Recycling Polyurethane Materials: A Comparison of Polyol from Glycolysis with Micronized Polyurethane Powder in Particleboard Applications

An Mao, [a,b] Rubin Shmulsky,[b] Qi Li, [b] and Hui Wan [b,]*

Three different types of recycled polyurethane (PUR) material, two in powder form from a pulverizing process (one < 50 µm and one < 250 µm) and one in polyol form from a glycolysis process, were used as substitutes for polymeric methylene diphenyl diisocyanate (pMDI) resin at 5%, 15%, and 30% ratio, respectively, to replace the pMDI resin for particleboard manufacturing at 8% resin loading. The reactions between pMDI resin and recycled PUR powder and polyol were investigated with Fourier transform infrared (FT-IR) spectroscopy. It was found that 5% substitution of pMDI with recycled PU powder of < 50 µm resulted in significantly higher panel internal bonding (IB) strength than pure pMDI resin, which also tended to increase panel modulus of rupture (MOR), and modulus of elasticity (MOE). Polyol did not show advantages over PUR powder in particleboard application. Increasing the size of recycled PUR powder from < 50 µm to < 250 µm decreased the panel IB, which also tended to decrease MOR and MOE. Recycling PUR materials in either powder or polyol form in particleboard manufacturing did not improve panel thickness swelling, but did appear to improve panel water absorption.

Keywords: Recycling; Polyurethane Powder; Glycolysis; Polyol; Particleboard; pMDI

*Contact information: a: College of Forestry, Shandong Agriculture University, 271018, Taian, China, b: Department of Forest Products, Mississippi State University, P. O. Box 9800, Starkville, MS 39759-9820 USA; *Corresponding author: hwan@cfr.msstate.edu*

INTRODUCTION

Polyurethane (PUR) foams are commercially produced by reacting isocyanates, polyols, and foaming agents. Water usually is used as a blowing agent, which reacts with an isocyanate group during polymerization forming urea linkages and generating expanding gas, carbon dioxide, to form foam. Each year, more than 10 million tons of PUR foams are manufactured worldwide. The increasing use of PUR foam materials has brought about the need to recycle these materials.

According to Daniels *et al*. (2004), about 15 million cars and trucks reach the end of their service lives each year in the United States. Before a car is disposed of, hazardous materials such as batteries, oils, and other fluids are removed. The remaining material is pressed and fed through a shredder machine, then through a magnetic separator to separate out the recyclable ferrous metals. The nonferrous materials are put through a flotation process, from which the lighter portion, called automobile shredder residue (ASR) or automobile fluff, which mainly consists of polymeric materials, is usually sent to a landfill. In the U.S. approximately 5 million tons of ASR are generated each year, most of which goes to landfills and thus creates an environmental impact (Hook 2008).

The ASR mixtures contain plastics, rubber, fibers, PUR foams, and other materials. The increasing use of PUR foam materials in automobiles is a great challenge in terms of recycling.

In past years, efforts have been made to address this issue. One approach is to use materials synthesized from renewable resources (Desroches *et al.* 2012). The use of renewable resources can help reduce environmental impact brought by chemical synthesis of petroleum-based products. Another approach is reuse of waste petroleum-based PUR foams. Generally, there are two categories for recycling of PUR foams: physical and chemical. Angus and Sims (1994) reported the use of granulated foam scrap bonded with a moisture-curing isocyanate terminated pre-polymer to produce foams of various densities for carpet underlay, cushioning materials, and other energy-absorbing products. Waste reaction injection moulded PUR materials can be ground down to fine powders and used as fillers for polymer resins (*e.g.*, polyester and polypropylene) in new compression moulding compounds (Hulme and Goodhead 2003). Berthevas *et al.* (2005) used 10% to 30% of PUR powder for particleboard application and found that the replacement of 10% of the polymeric methylene diphenyl diisocyanate (pMDI) binder by PUR powders gave comparable internal bonding (IB) results as those obtained from pure pMDI resin. The replacement of 20% of the pMDI binder by PUR powders can still provide reasonable properties for exterior application with further cost savings. Berthevas *et al.* (2005) expected that at hot press temperature of 190 °C, PUR powder could partially degrade and recombine to give strong bonds. Mansouri and Pizzi (2007) discussed the method of adding flexible PUR foam powders to urea-formaldehyde (UF) and phenol-formaldehyde (PF) resins for bonding plywood and particleboard. It was found that PUR powders could serve as active fillers or extenders to improve the dry bonding strength of UF resin joints. The water resistance of UF and PF resins was also improved.

Various chemical procedures for decomposing used PUR foams have also been found (Behrendt and Naber 2009; White and Durocher 1997). These procedures were usually conducted with solvents at high temperatures with a catalyst. The solvents used in the decomposition reaction include water, alcohols, inorganic or organic acids, amines, and alkalines. When alcohols such as low molecule weight glycols are used as decomposing solvents, they break down the urethane linkages, resulting in short chain hydroxyl functional urethane oligomers, and the raw polyols used in the reaction of the original PUR foams are thus released (Behrendt and Naber 2009). This process is called glycolysis. The polyols recovered from glycolysis were reused in PUR foam manufacturing, but with limited success. Currently, recovered polyols can only partially replace commercial polyols in a PUR foam-forming reaction.

The objectives of this study were to compare the performance of particleboard made with recycling PUR foams *via* physical process-grinding and chemical process-glycolysis *versus* those made with only pMDI to determine the impact of the size of ground PUR powders on particleboard panel performance, and to use recycled PUR materials to improve pMDI resin efficiency and panel performance.

EXPERIMENTAL

Materials

Commercially available recycled micronized polyurethane (MPUR) powders with a specific gravity of about 1.2 were supplied by Mobius Technologies, Inc. (Lincoln, CA). These MPUR powders were produced from polyurethane industrial and post-consumer waste with patented technology (Martel *et al.* 2007). The powders were two sizes: one smaller than 250 µm (MPUR 300-2) and one smaller than 50 µm (MPUR 300-230). Both were sealed in bags with a moisture content of 0.57% and 1.6% for MPUR 300-2 and MPUR 300-230, respectively, and were utilized as received.

Flexible PUR foams were handpicked from ASR at Metal Management Inc. (Greenville, MS). Rubber, wood fibers, paper, glass, and other materials within the foams were removed and the foams were washed with water and then with acetone. The foams were then air-dried under a hood and ground into powders smaller than 1 mm by a grinding machine (Laboratory Mill, Model 4; Arthur H. Thomas Company, PA) using a 1-mm screen. The recycled PUR foam powders were then dried in an oven at 105 °C until the water in the materials was removed. Diethylene glycol (DEG) and sodium hydroxide, used as a decomposing solvent and catalyst, respectively, were obtained from Fisher Scientific Co. (PA).

The pMDI (Lupranate® M20FB) with an isocynate group (NCO) content of 31.5% and viscosity of 230 cps (measured with Brookfield (Brookfield, MA) viscosity meter at room temperature) was obtained from BASF Chemical Company (Wyandotte, MI). When mixed with different amounts of polyol and MPU powders, the viscosity of the mixtures varied. To adjust the resin mixture to a viscosity to approximately 230 cps for spraying, acetone were added. Mixed pine wood particles were obtained from Roseburg Forest Products Corp., a particleboard plant, located in Taylorsville, MS. The pH of the particles was 4.6 and the bulk density was 12 lb/ft^3. The particle size distribution is shown in Table 1.

Table 1. Pine Wood Particle Size Distribution (%)

>10 mesh	>14 mesh	>18 mesh	>30 mesh	<30 mesh
3.1	7.5	17.6	30	41.8

Note: >10 mesh means particle size is larger than 10 mesh
>14 mesh means particle size is larger than 14 but smaller than 10 mesh
>18 mesh means particle size is larger than 18 but smaller than 14 mesh
>30 mesh means particle size is larger than 30 but smaller than 18 mesh
<30 mesh means particle size is smaller than 30 mesh or on pan

Methods

Light microscope observations

The PUR powder images were taken with a Nikon SMZ 1500 (Nikon, NY) microscope equipped with SPOT™ (SPOT Imaging Solutions, MI) imaging software using reflective light.

Glycolysis of PUR foams obtained from ASR

The PUR foam glycolysis reaction was carried out under atmospheric pressure in a three-neck round-bottom flask equipped with a stirrer and reflux. A two-blade polyethylene terephthalate impeller was used. First, the DEG was placed in the flask and heated with a heating mantle to 210 °C. Then 1% sodium hydroxide (catalyst), based on the weight of PUR powder, and PUR foam powder (at a weight ratio of DEG to PUR of 3:1) were charged into the flask, successively. The reaction mixture was maintained at 210 °C for 3 h. The glycolysis reaction product (GRP) was vacuum-filtered through a No. 4 filter paper, cooled to room temperature, and stored. The hydroxyl number of obtained GRP was 246 mg KOH/g, determined with the Standard Method Cd 13-60 (AOCS 2009).

Fourier transform infrared (FT-IR) spectroscopy

The functional group analyses of resin samples were investigated with an FT-IR spectrophotometer (Varian 3100, DE). Various PUR materials, pMDI resin, and their mixes (Table 2) were cured and dried at 105 °C for 24 h and then ground to fine powders. A thin KBr plate was prepared with each sample and measurements were performed at wavenumbers from 3600 cm^{-1} to 600 cm^{-1}.

Table 2. Composition of Materials for FT-IR Analysis

Material Composition	Weight Ratio
MDI	–
MDI + GRP	2:1
GRP	–
MDI + MPUR 300-230	2:1
	1:1
	1:2

Table 3. Particleboard Preparation Parameters

Board No.	Resin Composition (Weight Percentage)				Notes
	pMDI resin	GRP	MPUR 300-230	MPUR 300-2	
1	100	0	0	0	
2	95	5	0	0	GRP was first mixed with pMDI and then sprayed on the particles
3	85	15	0	0	
4	70	30	0	0	
5	95	0	5	0	15% and 30% MPUR powders were first blended with wood particles; then, pMDI resin was applied 5% MPUR powder was first mixed with pMDI resin, then sprayed on the particles
6	85	0	15	0	
7	70	0	30	0	
8	85	0	0	15	
9	70	0	0	30	

Particleboard manufacturing

Particleboard manufacturing was carried out in the laboratory using the one-layer formatting process. Wood particles were first dried to a moisture content of 8.0% and put into a rotating blender, and then the resin was sprayed on wood particles using an air-atomizing nozzle with a blending time of approximately 15.0 min. The resin loading rate was 8.0%, based on the weight of oven-dried wood. The resin-blended particles were weighed and hand-laid on a steel caul plate within a 610 mm x 559 mm (24 in × 22 in) wooden box to obtain a uniform mat. After removing the box, another steel caul plate was placed on the mat and hot-pressing was carried out in a 34 inch x 34 inch automated Dieffenbacher (Dieffenbacher, GA) hot-press at 190 °C with a 5.0 min press time for each resin composition. The press-closing rate was initially 12.7 mm (0.5 in)/s to mat thickness of 25.4 mm (1.0 in) and then 7.6 mm (0.03 in)/s to reach the target board thickness of 12.7 mm (0.5 in). The particleboards were allowed to cool to room temperature for 24 h. Nine resin compositions were used, resulting in nine boards, as shown in Table 4.

Physical and mechanical test of particleboards

Internal bond strength, modulus of rupture (MOR), and modulus of elasticity (MOE) were tested on an Instron 5566 machine (Instron Corp., MA). Water-soak thickness swelling (TS) and water absorption (WA) values were measured in a 20 °C water bath according to ASTM D 1037-06a (2006). Eight IB samples, three bending samples, and two water-soak samples were tested from each board.

Statistical analysis

Means and standard deviations of the IB data obtained were calculated. Each IB datum was divided by the density of corresponding IB sample and then the data were analyzed statistically using Duncan's multiple range tests with SAS® 9.3 (SAS, NC).

RESULTS AND DISCUSSION

Images of Micronized Polyurethane Powders

Figures 1a and 1b show images of MPUR 300-2 powder and MPUR 300-230 powder, respectively. Comparing these two photos, it is evident that MPUR 300-2 powders still keep some features of foam material, whereas from the image of MPUR 300-230 powders the origin is difficult to determine. Based this information, to prevent them from clogging, the resin nozzle because of the size difference, MPUR 300-2 powders were added directly to wood particles while MPUR 300-230 powders were mixed with pMDI resin and sprayed on the wood particles during particleboard manufacturing.

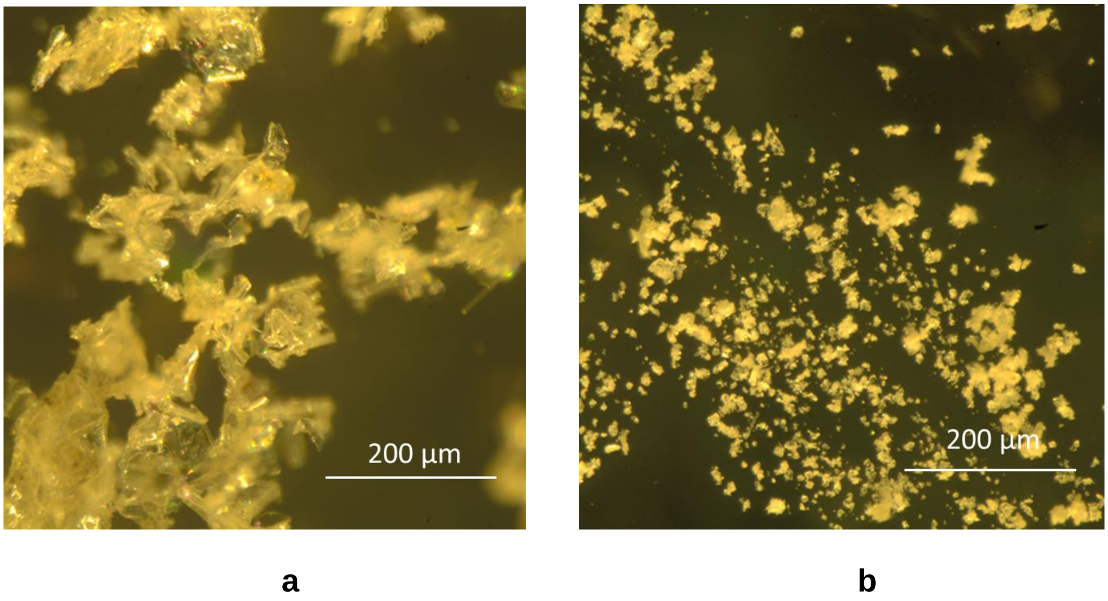

Fig. 1. Images of MPUR powders; (a) MPUR 300-2 and (b) MPUR 300-230

FT-IR Spectroscopy

The functional groups in the cured pMDI resin, MPUR 300-230 powder, pMDI-MPUR 300-230 mixtures, GRP, and pMDI-GRP mixture were investigated by FT-IR as shown in Figs. 2 and 3. Generally, in the FT-IR spectrum of the MPUR powder (Fig. 2), the absorption bands at about 1720 cm^{-1} and 1537 cm^{-1} correspond to the urethane carbonyl group (C=O in –NH–CO–O–) stretching and N-H bending vibration, respectively. The absorption bands at about 1662 cm^{-1} and 3310 cm^{-1} correspond to the urea carbonyl group (C=O in –NH–CO–NH–) and the stretching vibration of N-H groups, respectively. These groups are the products of the reaction between isocyanate and water, which was from MPUR powder and the atmosphere during resin curing (Beneš *et al*. 2012; Kwon *et al*. 2007; Wang and Chen 2006; Wu *et al*. 2003). In the cured pMDI resin, there were quite a few residual isocyanates (-N=C=O) at about 2237 cm^{-1} (Lee and Lin 2008), but once the pMDI resin reacted with hydroxyl groups in GRP (Fig. 3), the band disappeared, indicating that the reaction between pMDI and GRP had occurred. The FT-IR curves of pMDI and GRP in Fig. 3 also show the N-H bands at about wavenumber 3440 cm^{-1} and amide I bands (C=O stretch) at about wavenumber 1730 cm^{-1}, as expected.

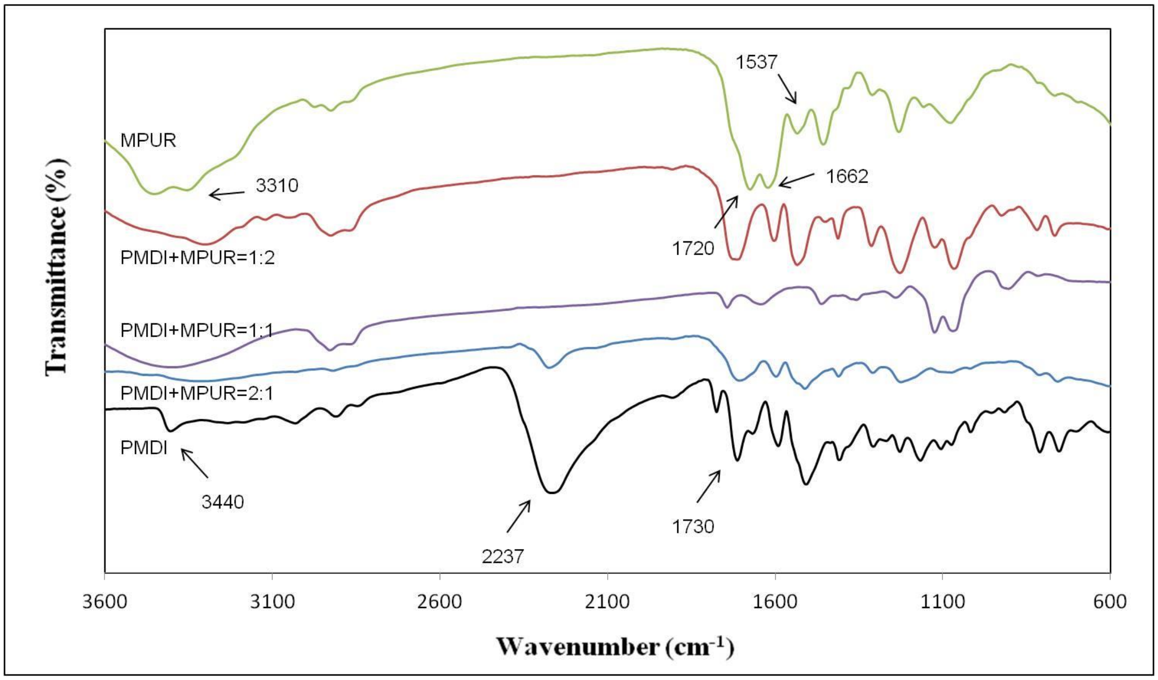

Fig. 2. FT-IR spectra of pMDI, MPUR, and their mixtures

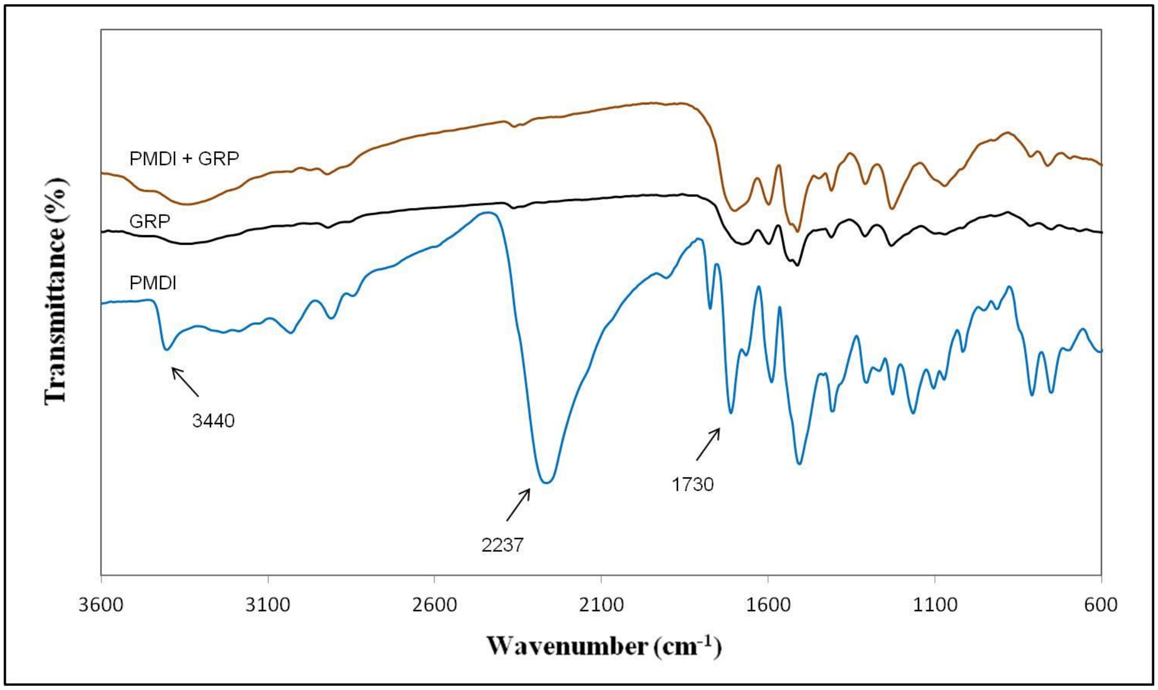

Fig. 3. FT-IR spectra of pMDI, GRP, and their mixtures (1:1)

It is evident that when pMDI was mixed with MPUR 300-230 at a weight ratio of 2:1, the amount of isocyanates (-N=C=O) (Fig. 2) in the cured mixture at 2237 cm^{-1} decreased compared to the amount in pure pMDI, and increasing the amount of MPUR 300-230 decreased the amount of residual isocyanates. This finding indicates the possible chemical reactions between the isocyanate and MPU powder. However, even at a pMDI to MPUR ratio of 1:2, there were still some isocyanates (-N=C=O) at 2237 cm^{-1}, indicating that the reactions between pMDI and MPUR 300-230 powder were not complete.

Panel Vertical Density Profile

It was found that there was not much difference in panel vertical density profile among the panels made with different amounts of recycled PUR materials. A typical panel vertical density profile (VDP) curve is shown in Fig. 4. It is relatively flat, implying that the panels made with isocyanate resin might be suitable for furniture frame application.

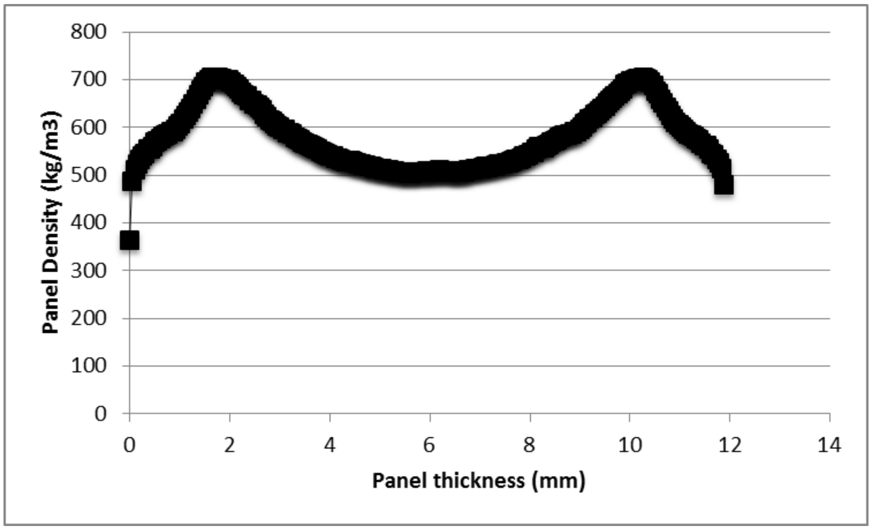

Fig. 4. A typical panel vertical density profile

Panel Physical Performances

Particleboard dry performance data are shown in Table 4 and wet performance data are shown in Table 5. The IB samples for the wet test were obtained from TS and WA test samples after the water soak test by drying at 105 °C for 24 h and testing for IB values. There were density variations among the panels and between the different test samples from the same panels. Thus, sample standard deviations were obtained and the conclusions, especially concerning IB strength values, were reached under unit density. Because there were only three samples for the flatwise MOE/MOR test, two samples for TS/WA tests, and four samples for the IB value after the water soak test, these data were presented as average values without sample standard deviation information. The related sample density information was listed for reference purposes.

Table 4. Particleboard Dry Performance

Panel No.	Density of IB samples (lb/ft^3)	IB** (psi)	Density of MOE/MOR samples (lb/ft^3)	MOR (psi)	MOE (kpsi)
1	45 (5)	268 (50)B	35	1142	135
2	44 (1)	250 (19)B	36	1035	139
3	42 (2)	148 (27)D	40	978	*
4	42 (1)	137 (13)D	38	904	108
5	46 (1)	300 (28)A	38	1672	198
6	45 (4)	277 (59)AB	38	1483	199
7	43 (1)	256 (16)B	39	1458	176
8	43 (3)	222 (50)C	37	1051	135
9	42 (1)	197 (24)C	38	1057	137

Notes: MOR and MOE values are the averages of three samples
Values in parentheses are sample standard deviations

*Due to test machine malfunction, the MOE value was lost
Multiply by 16.02 to convert lb/ft^3 to kg/m^3
Divide by 145 to convert psi to MPa
**The values with the same letter(s) are not different statistically at α=0.05

Table 5. Particleboard Wet Performance

Panel No.	Density of TS/WA/IB samples (lb/ft^3)	24 h thickness swelling (%)	24 h water absorption (%)	IB after 24 h water soak (psi)
1	48	7.0	81.4	155
2	44	7.7	78.3	172
3	40	12.6	76.6	93
4	42	11.1	79.1	72
5	43	8.2	71.3	205
6	47	7.8	75.6	174
7	42	8.8	73.5	181
8	46	9.0	80.5	134
9	43	8.6	80.1	130
Notes: TS/WA values are averages of two samples IB values are averages of four samples				

Internal bonding

Data in Table 4 indicate that substituting 5% to 30% GRP for pMDI resin resulted in decreased IB values (Panel No. 1 *vs.* Panels No. 2 to 4) especially at substitution levels of 15% to 30%. At unit density, statistical analysis shows that the IB value of panel bonded with 5% GRP substitute did not differ from that of panel bonded with pure pMDI, whereas with 15% and 30% GRP substitute, the IB values of the panels were significantly lower than that of panels with pure pMDI resin at the 0.05 significance level. Since, the FT-IR curve (Fig. 3) showed that there was a reaction between pMDI and GRP, based on IB data, it appears that GRP can be added at a 5% level or slightly higher. Further research on how to recycle GRP into pMDI resin for particleboard application for improving panel IB strength is necessary.

At < 50 µm, as MPUR 300-230 powder substitution level increased from 0% to 5%, panel IB values increased (Panel No. 1 *vs.* Panel No. 5). As the level further increased from 5% to 15% (Panel No. 5 *vs.* Panel No. 6), the panel IB value decreased but was still greater than that of the pMDI control panel. Further increasing the substitution level to 30% decreased panel IB value (Panel No. 7). Statistical analyses showed that, at unit panel density, substituting 5% MPUR 300-230 powder for MDI resin increased panel IB value at the 0.05 significance level; substituting 15% MPUR 300-230 powder resulted in the same panel IB as that of the control panel with pure pMDI resin. Further increasing the substitution level to 30% did not decrease IB value at the 0.05 significance level. As the FT-IR curves indicate (Fig. 2), possible chemical reaction might occur in pMDI-MPUR mixtures. In this case, the MPUR powder may serve not only as a filler but also as a reactive extender in pMDI-MPUR mixtures. In its filler function, it may help hold pMDI resin, reducing the chance of pMDI penetrating into particles and thus improving resin efficiency and panel IB. In its reactive extenders function, it may increase the molecular weight of adhesive mix and thus enhance bonding strength as well as reduce adhesive penetration into wood particles. However, further research is needed to verify this because of limited information obtained from FT-IR analysis. Moreover, it was reported that at a high temperature of around 190 °C, recycled thermoset PUR could partially degrade and recombine resulting in strong bonds as experienced in the recycling of reaction injection molding (RIM) polyurethane scrap by granulation followed by compression molding (Berthevas *et al.* 2005). Thus, the IB strength of particleboards might also be enhanced when incorporating an appropriate amount of PUR powders as investigated in this work.

At unit density, comparing the IB value of panels with GRP at different substitution levels (Panels No. 2 to 4) with that of panels with MPUR powder of different sizes (Panels No. 5 to 7 and Panels No. 8 to 9) indicates that at each substitution level, GRP resulted in lower IB value than MPUR powder, showing that under the current utilization method there were no advantages to using recycled polyol over MPUR powders.

At unit density, increasing MPUR powder size from 50 µm to 250 µm decreased panel IB at substitution levels of 15% and 30%, respectively (Panel No. 6 *vs.* Panel No. 8; Panel No. 7 *vs.* Panel No. 9) at the significance level of 0.05. Compared with the IB value of pMDI resin control panel (Panel No. 1), the IB value of panel with 15% MPUR 300-2 powder substitute (Panel No. 8) was lower at the 0.1 significance level and the IB value of panel with 30% MPUR 300-2 powder substitute (Panel No. 9) was lower at the 0.05 significance level. This indicates that increasing MPUR powder size deteriorated panel IB performance. Future research on the optimization of MPUR powder size should be conducted.

The IB data of samples after the water soak test show a similar trend as the dry particleboard data discussed above. Still, the IB of <50 µm panel with 5% MPUR powder substitute was the highest. This indicates that substituting 5% MPUR powder of <50 µm for pMDI resin improved panel IB performance.

Modulus of rupture and modulus of elasticity

Comparing the MOR value of Panel No. 1 with that of Panels No. 2 through 4 indicates that the pMDI control panel had higher MOR value than those of panels with GRP at substitution levels of 5%, 15%, and 30%, respectively, based on unit density. This demonstrates that recycling GRP for pMDI did not improve panel MOR. One can also tell that recycling GRP for pMDI did not improve panel MOE.

Comparing the MOR value of Panel No. 1 with those of Panels No. 5 through 7 indicates that pMDI control panel had lower MOR value than those of MPUR 300-230 panels at substitution levels of 5%, 15%, and 30%, respectively, based on unit density. This shows that recycling MPUR powder <50 µm with pMDI improved panel MOR. Since MOR and MOE are highly correlated, as expected, recycling MPUR powder <50 µm for pMDI resin improved panel MOE.

Comparing the MOR values of Panels No. 2 through 4 with those of Panels No. 5 through 7 and those of Panels No. 8 and 9 indicates that GRP resulted in a lower MOR than MPUR powder of different sizes. Concerning MOE, data in Table 4 show that the MOE values of panels with GRP were lower than those of panels with MPUR 300-230 powder at substituting levels of 5% and 30%, respectively. This demonstrates that recycling GRP for pMDI did not show advantages over using MPUR powder in terms of panel MOR and MOE strength.

Comparing the MOR values of Panels No. 6 and 7 with those of Panels No. 8 and 9 indicates that reducing MPUR powder size from 250 to 50 µm improved panel MOR at 15% and 30% MPUR substitution levels, respectively. Thus, recycling MPUR 300-230 powder for substituting pMDI appeared to improve panel MOR at 5% to 30% substitution levels and increasing MPUR powder size decreased panel MOR at 15% and 30% substitution levels. As for the impact of MPUR powder size on panel MOE, comparing the MOE values of Panels No. 6 and 7 with those of Panels No. 8 and 9 indicates that recycling MPUR 300-230 powder for pMDI appeared to improve panel MOE at 15% to 30% substitution levels, *i.e.*, increasing MPUR powder size decreased panel MOE at 15% and 30% substitution levels.

Thickness swelling and water absorption

The 24-h water soak test results are shown in Table 5. Comparing the TS value of Panel No. 1 with those of Panels No. 2 to 9 indicates that the pMDI control panel had a lower TS value than all other panels, which indicates that replacing pMDI resin with either MPUR powders or GRP did not improve panel thickness swelling property. Comparing the WA of the same panels, one can tell that pMDI control panel had higher WA value than other panels at all substitution levels, indicating that adding recycled PUR materials into pMDI improved panel WA performance.

Comparing TS values of Panels No. 2 through 4 with those of Panels No. 5 through 7 and those of Panels No. 8 and 9, respectively, indicates that at the 5% substitution level, GRP panel resulted in lower TS value (9.7%) than that (8.2%) of the MPUR 300-230 panel. At other substituting levels (15% and 30%), GRP panels resulted in higher TS values (12.6% and 11.1%) than MPUR 300-2 (7.8% and 8.8%) and 300-230 (9.0% and 8.6%) panels. Further research is needed to find the difference of MPUR and GRP in panel TS performance. Comparing the WA values of panels with GRP with those of panels with MPUR powders of different sizes, GPR resulted in higher WA values than MPUR 300-230 powder and lower WA values than MPUR 300-2 powder, showing a certain advantage of using GRP with pMDI in particleboard application, in terms of WA.

Comparing the TS values of Panels No. 6 and 7 with those of Panels No. 8 and 9 shows that at 15% substitution level, the TS value (7.8%) of the MPUR 300-230 panel was lower than that (9.0%) of the MPUR 300-2 panel, while at 30% substitution level, the TS value (8.8%) of the MPUR 300-230 panel was higher than that (8.6%) of the MPUR 300-2 panel, indicating that there was no evident advantage to using a smaller size of MPUR in terms of panel TS. For WA, data in Table 4 indicate that smaller MPUR powder size resulted in low WA values (Panels No. 6 and 7 *vs.* Panels No. 8 and 9).

CONCLUSIONS

1. At the 5% level, substituting MPUR 300-230 powder of < 50 µm for pMDI resin improved the panel IB and had a tendency to improve MOE and MOR.

2. There were no advantages to using GRP for particleboard application rather than MPUR powders in terms of panel properties measured and with the methods used.

3. Increasing the MPUR powder size from < 50 µm to < 250 µm decreased the panel IB and had a tendency to decrease MOE and MOR.

4. The impact of recycled PUR materials on panel TS and WA was relatively small, and further research was deemed necessary.

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