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Development and performance evaluation of a new thermal insulation material from rice straw using high frequency hot-pressing

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ABSTRACT

A new thermal insulation material made from rice straw (RSTIB) was developed using high frequency hot pressing. The goal of this study is to investigate the effect of high frequency heating, board density, particle size and ambient temperature on the properties of RSTIB. The results indicated that the optimum physical and mechanical properties of boards are obtained with a particle moisture content (MC) of 14%, a board density of 250 kg/m^3, and an L-type particle size. Additionally, the thermal insulation boards had fairly low thermal conductivity, ranging from 0.051 to 0.053 W/(m K). Comparison with conventional hot pressing confirmed that the pressing duration can be greatly shortened by high frequency hot pressing. The boards subjected to high frequency pressing had higher internal bonding strength (IB) values than the boards subjected to conventional hot pressing. As an environmentally friendly and renewable material, RSTIB is of interest for energy saving purposes when it is used as building insulation material for walls or ceilings.

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1. Introduction

China is rapidly developing in economy. The building industry has been identified as a vital engine of economic growth. The rising need of housing for the growing rural and urban population is a pressing issue. Statistically, at present more than 2 billion square meters new houses are built in China every year. To maintain rapid rate of economic growth in the 21st century it is important to put strategy for housing to meet the needs of the rural and urban population.

At present, bricks are used as the main wall materials in China, which causes a huge amount of farmland to be destroyed every year. Meanwhile, high energy consumption and serious environmental pollution for using bricks as the wall materials have great effect on the development of the building industry. To protect ecological environment and reduce energy consumption for building, a lot of attention is being paid to develop the environment-friendly and energy-efficient building materials.

Because energy efficiency in buildings will be evaluated not only based upon heating demand, but also according to the primary energy demand, the ecological properties of the building materials for the whole assessment has become essential. The demand for green building materials is rising sharply, especially insulating materials from renewable resources [1]. It is well known that agricultural straws (such as rice straw, wheat straw and so on) have been used as building insulation material for a long time due to their hollow structure, low density and outstanding characteristics of heat insulation. It has reported that typical thermal conductivity values for cellulose insulation materials are between 40 and 50 mW/(m K) [2]. Therefore, to improve the thermal-insulation properties of the exterior building envelope after straws being incorporated by means of advanced manufacturing technologies is scientific in theory and feasible in practice. The use of straws in building will not only solve the problem of straw as a waste, but also will help in building houses having significantly low impact on the environment without sacrificing most of comforts we have been accustomed to having.

The currently reported methods for the manufacture of thermal insulation materials for buildings from agricultural straws mainly include: (1) prefabricated straw-bale panels; (2) compressed straw-based boards. The prefabricated straw-bale panels are made from bales of straw (commonly wheat, rice, rye and oats straw) as structural elements, building insulation, or both are commonly used in natural building. Goodhew and Griffiths [3] showed that the straw-bales offer good insulation values of 0.067 W/(m K), which is much lower than that of wood and other building raw materials. Straw-bale construction is a sustainable method for building, from the standpoint of both materials and energy needed for heating and cooling [4,5]. The successful use of straw bales as

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thermal insulation within the external envelope of buildings has been demonstrated by the increasing number of successful contemporary projects around the world [6,7] Advantages of prefabricated straw-bale panels over conventional insulation materials include the renewable nature of straw, cost, and easy availability. However, they are sensitive to moisture content, susceptibility to rot and high space requirements for the straw itself.

The compressed straw-based boards are produced by bonding straws with natural adhesive (or self-bonding), synthetic resin, and inorganic cementing material at room temperature or high temperature. Evon et al. [8] manufactured new thermal insulation fiberboards by thermo-pressing from sunflower mixed with proteins and lignocellulosic fibers, acting respectively as binder and reinforcing fillers in what could be considered as a natural composite. The result showed that the heat insulation properties improved with decreasing fiberboard density, and thermal conductivity of the least dense fiberboard was only 0.0885 W/(m K) at 25 °C. Mati-Baouche et al. [9] carried out a research to develop a new insulating bio-based composite made with chitosan and sunflower's stalks particles. Composites with a thermal conductivity of 0.056 W/(m K) were obtained with a ratio of chitosan of 4.3% (w/w) and a size grading of particles higher to 3 mm. These thermal performances are competitive with those of other insulating bio-based materials available on the market. Panyakaew and Fotios [10] described the production of low density thermal insulation boards made from coconut husk and bagasse without the use of chemical binding additives. Both insulation boards have thermal conductivity values ranging from 0.046 to 0.068 W/(m K) which were close to those of conventional insulation materials such as cellulose fibers and mineral wool. Zhou et al. [11] used cotton stalk fibers to manufacture an environment friendly binderless fiberboard with a low thermal conductivity (0.059–0.082 W/m K) by high frequency heating, which is particularly suitable for ceiling and wall applications to save energy. More similar bio-based insulation materials have been developed from agricultural straw and natural adhesive [12–14]. These environment-friendly thermal insulation materials are excellent insulating components for building materials as wall or ceiling for energy conservation except for relative lower bonding strength and sensitive to moisture and humidity. Therefore compressed straw-based boards bonded with synthetic resin are more likely to be accepted. Cravo et al. [15] examined thermal properties of an ecological liner low density particle-based on agribusiness residues (peanut hulls and coconut fiber) agglutinated with bicomponent polyurethane resin. Experimental investigations revealed that adding agribusiness residues helps to solve the problem of thermal control in poultry houses. Binici et al. [16] had utilized sunflower stalks and cotton textile waste to manufacture thermal insulation materials with epoxy as binder. An experimental work concluded that samples having sunflower stalk with cottony tissue had low heat transfer coefficients. A useful construction material is produced while some waste materials causing environmental problems are warded off. Paiva et al. [17] set up an alternative expedite experiment to evaluate the thermal insulation performance of corn cob particleboards bonded by wood glue under real thermal and hygrometric conditions. The tests results showed a disappointingly low thermal insulating performance of the studied particleboards compared with expanded polystyrene and extruded polystyrene, but it is still acceptable in terms of thermal insulating building purposes. Korjenic et al. [1] developed a new organic thermo insulating material from renewable resources (jute, flax and hemp) and binders (bicomponent fibers) with comparable building physics and mechanical properties to convectional insulations materials. Other authors [18–20] have been studying the technical potential of using other types of synthetic resins for producing bio-based thermal insulation materials, such as soy protein-based adhesive, urea-formaldehyde adhesive, and hybrid organic–inorganic binder. Except for the aforementioned products made from agricultural straw and synthetic resin, thermal insulation materials produced from straws and inorganic cementing materials are also being concerned. Several authors [21–26] have already proposed using different agricultural residues, such as wheat straw, barley straws, date palm fibers, olive stone, coconut and durian mixture, as reinforcement and sand concrete, plaster concrete, gypsum, cement lime mortar as matrix to develop new lightweight construction materials with a lower thermal conductivity. The research results reveal that agriculture straws loading induce a high effect on the mechanical and thermal properties of the composites. In summary, there are undoubtedly strong reasons to believe that developed alternative products from agricultural straws are promising in a thermal insulating perspective [27].

Among these products, the thermo-pressed straw-based thermal insulation boards are paid much more attention due to its simple and efficient production process. However, it still takes long time to prepare thick insulation materials by means of traditional platen-pressing process. To further improve production efficiency, a new process for manufacturing insulation materials from rice straw using high frequency hot-pressing is developed in this study and the effect of high frequency heating, board density, particle size and ambient temperature on the properties of rice straw insulation materials are investigated.

2. Material and methods

2.1. Material

Rice straw was harvested in an agricultural field of Nanjing, Jiangsu Province in China. Methylene diphenyl diisocyanate (MDI) resin (100% solid) was provided by the Huntsman Company (Germany), and it was a dark yellow liquid with a viscosity of 275 MPa s (25 °C). Acetone purchased from Nanjing Chemicals Reagents Company in China was used as a diluent for MDI.

2.2. Methods

2.2.1. Rice straw preparation

Rice straw was chipped into particles with lengths of 10–30 mm. To investigate the effect of high frequency heating on panel properties, the moisture content (MC) of particles was adjusted to 10, 14 and 18%. In addition, five types of particles were obtained by screening. Table 1 shows the distribution of particle size determined by the screening analysis.

2.2.2. Manufacturing of rice straw thermal insulation boards (RSTIB)

The resin content of MDI was 8% based on the weight of the oven-dried rice straw particles. To reduce the viscosity of MDI, acetone was added into the adhesives for diluting at a quantity ratio of 1:1. The MDI resin–acetone mixture was stirred to make it uniform, and then, the mixture was sprayed onto the particles using a rotating drum blending machine with an air-atomization nozzle. The blended particles were shaped using a forming box

Table 1
Screening analysis for five particle types.

Particle type	Weight ratio (%)			
	+10	−10+20	−20+40	−40
F	95.5	4.5	0	0
S	62.6	10.8	23.6	3.0
L	45.6	13.5	14.3	26.6
M	38.0	24.5	26.5	11.0
N	21.0	33.5	30.0	15.5

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