

# EFFECT OF EXTENDED MAT OPEN ASSEMBLY TIME ON PROPERTIES OF OSB BONDED WITH PMDI

*Kate E. Semple*†

Post Doctoral Fellow

*Emmanuel K. Sackey*

Graduate Research Assistant

*Hamid R. Fakhri*

Graduate Research Assistant

*Trevor McConchie*

Research Assistant

and

*Gregory D. Smith*†\*

Assistant Professor

Department of Wood Science

FSC 2935-2424 Main Mall

University of British Columbia

Vancouver BC Canada V6T 1Z4

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## ABSTRACT

In this study, the effect of increasing mat open assembly time on the strength properties of oriented strandboards bonded with polymeric methylene diphenol di-isocyanate (pMDI) resin was examined. Isocyanates are more sensitive to open assembly times than other resin systems such as phenol formaldehyde (PF), and the storage capacity of pMDI-blended wood furnish is believed to be no more than about 5 h. On the other hand, previous research works on bonding of wood elements with pMDI allude to the growth of an interpenetrating network (IPN) of cross-linked polyurea as being responsible for the high bonding capacity with pMDI and that this is enhanced with long pre-cure times (greater than 10–15 h). There was no evidence that this effect enhances the strength of OSB made from shortleaf pine, as boards pressed after a delay of 10 or more hours after blending were significantly lower in internal bond (IB) strength than those pressed within half an hour of blending. However, after a reduction of approximately 28% between 0 and 10 h, IB remained relatively stable with open assembly times up to 18 h, suggesting the potential for recycling such strands by partial substitution of them with freshly blended strands. The discrepancy between our findings and the pMDI bonding theory based on previous small-scale laboratory experiments was thought to have arisen from differences in resin distribution on the strands due to their different methods of application, and the cure temperature and moisture conditions in the core of boards being sub-optimal for the formation of an extensive network of fully cross-linked polyurea.

*Keywords:* Oriented strandboard, shortleaf pine, resins, polymeric methylene diphenol di-isocyanate (pMDI), interpenetrating networks, open time.

## INTRODUCTION

Manufacture of OSB commonly employs polymeric methylene diphenol di-isocyanate

(pMDI) resin in the core of boards for its rapid curing and high bond strength. The mechanism behind high bond strength with isocyanates is still subject to conjecture but is believed to be the result of chemical modification of the wood cell wall which, unlike urea-formaldehyde (UF) and

† Member of SWST.

\* Corresponding Author

phenol-formaldehyde (PF) resin systems, creates not only a physical but also a chemical interlock between strands (Deppe 1977; Chelak and Newman 1991; Frazier et al. 1996; Marcinko et al. 1994, 1998; Bao et al. 2003). Bonding between wood and pMDI takes place via several reaction pathways, two major ones being (1) through initial reactions with moisture in the wood cell wall to form a network of filler structures based on polyurea, and (2) direct reaction with hydroxyl groups on the wood constituents (cellulose, hemicelluloses, and lignin) to form urethane structures (Johns 1980; Wendler and Frazier 1996a, b; Frazier and Ni 1998; Bao et al. 2003). pMDI reacts first with available water in the system to form polyurea chains, and then any remaining pMDI reacts preferentially with ammonia groups on the polyureas to form cross-linking biuret structures, with some co-occurring reactions with wood hydroxyls to form urethanes. The presence of moisture in the wood strongly favors the formation of polyurea during curing (Wendler and Frazier 1996a). Rosthauser et al. (1997) suggested that the formation of polyurea and subsequent cross-linking via biuret structures is primarily responsible for the high bond strength of pMDI bonding in wood composites, which was based on their finding no significant difference observed in the internal bond strength (IB) of pMDI-bonded boards formed with and without urethane linkages to wood hydroxyl groups. The chemistry at the bondline, i.e. the balance between polyurea, biurets, and urethanes, through the thickness of boards will likely vary considerably because it is strongly affected by factors such as phenolic content of the wood, moisture availability, cure temperature gradient, and time (Wendler and Frazier 1996a, b).

It is believed that with time, un-reacted, low molecular weight pMDI penetrates deeper into the wood cell walls and middle lamellae which when cured at high temperature form an interpenetrating network (IPN or 'interphase' region) of polyurea chains and biuret crosslinks embedded within the network of woody polymers, which bridges across to a similar network in the subsurface of an adjacent wood element (Mar-

cinko et al. 1994; Rosthauser et al. 1997; Bao et al. 2003). Nuclear Magnetic Resonance (NMR) spectra and comparison of dynamic loss tangent ( $\tan \delta$ ) for untreated and pMDI-treated aspen (Marcinko et al. 1994, 1999) and southern pine (Marcinko et al. 1998) revealed marked changes in molecular motion and packing configuration within the wood treated with pMDI, resulting in a stiffening of the cell wall.

Based on this, it is hypothesized that if blended OSB strands are left to stand for some time prior to heat curing, then the growth of such an IPN should result in higher bond strengths than if the blended strands are pressed immediately. If uncured resin has a longer time to seep into and react with the wood, then the IPN may become more extensive leading to higher bond strengths. In keeping with this theory, a steady increase in bond strength between aspen strands treated with pMDI with increasing delay between application and pressing was observed by Smith (2004). While there was little change in bond strength with open times up to 10 h, the greatest rate of increase in bond strength occurred with open times between 15 and 24 h. It was concluded from that study that a substantial IPN of cross-linked polyurea must be formed in order for pMDI to form strong bonds between wood flakes.

During commercial OSB manufacture, most of the blended furnish is pressed within 20 to 30 min of blending; however, irregularities in mat forming or stoppages in the process can introduce delays of up to several hours between blending and pressing. While isocyanates are known to be sensitive to extended assembly times, more so than PF resins (Johns 1980), there appears to be no published information on how board strength properties are affected by longer delay times between bending and pressing. The storage stability of wood furnish blended with pMDI at room temperature is approximately 5 h (Sachs 1997), after which blended furnish is normally discarded. This study examines the strength properties of OSB made from pMDI-blended furnish formed into mats and left exposed at ambient temperature

and relative humidity for different durations between 10 and 18 h.

The most compelling evidence that board strength may not deteriorate markedly or perhaps even improve with extended mat open assembly times comes from the abovementioned lap-shear strength study by Smith (2004). However, since most published studies and theories on pMDI bonding are based on small-scale experiments under laboratory conditions that are not necessarily representative of industrial conditions (Bao et al. 2003), it is uncertain whether this translates into increased OSB strength with increasing mat open time. The objectives of this study were to (1) test the effects of longer open assembly times on strength properties of OSB, and (2) interpret the findings in relation to the previous proposed models for pMDI bonding of wood. Better knowledge of how long pMDI-resinated OSB strands could realistically be retained prior to pressing could improve decision-making on when to discard furnish after a process disruption in a mill.

## MATERIALS AND METHODS

### *Experimental design and statistics*

A total of 24 resinated OSB mats were assembled by hand and set aside for 0, 10, 12, 14, 16, or 18 h prior to hot-pressing, and their mechanical properties—IB, modulus of rupture (MOR) and modulus of elasticity (MOE)—were tested. The fully balanced experimental design consisted of 4 replicate boards for each of 6 open times. The 6 open time treatments for replicate 1 were manufactured first, followed by those for replicate 2, and so on to avoid any time-related bias. All 24 boards were fabricated over a period of approximately 3 weeks. The effects of open time on average board density, IB, MOR, and MOE were assessed using single-factor Analysis of Variance and the statistical software JMP version 4 (SAS) to test the fixed effect of open time at an  $\alpha$ -level of 5%, with replicate and specimen acting as random effects. Statistical inference was made using Tukey-Kramer means comparisons, and for IB which is shown graphically in

Fig. 2, the least significant difference (LSD) is presented to facilitate visual comparison of means.

### *Board fabrication and testing*

Each pressed board measured  $760 \times 760 \times 19$  mm, and consisted of 7.96 kg of air-dried strands (at 6% MC) of shortleaf pine (*Pinus echinata*) measuring  $181 \times 19 \times 0.76$  mm. The strands for each board were blended in a drum blender measuring 1.52 m in diameter and 0.6 m in depth and rotated at 34 rpm. Liquid pMDI resin (Isobind 1088 from Dow Chemical) was applied at 5.5% of furnish dry weight. Resin loading was higher than normal industry practice, which is around 2% in the core of boards, in an attempt to reduce variance within the data sets and aid interpretation of results. The resin was sprayed in using a compressed air nozzle over a period of 10 min, the furnish tumbled for 10 min, followed by a settling period of 10 min. Blended furnish was evenly distributed by hand into a forming box containing 12 cells measuring 55 mm in width on a  $965 \times 762 \times 5.2$  mm steel tool plate. Approximately 60% by weight of furnish was unidirectionally oriented to form the top and bottom layers, and 40% was placed in the core and oriented perpendicular to that of the surface layers. Each assembled mat was left to sit for its allotted open time before pressing. Platen temperature was set at 200°C and boards were pressed for approximately 3 min to a target density of 725 kg/m<sup>3</sup>. The boards were conditioned for 1 week at room temperature prior to cutting and testing 48 density/internal bond test samples and 5 MOR/MOE samples per board; the cutting pattern for boards is shown in Fig. 1. Specimen sizes and testing procedures for IB and flexural properties were as specified in ASTM D1037 (2000). Test samples were conditioned for 2 weeks at 20°C and 65% relative humidity prior to testing to a final MC of 11%.

## RESULTS AND DISCUSSION

The mean values and coefficients of variation for board density, IB, MOR, and MOE for each

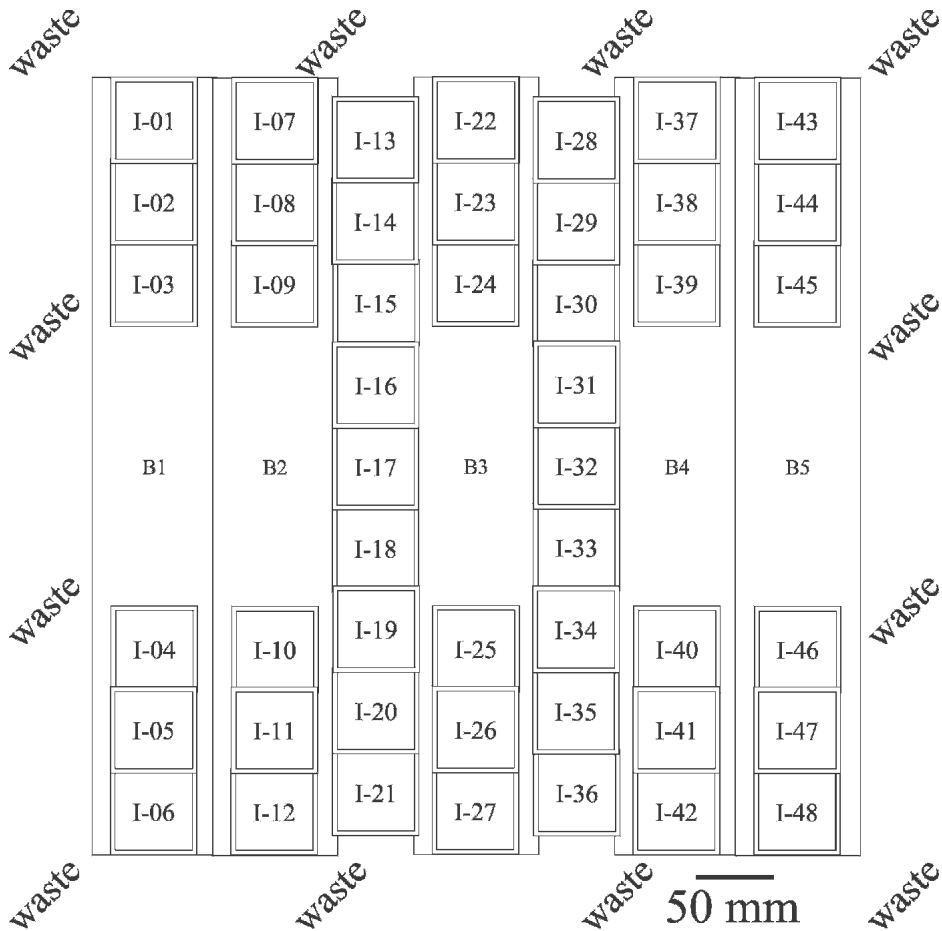


FIG. 1. Cutting pattern for OSB boards. I-1 to 48 denote internal bond (IB) strength specimens, and B1 to B5 denote MOR/MOE specimens.

of the open assembly times are given in Table 1. Board density was statistically consistent across open times, but densities were slightly higher than the board target density of 737 kg/m<sup>3</sup>.

There were statistically significant effects of mat open time on IB ( $p < 0.001$ ) and MOR ( $p = 0.039$ ), but as can be seen in Table 1, the effects of mat open time on MOR and MOE were rela-

TABLE 1. Average and coefficient of variation (CoV) for density, IB, MOR, and MOE for open assembly times.  $n = 192$  for density and IB,  $n = 20$  for MOR and MOE.

| Open time (h) | Density (kg/m <sup>3</sup> ) |         | IB (MPa) |         | MOR (MPa) |         | MOE (GPa) |         |
|---------------|------------------------------|---------|----------|---------|-----------|---------|-----------|---------|
|               | Mean                         | CoV (%) | Mean     | CoV (%) | Mean      | CoV (%) | Mean      | CoV (%) |
| 0             | 771.60                       | 6.4     | 0.97     | 29.5    | 63.9      | 16.4    | 10.00     | 10.6    |
| 10            | 785.59                       | 8.8     | 0.71     | 33.9    | 63.94     | 14.4    | 9.55      | 11.9    |
| 12            | 780.46                       | 5.7     | 0.69     | 37.4    | 60.49     | 14.1    | 9.40      | 8.8     |
| 14            | 788.25                       | 5.4     | 0.74     | 29.3    | 69.86     | 17.3    | 9.34      | 8.7     |
| 16            | 776.68                       | 5.6     | 0.62     | 35.3    | 54.24     | 13.6    | 9.12      | 8.5     |
| 18            | 762.80                       | 7.5     | 0.59     | 23.1    | 59.64     | 14.5    | 9.80      | 1.20    |

tively small. The effect of open time on IB is shown graphically in Fig. 2, whereby all of the open times between 10 and 18 h resulted in significantly reduced IB compared with 0 h. Most of the decline in strength was in IB and this occurred within the first 10 h after blending, with IB decreasing by almost 28% between the 0- and 10-h treatments. This finding supports the suggested practice in Sachs (1997) that pMDI-blended furnish should not be retained for more than a few hours after blending. The interesting thing to note is that between 10 and 18 h, there was little further decline in strength properties. The small (but not statistically significant) increase in IB strength between 10 or 12 and 14 h corresponds to the slightly higher average density of boards in this treatment (Table 1). Bond strength remained relatively stable (albeit at a reduced level) in furnish left for longer periods, suggesting that uncured pMDI droplets on wood strands retain much of their adhesive capacity. However, any specific recommendations about how long to keep OSB furnish after blending cannot be made here because it is likely that furnish with the lower resin loading of commercial products kept longer than a few hours after blending would produce sub-standard boards. However because bond strength does not de-

teriorate drastically between 10 and 18 h open time, it begs the question of whether such furnish could be recycled by re-mixing with freshly blended furnish, and in what ratio, without compromising board properties. This is worthy of further investigation.

Our results for OSB made from shortleaf pine wood contrast with the findings of Smith (2004) for aspen wafers uniformly coated with pMDI, the differences in method of resin application and the resulting distributions being a possible contributing factor. Our study differed from that of Smith (2004) whereby we blended the strands with adhesive in a manner that is much closer to that found in the industrial setting, resulting in non-uniform distribution over strand surfaces. Strands are spot-welded together largely by isolated small droplets of resin on one surface contacting an adjacent, usually resinless surface. The high bond strength produced in boards pressed immediately after mat formation and blending (pressing actually took place approximately 30 min after blending accounting for hand assembly of mats) is likely aided by the high wettability of pMDI providing intimate contact on and just beneath the wood surface within a very short time, which contributes significantly to bond strength (Shi and Gardner 2001). In addition, the NMR spectra for pMDI-treated southern pine by Marcinko et al. (1998) provide evidence that pMDI rapidly interacts at the molecular level with wood cell-wall constituents. When wood is treated with pMDI and cured immediately, reactions with surface and sub-surface moisture result in very rapid formation of high molecular weight polyurea, leaving less of the low molecular weight unreacted pMDI to retreat further away from the bond interface (Bao et al. 2003). With the high seepage rate of pMDI into the wood and at such low levels of resin application and spread, further delay between resin application and pressing may have resulted in 'starving' of the glue-line between adjacent wood surfaces.

Another reason for the discrepancy between the expected increase in bond strength with time and our results may have been the cure conditions. NMR spectra for pMDI-treated southern

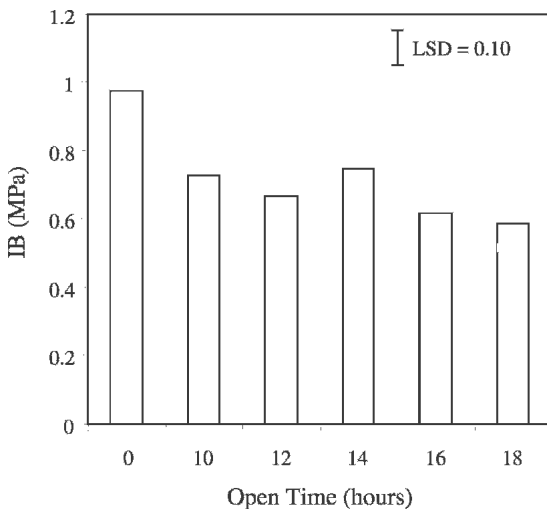


FIG. 2. Average internal bond (IB) strength for each of the six mat open assembly times. Means may be compared using the LSD (least significant difference) bar.

pine samples by Bao et al. (2003) found a high percentage of polyurea and biuret cross-linking structures only when wood moisture content and cure temperatures were high, i.e. 14% and 220°C. This may also have been reflected in the results of Smith (2004), who found significantly higher bond strength at wood MC above 14% and at higher cure temperature (160°C). In industrial processing of OSB, and in our case, the wood MC is much lower (4 to 6%); and the temperature in the core is ambient during the open assembly time and mostly between 100 and 160°C during pressing. For similar conditions, even during pressing, Bao et al. (2003) found low percentages of biuret structures when wood MC was 7% and cure temperature was 160°C. This suggests that at core moisture and temperature conditions similar to those found in the commercial production of OSB from southern pine, the model of a deeply penetrating network of polyurea cross-linked by biuret structures may not fully explain bond strength, at least within the narrow processing window normally encountered during OSB manufacture.

According to Frazier and Ni (1998), the formation of the IPN, which is contingent upon swelling and plasticization of the wood cell wall, is also subject to conjecture depending on the species used. The formation of urethanes and polyurea swells and adds weight to the wood cell wall, as found in southern pine by Rowell and Ellis (1979). In contrast, Frazier and Ni (1998) found little evidence of modification of the wood cell wall of yellow poplar (*Liriodendron tulipifera*) wood. They did not discount the possibility that it could take place at a slower rate given sufficient time, i.e., several hours, but noted that with such long reaction times the IPN bonding model may have little practical relevance with respect to the rapid production rates of OSB manufacture.

#### CONCLUSIONS

1. The IB strength of OSB blended with pMDI decreased significantly by about 30% as mat open assembly time was extended to 10 or more hours. This was in contrast to the hypothesis based on previous research that the development of an interpenetrating network with time enhances bond strength. The MOR and MOE of boards were not as greatly affected by extended mat open times.
2. Results indicate that it is preferable to press pMDI-blended mats shortly after blending; but between 12 to 18 h open time there was little further change in the reduced IB values, which suggests there may be some potential for recycling furnish that has experienced an unavoidable long delay between blending and pressing.
3. Possible explanations for the discrepancy between our results and those of previous laboratory studies on pMDI bonding include uneven resin distribution on strands, and the wood moisture content and core cure temperature used in this study being lower than what is thought to be optimal for the formation of polyurea and biuret cross-linked networks deeply penetrating the wood flake substrate.

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