycling or "regeneration" Up to now, such strategies have been scarcely explored

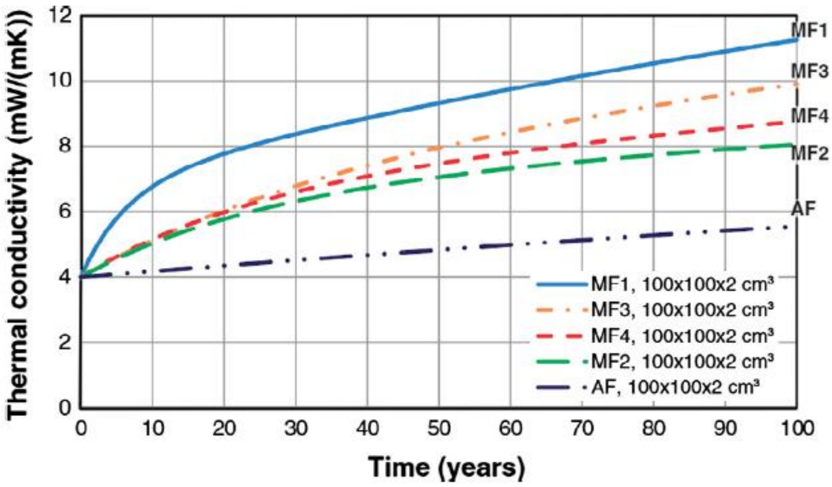

Figure 4. Prediction of the evolution of the thermal conductivity of several VIP's panels as a function of time, showing the aging of these panels, i.e. a progressive increase in their thermal conductivities (Kanes and Jelle, 2014).

To **enhance and tailor the lifespan** or to **recycle** VIP's, it is thus crucial to better understand the aforementioned mechanisms and their couplings as well as their effects on the structural evolution of

VIP's, the mechanical properties of the core and envelope materials, and the resulting increase of their thermal conductivity (Chal et al. 2021). Why does this detrimental evolution occur? What are the fine scale deformation mechanisms that affect the core material that are at the origin of this evolution? What is the role played by water uptake? Where and how is water entrapped in the fibrous network? Is it possible to regenerate the materials that constitute the VIP's structure by thermo-hygromechanical treatments? Answering these questions is all the more important for emerging core materials made of hygroscopic and viscoelastic biosourced or polymer fibers (Zach et al. 2023).

In this project, an original multiscale and multiphysics approach is proposed to relate the evolution of the thermal properties of VIP's with their microstructural evolution induced by cyclic thermo-hygromechanical loading conditions, mimicking the long-term aging conditions, using for that advanced experimental techniques and numerical simulation tools. The results gathered will be used to propose regeneration processing routes consisting thermo-hygromechanical treatments.

Research program
Task 1 – Materials

- Choice of VIP's materials with aged and non-aged, aged and regenerated core materials made of glass or biosourced fibres obtained with different manufacturing techniques and various types of fibers and envelopes.

Task 2 – Sorption properties of VIP's

- Characterization of the sorption-desorption behavior of VIP's under various thermo-hygromechanical loading conditions.
- Phenomenological modelling of the sorption-desorption phenomena.

Task 3 – Mechanical properties in controlled environmental conditions

- Lab-scale cyclic tensile and compressive mechanical tests coupled with surface DIC measurements techniques in controlled varying environmental conditions (T and r.h.) on sealed and non-sealed fibrous core materials.
- In situ mechanical cyclic compression tests using X-ray microtomography imaging coupled with 3D DIC measurements in controlled varying environmental conditions (T and r.h. and pressure) on sealed and non-sealed fibrous core materials. The recent DTHE investment enables multiscale analysis from the panel size down to a few tens of microns.
- Study of the deformation mechanisms of the core fibrous materials at the fiber and fiber-fiber contact scale, and of the evolution of the microstructure (pore spatial distribution, pore size, pore connectivity, fiber length, orientation and curvature, specific surface area, number of fiber-fiber contacts, fiber-fiber contact areas). Tests performed at ESRF or with similar equipment.

Task 4 – Thermal properties

- Characterization of thermal and radiative properties of the various types of non-deformed and deformed VIP's in controlled varying environmental conditions (T and r.h.) on sealed and non-sealed fibrous core materials using dedicated measuring devices (Kobari et al. 2015).
- Fiber scale numerical simulation of the thermal properties using 3D images acquired in Task 3 of deformed real fibrous core materials and numerically generated fibrous networks
- Comparison with experiments.

The experimental and numerical data will contribute to the modelling of the thermo-hygromechanical properties of non-aged and aged VIP's. They will also enable to propose original strategies to improve the durability and to recycle these materials as well as to expand their use for other applications.

Organization of the PhD work and locations

- 18 months at LaMCoS and MateIS laboratories (Lyon, France) for Tasks 1,2 and 3.
- 12 months at IFS and ELyTMaX, Tohoku University (Sendai, Japan) for Task 4 and the writing of an article related to Tasks 1 to 3.
- 6 months at LaMCoS and MateIS laboratories (Lyon, France) for the writing of the PhD manuscript and PhD defense.

The PhD candidate will be basically based in Lyon, and will have to move to Japan for the 12 months research work at Tohoku University in the form of a long term business trip. The incurred extra expenses (transportation and lodging in Japan) will be supported by ELyTMaX laboratory, while keeping the PhD base salary. Additional short-term business trips to Oyonnax may be considered depending on the orientations of the research and the results from the first tasks, and supported by the laboratories.

Regular meetings (at least monthly or more frequent) with all the PhD advisors from France and Japan will be organized throughout the three years of the PhD work.

Framework of the international cooperation

INSA Lyon and Tohoku University have long-lasting education and research agreements, including a double degree PhD program since 2014. Around 30 students were enrolled successfully in this program since its beginning.

ELyTMaX is an International Research Laboratory, created in 2016 by CNRS, INSA Lyon, Centrale Lyon, Université Claude Bernard Lyon 1, and Tohoku University (Japan). On average, 3 permanent researchers from France are based at Tohoku University, and 4 double degree students. Since its creation, the laboratory welcomed 15 double-degree PhD students.

This project will benefit of the ancient relationships established by MATEIS with Swiss and German colleagues from EMPA and va-Q-tec.

Co-direction Team

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[2] http://lamcos.insa-lyon.fr/?L=1

[3] http://www.ifs.tohoku.ac.jp/LyC/jpn/index.html

[4] https://mateis.insa-lyon.fr/

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