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Optimized vegetal wools for indoor comfort: coupling fire treatment with acoustic and hygrothermal performances

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Abstract.

Vegetal wools are used as an alternative to traditional wall insulator materials, as they present great hygrothermal and acoustic properties, therefore providing interior building comfort. However, one major concern regarding the material's flammability arises, as generally, bio-based materials are poorly classified in terms of flame resistance. Therefore, fireproof treatments are needed and the knowledge regarding their influence on the wool's microstructure, and consequently, on its acoustic and hygrothermal performance, is lacking. This article presents the state of the art and the methodology that will be used to choose and optimize the fireproof treatment on the vegetal wools, and comprehend how it affects the material's microstructure and its acoustic and hygrothermal performances. In order to optimize the performance of the vegetal wools, the final objective of this project will be to develop models to describe the correlation between their micro and macro properties.

Keywords: sustainable building materials, vegetal wools, fireproof treatment, acoustics, hygrothermics

1 INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) reported that the global warming effects are happening faster each year, and in order to change this scenario, urgent actions must be taken [1]. For the building sector, the development of efficient and resilient buildings aiming to decarbonize the industry is a key solution as this sector is

responsible for more than one third of the total carbon dioxide emitted and energy consumed in the world, per year, considering pre-pandemic data from 2019 [2]. In addition to the issues of climate change and energy consumption, the noise pollution should also be addressed, as it is the second highest cause of health problems for citizens, after air pollution [3]. Therefore, efficient wall insulation can contribute to the peoples' health and comfort.

In order to tackle both of these problems, bio-based insulators emerges as a candidate as they temporarily store carbon and are great acoustic and thermal insulators [4]–[7]. Among several possibilities of bio-based insulation materials, this work focuses on vegetal wool. This material presents interesting characteristics for a wall insulation application, such as its physical, hygrothermal and acoustic properties. However, one major concern arises regarding the material's fire resistance, especially for this application, as bio-based materials usually present low resistance against fire [8]. Therefore, to expand the applications of vegetal wools for green building envelope a fireproof treatment for this material should be considered. On the other hand, the application of a fireproof treatment on the vegetal wools could be modifying its microstructure [9]–[11]. As their hygrothermal and acoustic properties are directly related to their microstructure the fireproof treatment will, consequently, affect the material's hygrothermal and acoustic performances. Thus, this should be evaluated, in order to ensure that the treated vegetal wools would still be considered a good alternative for the development of green buildings.

This paper presents the methodology that will be used to identify eco-friendly fireproof treatments and study their impact on the thermal and acoustic performances of vegetal wools. The three main objectives are:

1. Evaluate the alternatives and the application methods of the fireproof treatment in the vegetal wools;
2. Comprehend the influence and optimize the fireproof treatment on the fibers and microstructure of the vegetal wools;
3. Adapt micro-macro modeling methods to simulate the impact of the fireproof treatment on acoustic and hygrothermal properties of the vegetal wools.

In this article, the current state of the art on vegetal wools and their properties is presented, as well as the main mechanisms of flame retardancy of fireproof treatments and the main methods used to increase flame retardancy of vegetal fibers. The proposed methodology for this study is then detailed.

2 STATE OF THE ART

2.1 Vegetal wools

Vegetal wools are manufactured products made of lignocellulosic and synthetic fibers. The manufacturing process can be done by three different methods: mechanical bonding (needle-punching), chemical bonding and thermal bonding [12]. Among the options, thermal bonding is the most popular for nonwovens manufacture, at it provides

high production rates, while demanding less energy than chemical bonding, for example [12]. Hence, the focus of this paper will be specifically on thermal bonding process.

In this process, the vegetal fibers are mixed with thermoplastic polymeric ones, and are then heated until the melting or softening temperature of the synthetic fibers, followed by subsequent cooling to solidify and form a bond between the vegetal fibers [12]. Then, the vegetal wools obtained are bi-component materials where the thermoplastic fiber acts as a binder and the lignocellulosic fiber is the base fiber. For this study, hemp and flax will be used as the base fiber, and polylactic acid (PLA) as the binder.

The vegetal wools are generally composed by 80 to 90 wt.% of vegetal fiber, and 10 to 20 wt.% of polymeric fiber [13]. For example, in Freivalde et al. [14] hemp wools were made of 92% of hemp fibers and 8% of polyethylene-polypropylene fibers. Fig. 1a and Fig. 1b shows the visual aspects of a vegetal wool and a SEM observation of polymer and vegetal fibers, respectively.

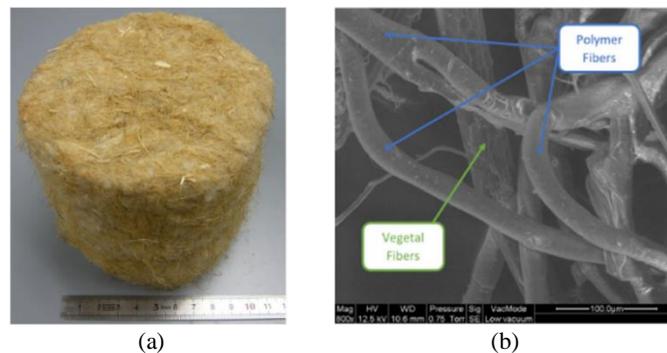


Fig. 1. (a) Hemp wool sample; (b) SEM observation of polymer and hemp fibers [23].

For the manufacturing process of flexible insulation panels traditionally used in the building field, the material generally presents a low density of less than $50 \text{ kg}\cdot\text{m}^{-3}$ and a high porosity greater than 90% [14]–[17].

Acoustic and hygrothermal properties of vegetal wools have been measured and evaluated by a few studies, showing promising results, but further studies are needed to consolidate the knowledge around it.

For the acoustic properties research works have been done not only on vegetal fibers and shives [18]–[22], but also on vegetal wools [17], [23]. Fig. 2a shows some results of sound absorption from hemp wool with different thicknesses. It underlines the high sound absorption potential of these materials in a wide range of frequencies, sustaining the argument that it is a good acoustic insulator.

Regarding the hygrothermal properties, some studies explored these properties in vegetal wools [15], [16], [24]–[26]. On the hygric point of view, Collet et al. [15] showed that hemp wools can absorb about ten times more water than mineral wools (comparing to the literature), and that both materials show similar water vapor permeability. Fig. 2b shows the sorption curve of a hemp wool sample. For their thermal properties, hemp and flax wools shows values of thermal conductivity ranging usually

between 40 and 55 $\text{mW}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ [16], [24]–[26], depending on the wools' density and porosity.

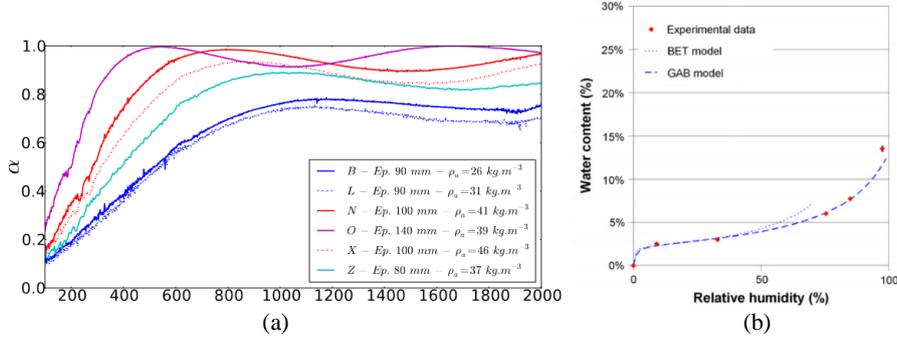


Fig. 2. (a) Hemp wool sound absorption [13]; (b) Hemp wool sorption curve [15]

To sum up, vegetal wools have a great potential to be used as a sustainable insulator material for green building applications, being, therefore, an alternative to traditional building materials [27].

2.2 Fireproof treatments

Despite their performances adapted to the building sector, there is still a concern regarding the flammability of vegetal wools, as, indeed, bio-based materials are usually poorly classified regarding their fire resistance [28], [29]. Therefore, the application of a fireproof treatment could improve the vegetal wool's resistance to fire, and allow it to be applied in buildings without introducing any hazard.

Commonly used flame retardants (FR) are mineral, halogenated, phosphorous-based, silicon-based and nitrogen-based products [30]–[32]. For vegetal fibers, great results have been achieved through grafting of phosphorous into the fibers composition [31], [33], [34], [9]. Phosphorous-based FR promotes the formation of a carbonized layer, called char, which acts as a physical barrier, reducing both the thermal and oxygen diffusion, as well as the volatilization of combustible products [11], [30], [32]. Furthermore, they are not toxic [34]. With bio-based materials, the use of phosphorous-based products, associated with nitrogen-based products forms intumescent flame retardant systems (IFRS). The IFRS forms an expanded char during thermal degradation, which acts as an insulating barrier, reducing heat transfer between the heat source and the material's surface, and limiting the fuel transfer and the oxygen diffusion [30]. For the formation of a IFRS, three components are required: an acid source, provided by the phosphorous thermal decomposition; a carbonizing agent, which is the bio-based material; and a blowing agent, which can be obtained from nitrogen products [30], [32], [35].

To graft the phosphorous on the fiber's molecules, different techniques might be used, in particular, chemical grafting and silane coating. The chemical grafting aims to form covalent bonds between the phosphorous and the chemical components of the

fiber. If the treatment is performed in mild conditions (low temperature, short duration), a condensation reaction occurs between the phosphorous and the aromatic groups present in lignin. On the other hand, in severe conditions (high temperature, long duration), a phosphorylation reaction occurs, grafting the phosphorous on cellulose [9], [31], [33], [36].

Alternatively, the silane treatment aims to form a coating layer on the fiber's surface, creating a thermal shield and reducing oxygen diffusion [37]. When associated with phosphorous and nitrogen products, it can form a IFRS with enhanced performance [38]. Nevertheless, the work carried out with these treatments concerns applications on small quantities of fibers. It is therefore essential to evaluate whether these methods are viable for the treatment of lignocellulosic fibers on a larger scale, particularly in the context of industrial manufacturing.

Moreover, as a side-effect, the incorporation of phosphorous-based FRs can, potentially, increase the fungus development in the vegetal wools, because phosphorous is one of the possible elements that stimulates the microbial growth [39], [40]. This will therefore be another important aspect to consider for the flame retardant overall effectiveness.

3 METHODOLOGY

Aiming to develop optimized fireproof treated vegetal wools for insulation, the proposed methodology scheme for this work is presented on Fig. 3. For this study, two types of vegetal fibers will be considered: flax and hemp fiber. Both fibers are largely available in France, and have been used for flax and hemp wools production. The first step of this study will consist on understanding the manufacturing process of turning the vegetal fibers into vegetal wools as described in section II.

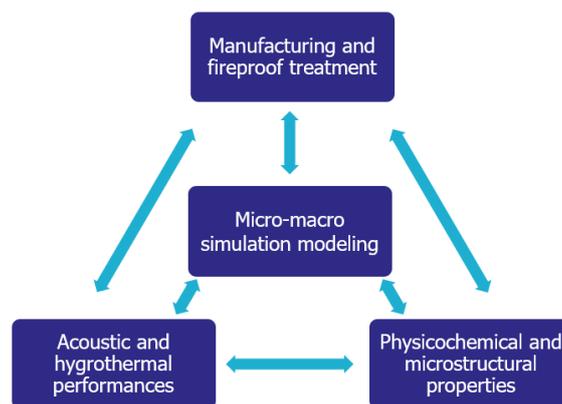


Fig. 3. Methodology scheme

Then, a study about fireproof treatment of the vegetal wools will be carried out, with the objective to define which flame retardant and application method that provide the

desired performance. Three approaches will be evaluated: grafting with mild conditions; grafting in severe conditions; and silane treatment. The FRs considered are (3-trimethoxysilylpropyl)diethylenetriamine (TRIAMO), dihydrogen ammonium phosphate (DAP), phytic acid (PA) and urea. These compounds were chosen aiming to form IFRS and to be viable for a usage in large scale. The fire properties will be evaluated through cone calorimeter test and thermogravimetric analysis. Moreover, as the main substances considered for the fireproof treatment are phosphorous-based, components that may be nutrients for fungus development, a specific study will be conducted to assess their impact on fungal growth.

In the following, it will be necessary to comprehend the physicochemical and the microstructural properties of the vegetal wools, due to the fact that the application of a fireproof treatment on the fibers could change some of its properties on both micro and meso scales. For example, fireproof treatment could impact important parameters such as porosity, airflow resistivity, density and fiber radii. Consequently, macro-scale properties such as acoustic and hygrothermal, could also be affected. This step will be fundamental to the fully comprehension and control of the vegetal wools' acoustic and hygrothermal performances. It will be done by image analysis on the optical and electronic microscopy, pycnometry and airflow resistivity meter.

Next, the acoustic and hygrothermal parameters of treated and non-treated vegetal wools will be evaluated and compared. This comparison will allow the enrichment of the existing database for untreated vegetal wools, and to provide new knowledge on the treated material. The acoustic properties can be obtained with Kundt tube characterizations and the hygrothermal properties can be obtained through the dynamic vapor sorption (DVS) test, the moisture buffer value (MBV), water vapor permeability (WVP) measurement and hot disk test [15], [28].

This work also includes the adaptation of modelling methods to describe the hygrothermal and acoustic behavior of fireproof treated vegetal wools. The use of these models will permit numerous simulations to be carried out by varying the input parameters and will also be useful for identifying possible improvements that could be done to optimize the treated vegetal wool performance. To do so, there are many different possible approaches, and for this study, the micro-macro approach was chosen, using the self-consistent method (SCM). This method consists on an homogenization between microscopic scale parameters and macroscopic scale properties [16]. Through this method, it is possible to create direct analytical relationships between micro and macro scales and to carry out rapid inverse analysis [17].

Piégay et al. [16] applied this method to develop a model for the thermal conductivity of untreated vegetal wools and achieve a mean relative deviation from experimental results of less than 2%. For the acoustics, Piégay et al. [17] used the SCM method to obtain the sound absorption of untreated vegetal wools. This study would incorporate the changes in the microstructure with the use of flame retardants into the modelling approach, and validate it by comparing with the previous experimental tests. Based on these modelling methods, it will be possible to manufacture optimized fireproof treated vegetal wools panels prototypes.

4 CONCLUSION

In this study, a novel fireproof treated vegetal wool will be developed. Studies about the physicochemical and microstructure properties, as well as the modelling methods, will be used to understand and optimize the eco-friendly fireproof treatment and the acoustic and hygrothermal performances of the vegetal wools. After this study, it will be possible to expand the applications of vegetal wools for green building envelope.

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