Energy and Buildings 42 (2010) 1070–1074

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

An environment-friendly thermal insulation material from cotton stalk fibers

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ARTICLE INFO

Article history:
Received 26 November 2009
Received in revised form 18 January 2010
Accepted 29 January 2010

Keywords:
Cotton stalk
Binderless fiberboard
Thermal conductivity
Environment-friendly

ABSTRACT

A new environment-friendly thermal insulation material—binderless cotton stalk fiberboard (BCSF) made from cotton stalk fibers with no chemical additives was developed using high frequency hot-pressing. The goal of this paper was to investigate the effect of board density, fiber moisture content (MC) and pressing time on thermal conductivity and mechanical properties of BCSF. The results showed that the board with a density of 150–450 kg/m^3 had the thermal conductivity values ranging from 0.0585 to 0.0815 W/m K, which was close to that of the expanded perlite and vermiculite within the same density range. The thermal conductivity values had a strong linear correlation with the board density. The internal bonding strength (IBS) of boards was good at the relatively low-density level, which can be significantly improved with increasing the fiber MC and prolonging pressing time. The same trend was observed for modulus of rapture (MOR) and modulus of elasticity (MOE) of the boards. As an environment-friendly and renewable material, the BCSF is particularly suitable for ceiling and wall applications to save energy.

1. Introduction

Increased energy consumption and environmental pollution is a big challenge we are facing in the 21st century. The fossil fuel supplies are depleting daily due to a drastic increase in demands from which major environmental pollution results [1]. Particularly, this has become a pressing issue in the developing countries, such as China that has become the second largest global energy consumer and carbon dioxide emitter [2].

Over the past several years, the Chinese government has devoted tremendous efforts to address the energy-saving issue in the construction sector which is the no. 3 major energy consumption field followed by industry and transportation. At present, China's urban construction is developing rapidly and the building energy consumption grows annually. According to the survey, nearly 16–20 billion m^2 buildings are erected in various forms such as industrial parks, high-rise building complex and small townhouses. At that rate, the total building area will reach about 70 billion m^2 by 2020. Up to now, there are about 40 billion m^2 residential buildings, in which 95% are classified as non-energy-saving. The total nation wide building energy consumption (TNBEC) is 16 billion tons standard coal which accounts for 20.7% of the total energy consumption [3,4]. Therefore, the promotion of energy-saving buildings in China is urgent and imperative.

As the largest building component, the thermal insulation materials play an important role in achieving buildings' energy efficiency. Many types of thermal insulation in buildings are available which fall into the following three categories [5]: (1) inorganic materials such as fibrous (glass, rock, and slag wool) and cellular (calcium silicate, bonded perlite, vermiculite, and ceramic products); (2) organic materials such as fibrous (cellulose, cotton, wood, pulp, cane, or synthetic fibers) and cellular (cork, foamed rubber, polystyrene, polyethylene, polyurethane, polyisocyanurate and other polymers, and (3) metallic or metalized reflective membranes, which must possess air-filled, gas-filled, or evacuated space to be effective. Among all, as environment-friendly and renewable materials, natural fibrous materials have numerous advantages over other materials and thus are the most promising for building. So far, many researchers have studied thermal insulation materials from lignocellulosic fibers. Khedari et al. [6,7] developed a new low cost particleboard from durian peel and coconut coir mixture with a lower thermal conductivity, which was effective for energy saving when used as ceiling and wall insulating material. Xu et al. [8] presented a low-density binderless particleboard from kenaf core using steam-injection pressing, with a thermal conductivity similar to those of insulation material (i.e., rock wool). A new composite board with low-thermal conductivity made from a mixture of solid wastes from tissue paper manufacturing and corn peel was reported by Lertsutthiwong et al. [9]. Zhou et al. [10] developed a low-density composite board from hollow wheat straw using the following process: cutting, screening, blending, forming and low-pressure steam-injection pressing. This product retains some voids within and between the wheat straw to achieve a low-thermal conductivity.

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doi:10.1016/j.enbuild.2010.01.020

Table 1
Average chemical composition of cotton stalk.

Fraction	%Dry solid basis	Reference
Ethanol/toluene extractives	1.28	[29]
Cellulose	39.16	[27]
Xylans (hemicelluloses)	13.38	[28]
Klason lignin	25.74	[30]
Ash	8.16	[29]

Cotton stalks contain about 32–46% of cellulose, 20–28% of hemicellulose and about 26% of lignin and can be used as a raw material for manufacturing such products as pulp, particleboard, compressed blocks and fuel [11–14]. Fibers from cotton stalks with a length of 0.75–0.91 mm, a diameter of 16.4–22.8 μm and a cell wall thickness of 2.7–4.1 μm have very good flexibility and runkel ratios (2$\times$ fiber cell wall thickness/lumen diameter) for yielding fibrous products [15]. This paper showcases an environment-friendly thermal insulation material—binderless cotton stalk fiberboard (BCSF) from cotton stalk fibers without resins and any chemical additives, and investigates the effect of processing variables such as board density, fiber moisture content (MC) and pressing time on thermal conductivity and mechanical properties of the boards.

2. Material and methods

2.1. Material

Cotton (*Gossypium hirsutum*) stalk was harvested in an agricultural field of northern Jiangsu Province in China. For sample stalk collected, its husks and other impurities were cleaned and its branches were removed. Then its stem was chipped and screened to an average size of 25 mm $\times$ 10 mm $\times$ 5 mm for fiber preparation. The chemical component of the cotton stalk is shown in Table 1. The cotton stalk is rich in cellulose and lignin, which are the two major compositions for producing binderless fiberboard.

2.2. Methods

2.2.1. Fiber preparation

Chips were soaked in tap water overnight and then softened in a pressure tank with a steam pressure of 1.2 bar. The steamed chips were then fiberized rapidly using a laboratory atmospheric refiner. Refining was necessary with regard to the morphology and size of fibers. The fiber size distribution was determined by a PTI Fiber Classifer as illustrated in Fig. 1. The fibers were gradually collected and dried in a convective oven at 100 °C. To investigate the effect of fiber MC on panel mechanical properties, the MC of fibers was adjusted to 7, 10 and 13%, respectively.

2.2.2. Manufacturing of binderless cotton stalk fiberboard (BCSF)

The oven-dried fibers were shaped using a forming box (300 mm in length and 300 mm in width). 25 mm thick BCSF mats were prepared with a target density of 250, 350 and 450 kg/m^3. After forming, the mats were pressed in a CGM-30 high frequency (HF) press. HF is one kind of the electromagnetic (EM) radiation with frequencies above 400 MHz (generally from 0.95 to 2.45 GHz). Lignocellulosic fibers are good electrical insulators but interact with EM radiation due to their composition of asymmetric molecules and water. For manufacturing bio-composites, EM radiation from HF had faster moisture leveling and more uniform resin cure, leading to a more efficient hot-pressing process. It was beneficial to improve production and yield thicker boards [16].

After the mat was loaded into the press, the two parallel platens with electrodes were closed to the target mat thickness that was controlled by thickness gauge. Then the HF generator was switched

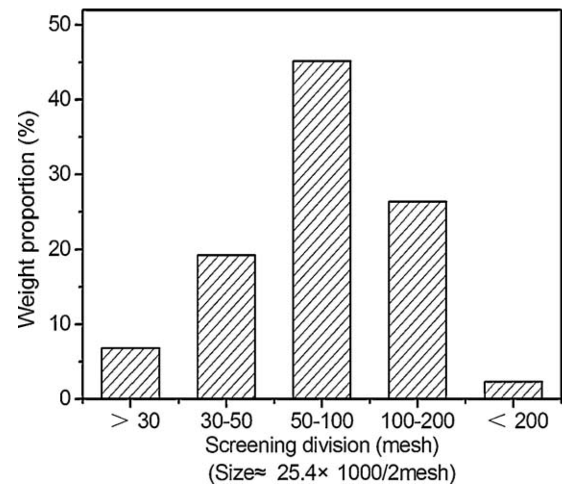

Fig. 1. Screening distribution of the cotton stalk fiber.

on with a voltage of 2.2 kV and a frequency of 1.36 GHz. The operating conditions were shown in Table 2. After pressing, the specimens were stored at 25 °C and 65 $\pm$ 5% relative humidity (RH) for one week to achieve a target MC of about 8% (weight percent). For each condition three replicates were used.

The process of binderless cotton stalk fiberboard is very similar to wood-fiber production. The main energy consumption of wood-fiber production is for fiber preparing, fiber drying and hot-pressing. The mechanical energy consumption and thermal energy consumption of wood-fiber production in commercial production line are normally 220–240 KW h/m^3 and 2.6–3.2 GJ/m^3 respectively, in which 60% thermal energy consumption is for fiber drying. Since BCSF does not use binders, the moisture content of fiber before drying is lower than that of resin blended fibers. In general, the resin content of wood-fiber production is about 10%, which will lead to 10% moisture content increase of fiber (based on 50% solid content of the resin) after resin blended. In addition, the requirement of fiber moisture content after drying for BCSF is 3–5% higher than that of wood-fiber production. Therefore, at least 13–15% thermal energy can be saved during fiber drying for BCSF compared with the wood-fiber production.

2.2.3. Thermal conductivity

The thermal conductivity of all fiberboards was measured at room temperature and normal pressure using the steady-state Bi-substrate technique, a well-established approach for bulk material [17–19]. The basic principle of operation is to create one-dimensional axial heat flow through the sample in order to use the Fourier equation of heat conduction:

$$q = -kA\frac{dT}{dx} \tag{1}$$

Table 2
The board manufacturing conditions.

Board density (kg/m^3)	Fiber moisture content (MC, %)	Pressing time (s/mm)
150	13	25
250	13	25
350	13	25
450	13	25
350	7	25
350	10	25
350	13	25
350	13	20
350	13	25
350	13	30