THE EFFECT OF SOME PROCESS VARIABLES ON THE LAP-SHEAR STRENGTH OF ASPEN STRANDS UNIFORMLY COATED WITH pMDI-RESIN

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ABSTRACT

The effect of bond time, resin level, moisture content, and press temperature on the lap-shear strength of hot-pressed specimens coated with polymeric diphenyl methane diisocyanate (pMDI) has been examined. The strength was found to increase with press temperature, bond time, and moisture content, but decrease with resin level. It was concluded that significant moisture is necessary to obtain high bond strengths. A significant open assembly time effect was also noted with lap-shear strengths increasing with open time.

Keywords: Processing window, resin level, moisture content, press temperature, bond time, pMDI, OSB.

INTRODUCTION

The manufacture of reconstituted wood composites using a pMDI-based resins is relatively commonplace nowadays. However, there is still some debate as to the actual bonding mechanism responsible for binding the wood particles together. In theory, there are a number of pathways through which the isocyanate resins can bond with woody materials (Wendler and Frazier 1996a,b). Chelak and Newman (1991) hypothesized that there are two predominant reaction pathways responsible for the bonding: (1) the reaction with water to form polyurea and (2) the reaction with the wood surface to form a urethane bond. The latter was thought to be responsible for the high bind strengths obtained with these resins. Bao et al. (2003) and Wendler and Frazier (1996b) also noted that additional side reactions may be the reaction of pMDI with urea to form biuret and pMDI with urethane to form allophanate.

Frazier et al. (1996) and Frazier and Ni (1998) noted that due to its low molecular weight and the absence of an entropic barrier for molecular mixing, pMDI should be able to penetrate into the wood with true molecular mixing occurring. They speculated that once cured, the pMDI forms an interpenetrating network (IPN) of polyurea and biuret within the woody material. Wendler and Frazier (1996a,b) found that above a furnish moisture content of 4.5 wt%, the majority of the resin reacts with water during curing to form polyurea. At lower moisture contents, less polyurea is formed, and the resins convert primarily to biuret-type structures with the biuret formation occurring even for very dry furnish. However, their results are complicated by the fact that the resin used in that work had a weight average molecular weight approximately 10 times that of industrial pMDI-resins. In later work, using a resin with a molecular weight similar to industrial resins, Ni and Frazier (1998) found that the general nature of the cure was similar, i.e., reaction with moisture to form polyurea, but that urethane formation may be more common and biuret formation less common for the low molecular weight resin.

Wendler and Frazier (1996b) also found that press temperature plays a significant role. At low

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press temperatures, i.e., 120°C, they found that curing is dominated by the formation of polyurea with lesser amounts of biuret. As the temperature increases, the formation of biuret dominates and lesser amounts of polyurea are formed. At higher temperatures, the biurets thermally cleave and liberate isocyanate that may react with the wood if it is sufficiently dry. In related work, Zhou and Frazier (2001) present results that strongly suggest urethane linkages are present in bonds made at 165°C, while no urethane bonds were formed for material pressed at 185°C; they attribute the absence of urethane bonds to the thermal decomposition of those linkages. They also mention that the large temperature gradient present in commercially pressed boards will result in changes in the nature of bondline chemistry through the thickness of the board.

Rosthauser et al. (1997) examined the contribution of the proposed urethane linkages to the overall bond strength of particleboard. They made three series of hot-platen pressed boards using particleboard furnish with pMDI-resin. The furnish for their first series of boards was refluxed in a mixture of acetone and phenyl isocyanate, the furnish for the second series was refluxed in acetone only, and the furnish for the final control series untreated. They state that treating the furnish with the acetone/phenol isocyanate mixture reacts most of the available OH sites on the wood surface with the phenol isocyanate, thus reducing the number of potential urethane bonding sites. They found no significant difference between the internal bond strength of boards made from each furnish and concluded that the bonding mechanism in pMDI/wood composites is due to the mechanical interlocking of adjacent wood particles through the formation of polyurea. These results show that urethane linkages do not significantly affect the short-term internal bond strength. That said, the long-term bond strength, or durability, of these bonds may be affected. One would expect that urethane linkages, when present, anchor the polyurea network to the wood polymers, thus improving the durability of a wood composite product; but this is only speculation since theses samples were not subjected to any durability tests.

Marcinko et al. (1998, 1999) conducted a series of dynamic mechanical analysis experiments on southern pine samples coated with pMDI-resin. Although they did not mention IPNs in their work, they found good evidence for it. They performed a series of dynamic mechanical analysis (DMA) tests by heating resin-coated samples twice in the DMA apparatus; the first heat cured the samples, and the second heat permitted the effect of the cured resin to be examined. They observed that the tan δ peak of the coated samples occurred at a lower temperature and was broader than the control samples and concluded that the pMDI-resin penetrates deeply into the woody material and is intimately associated with the wood molecules, as would be the case if an IPN was formed. More recently, Bao et al. (2003) have done further work on pMDI using two-dimensional NMR spectroscopy to investigate the curing of pMDI with wood. They found that at high temperatures and low moisture contents, pMDI can react with the urea NHs to form crosslinking biuret and/or dimer, and trimer structures. They also describe a model for the bonding of pMDI with wood where the pMDI forms a network consisting of linear polyurea structures cross-linked together by biuret/dimer/trimer structures. They concluded that the excellent adhesion properties of pMDI might be due to its ability to penetrate deeply into the wood materials and then cross-link, effectively anchoring the cured resin within the wood.

Based on these earlier works, it appears that pMDI penetrates into the woody materials on a molecular level and reacts with water to form a network of polyurea and biuret interlocked within the woody material. Because of the structure of the urea and biuret molecules, there will be significant secondary bonding occurring between the urea and biuret dipoles and the wood surface to resist the pull-out of these polymer chains from the wood polymers. Upon further heating, the biuret will cleave, producing an isocyanate group which, if the wood is sufficiently dry, can react to form a urethane linkage. At higher temperatures, the linkage will thermally decompose to produce more isocyanate. Urethane linkages are therefore likely present, but

their frequency will depend on the presence or absence of moisture and the temperature. Thus, the picture of pMDI cure is at best complex, with the form of the resin depending on its location within the board and its local moisture content and thermal history.

This work focuses on identifying the processing window for the hot-pressing of pMDI/wood composites using strands similar to those used for oriented strandboard (OSB) and examines the effect of bond time, strand moisture content, resin level, and press temperature on the lap-shear strength of hot-pressed strands.

MATERIALS AND METHODS

The wood samples used in this work were made from sliced aspen (*Populus tremuloides*) veneer 0.69 mm thick. To eliminate any variability that may be introduced by different wood planes on the face of the veneer sheets, only quarter-sawn sheets were used. Each sheet was cut into either 20-or 25.4-mm-wide strips with the grain direction parallel to the long edge of the strips. Strands were cut from the strips to a length of 125 mm. The samples were spread out on perforated trays and conditioned in controlled humidity rooms at 30%, 50%, 65%, and 90% relative humidity and 25°C for at least 3 days prior to use. The moisture content, M, of the samples was calculated in accordance with ASTM D1037 (ASTM 2000). To minimize changes in moisture content, the strands were placed in sealed plastic bags before removing them from the conditioning room.

The pMDI-resin used in this work is Bayer Mondur 541 with an isocyanate equivalent NCO content of 31.5%, a functionality of 2.7, a density of 1240 kg/m³, and a viscosity of 200 mPa·s at 25°C. The resin was dyed red by adding 0.3 wt% Reactint Red X64 dye from Milliken Chemicals. The initial mass of an as-conditioned strand before coating, m_{ic}, and the resinated mass of the strand, m_f, were measured and recorded. The resin level, R, applied to the surface of the strands was calculated from the moisture content, M, as a percentage of oven-dry wood weight (wt%) as follows,

$$R = \left(\frac{m_f}{m_{ic}} - 1 \right)\left(1 + \frac{M}{100} \right). \qquad (1)$$

Resin was applied to the strands using a flexo-graphic printing technique on a laboratory-scale Prüfbau proof press. A proof press is typically used to determine the printability of various types of paper. This apparatus consists of a small elastomeric roller in contact with a second roller. Ink is applied to the surface of the first roller, which is then spread out evenly over its surface by the second roller. A paper sample is attached to a shuttle and resin transfers from the roller to the paper as the shuttle passes under the roller. In this work, pMDI-resin was substituted for the ink and strands for the paper. Each strand was resinated as follows: the strand was removed from the sealed bag, its mass measured to the nearest 0.001 mg and recorded, the resin applied to the strand using the proof press, the strand mass measured and recorded, and the strand placed back in its original bag and sealed. Approximately 2 to 3 h was required to prepare a batch of 64 strands.

Lap-shear specimens were made by bonding two strands together using an Automated Bond Evaluation System (ABES) similar to that described by Humphrey and Zavala (1989) and identical to that used in earlier work by the author (Smith 2003). The ABES is a lab-scale, automated hot-platen press in which two strands are place, hot-pressed together, and lap-shear strength of the bonded strands measured *in situ*. During the manufacture of commercial OSB, the strands are compressed approximately 35% (Smith 2003); this was simulated in this work by setting the pressure in the ABES press so that the thickness reduction in the hot-pressed region is 35%. Lap-lengths of 25.4 mm, 12.7 mm, and 10 mm were used.

Study 1 was a preliminary investigation of the effect of moisture content, resin level, press temperature, and bond time on lap-shear strength and consisted of a fractional factorial experimental design that minimizes the number of samples needed to determine the effects of these factors. The design of experiment (DOE) for this

study is listed in Table 1. Due to logistics, randomizing the press temperature sequence was not practical, and this parameter was treated as block variable and the block sequence randomized. These strands were 24.5 mm wide, uniformly coated with resin on only one face, and had a lap-length of 25.4 mm.

Study 2 was also a preliminary study and examined the effect of press temperature and bond time on lap-shear strength for strands with a moisture content of 9.1 wt% and a resin level of 5 wt% using a response surface, full-factorial design with 2 replications; the DOW for this study is listed in Table 2. A total of 18 bonds were made with a strand width of 25.4 mm and a lap-length of 12.7 mm.

Study 3 examined the variability of the lap-shear strength using a response surface DOE, as shown in Table 3. The moisture content, resin level, strand width, and lap-length were the same as in Study 2. Eight bonds were made under identical conditions with a press temperature of 135°C and a bond time of 150 s and 8 more bonds made over a wider range of bond times and press temperatures.

Study 4 examined the effect of open assembly time on lap-shear strength using a fractional DOE with 8 replications. The moisture content, resin level, strand length and width, and lap-length were the same as in Study 2. Seven sets of 16 strands were coated with resin and placed in a fume-hood at 22°C and a relative humidity of 40%. Each set of strands was left in the fume-

TABLE 2. *Manufacturing sequence and factor levels for Study 2. Note that two replicates were performed for each set of conditions.*

Sequence	Bond time (s)	Press temperature (°C)
1,2	20	120
3,4	240	120
5,6	130	120
7,8	20	100
9,10	240	100
11,12	130	100
13,14	20	130
15,16	130	130
17,18	240	130

hood for predetermined intervals of 0, 1, 2, 3, 8, 16, or 24 h, after which the set was removed and tested in the ABES apparatus at 135°C for 150 s. The open time for a given set of strands was assigned randomly.

Study 5 examined the effect of bond time, resin level, moisture content, and press temperature on lap-shear strength using a full-factorial design with 8 replications for a total of 256 bonds. The bond times used were 45 and 90 s, resin levels of 1 and 5 wt%, and press temperatures of 130 and 160°C. Four levels of strand moisture content were used: 6.9, 9.1, 13.9, and 22.8 wt%. The strand width was 20 mm and the lap-length 10 mm. For convenience, the study was carried out in two parts as two full-factorial designs with full resolution of all 2 level interactions. The moisture content of the strands for the

TABLE 1. *Manufacturing sequence and factor levels for Study 1.*

Sequence	Moisture content (wt.% odw)	Resin level (wt.% odw)	Bond time (s)	Press temperature (°C)
1	9.1	9	20	140
2	22.8	1	130	140
3	0.0	5	240	140
4	9.1	5	130	130
5	22.8	9	240	130
6	0.0	1	20	130
7	22.8	5	20	150
8	9.1	1	240	150
9	0.0	9	130	150

TABLE 3. *Manufacturing sequence and factor levels for Study 3.*

Sequence	Bond time (s)	Press temperature (°C)
1–8	150	135
9	65	135
10	235	135
11	90	150
12	210	150
13	150	156
14	150	114
15	90	120
16	210	120

first part was 6.9 and 13.9 wt% and the second part with 9.1 and 22.8 wt%.

RESULTS AND DISCUSSION

The moisture contents of the conditioned strands were found to be 6.9, 9.1, 13.9, and 22.8 ± 0.2 wt%. Note that the precision of a value when given corresponds to a 95% confidence interval calculated using a pooled estimate of the standard error. The statistical properties for a batch of 60 strands coated with a nominal 5 wt% resin level are listed in Table 4 and show that the precision of the resin content is ±0.2 wt%.

The lap-shear strength results of Study 1 were analyzed by performing a one-way ANOVA analysis for each factor; the results of each analysis are listed in Table 5. Examination of the p-value for each factor shows that only moisture content significantly affects strength (p-value = 0.022). To determine which moisture content levels are significantly different, the results were further examined using a Tukey-Kramer analysis with an α-value of 0.05. Only the oven-dry samples have significantly lower strengths than either the 9.1 or 22.8 wt% moisture content bonds, with neither of the higher moisture contents having significantly different strengths. The lap-shear strength of the 9.1 wt% moisture content bonds is approximately eight times that of oven-dry bonds.

TABLE 4: *Resin level distribution characteristics of 60 strands coated with 5 wt% resin.*

Parameter	wt % odw
Mean	5.28 wt%
Standard deviation	0.72 wt%
Standard error mean	0.09 wt%
Upper 95% mean	5.46 wt%
Lower 95% mean	5.09 wt%

Although dry furnish favors urethane formation (Frazier et al. 1996), these bonds were pressed up to a maximum of only 240 s. This may be far less time than is needed to create the urethane linkages or for the polyurea and biuret network to fully form. Indeed, Wendler and Frazier (1996a) pressed wood flakes at 120°C for 60 min and produced bonds with sufficient strength to hold the flakes together. Based on this, one can conclude that the oven-dry strands used in this study might have bonded if pressed long enough. Thus, although urethane linkages are likely present, it is clear that there must be sufficient water in the system to enable the polyurea and biuret network to fully form within the pressing time used. If the polyurea and biuret network are not fully formed, this will limit their ability to transfer load across the interface.

The lap-shear strength results for Study 2 were also analyzed using one-way ANOVA analysis and are listed in Table 6. In this case, the

TABLE 5. *Summary of one-way ANOVAs for each factor in Study 1.*

	Summary of group averages for each factor				Single factor ANOVA analysis for each factor					
Factor	Group	Count	Average* (MPa)	Variance (MPa)²	Source of variance	Sum of squares	Degrees of freedom	Mean square	F-ratio	p-value	F-critical
	20 s	3	0.354	0.102	Between groups	0.369	2	0.185	0.889	0.459	5.143
Bond time	130 s	3	0.840	0.227	Within groups	1.246	6	0.208			
	240 s	3	0.682	0.294	Total	1.615	8	0.202			
	1 wt.%	3	0.665	0.334	Between groups	0.007	2	0.004	0.014	0.986	5.143
Resin level	5 wt.%	3	0.612	0.284	Within groups	1.607	6	0.268			
	9 wt.%	3	0.598	0.185	Total	1.615	8	0.202			
	0 wt.%	3	0.122	0.022	Between groups	1.166	2	0.583	7.797	0.022	5.143
Moisture content	9.1 wt.%	3	0.812	0.133	Within groups	0.449	6	0.075			
	22.8 wt.%	3	0.942	0.069	Total	1.615	8	0.202			
	130°C	3	0.743	0.406	Between groups	0.072	2	0.036	0.141	0.872	5.143
Press temp	140°C	3	0.526	0.275	Within groups	1.543	6	0.257			
	150°C	3	0.606	0.091	Total	1.615	8	0.202			

* mean lap-shear strength.

bond time was found to have a significant effect, with press temperature being only borderline significantly different. After performing a Tukey-Kramer analysis of these data, it was found that only the 20 s bond time is significantly different from the others. Close examination of the samples during pressing did reveal differences in their pressing behavior. The bonds made at 100°C were very weak, with the strands falling apart as the press opened. It was also observed that almost no steam was produced at this press temperature. Bonds made at the higher press temperatures, where steam was expelled from the strand ends, had much higher strengths. Although only borderline significantly different (p-value = 0.079), the strength values trend upward with both bond time and press temperature. These results were interpreted as follows: At low temperatures, close to 100°C, more time is required to evaporate the absorbed moisture and steam percolates slowly through the bond region and comes into contact with the pMDI-resin. At higher press temperatures, more thermal energy is available and the absorbed moisture vaporizes more rapidly while simultaneously forming more polyurea. Based on these results, it was concluded that the formation of a polyurea network is necessary to support measurable loads.

Studies 1 and 2 were preliminary studies to identify a processing window that would produce bonds with measurable strengths. The DOE for Study 3, Table 3, is a response surface design and was undertaken to estimate the variability of the lap-shear strength and examine the effect of higher press temperatures over a narrower range

of bond times. The DOE has 8 replicates under identical conditions and another 8 that cover a range of factor levels. The mean lap-shear strength of the first 8 bonds was found to be 1.61 ± 0.14 MPa with a standard deviation of 0.20 MPa and a standard error of 0.07 MPa. The range covered by the 95% confidence interval corresponds to ±9% of the mean lap-shear strength; thus only 8 samples are needed to detect a difference of this magnitude.

The inclusion of the other 8 bonds (9–16 in Table 3) with the first 8 bonds permits a number of different analyses to be performed on the data. The significance of bond time and press temperature can be seen from the two one-way ANOVA analyses listed in Table 7. Comparing the p-values for each analysis, only the press temperature has a significant effect. In Study 2, press temperature did not have a significant effect, whereas the bond time did. Although it may be tempting to attribute that difference to the temperature range studied, one must remember that the results of Study 2 were based on only 9 bond samples with no replication. This study has twice that number and is therefore a more reliable description of the true bond behavior. A Tukey-Kramer analysis of the data showed that the only significant differences are between the 114 and 120°C bonds and the 156°C bonds (there is no significant difference between the 114 and 120°C bonds) leading to the expected conclusion that higher press temperature result in higher bond strengths.

The DOE of this study permits a contour plot of the lap-shear strength as a function of bond time and press temperature to be generated (Fig.

TABLE 6. *Summary of one-way ANOVAs for each factor in Study 2.*

Summary of group averages for each factor					Single factor ANOVA analysis for each factor					
Factor	Group	Count	Average (MPa)	Variance (MPa)^2	Source of variance	Sum of squares	Degrees of freedom	Mean square	F-ratio	p-value	F-critical
Bond time	20 s	6	0.055	0.004	Between groups	1.645	2	0.825	7.56	0.005	3.68
	130 s	6	0.390	0.044	Within groups	1.636	15	0.109			
	240 s	6	0.796	0.280	Total	3.286	17	0.193			
Press temp	100°C	6	0.695	0.302	Between groups	0.942	2	0.471	3.01	0.079	3.68
	110°C	6	0.134	0.015	Within groups	2.344	15	0.156			
	120°C	6	0.412	0.152	Total	3.285	17	0.193			

TABLE 7. *Summary of one-way ANOVAs for each factor in Study 3.*

	Summary of group averages for each factor				Single factor ANOVA analysis for each factor					
Factor	Group	Count	Average (MPa)	Variance (MPa)²	Source of variance	Sum of squares	Degrees of freedom	Mean square	F-ratio	p-value	F-critical
Bond time	65 s	1	1.07	–	Between groups	0.679	4	0.170	1.002	0.447	3.35
	90 s	2	1.14	0.222	Within groups	1.863	11	0.169			
	150 s	10	1.60	0.140	Total	2.542	15				
	210 s	2	1.75	0.385							
	235 s	1	1.69	–							
Press temp	114°C	1	0.83	–	Between groups	1.603	4	0.401	4.694	0.019	3.36
	120°C	2	1.06	0.125	Within groups	0.939	11	0.085			
	135°C	10	1.57	0.062	Total	2.542	15				
	150°C	2	1.83	0.253							
	156°C	1	2.22	–							

1). Since there was no significant difference between the bond time results, the contours show in the figure only indicate trends with higher bond strengths for longer bond times and higher press temperatures.

The significance of open assembly time on lap-shear strength can be seen in Table 8. Since the p-value is less than 0.001, one can conclude that this factor significantly affects bond strength. A Tukey-Kramer analysis of these data revealed that for open assembly times of 16 h and less, there is no statistically significant difference between the mean lap-shear strengths. However, plotting these means as a function of open time, Fig. 2 shows

that lap-shear strength increases steadily with open time. Although not significantly different, the strength of the 16-h open time bonds trends upwards with the strength of the 24-h open time bonds being significantly higher. These results are interpreted as follows: 24 h of open time allows the resin to be absorbed more deeply into the strand surface compared with the shorter open times. After pressing, the resin will cure to create an interphase region that is thicker for these strands compared with those strands pressed after shorter open times. One would expect that bonds
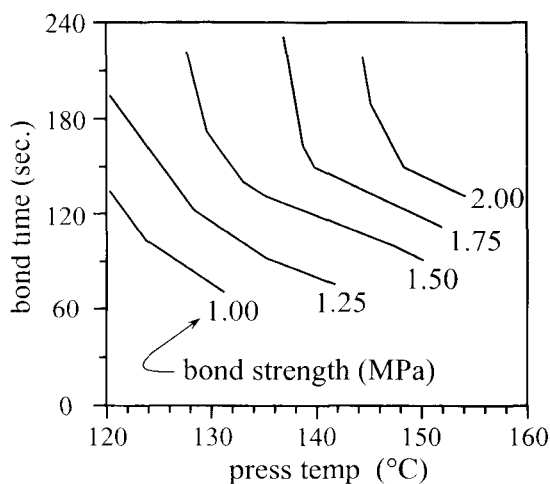

FIG. 1. Contour plot of the lap-shear strength as a function of bond time and press temperature for Study 3.
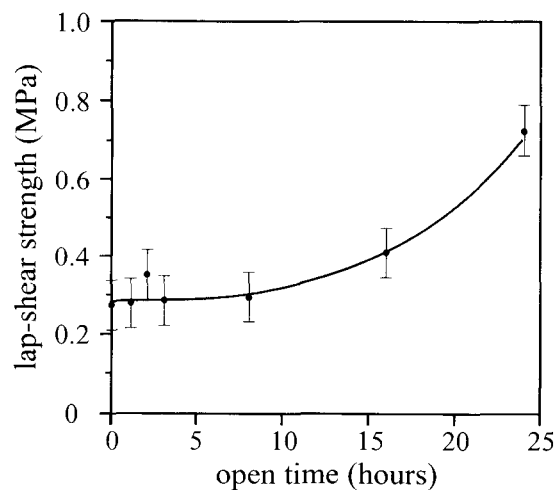

FIG. 2. The effect of open assembly time on lap-shear strength; the error bars in the figure correspond to 95% confidence intervals that the true mean lies within that range and is calculated using a pooled estimate of error variance.

TABLE 8. *Summary of one-way ANOVAs for each factor in Study 4.*

Summary of group averages for each factor					Single factor ANOVA analysis for each factor					
Factor	Group	Count	Average (MPa)	Variance (MPa)²	Source of variance	Sum of squares	Degrees of freedom	Mean square	F-ratio	p-value	F-critical
Open assembly time	0 hr	8	0.2808	0.0048	Between groups	1.271	6	0.212	20.16	<0.001	2.29
	1 hr	8	0.2875	0.0021	Within groups	0.515	49	0.011			
	2 hr	8	0.2316	0.0069	Total	1.785	55				
	3 hr	8	0.2981	0.0158							
	8 hr	8	0.3028	0.0065							
	16 hr	8	0.4209	0.0041							
	24 hr	8	0.7348	0.0340							

with thicker interphases would have higher lap-shear strengths than bonds with thinner ones. Thus, the open assemble time effect show in Fig. 2 may be indirect evidence of the formation of inter-penetrating networks of polyurea within the woody material.

Study 5 was similar to Studies 1 and 2, but with a total of 8 replications for each condition. An ANOVA analysis of the results is shown in Table 9. The overall lap-shear strength results for the first-order effects are compared in Fig. 3. These lap-shear strengths are slightly higher than those in either Study 1 or 2, and may be the result of the smaller overlap area in this study. The lap-shear strength increases with increasing

bond time, moisture content, and press temperature, generally in agreement with the trends observed in Studies 1 and 2. Interestingly, the lap-shear strength decreases as the resin level increases from 1 to 5 wt%. This suggests that it may be possible to make OSB with low resin levels if the strands can be uniformly coated with resin, although it would be expected that other properties such as thickness swell would be reduced. In practice, the amount of resin used for a given product will be determined by choosing a resin level that minimizes cost while still achieving a set of predefined board properties.

A more in-depth understanding of the results can be obtained by examining the interactions,
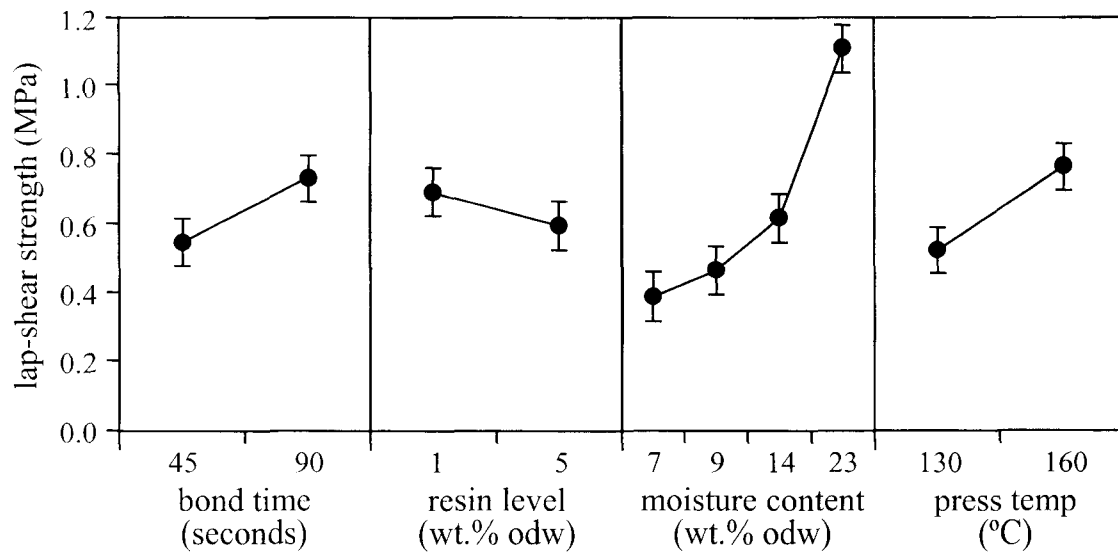

FIG. 3. The overall mean lap-shear strength results as a function of the experimental parameters for Study 5.

TABLE 9. *Summary of one-way ANOVAs for each factor in Study 5.*

	Summary of group averages for each factor					Single factor ANOVA analysis for each factor					
Factor	Group	Count	Average (MPa)	Variance (MPa)^2	Source of variance	Sum of squares	Degrees of freedom	Mean square	F-ratio	p-value	F-critical
Bond time	45 s	128	0.552	0.101	Between groups	2.173	1	2.173	14.05	<0.001	3.88
	90 s	128	0.736	0.208	Within groups	39.29	254	0.155			
					Total	41.47	255	0.163			
Resin level	1 wt.%	128	0.693	0.142	between groups	0.618	1	0.618	3.841	0.051	2.64
	5 wt.%	128	0.595	0.180	Within groups	40.86	254	0.161			
					Total	41.48	255	0.163			
Moisture content	6.9 wt.%	64	0.388	0.030	Between groups	20.03	3	6.675	78.46	<0.001	3.88
	9.1 wt.%	64	0.465	0.046	Within groups	21.44	252	0.085			
	13.9 wt.%	64	0.616	0.036	Total	41.47	255	0.163			
	22.8 wt.%	64	1.107	0.228							
Press temp	130°C	128	0.524	0.081	Between groups	3.690	1	3.691	24.82	<0.001	3.88
	160°C	128	0.764	0.216	Within groups	37.77	254	0.149			
					Total	41.47	255	0.163			

or second-order effects, between the parameters. The results of an ANOVA analysis that examines all possible second-order effects are listed in Table 10 and permit the probability of specific interactions to be compared statistically—note that only significant interactions with p-values less than 0.05 are listed.

Although the p-value indicates the statistical significance of the interaction, these results are more easily compared graphically, as shown in Fig. 4. The numerical values at the bottom of each column in the figure are the levels of the factor listed in that column with which those bonds were made. The numbers to the right of the means within a cell refer to the levels of the factor listed in that row with which the bonds were made. The

TABLE 10. *Interaction results for Study 5.*

Source	Degrees of freedom	Sum of squares	F-ratio	p-value
resin level	1	0.250	4.87	0.028
moisture content	3	1.110	7.21	<0.001
bond time × moisture content	3	0.600	3.90	0.001
resin level × moisture content	3	0.413	2.68	0.047
press temperature	1	0.225	4.38	0.037
moisture content × press temperature	3	1.472	9.57	<0.001

range of the error bars associated with each mean corresponds to 95% confidence intervals that the true mean for that condition lies within that range—two means are significantly different if the intervals do *not* overlap. If the lines connecting the means of each level of treatment are parallel, there is no interaction between these parameters, and the effect of each parameter is additive. If the lines converge, there is a slight trend, the magnitude of which is not sufficient to make them significantly different. If the lines cross, the interaction is significant.

From the figure, neither the bond time nor the press temperature has any significant interaction with the other parameters. For bond time, the confidence intervals of the resin level means overlap, showing that there is no significant difference between 1 and 5 wt%. The means for the press time are significantly different at 90 s and borderline significantly different at 45 s. Moisture content has the largest effect on bond time with the means at 22.8 wt% being significantly higher than all other moisture contents; the mean strengths of the lower moisture content bonds are clustered together with only a borderline significant difference between the 6.9 and 13.9 wt% moisture content means at the 90-s bond time. The results in the press temperature column are similar to the bond time column with the moisture content having the largest effect.
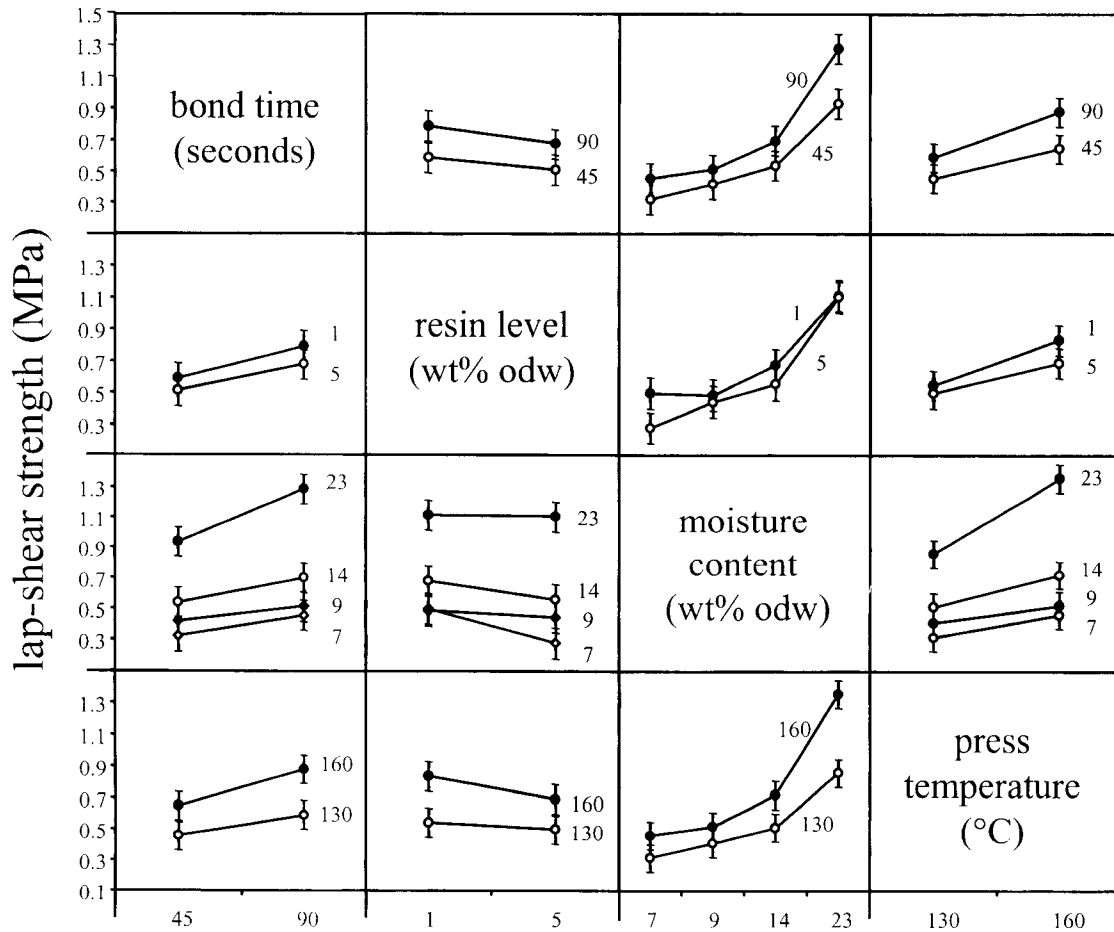
FIG. 4. Interaction plot for Study 5.

The results for the resin level are somewhat different with the lines connecting the 6.9 and 9.1 wt% moisture content means converging at the 1% resin level. The next column compares the effect of moisture content on the other factors. The means for the 45- and 90-s bond times are not significantly different for moisture contents less than 22.8%. Similar behavior is also observed for the press temperature where there is no significant difference between the means for moisture contents less than 13.9 wt%. Both of these parameters behave similarly at low moisture contents with significant differences at high moisture contents. The opposite trend is observed for resin level where there is a significant difference between the 1 and 5 wt% levels for the 6.9 wt% moisture content, and no significant differences at higher moisture contents. Together, these results show the strong interaction between moisture content and resin level. Small amounts of resin applied to strands of high moisture content produce strong bonds, whereas large amounts of resin on dry strands produce only weak bonds. Both scenarios are two aspects of the same local condition within the interface. At low MC or with excess resin, unreacted resin remains within the bondline, resulting in an IPN with a limited number of linkages across the interface and correspondingly lower bond strength.

CONCLUSIONS

In light of this investigation, the following conclusions can be drawn:

1. Lap-shear strength was found to increase with press temperature, bond time, and moisture content, and decrease with resin level within the limits of the test conditions for this study.
2. Lap-shear strength was found to increase monotonically with moisture content.
3. The highest bond strengths were for those strands coated with lowest resin levels and highest moisture contents. Based on this result, it was concluded that a substantial polyurea network must be formed in order for pMDI to bond wood particles together with significant strength.
4. There is a very pronounced open assembly time effect with lap-shear strength values increasing substantially after 16 h of open time.

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