Characteristics of particleboard made from recycled wood-waste chips impregnated with phenol formaldehyde resin

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Received 1 July 2005; received in revised form 23 August 2005; accepted 26 August 2005

Abstract

The main purpose of this study was to manufacture water-resistant particleboard for use in kitchens and bathrooms, and as flooring-based material and in outdoor environments. The chips were from recycled wood wastes of different wood species. The chips were divided into coarse chips with dimensions of 5–8 mesh and fine chips of 8–20 mesh, then, these chips were immersed in water-soluble phenol formaldehyde (PF) resin solution at concentrations of 4.5%, 6.5% and 10%. After 5 min, they were removed from the PF solution and dried in an oven until in a half-hardened condition. Three-layer mats with target densities of 0.70 and 0.80 g/cm³ were formed by using fine chips for the face layer (25%) and back layer (25%) and coarse chips for the core layer (50%). A conventional hot press was used for fabrication of the particleboard, and the temperature, pressure and pressing time were 453 K, 2.9 MPa, and 5 min, respectively. The nominal dimensions of particleboard were 500 × 500 × 12 mm (thick).

Result showed that the PF resin absorption content of chips (RC) increased linearly with an increase in the concentration of PF solution. Their relationship could be represented by the linear regression formula. The bending strength, internal bonding strength, and thickness swelling (%) of the PF-impregnated particleboards exhibited excellent performances compared to those made in the past, and the retention rate (%) of the modulus of rupture (MOR) and modulus of elasticity (MOE) of PF-impregnated particleboard after treatment in hot water (343 K) for 2 h were maintained at 48.7–84.5% and 49.2–82.7%, respectively. Characteristics of the ultrasonic velocity in the mechanical direction were similar to those in the vertical direction. In addition, there were significant relationships between the ultrasonic velocity and the mechanical properties of the particleboard, and this meant that we could evaluate the properties of the particleboard using ultrasonic velocity.

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Keywords: Ultrasonic wave velocity; Bending strength; Internal bonding strength; Thickness swelling; Retention rate of bending strength

1. Introduction

Wooden materials in the building industry have always been popular in many countries as a result of their excellent properties. Due to its use for furniture, architecture, and indoor decoration, wood has always been the largest proportion of material used. According to information provided by the Industrial Pollution Control Crops (IPCC) [1], the wood consumption rate in 1989 was $3.5 \times 10^9 \text{ m}^3$.

By 2010, it is forecast to reach $5.1 \times 10^9 \text{ m}^3$. We can see from this that with the advance of human civilization, the consumption of wood has increased; in general, the use of this material creates a lot of wastes. In recent years, wood wastes have caused environmental concerns to move to the forefront in Taiwan.

Today, the topics of recycling systems and reuse techniques of wood wastes in Taiwan are widely discussed in public and are becoming increasingly important because $2\text{--}3 \times 10^6 \text{ m}^3$ of wood wastes are generated in Taiwan annually, and only 4.38–5.13% of these are recycled and reused. Furthermore, wood-based wastes such as flooring, ceiling, and decorations from construction and demolition

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sites comprise 10% of the total generated wastes by volume, only exceeded by concrete wastes. These wood-based wastes from construction and demolition sites are usually not included in any recycling lists. They are sent to either combustion facilities or landfills.

Recently, wooden wastes are being recycled into other wood products at an increasing rate. The topics of how to recycle wood residues into usable products have been studied for decades [2–4]. In these reuse products, particleboard has found typical applications as flooring, wall and ceiling panels, office dividers, bulletin boards, furniture, cabinets, counter tops, and desk tops [5], and it seems that the manufacture of particleboard from recycled wood-based wastes is the most common way to reuse them.

Moreover, a series of studies has been conducted to investigate the use of non-destructive evaluation (NDE) technologies to aid in wood-based product quality assessment [6–8]. These studies yielded similar results and established relationships between mechanical strength and dynamic properties.

The purpose of this study was to investigate the density, bending properties, internal bonding strength, and thickness swelling (TS) of particleboard made from different recycled wood species chips, which were impregnated with phenol formaldehyde (PF) resin. Furthermore, the properties after accelerated aging and the ultrasonic properties of the manufactured particleboard were also evaluated.

2. Experimental materials and methods

2.1. Materials

Chips from mixed hardwood species including oak (*Quercus* spp.) and lauan (*Shorea* spp.) were prepared from recycled new construction and demolition wastes which were gathered and then classified by Jen-Chun Enterprise in Feng-Yuan, Taiwan.

The adhesive used was a water-soluble PF resin (76–78% solid content and pH 8–9 produced by Tai-Lin Resin, Co., Taipei, Taiwan).

2.2. Production process of chips

Chips were divided into four grades using 5, 8, and 20 meshes, and were divided into coarse chips which passed through 5 mesh stop on 8 mesh and fine chips with through 8 mesh stop on 20 mesh. The chips were oven-dried to 2–4% moisture content (MC), at a temperature of 338 ± 2 K. Then, they were immersed in a water-soluble PF resin.

The PF resin absorption content can be expressed as

$$RC (\%) = \left(\frac{W_2 - W_1}{W_1} \right) \times 100, \quad (1)$$

where RC is the PF absorption content, W_1 is the oven-dried weight of the chips before impregnation, and W_2 is the oven-dried weight of chips after impregnation.

Next, the chips were dried in an oven until in a half-hardened condition, and then were placed into a frame of 50×50 cm. The particleboard was formed using fine chips for the face layer (25%) and back layer (25%) and coarse chips for the core layer (50%). A conventional hot press was used for fabrication of the particleboard and the temperature, pressure and pressing time were 453 K, 2.9 MPa and 5 min, respectively. The nominal dimensions of particleboard were $500 \times 500 \times 12$ mm (thick), with three layers. The thickness of particleboard was controlled by stop bars. Two kinds of target densities of particleboard (D1 group was 0.8 g/cm^3 , and D2 group was 0.7 g/cm^3) were fabricated in this study.

2.3. Testing method

The particleboards produced for this study, were tested under the American Society Testing and Materials (ASTM) method standard D-1037 [9], in conducting various tests.

2.3.1. Ultrasonic wave test

Prior to testing, PF-impregnated particleboards were conditioned at 293 K and 65% relative humidity, and the full panels of each particleboard were prepared for the ultrasonic wave tests. The test points of two corresponding sides of a particleboard were considered the investigated points and at intervals of 50 mm, an ultrasonic wave instrument (Pundit, 54 kHz, C.N.S. Electronic Ltd.) which sends an ultrasonic pulse through the specimen was used to measure the time required for the transmission of the pulse through the specimen. The ultrasonic velocity was then calculated from the length of the specimen divided by the propagation time.

After the ultrasonic investigation, the full piece of tested particleboard was cut into static bending specimens and internal bond (IB) strength specimens following ASTM D-1037 [9], and their positions relative to the full piece of particleboard were recorded. These static bending specimens were first used to conduct an ultrasonic wave test to obtain the ultrasonic velocity (Vl) through the face direction using a Pundit ultrasonic apparatus at a frequency of 54 kHz. However, transit times of the ultrasonic pulse for IB specimens were measured at a frequency of 500 kHz in the thick direction to the surface of each specimen by the Pundit ultrasonic apparatus. The velocity was then calculated by dividing the length. The waves traveled by the transit time. The ultrasonic velocity and dynamic modulus of elasticity (DMOE) were calculated by the following formulae:

$$Vl(Vt) \text{ (m/s)} = \frac{L}{t}, \quad (2)$$

$$DMOE \text{ (MPa)} = Vl^2 \times \rho, \quad (3)$$

where Vl is the ultrasonic velocity in the face direction of particleboard, Vt is the ultrasonic velocity in thick

direction of particleboard, L is the length, t is the transit time, DMOE is the dynamic modulus of elasticity, ρ is the density.

2.3.2. Density and moisture content

Fabricated particleboards, placed under room humidity for 1 week, were tested for their density and MC, which used the following formulae:

$$\text{Air-dried density (g/cm}^3\text{)} = \frac{W_a}{V_a}, \quad (4)$$

$$\text{Moisture content (\%)} = \frac{W_a - W_0}{W_0} \times 100, \quad (5)$$

where W_a is the air-dried weight, V_a is the air-dried volume, and W_0 is the oven-dried weight of the particleboard.

2.3.3. Static bending test

After the ultrasonic wave test for obtaining the ultrasonic velocity, the conditioned samples, 7.62×20.32 cm (3×8 in), two from each of two panels, were tested for the modulus of rupture (MOR) and modulus of elasticity (MOE) per ASTM standard D-1037-96 [9]. The MC, nominal thickness, and density were determined for these specimens.

The MOR and MOE of each specimen are represented by the following formulae:

$$\text{MOR (MPa)} = \frac{3P_b L}{2bh^2}, \quad (6)$$

$$\text{MOE (MPa)} = \frac{P_{bp} L^3}{4bh^3 Y_p}, \quad (7)$$

where MOR is static bending strength (MPa), MOE is static bending modulus of elasticity (MPa), P_b is maximum load (N), P_{bp} is the load at the proportional limit (N), Y_p is the deflection corresponding to P_{bp} (mm), b is the width of the specimen (mm), h is the thickness of the specimen (mm), and L is the span (mm).

2.3.4. Internal bond strength

The tensile strength perpendicular to the surface was determined using nine square conditioned specimens of 5.08×5.08 cm (2×2 in) from each panel according to ASTM standard D-1037-96 [9]. The rupture load (P_s) was determined and IB strength was calculated from the following formula:

$$\text{IB (MPa)} = \frac{P_s}{bl}, \quad (8)$$

where IB is the internal bond strength, P_s is the rupture load, and l is the length of the specimen. However, the ultrasonic velocity of IB specimens was detected as described above before the IB test.

2.3.5. Thickness swelling

Conditioned samples, 15.24×15.24 cm (6×6 in) for the evaluation of TS were prepared according to ASTM

standard D-1037-96 [9]. The thickness at the middle of the test specimen was measured with a micrometer. Then, the test specimens were placed parallel into the water for 30 mm and soaked for 2 and 24 h for measurement of the thickness. The TS rate was determined from the following formula:

$$\text{TS}_2 (\%) = \frac{t_2 - t_0}{t_0} \times 100, \quad (9)$$

$$\text{TS}_{24} (\%) = \frac{t_{24} - t_0}{t_0} \times 100, \quad (10)$$

where TS is the thickness swelling rate, t_0 is thickness at the middle of the test specimen before soaking in the water, and t_2 and t_{24} are the thicknesses in the middle of the test specimen after soaking into water for 2 and 24 h, respectively.

2.3.6. Accelerated degradation tests

Specimens were soaked in hot water (343 K) for 2 h and then soaked in cold water (at room temperature) for 1 h for cooling. The static bending tests were conducted on specimens while they were in a wet condition. The MOR and MOE retention rates were evaluated from the following formula:

$$\text{MOR retention rate (\%)} = \frac{\text{MOR}_2}{\text{MOR}_1} \times 100, \quad (11)$$

$$\text{MOE retention rate (\%)} = \frac{\text{MOE}_2}{\text{MOE}_1} \times 100, \quad (12)$$

where MOR_1 , MOE_1 , MOR_2 and MOE_2 represent the MOR and MOE values in an air-dried condition and after soaking in hot water (343 K) for 2 h, respectively.

3. Results and discussion

3.1. PF resin absorption content

In this study, chips of mixed wood species were immersed in a water-soluble PF resin solution with concentrations of 10% (P10 group), 6.5% (P6 group), and 4.5% (P4 group) for 5 min. It was found that the PF resin absorption content increased linearly with an increase in the treatment concentration (Fig. 1). The previous study also indicated that a high correlation ($r^2 = 0.934\text{--}0.969$) existed between the PF resin absorption content and treatment concentration for the oriented strand board (OSB) [10].

3.2. Ultrasonic velocity obtained from the full piece particleboard

Values of the ultrasonic velocity (V) obtained from the full-piece specimen at intervals of 5 cm in the mechanical direction or vertical direction are shown in Fig. 2. It was obvious that the ultrasonic velocity which propagated through the mechanical direction was similar to that in the

vertical direction. This means that the V value was not affected by the resin content of the chips. The particleboard manufactured in our study had no orthotropic properties,

Fig. 1. Relationship between resin content (RC) and treatment concentration (C).

Fig. 2. Ultrasonic velocity for PF resin-impregnated particleboard in mechanical and vertical directions. P10D1: D1 group whose particles are impregnated with 10% PF resin; P6D1: D1 group whose particles are impregnated with 6.5% PF resin; P4D1: D1 group whose particles are impregnated with 4.5% PF resin; P10D2: D2 group whose particles are impregnated with 10% PF resin; P6D2: D2 group whose particles are impregnated with 6.5% PF resin; P4D2: D2 group whose particles are impregnated with 4.5% PF resin.

which exist on the surfaces of OSB and plywood [10–12]. In a comparison to our former studies [10,18,19], the ratio of ultrasonic velocity of PF resin-impregnated OSB and particleboard was about 2:1.

In a study by Yang et al. [10], the value of the ultrasonic velocity of PF resin-impregnated OSB in the flake length direction was not affected by the resin content of the flakes. This may have been the reason that the value of ultrasonic velocity of the flakes was greater than that of the PF resin. However, values of the ultrasonic velocity of PF resin-impregnated particleboard of the D1 (density was 0.8 g/cm^3) and D2 groups (density was 0.7 g/cm^3) increased linearly with increase in the concentration of the PF solution (Table 1). The value of the ultrasonic velocity of specimens of the D1 group, which were denser, was more significantly affected by the concentration of the PF solution. This is because the dimension of the chips was small, irregular, and anisotropic. The effect of fiber direction on the ultrasonic velocity was not obvious at any PF resin contents.

However, the ultrasonic wave velocity which propagated through the thick direction of the particleboard (V_t) increased linearly with an increase in the PF resin absorption content of the chips (Table 1). A good correlation ($r^2 = 0.54$) was also found between PF resin absorption content and V_t for the OSB in a study [10].

3.3. Bending strength properties of particleboard

Values of MOR and MOE of the PF-impregnated particleboard are shown in Table 2. It was found that in the D1 group, density (ρ) was 0.80 g/cm^3 , the MOR range from 14.6 to 29.0 MPa, and the MOE range from 3136.0 to 5331.2 MPa; whereas in the D2 group, ρ was 0.70 g/cm^3 , the MOR range from 11.1 to 18.0 MPa, and the MOE range from 1734.6 to 3224.2 MPa. The results indicated that the values of MOR and MOE of PF resin-impregnated particleboards manufactured in our study were higher than

Table 1

Correlation among resin content (RC), ultrasonic wave velocity (V), modulus of rupture (MOR), modulus of elasticity (MOE), dynamic modulus of elasticity (DMOE) and internal bonding strength (IB) analyzed by linear regression ($Y = AX + B$) formulae for PF resin-impregnated particleboard

Sample	Y	X	A	B	r^2	F values
D1 group	Vl	RC	17.76	1914	0.80	211**
	Vt	RC	11.11	808	0.78	55**
	MOR	Vl	0.03	−61.3	0.93	475**
	MOE	Vl	5.3	−9291.5	0.85	189**
	IB	Vt	0.005	−3.48	0.87	225**
D2 group	Vl	RC	9.94	1919	0.65	95**
	Vt	RC	11.89	717	0.82	73**
	MOR	Vl	0.02	−26.6	0.71	68**
	MOE	Vl	4.42	−7306.8	0.89	222**
	IB	Vt	0.004	−2.71	0.73	91**

Vl: ultrasonic velocity propagated through the face direction of the particleboard.

Vt: ultrasonic velocity propagated through the thick direction of the particleboard.

** : Significant difference at the 1% level ($P < 0.01$).

Table 2
Resin content, air-dried density, bending strength, ultrasonic velocity of different PF resin-impregnated particleboard

Symbols	Resin content (%)	Air-dried density (g/cm ³)	MOR (MPa)	MOE (MPa)	Ultrasonic velocity (m/s)	MOR after accelerated aging (MPa)	MOE after accelerated aging (MPa)	MOR retention rate (%)	MOE retention rate (%)
P10	31.9	0.82 ± 0.03	29.0 ± 1.4	5331.2 ± 468.5	2735 ± 70	24.5 ± 1.2	4410.0 ± 156.8	84.5	82.7
D1									
P6	16.9	0.81 ± 0.03	19.6 ± 0.98	3773.0 ± 215.6	2482 ± 42	15.2 ± 0.78	2165.8 ± 62.7	77.6	57.4
D1									
P4	11.1	0.80 ± 0.02	14.6 ± 1.2	3136.0 ± 205.8	2298 ± 67	10.8 ± 1.5	1666.0 ± 88.2	74.0	53.1
D1									
P10	31.9	0.71 ± 0.03	18.0 ± 0.1	3224.2 ± 220.5	2367 ± 66	12.3 ± 0.6	2058.0 ± 107.8	68.3	63.8
D2									
P6	16.9	0.70 ± 0.04	13.8 ± 0.3	2920.4 ± 264.6	2331 ± 20	8.8 ± 0.6	1568.0 ± 137.2	63.8	53.7
D2									
P4	11.1	0.70 ± 0.03	11.1 ± 1.2	1734.6 ± 127.4	2065 ± 59	5.4 ± 0.6	852.6 ± 49.0	48.7	49.2
D2									

those of urea adhesives sprayed particleboards [13], whose MOR range from 9.9 to 11.2 MPa; similar results were also obtained for particleboard made out of Korea pruning logs [14]. This means that the PF resin-impregnated chips using the manufacturing process of particleboard under a hot press (453 K) showed plasticity and flow ability. After the hot press process, the distribution of PF resin on the surface and back of the particleboard could be more even and dense, and values of the MOR and MOE thus could be even higher [10]. Some studies on the density profile also indicated that the bending strength depends on the pick density, mean density (MD), and other density parameters. Wong et al. [15] indicated that peak density (PD) has relative higher effect on both MOR and MOE at high MD level, whose r values were 0.875 and 0.954, respectively. Wong et al. [16] indicated that PD, MD, and peak distance (Pdi) were the density factors affecting MOE ($r^2 = 0.998$), and increment in PD leads to a proportional increase in MOE.

It was found that the values of MOR and MOE increased linearly with an increase of the values of the ultrasonic velocity (VI), as can be seen from Table 1. This means that the values of ultrasonic velocity (VI) can be considered as an evaluation index of the static bending strength of the particleboard. When comparing DMOE and MOE, it is evident that the DMOE was higher than the MOE. It was also found that the relation between the DMOE and MOE was significant (Fig. 3).

3.4. Internal bond strength

A higher value of the IB strength of different PF-impregnated particleboard groups was observed in our study because of the even distribution of the PF resin on the chips. The IB of groups D1 and D2 reached 0.67–1.86 and 0.59–1.72 MPa, respectively. The IB values of PF-impregnated particleboard in our study were superior to those (0.12–0.42 MPa) of particleboards manufactured by PF resin sprayed [13] compared to the particleboard made by mixed species [17] which included pines, aspens, oaks and other hardwoods. The IB value in our study was also higher than theirs (IB = 0.56 MPa).

Moreover, values of IB increased linearly with an increase in the values of the ultrasonic wave velocity (Vt) which propagated through the thick direction of the particleboard (Table 3). This result is in agreement with a previous report [7] in which a high correlation existed between the ultrasonic velocity measured in the length or thickness direction and the IB for the particleboard, the r values were 0.81 and 0.96, respectively. The previous studies also indicated that a high correlation existed between the values of the ultrasonic wave velocity (Vt) propagated through the thick direction and IB of PF resin-impregnated OSB [10,18,19]. This suggests that the ultrasonic velocity could be utilized satisfactorily to assess the IB of the boards.

3.5. Thickness swelling

Results showed that the values of TS of particleboards manufactured in our study for groups D1 and D2 were lower than 12% (Fig. 4). Fig. 4 also showed that the TS decreased linearly with an increase in the treatment concentration of the PF solution, namely the PF resin content. Halligan [20] indicated two opposing mechanisms for TS, densification and resin efficiency, and a higher compaction ratio improved the efficiency of adhesive bonds, which would reduce the TS. In our study, we found the TS of group D2 ($\rho = 0.7 \text{ g/cm}^3$) was lower than that of the group D1 ($\rho = 0.8 \text{ g/cm}^3$). This was because when the same density wood materials are dominant in a process, the compaction ratio increases, which increases the TS. A highly negative correlation between the values of the ultrasonic wave velocity (Vt) which propagated through the thick direction and TS for the PF resin-impregnated particleboard was also observed in our study (Fig. 5).

3.6. Accelerated degradation tests

Values of the bending strength (MOR and MOE) of PF resin-impregnated particleboard after treatment in hot water (343 K) for 2 h are shown in Table 2. A similar correlation existed between the MOR and MOE retention rates (%) of OSB and the PF resin content, after 2 h at 343 K. [10] However, the MOR_{||} and MOE_{||} (specimens

with grain direction of face parallel to length axis) retention rates (%) of the PF resin-impregnated OSB were maintained at 75.9–95.6% of the MOR_{||} for Japanese cedar OSB, at 60.2–88.3% of the MOR_{||} for *Shorea* OSB, at 54.5–84.6% of the MOE_{||} for Japanese cedar OSB, at 26.8–82.1% of the MOE_{||} for Lauan OSB. The bending strength retention rate (%) decreased with a decrease in the resin content. However, the MOR_{||} retention rate (%) of PF resin-impregnated OSB remained above 50% [10].

Sekino [21] indicated that the MOR retention rate (%) of MDF and particleboard in a wet condition decreased linearly with an increase in the TS. In service conditions, values of TS were 8% for MDF and 14% for particleboard, assuming the retention rate (%) of MOR was 60%.

Fig. 4. Relationship between thickness swelling (TS) and resin content (RC).

Fig. 3. Relationship between modulus of elasticity (MOE) and dynamic modulus of elasticity (DMOE).

Fig. 5. Relationship between thickness swelling (TS) and ultrasonic velocity through the thick direction (Vt).

Table 3

Correlation among modulus of rupture retention MOR(%), modulus of elasticity retention MOE(%), and thickness swelling (TS), analyzed by the linear regression ($Y = AX + B$) formulae for PF resin-impregnated particleboard

Sample	Y	X	A	B	r^2	F values
D1 group	MOR (%)	TS	-1.65	90.37	0.63	32**
	MOE (%)	TS	-4.48	96.42	0.79	70**
D2 group	MOR (%)	TS	-2.04	72.45	0.82	74**
	MOE (%)	TS	-1.61	65.49	0.66	30**

D1 group: The particleboard had a density of 0.8 g/cm^3 .

D2 group: The particleboard had a density of 0.7 g/cm^3 .

** : Significant difference at the 1% level ($P < 0.01$).

The relationship between TS and the MOR (MOE) retention rate is shown in Table 3. It was found that MOR (%) and MOE (%) decreased linearly with an increase in the TS. A negative regression analysis was performed to determine the correlation between MOR (%) and MOE (%) and TS (Table 3). As TS reached 10%, MOR and MOE retention rates in group D1 were, respectively, 74% and 52%, as for group D2, the MOR and MOE rates were 52% and 50%. However, its retention rate fell below 50%.

4. Conclusions

This study focused on investigating the properties of PF resin-impregnated particleboard produced using recycled wood-waste particles, and results showed that the values of MOR, IB, and TS of PF-impregnated particleboards were superior to those of conventionally manufactured particleboard. In addition, the positive relationships between the resin content of the chips and the MOR, MOE, and IB values could be represented by linear regression formulae, however, the TS of PF resin-impregnated particleboards decreased linearly with an increase in the PF resin content of the chips (RC). The retention rates (%) of MOR and MOE of PF resin-impregnated particleboard after treatment in hot water (343 K) for 2 h were maintained at a range from 48.7% to 84.5% and from 49.2% to 82.7%, respectively.

The ultrasonic wave velocity (Vl) which propagated through the face direction increased linearly with increases in the bending strength, in the internal bonding strength, and the retention rate of the bending strength. However, the ultrasonic wave velocity (Vt) which propagated through the thick direction of the particleboard increased linearly with a decrease in the thickness swelling. This suggests that ultrasonic velocity can satisfactorily be utilized to assess the properties of PF resin-impregnated particleboard.

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