Comparison of Water Resistance for Modified Medium-Density Fiberboard

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Abstract

Commercial medium-density fiberboard (MDF) products, specifically manufactured for water resistance, were evaluated over 8 days under three water exposure regimes: 90 percent relative humidity, one-sided water spray, and one-sided wet pad. A three-cycle wet-pad and drying exposure test was also performed. Rate of swelling, extent of swelling, and irreversible thickness swelling were determined. Acetylated MDF (AMDF) had the best overall performance, followed by steam-injection pressed MDF (SMDF) and polymeric methylene-diphenyl-diisocyanate–bonded moisture-resistant MDF. The fastest rate of thickness swell and linear expansion occurred with exposure to one-sided water spray and the slowest with 90 percent relative humidity exposure. While AMDF was clearly superior after 24-hour exposure, the other MDF products were nearly identical. Significant difference in thickness swell and water absorption between moisture-resistant MDF and SMDF developed after 24 hours. Regardless of the method of water exposure, the trend of best to worst MDF performance was the same.

Resistance to water, in particular, dimensional stability in the presence of changing moisture environment, is a desirable characteristic for medium-density fiberboard (MDF). Water resistance is important for interior products, such as furniture, cabinet, and engineered flooring applications. Increasingly, MDF is placed in exterior service, such as exterior cladding and trim for building construction. MDF may encounter water by rain, pooling water, or high humidity. Liquid water then wets the surface and may be absorbed into MDF by capillary force between fibers or within cell lumens. At a much slower rate, diffusion of bound water and vapor occurs through the cell walls of fibers. Water vapor enters MDF through interfiber voids or cell lumens, or water vapor may condense and diffuse into cell walls. When water enters the cell wall, swelling occurs as water molecules are attracted to the hydroxyl groups in cellulose, hemicelluloses, and lignin. Secondary molecular bond forces cause the cell wall polymers to separate and accommodate the water molecules. Thus, swelling occurs.

Since MDF is produced by a hot-pressing process, the panel is compressed in the thickness direction. Compression is a combined effect of bending randomly oriented fibers and the collapse of cell lumens. Heat and accompanying steam (from evaporated moisture in wood) in the hot-press soften the cell walls to facilitate compression and ultimately allows for adequate fiber-to-fiber contact for adhesive bonding. While there is some viscous deformation, much of the elasticity of the cell walls is retained (Wolcott et al. 1994). Temperature and moisture content are highly nonuniform through the mat thickness during hot-pressing. Consequently, MDF forms a density profile with greater density at the surfaces and lower density in the core (called vertical density profile [VDP]). The fibers are locked into their new configuration by adhesive bonds and some weak interfiber bonding forces. Fibers are oriented largely perpendicular to the thickness direction and consequently provide significant resistance to swelling in the length and width directions (linear expansion). However, thickness swelling can be substantial when water disrupts bonding and fibers recover their shape.

MDF is manufactured using thermoset adhesives, such as urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF), and, to a lesser extent, phenol-formaldehyde (PF) and polymeric methylene-diphenyl-diisocyanate (pMDI). PF and pMDI are used to reduce or eliminate formaldehyde

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emission from MDF and improve resistance to water. Typical adhesive loading in MDF is 8 to 12 percent weight of UF or MUF resin solids per dry weight of wood. However, actual loading depends on the type of adhesive and intended product application. Loading of pMDI may be as low as 2 percent. In addition, a petroleum-based wax is added (typically 0.5% to 1.5%) to improve resistance to liquid water. Both thermoset adhesives and waxes add some degree of water resistance by reducing the surface energy of the wood fibers. However, the quantity of adhesive and wax is not sufficient to coat the fibers and form a barrier to water absorption into the cell walls.

Various research strategies have been implemented to improve water resistance of MDF ; (Li et al. 2011; Mai et al. 2016; Ahmed et al. 2020). Some of these technologies have been commercialized, including acetylation and steam-injection pressing (SIP). SIP introduces pressurized steam into the fiber mat during hot-pressing. Steam induces more viscous flow of the cell wall polymers, and less elasticity is retained in the fibers. Furthermore, SIP creates a near uniform distribution of temperature and moisture content in the mat during hot-pressing, which leads to a rather flat VDP. The result is less moisture-induced thickness swell. Adding more thermoset adhesive (particularly PF or pMDI) further enhances dimensional stability. Extira by JELD-WEN (Towanda, PA, USA) is made with SIP technology and PF adhesive. Another approach to dimensional stabilization of MDF is by acetylation of the fiber prior to manufacture. Tricoya by Tricoya Technologies Ltd (London, UK) replaces hydroxyl groups in the wood cell wall with acetyl groups, which permanently swell the cell wall and block hydrogen bonding with water (Rowell 2006). Bonding is by pMDI. Extira and Tricoya are intended for high-moisture environments and exterior applications. Other interior moisture-durable MDF products are manufactured using untreated fiber and conventional hot-pressing techniques along with enhanced loading of either MUF, PF, or pMDI adhesive systems. These moisture-resistant MDF products have greater adhesive loading than other MDF products. In the United States, moisture-resistant MDF intended for interior applications is graded and marked as ''MR'' by product standard ANSI A208.2 (American National Standards Institute [ANSI] 2016), where the ''MR'' designation requires at least a 50 percent improvement of thickness swell compared to other grades covered in the product standard. In general, moisture-resistant MDF intended for interior applications is specified in product standard ANSI 208.2 to have a maximum 5.5 percent thickness swell after 24-hour submersion in water. MDF intended for exterior cladding or trim is tested for weatherability using cyclic exposure to water submersion, drying, and freezing and 24-hour water submersion (ANSI 2020b). Grade 2 MDF by ANSI 208.7 requires maximum residual thickness swell of 10 percent after cyclic wetting, drying, and freezing and a maximum thickness swell of 5 percent after 24-hour water soak. Test specimen dimensions are different for ANSI 208.2 and ANSI 208.7.

Comparison of dimensional stability of moisture-resistant MDF products requires standardized test procedures (American Society for Testing and Materials 2020; ANSI 2020a, 2020b). The standardized tests do not capture time-dependent behavior. However, the rate and extent of swelling of different products may respond differently to the method of water exposure. Therefore, this research compared the dynamic moisture resistance of three MDF products subjected to three methods of water exposure. The water exposure methods attempted to mimic in-service conditions for typical applications of water-resistant MDF.

Materials and Methods

All MDF samples were commercial products (Table 1). Consequently, adhesive loading levels and details of the hot-pressing schedule are proprietary. MR10 is intended for interior applications where higher moisture resistance is desired. Acetylated MDF (AMDF) and steam-injection pressed MDF (SMDF) are intended for exterior applications.

All specimens (10 replications for each treatment) were cut to 28 by 28 cm and conditioned at 30 percent relative humidity (RH) and 30°C for at least 4 weeks prior to the experiment. The specimens were installed inside an environment chamber and, during separate trials, subjected to one of three modes of water intrusion: 90 percent RH, liquid water spray from above (water spray), or liquid water contact from below (wet pad). The modes of water exposure simulate potential water exposure during service life. High-humidity exposure was constant 90 percent RH and 25°C with free air circulation. Water-spray exposure consisted of specimens supported horizontally on a metal wire rack that allowed free air circulation and water-spray nozzles delivering 0.44 L/min per specimen to the top surface. The liquid water from below exposure consisted of horizontal specimens on top of saturated cellulosic pads (BLU100, New Pig Corp., Tipton, PA), which were placed in an aluminum pan that was filled with water; room conditions were 50 percent RH and 25°C. All water exposure tests were conducted for 8 days. After completion of water exposure, the specimens were oven-dried at 103°C and then reconditioned at 30 percent RH and 30°C.

Dimensions and weight were obtained at 24-hour intervals. Thickness was measured at the midpoint on four sides, with the measurement points at the extreme edge and 25 mm from the edge as well as at the center of the panel. Length was measured as the distance between the center points of two opposing edges. Specimen weight was also measured to determine the weight of water absorption and calculate moisture content. At the completion of water exposure, specimens were equilibrated at 25°C and 30 percent RH and measured to determine irreversible thickness swell.

The wet-pad exposure method was selected for cyclic water exposure testing. The steps are shown in Table 2, with steps 2 and 3 repeated three times. Three replications were

Table 1.—Summary of MDF types and specifications.[a]

Material code	Description	Nominal thickness, mm	Ovendry density, kg/m^3
MR10	Untreated fiber and pMDI	12.7	751
AMDF	Acetylated fiber and pMDI	12.0	688
SMDF	Untreated fiber, PF, and steam-injection pressing	12.7	739

[a] MDF = medium-density fiberboard; AMDF = acetylated medium-density fiberboard; SMDF = steam-injection pressed medium-density fiberboard; pMDI = polymeric methylene-diphenyl-diisocyanate; PF = phenol-formaldehyde.

Table 2.—Cyclic testing steps: steps 2 and 3 repeated three times.[a]

Step	Conditions		Time, d
	Temperature, °C	RH, %	
1	25	50	7
2	25	Wet pad and 50	4
3	40	10	3

[a] RH = relative humidity.

performed. Thickness was measured at the completion of steps 1 to 3. Thickness swell was determined using

$$\mathrm{TS}_{wi} = \frac{t_{wi} - t_0}{t_0}, \qquad i = 1, 2, 3 \tag{1}$$

where t_0 corresponds to the initial average thickness after step 1 and t_{wi} corresponds to a subsequent average thickness measurement taken after step 2 for the first, second, or third cycle. Similarly, thickness shrinkage after repeated drying cycles was determined using

$$\mathrm{TS}_{di} = \frac{t_{di} - t_0}{t_0}, \qquad i = 1, 2, 3 \tag{2}$$

where t_{di} corresponds to a subsequent average thickness measurement taken after step 3 for the first, second, or third cycle.

Statistical analysis was conducted using Tukey-Kramer (honestly significant difference) family-wise comparison procedure when the variance of the groups were not significantly different. If the variance between groups was observed to be significantly different, the pairwise comparison using t tests with nonpooled standard deviation was used. The analysis to estimate the exposure effect was conducted using the full data set, thus allowing a larger degree of variability and resulting in more conservative conclusions. The data used to estimate the material type effect were limited to the specimens that underwent the exposure type being analyzed. Significant difference was based on 95 percent confidence. Statistical analysis was conducted using RStudio (RStudio Team 2019).

Results and Discussion

Constant water exposure conditions

Figure 1 shows thickness swell results for water-spray, wet-pad and 90 percent RH exposures. Specimens exposed to water spray had the greatest amount of swelling, followed by wet pad and 90 percent RH. As expected, direct contact with liquid water causes faster absorption than exposure to water vapor. Capillary action into the voids between fibers facilitates uptake of liquid water. The water-spray condition is associated with 100 percent RH surrounding the specimen, and liquid water flows over, and comes in direct contact with the edges of the specimen, whereas the wet-pad exposure was conducted in a chamber controlled at 50 percent RH, and no liquid water was in direct contact with the edges of the specimen. Consequently, the water-spray exposure caused approximately twice the rate of thickness swelling than the wet-pad exposure.

Except for the AMDF, all specimens were continuing to swell when the test was terminated at 192 hours. At the completion of the water-spray test, AMDF had a maximum

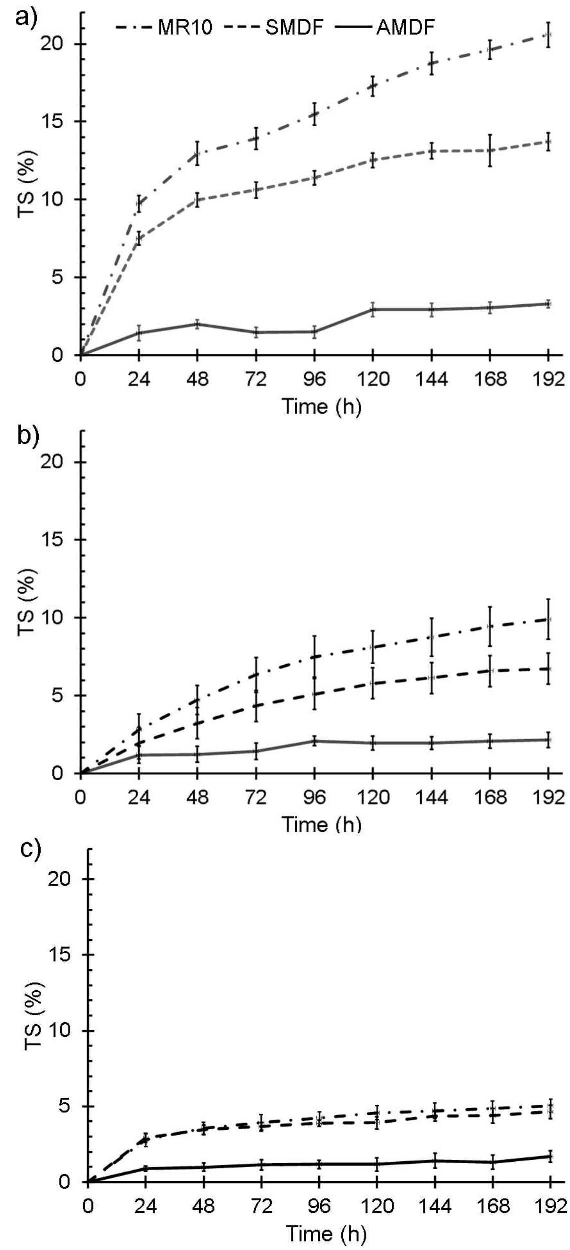

Figure 1.—Average percent thickness swell (TS) during exposure to (a) water spray, (b) wet pad, and (c) 90% relative humidity. Measurement 25 mm from edge.

thickness swell of 3.3 percent. AMDF subjected to the wet-pad exposure appears to reach constant thickness swell of 2.2 percent after 92 hours. Since the wet-pad test was conducted at 50 percent RH, it is probable that the top of the specimen was losing moisture to the environment inside the chamber.

In the 90 percent RH exposure, there is little difference between MR10 MDF and SMDF over the duration of the test. The SMDF exhibited approximately 0.5 percent less thickness swell than MR10. AMDF exhibited a significantly slower rate of swelling than the other specimens. Nevertheless, one would not expect the SMDF to exceed 3.3 percent thickness swell at 90 percent RH, shown by the SMDF subjected to wet-pad exposure. As expected, the extreme edge had the most irreversible thickness swell, while there was no difference between the center and 25 mm from the edge.

Thickness swell was measured at three locations: the extreme edge, 25 mm from the edge, and the center of each specimen. Standard test procedures measure thickness at 25 mm from the edge. Figure 2 compares thickness swell by location for all MDF specimens subjected to water-spray exposure. Note that water spray was the most severe exposure. As expected, the extreme edge had the greatest rate of thickness swell, and the center location had the slowest rate for MR10 and SMDF. There was no difference between locations for thickness swell of AMDF. Thickness swell of AMDF was very low, and variability of the measurement occluded any difference by measurement location. The measurements at the center and 25 mm from the edge did not differ by more than 2 percent during the duration of the test.

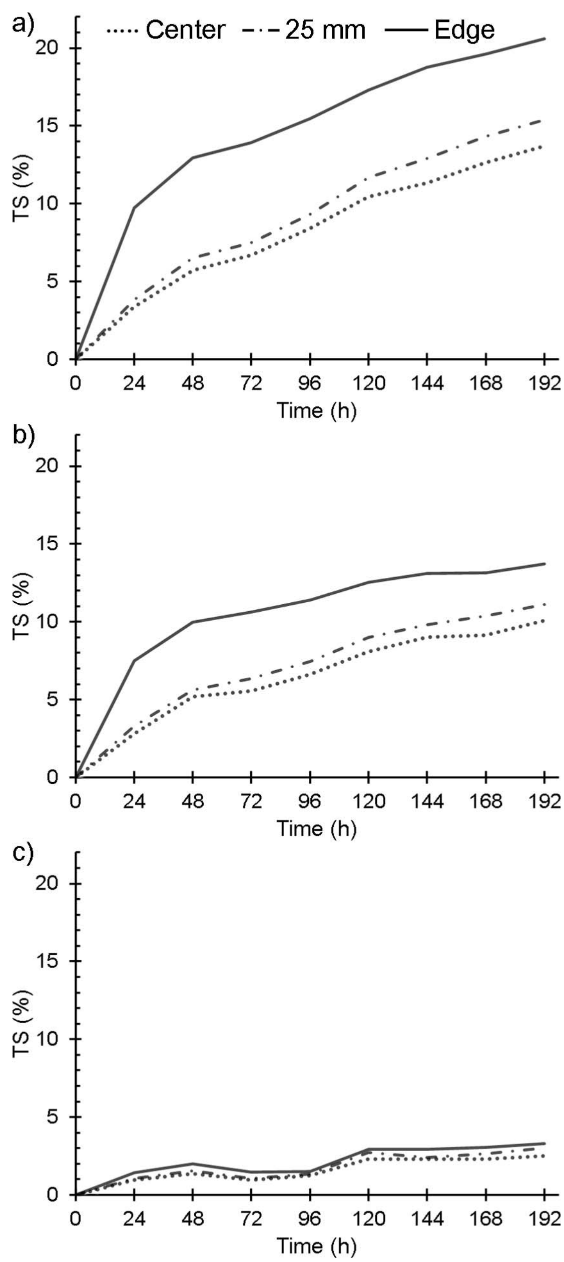

Figure 2.—Comparison of thickness swell measurement locations during water-spray exposure for (a) MR10 medium-density fiberboard (MDF), (b) steam-injection pressed MDF, and (c) acetylated MDF.

Irreversible thickness swell was different between MDF types and between methods of water exposure (Table 3). MR10 MDF had the most irreversible thickness swell, while SMDF and AMDF were the same. Note that some specimens revealed negative irreversible thickness swell, which may indicate that oven-drying prior to the final equilibration may have affected the panel's ability to absorb moisture at 30 percent RH and 30°C. The water-spray exposure resulted in the most irreversible thickness swelling, and the 90 percent RH exposure had the least.

Linear expansion (LE) results (Fig. 3) show that acetylation greatly improved stability in all test environments. LE of AMDF was less than 0.17 percent after 192-hour water spray, which was the most severe. Contrary to thickness swell, SMDF had greater LE than MR10 MDF. This result could be due to a Poisson effect, where thickness swell creates a strain component opposing linear expansion. Sebera et al (2014) recorded Poisson's ratio of MDF subjected to compression in the range 0.02 to 0.04, which is sufficient to explain the contradiction of LE and thickness swell (TS) for the MR10 and SMDF specimens. The MR10 and AMDF specimens were increasing LE after 192 hours in all water exposure conditions. AMDF reached a stable linear dimension within 120 hours.

All MDF types had the least amount of LE in the wet-pad exposure. RH in the test chamber during wet-pad exposure was 50 percent compared to the 90 percent RH exposure test. Apparently, evaporation from the top of the specimens during wet-pad exposure mitigated some of the influence of liquid water uptake from the wet pad.

Water absorption of MDF cannot be directly related to the moisture content (MC) of solid wood due to the presence of resin solids in MDF. Evaluation of MC of AMDF is further complicated by the presence of acetyl groups, which may constitute up to 25 percent of the dry weight (Hill 2006). For acetylated wood, a reduced MC is often calculated, where reduced MC is based solely on the dry weight of wood prior to acetylation (Passarini et al. 2017). Results reported here are based on the ovendry weight, including acetyl and adhesives.

Water absorption in the three exposure protocols consists of adsorption into the cell wall of MDF fibers as well as

Table 3.—Irreversible thickness swell for all exposure conditions, MDF types, and measurement locations. Standard deviations in parentheses.[a]

Exposure	Material	Extreme edge, %	25 mm from edge, %	Center, %
Water spray	MR10	8.30 (0.74)*	2.55 (0.55)*	2.96 (1.48)*
	AMDF	0.52 (0.35)	0.44 (0.35)	0.73 (0.70)
	SMDF	1.20 (0.85)	−0.21 (0.80)	0.00 (1.01)
Wet pad	MR10	2.17 (0.57)*	−0.02 (0.51)*	0.10 (0.72)*
	AMDF	−0.02 (0.46)	0.05 (0.56)	0.21 (0.66)
	SMDF	−0.72 (0.44)	−1.22 (0.40)	−0.86 (0.30)
90% RH	MR10	−0.34 (0.51)	−0.39 (0.42)	−0.29 (0.66)
	AMDF	0.16 (0.41)	0.29 (0.45)	0.52 (0.55)
	SMDF	−0.34 (0.43)	−0.28 (0.36)	−0.29 (0.46)

[a] Asterisks indicate significant difference at 95% confidence level. MDF = medium-density fiberboard; AMDF = acetylated medium-density fiberboard; SMF = steam-injection pressed medium-density fiberboard; RH = relative humidity.

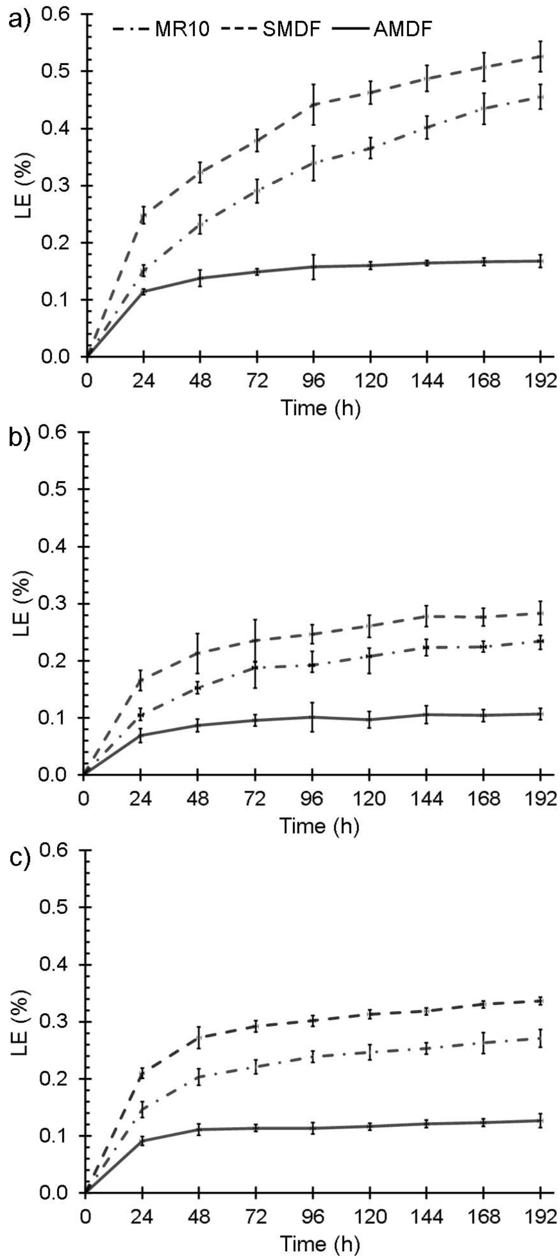

Figure 3.—Average percent linear expansion (LE) during exposure to (a) water spray, (b) wet pad, and (c) 90% relative humidity

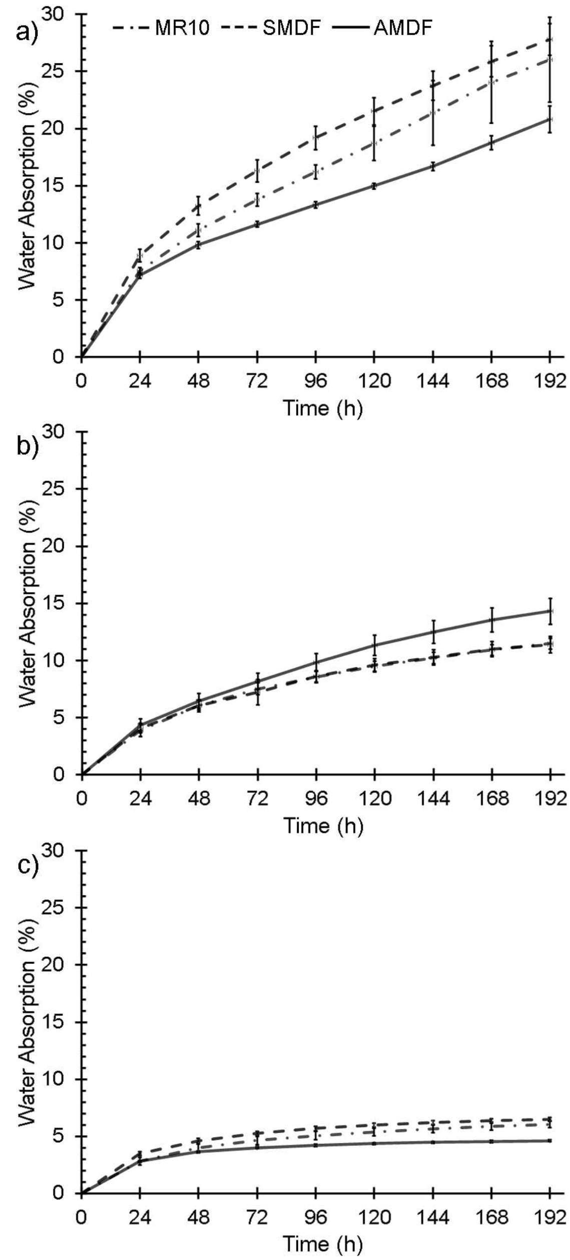

Figure 4.—Average percent water absorption during exposure to (a) water spray, (b) wet pad, and (c) 90% relative humidity

accumulation of liquid water in the voids between fibers and into cell lumens. Only adsorption into the cell wall will initiate fiber swelling. However, if liquid water disrupts bonding between fibers, fibers may reverse some compression deformation, resulting in bulk swelling of MDF. All water exposure tests included water adsorption into cell walls. Water-spray and wet-pad tests also included liquid water absorption.

Water absorption was still occurring for all specimen types and all exposure conditions at 192 hours (Fig. 4). Even the AMDF was continuing to absorb water, particularly during wet-pad and water-spray exposures. Yet AMDF appeared to reach maximum TS and LE before 192 hours. Water absorption at the completion of the water-spray test was 28, 26, and 21 percent for SMDF, MR10, and AMDF, respectively. Water absorption at the completion of the 90 percent RH test was 5, 5, and 2 percent for SMDF, MR10, and AMDF, respectively. Since a moisture content gradient is expected, one cannot be certain if fiber saturation was achieved at any point in the specimens. Popescu et al. (2014) reported equilibrium moisture content (EMC) of acetylated European white birch (*Betula pendula*), with 16 percent acetyl weight gain, at 90 percent RH to be approximately 11 percent and fiber saturation at approximately 14 percent. Passarini et al. (2017) reported the fiber saturation of acetylated loblolly pine (*Pinus taeda*), with 21 percent acetyl weight gain, at 9 percent. The degree of acetylation in AMDF was not reported by the manufacturer. Therefore, AMDF may have achieved fiber saturation and thus stopped swelling at the completion of the water-spray and wet-pad tests. However, AMDF in the 90 percent RH exposure test would likely continue to swell if given more time to adsorb water into the cell wall.

Steam injection appeared to cause more rapid water absorption during water-spray exposure than MDF made by conventional hot-pressing. The overall density of SMDF and MR10 were nearly the same, suggesting that porosity was nearly the same. Perhaps the flat density profile of SMDF was more conducive to liquid water absorption than MDF with a high-density surface. Only the water-spray exposure created direct contact of liquid water to the edges of the MDF. There was no difference in the rate of water absorption between SMDF and MR10 during wet-pad or 90 percent RH exposures. Note that SMDF had less thickness swell than MR10. Therefore, the combined observations of thickness swell and water absorption behavior suggests that steam injection causes a relaxation of internal stress and reduced response to water-induced swelling.

Cyclic exposure conditions

Cyclic wet-pad and drying results are shown in Figure 5. The trend in thickness swell performance matched the results for constant wet-pad exposure Figure 1b. MR10 MDF and SMDF increased thickness with each successive wet-pad exposure step. AMDF exhibited consistent swelling and shrinking in each of the three cycles. MR10 had greater swelling than SMDF. All specimens were preconditioned at 30 percent RH, and the drying step was at 10 percent RH. Therefore, the first drying cycle revealed a net shrinkage from the initial thickness.

Regarding overall water resistance and stability, the AMDF had the best performance, and, as expected MR10 MDF (intended for interior applications) had the worst. Differences between types of MDF were less apparent during the 90 percent RH exposure. There was statistically no difference between types of MDF for irreversible thickness swelling after 90 percent RH exposure. Differences were sometimes not apparent after only 24 hours of exposure at any of the test conditions.

Conclusions

Not enough information is known about the production parameters, such as adhesive loading and details of the hot-pressing schedule of these commercial products, to make broad conclusions by panel type. Certainly, acetylation greatly improves water resistance. Even under cyclic wetting and drying, the AMDF retained consistently low swelling and shrinking behavior. However, increased loading of highly water-resistant adhesive in MDF made from untreated fiber may yield similar results. Nonetheless, for the specimens evaluated in this experiment, MR10, which was bonded with pMDI, had the worst overall performance. SMDF was closer in performance to MR10 than AMDF. Interestingly, steam injection appeared to cause more rapid water absorption than MDF made by conventional hot-pressing. Yet SMDF had less thickness swelling than MR10. Regardless of the method of water exposure, the trend of best to worst MDF performance was the same. Differences in swelling behavior may not be apparent after only 24 hours of water exposure due to the dynamic behavior of water absorption and the nature of the exposure.

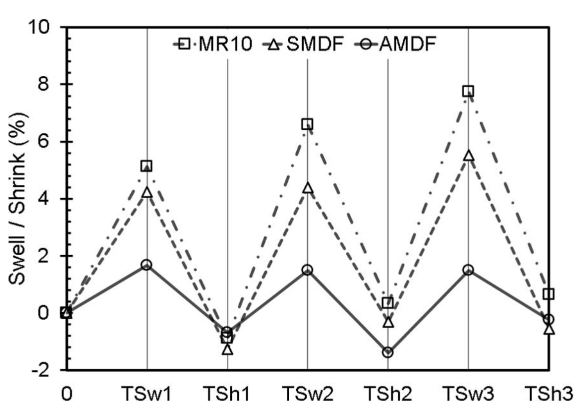

Figure 5.—Three cycles of thickness swelling and shrinking for three types of medium-density fiberboard (MDF) exposed to the wet pad and 10% relative humidity.

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Literature Cited

Ahmed, S. A., S. Adamopoulos, J. Li, and J. Kovacikova,. 2020. Prediction of mechanical performance of acetylated MDF at different humid conditions. *Appl. Sci.* 8712. doi:10.3390/app10238712.

American National Standards Institute (ANSI). 2016. Medium density fiberboard (MDF) for interior applications. ANSI A208.2-2016. Composite Panel Association, Leesburg, Virginia.

American National Standards Institute (ANSI). 2020a. Engineered wood siding. ANSI A135.6-2012(R2020). Composite Panel Association, Leesburg, Virginia.

American National Standards Institute (ANSI). 2020b. Engineered wood trim. ANSI A135.7-2012(R2020).Composite Panel Association, Leesburg, Virginia.

American Society for Testing and Materials. 2020. Standard test methods for evaluating properties of wood-base fiber and particle panel materials. ASTM D1037-12(R2020). ASTM International, West Conshohocken, Pennsylvania.

Hill, C. A. S. 2006. Wood Modification: Chemical, Thermal and Other Processes. Chichester: John Wiley & Sons.

Li, X., X. Zheng, and H. Li. 2011. Steam-injection pressing technology of man-made board. *Key Eng. Mater*. 474:1351–1355. doi:10.4028/www.scientific.net/KEM.474-476.1351.

Mai, C., M. Direske, D. Varel, and A. Weber. 2016. Light medium-density fiberboards (MDFs): Does acetylation improve the physico-mechanical properties? *Eur. J. Wood Wood Prod*. 75:739–745.

Passarini, L., S. L. Zelinka, S. V. Glass, and C. G. Hunt. 2017. Effect of weight percent gain and experimental method on fiber saturation point of acetylated wood determined by differential scanning calorimetry. *Wood Sci. Technol*. 51:1291–1305.

Popescu, C.-M., C. A. S. Hill, S. Curling, G. Ormondroyd, and Y. Xie. 2014. The water vapour sorption behaviour of acetylated birch wood: How acetylation affects the sorption isotherm and accessible hydroxyl content. *J. Mater. Sci*. 49:2362–2371.

Rowell, R. 2006. Acetylation of wood—A journey from analytical technique to commercial reality. *Forest Prod. J*. 56(9):4–12.

RStudio Team. 2019. RStudio: Integrated Development for R. http://www.rstudio.com. Accessed November 10, 2019.

Sebera, V., J. Tippner, M. Šimek, J. Šrajer, and K. Decký. 2014. Poisson's ratio of the MDF in respect to vertical density profile. *Eur. J. Wood Wood Prod*. 72:407–410.

Wolcott, M., F. A. Kamke, and D. A. Dillard. 1994. Fundamental aspects of wood deformation pertaining to manufacture of wood-based composites. *Wood Fiber Sci*. 26(4):496–511.