Veneer-Reinforced Particleboard for Exterior Structural Composition Board

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Abstract

Two experiments were performed to determine the physical and mechanical characteristics of panels consisting of a veneer face and a particleboard core composed of mixed wood particles/powdered-recycled polyethylene (PE) bag waste (MWP) using urea-formaldehyde (UF) resin as a binder. The addition of 25 percent powdered-recycled PE bag waste to the MWP panels did not adversely affect nonaged bonding strength but did result in substantial improvement in internal bond (IB) retention after a 24-hour water soak and improved dimensional stability. Average MWP panel IB retention was more than 300 percent higher than the IB retention of wood particle (WP) panels and MWP thickness swell and linear expansion were 70 and 44 percent lower, respectively, than the values for WP panels. For the veneer overlay composite, the mean modulus of rupture (MOR) parallel to the surface grain veneer ($MOR_{||}$) was lowest (3,668.2 pounds per square inch [psi]) for panels with two veneers cross-laminated on each face over a WP core. Conversely, $MOR_{||}$ was greatest (8,535.6 psi) for panels with single 1/8-inch veneers on each face over an MWP core. However, the large percentage of shear failure when stressed parallel to face veneer grain hindered an accurate determination of true MOR. As expected, all specimens tested in bending parallel to the surface grain of the veneers resulted in higher modulus of elasticity (MOE) than those tested perpendicular to the grain. For a single veneer overlay on each face, it is interesting to note that thinner veneers (i.e., 1/8 in.) resulted in higher MOE than thicker veneers (i.e., 3/16 in.).

Particleboard is used widely in the manufacture of furniture, cabinets, and underlayment. The use of industrial grade particleboard as a core stock for wood veneer overlays (i.e., composite panels) is one of its prime applications. While the smoothness, surface integrity, uniform thickness, uniform mechanical properties, ease of layup, and ability to stay flat of particleboard make it an ideal core material, the decorative quality, originality, and the look and feel of real wood of the veneer provide the performance characteristics of veneered particleboard construction. Structurally, a veneered particleboard beam bends with the face veneers carrying direct compression and tension loads and the particleboard core carrying shear loads. It was shown that 1/36-inch walnut veneer overlaid particleboard composite increased the modulus of elasticity value in bending to more than 50 percent (Chow 1972), suggesting the potential for particleboard panels to develop structural applications. However, problems associated with hygroscopicity and dimensional stability limit their application. Thus, developing new particleboard-based composites with structural exterior grade performance will not only enhance their competitive capability but also create new markets. As a result, many exterior structural composite products were under development by Forest Industries, Potlatch Corporation, Elmendorf Research, and others in the early 1970s (Countryman 1975). A new composite product with strand board core and veneer faces combination, generally known as composite plywood, has been developed by Potlatch

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Forest Prod. J. 62(2):139–145.

(McKean et al. 1975). With a modulus of rupture (MOR) of approximately 8,000 pounds per square inch (psi) and modulus of elasticity (MOE) of over 1,000,000 psi, the structural properties of the composite plywood are similar to conventional plywood in that the two types can be used interchangeably. Similar composite panels with various core and face materials and construction methods were studied by many other researchers. For instance, Biblis and Mangalousis (1983) and Biblis (1985) evaluated the physical and mechanical properties of composite plywood with southern pine (*Pinus tadea*) veneer faces and cores of various wood species, Chow and Janowiak (1983) and Chow et al. (1986) determined the effects of accelerated aging on panel strength retention of hardwood composite panels, Hse (1976) studied composite panels with southern pine veneer and cores of southern hardwood flakes, and Koeningshof et al. (1977) evaluated the possibility of producing house framing and structural panels with particleboard cores and veneer facings. These studies have shown that application of exterior grade adhesives significantly improved panel durability and that the addition of a veneer to various wood-based cores resulted in greater mechanical properties than those achieved from similar panels without veneer overlay.

Discarded plastic bag waste has long been considered an environmental problem: plastic bags litter the landscape, clog waterways, and endanger wildlife. The problem is further escalated by the increasing rate of the bag use, the nonbiodegradable property of the bags and corresponding slow degradation period, and the low rate of recycling. Thus, the need is urgent and the interest has risen for the development of plastic bag waste recycling. One unique property of the bag is its hydrophobic nature, which is only minimally affected by atmospheric humidity. Thus, the combination of wood particles and the powdered plastic bag waste in the fabrication of particleboard could result in the improvement of water resistance properties of the products, if low-cost adhesives or coupling agents can provide a satisfactory glue bond between the hygroscopic/hydrophobic interfaces. In the present study, we manufactured particleboards containing powdered polyethylene (PE) bag waste by means of a method currently used in the particleboard industry, and we used the most cost-effective urea-formaldehyde (UF) resin. The primary objective of this study was to investigate the possibility of making particleboards with a combination of powdered PE bag waste and wood particles using UF resin as binder. The final objective was to apply the particleboard as a corestock to develop southern pine veneer overlay composite panels for structural applications. Some potential advantageous applications for this panel type include mobile homes and industrial work floors.

Materials and Methods

Wood particles and PE powder

Wood particles, classified in the mill as core furnish, were obtained from the dry end of a local particleboard plant. The particles were stored in plastic bags, placed in a drum, and used without further preparation. Average moisture content of the wood particles was 4 percent based on ovendry weight.

Low-density PE plastic bags were shredded, chilled in a freezer, and then reduced with a disc definer into powder.

Table 1.—Particle size distribution of wood particles and polyethylene powder by the sieve analysis.

Particle size		Wood particles (%)	Polyethylene powder (%)
	+10 mesh	14.3	12.9
−10 mesh	+20 mesh	42.9	41.9
−20 mesh	+40 mesh	25.0	29.0
40 mesh	+70 mesh	10.7	9.7
	−70 mesh	7.1	6.5

The sieve analysis of wood particles and PE powder are shown in Table 1. The two types furnished for the manufacture of particleboards are shown in Figure 1.

The study was conducted in a sequence of two experiments: (1) fabrication of particleboard and (2) manufacture of veneer overlay composite panel. All panels were prepared in the laboratory with three replicates. The data were analyzed in SAS (2008) by using analysis of variance (ANOVA). Also, means were separated by Duncan's multiple range tests at the 0.05 level of probability.

First experiment: Manufacture of particleboard

The first experiment evaluated the bonding strength, mechanical strength, and dimensional stability of the particleboard. The construction variables consisted of (1) two types of particleboards (based on the particle material mix)—a panel with 100 percent wood particles (WP) and a panel with 75/25 (wt/wt) mixture of wood particles/PE plastic bag powder (MWP), and (2) two UF resins—a UF resin (UF-I) prepared in the laboratory, which was formulated with 51 percent resin solids reacting at pH 5.1 with a molar ratio of formaldehyde to urea of 1.2, and a commercial UF resin (UF-II) with a 64.8 percent resin solid, which was used as a control. The general conditions used for manufacture of these panels were as follows:

Panel density: 50 pounds per cubic foot (pcf; 0.8 g/mL) based on ovendry weight and volume at 4 percent moisture content.

Resin content: 6 percent based on the ovendry weight of materials.

Panel size and panel thickness: 36 by 36 inches (91.4 by 91.4 cm) and 3/4 inch (1.9 cm).

Hot press temperature and time: 340°F (171°C) and 9 minutes total.

To fabricate the panels, PE powder and wood particles were weighed according to the designated weight percentage to yield a panel density of 50 pcf (0.8 g/mL) and placed in a rotating drum–type blender. Resins (6% based on the ovendry weight of materials) were sprayed on the tumbling wood particle and plastic powder through an air-atomizing nozzle to get a fine dispersion of resin over the materials. The particles, after blending, were carefully felted on a caul plate in a 36 by 36-inch (91.4 by 91.4-cm) forming box. The formed mat was transferred immediately to a 40 by 40-inch (101.6 by 101.6-cm) single-opening hot press at 340°F (171°C). Sufficient pressure (about 400 psi; 2.75 Mpa) was applied so that the plates closed to 3/4-inch stops in approximately 45 seconds. Closed press time was 8 minutes 15 seconds. After hot pressing, all boards were conditioned in a chamber at 50 percent relative humidity and 80°F

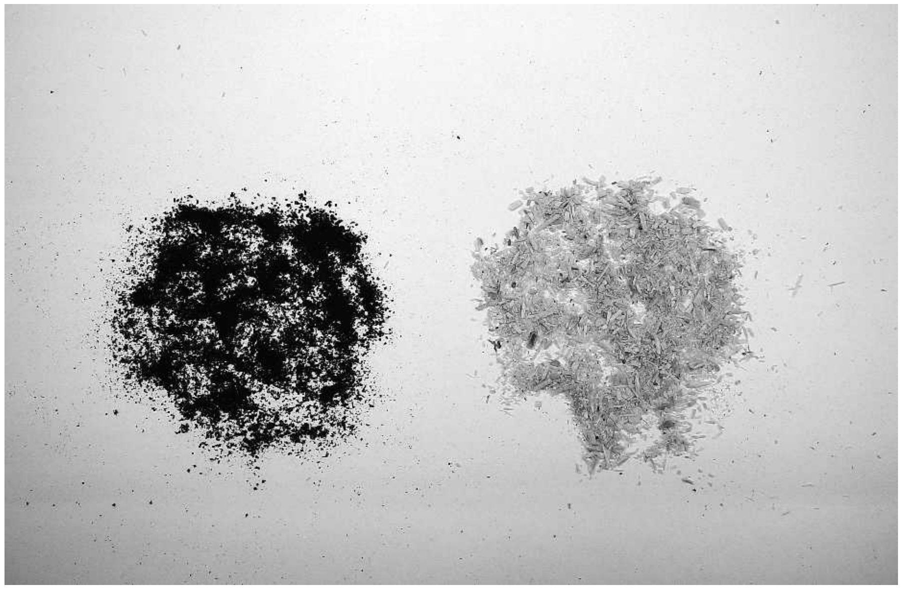

Figure 1.—Two types of furnishes for the particleboard. (Left) Wood particles. (Right) Powdered polyethylene bag waste.

(26.7°C) before testing. After conditioning, each board was cut to yield 30 internal bond (IB) specimens (2 by 2 in.; 5.08 by 5.08 cm), 8 dimensional stability specimens (4 by 6 in.; 10.16 by 15.24 cm) for linear expansion (LE) and thickness swell (TS), and 6 static bending specimens (2 by 30 in.; 5.08 by 76.2 cm). The dimensional stability tests consisted of soaking the samples in tap water for 24 hours (four specimens per panel) and 5-hour boiling (four specimens per panel). Thickness and lengths were measured before and after soaking or boiling. The tension perpendicular to the grain (IB) and MOR and MOE in bending tests were performed according to ASTM D1037-06a (ASTM International 2006). For the MWP panels, the IB, MOR, and MOE were also evaluated using 24-hour soaking and 5-hour boiling in addition to the untreated dry specimens for the determination of the strength retained.

Second experiment: Manufacture of veneer overlay composite

The second experiment determined the mechanical properties of exterior structural composite panels with southern pine veneer faces and cores composed of 3/4-inch (1.9-cm)-thick particleboard panels. The composite core panels (40 by 40 in.; 101.6 by 101.6 cm) were made with two particleboard types (i.e., MWP and WP) as described in the first experiment with UF-I resin. For each core panel, there were three types of veneer overlay arrangement: (1) a single 1/8-inch (0.317-cm)-thick southern pine veneer on each face, (2) a single 3/16-inch (0.476-cm)-thick southern pine veneer on each face, and (3) two 1/8-inch (0.318-cm)-thick cross-laminated veneers on each face.

Clear southern pine veneers were obtained from the dry end of a local plywood mill. The veneers with an average moisture content of 3 percent were transported to the laboratory, cut to 40 by 40-inch (101.6 by 101.6-cm) dimensions, and stored in sealed plastic bags until use. UF resin was sprayed on veneers to achieve 5 pounds (453 g) of resin solids per 1,000 ft^2 (92.9 m^2) of single glueline. After resin spraying, the veneers were carefully placed on both sides of the cores and transferred to a 40 by 40-inch (101.6 by 101.6-cm) single-opening hot press at 340°F (171°C). Hot press pressure was 165 psi (1.13 Mpa) and press time was 10 minutes.

After conditioning in a room maintained at 50 percent relative humidity at room temperature for 3 weeks, each board was cut to yield 12 bending test specimens (2 by 24 in.; 5.08 by 61 cm) with half of the specimens with the lengthwise parallel to the face veneer grain and other half with lengthwise perpendicular to the face veneer grain. Mechanical tests were performed in accordance with ASTM D1037-06a (ASTM International 2006). The MOR and MOE were tested parallel ($MOR_{||}$, $MOE_{||}$) and perpendicular ($MOR_{\perp}$, $MOE_{\perp}$) to the face veneer grain and calculated with the assumption that the cross section of the composite panel was homogenous.

Results and Discussion

First experiment

Internal bond.—Table 2 summarizes the mean IB, IB after 24-hour water soak, and IB after 5-hour water boil of the panels. The Duncan's multiple range test (Table 3) indicated that the effects of the particleboard types on IB of the panels without postfabrication treatment (i.e., original IB) were not significant. Moreover, the different UF resins also had no significant effect on IB. Therefore, the addition of 25 percent PE plastic powder to the core composite panels seemed to have no adverse effect on bonding. The most interesting result on the IB, however, was the significant effect of 24-hour water soaking and 5-hour water boiling on the performance of the panels. After 24-hour water soaking, the MWP panels had significantly higher IB than the WP panels (Fig. 2). It is generally recognized that the performance quality of the hybrid composites combined the characteristics of their component materials. The hydrophobic characteristic of PE plastic powder in the mix provided good water resistance to retard the hydrolytic weakening effect during the 24-hour water soaking on the glue bond and resulted in retaining higher IB than did the WP panels. Furthermore, it is noted that the UF-I resin performed better after 24-hour water soaking than did

Table 2. —Effects of particleboard type and resin adhesive on internal bond (IB), thickness swell (TS), linear expansion (LE), and water adsorption (WA).[a]

	IB							
	Nontreated (psi)	24-h soak (psi)	Retention (%)	5-h boil (psi)	Retention (%)	TS (%)	LE (%)	WA (%)
MWP								
UF-I	92.1 (3.81)	52.8 (6.5)	57.3	5.0 (0.38)	5.4	15.7 (1.50)	1.56 (0.17)	45.3 (7.6)
UF-II	94.6 (12.6)	36.0 (3.16)	38.1	5.1 (1.78)	5.3	15.9 (1.78)	1.60 (0.29)	46.3 (10.1)
WP								
UF-I	94.7 (5.3)	17.7 (2.8)	18.7	2.4 (0.34)	2.5	47.1 (5.6)	2.34 (0.35)	87.8 (9.6)
UF-II	89.6 (8.4)	10.8 (1.2)	12.1	2.8 (0.24)	3.1	60.3 (7.8)	3.29 (0.51)	122.4 (15.3)

[a] Values are means (standard deviations). MWP = particleboard with mixed wood particles/recycled plastic; UF = urea-formaldehyde resin; WP = wood particleboard.

the UF-II resin. The UF-I resin was formulated under a weak acidic condition without a caustic catalyst, which was considered one of the favorable conditions against the hydrolytic degradation in the glueline. The swelling and penetration ability of caustic in wood is well known (Stamm 1964). Previous studies (Blomquist 1962) have shown that residue alkaline induced chemical damage to wood, which promoted swelling and shrinkage of the wood in the glueline boundary area and adversely affected the glue bond. However, after 5-hour boiling, which was a severe degradation test, no significant difference in IB was found between the UF resins, indicating the degrading effects of the 5-hour boil were so severe that the UF resins were not good enough to withstand the effect. The 5-hour boil was intended in this study as a substitute for the ASTM six-cycle test. The results indicated that the 5-hour boil was not a sufficient test for proper evaluation of glue bonds of UF resins. Nevertheless, the IB of MWP panels was shown to be significantly higher than the IB of WP panels, indicating again the functional advantage of combining the PE powder in the construction of the panels.

The IB retention after the 24-hour soak ranged from 12.1 to 57.3 percent. The high retention value (i.e., 57.3%) for MWP panels with UF-I resin is the most significant result in the study. Although the retention value was substantially lower than those reported for hardwood veneered particleboard composites fabricated with phenolic resin (Chow et al. 1986), the significant improvements brought about by MWP construction compared with improvements brought about by WP panel construction suggest that the combination of powdered PE bag waste with wood particles creates the opportunity for further development of the functional composite products.

Table 3.—Duncan's multiple range tests for internal bond (IB), modulus of rupture (MOR), modulus of elasticity (MOE), thickness swell (TS), linear expansion (LE), and water adsorption (WA).[a]

Variable	IB (psi)	MOR (psi)	MOE (psi)	TS (%)	LE (%)	WA (%)
Resin						
UF-I	93.4 A[b]	1,882 A	348,028 A	38.1 A	1.95 A	67.5 B
UF-II	92.1 A	1,619 B	330,643 A	31.4 B	2.44 B	84.3 A
Particleboard type						
WP	93.4 A	1,783 A	360,863 A	53.7 A	2.81 A	106.1 A
MWP	92.1 A	1,717 A	317,808 B	15.8 B	1.58 B	45.8 B

[a] UF = urea-formaldehyde resin; WP = wood particleboard; MWP = particleboard with mixed wood particles/recycled plastic.

[b] Values with the same letter are not significantly different at alpha = 0.05.

Dimensional stability.—The mean TS, LE, and water adsorption (WA) of the panels are summarized in Table 2. Duncan's multiple range tests indicated that the TS of MWP panels were significantly less than those of WP panels. For the UF-I and UF-II resins, TS for MWP panels improved 67 and 73 percent, respectively, over the TS values for WP panels.

ANOVA indicated that the interactions of resin and particleboard type were significant (Fig. 3). The panels constructed with UF-II and WP yielded the highest TS (60.3%), and that with UF-I and MWP had the lowest TS (15.7%). Furthermore, with MWP panels, the difference in TS between UF-I and UF-II was not significant.

The mean LE of MWP panels (1.58%) was also significantly lower than that of WP panels (2.81%). Again, the UF-I resin yielded a slightly lower LE (1.95%) than did the UF-II resin (2.44%). It should be noted that the resin interacted with particleboard type to significantly affect LE (Fig. 4). Similar to the effects on TS, the panels constructed with UF-II and WP yielded the highest LE (3.29%) and the panels with UF-I and MWP had the lowest LE (1.56%), and the difference in LE between UF-I and UF-II was not significant within MWP panels.

ANOVA indicated that the WA was significantly affected by particleboard type but was not significantly affected by

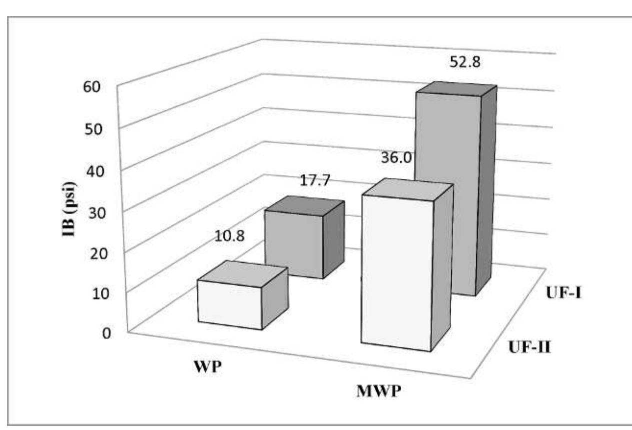

Figure 2.—Particleboard types interacted with urea-formaldehyde (UF) resins to affect the internal bond (IB) of the panel after 24-hour water soak. WP = wood particleboard; MWP = particleboard with mixed wood particles/recycled plastic.

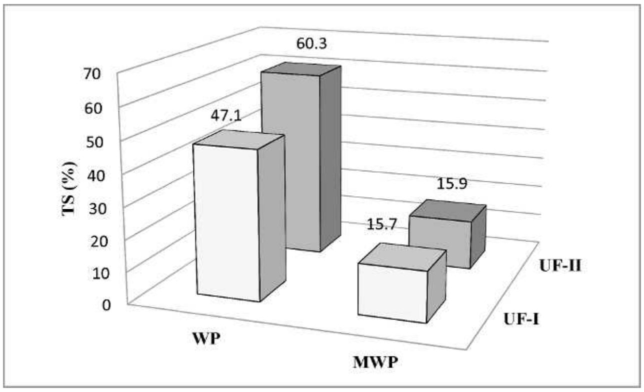

Figure 3.—Particleboard types interacted with urea-formaldehyde (UF) resins to affect the thickness swell (TS) of the panel after 24-hour water soak. WP = wood particleboard; MWP = particleboard with mixed wood particles/recycled plastic.

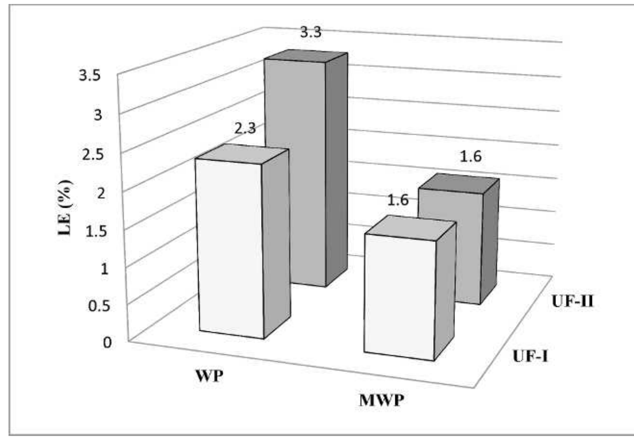

Figure 4.—Particleboard types interacted with urea-formaldehyde (UF) resins to affect the linear expansion (LE) of the panel after 24-hour water soak. WP = wood particleboard; MWP = particleboard with mixed wood particles/recycled plastic.

resin. As expected, the WA of the MWP panels was less than half that of the WP panels, mainly because of the hydrophobic characteristics of the PE powder in the MWP panels.

Bending properties.—The mean MOR and MOE in bending are summarized in Table 4. ANOVA showed that the panels with UF-I yielded significantly higher MOR than did the panels with UF-II, indicating UF-I was better resin than UF-II, which agreed with the previous results in evaluation of IB performance. It is noted that the combination of PE powder and wood particles had no significant effect on MOR.

ANOVA indicated that the effect of resins on MOE was not significant, but the combination of PE powder with wood particles resulted in significantly lower MOE compared with that of wood particleboard panels, which is probably due to the large elastic deformation with lower strength property of PE plastic compared with that of wood particles (Zhao et al. 2008).

The bending properties of MWP panels with the UF-I resin were also evaluated after 24-hour water soaking. The bending properties of WP panels were not evaluated because of their relatively poor performance in water soaking. Average MOR and MOE after 24-hour water soaking were 686 psi (4.7 Mpa) and 62,294 psi (429.6 Mpa), indicating the panels retained about 37.6 and 20.1 percent of their original MOR and MOE, respectively. Chow and Janowiak (1983) showed strength retention values after weathering of 40 and 50 percent for MOR and MOE, respectively, for hardwood composite panels fabricated with phenolic resin. Although the values obtained in our study are substantially lower, particularly those of MOE, considering that low-cost interior grade UF resin was used in the experiment, these retention values were rather encouraging. Further efforts to improve the performance with resin modification are needed.

Second experiment

Modulus of rupture.—The mean MOR and the test specimen failure modes of the panels are summarized in Table 5. The effects of veneer thickness, core construction, and grain angle (i.e., stressed perpendicular or parallel to grain of the outermost face veneer) were evaluated by ANOVA.

The mean $MOR_{||}$ was lowest (3,668.2 psi) for panels with two veneers cross-laminated on each face over a WP core. Conversely, $MOR_{||}$ was greatest (8,535.6 psi) for panels with single 1/8-inch veneers on each face over an MWP core. The ANOVA showed that veneer thickness and grain angle significantly affected MOR (Table 5). However, the effect of the core construction on MOR was not significant.

As expected, with a single veneer on each face, the mean MOR increased as veneer thickness increased from 1/8 to 3/16 inch. However, MOR decreased when two 1/8-inch veneers were cross-laminated on each face. This unexpected decrease was largely attributed to horizontal shear failures.

Table 4.—Effects of particleboard type and resin adhesive on bending modulus of rupture (MOR) and bending modulus of elasticity (MOE).[a]

	MOR (psi)			MOE (psi)		
	Unexposed	24-h soak	Retention	Unexposed	24-h soak	Retention
MWP						
UF-I	1,829 (123.9)	686	37.5	310,455 (10,561)	62,294	20.1
UF-II	1,738 (185.7)	701	40.3	325,160 (24,463)	61,130	18.8
WP						
UF-I	1,935 (122.8)	148	7.6	385,600 (37,356)	28,508	7.4
UF-II	1,499 (355.6)	—		336,125 (63,172)	—	

[a] Values are means (standard deviations). MWP = particleboard with mixed wood particles/recycled plastic; UF = urea-formaldehyde resin; WP = wood particleboard.

Table 5.—Modulus of rupture (MOR) and test failure modes of panels with southern pine veneer face and cores of mixed wood particles/recycled plastic and wood particleboards.

Face construction and veneer thickness	Core construction[a]	Stressed perpendicular to grain		Stressed parallel to grain	
		$MOR_{\perp}$ (psi)	Specimen failure mode	$MOR_{\|\|}$ (psi)	Specimen failure mode
Single 1/8-in. veneer on each face	MWP	781	All in tension	7,519	6 in tension 3 in shear
	WP	814	All in tension	8,536	6 in tension 3 in shear
Single 3/16-in. veneer on each face	MWP	584	All in tension	8,252	5 in shear 4 in tension
	WP	733	All in tension	8,465	7 in shear 2 in tension
Two plies, cross-laminated (1/8-in. veneers) on each surface	MWP	4,885	3 in shear 6 in tension	4,388	All in shear
	WP	3,428	All in shear	3,668	All in shear

[a] MWP = mixed wood particles/recycled plastic composite; WP = wood particleboard.

Of all the specimens with two plies cross-laminated on each face, more than 67 percent failed in horizontal shear when tested stress perpendicular to the face veneer grain, and all (100%) failed in horizontal shear when stressed parallel to the face veneer grain. In distinct contrast, none of the single veneer (either 1/8- or 3/16-in.) overlays on both faces failed in horizontal shear when tested stress perpendicular to the face veneer grain, and only 50 percent failed in horizontal shear when tested parallel to the face veneer grain. These shear failures precluded accurate determination of true MOR (Table 5).

Veneer thickness interacted with grain angle to affect the MOR of the panels. Because core construction had no significant effect on MOR, values for all core constructions were pooled. Table 6 presents mean values for veneer thickness and face construction together with computed thickness ratios of core to veneer and ratios of $MOR_{\perp}/MOR_{||}$.

Of all the panels with a one-ply veneer overlay, those with 3/16-inch-thick veneers yielded the greatest mean MOR when stressed parallel to the grain of the face veneer ($MOR_{||}$ = 8,358.0 psi) and the smallest mean MOR when stressed perpendicular to the grain of the face veneer ($MOR_{\perp}$ = 659 psi; Table 6). However, panels with only one 1/8-inch veneer overlay yielded comparable MOR ($MOR_{||}$ = 8,027.1 psi) when stressed parallel to the grain of face veneer, but the $MOR_{\perp}$ (841.8 psi) was slightly greater than that of 3/16-inch overlay panels (Table 6). A decrease in panel strength with a decrease in veneer thickness was to be expected. However, it was not expected that the MOR of 3/16-inch-thick veneer would yield lower MOR than that of 1/8-inch veneer overlay when stressed perpendicular to the grain of face veneer. Evaluation of the $MOR_{\perp}/MOR_{||}$ ratio (i.e., strength across the grain over strength parallel to the grain; Table 6) also seems to indicate that the ratio for the 3/16-inch-thick veneer overlay was lower than expected because the tabulated values for the effect of grain slope on MOR from the tests showed that the ratio for MOR fell very close to 0.1 (US Department of Agriculture 1974). Visual examination of veneer quality indicated that the 3/16-inch veneer appeared to be rougher with deeper lathe checks than the 1/8-inch veneer. It is possible that the veneer quality of the 3/16-inch veneer might have resulted in lower than expected MOR when stressed perpendicular to the grain of face veneer.

Table 6.—Effect of face construction and veneer thickness with stress applied parallel (//) and perpendicular (⊥) to the grain of the outermost face veneer on modulus of rupture (MOR).

Veneer thickness	Thickness ratio, core/veneer	MOR (psi)		$MOR_{\perp}/MOR_{\|\|}$
		$MOR_{\|\|}$	$MOR_{\perp}$	
Single veneer on each face				
1/8-in.	2.0	8,027	798	0.099
3/16-in.	1.0	8,358	659	0.079
Two veneers cross-laminated on each face				
1/8-in.	0.5	4,028	4157	1.032

MOR of panels with two-ply cross-laminated veneer overlays on each face resulted in the most uniform MOR distribution across the panel (i.e., $MOR_{\perp}/MOR_{||} = 1.032$). It should be noted, however, that when stressed parallel to the grain of the face veneer, the two-ply cross-laminated panels yielded the lowest mean MOR (i.e., 4,028.0 psi) as a result of horizontal shear failure of the entire tested specimens, as previously indicated (Table 5).

Modulus of elasticity.—Mean MOE of all combination variables are summarized in Table 7. The ANOVA indicated that MOE varied significantly with grain angle. Furthermore, the interaction of veneer thickness with stress directions significantly affected MOE.

As expected, all specimens tested in bending parallel to the grain of surface veneers resulted in higher MOE than

Table 7.—Modulus of elasticity (MOE) of panels with southern pine veneer faces and cores of mixed wood particles/recycled plastic and wood particleboards.

Veneer thickness	Core construction[a]	MOE (psi)[b]	
		$MOE_{\perp}$	$MOE_{\|\|}$
Single 1/8-in. veneer on each face	MWP	124,800	1,187,400
	WP	172,300	1,038,000
Single 3/16-in. veneer on each face	MWP	094,600	1,092,000
	WP	109,800	1,089,800
Two plies, cross-laminated (1/8-inch veneers) on each surface	MWP	522,000	935,800
	WP	490,000	805,100

[a] MWP = mixed wood particles/recycled plastic; WP = wood particleboard.
[b] Panels stressed perpendicular (⊥) and parallel (||) to the outer veneer face grain.

Table 8.—Effect of face construction and veneer thickness with stress applied parallel (//) and perpendicular (⊥) to the grain of the outermost face veneer on modulus of elasticity (MOE).

Veneer thickness	Thickness ratio, core/veneer	MOE (psi)		$MOE_{\perp}/MOE_{\|\|}$
		$MOE_{\perp}$	$MOE_{\|\|}$	
Single veneer on each face				
1/8-in.	2.0	148,600	1,189,100	0.124
3/16-in.	1.0	102,200	1,091,100	0.093
Two veneers cross-laminated on each face				
1/8-in.	0.5	506,000	870,500	0.581

those tested perpendicular to the grain. Since core construction had no significant effect on MOE, values for all core constructions were pooled. The interaction of veneer thickness with grain angle on MOE, the calculated thickness ratios of veneer to core, and $MOE_{\perp}/MOE_{||}$ ratios are given in Table 8.

Panels with two-ply cross-laminated veneers resulted in significantly higher MOE (i.e., 506,000 psi) when stressed perpendicular to the grain of face veneer than the MOE of single veneer overlay panels. However, two-ply cross-laminated veneers yielded lower MOE when stressed parallel to the grain of the face veneer (870,500 psi). The higher $MOE_{\perp}$ demonstrated the advantage of cross-laminated veneers on the composite panel surface, while the lower $MOE_{||}$ was mainly due to the effects of horizontal shear failure. Calculated $MOE_{\perp}/MOE_{||}$ ratios showed that panels with two-ply cross-laminated veneers on each face also had the highest $MOE_{\perp}/MOE_{||}$ ratio (i.e., 0.581); Table 8 indicates the advantage of uniform strength distribution in both panel directions as expected.

For a single veneer overlay on each face, it is interesting to note that thinner veneers (i.e., 1/8 in.) resulted in higher MOE than thicker ones (i.e., 3/16 in.; Table 8). It should be noted that the mean increase in MOE was more than 45 percent when stressed perpendicular to the grain of the face veneer. However, the mean increase in MOE was much less (i.e., slightly less than 9%) when stressed parallel to the grain of the face veneer.

Conclusions

The purposes of this research were to evaluate the properties of particleboard with a combination of wood particles and recycled plastic powder and determine the optimum configuration of an exterior structural panel with faces of southern pine veneer and a core of mixed wood particles and recycled plastic. MWP panels were not significantly different from WP panels for nonaged IB strength, but MWP panels were significantly better than WP panels for aged IB and dimensional stability. This finding suggests that MWP panels offer great potential for the development of structural panel products with improved moisture resistance, more competitive capabilities, and new markets. The panels used in this study with veneer faces and a particleboard core of mixed wood particles/recycled plastic can likely meet the necessary strength and dimensional stability performance requirements for mobile homes and industrial work flooring systems. Furthermore, both strength and dimensional stability can be modified by altering the thickness of the face veneers, core density, and construction. Even though panels with single-ply faces yielded lower strength and are likely less stable across the grain direction of the face veneer, these panels yielded properties more than adequate for most structural applications. Moreover, these panels are particularly advantageous as a result of the lower costs associated with single-ply faces and UF resin.

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