Bending Strength of Sandwich-Type Particleboard Manufactured from Giant Reed (*Arundo donax*)

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Abstract

This study evaluated the effects of treatment type of reed (*Arundo donax*) particles bonded with urea-formaldehyde resin in panels, press closing time, and amount of almond shell powder used as an extender in the glue line had on the modulus of rupture (MOR) of sandwich panels in dry and wet conditions. The differences between the bending strength parallel and perpendicular to the face/back veneer grain in dry (MOR||dry and MOR⊥dry) and wet (MOR||wet and MOR⊥wet) conditions were determined using the *t* test. According to the results, the selected variables significantly affected the bending strength. The highest dry and wet MORs were obtained by using hot-water–leached particles in the core layer, increasing the press closing time, and increasing the extender content in the glue line. According to the *t* test, there was a statistically significant difference between the *t* values of MOR||dry and MOR⊥dry and also between MOR||wet and MOR⊥wet. The maximum MOR||dry and MOR||wet (15.33 and 13.13 N/mm^2, respectively) were observed to be higher than those of MOR⊥dry and MOR⊥wet (13.37 and 12.41 N/mm^2, respectively).

The increasing lack of wood on the one hand and the constant growth in the production and consumption of wood-based panels on the other have led to evaluations using fast-growing or annual crops in manufacturing wood composite materials, such as lightweight panels. These annual or agricultural materials exhibit many advantageous properties as reinforcement for composites (Yuhazri et al. 2010). One way to reduce the weight of panels during the manufacturing process is to modify their structure by replacing the high-density material of the members with a lower-density material (Iejavs and Spulle 2013). However, it is not possible to show examples of natural fiber composites being a good choice, mainly due to the various anatomical, physical, and chemical characteristics affecting the properties of panels. To improve the properties of particleboard, such as lightweight panels manufactured by nonwood materials, hydrothermal pretreatments of particles (Bekhta et al. 2013, Jabeen et al. 2014), lamination of panels made from wood or lignocellolosic crops (Nazerian 2013), alternative resin type used in the glue line between substrate and veneer (Hojilla-Evangelista and Bean 2011), press variables such as closing time, and densities of wood-based panels (Miyamoto et al. 2002), could be effective factors in terms of the physicomechanical properties of the boards.

It was determined that the heat and hydrothermal treatments of a particle can affect the properties of panel in different ways (Bekhta et al. 2013, Jabeen et al. 2014). When a particle is dried at a high temperature, the equilibrium moisture content of particles can be improved (Suematsu et al. 1980). This causes a decrease in water absorption of hydroxyl groups and improves the thickness swelling of panels. Moreover, degradation of the hemicelluloses forms free sugars, which in turn form furan intermediates that can undergo polymerization during hot pressing and result in the formation of an adhesive (Rowell 2004) so that the internal bond (IB) strength increases. According to Kakaras and Papadopoulos (2006), the IB strength of particleboard increases by increasing the drying temperature owing to the interaction of the mechanical breakdown and the thermal degradation of the wood particles that occurs under high temperatures. In contrast, Mohebby and Ilbeighi (2007) stated that the IB strength could be related to the loss of adhesion between fibers because of the loss of wettability. In fact, fibers become hydrophobic after treatment, and their wetting capability decreases after heat treatment (Hakkou et al. 2005). Sundqvist et al. (2006) showed that the modulus of rupture

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Forest Prod. J. 65(5/6):292–300.
doi:10.13073/FPJ-D-14-00046

(MOR) and modulus of elasticity (MOE) could be negatively affected by hydrothermal treatment. This loss of bending strength is created due to the formation of formic acid and acetic acid from the degradation of hemicellulose and the effect of these acids on the breakdown of long-chain cellulose into short chains (Sundqvist et al. 2006), so the strength of the wood and wood composites could be affected.

Although hydrothermal treatments improve moisture resistance, they have a negative effect on the mechanical properties of panels. One way to overcome the negative effect of the treatment on mechanical properties is to change the press variables, such as the closing time. Longer closing time leads to a higher degree of particle plasticity (Liiri 1969). Moreover, as the closing time increases, the resulting core density increases. These increase the IB strength owing to the increase of the contact surface area among fibers (Wong 1999, Onuorah 2011), but the bending strength is adversely affected. The press closing time affects the formation of the density profile of panels. It was determined that decreasing the press closing time improves MOE and MOR, while IB strength decreases (Warmbier et al. 2011). In contrast, Gatchell et al. (1966) and Heebink et al. (1972) believe that press speed can be used to create the density profile and enhance the IB.

Lamination is thought to be one of the best methods for improving the mechanical properties of agro- and wood-based composites (Nazerian 2013). However, many factors, such as surface roughness, affect the properties of veneered panels via press closing time. Hiziroglu and Graham (1998) showed that particleboard made using a longer press closing time with the same out-of-press thickness resulted in a surface rougher than that made using a shorter press closing time. In fact, the rough surface of particleboard influences the bond formation because of a lower surface-to-surface contact, allowing for gaps in the adhesive line that may weaken the adhesive strength of the bond (Brady and Kamke 1988).

Some agricultural residues, such as reed stalks, cannot be fully plasticized because of the waxy layer and the low degree of wettability on the surface (Han et al. 2001, Zhang and Hu 2014) and the brittle characteristic of the particles due to a low water vapor transmission rate into the interior layer of particles (Wong et al. 2000). Hence, the surface of the panels made by these materials has many holes and pores. By veneering, not only the surface quality but also the physical and mechanical properties of these panels can be improved (Buyuksari 2012, Nazerian 2013). However, the improvement of the properties may be negatively affected by the high penetration rate of resins due to the existence of pores. Using an extender with resin in the glue line can improve the properties of panels (Hojilla-Evangelista and Bean 2011). Adhesive is often mixed with the extender to increase the viscosity. This extender is used to fill up all these holes at the surface of the panels for strengthening the bonding interactions between the substrate and the veneer. In addition, it could be used to control the penetration of resin into the small holes of the substrate (Pizzi 1994). According to Ong et al. (2012), extender is important for enhancing the wood performance for wood adhesive. They stated that a higher amount of protein in the extender increases the strength of the wood adhesive. Ong et al. (2011) illustrated that using more extender increases the mechanical properties of the laminated wood panels because the amino group $-NH_2$ inside the extender enhances the adhesion strength between the resin and the surface of the substrate. In fact, the porosity reduces the load-bearing volume of the sample and introduces stress concentrations that make the material less stiff and resistant. Nemli et al. (2003) showed that as the porosity increases, water penetrates more into the sample. On the other hand, according to Batalla et al. (2005), the strengths of wood panels decrease as the filler content increases because the void content also increases.

The negative influence of the high density of commercial wood materials on the properties of particleboard was illustrated by different researchers. It was confirmed that better properties can be achieved using annual green materials and crops, such as reed, in the particleboard and sandwich panels because of a higher slenderness ratio and lower density of reed particles, both of which improve adhesion and densification (Ghalehno et al. 2011). Thus, this was the motivation for this research, and the approach has been already successful for giant reed. One of the most important factors that can affect the bending strength of panels is the outermost surface layer density of panel. Using low-density wood veneer causes an increase in peak density owing to the increment of the compaction ratio of species with low density. Moazami and Nazerian (in press) evaluated the effects of end-to-end joint types of athel strips used in core layer veneered with three wood species (fir, beech, and oak) on the bending strength of blockboard. It was determined that the type of joint and species of wood veneer had an effect on bending strength, so the panels having short strips jointed with an end-to-end half lap joint in the core layer coated with fir veneer had the highest strength properties. According to Nazerian (2013), it was determined that the bending properties of particleboard veneered with low-density woods (such as poplar) had the highest MOR compared with others with higher densities.

The purpose of this study was to investigate the effects of hydrothermal treatment of the giant reed particle (*Arundo donax*) used in the core layer, press closing time, and amount of almond shell powder used as an extender in the glue line between panel and veneer had on the bending properties of sandwich panel veneered by fir.

Materials and Methods

Board preparation

Three-layer lightweight particleboards (sandwich panels) were manufactured in laboratory conditions using giant reed (*A. donax*) in the core layer and fir (*Abies nordmanniana*) veneers in the surface layers. Giant reed stalks with a height of 3 m were cut from above the waterline and split along the grain by a local harvester with the dimensions of 10 to 30 mm (length) by 1 to 5 mm (width) by 0.1 to 1 mm (thickness). A total of 162 (2[27 × 3]) sandwich panels were manufactured at the Laboratory of Wood Science and Technology, University of Zabol, Zabol, Iran. From each panel type, three specimens were prepared with the veneer parallel to the load direction and three specimens with the veneer perpendicular to the load direction in order to determine the effect of the load direction to the grain orientation of the face veneers on the bending properties of panels (Fig. 1).

At first, the particles were divided into three series: unleached, heat treated (at 150°C for 30 min), and hot-water

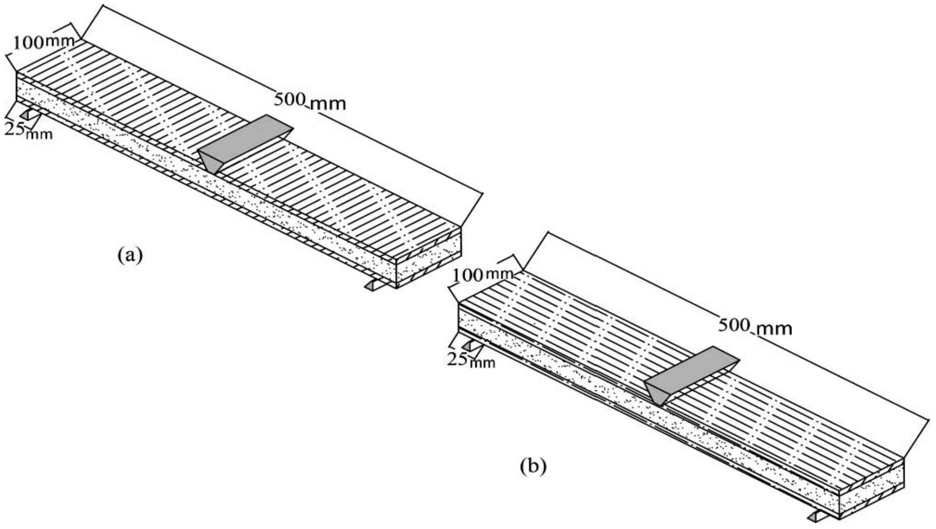

Figure 1.—Specimens with veneer parallel (a) and perpendicular (b) to the load direction for the bending test.

leached (at 80°C for 2 h). After these processes, a laboratory-made hot-air dryer was used to decrease the moisture of all particles from between 15 and 20 percent to 3 percent. Preweighed raw materials were placed into a resin-blending chamber equipped with a rotary electric agitator. A commercial urea-formaldehyde (UF) particleboard resin (65% solid content) and 2 percent ammonium chloride (based on resin solids) as the hardener was used for manufacturing the boards. Ten percent resin (solids on ovendry mass of particles) was added in all cases.

The target moisture content level of the mat was 10 percent. The total blending and mixing time was 3 minutes. Mattresses were hand formed and hot pressed at 175°C for 11 minutes by a maximum pressure of 3.7 MPa. After prepressing by hand, the thickness of the mat ranged from 12 to 15 cm (proportional to the treatment type of particles). As the second variable, the press closing time was selected at two levels: 20 and 40 seconds. The target board density was 0.40 g/cm^3. A 25-mm target board thickness was provided using a distance bar.

After production, all of the boards were coated with sliced fir veneers (1-mm thickness) using a UF adhesive mixed with almond shell powder as an extender at three levels (3%, 18%, and 33%, based on solid resin weight used in the glue line). The conception of the mixed resin was fixed at 100 g/m^2. UF resin with 63 percent solid content, specific gravity of 1.263 g/cm^3, viscosity of 71 seconds, gel time of 82 seconds, and pH of 7.32 was supplied by a local resin manufacturing plant. Panels overlaid by glued veneers were pressed at 160°C for 120 seconds by a maximum pressure of 0.5 MPa. The final density of panels ranged from 0.45 to 0.47 g/cm^3. After veneering and edge trimming, the

Table 1.—Experimental design and bending properties of sandwich panels.

Panel type	Variable Treatment of particles[a]	 Extender content (%)	 Press closing time (s)	Mean (SD) bending strength values (N/mm^2) MOR||dry	 MOR⊥dry	 MOR||wet	 MOR⊥wet
A	Ut	3	40	9.60 (0.98)	7.18 (0.85)	8.00 (0.39)	6.56 (0.23)
B	Ut	3	20	8.00 (0.78)	5.99 (0.34)	7.33 (0.14)	4.99 (0.45)
C	Ut	18	40	10.93 (0.93)	9.82 (0.87)	10.03 (0.47)	7.92 (0.98)
D	Ut	18	20	10.00 (0.59)	8.00 (0.23)	9.02 (0.98)	6.96 (0.34)
E	Ut	33	40	12.89 (1.1)	11.01 (0.98)	11.70 (1.2)	9.88 (0.23)
F	Ut	33	20	11.03 (0.67)	9.00 (0.48)	9.88 (1.1)	8.98 (0.48)
G	Tt	3	40	13.00 (0.67)	10.96 (0.18)	10.26 (0.67)	9.89 (0.28)
H	Tt	3	20	9.99 (0.39)	7.80 (0.87)	8.21 (0.58)	7.66 (0.47)
I	Tt	18	40	13.06 (0.89)	10.96 (0.63)	11.00 (0.91)	10.00 (0.45)
J	Tt	18	20	12.38 (1.2)	10.17 (0.64)	10.95 (0.48)	8.92 (0.89)
K	Tt	33	40	14.58 (0.87)	12.22 (0.83)	12.49 (0.48)	11.7 (0.89)
L	Tt	33	20	13.00 (0.67	11.16 (0.67)	11.45 (0.78)	9.81 (0.49)
M	Ht	3	40	10.81 (1.3)	8.99 (0.63)	9.00 (0.57)	8.15 (0.12)
N	Ht	3	20	10.93 (0.39)	8.93 (0.83)	9.53 (0.78)	8.11 (0.34)
O	Ht	18	40	14.60 (0.98)	12.10 (0.93)	12.02 (0.34)	11.10 (0.88)
P	Ht	18	20	11.92 (0.87)	9.33 (0.49)	10.00 (0.23)	9.07 (0.38)
Q	Ht	33	40	15.53 (0.45)	13.37 (0.71)	13.13 (0.89)	12.40 (0.48)
R	Ht	33	20	11.93 (0.72)	10.17 (0.48)	11.00 (0.83)	9.88 (0.98)

[a] Ut = untreated particles; Tt = thermal-treated particles; Ht = hot-water–leached particles.

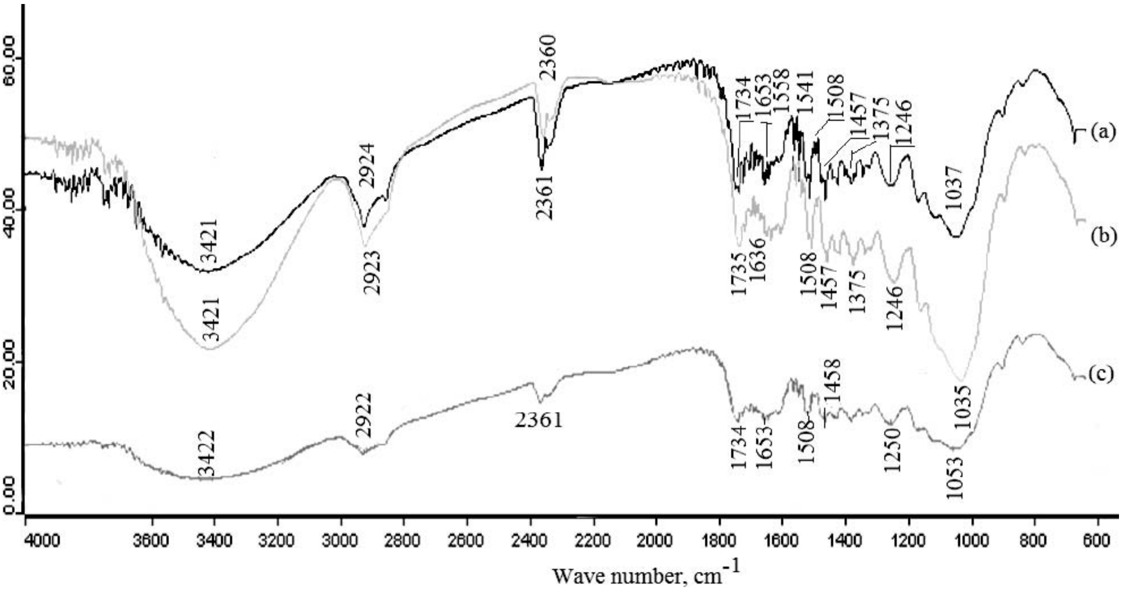

Figure 2.—Fourier transform infrared spectra of untreated (a), heat-treated (b), and hot-water–treated (c) reed particles.

dimensions of the sandwich panels became 3 by 10 by 2.7 cm. The experimental design is shown in Table 1. In order to evaluate the effect of variation in pH on the properties of panels, the acidity of untreated and treated particles was determined.

All of the panels were conditioned for about 3 weeks at a relative humidity of 65 ± 5 percent and a temperature of 20°C ± 3°C prior to the tests. The specimens were prepared for the MOR test based on European Standard EN 310 (European Committee for Standardization 1999), parallel and perpendicular to the grain orientations.

Statistical analysis

Data for each test were statistically analyzed. Analysis of variance was conducted ($\alpha \leq 0.05$) to examine the effects of the production parameters (treatment type of particles used in the core layer, the press closing time, and the content of almond shell powder used as an extender in the glue line) on the bending strength (MOR) parallel and perpendicular to the face–back veneer grain in dry (MOR||dry and MOR⊥dry) and wet (MOR||wet and MOR⊥wet) conditions and to determine the statistical differences of these properties of the sandwich panels. A Duncan multiple range test was conducted at the 5 percent probability level to determine the significance of the differences among the experimental panels using the SPSS statistical software package. The *t* test was used to determine the differences between MOR|| and MOR⊥ in dry conditions and also between MOR|| and MOR⊥ in wet conditions.

FTIR spectroscopy

A Bruker Optics TENSOR 27 Fourier transform infrared (FTIR) spectrometer was used to characterize the molecular vibration of the functional groups in the composites. Anhydrous potassium bromide was used as a dispersing material, and all spectra were scanned within the range of 800 to 4,000 cm^{-1}, with a total of 20 scans and a resolution of 8 cm^{-1}.

Results and Discussion

FTIR analysis

FTIR spectra of the untreated, heat-treated, and hot-water–treated reed particles and composites made by them were taken between wavelengths of 4,000 and 600 cm^{-1} (Figs. 2 and 3, respectively). The significant difference between the three particles and panels is the 60 and 70 percent lower adsorption of the hot-water–treated particles than untreated and heat-treated particles at 1,734 cm^{-1}, respectively. This peak corresponds to the C=O stretching in the carboxyl group (Colom et al. 2003) and shows that hemicelluloses of hot-water–treated particles contain less acetyl side groups than those of untreated and heat-treated particles. This can increase the hydrophilicity of particles, resulting in the formation of higher chemical bonding between resin polymers and OH groups of hemicellulose. There is a significant change in peak area of infra-absorbance spectra at 1,508 cm^{-1} not only for hot-water–treated particles but also for composites made from hot-water–treated particles. The peak at 1,508 cm^{-1} indicates splitting of the aliphatic side chains in lignin and cross-linking formation by condensation reactions of lignin (Colom et al. 2003, Muller et al. 2003). New cross-linking in the lignin network (Boonstra and Tjeerdsma 2006) can increase the IB and bending strengths of panels.

The spectra of the giant reed particle–resin composites are displayed in Figure 3. When comparing the untreated and treated reed particle–resin composites, the spectra showed similar behavior with peaks occurring at the same wave numbers. However, a noticeable difference in peak breadth was observed at ~3,420 cm^{-1} (OH stretching), with hot-water particles (Fig. 2) and with hot-water–leached particle composites (Fig. 3) displaying broader OH peaks than the prepared heat-treated or untreated particles and composites. Infrared peak broadening is related to an increase in the total number of hydrogen bonds, indicating a greater occurrence of H bonding within the composites (Coates 2000). Furthermore, the hot-water–treated particle–UF composite OH peaks appeared at lower wave numbers

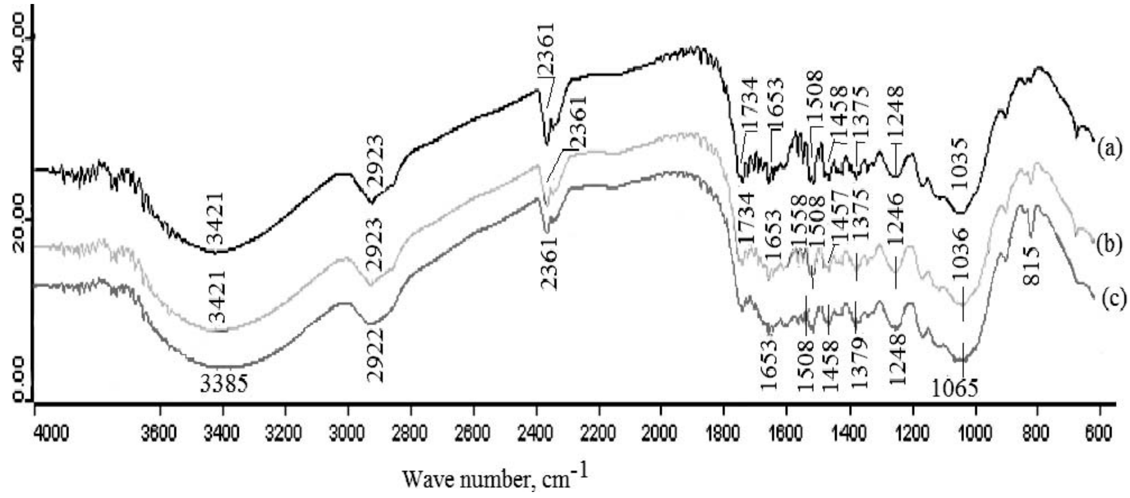

Figure 3.—Fourier transform infrared spectra of composites made by untreated (a), heat-treated (b), and hot-water–treated (c) reed particles.

(~3,385 cm^{-1}) than heat-treated– or untreated particle–UF composites (~3,420 cm^{-1}). A shift toward a lower wave number indicates an increase in hydrogen bond strength (Lee et al. 2007). Therefore, the hot-water–pretreated particles exhibit more stable, strong interactions between the resin and reed particles than the heat-treated particles or untreated particle–UF resin composites. A significant difference in peak breadth was observed at ~1,375 cm^{-1} (OH plane bending), with hot-water–leached particle composites (Fig. 3) displaying the formation of an ether linkage from the hydroxyl group within hemicelluloses and lignin (Colom et al. 2003) and the increment in the strength properties of composites. The small adsorption bands appeared at ~1,458 cm^{-1}, characteristic of the aromatic vibrations of phenyl groups (Bodirlau et al. 2012), and ~1,248 cm^{-1}, characteristic of the syringyl ring and C-O stretch in the lignin and xylan (Pandey and Pitman 2003) or C-H and -OH deformation and C-O-C stretching vibration of the cellulose (Gierlinger et al. 2008). The composites made by untreated, heat-treated, and hot-water–treated particles behaved quite similarly at these points. There are no significant differences between spectra for untreated panels and treated panels. Some shifts of the absorption bands to higher wave numbers (1,065-cm^{-1} band [in panels made by hot-water–treated particles] attributed to the aromatic C-H in plane deformation of the guaiacyl type) are evidenced (Bodîrlău and Teacă 2009). This was probably caused by interactions among functional groups. It can be clearly seen that the latter absorption peak at 815 cm^{-1} appeared and increased during the manufacturing of panels by hot-water–treated particles. This might be due to a substituted aromatic ring, namely, a substituted C═C aliphatic group, during the pressing of the panels.

Bending properties

Mean values of the bending strength (MOR) parallel and perpendicular to the face–back veneer grain in dry (MOR||dry and MOR⊥dry) and wet (MOR||wet and

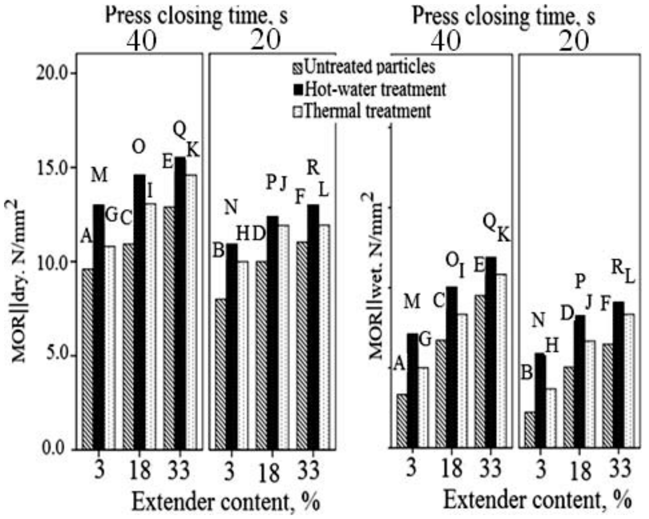

Figure 4.—Effects of studied variables on the modulus of rupture of panels in dry (left) and wet (right) conditions parallel to the grain (MOR//dry and MOR//wet).

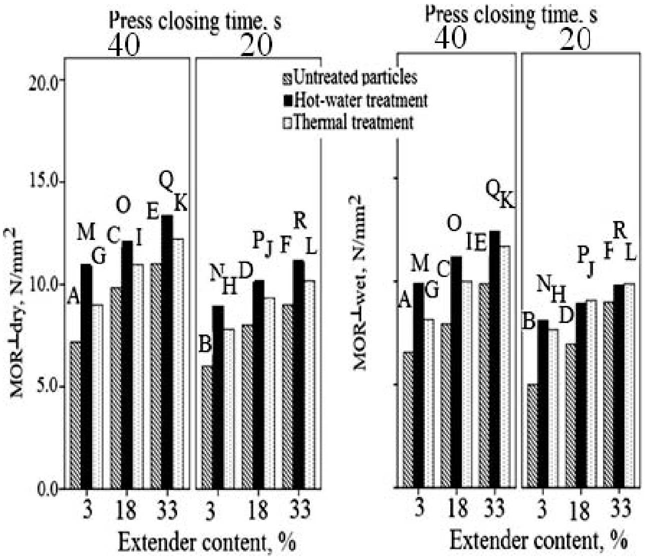

Figure 5.—Effects of studied variables on the modulus of rupture of panels in dry (left) and wet (right) conditions perpendicular to the grain (MOR⊥dry and MOR⊥wet).

Table 2.—Multifactor analysis of variance on effects of particle treatment, extender content, and press closing time on bending strengths.[a]

Test	Source of variation	*F* ratio
MOR||dry	Treatment	197.9
	Extender content	192.9
	Press closing time	226.9
MOR⊥dry	Treatment	291.5
	Extender content	350.1
	Press closing time	406.4
MOR||wet	Treatment	234.0
	Extender content	551.2
	Press closing time	253.2
MOR⊥wet	Treatment	135.1
	Extender content	166.3
	Press closing time	130.7

[a] All results are significant at the 99 percent confidence level.

Table 3.—The statistical analysis of the properties for different variables.

	Bending strength (N/mm^2)[a]			
Variable	MOR||dry	MOR⊥dry	MOR||wet	MOR⊥wet
Untreated	10.41 A	8.50 A	9.32 A	7.55 A
Thermal treatment	12.05 B	9.91 B	10.28 B	9.40 B
Hydrothermal treatment	13.24 C	11.11 C	11.22 C	10.05 C
Extender (%)				
3	10.38 D	8.31 D	8.72 D	7.50 D
18	12.10 E	10.06 E	10.50 E	9.00 E
33	13.16 F	11.15 F	11.61 F	10.44 F
Press closing time (s)				
20	10.24 G	8.33 G	9.41 G	8.71 G
40	12.81 H	10.84 H	10.93 H	9.98 H

[a] Different letters represent statistical differences ($P < 0.05$).

MOR⊥wet) conditions of the panels are presented in Table 1 and Figures 4 and 5. As shown in Table 1, the mean values of MOR parallel and perpendicular to the face–back veneer grain in dry and wet conditions ranged from 8 to 15.53 N/mm^2, 7.33 to 13.13 N/mm^2, 5.99 to 13.37 N/mm^2, and 4.99 to 12.40 N/mm^2, respectively.

According to Table 1 and Figures 4 and 5, Q- and O-type panels manufactured using particles treated with hot water, pressed with a longer press closing time (40 s), and veneered with a higher perecent of the extender in the glue line (33% and 18%, respectively) achieved the highest MOR||dry and MOR||wet values (from 15.53 to 13.13 N/mm^2 and 14.60 to 12.02 N/mm^2, respectively),while B-type (untreated particles), H-type (thermal-treated particle pressed with a short press closing time), and A-type (at higher press closing time) panels manufactured using untreated particles veneered with the lowest amount of the extender in the glue line had the lowest MOR||dry and MOR||wet values (from 8.00 to 7.33 N/mm^2, 9.99 to 8.21 N/mm^2, and 9.60 to 8.00 N/mm^2, respectively). Q- and O-type panels manufactured using particles treated with hot water, pressed with a longer press closing time (40 s), and veneered with a higher percent of the extender in the glue line (18% and 33%, respectively) achieved the highest MOR⊥dry and MOR⊥wet values (from 13.37 to 12.41 N/mm^2 and 12.10 to 11.10 N/mm^2, respectively), while B-type (untreated particles pressed with a short press closing time), A-type (untreated particles) and H-type (thermal-treated particle pressed with a short press closing time) panels veneered with the lowest amount of the extender in the glue line had MOR⊥dry and MOR⊥wet values ranging from 5.99 to 4.99 N/mm^2, 7.18 to 6.56 N/mm^2, and 7.8 to 7.66 N/mm^2, respectively.

A multifactorial variance analysis was used for data with SPSS version 16 to determine the effects of the selected variables on the bending strengths of the manufactured panels (Table 2). The Duncan multiple test was used to compare the panel types according to every property tested if the variance analysis was significant (Table 3). As shown in Table 3, using hot-water–leached particles in the core layer significantly increases the bending strength. In addition, the MOR of the experimental sandwich panels increased as the press closing time and the extender content in the glue line increased. This suggests that using the hot-water–leached particles in the core layer, the extender content in the glue line, and the press closing time had a significant effect on the MOR||dry, MOR⊥dry, MOR||wet, and MOR⊥wet of panels (Table 3). Therefore, it may be possible to manufacture stronger and stiffer panels by changing the production variables.

Hydrothermal and thermal treatments might contribute to the improvement of the properties of the sandwich panels through changing the structure and surface properties of the reed particles. A large amount of a waxy compound on the surface reed particles should be avoided in order to achieve better strength. According to Zheng et al. (2007), this could be attributed to the low wettability caused by an extractive such as hydrophobic wax and inorganic silica at the surface. Because of it, chemical bonding through hydrogen bonds and UF covalent bonds decreases.

As can be seen in Tables 2 and 3, treatment of particles significantly affected MORs. It was seen that the color of the heat-treated and hot-water–treated particles was much stronger than that of the untreated particles. During the treatment, alkaline oxidant extractives in particles can negatively affect the curing of UF under the hot press. Hydrothermal treatment may have removed these alkaline oxidant extractives, decreased the pH, and increased the absolute acid-buffering capacity of particles (Xing et al. 2004). According to Matyas et al. (2012), the content of alkaline extractives and ash is high in reed stalks. They showed that a short leaching in cold water can remove a large fraction of unwanted elements from the reed. About 52 wt% of total Ca, 78 wt% of total Mg, 80 wt% of total P, 98 wt% of total K, 70 wt% of total Na, 75 wt% of total S, and 98 wt% of total Cl can be removed from the dried reed. This improves the interaction between the UF and particle so that the panel made from hot-water–leached particles bonded by UF has better qualities than that made from untreated particles (Xing et al. 2004). The pH should be 5 to 6 for good adhesion between particles (Nemli and Aydin 2007). According to the test results, pH values of untreated reed particles ranged from 6.5 to 7.5. This high pH value delays curing the adhesive in hot pressing so that resin polycondensation cannot be completed, and, consequently, bonding strength between particles becomes weak. UF resin used in panels as a binder has a pH value from 5.2 to 6.1. The pH of hot-water–treated particles was 5.1. This pH level can create good bonding between resin and particles due to the formation of abundant cross-linkages during the limited press time. This causes the breaking down of samples by pure bending stress, not shear stress. Moreover, due to the presence of a large number of extractives, bonding becomes difficult, and the IB strength of the panels decreases (Nemli et al. 2004, Nemli and Aydin 2007).

It was determined that MORs are affected by the press closing. According to Wong et al. (1998), at a low density level (0.5 g/cm^3), the shorter closing time increases the face density of panels, while the core density decreases. This creates some shear stresses induced by the large contrast between the face and core density in panels, hence reducing the MOR (Wong et al. 2000). The higher press closing time creates more homogeneous profile density in the thickness of the board, so any change in the bending strength can be attributed solely to the difference in the board mean density (Wong et al. 1999). Moreover, due to the longer press closing time, more stress relaxation may occur before the final thickness is achieved, which affects the heat transfer, the moisture distribution inside the mat, and the rate of the adhesive cure.

According to the results (Tables 2 and 3), the extender content significantly affected the MORs. Moreover, the increase of the extender content increased the MORs (Figs. 4 and 5). After manufacturing, the pores between particles could be easily seen on the unveneered panel surface due to using coarse reed particles, so not all the particles were bonded well by the resin. As expected, higher extender content fills more pores of the surface on the glue line, providing better bonding between substrate and veneer. Using a higher amount of extender in the glue line creates an even tighter and continuous structure on the surface layers and increases the neat transfer to the core layer. Therefore, this decreases the roughness of the surface and allows the adhesive to flow more freely, and thus a more uniform thin layer of the adhesive and more chemical bonds are formed in the glue line between the substrate and the veneer (Vick 1999). Moreover, the pure resin in the glue line has a special brittleness. By using a higher extender content, it can be expected that the brittleness of the glue line will decrease (Scheikl and Walinder 2002) because of the transition of the tension created by loading in the bending test to the different directions of panels and the increment elastic properties of the glue line. Some adhesive is lost by overpenetration into the substrate (veneer or board) and, consequently, the shortage of binder is created in the substrate, so that a starved glue line on the glued surface is formed (Nazerian 2013). Deeper penetration of resin into the microstructure of the fir veneer can be limited by adding extender to the resin, thereby increasing the concentration and the viscosity of resin and decreasing the penetrability of the wood substrate.

When the *t* test was performed to determine the differences between the bending strength parallel (in dry or wet conditions) and perpendicular (in dry or wet conditions) to the face–back veneer grain, there was a statistical difference between the *t* values of the MORs at the 1 percent probability level. Testing at the perpendicular direction to the grain orientation of the face plies showed significantly lower MORdry and MORwet than that at the parallel direction to the grain orientation. This might be due to the fact that the bending strength of the wood mass along the grain orientation is much higher than across the grain orientation.

In bending, the maximum stress occurs in the outermost layers. Owing to the decrease of the stiffness and strength of lignin compounds, fracture can occur easily in the lamella (enriched by lignin) of the face–back wood veneer (Tuttle 2003) coating perpendicular sandwich panels. In dried or moistened parallel sandwich panels, fibers of face–back veneers containing mainly cellulose carry the main load. Because cellulose chains are higher than lignin and the parallel orientation of fiber increases the strength of veneer, the bending strength of parallel sandwich panels is higher (Tuttle 2003).

Wood-laminated lumber has different swelling values in different directions. Accordingly, ultimate tensile stress involves stresses generally parallel to the axis of the cellulose chain (Kretschmann and Green 1996). When this material is manufactured from sheets of cross-laminated layers, stress resultants created by swelling in the core and surface layers can be increased. This stress destroys the glue line. Hence, the bonding strength between the substrate and the layer will decrease. In fact, interlaminar shear stresses are the most likely causes of failure (Starnes et al. 2001).

Conclusions

According to this study, the following conclusions can be drawn in relation to the properties of sandwich panels:

- It was shown that the performance of the sandwich panels is highly dependent on the treatment of particles used in the core layer, the press closing time, and the extender content used in the glue line. Using hot-water–leached particles in the core layer, the dry and wet static bending strengths (MOR) increased. Specimens with untreated particles exhibited low values of MOR.
- It was determined that as the press closing time increased, the bending strengths of panels increased owing to the formation of homogeneous profile density along the board density and the increase of the IB strength.
- Compared with the panels glued to resin with a lower extender content, panels glued to an extender with a higher content in the glue line exhibit stronger performance because of the higher connectivity between veneer and substrate and the formation of a continuous structure in the glue line.
- Dry and wet bending strengths of the specimens were more or less affected by the type of loading. According to *t* tests, there was a statistical difference between the mean values of the bending strength parallel (in dry or wet conditions) and perpendicular (in dry or wet conditions) to the face–back veneer grain. Testing at the perpendicular direction to the grain orientation of the face plies resulted in lower MORdry and MORwet than at the parallel direction to the grain orientation owing to the higher strength of the wood mass along the grain orientation compared with that across the grain orientation.

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