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Mechanical, thermal and acoustical characterizations of an insulating bio-based composite made from sunflower stalks particles and chitosan

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ABSTRACT

This study has for objective the determination of thermal, mechanical and acoustical properties of insulating bio-based composite made with chitosan and sunflower's stalks particles. An experimental design was established to find the size grading of particles, the ratio chitosan/sunflower particles and the stress of compaction influencing the thermal and mechanical properties. Composites with a thermal conductivity (κ) of 0.056 W m^{-1} K^{-1}, a maximum stress (σ_{max}) of 2 MPa and an acoustic coefficient of absorption (α) of 0.2 were obtained with a ratio of chitosan of 4.3% (w/w) and a size grading of particles higher to 3 mm. These mechanical and thermal performances are competitive with those of other insulating bio-based materials available on the market.

1. Introduction

The implementation of agro-industrial residues in the development of composite materials for building trades is now a research of growing interest (Cole, 1999; Gustavsson and Sathre, 2006; Morel et al., 2001). One of the major challenges of this industry for the next decade is to improve the energy performance of existing buildings taking into account the increasing social emphasis on issues of the environment, waste disposal, and the depletion of non-renewable resources. The motivation includes cost, mechanical, thermal and acoustical performance enhancements, weight reduction, and environment concerns (Glé et al., 2012). In this context, bio-based insulator materials made from by-products of agriculture are an interesting alternative to those obtained from fossil carbon. Thermal insulation is known to play a critical role in saving energy by reducing the rate of heat transfer (Keynakli, 2012). A material is considered as a thermal insulator when its thermal conductivity (κ) is lower than 0.1 W m^{-1} K^{-1}, some of them reaching 0.035 W m^{-1} K^{-1} (Al-Homoud, 2005). They include fibrous and cellular inorganic materials, organic materials and metallic or metalized reflective membranes. Among them, those obtained from agricultural by-products have numerous advantages as they are eco-friendly and renewable. Moreover the high fiber content of some of them (wood, hemp, flax...) authorizes the reinforcement of composites (Liu et al., 2006). This property leads to the development of bio-based composites with natural fibers not only in the field of thermal insulators but also in other industrial areas such as paper or thermoplastic industries (Ashori, 2013; Ashori and Nourbakhsh, 2010; Ashori et al., 2014; Zahedi et al., 2013). Onésippe et al. (2010) have used sugar cane bagasse fibers in cement composites. The bio-sourced material obtained had higher thermal conductivity and mechanical strength compared to cement alone. Korjenic et al. (2011) carried out a research project to develop a new insulating material from jute, flax and hemp. Results showed that the correct combination of natural materials is comparable with convectional materials for mechanical properties. Furthermore, Elfordy et al. (2008), Nguyen et al. (2010), Nozahic and Amziane (2012) and Nozahic et al. (2012) characterized the hemp concrete, a new insulating material. Its thermal conductivity and its compressive strength were evaluated ranging between 0.1 and 0.4 W m^{-1} K^{-1} and from 0.2 to 0.8 MPa, respectively.

Sunflower is widely cultivated all over the world. In 2010, the harvested area in Europe was 3.68×10^6 ha representing 16% of the total harvested area in the world (Sun et al., 2013). The crushed

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sunflower stems have no real application in agriculture and it has been estimated that each hectare of sunflower can produce 3–7 tons of dry biomass including stems (Marechal and Rigal, 1999). The stems are usually burnt, used as natural fertilizer, for animal feed or for fuel production (Chen and Lu, 2006; Sun et al., 2013). In this context, non-food uses of a part of this biomass would have a significant economic impact on this culture (Ashori and Nourbakhsh, 2010; Laufenberg et al., 2003). Several authors reported that building products/composites produced from various agro-waste materials, including sunflower stalks, have higher mechanical properties, lower thermal conductivity and density, are cheaper, durable, lightweight, available in abundance, much less abrasive and environmental friendly compared to conventional ones (Ashori et al., 2014; Díaz et al., 2011; Madurwar et al., 2013; Zahedi et al., 2013). Bark of sunflower stems exhibit favorable mechanical properties whereas its pith has good insulation ones (Sun et al., 2013). Hence, this by-product could find use in a total bio-sourced composite with thermal insulator properties using a natural organic binder contrary to classical strategies which employed cement (Elfordy et al., 2008; Nguyen et al., 2010; Nozahic and Amziane, 2012 and Nozahic et al., 2012) or epoxy resin (Binici et al., 2014). Chitosan is a natural polymer obtained industrially by deacetylation of chitin from crustacean shells (Dash et al., 2011; No et al., 2007). This polysaccharide, which is the most abundant polysaccharide after cellulose (Barbosa et al., 2005), is a heteropolymer of β-(1,4)-linked 2-acetamido-2-deoxy-D-glucopyranose and 2-amino-2-deoxy-D-glucopyranose units. It is the sole cationic polysaccharide described due to its positive charges (NH_3^+) at acidic pH (pH < 6.5) (Barbosa et al., 2005). Over the past few decades, chitosan has received attention as a functional non-toxic, antimicrobial, biocompatible and biodegradable biopolymer useable in the area of biomaterials and/or biosourced materials (Ashori et al., 2013; Dash et al., 2011; Kumar, 2000; Muzzarelli et al., 2012; Nair and Laurencin, 2007; No et al., 2007; Patel et al., 2013; Shalaby et al., 2004; Umemura et al., 2010). In the light of all its features chitosan was selected as a natural binder for the conception of a thermal insulating material using sunflower stalks particles as reinforcement.

2. Material and methods

2.1. Raw materials

2.1.1. Shredded sunflower stalks

The sunflower (reference LG5474) stalks used in this study were harvested in 2009 (Perrier, France). Grinding of sunflower stalks was performed using a cutting mill SM 300 (Retsch) with a sieve of 20 mm mesh. The speed cut applied was 1000 rpm. The particles obtained were sieved at room temperature (20 °C) using Controlab sieve-tronic to obtain different particles sizes between 1 and 6.3 mm. Particles were stored at room temperature.

2.1.2. Binder

Chitosan from Shrimp Shell with a molecular weight of 98 kDa and a deacetylation degree of 90% was supplied by France-Chitin (France) with the reference number 342. The polysaccharide was solubilized at room temperature (20 °C) for 2 h under stirring at concentrations ranging between 2 and 9% (w/v) in acetic acid 1–2% (v/v) (Sigma Aldrich, 98.9%).

2.2. Bio-based composite

The process for obtaining bio-based composites from shredded stems of sunflower and chitosan is shown in Fig. 1. Chitosan solutions were mixed for 5 min with sunflower's stalk particles having different particle sizes (between 1.6 and 6.3 mm). Ratios

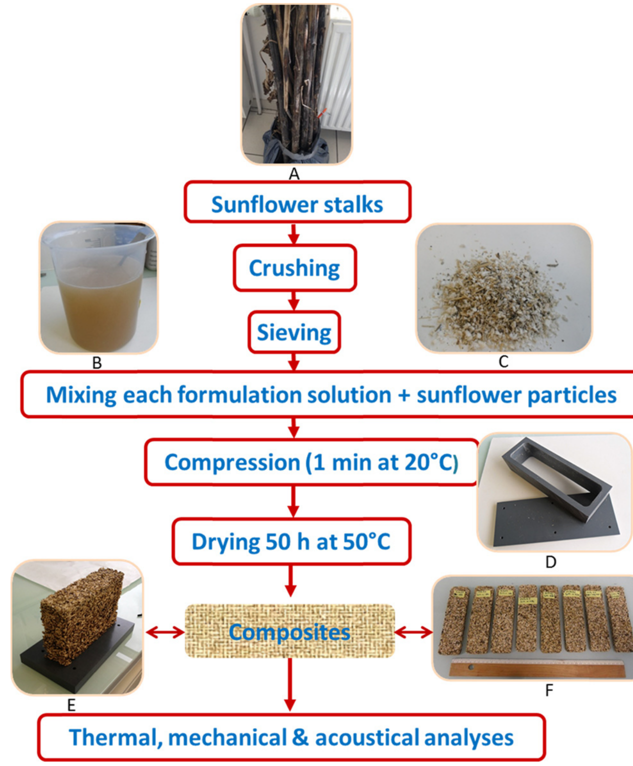

Fig. 1. Process of obtaining agro-composite from sunflower stalks and chitosan. (A) sunflower stalks (LG5474), (B) chitosan solutions at 2–9% (w/v), (C) sunflower stalk particles (1–6 mm), (D) PVC mold, (E) composite sunflower/chitosan obtained for compressive analysis, (F) composites obtained for the tensile analysis.

chitosan/sunflower particles were between 0.04 and 0.15 g/g. Each type of mixture was prepared twice in two polyvinylchloride (PVC) molds: 180 mm × 50 mm × 40 mm for tensile tests and 180 mm × 50 mm × 120 mm for compressive measures. Each set was compacted during 1 min at 20 °C under pressures between 1×10^{-3} and 32×10^{-3} MPa using weights or compressive press machine (Zwick-Roell) equipped with a ±20 kN load cell for pressures between 156×10^{-3} and 574×10^{-3} MPa. After drying at 50 °C for 50 h in an oven, the resulting composites were firstly thermally characterized (Fig. 1) and then cut with a band saw to obtain slender shapes of 180 mm × 24 mm × 12 mm for tensile mechanical characterization (Fig. 2). Specimens obtained for compressive tests were also cut to obtain slender shape (Fig. 2). Composites failed by buckling when their critical load was reached. As a consequence, the shape of specimens was defined at 80 mm × 50 mm × 50 mm using Euler equation (1) to avoid the phenomenon of buckling during compressive tests:

$$P = \frac{\pi^2 EI}{l^2} \qquad (1)$$

where "P" is the allowable load (N); "E" the Young modulus (kPa); "I" is the moment of inertia (mm^4) and "l" is the length of the sample (mm).

For the acoustical analysis, five composites made with sunflower particles of 5 mm, a ratio chitosan/sunflower stalks particles of 6% (w/w) and a compaction pressure of 32 kPa, were cut into circles with a diameter of 29 mm and a thickness of 13 mm.

Composites with labelled chitosan were built using 2 g of RITC-labelled chitosan dissolved in a solution of 50 ml of 1% (v/v) acetic acid. This solution was mixed with 30 g of sunflower stalk particles. After that, the set was compacted with a stress pressure of 32 kPa in PVC mold of 180 mm × 50 mm × 20 mm before being dried in an oven for 50 h at 50 °C.