Anisotropic Physical and Mechanical Performance of PF-impregnated Oriented Strand Board

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This study investigated several key mechanical and physical properties of oriented strand board (OSB) made from China fir strands impregnated with phenol-formaldehyde (PF) resin. Results showed that accumulated percentages of strand alignment angles between strand length direction and mechanical alignment direction on OSB face and bottom layer were within 0° and 30° *vs.* 88.2% and 76.2%, respectively. Ultrasonic velocity at 0° strand angle (V_0) was the highest, decreasing rapidly with increasing aligned angle (θ). The lowest ultrasonic velocity was found at 90° of strand's angle (V_{90}). The relationship between θ and V could be represented by Hankinson's formula, where the optimal n exponential values were between 1.59 and 1.88. The anisotropic properties of the OSBs, defined as the ratio of V_0/V_{90}, were 2.23 to 2.45 for the bending specimens. The ratios of MOR_p/MOR_v and MOE_p/MOE_v were 3.79 to 4.15 and 4.18 to 5.42, respectively. Effects of PF-impregnation on the bending properties showed superior performance. The parallel bending strength (MOR_p) was 64.7 to 84.8 MPa and the MOE_p was 13.0 to 15.9 GPa, respectively. After accelerated deterioration testing, the retention rates of MOR_p and MOE_p (%) were 78.3% to 88.2% and 68.0 to 83.1%, respectively. Further, the dimensional stability of PF-impregnated OSB showed good performance in thickness swelling (TS) and linear expansion (LE).

Keywords: Cunninghamia lanceolata; Oriented strand board; Ultrasonic wave velocity; Anisotropic properties; Strength retention rate

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INTRODUCTION

Oriented strand board (OSB) and plywood are two major types of wooden structural panels used in North America. These two materials amounted to approximately 44.3% and 14.9%, respectively, of the construction materials in new homes in 2009 (UN 2010). OSB is widely used in wall and diaphragm structures and in the webs of I-joists. The manufacturing processes of OSB are continuously being improved, which has significantly boosted the production rates and reduced costs of this building material. The market share of OSB has been increasing steadily since 2000 (RISI 2008), and it has become more important than plywood in wood house construction. The UN (2011) indicated that European OSB production grew by 7.5% in 2010, exceeding 4.1 million m^3.

Many studies have been carried out to quantify the mechanical properties of OSB in past decades. Suzuki and Takeda (2000) stated that the alignment angle distribution of strands was affected by both the free fall distance and the strand length. Longer strands provide better bending properties of the board, which can be attributed to the contributions of longitudinal properties in the strand. Wang and Chen (2001) reported similar results on strand alignment efficiency. Okino *et al*. (2004) investigated the properties of OSB made of Brazilian wood with 80 mm long strands, and Cloutier *et al*. (2007) analyzed the impact of radiata pine juvenile wood on physical and mechanical properties of OSB. Beck *et al*. (2010) compared the performance of OSB made from trembling aspen and paper birch. Stürzenbecher *et al*. (2010) investigated the development and engineering design of high-performance OSB in great detail.

It is well known that OSBs fabricated with strands that have larger length-to-width ratio exhibit a high efficiency of strand alignment, meaning that the modulus of rupture (MOR) and modulus of elasticity (MOE) in OSB bending generally meet the requirements for structural use. Moreover, the performance of OSBs can be altered in terms of geometrical form, strand alignment, and layer construction. It has previously been hypothesized that improvements in the mechanical and physical properties of OSBs can be achieved by optimal strand orientation during panel fabrication. Nishimura *et al*. (2001) stated that the key to OSB bending strength is the disposition of strands in the board surface, where the bending moments are greatest and the distribution of flaws is the most critical. Similar results were also reported by Geimer *et al*. (1993).

An important concern of using OSB for constructional purpose is its dimensional stability. Wood chips are heterogeneous particles that perform differently in three axial directions. This dimensional behavior due to changes of humidity may cause swelling and significantly affect the properties of OSB. Swelling of OSBs can be classified into two categories, thickness swelling (TS) and linear expansion (LE). Swelling can greatly affect the state of stress in the material. In-plane movement can cause high internal stresses due to restraint from fastenings such as nails or screws. These stresses may be great enough to cause buckled panels, pushed-out nails, or separation of panel from the structure (Lang and Loferski 1995; Wu and Suchsland 1996). Earlier field studies showed that dimensional changes of OSB were affected by many parameters, *e.g.*, strand orientation, ratio of strand weight between face layer and core layer, degree of bonding, density, and density gradient. Wu and Suchsland (1996) measured the LEs of five commercial OSBs at different relative humidity (from 35% to 95%) and indicated that LE occurred when the increase of MC was within the hygroscopic range: at a lower MC, LE for all OSB occurred at greater rates, and *vice versa*. An improvement of strand alignment and better panel design can significantly reduce the impact of increasing MC and can lessen the overall LE of the OSBs. Furthermore, Wu (1999) investigated the effects of panel processing variables on LE of OSB and demonstrated that the relationship between LE and MC is a function of the level of panel alignment and test direction. Total LE of oven-dried to water-soaked panels differed significantly due to strand orientation distribution and density. The influence of resin contents on LE, at the levels used by the authors, was relatively small. Lee and Wu (2002) investigated the dimensional stability of three-layer OSB and confirmed these results. The relationship between LE and changes in MC was curvilinear with larger expansion rates at lower MCs. The strand alignment and strand weight ratios are two primary variables that can significantly affect the magnitude of LE. Cloutier *et al*. (2007) demonstrated that LE was affected by the strand direction. A higher LE was found in the case of panels formed with tangential strands.

In previous research, PF resin impregnation has been widely used to improve the mechanical properties and dimensional stability of wood and wood-based products. Shams and Yano (2011) investigated the strength and dimensional stability of highly compressed dimensional stable resin-impregnated wood. Gabrielli and Kamke (2010) produced dimensional stable and mechanically improved wood-based products with PF-impregnation, and Yang *et al*. (2007) evaluated the characteristics of PF-impregnated particleboard. For the potentiality of developing an OSB with good mechanical properties and dimensional stability, PF resin was selected to manufacture the PF-impregnated OSBs. The goals of this work were to quantify the influences of the introduced variables, *i.e.*, strand's aligned angle and resin content, on the mechanical properties of OSB made from China fir strands. Bending properties, internal bond strength, and dimensional stability, including TS and LE of different PF-impregnated OSBs, were evaluated, as well as the property changes after accelerated aging and dynamic properties during testing. The results of this study were used to develop a fundamental understanding of the OSB manufacturing process, which can be of help for future developments.

MATERIALS AND METHODS

Experimental Materials and Specimen Fabrication

China fir (*Cunninghamia lanceolata*) waste sawn lumber was used to produce the wood strands for the OSB manufacturing process. The wood was cut into blocks with dimensions of 75 mm in length and 13 mm in thickness with various widths. The blocks were immersed in water at room temperature for 24 h before disk slicing. Water-soluble phenol-formaldehyde resin (No. FR-6504, PF resin) provided by TAILIN Resin Co. (Taiwan) was used as the adhesive in OSBs. The resin content and the pH of the PF resin were 76% and 8.5, respectively. The dimensions of the wood strands were 75 mm (length) × 13 mm (width) × 0.4 to 0.6 mm (thickness). The strands were oven-dried to 2% MC at 60 °C and weighed. The strands were then impregnated with the water-soluble PF resin at three concentrations (3%, 6.5%, and 10%) for 5 min. The resin solution was allowed to trickle freely on the surface of the strands, and the PF-impregnated strands were dried in an oven at 60 °C to a semi-hardened condition and weighed again.

Experimental boards were manually formed with an experimental orienter with a plate spacing of 25 mm. Strand free falling distance was set at 20 mm to form a single layer board. After strand alignment, the board was covered by teflon plates on both sides and put into a conventional hot press for fabrication. The fabrication temperature, pressure, and pressing time were 180 °C, 2.94 MPa, and 6 min, respectively. The nominal thickness of OSB was set to 12 mm and target density was 700 kg/m^3. The dimensions of the final OSB boards were 500 mm × 500 mm × 12 mm; six replicates were made for the three groups of strands impregnated at three different resin concentrations.

Determination of Orientation Angle of Strands

Measurement of the orientation angles of the strands was performed with a protractor, and the orientation angles were quantified from the direction of strand alignment at the top faces of the OSB. The orientation angle was defined as 0° when the length direction of the face strands was parallel to the mechanical alignment direction and 90° when the length direction of the face strands was perpendicular to the mechanical alignment direction. The amount and accumulated percentages of the aligned strands were counted at the intervals from 5° to 30° to obtain the average orientation angles of the studied OSBs.

Ultrasonic Wave Test and Bending Test

The PF-impregnated OSBs were conditioned at 20 °C and 65% RH prior to the ultrasonic wave tests. The ultrasonic wave tests were performed using a Swiss-made ultrasonic wave instrument, SYLVATEST, with 22 kHz transmitting and receiving transducers. The intersection of the two edges between 0° and 90° aligned angles was considered as the initial point. The ultrasonic wave instrument sent ultrasonic pulses through the specimen at intervals of 15° (namely 0°, 15°, 30°, 45°, 60°, 75°, and 90°), and its transmission time was measured to calculate the wave velocity.

After the ultrasonic wave tests, each of the tested OSB panels were cut into bending test and internal bond strength (IB) specimens according to CNS 2215 (2006). Two types of bending test specimens were prepared based on the grain direction of face veneer: (I) parallel to length axis (p-group) and (II) perpendicular to length axis (v-group). These specimens were tested with the ultrasonic wave instrument at 0° (parallel direction) and 90° (perpendicular direction) to the angle between the strand's length direction and the mechanical alignment direction. In the second set of ultrasonic wave tests, 200 kHz ultrasonic pulse (C.N.S. Electronic LTD, PUNDIT) was generated to measure the transmission time of IB specimens in the thickness direction. Wave velocity was calculated by dividing the length or thickness by the transmission time.

The static bending tests were conducted in accordance with Chinese national standard CNS 2215 (2006) using a Shimadzu AG-250KNI universal-type testing machine. A concentrated bending load was applied to the center with a span of 15 times the thickness of the specimen. After central concentration bending test, the modulus of rupture (MOR_p and MOR_v) and modulus of elasticity (MOE_p and MOE_v) of each specimen were calculated,

$$\mathrm{MOE} = \frac{\Delta P \ell}{4 \Delta y b h^3} \tag{1}$$

$$\mathrm{MOR} = \frac{3 P_{max} \ell}{2 b h^2} \tag{2}$$

where ℓ is the span, ΔP is the difference between upper and lower loads within the proportional limit, Δy is the difference of deflections corresponding to ΔP, $P_{\max}$ is the ultimate load, b is the width of the specimen, and h is the thickness of the specimen.

Internal Bonding Strength

The dimensions of the specimens for the internal bond strength tests were 50 mm in length and 50 mm in width, according to CNS 2215 (2006). Ultrasonic wave tests were conducted to measure the specimens in the thickness direction. For IB testing, specimens were bonded together with two steel blocks using polyethylene resin adhesives. The two steel blocks with specimen were clamped with tensile grips at a constant speed of 2 mm/min. The rupture load (P) was measured, and the internal bond strength (IB) was calculated by dividing P by the cross section area (50 mm × 50 mm) of the specimens.

Formaldehyde Emission

Emission of formaldehyde was tested in a 120 mm diameter, 60 mm high glass container with 300 mL of distilled water placed at the bottom of a 240 mm diameter desiccator with a total capacity of 10 ± 1 L according to CNS 2215 (2006). Nine specimens with dimensions of 12 mm (thickness) × 50 mm (width) × 150 mm (length) were put on a metal supporter at 20 °C for 24 h. The specimens were carefully installed on the supporter without contacting any other specimen. Formaldehyde released from the specimens was dissolved in the distilled water, and the concentration of formaldehyde was determined using the acetylacetone-ammonium acetate method with colorimetric detection at 415 nm.

Dimensional Stability

TS tests were performed using 50 mm square specimens according to CNS 2215 (2006). The thickness of the OSB was measured at the center of the specimen with a micrometer. The specimens were immersed in 30 mm deep water and soaked for 24 h. TS was determined by the following formula,

$$\text{TS} = (T_t - T_1)/T_1 \times 100 \quad (3)$$

where TS is the thickness swelling rate (%), T_1 is the thickness at the center of the specimen before soaking (mm), and T_t is the thickness at the center of the specimen after soaking at 2 hour intervals (mm).

Samples with dimensions of 200 mm (length) × 50 mm (width) were used to evaluate the linear expansion (LE) of the OSBs. The samples were conditioned at 24 °C and conditioned in a controlled conditioning chamber according to the following schedule: 0%, 35%, 55%, 75%, 85%, and 93% RH. Measurements of changes in dimensions were performed after conditioning for 8 weeks at each specified RH level. LE was calculated by the following formula,

$$\text{LE} = \frac{L_1 - L_0}{L_0} \times 100 \ \% \quad (4)$$

where LE is the linear expansion rate, L_0 is the length of specimen at 0% RH, and L_1 is the length of specimen at each specified RH level.

Accelerated Deterioration Test

In this test, the OSB specimens were immersed in hot water (70 °C) for 2 h and then in water of room temperature for 1 h (25 °C) according to CNS 2215 (2006). The static bending tests were conducted on specimens under wet conditions. The MOR and MOE retention rates were evaluated with the following formula,

$$\text{MOR(MOE) retention rate} = MOR_2(MOE_2)/MOR_1(MOE_1) \times 100 \ \% \quad (5)$$

where $MOR_1(MOE_1)$ and $MOR_2(MOE_2)$ are the MOR(MOE) measured under air-dried conditions and after soaking in hot water (70 °C) for 2 hours, respectively.

Analysis of Variance

All results were expressed as the mean ± standard deviation (SD). The significance of the difference was calculated by Scheffe's test. P values < 0.05 were considered significant.

RESULTS AND DISCUSSION

PF Resin Absorption and Strand Alignment Efficiency

Absorption of the PF resin in the wood strands increased from 7.8% to 37.4% with increasing PF concentrations in the soaking liquors (*i.e.*, from 3% to 10%). The strand alignment efficiencies were evaluated by measuring the accumulated percentages of strands on both the surface layer and the bottom layer of the OSBs. The results were presented at 5 degree intervals. Within the interval 0 to 5 degrees, the average strand alignment efficiency was 32.9% in the top layer and 21.3% in the bottom layer, respectively. The percentages of the same index increased to 52.2% and 34.3% at 0 to 10 degrees, and 62.6% and 45.6% at 0 to 15 degrees. Up to 30 degrees, the accumulated strand efficiency was 88.2% in the top and 76.2% in the bottom, respectively. The distribution and accumulation percentages of the aligned strands are shown in Fig. 1.

The strand alignment efficiencies were higher than the previous study performed by Wang *et al*. (1995), who reported that the accumulated percentage of the strands at 30° was between 69.5% and 78%. The accumulated strand percentage in the top layer was higher than the bottom layer, due to changing free-falling distances during the manufacturing process. When the wood strands started to accumulate on top of the processing plate during the aligning process, the free-falling distance between the orienter and panel surface was reduced, and thus the chances of the strands falling into the desired orientation were increased.

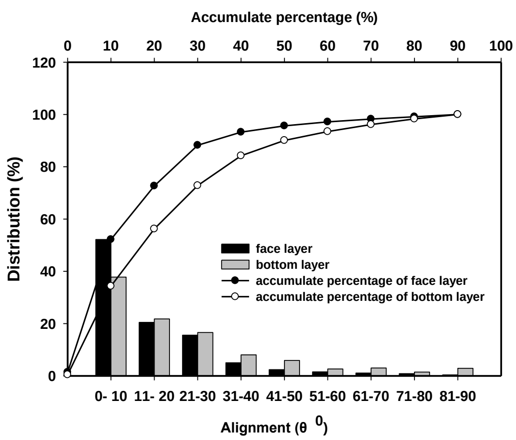

Fig. 1. Strand alignment distribution and accumulation percentage of the PF-impregnated OSBs

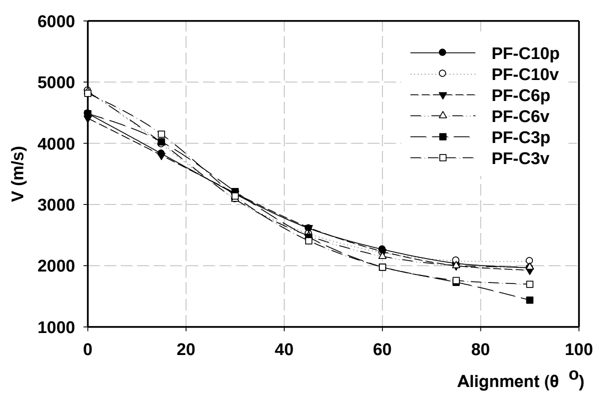

Fig. 2. Effects of strand alignment angles (θ°) on the ultrasonic velocity (V) of the PF-impregnated OSBs

Ultrasonic Wave Velocity of Whole OSBs

The ultrasonic wave velocities measured from the parallel direction (V_p) of the whole OSB samples were significantly higher than the velocities measured from the perpendicular direction (V_v), due to the heterogeneous characteristics of the OSBs. An index to quantify the board's heterogeneous nature was defined as V_p/V_v, and the values were typically greater than 1. The measured value of V_p of the studied OSBs was between 4,815 and 4,860 m/sec, and the V_v was between 1,695 and 2,075 m/sec. The heterogeneity index was therefore from 2.34 to 2.84. The highest ultrasonic wave velocity was measured at 0° aligned angle and decreased rapidly with increasing aligned angles, as shown in Fig. 2. This trend was also similar to the relationships between ultrasonic velocity and grain direction of wood.

The ultrasonic wave velocity decreasing rate percentage, d%, was defined as the reduced wave velocity divided by the wave velocity at zero aligned angle (Table 1). When the aligned angle increased at 15 degree intervals, the d% values were 10 to 15%, 28 to 29%, 41 to 45%, 49 to 56%, 55 to 61%, and 56 to 68%. The results of wave velocity divided by V_{90}, increasing from 0° aligned angle to 75° every 15 degrees, were 2.29 to 3.12, 1.95 to 2.80, 1.62 to 2.24, 1.33 to 1.72, 1.15 to 1.38, and 1.04 to 1.20.

Table 1. Ultrasonic Velocity Decreasing Rate Percentage from Strand's Angle of 0 to 90 Degrees

Specimen No.	PF-C10			PF-C6			PF-C3		
Angle	V_θ	V_θ/V_{90}	d%	V_θ	V_θ/V_{90}	d%	V_θ	V_θ/V_{90}	d%
0	4486	2.29	0	4409	2.29	0	4483	3.12	0
15	3830	1.95	15	3802	1.98	14	4024	2.80	10
30	3171	1.62	29	3184	1.66	28	3211	2.24	28
45	2609	1.33	42	2622	1.36	41	2463	1.72	45
60	2265	1.15	50	2229	1.16	49	1976	1.38	56
75	2037	1.04	55	1996	1.04	55	1727	1.20	61
90	1963	1.00	56	1924	1.00	56	1436	1.00	68

PF-C10, PF-C6, and PF-C3 represent the OSB made from concentrations of 3%, 6.5%, and 10% PF resin-impregnated strands, respectively

To demonstrate the relationship between the ultrasonic wave velocities and the strands' alignment angle, the following function based on Hankinson's formula was used,

$$V_\theta = \frac{V_0 \times V_{90}}{V_0 \sin^n \theta + V_{90} \cos^n \theta} \tag{6}$$

where n is an empirically determined exponent.

The optional n values in this study were about 1.59 to 1.88. The experimental results illustrated that the ultrasonic wave velocity decreased significantly with increasing aligned angle. The results were similar to a previously reported non-PF-impregnated OSB by Wang and Chen (2001). The authors indicated that optimal n values for Equation 6 were 2.6, 1.9 to 2.0, and 1.8 to 1.9 for Japanese cedar OSB, Japanese cedar (50%) mixed with Taiwan paulownia (50%) OSB, and China fir (50%) mixed with Taiwan paulownia (50%) OSB, respectively.

The variables V_0 and V_{90} in Equation 6 were defined as the ultrasonic wave velocity of bending test specimens at 0° and 90° angles between the strand's lengthwise direction and mechanical alignment direction, respectively. In this study, V_0 values were between 4,563 m/s and 4,937 m/s, while V_{90} values were between 1,850 m/s and 2,213 m/s.

The anisotropic properties of the PF-impregnated OSBs were 2.34 to 2.84 for whole OSBs and 2.23 to 2.45 for the bending test specimens. These results were similar to those of the non-PF-impregnated OSBs manufactured by Wang and Chen (2001), who reported ratios of V_{90}/V_0 from 2.9 to 3.2 for whole OSBs and 2.9 to 3.1 for bending test specimens.

Bending Strength Properties of OSBs

The bending strengths MOR_p and MOE_p (defined as the face strand's aligned angle when the span direction is 0°) were 64.7 to 84.8 MPa and 13.0 to 15.9 GPa, respectively (Table 2). However, MOR_v and MOE_v (defined as the face strand's aligned angle when the span direction is 90°) were 15.6 to 21.8 MPa and 2.4 to 3.8 GPa, respectively. The reported MOR_p and MOE_p values of the OSBs met the minimum requirements for type 24-10 particleboard defined in CNS 2215 (2006), in which the MOR must be higher than 17.65 MPa and the MOE higher than 2.45 GPa. The OSBs also met the requirements of CSA 0437-93 (1993) for OSBs and strand boards. In this regulation, the MOR must be higher than 29.0 MPa and MOE must be higher than 5.5 GPa. The OSB's superior bending properties could be attributed to the high length-to-width ratio (5.8), the regular shape of strands, and higher resin contents than earlier studies on non-PF impregnated OSBs (Canadido *et al*. 1988; Wang and Chen 2001; Okino *et al*. 2004; Cloutier *et al*. 2007; Beck *et al*. 2010). Because PF-impregnated OSBs were formed at a higher temperature than the non-PF-impregnated ones, the potential effects of plastic deformation of the strands were reduced and PF resin mobility was improved. Improving PF mobility may result in better resin distribution, especially on the board surface; the top and bottom layers of OSB become denser and smoother than the inner layer, creating better bending strength. Additionally, the superior bonding might also be related to use of PF, since the mechanical properties of PF resin are higher than other formaldehyde-based resins.

Table 2. Physical and Mechanical Properties of PF-impregnated OSBs

No.	C (%)	RC (%)	MOR_p (MPa)	MOR_v (MPa)	$\frac{MOR_p}{MOR_v}$	MOE_p (GPa)	MOE_v (GPa)	$\frac{MOE_p}{MOE_v}$	V_0 (m/s)	V_{90} (m/s)	$\frac{V_0}{V_{90}}$	IB (MPa)	F (mg/L)
PF-C10	10	37.4^a (0.7)	84.8^a (3.9)	21.8^a (1.5)	3.89	15.9^a (0.6)	3.8^a (0.2)	4.18	4937^a (102)	2213^a (70)	2.23	1.37^a (0.07)	0.60^a (0.03)
PF-C6	6.5	16.0^b (0.8)	70.5^b (2.8)	18.6^b (0.9)	3.79	14.1^b (0.7)	3.2^b (0.2)	4.41	4648^b (100)	2028^b (57)	2.29	1.13^b (0.05)	0.48^b (0.01)
PF-C3	3	7.8^c (0.5)	64.7^c (4.1)	15.6^c (1.6)	4.15	13.0^c (0.6)	2.4^c (0.2)	5.42	4563^b (138)	1864^c (49)	2.45	0.41^c (0.04)	0.29^c (0.02)

C: impregnated resin concentration, RC: resin content, F: formaldehyde emission
Different letters within a column indicate a significant difference ($P < 0.05$).

McNatt *et al*. (1992) investigated the effects of strand alignment on strand board performance and indicated that better face strand alignment can improve the bending strength and stiffness. Xu (2000) reported that improving the percent alignment can increase MOE_p and decrease MOE_v, and the decrease of MOE_v in this study was more than 50%. The strength anisotropic properties of MOR (MOR_p/MOR_v) and MOE (MOE_p/MOE_v) were 3.78 to 4.14 and 4.19 to 5.40, respectively.

The relationship between bending performance and acoustic properties is shown in Fig. 3a to Fig. 3c. The R^2 values were 0.88 for MOR and MOE, 0.73 for MOR and DMOE, and 0.82 for MOR and *V*. In the case of OSBs, the bending performance in the parallel direction was significantly better than in the perpendicular direction.

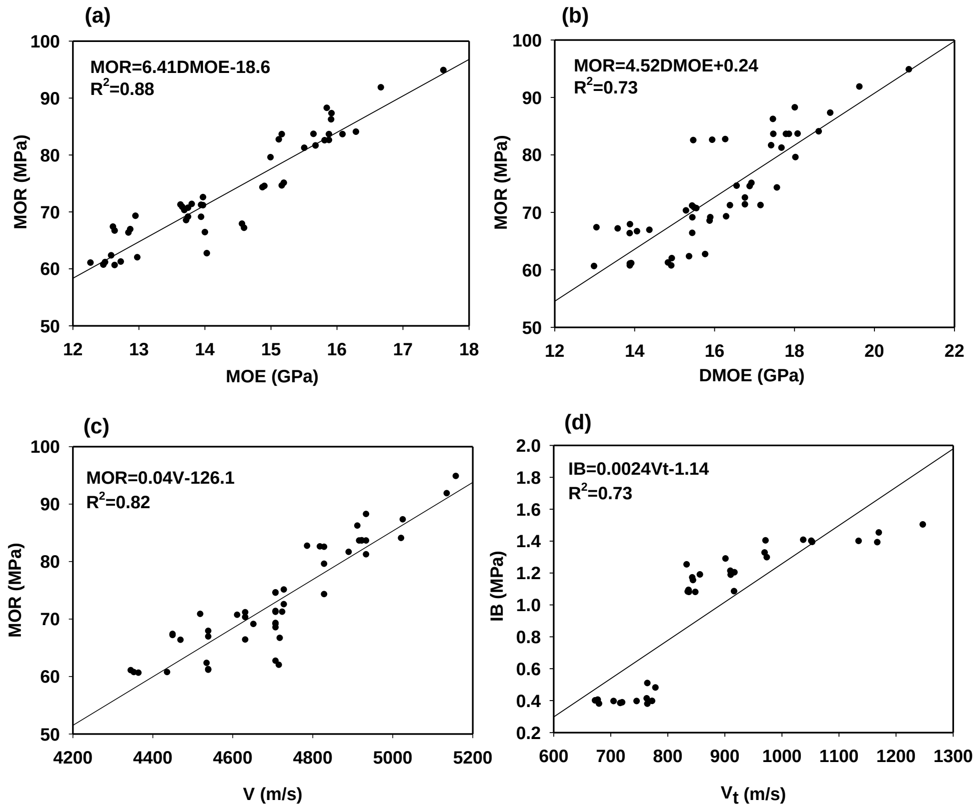

Fig. 3. Relationship between different properties of the OSBs: (a) MOR and MOE, (b) MOR and DMOE, (c) MOR and *V*, and (d) IBs and V_t

Internal Bonding Strength of OSBs

The results of IB tests are shown in Table 2. The results of ANOVA showed that the resin content had a significant positive effect on improving the IB strength of the OSBs. The average IB strength was 0.41 MPa when impregnated with the PF resin at 3% concentration, and the IB strength increased to 1.13 MPa and 1.37 MPa when impregnated with the PF resin at 6.5% and 10% concentrations, respectively. The IB of all the specimens was well above the minimum requirements of type 24-10 particleboard in CNS2215 (IB > 0.3 MPa). Since IB increased with increasing resin dosage, the test results also showed that IB was higher than in previous reports (Suzuki and Takeda 2000).

The relationship between V_t and IB strength is shown in Fig. 3d. The IB strength increased linearly with increasing ultrasonic wave velocity. In addition, Fig. 3d illustrates a good correlation between ultrasonic velocity and IB strength for the studied OSB. The ultrasonic velocity can be used as an index to assess the IB strength of the wooden panels.

Formaldehyde Emission

The results for formaldehyde emission from OSB are shown in Table 2. The formaldehyde emission was only 0.29 to 0.60 mg/L, which met the F_1 (<0.3 mg/L), F_2 (<0.5 mg/L), and F_3 (<1.5 mg/L) standards in CNS 2215. The two main potential sources of formaldehyde emissions from wood composites were unreacted free formaldehyde and formaldehyde resulting from resin breakdown. In comparison with European standards, the emission limit of the F_3 class is more or less equivalent to the European E_1 class, according to German regulations, while the F_2 and F_1 emission limits are much lower than the E_1 class. Further, the emission of F_1 class (<0.3 mg/L) wood-based board is close to that of natural solid wood (Marutzky and Dix 2004). The PF-impregnated OSB made from 6.5% and 3% PF resin concentrations both had low formaldehyde emissions.

Dimensional Stability

The results of thickness swelling (TS) tests are shown in Fig. 4. The TS of the OSBs met the requirements of type 24-10 particleboard in CNS 2215 (TS < 25%), and OSB and strand board in CSA 0437 (TS < 15%). In addition, Fig. 4 also indicates that the TS values decreased with increasing PF resin content. The linear expansion (LE) of PF-impregnated OSB evaluated from 35% to 95% relative humidity is shown in Fig. 5. It was found that LE in the mechanical direction ranged from 0.016 to 0.062% for the PF-C10 group, 0.017 to 0.078% for the PF-C6 group, and 0.019 to 0.097% for the PF-C3 group. In the perpendicular direction, LE ranged from 0.114 to 1.008% for the PF-C10 group, 0.103 to 0.987% for the PF-C6 group, and 0.097 to 0.967% for the PF-C3 group, respectively. The results indicated that LE in the parallel direction was smaller than in the perpendicular direction, which confirmed the previous findings reported by Wu (1999). In addition, Wu and Suchsland (1996) tested the LE of five different commercial OSBs at five relative humidities: 35, 55, 75, 85, and 95%. The authors showed that the LE in the parallel direction ranged from 0.07 to 0.17 for southern pine OSBs, and from 0.04 to 0.19 for aspen OSBs. In the perpendicular direction, the LE of the southern pine OSBs ranged from 0.11 to 0.35 and from 0.09 to 0.36 for the aspen OSBs. The LE was larger in the perpendicular direction than in the parallel direction, disregarding the alignment levels of OSBs.

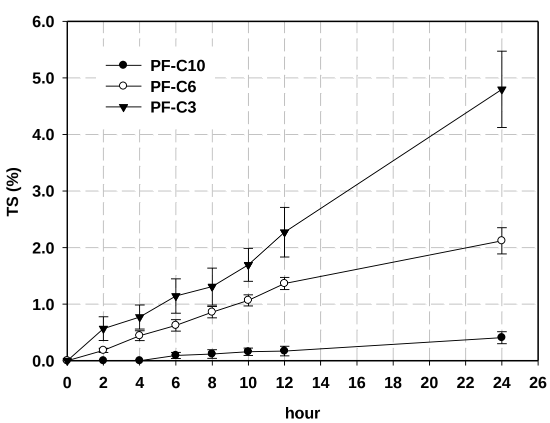

Fig. 4. Thickness swelling of the PF-impregnated OSB

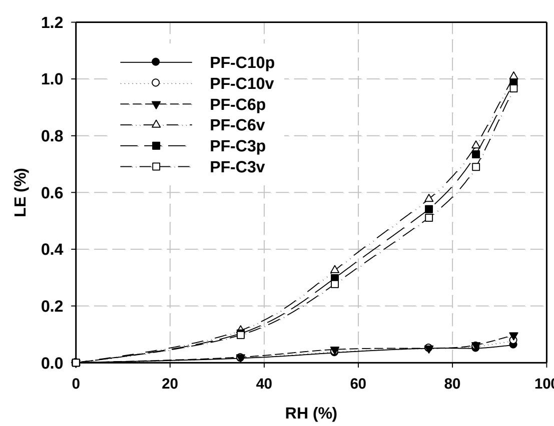

Fig. 5. Linear expansion of the PF-impregnated OSB

Accelerated Deterioration Testing

The residual bending strength (MOR_p and MOE_p) of the OSBs after accelerated deterioration was between 49.6 MPa and 74.5 MPa for MOR_p and between 8.8 GPa and 13.2 GPa for MOE_p, respectively. The retention rate of MOR_p and MOE_p was 78.3% to 88.2% and 68.0% to 83.1% (Fig. 6). The retention rate of strength decreased from 100% to 50% of the original values (results measured from air-dried samples), and it was considered a criterion to evaluate the materials' resistance to accelerated degradation

(Wang 1990). Wang *et al.* (1997) reported that non-PF impregnated OSBs (resin content 6.5%) had a 47 to 63% MOR_p retention rate after accelerated deterioration; the results were significantly lower than the measurements collected from PF-impregnated OSBs in this study.

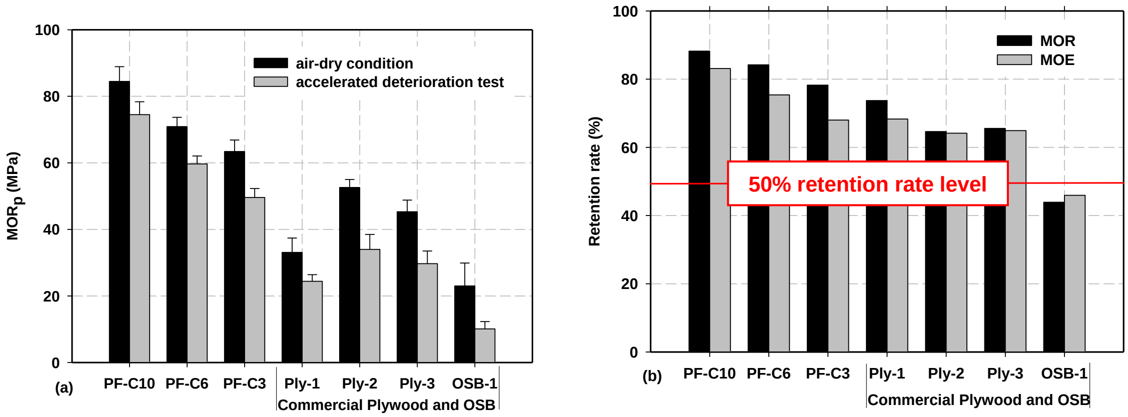

Fig. 6. Comparison of the bending properties and strength retention rate of PF-impregnated OSB specimens and commercial structural boards: (a) bending strength, (b) strength retention rate
Note: Commercial structural boards included three plywood (Ply-1, Ply-2 and Ply-3) and one OSB (OSB-1).

The manufactured PF-impregnated OSBs provided superior and/or comparable mechanical characteristics to the commercial structural plywoods and OSBs, even though the MOR dropped significantly after accelerated deterioration. The MOR of the tested OSBs ranged from 23.0 MPa to 52.6 MPa, and the residual bending strength of the commercial structural plywood and OSB was from 10.1 MPa to 34.0 MPa. In addition, the retention rates of the commercial structural plywoods and OSBs were 43.9% to 73.7% for MOR and 45.9% to 68.3% for MOE, which are all significantly lower than the PF-impregnated OSBs (Fig. 6).

CONCLUSIONS

1. A single layered PF-impregnated OSB made from China fir strands was developed and evaluated. Based on the results of these experiments, it can be concluded that the accumulated strands' aligned angle percentages in the top layer of the OSBs were between 76.2% and 88.8% from 0° to 30°.
2. The ultrasonic wave velocity at 0° strand angle (V_0) was the highest and decreased rapidly with increasing aligned angle (θ). The relationship between θ and V could be represented by Hankinson's formula, and the optimal n exponential values for the formula were 1.59 to 1.88 for PF-impregnated OSBs.
3. The velocity anisotropic properties of PF-impregnated OSBs were 2.34 to 2.84 for whole OSBs and 2.23 to 2.45 for the bending test specimens. Compared to the bending anisotropic properties, the ratios MOR_p/MOR_v and MOE_p/MOE_v were higher, with values of 3.79 to 4.15 and 4.18 to 5.42, respectively.

4. The bending properties of PF-impregnated OSB were 64.7 to 84.8 MPa for MOR_p, and 13.0 to 15.9 GPa for MOE_p. In addition, the retention rates of MOR_p and MOE_p were 78.3 to 88.2% and 68.0 to 83.1% after accelerated deterioration testing.

REFERENCES CITED

Beck, K., Cloutier, A., Salenikovich, A., and Beauregard, R. (2010). "Comparison of mechanical properties of oriented strand board made from trembling aspen and paper birch," *Eur. J. Wood Prod*. 68, 27-33.

Canada Standards Association 0437.0 (1993). "OSB and waferboard," Resdale, Ontario.

Chinese National Standard 2215 (2006). "Particleboard," Bureau of Standards, Metrology and Inspection, Ministry of Economic Affairs.

Canadido, L. S., Saito, F., and Suzuki, S. (1988). "Effect of particle shape on the orthootropic preperties of oriented strand board," *Mokuzai Gakkishi* 34(1), 21-27.

Cloutier, A., Ananias, R. A., Ballerini, A., and Pecho, R. (2007). "Effect of radiata pine juvenile wood on the physical and mechanical properties of oriented strandboard," *Holz als Roh Werkst*. 65, 157-162.

Geimer, R. L., McDonald, K. A., Bechtel, F. K., and Wood, J. E. (1993). "Measurement of flake alignment in flakeboard with grain angle indicator," *Res. Pap. FPL-518*, USDA Forest Serv., Forest Prod. Lab., Madison, WI, USA.

Gabrielli, C. P., and Kamke, F. (2010) . "Phenol-formaldehyde impregnation of densified wood for improved dimensional stability," *Wood Sci. Technol*. 44, 95-104.

Lang, E. M., and Loferki, J. R. (1995). "In-plane hygroscopic expansion of plywood and oriented strandboard," *Forest Prod. J*. 45(4), 67-71.

Lee, J. N., and Wu, Q. (2002). "In-plane dimensional stability of three-layer oriented strandboard," *Wood and Fiber Sci*. 34(1), 77-95.

McNatt, J. D., Bach, L., and Wellwood, R. W. (1992). "Contribution of flake alignment to performance of strandboard," *Forest Prod. J*. 42(3), 45-50.

Marutzky, R., and Dix, B. (2004). "Adhesive related VOC- and formaldehyde-emissions from wood products: Tests, regulations, standards, future developments," *Proceedings of the COST E34 Conference: Innovations in Wood Adhesives*, University of Applied Sciences Bern, HSB, Biel, Switzerland, 91-106.

Nishimura, T., Ansell, M. P., and Ando, N. (2001). "The relationship between the arrangement of wood strands at the surface of OSB and the modulus of rupture determined by image analysis," *Wood Sci. Technol*. 35, 555-562.

Okino, E. Y. A., Teixira, D. E., Souza, M. R., Santana, M. A. E., and Sousa, M. E. (2004). "Properties of oriented strandboard made of wood species from Brazilian planted forests: Part 1: 80 mm-long strands of *Pinus taeda* L.," *Holz als Roh Werkst*. 62, 221-224.

Suzuki, S., and Takeda, K. (2000). "Production and properties of Japanese oriented strand board. I: Effect of strand length and orientation on strength properties of sugi oriented strand board," *J. Wood Sci*. 46, 289-295.

Stürzenbecher, R., Hofstetter, K., Bogensperger, T., Schickhofer, G., and Eberhardseiner, J. (2010). "Development of high-performance strand board: Engineering design and experiment investigations," *Wood Sci. Technol*. 44, 13-29.

Shams, M. I., and Yano, H. (2011). "Compressive deformation of phenol formaldehyde (PF) resin-impregnated wood related to the molecular weight of resin," *Wood Sci. Technol*. 45, 73-81.

UN (2010). "Forest products annual market review, 2009-2010," United Nations Food and Agriculture Organization.

UN (2011). "Forest products annual market review, 2010-2011," United Nations Food and Agriculture Organization.

Wang, S. Y. (1990). "Reduction of mechanical properties of seventeen Taiwan native-wood species subjected to a seven-year exposure in an outdoor environment," *Mokuzai Gakkishi* 36(1), 69-77.

Wang, S. Y., Chen B. J., and Tang, R. C. (1995). "Assessment production of oriented strand board from plantation grown small diameter China fir and its properties," *Q. Jour. Chin. For*. 28(2), 87-108.

Wang, S. Y., Lo, S. F., and Tang, R. C. (1997). "Temperature and moisture induced degradation in some physical and mechanical properties of fire-retardant treated of oriented strand boards," *Forest Products Industries* 16(1), 78-90.

Wang, S. Y., and Chen, B. J. (2001). "The flake's alignment efficiency and orthotropic properties of oriented strand board," *Holzforschung* 55(1), 97-103.

Wu, Q., and Suchsland, O. (1996). "Linear expansion and its relationship to moisture content change for commercial oriented strand boards," *Forest Prod. J*. 46(11/12), 79-83.

Wu, Q. (1999). "In-plane dimension stability of oriented strand panel: Effect of processing variable," *Wood and Fiber Sci*. 31(1), 28-40.

Xu, W. (2000). "Influence of percent alignment and shelling ratio on modulus of elasticity of oriented strandboard: A model investigation," *Forest Prod. J*. 50(10), 43-47.

Yang, T. H., Lin, C. J., Wang, S. Y., and Tsai, M. J. (2007). "Characteristics of particleboard made from recycled wood-waste chips impregnated with phenol formaldehyde resin," *Building and Environment*. 42, 189-195.

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