Effects of panel density and mat moisture content on processing medium density fiberboard

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Abstract

Development of a fundamental understanding of heat transfer and resin curing during hot-pressing will help to optimize the manufacturing process of medium density fiberboard (MDF) allowing increased productivity, improved product quality, and enhanced durability. Effect of mat moisture content (MC) and panel density on performance of MDF panels, heat transfer, internal steam pressure, and pre-curing on the surface were systematically studied in this project. Both panel density and mat MC have significant effects on the internal steam pressure and internal bonding. We found that if the maximum internal steam pressure exceeded 100 kPa (15 psi), delamination would occur. Our analysis indicated that the optimized mat MC for internal bonding performance was dependent on panel density. For low-density panels (673 kg/m^3), the optimized mat MC was between 12.1 and 15.3 percent. For medium (769 kg/m^3) and high (833 kg/m^3) density panels, the range of the optimized mat MC was narrowed and shifted to lower values. Panel density showed a positive relationship with mechanical performance, internal steam pressure, and maximum core temperature, but it slowed down the rate of temperature increase in the core and reduced the pre-cure thickness gradient (distance from face to position of maximum density). Mat MC also showed a positive relationship with internal steam pressure and the maximum core temperature.

Medium-density fiberboard (MDF) is widely used in the furniture and cabinet industries because of its excellent surface and moulding characteristics. MDF production in the United States was 2.7 million m^3 in 2002, an increase of about 14.6 percent from the previous year (Howard 2004). Fiber drying and hot-pressing are the most important and energy-consuming processes in MDF manufacturing. Many parameters affect hot-pressing time, such as press temperature, mat moisture content (MC), panel thickness, press closing speed, and resin characteristics. Developing a fundamental understanding of heat transfer into the fiber mat, its interaction with target density and MC, and its effect on resin curing during hot-pressing will help to optimize our control of the manufacturing process by increasing productivity, improving product quality, and enhancing durability.

During hot-pressing, the heat initially transfers from the hot platens to outer layers of the fiber mat by conduction and then continues to migrate toward the core. The heat raises the temperature of the wood fiber mat, plasticizing the wood fiber and curing the resin binder, which in turn adheres the MDF panel. The speed of heat penetration into the mat determines the press time, which is critical to the productivity and development of panel properties such as modulus of elasticity (MOE), modulus of rupture (MOR), internal bonding (IB), and in-service moisture sorption. The speed of heat transfer depends on a number of process variables. Many individual studies have been conducted to investigate the effect of process variables on hot-pressing, and some theoretical models have been developed to simulate the hot-pressing process (Humphrey and Bolton 1989, Kamke and Wolcott 1991, Length and Kamke 1996, Dai and Wang 2004, Frazier 2004). Mat MC prior to pressing was consistently found to be one of the most significant factors that affects the transfer of heat in the mat. Although the theoretical models provide a better understanding

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of the hot-pressing process, a simple and practical method to optimize the process would be very helpful for the wood-based composite industry (Park et al. 1999).

Many empirical studies have investigated the effect of various hot-pressing processes on the performance of various wood composites, especially particleboard and flakeboard. Significant laboratory work on MDF was also reported by Suchsland and Woodson (1986) and Woodson (1977). Relatively less published work, however, addresses the MDF hot-pressing process because we lack research facilities with the capacity to emulate industrial practice (McLaughlan 1996, Hague et al. 1999). Chow and Zhao (1992) investigated typical process relationships for MDF at a single target density of 830 kg/m^3 using phenol-formaldehyde (PF) resin and a full-factorial design with three variables (pressing temperature, mat MC, and resin content) at three different levels. They found that mat MC influenced all of the properties. However, MDF panels made with a mat having an MC of 12 percent had better average properties than MDF made from a mat having 6 or 9 percent MC prior to pressing. Park et al. (1999) conducted a similar study on MDF at a target density of 750 kg/m^3 made with PF resin with three variables (mat MC, closing speed, and platen position) at three levels. Unlike Chow and Zhao's full factorial design, Park et al. employed response surface methodology to identify the optimal output, or response, of a system as a function of its process variables. According to their study on mat MC at levels of 8, 11, and 14 percent, they found that each individual property has its own optimum mat MC. A mat MC of 13.4 percent was found to closely relate to the overall optimum mat MC for making MDF. Lee and Maloney (1995) focused on the effect of mat MC (from 5% to about 15%) on the physical and mechanical properties of urea-formaldehyde (UF) MDF panels. Lee and Maloney (1995) found that relationships between mechanical properties (MOE, MOR, and IB) and the mat MC were best fitted by polynomial regression. All regression curves were almost identical because of the scarcity of data points between the critical 11 and 15 percent MC range. They concluded that a mat MC of 13 percent was optimum mat MC for the best MOE, MOR, and IB for MDF panels with the target density of 750 kg/m^3. This result for UF MDF is very similar to what Chow and Zhao and Park et al. had observed for MDF panels made with PF resin, even though the densities of panels varied by as much as 10 percent. Hague et al. (1999) investigated the influence of various process variables on MDF properties by conducting a series of uni-variable experiments; one variable was changed while an effort was made to keep all others constant. After extensive study on resin level, wax level, mat MC, and dryer inlet temperature, they concluded that mat MC played a highly significant role in determining the IB strength and thickness swelling (Hague et al. 1999). However, they did not relate their data to MOE, MOR, and the rate of heat transfer to the core.

The objective of this study is to examine the effect of various mat MCs on manufacturing MDF panels with different densities. Specifically, this study investigated the interrelated effect of mat MC and board density on 1) performance of MDF panels; 2) heat transfer during the hot-pressing; 3) internal steam pressure; and 4) pre-curing on the surface. The results provide useful information necessary for optimizing the MDF manufacturing process by balancing product qualities and productivity.

Materials and procedures

Mixed-species wood fibers (about 20% each for white pine, birch, maple, basswood, and aspen) were obtained from a commercial fiberboard plant in northern Wisconsin. The fibers were conditioned at six different MC levels (4%, 6%, 8%, 10%, 12%, and 14%) by drying at different conditions. Liquid urea-formaldehyde (UF) resin (GP 402D32) with 65 percent solid content was provided by Georgia Pacific Resin Company (Atlanta, GA). The resin was diluted to 50 percent solids content to decrease the viscosity for better resin coverage. The diluted resin was sprayed at 310 kPa to the conditioned fibers, which were circulating at high speed in a closed-loop tube blender. The relatively dry fibers, circulating at high speed in the tube, were prevented from forming into fiber balls that were normally produced by the drum blender during the addition of the resin. This dry-tube blending process replicates more new state-of-the-art industrial rotary blending techniques because it promotes high resin efficiency and minimizes fiber bundles. Twelve percent resin, based on the oven-dried weight of the fiber, was applied for all panels made in this study. After adding resin, MC of the resinated fibers was measured using a CENCO moisture meter, which was calibrated. The levels based on ovendry weight were 10.8, 12.1, 13.7, 15.3, 16.6, and 18.5 percent, respectively.

The resinated fibers were laid up by hand into a 50.8-cm by 50.8-cm (20-in by 20-in) mat on a caul plate. The initial MDF mat thickness was about 15.0 cm and the target thickness of the panel was 1.27 cm (0.5 in). To properly position the temperature/gas pressure probe in the exact middle of the mat, half of the fibers were added to the forming box and leveled first. A small guide tube sufficient to accommodate the future insertion of the probe was then placed on top of the half-finished fiber to precisely locate the probe in the center of the mat. The rest of the fibers were then added to the mat and it was leveled. Just prior to press closing, the temperature/pressure probe was inserted from one side and the small guide tube was withdrawn out from the other side. The mat with caul plates on its top and bottom was transferred to a conventional oil-heated press (91 cm by 91 cm) with a computerized control system. The press temperature was 196°C. The press initially closed at its full capacity until it reached 108 percent of the final target thickness (1.27 cm), which took about 20 seconds Over the next 100 seconds, the mat was further compressed from 108 percent to its final thickness, at which time the core temperature now exceeded 100°C. The panel was held at the target thickness for 140 seconds before the press opened gradually over a 40-second period to release the internal steam pressure.

To examine the effect of panel density and mat MC effect on producing unsanded MDF panels, three different density (targeted at 4% MC) levels were selected: low (673 kg/m^3), medium (769 kg/m^3), and high (833 kg/m^3). Each density level had six mat MC levels (10.8%, 12.1%, 13.7%, 15.3%, 16.6%, and 18.5%). The wide range of MCs was purposely selected to examine the heat transfer, internal steam pressure, and surface pre-cure. Factorial design of the two variables with the levels indicated above resulted in 18 experimental runs. The MDF panels were usually uniform in their forming process and performance. Our experience during recent MDF panel processing at the Forest Products Laboratory (Madison, WI) indicated that our MDF panels had no significant differences in bending or IB properties for laboratory mats made

Table 1. — Physical properties.[a]

Specimen[a]	Mat MC	Target density	Actual density	Thickness	MC	MOE	MOR	IB
	(%)	(kg/m^3)		(cm)	(%)	(MPa)		
L1	10.8	673	683 (20)[b]	1.295 (0.002)	7.3 (0.2)	2787 (234)	26.8 (2.8)	0.88 (0.16)
L2	12.1	673	663 (25)	1.283 (0.002)	7.3 (0.2)	2913 (281)	29.8 (2.9)	1.15 (0.09)
L3	13.7	673	659 (17)	1.278 (0.003)	7.1 (0.2)	3008 (160)	32.0 (1.2)	1.16 (0.10)
L4	15.3	673	649 (19)	1.260 (0.003)	7.2 (0.1)	3021 (263)	28.1 (1.5)	1.15 (0.11)
L5	16.6	673	658 (20)	1.28 (0.003)	7.3 (0.1)	2945 (132)	24.1 (1.9)	0.89 (0.07)
L6	18.5	673	669 (15)	1.266 (0.002)	7.5 (0.1)	3005 (227)	26.2 (2.2)	0.72 (0.07)
M1	10.8	769	750 (20)	1.285 (0.002)	7.1 (0.2)	3452 (221)	34.4 (1.9)	1.09 (0.08)
M2	12.1	769	733 (33)	1.279 (0.002)	7.1 (0.1)	3282 (217)	32.3 (2.3)	1.15 (0.07)
M3	13.7	769	773 (17)	1.275 (0.003)	6.8 (0.2)	3472 (376)	34.7 (5.2)	1.24 (0.08)
M4	15.3	769	749 (28)	1.266 (0.002)	7.1 (0.2)	3546 (143)	34.0 (1.2)	1.07 (0.09)
H1	10.8	833	842 (12)	1.287 (0.005)	6.7 (0.0)	4078 (237)	42.2 (2.4)	1.12 (0.07)

[a]Specimens with delamination are excluded from the table.
[b]Values in parentheses are standard deviations.

using the same MC and same press conditions. Further, we also found that the temperature and internal pressure curves as recorded from the PressMan software were virtually identical for MDF (variation less than 1.5%) mats having the same MC and process variables. Since the purpose was to investigate the heat transfer, surface procuring, and internal pressure build-up, only one panel for each run was prepared in this study. Eight IB samples and four MOE-MOR samples were cut from each panel. The MOE and MOR samples were conditioned at 22°C and 65 percent relative humidity for 2 weeks before they were tested according to the American Society for Testing of Materials standard D 1037 (ASTM 2001).

Results and discussion

Physical properties in bending and IB specimens after conditioning are summarized in **Table 1**. No information is presented in the table for the panels with delaminations. The densities were measured at their tested MC (air-dried to constant weight at 65% RH). The coefficients of variation (COVs) of the tested properties were between 5.1 and 9.5 percent. The average MC of samples from bending specimens was 7.1 percent with a COV of 3.6 percent shortly after the mechanical bending test.

Steam pressure and IB

Steam is generated when the moisture within fibers on the mat surface evaporates on contact with the hot-press plates. Moisture initially migrates toward the mat core. In most laboratory and industrial processing regimens, the core steam pressure increases as steam continues to migrate from the hotter surfaces toward the cooler core. Eventually, as the core steam temperature and pressure begin to rise, they push steam outward toward the edge of the MDF mat where it escapes. When the sum of steam generated equals the sum of steam loss caused by condensation and edge flow, the core steam pressure will first reach a maximum and then begin to decline. **Figures 1** and **2** show the maximum core steam pressure (MCSP) and the time to reach the MCSP. Both panel density and mat MC have an effect on the MCSP. As expected, higher mat MC will generate more steam, and higher mat density will accelerate consolidation of the mat to further prevent steam escape. The results of statistical analysis provided a 2-parameter linear relationship ($r^2 = 0.95$) to predict MCSP (kPa) as function of panel density (kg/m^3) and mat MC (%):

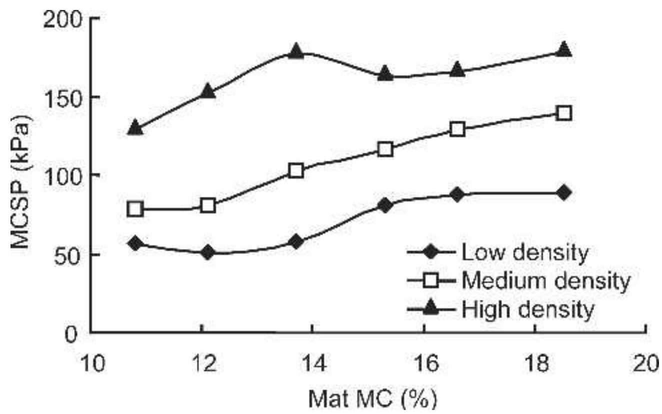

Figure 1. — Maximum core steam pressures (MCSP) for MDF mats at various MCs.

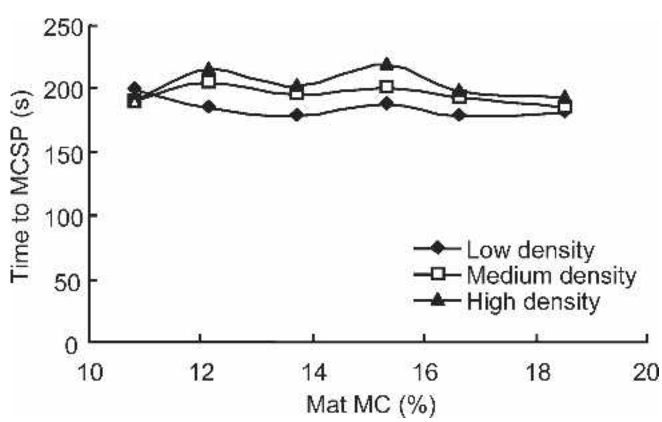

Figure 2. — Time to reach maximum core steam pressures (MCSP) for MDF mats at various MCs.

$$MCSP = -396 + 0.55 \times Density + 6.4 \times MC \qquad [1]$$

However, the mat MC had no apparent effect while the panel density had minor effect on the time to reach the MCSP (**Fig. 2**) for the size of panels made in this study.

IB between the wood fibers is developed when the applied resin is cured under elevated temperature. Generally, the resin curing is not fully completed during the designated hot-pressing cycle; thus, residual internal steam pressure could

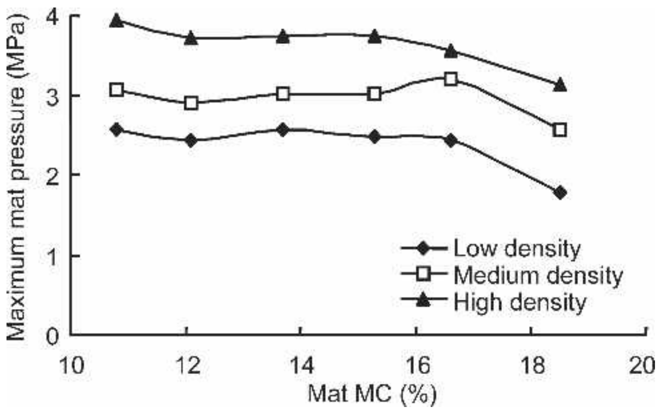

Figure 3. — Maximum mat pressure for MDF mats at various MCs.

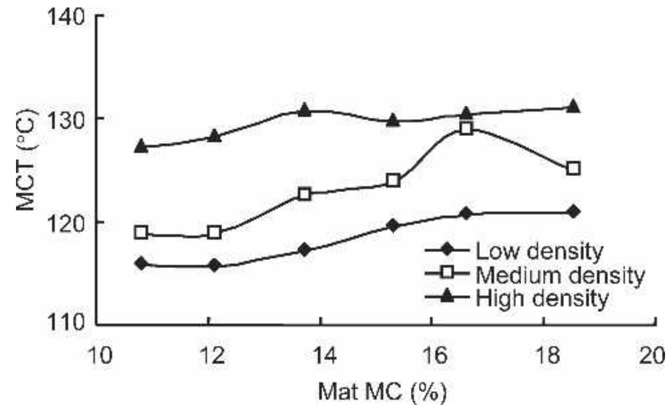

Figure 4. — Maximum core temperature (MCT) for MDF mats at various MCs.

sometimes exceed the still-developing IB strength, which caused the board to delaminate as soon as pressing pressure was released. This is often called a "blow." During the experimental design, the mat MC range was purposely selected to cover a broad range of possible mat MCs, some of which we anticipated would cause blows. These blows could have been compensated for by use of extended degassing (very slow mat pressure relief), but we believe it was critically important to evaluate fixed pressing schedules to more clearly identify mat density and MC effects without the complications of variable pressing scenarios. Future work will address these concerns.

No blows occurred in low-density panels at any designated mat MC levels, but high-density panels with MC over 12.1 percent and medium-density panels with MC over 15.5 percent each experienced a blow or delamination in the core. Thus, no mechanical properties were measured above these MC levels. As a general rule for this study on 50.8-cm by 50.8-cm (20- by 20-in) panels, we noted that if the maximum internal steam pressure exceeded 100 kPa (15 psi) before the mat pressure was released, the panel would delaminate. Although blows occurred in some of these high- and medium-density panels, the information on the heat transfer, mat MC effect, internal stream pressure, and surface pre-cure are valid and help us to better understand the fundamental process parameters.

Mat pressure

Figure 3 illustrates the maximum mat pressure generated during hot-pressing for different mat MCs and densities. The maximum mat pressure is closely related to the press capacity and pressing speed. As expected, the high-density panel needs more hydraulic power to press to the target thickness. Mat MC is usually considered as one of the major parameters that affects maximum mat pressure. Because of increased fiber plasticity with a higher mat MC, it is easier for the fiber mat to be compressed (Park et al. 1999). However, this is true for a slowly compressed mat. For the mats under fast pressing/closing speed, which is quite common in manufacturing MDF, our results indicate that maximum mat pressures are about the same below 17 percent MC. Only above a certain MC level (about 17% in this study), the increased fiber plasticity from high MCs starts to decrease the maximum mat pressure up to 25 percent. The decreasing maximum mat pressure might be a significant benefit to increase the press capacity, especially for multiple-opening presses because mat MC might be increased (up to the pressure limits found to cause blows), resulting in faster press closing caused by increasing fiber plasticity. However, the press cycle (especially the degas cycle) needs to be carefully monitored and adjusted to prevent potential delamination. To quantitatively determine the relationship between the maximum mat pressure and both mat MC and density for different materials, further studies are needed and are being conducted.

Core temperature

Core temperature of the mat during hot-pressing is the key indication of heat transfer due to conduction and convection in the mat and heat released during resin curing process. The maximum core temperature (MCT) and the time to reach MCT (started from the time when the mat reached the maximum press pressure) are important parameters that need to be understood for optimizing the MDF manufacturing processes. **Figures 4** to **6** show the MCT, time to reach MCT, and the rate of core temperature rise from 40° to 100°C, respectively. Again, the panel density has a dominating effect on heat transfer into the MDF mat. At the same press temperature and closing speed, the higher density panels have higher maximum core temperatures because of their capability to build higher internal steam pressure (**Fig. 4**). The mat MC also affects the MCT. The higher mat MC will produce more steam, which could increase the internal steam pressure. The results of statistical analysis were again used to develop a 2-parameter linear relationship between MCT (°C) and panel density (kg/m^3) along with the mat MC (%). The model (r^2 = 0.89) is expressed as:

$$MCT = 60 + 0.069 \times Density + 0.79 \times MC \qquad [2]$$

The high-density panels, however, take longer to reach MCTs (**Fig. 5**) and are slower to increase core temperature from 40° to 100°C (**Fig. 6**). The medium and low-density panels, on the other hand, have a similar time to reach MCT and similar rate of core temperature rise. The reason might be that low- and medium-density mats have more porosity in the mat and make it relatively easy for steam to penetrate/migrate to the core and high-density mats, which have both more fibers and mass, may mainly rely on heat conduction to raise the core temperature.

Mat MC is widely believed to have an influence on transferring heat from the faces to the core. Usually, the higher mat MC will increase the heat conductivity, which will speed up the heat transferring. This may also be true for the low-density mat. However, for mat MCs between 10.8 and 18.5 percent

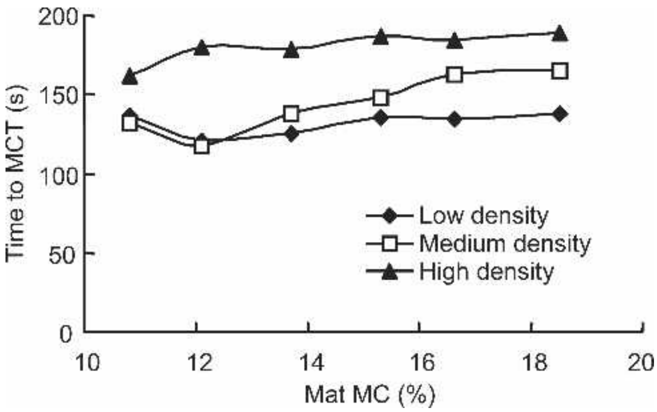

Figure 5. — Time to reach maximum core temperature (MCT) for MDF mats at various MCs.

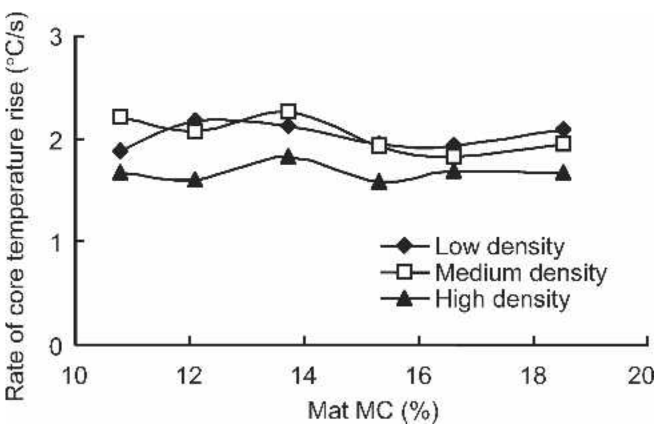

Figure 6. — Rate of temperature rise from 40 to 100°C for MDF mats at various MCs.

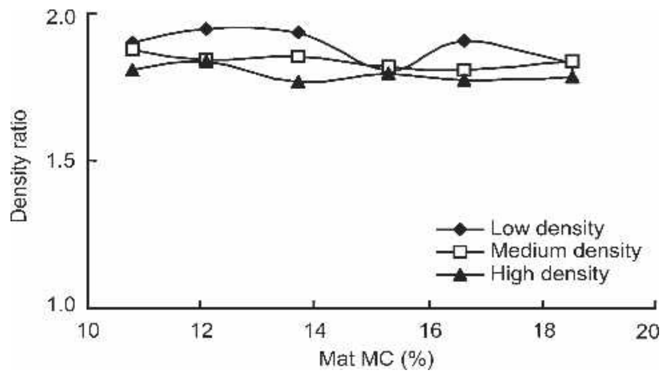

Figure 7. — Density ratios for different MDF panels.

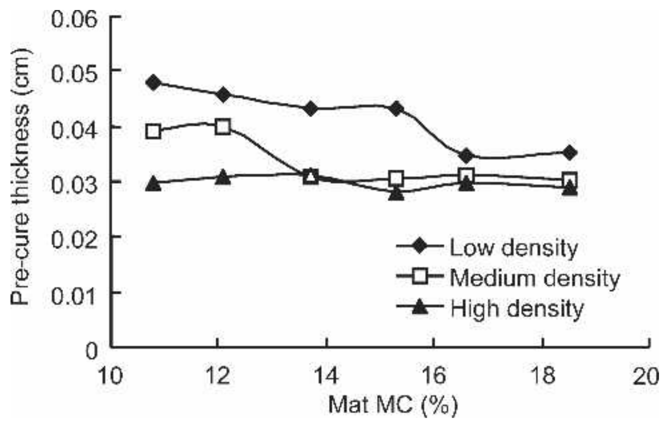

Figure 8. — Pre-cure thickness for different MDF panels.

(mat MCs that may be possible when using isocyanate resins), we expected that the mat MC would have a significant influence on the rate of temperature increase (**Fig. 6**). The mat MCs do not have a significant effect on the time to reach the maximum core temperature, except for the medium MDF panels where a higher mat MC increases the time to reach MCT. During hot-pressing, the MDF mats exhibit different mat consolidation and porosity that affects the steam vapor pressure, water evaporation, lateral steam flow, and dynamic equilibrium of these parameters. Unlike the research results on particleboard (Maku and others 1959) and flakeboards (Kamke 2004), the temperature plateau observed in this study was between 115°C and 130°C.

Vertical density profile

Although the pressing stresses applied to the mat during hot-pressing are always the same through the thickness, mat consolidation through the thickness is quite different because of gradients of heat transfer, moisture movement, and resin curing. The different mat consolidations will finally result in uneven density distribution through the thickness direction commonly referred to as vertical density profile (VDP). The VDP, which is closely related to both pressing process and mat configuration, is empirically used to evaluate the quality of panels. The face-to-core density ratio (the maximum face density divided by the minimum core density) and pre-cure thickness (defined as vertical distance from the surface to the position where the maximum face density is located in the vertical density profile) are often extracted from the VDP data to evaluate the combined effects of heat and moisture on mat consolidation and resin cure, respectively. **Figure 7** shows that both density and mat MC have no practical significant effect on the density ratio of VDP when taking density and MC variations into account. On the other hand, panel density and mat MC have different influences on the pre-cure thickness (**Fig. 8**). For low mat MCs, the higher panel density generated higher mat pressure during the initial closing stage, which dominated the surface mat consolidation. Hence, the pre-cure thickness stayed the same. For low- and medium-density panels, the mat MC along with increasing temperature affected the fiber plasticity, which in turn progressively changed the surface mat consolidation. We observed a sudden decrease (up to 25%) in the pre-cure thickness for low- and medium-density panels (**Fig. 8**). Note that pre-cure thickness of high-density panels was relatively stable as mat MC increased from 11 to 19 percent, but the low- and medium-density panels underwent a characteristic shift in pre-cure thickness at 16 and 13 percent mat MC, respectively. This indicates that careful selection of mat MC based on the target panel density could reduce pre-cure thickness up to 25 percent, which might result in a potential savings in material and sanding costs.

Mechanical properties

During the experimental design, the mat MC range was purposely selected to cover a broad range of possible mat MCs. High-density panels with MC over 12.1 percent and medium-density panels with MC over 15.5 percent each experienced a blow or delamination in the core. Thus, no mechanical properties were measured. **Table 1** shows the average value with one standard deviation of IB, MOE, and MOR for the solid panels under different mat MC conditions. Previous authors have shown that panel density has a significant effect on the mechanical properties (Woodson 1977, Hague et al. 1999). Increasing panel density was expected to improve the mechanical performance, but we found those improvements had limits and could be influenced more appropriately by various parameters. For example, when comparing the medium-density panels and the limited number of high-density panels, the IB values exhibited no significant differences. Mat MC, which determines the amount of steam generated inside the panel, seems to have significant effects on the resin cure and development of IB. For low-density panels (673 kg/m^3), IB strength as a function of mat MC demonstrates a saddle shape, as reported by many researchers (Chow and Zhao 1992, Lee and Maloney 1995, Park et al. 1999). The optimized mat MC for maximizing IB values appears to be between 12 percent and 15.3 percent. For medium-density panels (769 kg/m^3), the optimized mat MC is further narrowed down to around 13 to 14 percent. Also, our results suggest that if the mat MC exceeds 12 and 15 percent, delamination of high- and medium-density panels will probably occur. This further indicates that the overall effect of mat MC on IB is a function of the panel density. Specifically, the optimized mat MC for IB performance will be narrowed and shifted to lower MC, when the panel density increases.

Increasing panel density clearly had a substantial influence on panel MOE and MOR. The effect of mat MC (within the range of 10.8% to 18.5%) on the mechanical performance, however, is quite different. Within the range of MC that was studied, mat MC had no significantly practical influence on the development of panel MOE and MOR values considering the normal variations, although mat MC had a substantial effect on the pre-cure thickness. This is the same result as reported on polyisocyanate-bonded fiber hardboard within a mat MC between 8 to 22 percent (Hawke et al. 1992). It also coincides with the previous observation (**Fig. 7**) that mat MC has no significant effect on the density ratio, which is closely related to the MOE and MOR.

Conclusions

Effect of mat MC and panel density on mechanical properties of MDF panels, heat transfer during the hot-pressing, internal steam pressure, and pre-curing on the surface were investigated. The following results/observations were obtained:

1. The maximum core steam pressure generated during pressing was shown to be linearly related with panel density and mat MC. However, the time to reach the maximum steam pressure was not significantly related to panel density and mat MC. We also found that the problem of blows in MDF panels was a dual function of panel density and mat MC. Delamination would occur for UF-bonded MDF studied at the designated density level, when internal steam pressure exceeded 100 kPa (15 psi) at the time of press opening. For low-density panels (673 kg/m^3), we were able to make panels with mat MC up to 18.5 percent without any blows. For medium-density panels (769 kg/m^3), delamination of the panel will probably occur if the mat MC exceeds 15.3 percent. For the high-density panels (833 kg/m^3), delamination occurred in all panels except at 10.8 percent mat MC.
2. The maximum mat pressing pressure was directly related to panel density (i.e., higher density yielded higher max mat pressing pressure), but was not affected by mat MC below 17 percent.
3. The maximum core temperature was linearly related with panel density and mat MC. It also took a longer pressing time for the higher density panels to reach the maximum core temperature.
4. The pre-cure thickness as determined from VDP showed a negative relationship with both panel density and mat MC. However, the density ratios showed no direct relationship with either density or mat MC.
5. Panel density, not mat MC, positively affected MOE and MOR values. Both mat MC and panel density were observed to affect the IB. The optimized mat MC for attainment of maximum IB was narrowed and shifted to lower MC values when the panel density increased.

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