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Influence of thermo-pressing conditions on insulation materials from bamboo fibers and proteins based bone glue

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ABSTRACT

Reducing energy consumption for future buildings using bio-based insulation materials is currently one of the most attractive research pursuits. The specific purpose of this research was to optimize thermo-pressing conditions for new low-environmental-impact bio-insulation fiberboards from bamboo fibers and protein-based bone glues. The microstructure, thermal insulation, water sensitivity, and mechanical properties of these fiberboards were investigated in this study. As illustrated by the results, protein-based bone glue acts as a good internal binder for bamboo fiberboards when 30% (w/w) of glue was added and elaborated under specific thermo-pressing conditions (150 kgf/cm^2, 160 °C) during 15 min. Indeed, this board presents the best mechanical properties and water resistance due to the effective adhesion of the proteins. The thermal conductivity of all the fiberboards is in a low range, between 0.0582 and 0.0812 (W.m^{-1}K^{-1}) at 57% RH and 25 °C, and it changes according to relative humidity levels and moisture content variation. The bamboo fibers have great potential for buildings thermal insulation with a thermal conductivity below 0.082 Wm^{-1}K^{-1}.

1. Introduction

Building insulation materials form the thermal envelope of a building and reduce heat transfer. They are part of the complex structural elements of a wall or a roof. Consequently, insulation materials are indispensable parts in the design and construction of buildings. They can contribute to moisture buffering performance and participate in the humidity control of the indoor air in buildings through moisture uptake and release (Cerolini et al., 2009; Osanyintola and Simonson, 2006; Palumbo et al., 2016).

Recently, strategies and policies on the environment and energy for buildings have been proposed in Europe with the aim of achieving energy conservation and reducing the environmental impact. The energy demand is expected to be reduced by 8% in 2020, 12% in 2030, and 17% in 2050 in comparison with 2005 data (Asdrubali et al., 2015). One way to reduce building energy consumption is to enhance the performance of insulation materials (Aditya et al., 2017; Asdrubali et al., 2015; Zhang et al., 2016 Zhao and Magoulès, 2012). Therefore, using bio-insulation materials is one of the most urgent research lines today.

In addition, the natural fibers have not only good thermal insulation properties but are also potential materials for sound absorption application. In literature, some natural fibers such kenaf, wood, hemp, coconut, straw, and cane are investigated for sound absorption applications in buildings (Berardi and Iannace, 2015, 2017). The results show that these natural fibers have good sound absorption coefficients, especially at medium and high frequencies. Moreover, the composites based on palm and two different binders (lime and corn starch) can be used for thermal insulation and acoustic absorption (Belakroum et al., 2017). The best acoustic absorption is around 0.7 for samples with 20% of fiber and 80% of starch.

Bamboo is widely distributed and used in Asia, Pacific Islander and America. Bamboo is a sustainable material and it is also one of the fastest growing plants in the world. The bamboo products are considered as building materials for the same uses as timber: floors, ceiling, wall, and building envelopes in both exterior and interior design elements (Zhang et al., 2002). Moreover, bamboo materials have great advantages including low cost and attractive aesthetic appearance; they are therefore an ideal alternative to traditional materials for sustainable building (Moroz et al., 2014). Bamboo, and more precisely bamboo fibers, can be used also as reinforcement in composite materials.

Therefore, recently, bamboo is the subject of a great interest in

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many areas such as composite and building applications. For example, for composite materials, bamboos were steam-treated as feedstock for plastic composites (Nishidaa et al., 2017). The bamboo components and structure were changed due to different processing conditions. For buildings, bamboo is mainly used as bamboo canes (Villegas, 2013) and to our knowledge there are very few studies on the use of bamboo particles or fibers to elaborate boards (Gao and Xiao, 2017; Hiziroglu et al., 2008; Suhaily et al., 2013). Sanchez et al. have worked on panels from bamboo fibers and bio-based polyurethane adhesive (Sánchez et al., 2017). Their results showed a low water absorption capacity and swelling and a higher tensile strength compared to other natural fiberboards.

The hygrothermal properties of different bamboo pieces have been compared to timbers (Huang et al., 2017a,b). The results show that the bamboo pieces have higher heat storage and vapor resistance but weaker heat transport performance under different climate conditions. The thermal and energy performance of a lightweight steel-bamboo wall was computed by Li et al. (Li et al., 2017b).The steel-bamboo wall has a high thermal performance and leads to a lower heating demand in winter compared to common wall structures.

Up to recently, the majority of industrial fiber or particleboards are made with formaldehyde-based glues which can release some toxic products (Meyer et al., 1986; Meyer and Hermanns, 1985, 1986). To replace these glues, different kinds of bio-adhesives are investigated in the literature, such as for example linseed oil with flax fibers (Lazko et al., 2011), starch with palm petiole fibers (Belakroum et al., 2017).

To date, only a few studies have been conducted on fiberboards from natural fibers and protein binders. For example, flax shives and protein binder based on casein and vinegar were investigated in (Hajj et al., 2012). The presence of flax-shives leads to decrease the thermal conductivity of the composites. The compressive and flexural stress also decrease as a function of fibers content and size due to a less compaction of these composites. According to Guo et al., the whey proteins lead to performing adhesives for wood product applications because of their crosslinking and their stability with different types of wood (Guo and Wang, 2016). Moreover, the protein–based cottonseed meals have been used as biodegradable high-performance adhesives for wood boards (Li et al., 2017a). Bone glue and nerve glue are well known in marquetry (Dallongeville et al., 2011) but, to our knowledge, there is no study about fiberboards or particleboards made from natural fibers and this kind of protein glue.

On another hand, for production of bio-based panels, different methods can be performed: thermo-molding including heated pressing, compression, injection molding or twin-screw extrusion. A short overview of the literature of bio-material processing is presented here.

A twin-screw extruder was used to produce thermal insulation fiberboards from a sunflower bio-refinery plant (Evon et al., 2014) with molding conditions including mold temperature (140–200 °C), pressure (150–250 kgf/cm^2), and molding time (40–76 s). The board's density ranged from 500 to 858 (kg/m^3). These authors also reported the deoiled sunflower-based biodegradable fiberboard produced on a co-rotating twin-screw extruder with thermo-pressing and the following characteristics: pressure range (24.5–49.0 MPa), molding time (60–300 s) and mold temperature (156–204 °C) (Evon et al., 2015). The results showed density increasing from 1162 to 1324 (kg/m^3) as the molding conditions increased. Additionally, the flexural modulus was not affected by processing parameters for wheat gluten powder (Jansens et al., 2013), but the optimized conditions (5 min at 170 °C) increased the cross-linking degree of protein. The fiberboards from coriander fibers were studied on twin-screw extrusion with the optimized process conditions (21.6 MPa, 300 s, 205 °C), resulting in a density of 1323 (kg/m^3), flexural strength of 23 MPa, elastic modulus of 4.4 GPa, and 31% thickness swelling (Uitterhaegen et al., 2017). Indeed, under thermo-molding methods, the binders can act as internal adhesion, leading to a high compaction level for fiberboards, while the fibers can act as reinforcing fillers, enhancing mechanical properties.

The building bio-insulation fiberboards from natural fibers are expected to have two applications: control humidity inside buildings and thermal insulation. The hygric properties of bamboo fiberboards were presented in a previous report (Nguyen et al., 2017). Therefore, this study focuses on the thermal insulation performance of bamboo fiberboards under different amount of binder and humidity levels. The energy consumption of buildings can be reduced using low-thermal-conductivity materials. The thermal conductivity (k-value) depends on the material's density, porosity, moisture content and temperature. In general, a higher temperature leads to higher k-values (Bo-Ming et al., 2008; Budaiwi and Abdou, 2013; Budaiwi et al., 2002). For example, (Bo-Ming et al., 2008) found a non-linear relationship between thermal conductivity and temperature. Indeed, the authors measured an "effective thermal conductivity" which takes in account conduction, convection and radiation effects. So, the non-linearity comes from the radiation heat transfer which is related to the four power of temperature and is more dominant when the temperature rises. However, the evolution of thermal conductivity is a function of temperature, most of the materials exhibit a linear dependence between thermal conductivity and temperature (Abdou and Budaiwi, 2013; Berardi and Naldi, 2017; Budaiwi and Abdou, 2013). The k-value is also related to the moisture absorption capacity of materials: higher k-values are obtained when the moisture content rises (Evon et al., 2014; Kondo et al., 2010). Consequently, the variations in k-value with the moisture content of insulation materials must be investigated to evaluate their influence on a building's energy performance. In addition, the k-value of building insulation materials depends on their density: the higher the density the higher the conductivity. Hemp fiber-based insulation board density ranges from about 369 to 475 (kg/m^3) with a k-value ranging from about 0.0899 to 0.1079 (Wm^{-1}K^{-1}) (Benfratello et al., 2013). The k-value is about 0.150 (Wm^{-1}K^{-1}) for palm fiber insulation board with a density of 754 (kg/m^3), as reported by (Chikhi et al., 2013).

The present study aims at manufacturing novel, environment-friendly insulation fiberboards from bamboo fibers and protein-based bone glue using thermo-pressing on a heated hydraulic press. The influence of thermo-pressing conditions and the amount of proteins on porous structure, pore morphology, thermal insulation properties, mechanical properties, and water sensitivity are investigated in this study. The relationship between thermal conductivity and density, the amount of proteins, humidity levels, and moisture content variation are also reported in this study.

2. Material and experiment

2.1. Materials

Bamboo fibers (Bambusa stenostachya) are collected at a scientific research center for conservation of natural resources in Vietnam. The fibers are extracted from bamboo trees using the roller mill technique (RMT). Then the fibers are more finely separated using a specific machine at high speed (29000 rpm) for 1 min. The components of the bamboo fibers are also discussed in this study.

Protein-based bone glue is made from collagen in bones, often sold in granular form. It is soluble in water with pH 6.5, supplied by a French manufacturer of adhesives and gelatin (Bordet, Inc., France).

2.2. Manufacturing bamboo fiberboards

The experiments combine proteins and bamboo fibers using a pressing method. First of all, a predetermined mixture of bamboo fibers and bone glue (30 g bone glue and 70 g bamboo fibers) is molded by flat-pressing in different thermo-pressing conditions using an AEM3 heated hydraulic press (Italy). The different thermo-pressing conditions including mold temperature, applied pressure, and molding time are reported in Table 1. In terms of preparing raw materials, 30 g bone glue was soaked in 200 g of water until completely dissolved. Then the glue