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MANUFACTURE OF BINDERLESS FIBERBOARD MADE FROM BAMBOO PROCESSING RESIDUES BY STEAM EXPLOSION PRETREATMENT

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ABSTRACT

The objective of this investigation was to evaluate the properties of binderless manufactured from bamboo (*Phyllostachys heterocycla* cv. *pubescens*) processing residues by steam explosion treatment. In particular, the effect of steam explosion retention time on fiber morphology, chemical composition and the properties of the boards was studied. The bamboo fibers were separated by steam explosion fully, and the hemicellulose degradation products and lignin were liberated from the fibers by steam explosion treatment and accumulated on the surface of the fibers, which contributed to the bond formation in the boards. The board properties evaluated were modulus of rupture (MOR), internal bond strength (IB), thickness swelling (TS) and water absorption (WA). The boards made from fibers treated under 180 s retention time exhibited the highest MOR value of 15.9 MPa. All boards passed the Japanese Industrial Standard A 5905-2003 for IB values except for the board made with fibers underwent extraction with hot water and hot-grind bamboo fibers. By increasing the retention time from 60 to 180 s, the thickness swelling was reduced by 73 %, and the water absorption decreased by 44 % respectively. In accordance with BS EN 622-5-2006, only the boards 3.0/120 and 3.0/180 matched the all requirementsfor ultra-light medium density (MDF) boards for use in dry conditions.

KEYWORDS: Steam explosion, bamboo fibers, binderless, morphology, physical and mechanical properties.

INTRODUCTION

Steam explosion technology was invented by Mason in 1926, which used to disintegrate the wood and the like (Mason 1926), as one of the most effective ways which is to be used in biological energy and production of the panels (Kabel et al. 2007, Shen 1991). Steam explosion is a very complex physicochemical treatment of raw materials that involves an instantaneous release of high steam pressure in a in closed container (Yu et al. 2012). The principle of steam explosion pretreatment is using the high temperature and high pressure steam to process the plant fiber raw materials in order to make the hemicellulose degradation and lignin softening, and decrease the lateral connection strength between the fibers (Shao et al. 2008). After a period of high temperature and high pressure treatment, the steam is released in a short time to achieve the effect of the chemical composition separation and the structural change (Vignon et al. 1996). Hence, processing parameters such as steam temperature and pressure, retention time, and pre-soaking in water, are important for the materials processing (Han et al. 2010).

As the decreasing supply of fiber raw materials and the need of environment friendly fiberboard, much biomass composite panels without synthetic resin was focused and studied (Anglè et al. 2001). Some studies point out that, self-bonding process occurs when wood or non-wood materials are inclined to boards by steam or heat treatment with intrinsic bonding components (Quintana et al. 2009, Fahmy and Mobarak 2013), such as cellulose, hemicellulose and lignin, which are separated richly in bamboo. The effective method for manufacturing binderless board is to pretreat the raw materials so that the chemical compositions have enough activity (Sasaki 1980). The chemical compositions include free sugars of hemicellulose degration and hydrolysates of part cellulose (Hashim et al. 2011, Widyorini et al. 2005), the thermal softened cell wall matrix (Thanahashi et al. 1989), and lignin (Borysiuk et al. 2007, Shao et al. 2009). Lignin are accumulated on the surface of fibers from steam explosion pretreatment (Hsu et al. 1998, Shao et al. 2009). The cross-linking action between lignin and polymers provide the strength of boards (Suzuki et al. 1998).

China has the largest volume of bamboo forest in the world. Compared with natural forest, bamboo has many advantages, such as rapid growth rate, abundant resources and cyclic utilization. Production binderless board from bamboo processing residues is a useful method to make full use of the waste from one industry as the raw materials for another industry. The objective of our study was to evaluate the properties of binderless board made from bamboo processing residues. The board physical and mechanical properties, including modulus of rupture (MOR), internal bond strength (IB), thickness swelling (TS), water absorbtion (WA) were investigated to evaluate the self-bonding ability. Fourier transform infrared (FT-IR) and scanning electron microscopy (SEM) were used to characterize the properties of fibers by steam explosion pretreatment.

MATERIAL AND METHODS

Material

Bamboo (*Phyllostachys heterocycla* cv. *pubescens*) residues were obtained from Wood Processing Lab of Nanjing Forestry University. The bamboo residues were cut into chips to attain furnish with 5 cm length. The moisture content of the original materials was 10 %.

Steam explosion

The bamboo chips were subjected to a steam explosion pretreatment in a 400 ml cylinder. The chips were treated under various steam explosion conditions shown in Tab. 1. Steam pressure was 3.0 MPa and the retention time was 60, 120 and 180 s respectively. The treatment was conducted using QBS-80 designed by Hebi Gentle Bioenergy Company. The steam was adjusted to the expected pressure as shown in Tab. 1. Counting retention time, then shut off the steam supply valve and release the steam pressure by auto-device within 0.0875 s. The steam-exploded bamboo fibers (SEBF) were collected together with black liquor. Some bamboo chips were used by triditional thermofiner for 10 mins by cutting mill.

Tab. 1: Summary of bamboo chips treatment condition.

Sample code	Steam pressure (MPa)	Retention time (s)	Pre-soaking in water (°C.h^{-1})
3.0/60	3.0	60	25/2
3.0/120	3.0	120	25/2
3.0/180	3.0	180	25/2

Morphology and Chemical composition

The bamboo fibers before and after several treatment conditions were air-dried and coated with gold powder in a sputter coater and observed on a Quanta 200 scanning electron microscope operated at 15 kV. FT-IR analysis was conducted to observe the functional groups in fibers before and after steam explosion using Nicolet is10. All spectra were collected in the wave number range of 4.000-650.cm^{-1} with 4.cm^{-1} resolution and 32 scans each sample.

Board production

The pretreated SEBF and hot-grind bamboo fibers (HGBF) were dried to the equilibrium moisture content about 10 % in a climate chamber. Part of the 3.0/120 SEBF were extracted with 50°C water for 5 h and then filtered using a Buchner funnel. There were five types of fiberboards with four repetitions for each treatment condition: Extracted 3.0/120, 3.0/60, 3.0/120, 3.0/180, hot-grind. Fenton's reagent (ferrous chloride and hydrogen peroxide) was added, and the 4.0 % hydrogen peroxide (H_2O_2) was used. Ferrous ions and hydrogen peroxide would happen catalytic reactions, and the created hydroxyl radicals (HO*) can attack the lignin and carbohydrates, resulting in activated lignocellulosic components (Halvarsson et al. 2009). Fenton's reagent was sprayed evenly, as per kilogram of the all pretreated fibers with 10 ml solution. The boards were shaped by hand using a forming box (300 mm in length and 300 mm in width). All panels had a target density of 0.80 g.cm^{-3} by hot pressing at 180°C for 20 min with 5 MPa pressure. The dimentions of binderless fiberboards were 300 (W)×300 (L)×10 (H) mm.

Evaluation of board physical and mechanical properties

MOR, IB, TS and WA of the binderless boards were evaluated in accordance with the Japanese Industrial Standard A 5905-2003. Four MOR and five IB samples were cut from each board to characterized the mechanical properties. Four samples, measuring 5×5 mm, were used to determine TS and WA properties tests for 24 h water immersion.

RESULTS AND DISCUSSION

Fiber morphology

Fig. 1 showed the untreated bamboo chips and the 3.0/180 steam-exploded bamboo fibers. Through the steam explosion process, the bamboo chips were under high wet, high temperature and high pressure state. The steam could infiltrate into the cell wall and the pore between fibers. It led to the part of hydroxyl group in cellulose produce bonding interaction. Under the combination effect of the steam and heat, the fiber began to soften and the chemical structure change, low molecular substances started to dissolve out from the fibers, and the connection between fibers began to weaken. In a very short time unloading the pressure, the high steam pressure released from the pore, the softened fiber bundles were suffered from mechanical separation and fracture.

Tab. 2 showed the SEBF morphology characteristics under different retention time. With the increase of the retention time, the effect of fibers separation became better and better. The steam could fully infiltrate into the cell wall and pore between fibers within long retention time, and the pressure could uniformly applied to fiber chemical composition along with fiber separation and colloid removal. However the retention time is not as long as possible, when it came to 180 s, a part of fibers occurred slightly burnt phenomenon.

Fig. 1: The untreated bamboo chips and steam-exploded bamboo fibers (3.0/180).

Tab. 2: The SEBF morphology characteristics under different retention time.

Retention time(s)	Colour and lustre	Morphology
0	Bright yellow	Very little separation, fiber strip-like, feel hard
60	Light brown	Most separation, fiber silk-like
120	brown	Fiber net-like, feel soft
180	Dark brown and taupe	Completely separation, slightly burnt

* retention time "0" refers to untreated bamboo fiber

Scanning electron micrographs

Scanning electron micrographs showed the surface of the SEBF in various conditions in Fig. 2. It can be observed that there were no significant differences in fiber length, while the fiber surface changed. The surface of bamboo fibers without steam explosion treatment were smooth and neat, and there were no significant damage or porosity. It was observed that the surface of steam-exploded bamboo fibers was rough. Fibers and fiber bundles were damaged and separated, and appeared curly fold, loose and messy. The surface of SEBF covered with many particles, suggesting that those particles are hemicellulose degradation products and lignin liberated from cell wall by steam explosion treatment. Comparing Fig. 2 d with b and c, as the retention time increased, more fragmented materials appeared on the fiber surface. It can be concluded that the steam explosion treatment were effective to damage the bamboo cell walls, separate and isolate the native chemical components, and dissolve the hemicellulose degradation products and lignin to accumulate on the surface. These dissolved matter could provide the connection strength between the fibers by hot pressing. The hot-grind bamboo fibers had not been separated, and there was no granular dissolution on the fiber bundle surface.

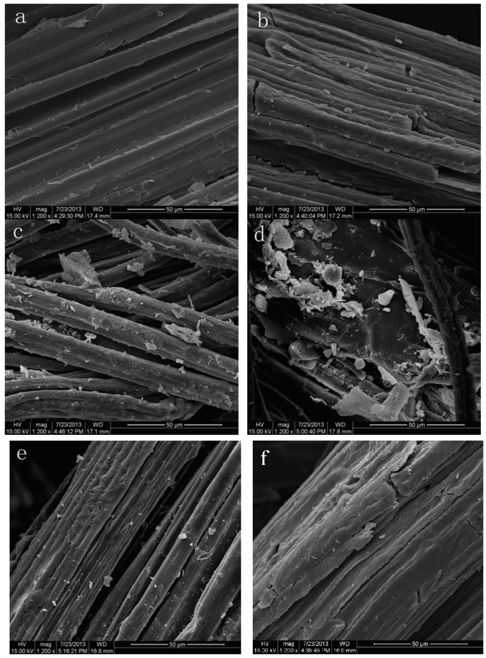

Fig. 2: Scanning electron micrographs (1200×) of bamboo fibers before and after steam explosion and hot-grind pretreatment a)untreated bamboo fibers b)3.0/60 SEBF c)3.0/120 SEBF d)3.0/180 SEBF e) extracted 3.0/120 SEBF f)Hot-grind bamboo fibers.

Infrared spectra

The chemical structures of the bamboo fibers before and after steam explosion pretreatment were investigated by FTIR, as shown in Fig. 3. The FTIR spectrum of the untreated bamboo fibers was similar to the typical spectrum of lignocellulosic material. Comparing a and f, the spectrum of hot-grind fibers was almost the same as the untreated bamboo fibers. Comparing SEBF spectra with a, no new functional groups were introduced to the fiber structure by steam explosion pretreatment, while some absorption peaks in SEBF were changed. The absorption band appearing in 3330-3270.cm^{-1} region in all samples was attributed to stretching vibrations of hydroxyl (OH) groups. The band at the 2915.cm^{-1} corresponded to the aliphatic CH stretching vibrations in lignin and polysaccharides (cellulose and survived hemicelluloses) (Sun et al. 2005). A particular shoulder at 1734.cm^{-1} in the untreated bamboo fibers was attributed to the carboxyl groups and ester groups in hemicellulose, and was destroyed in the pretreated bamboo fibers. The absorption peak of SEBF at 1700.cm^{-1} had a right shift by 34.cm^{-1}. The absence of absorption at 1734.cm^{-1} indicated that the steam explosion pretreatment broke hemicellulose structure and a portion of the hemicellulose was hydrolyzed.

The peaks at 1600.cm^{-1} and 1500.cm^{-1} are characteristics of the functional groups in lignin. All five spectra demonstrated the peaks at these two wave numbers. The SEBF had a higher relative peak intensities than the untreated bamboo fibers. It revealed that the SEBF had a higher quantity of lignin. Comparing Fig. 3 d with c, a portion of lignin was extracted and removed by the hot water. Associated with the SEM observation, it can be concluded that the structure of the bamboo fibers was changed because of the steam explosion pretreatment.

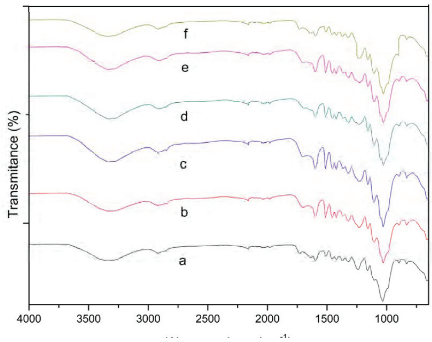

Fig. 3: FTIR spectra of bamboo fibers before and after steam explosion and hot-grind pretreatment a) untreated bamboo fibers b)3.0/60 SEBF c)3.0/120 SEBF d)extracted 3.0/120 SEBF e)3.0/180 SEBF f)Hot-grind bamboo fibers.

Physical and mechanical properties

Fig. 4 presents the modulus of rupture (MOR) and internal bond strength (IB) values for all four boards. The highest MOR value of 15.9 MPa was determined for the board made by the 3.0/180 SEBF, and the lowest MOR value, 2.5 MPa, was determined for the boards with hot-grind bamboo fibers. With the increase of the steam explosion retention time, the boards improved the rupture strength. Similar as the trends of MOR, the internal bond strength (IB) values increased as the retention time increased, and the MOR and IB results were correlated with each other. Only the board made by the 3.0/180 SEBF met the requirements of the Japanese Industrial Standard A 5905-2003 for MOR of 15.0 MPa. The maximum IB value was 0.48 MPa, followed by the panels made by the 3.0/120 SEBF, which had an IB value of 0.42 MPa. All the boards passed the Japanese Industrial Standard A 5905-2003 for IB values of 0.3 MPa except for the board made by E3.0/120 SEBF underwent extraction with 50°C hot water and had an IB value of 0.17 MPa and HGBF 0.15 MPa. Comparing the increment in MOR and IB values and the decrement of the extracted fiberboard indicated that the hemicellulose degradation products and lignin played an important role in the properties of boards.

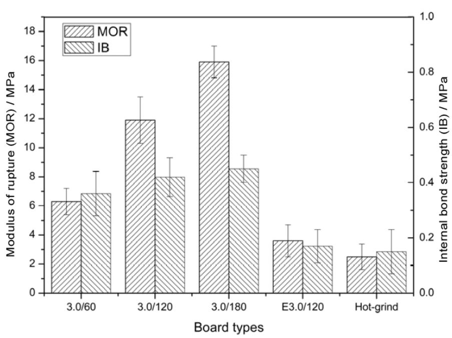

Fig. 4: Modulus of rupture and internal bond strength of different board types.

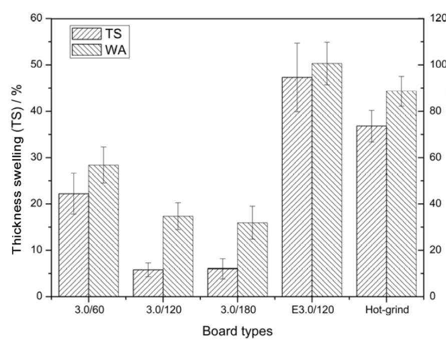

Fig. 5: Thickness swelling and water absorption of different board types.

Thickness swelling (TS) and water absorption (WA) values are illustrated in Fig. 5.

The TS and WA of the panels decreased with increasing steam explosion retention time. By increasing the retention time from 60 to 180 s, the thickness swelling was reduced by 73 %, and the water absorption decreased by 44 %. Only the TS of 3.0/120 and 3.0/180 was not more than the 12 % based on the Japanese Industrial Standards. High TS and WA in boards made from natural lignocellulosic material, including bamboo fiber due to the hydrophilic properties of lignocellulosic materials and the capillary action (Norul Izani et al. 2012). Steam explosion treatment cannot radically change the internal structure, but it is effective to weaken the action of this natural instincts.

In accordance with BS EN 622-5-2006, the requirement for ultra-light MDF boards for use in dry conditions(> 9 to 12), these properties are: Swelling in thickness 24 h is 18 %, internal bond is 0.15 MPa, bending strength is 7.7 MPa. Only the boards 3.0/120 and 3.0/180 matched the all requirements for ultra-light MDF boards for use in dry conditions.

CONCLUSIONS

Steam explosion treatment can separate the bamboo fibers, and the structure of the bamboo fibers was changed because of the steam explosion pretreatment. The hemicellulose degradation products and lignin were liberated from the fibers by steam explosion treatment and accumulated on the surface of the fibers, which contributed to the bond formation in the binderless boards.

The binderless fiberboards made by steam-exploded bamboo fibers have kind performance in physical and mechanical properties. The MOR of the board made by the 3.0/180 SEBF is 15.9 MPa, met the requirements of the Japanese Industrial Standard A 5905-2003 for MOR of 15.0 MPa, All the boards IB values passed the 0.3 MPa except for the board made with fibers underwent extraction with hot water and HGBF. The TS of 3.0/120 and 3.0/180 was not more than the 12 % based on the Japanese Industrial Standards. By increasing the retention time from 60 to 180 s, the thickness swelling was reduced by 73 %, and the water absorption decreased by 44 % respectively. In accordance with BS EN 622-5-2006, only the boards 3.0/120 and 3.0/180 matched the all requirements for ultra-light MDF boards for use in dry conditions.

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