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Novel lignocellulosic hybrid particleboard composites made from rice straws and coir fibers

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ABSTRACT

Novel lignocellulosic hybrid particleboard composites with low cost and high performance using the mixture of rice straws and coir fibers were developed in this work. NaOH (sodium hydroxide) aqueous solution was used to remove the wax and silica layer of rice straw surface. The effects of rice straws/coir fibers (R/C) mass ratios on the physical (thickness swelling) and mechanical (modulus of rupture, modulus of elasticity and internal bond strength) properties of particleboard composites were investigated. The results show that NaOH treatment was an effective method for improving wettability of rice straw surface with smaller contact angles and larger diffusivity–permeability constant. The SEM (scanning electron microscope) observation also gave some evidences such as more rough surface and less number of silica cells after NaOH treatment for improving wettability of rice straw surface. The coir fibers content had a significant negative linear effect on the bending properties and thickness swelling, but a significant positive linear effect on the internal bonding strength due to the lower wax and holocellulose content of coir fiber. When no diisocyanate resin applied, the particleboard composites made with only phenol formaldehyde resin at the optimal R/C ratio satisfied the requirements for load-bearing boards used in dry conditions based on Chinese Standard, indicated that the mixture of rice straws and coir fibers to make high quality particleboard composites was a cost-effective and environment friendly approach.

1. Introduction

Recently, increasing environmental awareness, concern for environmental sustainability, growing global waste problem, depletion of fossil fuels, and the increasingly higher price of crude oil have together created a groundswell of interest in renewable resources [1,2]. Agricultural residues, which are produced with large quantities annually throughout the world, are the main renewable resources. In China alone, the statistic outputs of rice and wheat in 2011 were about 201 and 117 million tons, respectively [3], so there was approximately 300 million tons yield of crop residues from the two main crops. Besides traditional utilizations for low-value purposes such as livestock feeding, fuel, fertilizer, soil amendment, and bedding materials for animals, an abundance of straw leftovers are utilized for industrial products such as particleboard, fiberboard, and filler for thermoplastic composites.

Compared with synthetic fibers such as glass, natural straw fibers have more advantages, such as low cost, low density, abundant and wide distribution, versatility, competitive specific mechanical properties, carbon dioxide sequestration, sustainability, recyclability, biodegradability and safe working environment [4,5]. So the straw-based particleboard composite, which made from straw fibers or particles and petroleum-based adhesives, has been developed and is commercially available in several countries. In some respects, straw-based particleboard has better properties than wood particleboard, such as it is lighter in weight and more water resistant; in addition, it can be used in a growing range of applications, including automotive parts, rigid packaging, furniture, housing and building materials [6].

Particleboard performance is mostly related to the properties of adhesives and their compatibility with particles or fibers [7]. The most commonly used petroleum-based adhesives are urea formaldehyde (UF), phenol formaldehyde (PF), and methylene diphenyl diisocyanate (MDI). The water-based adhesives such as UF and PF have been the major adhesives for wood-based particleboard, but their adhesion to straw is poor due to the high content of wax and inorganic silica on the straw surface [8–10]. The straw-based particleboards have low quality without proper pretreatments of raw materials when water-based adhesives are used. Therefore, several methods have been used to improve interfacial adhesion between straw surface and resin, such as thermotreatment and steam explosion [11,12], acid or alkali treatment [13,14], coupling agents modification [15], enzyme treatment [16,17], and so on. In these pretreatment methods, alkali, such as sodium hydroxide

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(NaOH), has been the most common chemical used to improve the interfacial compatibility.

After pretreatment of the straw particles, the properties of straw-based particleboard made with only UF or PF resin are still poor compared to wood-based particleboard, especially for internal bonding strength and long-term thickness swelling. As a result, an oil-based (100% organic solids) adhesive, methylene diphenyl diisocyanate (MDI) or polymeric methane diphenyl diisocyanate (PMDI) has been usually used to make high-quality straw-based particleboards [18]. MDI is an excellent binder that imparts superior properties to panels. Panels bonded with MDI are lightweight, biodegradable, free from formaldehyde emission, and have good water resistance, mechanical strength and dimensional stability [19].

However, diisocyanates also have disadvantages, including relatively higher price and higher toxicity of the uncured glue incomparison with other adhesives [20,21]. The cost of MDI or PMDI is about three to teen times more expensive than PF and UF resins in the Chinese market, resulting in MDI-bonded particleboard having much higher production cost than the PF or UF bonded particleboard. In addition to the economic disadvantages, conventional strawboard technology employing MDI binders has shown technical disadvantages during production. Specifically there are additional costs for release agents needed to prevent panels from sticking to press plates, and a lack of mat adhesiveness [19]. The cost and type of adhesive have become two important concerns of the straw-based particleboard industry for making cost-effective products. Therefore, there is a significant interest to find cost-effective methods to produce low-cost and high-quality straw-based particleboards for competing with wood particleboards in certain applications, as they satisfy the requirements of the related government standard.

In order to solve these problems, an appropriate combination of water-based adhesives with MDI resin, or an appropriate mixture of straw particles with low quality woody materials like wood, bamboo and other biomass residues [22–24], has been applied to improve bending strength, water resistance, and internal bond strength. However, with the decreases in forest resources, shortage of wood and increasing price of wood, there is a need to find alternative sources of woody materials for mixing with straw particles to produce high performance particleboard.

Among the biomass residues, coir is an abundant, versatile, renewable, cheap, and biodegradable lignocellulosic fiber used in many industrial applications, which obtained from the fibrous mesocarp of coconuts, the fruit of coconut palm (*Cocos nucifera*) cultivated extensively in the tropical regions [25]. Chemical constituents of coir fiber are cellulose (36–43%), lignin (41–45%), hemi-cellulose (0.15–0.25%), and pectin (3–4%), together with some amount of water-soluble materials [26]. Compared with other typical natural fibers such as flax, hemp, jute, ramie and sisal, coir fiber has low cellulose and hemi-cellulose, high lignin content and microfibrillar angle, as a result of which the fibers have several valuable properties, such as resiliency, rigidity, wettability, toughness, resistance to dampness, abrasion resistance, elongation at break, weather resistance [27–29]. Apart from the conventional uses of coir fiber as cordage, cushion, sacking and floor-furnishing materials, a new utilization of coir fiber as a reinforcement in clay, cement, particleboard, and polymer composites has been developed [30–32]. Therefore, based on the above properties and advantages, coir fiber can be used as an additive material to improve the qualities of straw-based particleboard fabricated with water-based adhesives in this research.

The objectives of this work were to (1) investigate the wettability of rice straw surface before and after alkali treatment for improving bonding quality; (2) study the physical and mechanical properties of particleboard composites manufactured with different mass ratios of rice straw particles to coir fibers; (3) analyze the effect of coir fibers content on the properties and screen for the optimal mass ratio; (4) study the properties of particleboard composite made without PMDI resin at the optimal mass ratio.

2. Methods

2.1. Materials

Rice straws were collected from a suburb near Shangzhi City in Heilongjiang Province of China. Rice straws were milled into particles using a hammer mill, and then the oversize and undersize particles were removed using a screening machine through mesh with 10 and 2 mm apertures. The rice straw particles were further air-dried to 12–14% moisture content (MC) before alkali treatment.

Coir fibers were obtained from Hainan Province of China. The coir fibers were cut into 1–4 cm lengths and then dried to 3 ± 1% MC in a hot air dryer at 90 °C. Fig. 1a illustrates the macrograph of coir fibers used in this work.

Commercial phenol formaldehyde resin used as adhesive for making particleboards was purchased from Beijing Dynea Chemical Industry Co., Ltd., China. Its type was 14L960, and its properties were given as follows: the specific gravity at 25 °C was 1.195–1.205, the viscosity at 25 °C was 60–100 mPa s and the solid content was 42.5–44.5 wt.%.

Polymeric methylene diphenyl diisocyanate resin used as another adhesive was purchased from Yantai Wanhua Polyurethanes Co., Ltd., China. Its type was WANNATE® PM-200, and its properties were given as follows: the specific gravity at 25 °C was 1.22–1.25, the viscosity at 25 °C was 150–250 mPa s and the content of –NCO was 30.2–32.0 wt.%.

And the sodium hydroxide was purchased from Tianjin Regent Chemicals Co., Ltd., China.

2.2. NaOH treatment and wettability of rice straw particles

The 1.5 wt.% NaOH solution was prepared with 20 °C (room temperature) distill water. The rice straw particles were soaked in NaOH solution at a ratio of 1 g to 5 ml at 20 °C (room temperature) for 12 h. The particles were then taken out and dried to final MC of 3 ± 1% in a hot air dryer at 90 °C. Fig. 1b illustrates the macrograph of alkali treated rice straw particles used in this work.

Dynamic contact angles were measured to evaluate the wettability of untreated and alkali treated rice straw particles. The wettability of PF resin onto the rice straw samples was determined using a contact angle goniometer (Model JC2000A, Shanghai Zhongchen Digital Technology Equipment Co., Ltd., China) under standard conditions (65% relative humidity at 20 °C). Images of the PF adhesive drop shape (drop volume was 2 μl) on the rice straw exterior surface were captured by a CCD (charge-coupled device) camera and saved every 10 s for a 15 min period. During the wetting measurements, as time elapsed, the drop shape tended to stabilize (equilibrium contact angle was obtained). The contact angle of the adhesive drop was averaged from the contact angles of both ends of the drop measured using image software. Fifteen data points were taken for each recorded drop to obtain a curve of contact angle vs. time (such as 0 s, 10 s, 20 s, 30 s, 40 s, 50 s, 100 s, 200 s, 300 s, 400 s, 500 s, 600 s, 700 s, 800 s, and 900 s). Three replicates were averaged for each sample.

With the wetting model developed by Shi and Gardner [33], the spreading and penetrating abilities of a liquid/solid system can be quantified. This is more useful and easier for the comparison of adhesive wettability. The final expression of the wetting model, in which the contact angle (θ) changes as a function of time (t), is:

$$\theta = \frac{\theta_i \theta_e}{\theta_i + (\theta_e - \theta_i)\exp\left[K\left(\frac{\theta_e}{\theta_e - \theta_i}\right)t\right]} \quad (1)$$