Selected Properties of Corrugated Particleboards Made from Bamboo Waste (*Phyllostachys edulis*) Laminated with Medium-Density Fiberboard Panels

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A simple, practical, and low-technology approach was developed to fabricate corrugated bamboo particleboards (CBP), a novel bamboo product with a corrugated structure, from bamboo waste (planer waste). This product could be manufactured anywhere in the world where the bamboo industry develops. The selected mechanical and physical properties of CBP were prepared with urea formaldehyde resin at three press temperatures and two density levels and were evaluated. The results showed that the performance of CBPs is highly dependent upon the board density. The static bending strength of CBP laminated with MDF initially increases, and then decreases with increasing press temperature. Increasing the magnitude of the press temperature has a slightly positive effect on the thickness swelling and water absorption. Compared with the excellent mechanical strength of CBP (laminated with MDF), the thickness swelling value of this bamboo-based particleboard without any waterproofing treatment was lower than the minimal requirement of the EN standard.

Keywords: Moso bamboo; Planer waste; Corrugated Urea Formaldehyde-bonded particleboard; Mechanical properties; Dimensional stability

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INTRODUCTION

Particleboard has become one of the most popular wood-based composite materials for integrating decoration because of its low density, good thermal insulation, sound absorption, and wonderful machining properties. The primary lignocellulosic material used in the particleboard industry is wood. The increased demands of raw materials in wood panel, pulp and paper manufacturing have led to worldwide shortages of forest resources. Over the past decades, many non-wood lignocellulosic biomasses, including bamboo, wheat straw, cotton stalks, bagasse, rice straw, sunflower stalk, and kenaf stalk, have been conducted to produce particleboard or other end-products (Papadopoulos *et al.* 2004; Biswas *et al.* 2011; Wang and Sun 2002; Heslop 1997; Mohammad *et al.* 2011; Bektas *et al.* 2005; Guler and Ozen 2004; Kalaycioglu and Nemli 2006).

Bamboo represents one of the greatest potential alternative sources of lignocellulosic raw materials, since it is the fastest-growing plant, found mostly in tropical and sub-tropical zones (Papadopoulos *et al.* 2004; Pannipa *et al.* 2011). In China, a bamboo industry worth over 16.3 billion dollars per year has been generated. Examples of bamboo-based products are bamboo flooring, plywood, glue-laminated bamboo composites, and bamboo decorated wood-base composites. In general, the utilization ratio of bamboo in bamboo-based panels in China is only 35% to 48% due to hollow, cylindrical-formed of nodes and internodes of the bamboo culm. Furthermore, the removal of the outer and inner skin is an indispensable process for producing these products, which results in better bonding performance between resin and materials. In addition, a huge amount of planing waste (more than 65%) has been obtained during bamboo strip preparation for panel development (Zhang *et al.* 2013; Sumardi *et al.* 2007; Pannipa *et al.* 2011). Many attempts have been undertaken to improve the utilization ratio of bamboo through reconstituting bamboo (Li *et al.* 2007; Nugroho and Ando 2000; 2001; Mhmad and Kamke 2005; 2011), but the production of high-performance bamboo-based panel is still impracticable due to the high resin addition and the free formaldehyde emission levels, and high capital requirements for facilities. Particleboard using thermo-pressing seems to be a viable alternative for the utilization of bamboo wastes. For bamboo fiber, the high longitudinal tensile and compression strength results in good quality of bamboo particleboard (Verma and Chariar 2012). However, the process for producing radial bamboo split is un-industrialized, and the product exhibits poor durability.

Several studies have been reported using bamboo particles (strands) in various composite panels. Rowell and Norimoto (1988) found that all boards made from acetylated particles using Phenol Formaldehyde (PF) resin had much lower equilibrium moisture contents than the control boards. Papadopoulos *et al.* (2004) developed one-layer experimental particleboard from bamboo chips bonded with Urea Formaldehyde (UF) resin; it was shown that bamboo chips can be successfully used, as an alternative lignocellulosic raw material, to manufacture P3 boards for interior fitments using a relatively law resin dosage (10% UF). Thickness Swelling (TS) of particleboard made from 14% UF resin and 1% wax could meet ANSI criteria (ANSI A208.1-1998). Ihak *et al.* (2007) investigated the effect of density and structure on strandboard properties. The strandboard in laboratory at five densities and three different structures including a randomly oriented homogenous board, a unidirectionally oriented homogenous board, and a three-layered board with a cross-oriented core layer (BOSB) were produced. It was found that bending properties increased with increasing density and were affected by layer structure. Research conducted by Pannipa *et al.* (2011) confirmed that oriented strand lumber (OSL) made from bamboo strands using 13% pMDI content at 750 kg/m^3 exhibits superior strength properties compared to the commercial products made from wood for the building sector. With regard to internal bond (IB), bamboo-based OSL shows less strength than wood-based boards. Moreover, all properties of the board improve generally with increasing resin content. Although many studies have examined bamboo-based panel products, few have been conducted to evaluate the properties of particles made from bamboo waste obtained during planing operations for bamboo splits for making rectangular strips of uniform thickness. Daisy *et al.* (2011) reported that planer waste and chips of bamboo are suitable for the production of particleboard. When UF resin was added as a binder, the panels (12 mm thickness) could be used for indoor applications, especially as a furniture component. These were produced at 3.5 N/mm^2 pressing pressure and 140 ^{o}C.

Generally, bamboo chips (strands) have higher length to thickness and length to width ratios and bulk density than industrial wood chip particles (Papadopoulos *et al.*

2004; Zhang *et al.* 2013; Sumardi *et al.* 2007). Furthermore, its fast growth rate can support intensive and sustainable use in the particleboard industry (Mahdavi *et al.* 2012; Umit *et al.* 2012). Corrugated composite, a kind of laminated plate with sandwich structure, is commonly used because of its ability to withstand higher loads before buckling compared to plain sheets. It has 3 to 7 times higher shear strength than honeycomb structure composite, and it can meet a higher requirement of product design (Sohrab *et al.* 2009a; 2009b; Rao. 1987). The main objective of this project was to investigate the technical feasibility of press molding corrugated bamboo particleboard (CBP) from bamboo waste and UF resin, followed by lamination with Medium Density Fiberboard (MDF) in the form of sandwich construction, and to evaluate the mechanical and physical properties of particleboard affected by various densities and press temperatures.

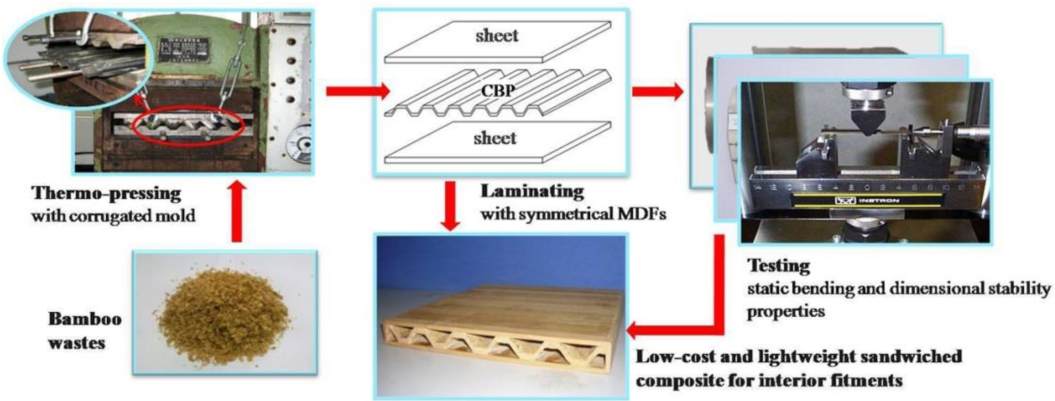

Fig. 1. Preparation process of sandwiched panel

EXPERIMENTAL

Fibrous Raw Material

The fibrous raw material, bamboo residue for manufacturing bamboo flooring, for this work was obtained from TaoHuaJiang Corporation (1904 Fu Rong Nan Road, Changsha, Hunan, China). The majority of the particles were flakes with little spread of sticks. The variety of this material was moso bamboo (*Phyllostachys edulis*) from Taojiang, Yiyang, Hunan, China, which is an important forest resource in China (Lee *et al.* 2012). The initial moisture content (MC) of the bamboo material was about 21%.

In order to fabricate bamboo flooring, bamboo culms (poles) were cut length-wise into several slats using a radial hydraulic splitting machine. Each slat was shaped into a regular strip to stack smoothly through two processes (steps I and II). Step I was to remove some amount of outer skin using a two-side planning machine, and step II was to obtain a rectangular strip using a four-side planing machine.

The majority of processing residues (almost 90%) could be utilized in these processes. It is noted that the inner and outer surface layer materials in residues of the step I of molding lead to weak adhesion due to containing wax and silica (Verma and Chariar 2012; Mahdabi *et al.* 2012; Nugroho and Ando 2001). Therefore, the suggested material used in this study was bamboo residues obtained in step II of the planing process.

Fabrication of CBP

For this study, the fibrous raw material was the abovementioned bamboo wastes of step II of the planing process, with a relatively large range in size. It is well known that the performance of particleboards is highly dependent upon the size of raw materials (Li *et al.* 2010). In our previous research, the effect of particle size distribution on the primary properties of UF-bonded corrugated bamboo particleboards was further investigated (Yang *et al.* 2011). To prepare the target size particle, a specific laboratory-scale hammer mill was used.

For the preparation of corrugated particleboard (Fig. 1), the bamboo wastes were broken into particles with a hammer mill, in which a perforated metal plate with particular opening size was used to ensure the particle size ranging from 5 to 10 mm in length and 2 to 5 mm in width. Then the broken particles were air-dried to a MC between 8 and 12%. A commercial UF resin obtained from Taohuajiang Corporation was used in this work. The resin content was 9% solid resin of UF based on the oven-dried weight. No wax or other additives were applied for board manufacturing. Ammonium chloride (99.3% NH_4Cl, on dry base) was added to 2 wt% as a common hardener.

The bamboo particles were put into a blender, and the adhesives were sprayed into the particles with a spray gun during the cycle before the MC was dried to 10% under ambient conditions. A corrugated molding box made from thin stainless steel plate was used. The materials were placed in the molding box and manually formed. The adhesive-coated mats along with molding box were then compressed.

A 400 mm × 400 mm SHANGHAI QT-100 hot-press equipped with a custom designed corrugated mold and PressMAN control system (Carver Inc. USA) were used to press the CBP with density of 550 kg/m^3 and 750 kg/m^3 at three press temperature levels (150, 180, 200 ^{o}C), respectively. Stops (5 mm thickness) were used to produce boards at a given thickness. The total hot press time of 450 s (60 s closing, 300 s at the target thickness, and 90 s opening) ensured the complete curing of the resin. After pressing, the formed corrugated boards were pulled off the stainless steel molding box with high releasability.

Lamination Process

Commercially manufactured MDF panels with a thickness of 5 mm were cut into 400 × 400 mm sections. The panels were placed in a climate chamber with a temperature of 20 ^{o}C and a relative humidity of 65%.

Both surfaces of CBP were sanded using an electric sander. Samples with smooth and symmetric surfaces were produced after removing the cured resin from the surface. The samples were laminated with MDF panels using commercial urea-formaldehyde (UF) resin at a spread rate of 120 g/m^2, and the adhesives were applied with a brush to both faces to be glued.

Sandwiched panels with corrugated core layer were compressed in a computer controlled hot-press using a contact pressure at 180 ^{o}C for 3 min. Specimens were conditioned in a climate chamber at a temperature of 20 ^{o}C and a relative humidity of 65% for two weeks before further tests. Data for each test were statistically analyzed. The effects of press temperature and density on the particleboard panels' properties were evaluated by analysis of variance (ANOVA) and were used to test for significant difference between factors and levels.

Mechanical and Physical Testing

The modulus of elasticity (MOE), modulus of rupture (MOR), linear expansion (LE), Thickness Swelling (TS), and water absorption (WA) of the CBP samples were tested in accordance with American standard test methods for evaluating properties of wood base fiber and particle panel material (ASTM D 1037-06a) and Requirements for general purpose boards for use in dry conditions (EN 312-2). For mechanical properties measurement, sandwiched panels were used due to corrugated particleboards are unsuitable for the static bending loading test. Each measurement presented herein is an average value of nine samples. For static bending measurement, the sandwiched panels were determined using an Instron 5582 testing machine. The TS and WA were measured after 2-h and 24-h immersion in distilled water at 20 ^{o}C.

RESULTS AND DISCUSSION

Flexural Properties

Figures 2 and 3 show the effect of press temperature and density on bending strength of CBP laminated with MDF. Both the MOR and MOE of the samples tested with parallel grain orientation of CBP were significantly higher than those of perpendicular grain oriented orientation. The superior bending properties of sandwiched composite along the grain orientation are thought to be attributable to a continuous plane in the parallel direction of CBP, which significantly enhances load capacity of the sandwiched composite, relative to a non-continuous plane in the perpendicular direction of CBP. In addition, face layers (face panels), which are symmetrically laminated with CBP, are a very important factor affecting the bending strength of the sandwiched plates. According to our pre-experiment, the de-lamination and separation between compressed veneers occurred because of excessively low bonding strength when plywood was laminated as face layers. That is the reason why MDF was laminated with CBP in the present study.

MOE in the parallel direction initially increased from 2270 to 3845 MPa and then decreased to 3266 MPa. Meanwhile, the MOR first increased from 16.7 to 21.3 MPa and then decreased to 20.9 MPa with increasing press temperature, and reached the maximum value when the press temperature was 180 ^{o}C. Comparable trends for MOR of perpendicular were observed (Fig. 2). When the press temperature changed from 150 ^{o}C to 180 ^{o}C, the increase of MOE and MOR was probably due to the increase of plasticizing and adhesive curing. The liquidity of the particles and adhesive was enhanced due to decreasing viscosity of adhesive and softening of particles in the mat, leading to the increasing of contact area between the resin and the bamboo particle. As a consequence, improved static bending values were obtained. Moreover, a high-hardness surface that is formed at the proper temperature and pressure is also an important factor for increased static bending. When the temperature was changed from 180 ^{o}C to 200 ^{o}C, a reverse trend was found. The reason for the slight decrease is not yet entirely understood, but it could be a result of the following reasons: material degradation at the superheated temperature, as well as a possible coking phenomenon, may lead to embrittlement of the surface (Mahdavi *et al.* 2012; Alireza and Amir 2008). In general, the effect of press temperature on the static bending of CBP (laminated with MDF) was significant. According to the statistical analysis (Table 1), all mechanical properties of the sandwiched composites were improved when the press temperature was increased from 150 to 180 ^{o}C, which indicates that the press temperature was not transferred to the core section of the mat at 150 °C.

Board density, which is classified by the mat weight compressed into CBP in this study, is an important factor affecting the mechanical properties of the sandwiched composite (Figs. 1 and 2). The MOR and MOE values were increased by 54.8% to 66.8% and 54.7% to 93% for 750 kg/m^3 samples at parallel orientation, while they were increased by 36.5% to 58.6% and 28.6% to 59.5% for 750 kg/m^3 at perpendicular orientation, respectively, when compared to 550 kg/m^3 samples. The result means that the effect of CBP density on the static bending properties in parallel orientation is more significant than those in perpendicular orientation. The reason might be dependent on its spatial structure.

The MOR and MOE of each board type increased with increasing board density. It is well known that Internal Bond strength (IB) is one of the important factors that affect the MOR and MOE of particleboard (Rowell and Norimoto 1988; Li *et al.* 2010; Verma and Chariar 2012). Furthermore, higher density does result in higher IB strength within particleboard. Similar results were also observed in previous studies, where it was found that the MOR and MOE of each board type increased almost linearly with increasing board density.

The bulk density of bamboo furnish was determined to be approximately the same with the wood chip furnish, and the rate of heat transfer to the core was approximately the same in both mats, probably reflecting the same values of bulk density (Lee *et al.* 2012). The statistical analysis showed that the effect of density on the bending properties of CBP was significant. Static bending values of the specimens were increased with increased density. However, larger density and higher temperature also mean higher production cost. Based on EN Standards, Proper conditions (550 kg/m^3; 180℃) depend on the cost of materials, and the properties of panels met the minimum requirements for MOR and MOE of particleboard panels for general uses.

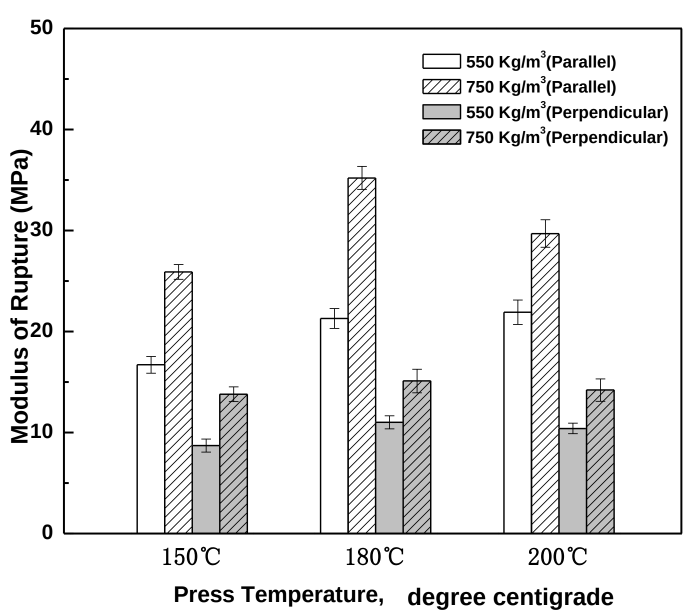

Fig. 2. Effects of press temperature and density on MOR of CBP (laminated with MDF)

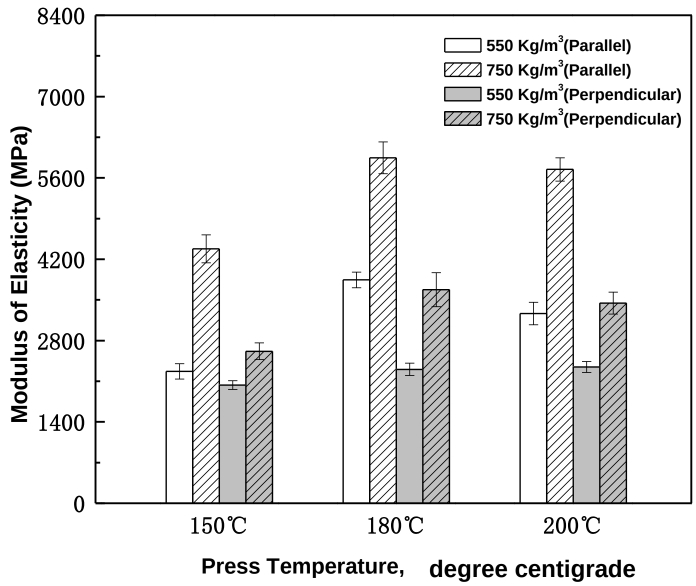

Fig. 3. Effects of press temperature and density on MOE of CBP (laminated with MDF)

Dimensional Stability

TS and WA are key parameters for dimensional stability of a bio-composite. In particular, TS is considered as a control factor qualifying the behavior of bio-composite exposed to moisture (Bryan 1962; Li *et al.* 2013). In general, TS and WA of particle-boards made from bamboo waste increased with an increasing soaking time. The results obtained in this study are in agreement with those reported by Bismas (2000), who successfully made particleboards from bamboo waste (*Bambusa balcooa* and *Bambusa vulgaris*).

For 24-h immersion time, all of the boards compressed at 150 ^{o}C had higher TS values in comparison to the boards compressed at 180 and 200 ^{o}C. This indicates that less resin within mat at 150 ^{o}C had been cured than those of boards at 180 and 200 ^{o}C. Beyond the sufficient temperature (180 and 200 ^{o}C), the TS and WA values, for 24-h immersion times decreased with increasing temperature, as illustrated in Figs. 4 and 5. Several reasons could be summarized for this experimental result. The first reason is that steam within a particle near the surface is transferred to the core of the mat at higher temperature, and this could accelerate the curing of an adhesive (Bryan 1962). Secondly, bamboo is compressed easily at higher temperature as a thermoplastic material. Decreasing of internal stresses results in good performance of dimensional stability. Third, the quantity of hydroxyl groups within bamboo molecules is decreased, leading to a decrease of hygroscopicity (Alireza and Amir 2008; Li *et al.* 2010, 2012). Consequently, many attempts including steam pre-treatment for particles and thermal treatment have been conducted by many researchers to improve the dimensional stability of such boards (Biswas *et al.* 2011; Li *et al.* 2013; Rowell and Norimoto 1988; Alireza and Amir 2008).

All panels compressed at 550 kg/m^3 had lower TS and WA values than those compressed at 750 kg/m^3. Higher TS and WA occurred, probably due to springback (the release of built in compressive forces brought about during manufacture) of the densification and decreasing porosity of board surface as a result of filling cell cavities with water under immersion condition. Under the combined influences of densification and heat temperature, cell lumens in bamboos collapse and a certain amount of fractures in cell walls develop (Li *et al*. 2013; Alireza and Amir 2008). As a result of such densification, the mass ratio in board surface increases. This concept becomes more intense with increasing board density, resulting in increasing thickness swelling and water absorption as a result of moisture absorption (Kutnar *et al.* 2009). The increased board density, depending on the pressure level, would increase the bamboo substance per unit volume, especially the amount of S1 and S2 layers in the walls of the bamboo cell per unit volume. This is responsible for the observed dimensional stability in the form of the hygroscopic swelling and shrinkage. S1 and S2 layers in the cell wall represent the swelling and shrinkage potential of bamboo fibers in the board (Alireza and Amir 2008; Wu 1999). The increase of TS with coating of a dense surface of board could be explained by an increasing springback effect. Similar results were observed by Kutnar *et al.* (2009). They found that the highest thickness swelling resulted when wood had been pressed to a higher degree of densification.

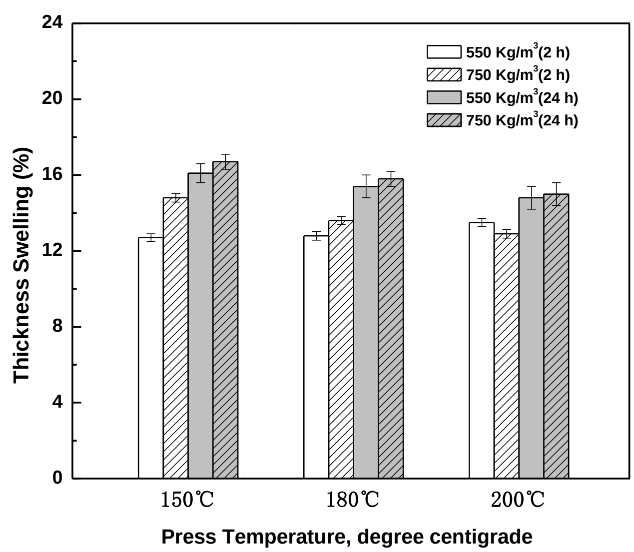

Fig. 4. Effects of press temperature and density on TS of CBP

In our experiment, particleboards did not satisfy the TS for 24 h requirement EN 312-4 1996 for general uses (15%), and it must be stressed that no wax was used in the manufacturing of the particleboards, which could delay moisture adsorption and water absorption, reduce TS and WA, and improve the dimensional stability of board substantially. Additionally, decreasing "springback" effect by reducing the density of the particleboards and acetylating the particles during the manufacturing process could be considered as the effective methods to improve the water resistance and TS properties (Rowell and Norimoto 1988; Zheng *et al.* 2006; Alireza and Amir 2008).

Future work can be suggested to optimize the approach for small-scale commercial manufacture. One area that could be improved is in the forming of the mat. Unexpected failures may well be due to non-uniform mat structure. It is recommended that further research be done to investigate other properties of the corrugated bamboo products, such as impact properties, biological resistance, finishing properties, and fastener-holding capacity. Moreover, further research should investigate the production of particleboard (strandboard) with corrugated structure using various species (wheat straw, bagasse, sunflower stalk, and kenaf stalk, *etc.*) to gain a more comprehensive understanding of properties of sandwiched panels made from various layered board structures (random oriented homogenous structure, unidirectionally oriented homogenous structure, and multi-layered structure with cross-oriented corelayer, *etc*.).

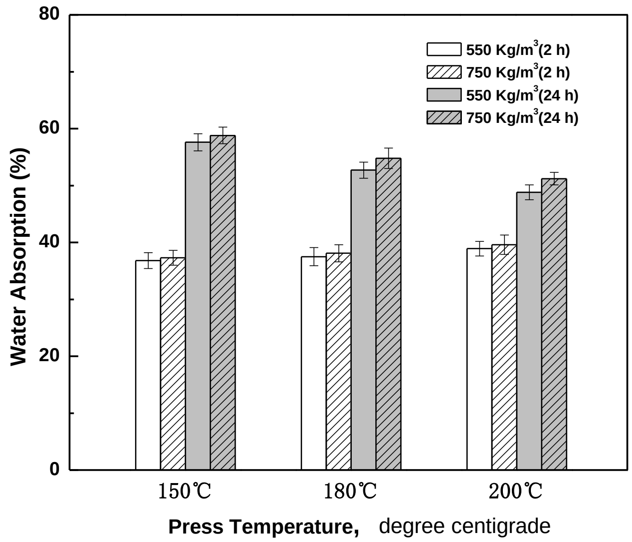

Fig. 5. Effects of press temperature and density on WA of CBP

Table 1. Influence of Press Temperature and Density on Mechanical Properties and Dimensional Stability of CBP (Sandwiched Panels for Mechanical Properties)

Source	DF	Mechanical properties				Dimensional stability			
		MOR		MOE		TS		WA	
		∥	⊥	∥	⊥	2h	24h	2h	24h
Temp.(T)	2	96.7**	4.9*	22.7**	10.6*	8.1 ^{NS}	72.4**	77.6**	25.3**
Dens.(D)	1	235.4**	84.5**	126.4**	63.6**	13.2*	15.4*	1.9 ^{NS}	4.1 ^{NS}
T×D	2	9.4	0.7 ^{NS}	0.4 ^{NS}	3.3 ^{NS}	1.8 ^{NS}	1.2 ^{NS}	7.6 ^{NS}	0.1^{NS}
Error	12	-	-	-	-	-	-	-	-
Total	18	-	-	-	-	-	-	-	-

∥: parallel grain orientation of CBP; ⊥: perpendicular grain orientation of CBP; ^{NS}: not significant; **: Significant at 1% level of significance; *: Significant at 5% level of significance.

CONCLUSIONS

1. The object of this study was to develop a simple and sustainable approach for corrugated bamboo particleboards (CBP) fabrication, which is an optimum alternative material for use. Press molding could be considered as an alternative way to develop corrugated type board for interior fitments (including furniture) for use in dry

conditions. In addition, the cost of bamboo wastes used in this work was lower than other raw materials.

2. Compared with samples tested with perpendicular grain orientation of CBP, specimens with parallel grain orientation exhibit much better performance due to the load capacity enhancement of a continuous plane.
3. Bending properties of the CBP laminated with medium density fiberboard (MDF) are enhanced with increased density. The bending properties initially increase and then decrease with increased press temperature (from 150 ^{o}C to 200 ^{o}C).
4. The TS of CBP also have higher values with increased density. Furthermore, increasing magnitude of the press temperature has a slight positive effect on the dimensional stability properties (TS and WA).

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