Soy Flour-Modified pMDI Resin Improves Wood Panel Properties by Suppressing Steam Generation

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Abstract

Soy flour (SF) tends to retain water, and its inclusion in polymeric methyl diphenyl diisocyanate (pMDI) resin leads to the absorption of some of the water in the furnish, which effectively raises the boiling point of water and inhibits the formation of steam in the mat. The role of steam inhibition was confirmed through use of sodium polyacrylate, a polymer that can hold several hundred times its own weight of water. The reduced steam generation decreases steam leakage during pressing and raises the internal board pressure. Measurements made on partially bonded panels during the early stages of pressing show that SF increases bond strength (which could potentially reduce press time), reduces press blows, and decreases springback. The vertical density profiles of fully developed boards also improve. The warp of thin wood pieces bonded with pMDI when exposed to humidity is reduced when SF is included in the resin. These benefits augment the previously described advantages of SF substitution in pMDI resin, namely resin cost savings, increased cold tack, reduced platen sticking, and higher board strength.

Soybean derivatives have been used as components of bioadhesives for bonding decorative hardwood plywood (Li 2007, Frihart and Satori 2013), and their use in other panel products has been proposed. Much has been written on the chemical basis of soy adhesion and the chemistry of soy interaction with conventional adhesives such as pMDI (Vnucec et al. 2017, Dunky 2020). The level of soy flour (SF) substitution in pMDI is limited to about 15 percent, beyond which the panel wet strength deteriorates (Asafu-Adjaye et al. 2020a). During hot pressing, heat from the platens is carried into the mat core through sequential evaporation/condensation cycles (Wei et al. 2016). However, these cycles will only occur near the platen surface where the temperature is high enough to overcome the boiling-point elevation caused by the press pressure. Steam generation depends on the applied pressure, which affects the boiling point of water. In other words, a pressure-cooker effect applies at high pressure where boiling is inhibited. For example, if the pressure within the mat is 2 MPa, then the corresponding boiling point of water is 212°C as per the steam tables. If the local temperature is lower than 212°C, then the water will be mostly present as a superheated liquid and will flash into steam only when the pressure drops, e.g., when the press opens, or at the edges of the board.

Now consider a situation where a water-retaining component such as SF or sodium polyacrylate (PA) is mixed with the adhesive. The additive will retain water, which will, in effect, raise the boiling point of water to compensate for the binding energy of water to the solid. The higher boiling point will reduce steam generation, which can improve several board properties. When the press is fully pressurized, the water in both soy-treated and control boards will exist as a superheated liquid; when it opens, more of the water in the control board will flash to steam because of its lower boiling point. In this paper we confirm the importance of water retention by using PA, a superabsorbent polymer that

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can absorb several hundred times its own weight in water (Ostrand et al. 2020, Asafu-Adjaye et al. 2023).

Materials and Methods

Pine strands (5% moisture content [MC]) and pMDI resin were provided by Huber Engineered Woods. Softwood fiber (11% MC) was obtained from Georgia-Pacific. Flakeboard panels were made with flakes conditioned for 96 hours at 20°C and 65 percent relative humidity. Wax (1%), followed by resin (4%), were sprayed onto the wood strands (or fibers in the case of fiberboard) in a rotating blender. The resin was either pMDI or mixtures of pMDI and SF (7B), soy protein (Arcon F), or PA, where the additives were substituted in the pMDI resin. Both soy products were obtained from Archer Daniels Midland. PA was added to pMDI at 0.4 percent of the resin mass, which is equivalent to 0.016 percent of fiber mass. The resinated flakes were formed without orientation into 43 by 43-cm panels and pressed for 5 minutes at 200°C and 2 MPa to a pre-set thickness of 11 mm. The press time was shortened for the delamination work to highlight the onset of delamination. X-ray vertical density profiles (VDP) were measured at Huber's Commerce, Georgia facility. Measurements of internal mat pressure were made with a Tekscan Flexiforce sensor (HT 201), which was placed in the core of a 12.7 by 12.7-cm fiber mat. The sensing area and thickness of the device is 9.53 mm and 0.2 mm respectively. It was assumed that these dimensions are too small to significantly interrupt heat and mass transfer within the board. Lap shear strength was measured ($n = 7$) to determine the effect of SF and protein on early bond development. Wood samples (107 by 23.4 by 6.8 mm, 10% MC) were pressed at 200°C and 2 MPa. The resins used were applied at a spread rate of 200 g/m^2.

Springback of flakeboard was measured as the difference between edge thickness after pressing and the target thickness of 11 cm. The press time was 1.5 to 2 minutes, which is less than the ~5 minutes typically required for the board to achieve its full strength under our conditions. The shorter pressing period was used because the springback of the fully cured boards was small, whereas it was amplified when the resin was only partially cured.

For the warp measurements, two 11 by 11 by 2.17-mm pieces of yellow poplar veneer were bonded with 80 g of resin, either pMDI or pMDI with 15 percent SF substitution. The veneers were pressed at 1.4 MPa for 5 minutes at 200°C. The bonded wood was placed on plastic cups containing 100°C water and then cooled over 10 minutes, after which the warp was measured. The wood samples eperienced a much higher humidity on its lower surface. The warp of the control and soy-treated samples decreased overnight to the point where they were indistinguishable from each other.

Results and Discussion

Internal board pressure of fiber mats

Measurements were made on mats prepared without resin. Steam release during the late stages of the press schedule and during press opening was visibly pronounced for mats made with fiber only, followed by those containing SF. Steam emission from the PA boards was minimal. Clearly, SF and PA retained water and suppressed its conversion to steam. Internal pressure profiles are illustrated in Figure 1. The fiber-only mat displays the lowest pressure because the internal pressure was partly relieved by the escaping steam during pressing. Because SF and PA both retain water, they retard steam generation, and the internal pressure remained elevated. The effect of PA was most apparent in the visuals; very little steam was seen to escape from the PA-treated boards. Less steam was released despite the higher internal mat pressure because the mass transfer of superheated water through the partially cured board is more difficult than the corresponding movement of steam. The escape of steam lowers the internal pressure for the control (soy-free) boards.

VDP of fiberboard

VDP results are shown in Figure 2. Soy substitution evens out the VDP, which improves product quality. The presence of water appears to enhance the effect as shown by the red and blue traces in Figure 2. The presence of SF raises the minimum density from ~500 to ~630 kg/m^3. Because density is related to strength, a higher density should also increase strength. Also, because the board is more even, stress concentrations will be lower. The best outcome is obtained when water is added to the soy (blue line) as compared with the result with the addition of dry SF (red curve). The effect of water on VDP was previously reported by Candan et al. (2012), although their conditions were very different from those used here. When panels are pressed with pMDI only, the moisture from the face layer is driven to the core. Hence, bonding occurs initially in the face layer and only later in the core. The uneven bonding profile leads to a proportionally uneven VDP. Because the SF-modified resin holds water, water movement from the face layer will be attenuated. Bonding will then be more even across the panel and a more uniform VDP should result. The VDP improvement was validated in several full-scale commercial trials with medium-density fiberboard.

Delamination of flakeboard

The pressure measurements described above indicate that SF and PA absorb water in the interior of the board

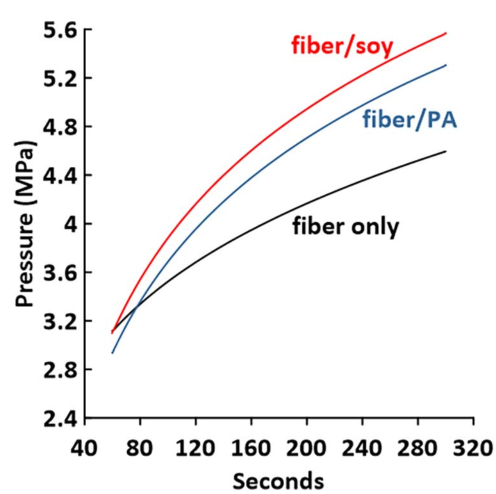

Figure 1.—Internal pressure of resin-free fiberboard during pressing.

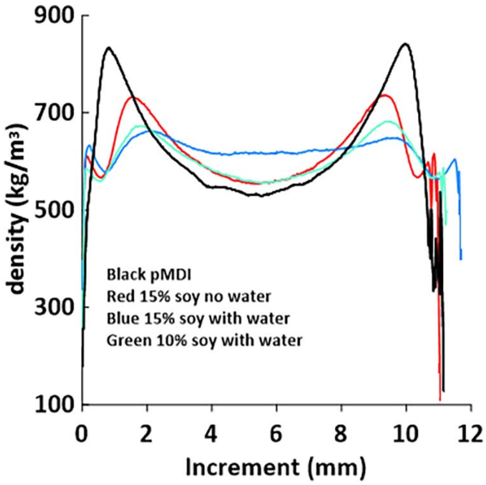

Figure 2.—Vertical density profiles. Moisture contents of the black, red, blue, and green curves were 5.4, 6.2, 10.6 and 6.1 percent, respectively.

during pressing, thereby reducing steam formation. This should also reduce the frequency of press blows (delaminations) when the press opens. We demonstrated this by (1) substituting pMDI resin with 15 percent powdered SF and (2) adding 0.3 percent PA to pMDI. Images of the board cross-sections taken after various press times are shown in Figure 3. The press times were chosen to be short because the fully bonded boards did not delaminate. Delamination is more likely to occur if the internal bond is less than fully developed. Clearly, SF decreases the degree of delamination. PA does so to a lesser extent probably because it is present at a much lower level than soy (0.4% vs.15%) and its effect is localized, leading to an uneven distribution of PA across the mat structure, as discussed above. Hence, the degree of delamination should be intermediate between the pMDI and pMDI-with-soy boards, as observed.

It seems paradoxical that a higher internal pressure in the soy boards (Fig. 1) leads to a lower level of delamination. The additional water retained by soy should flash to steam as the press opens, which should have led to increased delamination. The likely reason for the lower delamination is that the soy increases the internal bond strength, which counteracts the effect of higher internal pressure. Evidence for this position is available from the work of Cheng et al. (2019) where SF was found to increase the internal bond strength, modulus of rupture, and modulus of elasticity of partially pressed flakeboard.

Table 1.—Springback (%) of boards pressed with modified resins.[a]

Press time (min)	2	1.75	1.5
pMDI[b]	2.83 ± 0.01	3.11 ± 0.01	5.31 ± 0.01
4% SF[c]	2.22 ± 0.02	2.58 ± 0.02	5.27 ± 0.02
7% SF[d]	1.49 ± 0.03	2.09 ± 0.02	4.14 ± 0.04
0.4% PA[e]	2.07 ± 0.02	2.91 ± 0.04[e]	5.27 ± 0.02[e]

[a] $n = 16$.
[b] pMDI = polymeric methyl diphenyl diisocyanate; SF = soy flour; PA = sodium polyacrylate.
[c] Substituted.
[d] Added.
[e] Not statistically different from pMDI.

Springback of flakeboard panels

The degree of delamination is also reflected by the springback, the *z*-directional expansion of the board immediately after press opening. Results from the springback of panels pressed at various times are shown in Table 1. The differences between the soy-treated samples and p-MDI-bonded wood were well above the 99 percent confidence limit. However, this was not the case for all the PA values. The springback broadly tracks the degree of delamination. Also, springback correlates with strength (Mohebby et al. 2009). PA affects springback marginally (at best) because the concentration of PA is too low to affect strength. As above, we attribute the lower springback of the soy boards to a stronger internal bond.

Effect of soy substitution on early bonding

The ability of SF to retain water leads to an improvement in bond strength during early pressing. Lap shear strength was measured on samples bonded with pMDI and soy-amended pMDI resin pressed pairwise for the time periods shown in Figure 4. To compensate for pressure and other variations across measurements, the results for each pair of samples were normalized to the highest strength value in the pair. The Figure 4 comparisons demonstrate the difference in behavior between SF and soy

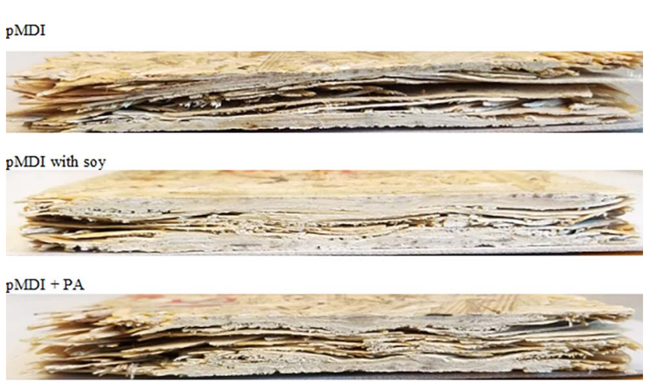

Figure 3.—Delamination of flakeboard.

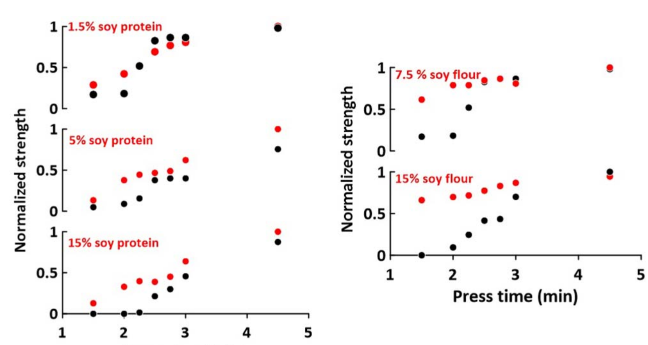

Figure 4.—Effect of soy protein (left) and soy flour (right) substitution on normalized lap shear strength. Black points represent boards bonded with only polymeric methyl diphenyl diisocyanate).

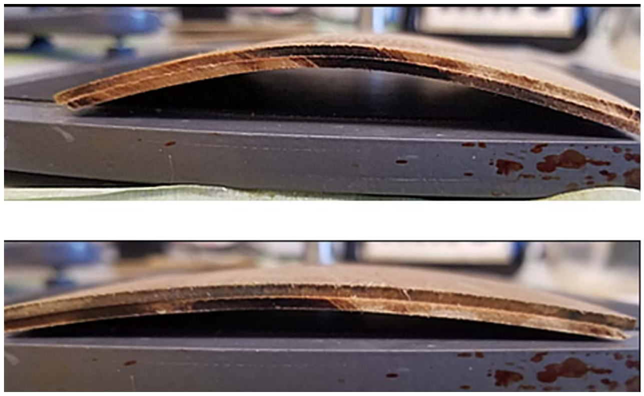

Figure 5.—Images of veneers bonded with polymeric methyl diphenyl diisocyanate (pMDI; top) and pMDI substituted (15%) with soy flour (bottom).

protein. The soy protein profiles are higher than those for pMDI, but only by a relatively small amount; the strength increase with SF is much greater at the shorter press times. SF differs from soy protein in that it can entrap water, the benefits of which have been discussed above. The practical outcome of early strength development is that the press time can likely be shortened. Because SF contains about 45 percent soy protein, its use combines the benefits of added strength provided by the protein and the water retention ability of the carbohydrate.

Effect of SF substitution on warp

Warp measurements were taken after exposing one surface of wood veneers bonded with either pMDI or 15 percent SF-substituted pMDI to high humidity. Typical images of a pair of boards are illusrated in Figure 5. The warp of the control samples averaged 10.6 $\pm$ 0.3 mm, whereas the corresponding value for the soy-substituted samples was 8.2 $\pm$ 0.2 mm ($P < 4 \times 10^{-7}$). The warp reduction induced by SF likely results from its ability to reduce the moisture gradient across the two surfaces.

Table 2.—Summary of benefits provided by substituting soy flour (SF) in polymeric methyl diphenyl diisocyanate (pMDI) resin.

Value	Reference
Reduced delamination resulting from lower internal pressure	This paper
Early bond strength development—faster pressing possible	This paper
Reduced springback and more uniform vertical density profile	This paper
Reduced warp	This paper
Increased strength and better panel properties	Asafu-Adjaye et al. 2020a
Lower resin cost—SF is cheaper than pMDI	Cheng et al. 2019
Higher cold tack—equivalent to urea–formaldehyde resin	Asafu-Adjaye et al. 2020b
Lower edge swell	Asafu-Adjaye et al. 2020a
Reduced platen sticking	Asafu-Adjaye et al. 2022a
Lower resin bleed and stronger bonding in veneer	Asafu-Adjaye et al. 2022b

Conclusions

Amending pMDI resin with SF or PA raises the internal pressure of boards during pressing, evens out the VDP, reduces springback, inhibits delamination, promotes the development of early bond strength during pressing, which could lead to a reduction in press time and increased throughput, and reduces warp. Also, as noted earlier (Cheng et al. 2019), SF promotes strength development. The effect of PA is especially striking because it is effective at a dose of only 0.016 percent of fiber mass. At this small dose PA is unlikely to affect the adhesive properties of pMDI, so its effect can be solely attributed to water retention.

The mechanism behind these benefits is the capture of mat water by SF or PA. This inhibits the formation of internal steam, which reduces delamination and attenuates heat flow (Di Maggio et al. 2020), which leads to more even z-directional bonding and a more uniform VDP. These benefits are limited to SF substitution of up to 15 percent; wet strength decreases at higher levels of soy substitution (Asafu-Adjaye et al. 2020a). Although this paper has mainly focused on the water retention effects of SF substitution, we recognize that SF also modifies the chemistry of pMDI resin, which provides added value (Hand et al. 2018). A summary of all the benefits provided by SF is listed in Table 2.

Acknowledgments

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