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Sound absorption properties of a sunflower composite made from crushed stem particles and from chitosan bio-binder

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ABSTRACT

A recent study investigated the mechanical, thermal and acoustical properties of a bio-based composite made from crushed particles of sunflower stalks binded together by chitosan, a bio-based binder. The acoustical performance in absorption was found to be poor as the material was highly compacted and with low porosity. The present study focuses on the acoustical properties of a higher porosity composite, with lower density while the mechanical rigidity remains fairly high. A higher absorption coefficient is obtained. The experimental results on the absorption coefficient are compared to the prediction of a model involving 5 physical parameters (porosity, tortuosity, airflow resistivity, thermal and viscous characteristic lengths). The characterization methods to determine these parameters are described. The comparison between experimental and theoretical results shows that this material exhibits peculiar microstructural features. It is found that the sound absorption properties can involve dead-end pores or clusters and multiple porosity scales in the material.

1. Introduction

In recent years, the development of sustainable economy in modern societies has encouraged research on eco-design and on sustainable building materials. There is a growing interest in the development of new materials capable of contributing in this emerging topic. Mati-Baouche et al. [27], have recently developed a method of manufacturing 100% natural eco-insulating composite materials based on sunflower stalks particles binded together with a bio-based glue obtained from chitosan [11,28]. Chitosan is a biopolymer of β-(1,4)-linked 2-acetamido-2-deoxy-D-glucopyranose and 2-amino-2-deoxy-D-glucopyranose obtained by alkaline deacetylation of chitin, the main component of the exoskeleton of crustaceans [29]. Chitosan is the only cationic polysaccharide due to its positive charges (NH_3^+) at acidic pH (<7) [6]. These charges increase retention at the site of application [19]. Chitosan is widely produced worldwide, especially in the east. The bio-based composites made from chitosan and sunflower particles are porous and their properties can be tailored mainly by varying the chitosan content and the compaction pressure used for the composite preparation, which have a direct influence on the density of the produced material. The main application of this study is to propose a new high performance 100% bio-based material for building engineering.

The new building materials are also required, if possible, to perform several functions simultaneously. They can be expected to satisfy structural, thermal and acoustical demands The study by Mati-Baouche et al. [27] showed that a fairly high compaction pressure is desirable to obtain certain thermal and mechanical performances.

The first studies on the acoustics of sustainable materials were proposed in the seventies and eighties with contributions on the acoustic properties of ground, vegetation, trees, foliage and plant leaves [4,5,9,25,26]. Studies on the acoustic properties of building materials containing bio-based particles were later proposed [36,40]. Recyclable materials were studied more recently with contributions by Swift et al. [38], Horoshenkov and Swift [20] or Benkreira et al. [7]. An exhaustive review on sustainable materials for acoustic application was recently proposed by Asdrubali et al. [2]. They proposed a classification and a rating of the sustainability of these materials, their environmental impact in terms of global warming or acidification potential and discussed their advantages and disadvantages. They distinguished the natural materials (plants, leaves trees, ground), the recycled materials, and composites materials containing bio based or recycled particles. In building engineering, the acoustic properties of these new materials are not yet fully known or mastered and databases on their

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acoustic properties can be necessary. The use of natural fibers in building engineering can contribute to CO_2 reduction through recycling process. However, this raises other issues related to safety (resistance to fire, toxicity). Natural and recycled materials represent a good way to reduce the emission impact. The possibilities offered by bio-based materials for sustainable development and building engineering seem limitless. Recent other studies involving the acoustical properties were proposed by Glé et al. [17], Glé et al. [18], Asdrubali et al. [3] or Chabriac et al. [10]. It should be noted that certain studies deal with special features of bio-based materials. Olny and Boutin [30] as well as Glé et al. [17] have shown the importance of the double porosity effect on the acoustical properties. Lagarrigue et al. [21] have shown that sound diffusers based on natural material such as bamboo rods can behave as sonic crystals and display metamaterial features. Verdière et al. [39] have shown that a parallel transfer matrix approach can be used to describe the acoustic properties of a parallel assembly of hollow cylinders such as straws.

In the present study, we focus on a new specific acoustical feature of bio-based materials related to the possible presence of dead-end pores or cluster in these materials. Sunflower composites with a mass ratio chitosan/sunflower of 4.3%, a mean particle size of shredded sunflower stalks of 6.3 mm and a density of 150 kg/m^3 were produced. The amount of chitosan and the compaction rate applied led to a material with a thermal conductivity of 0.06 W m^{-1} K^{-1} and a maximum stress at break of about 2 MPa. The acoustical properties were also studied. The results on the absorption properties were found to be rather poor with an absorption coefficient lower than 0.3 in the frequency range 50–4000 Hz. This study confirmed that high porosity is generally desired to achieve good sound absorption. This feature is fully compatible with light materials requirements but not necessarily with high tensile strength and maximum stress at break or with certain thermal properties. The acoustic absorption in a porous material strongly depends upon several physical parameters among which are the porosity and the airflow resistivity. For low values of porosity and high values of airflow resistivity, the sound absorption can be low and this can explain the poor results obtained. Higher values of absorption can be expected for more porous materials. Depending on the desired performance, the right trade-off between thermal, mechanical and acoustic properties needs to be determined. In the present study, a new sample with higher porosity was studied with a particular attention on its acoustical properties.

The article is organized as follows: In Section 2, the fabrication process of the sunflower composite is recalled. Mechanical and thermal properties are given. Physical parameters necessary for the acoustical description are presented and their measured values are given. The acoustical modelling using these parameters is summarized. In Section 3, the experimental results on the acoustic absorption coefficient and on the transmission loss are presented and discussed. A comparison between the experimental results with the theoretical predictions is proposed and analyzed to explain the discrepancies. It is shown that peculiar features of the microstructure must be taken into consideration.

2. Material and methods

2.1. Recall of the fabrication process of the bio-based composite

Bio-based composites from shredded stems of sunflower and chitosan were produced as described previously [27] but using conditions leading to samples with higher porosity (Fig. 1). A chitosan solution at 4% (w/v) was made in 1% (v/v) acetic acid and mixed for 5 min with sunflower stalk particles (mix of bark and pith particles) having particle sizes between 3 and 5 mm. The ratio chitosan/sunflower particles was 0.066 g/g. The mixture was used to fill a polyvinylchloride (PVC) mold (180 mm × 50 mm × 40 mm) and was compacted during 1 min at 20 °C under a pressure of 32 × 10^{-3} MPa using weights. After drying at 50 °C for 50 h in an oven, the resulting composites (180 mm × 50 mm × 20 mm see Fig. 1) were firstly thermally characterized as described previously [27]. They were then cut to obtain slender shapes of 180 mm × 24 mm × 12 mm to do tensile mechanical characterization (tensile tests) as described previously [27] or cylindrical shape of 44.4 mm diameter for the purpose of determining the acoustic properties.

2.2. Mechanical and thermal properties

Young's modulus (E' (MPa) corresponds to the stiffness of the specimen. The more Young's modulus increases, the more rigid is the material. σ_{max} (MPa) is the maximum stress reached during tensile tests that the sample can sustain before being broken. These two parameters characterize the mechanical strength of the material. The mechanical properties of the bio-based composite chitosan/sunflower stalks particles in tensile mode attained up to 0.14 MPa for σ_{max} max and 60 MPa for E'. These results are in agreement with those of Mati-Baouche et al. [27] obtained with similar bio-based composites.

The lower the thermal conductivity (k) of a composite is (less than 0.1 W m^{-1} K^{-1}), the more the thermal insulation is significant. The composite obtained in this study can be considered as thermal insulator because of its thermal conductivity that was measured at 0.077 W m^{-1} K^{-1}. It showed similar thermal properties compared with composites of Mati-Baouche et al. [27] which had thermal conductivities between 0.056 and 0.058 W m^{-1} K^{-1} depending on the manufacturing conditions.

2.3. Basic properties of the material for the acoustical description

The process described in the previous section was used to produce the new material studied in this article. For the acoustic modelling in this study, the size of the sample, its density and a set of physical parameters are necessary. It should be noted that this description assumes that only the fluid moves and is deformable. This fluid can be seen as an equivalent fluid in the rigid or limp frame approximations [33]. A more refined modelling (not studied in this article) involving the solid frame elasticity is possible. The physical parameters and their measurement techniques will be described in Section 2.5.

Two samples of bio-based composite (180 mm × 50 mm × 20 mm) were cut in a cylindrical shape of 44.4 mm diameter for the purpose of determining the acoustic properties in an impedance tube (Fig. 2). The samples were cut from the same rectangular block and so their basic properties are the same except for the thickness due to inhomogeneities of the sample surface (Table 1).

2.4. Method for measuring the acoustical performance

A 44.4 mm diameter impedance tube (Fig. 2) allows a plane wave normal incidence excitation between 150 and 4100 Hz. This impedance tube can be used to determine:

- The absorption coefficient in the two microphones setup configuration described by Dalmont [12].
- The transfer matrix and transmission loss (TL) in the transmission configuration with the three microphones and two loads described by Salissou et al. [34].