Comparative Performance of Modified Solid and Composite Wood Samples in Standard Tests

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Abstract

The properties of several modified wood products were evaluated using North American standards to provide comparative data for architects seeking to use these materials. In general, modified wood products had lower moisture uptakes and less shrinkage than unmodified products. Acetylated materials were highly resistant to fungal decay, whereas thermally modified and furfurylated materials were classified as decay resistant. All materials were susceptible to mold, although the nonacetylated moisture-resistant medium-density fiberboard was most susceptible. Thermally modified and furfurylated materials were similar in mold susceptibility to untreated radiata pine sapwood, whereas acetylated materials appeared to be more mold resistant.

Wood is among the most durable natural cellulosic polymers, but it is susceptible to biological degradation under the proper temperature, moisture, and oxygen conditions (Zabel and Morrell 1992). The heartwood of some wood species is resistant to degradation, but most species must be treated with chemicals that are toxic to the degrading organisms to improve their durability. Chemical protection of wood dates back thousands of years, although most treatments were largely ineffective. The era of effective wood protection dates to the middle of the 19th century with the development of the full cell process and the emergence of copper and creosote as effective wood protectants (Graham 1973). Preservative treatment has provided a highly effective method for extending the useful life of various wood products, but it also has drawbacks. Most of the chemicals used for wood treatment are, by necessity, broad-spectrum biocides that have the potential to affect nontarget organisms. They also have differing degrees of water solubility that allow them to migrate into the surrounding environment. Concerns about the use of these broad-spectrum biocides have encouraged a search for less toxic methods for protecting wood (Fell et al. 2006).

One alternative to traditional biocide protection of wood is to modify the natural wood chemistry to render it less susceptible to degradation. Wood modification is not a new concept, having been pioneered in the 1940s (Stamm and Seborg 1943), but it has attracted increasing interest as timber users seek nontoxic methods for prolonging wood service life.

One of the simplest methods for modifying wood is to soak it in so-called ‘‘bulking agents’’ like polyethylene glycol to alter the moisture behavior of the wood (Rowell and Barbour 1990, Hill 2006). However, this approach is costly, not permanent, and leaves the wood surface sticky and difficult to coat. More permanent approaches tend to alter the wood chemistry by heating to destroy specific wood polymers, by reactions that alter the inherent moisture behavior of the wood, or by filling the cell lumens with low-cost monomers that can then be polymerized in situ.

Thermal modification was originally developed for altering the appearance of lower-value, lighter colored woods to make them appear more like darker timbers (Stamm 1959). However, the heating processes used for this purpose also degrade the hemicelluloses and effectively alter the hygroscopicity of the wood (Seborg et al. 1953, Stamm et al. 1946). Thermal modification has been purported to increase resistance to fungal degradation (Esteves and Pereira 2009, Aro et al. 2014, Barnes et al.

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2016, Metsa-Kortelainen and Viitanen 2017), and this has led to increasing use in Europe; however, results elsewhere have been mixed and thermally modified wood has little or no resistance to termite attack (Shi et al. 2007, Vidrine et al. 2007).

Acetylation was also developed in the 1920s and involves reacting acetic anhydride with the hydroxyl groups in the wood to alter the moisture behavior of the timber (Fuchs 1928, Tarkow et al. 1946, Kumar 1994, Hill 2006, Rowell 2006b). Acetylation alters the ability of organisms to interact with the wood and a variety of field trials have shown it to be effective against fungi, some insects, and more recently, marine borers (Hill 2006, Rowell 2006b). This material is regularly used in Europe for exterior applications and occupies a growing niche in North America.

Furfurylation impregnates wood with large quantities of furfuryl alcohol, which is subsequently polymerized in situ. Like acetylation, furfurylation modifies the moisture-holding capacity of the wood, reducing the risk of fungal and marine borer attack (Westin et al. 2004).

Although these wood modification processes have been available for decades, a majority of the evaluations has been performed using European test methodologies. Introducing these materials into the North American market will require developing data using test methods appropriate to the market. In this report, we describe tests to characterize various modified wood-based materials in comparison with untreated radiata pine sapwood (*Pinus radiata*) and sapele heartwood (*Entandrophragma cylindricum*). Radiata pine was chosen because it is the primary substrate used for acetylation, commonly used for furfurylation, and is also a globally important softwood timber resource. Sapele was selected because its heartwood has a reputation for being naturally durable.

Materials and Methods

Commercially produced samples were obtained for each material as either lumber or panels and cut into test specimens appropriate for each material and test (Tables 1 and 2).

Equilibrium moisture content

Ten samples of each material were oven-dried (103°C) for at least 24 hours and weighed (nearest 0.01 g). The samples were then placed into a chamber maintained at 20°C and 65 percent relative humidity (RH). The samples were weighed at intervals until their weights had stabilized. The resulting increase in weight was used to calculate the equilibrium moisture content (EMC) at that condition as described in ASTM International Standard D4933 (2017c). The materials were then similarly exposed to 30°C and 90 percent RH until their weights stabilized (~72 days) and then placed into a chamber maintained at 30°C and 30 percent RH for approximately 75 days. The EMC for each condition was calculated on an ovendry basis.

Dimensional stability

Ten samples of each solid wood specimen were soaked in tap water at 20°C until their weight changes indicated that they were above fiber saturation point. The time required to reach this level varied with material. The samples were then immersed in cold water (5°C to 7°C) and the volume of water displaced was determined to obtain an indirect measure of volume. The samples were then oven-dried (103°C) to constant weight and the samples were again immersed in water to calculate water displacement. The difference between soaked and ovendry volume was used to calculate volumetric shrinkage (ASTM International Standards D143/1037; 2017a, 2017b).

The degree of volumetric swelling was assessed on the medium-density fiberboard (MDF) samples by measuring the dimensions on all sides of the samples before immersing them in water at room temperature for 24 hours. The sample dimensions were remeasured and the values were used to calculate volume before and after soaking.

Hardness

Ten samples of each material were conditioned at 20°C and 65 percent RH until the weights had stabilized. Hardness was measured on an Instron model 5582 universal testing machine (Instron, Norwood, Massachusetts) at four locations per specimen using methods prescribed by ASTM International Standard D143 (2017a). For solid wood, hardness was measured in two locations on the radial surface and two locations on the tangential surface. For MDF, hardness was measured at four locations on the face. Samples were then conditioned at 30°C and 90 percent RH and hardness was again measured at four locations per specimen.

Flexural properties

The specimens were conditioned to stable moisture content at 20°C and 65 percent RH before being tested in

Table 1.—Sources of materials evaluated in tests.

Material (trade name)[a]	Description	Manufacturer or source
Radiata pine (*Pinus radiata*) sapwood	Control (untreated)	Harvested from plantations in New Zealand
Sapele (*Entandrophragma cylindricum*)	Control (untreated).	Harvested and processed in Nigeria
Acetylated radiata pine (Accoya)	~20% acetylation	Acetylated in Arnhem, the Netherlands
Acetylated red alder (*Alnus rubra*; Accoya)	~20% acetylation	
Thermally modified ash (*Fraxinus* spp.; Thermory)	Thermally modified wood with heat and steam	Thermory, manufactured in Tallinn, Estonia
Furfurylated radiata pine (Kebony)	Proprietary	Kebony, Oslo (Skien), Norway
Acetylated MDF (Tricoya)	Exterior MDF made with acetylated radiata pine fiber	Medite, Clonmel, Ireland
Moisture-resistant MDF (MDI MDF; Medex)	MDF made with MDI resin	Roseburg MDF, Medford, Oregon
Extira MDF (PF-MDF)	MDF made with PF resin, steam injection press, and includes zinc borate.	Extira by JELD-WEN, Towanda, Pennsylvania

[a] MDF = medium-density fiberboard; MDI = methylene diphenyl diisocyanate; PF = phenol-formaldehyde.

Table 2.—Dimensions of samples used to evaluate various properties of solid wood and composite samples.[a]

Test	Sample dimensions	
	Solid wood	MDF
EMC (ASTM International D4933)	19 × 50 × 75 mm	50 × 75 mm × panel thickness (~17–18 mm)
Shrinkage (ASTM International D143/1037)	19 × 19 × 50 mm	19 × 50 mm × panel thickness (~17–18 mm)
MOR/MOE	19 × 19 × 500 mm	19 × 75 × 500 mm
Hardness	19 × 50 × 150 mm	19 × 50 × 150 mm
Decay (AWPA E10)	19 × 19 × 19 mm	19 × 19 × 17–19 mm
Mold (AWPA E24)	12.5 × 75 × 100 mm long	75 × 100 mm × panel thickness (~17–18 mm)
Internal bond	N/A	50 × 50 mm × panel thickness (~17–18 mm)

[a] MDF = medium-density fiberboard; EMC = equilibrium moisture content; MOR = modulus of rupture; MOE = modulus of elasticity; AWPA = American Wood Protection Association; N/A = not applicable.

third-point loading on an Instron universal testing machine at a loading rate of 1.3 mm/min to failure according to procedures described in ASTM International Standards D143 (2017a) for solid wood and D1037 (2017b) for the MDF samples. Load and deflection were continually recorded until failure. The resulting data were used to calculate modulus of elasticity (MOE) and modulus of rupture (MOR). Each material was tested on 10 beams. The tests were repeated after conditioning to stable moisture content at 30°C and 90 percent RH.

Decay resistance

Decay resistance was evaluated according to American Wood Protection Association (AWPA) Standard E10 (2017a). Decay chambers were prepared by half filling 454-mL French squares with moist forest loam and placing a western hemlock (*Tsuga heterophylla*; for brown rot fungi) or alder (*Alnus* spp.; for the white rot fungus) feeder strip on the soil surface. The bottles were then loosely capped and autoclaved for 45 minutes at 121°C. After cooling, the bottles were inoculated with 3-mm-diameter malt agar disks cut from the actively growing edges of cultures of the test fungi. The fungi evaluated in these procedures were *Gloeophyllum trabeum* (Pers.ex. Fr.) Murr. (isolate # Madison 617), *Rhodonia placenta* (Fries) Niemela, Larss., & Schigel (isolate # Mad 698), or *Trametes versicolor* (L. ex Fr.) Pilát (isolate # R-105). The first two fungi produce brown rot, whereas the latter species causes white rot. The agar plugs were placed on the edges of the wood feeder strips; then the jars were loosely capped (to allow air exchange) and incubated until the feeder strip was thoroughly covered with fungal mycelium. The sterile test blocks were weighed (to establish initial weight) and then placed on the surfaces of the feeder strips; the bottles were loosely capped and incubated at 28°C for 12 or 16 weeks for blocks exposed to brown or white rot fungi, respectively. Each treatment was evaluated on eight blocks.

At the end of the incubation period, the blocks were removed, scraped clean of adhering mycelium, and weighed to determine wet weight. The blocks were then oven-dried (103°C) and weighed. The difference between initial and final ovendry weight was used as a measure of the decay resistance of each material. The relative decay resistance of each material was categorized using a scale described in AWPA Standard E30 (2017c).

Mold resistance

Resistance to growth by mold fungi was evaluated following procedures described in AWPA Standard E24 (2017b). Briefly, this test suspends wood samples on rods over a moist soil bed maintained at 32°C to stimulate fungal growth. The soil is inoculated with spores and hyphal fragments of a range of fungi that have been shown to be capable of growth on wood-based materials under these conditions. The entire assembly is placed in a room maintained at 20°C. This ensures that high RH conditions in the chamber will lead to condensation that encourages fungal growth. Each material was tested on six samples. The samples were evaluated for degree of mold coverage at 2-week intervals on a scale as follows:

0, no visible growth.

1, <10 percent of surfaces covered. Growth not so intense or colored as to obscure >5 percent of surfaces.

2, 10 to 30 percent of surfaces covered. Growth not so intense or colored as to obscure >10 percent of surfaces.

3, 30 to 70 percent of surfaces covered. Growth not so intense or colored as to obscure >30 percent of surfaces.

4, >70 percent of surfaces covered. Growth not so intense or colored as to obscure >70 percent of surfaces.

5, 100 percent of surfaces covered or with less than 100 percent coverage and with intense or colored growth obscuring greater than 70 percent of surfaces.

Internal bond

Internal bond (IB) was evaluated according to procedures described in ASTM International Standard D1037 (2017b). Briefly, 50 by 50-mm squares of each of the MDF products were attached to specially designed aluminum blocks using hot melt glue. Once the glue had set, the blocks were placed into a specially designed jig on an Instron universal testing machine and the materials were pulled apart perpendicular to the panel faces at a rate of 1.4 mm/min. The maximum load to induce failure was measured and used as the IB strength. Each material was evaluated on 20 samples.

Data for dimensional stability, durability, hardness, and IB were analyzed via one-way analyses of variance (ANOVAs) to examine differences between materials. Data were then subjected to a series of unpaired *t* tests.

Results and Discussion

Equilibrium moisture content

Untreated radiata pine sapwood had an average EMC of 12.72 percent after 50 days at 20°C and 65 percent RH, whereas untreated sapele had a slightly lower average EMC of 12.21 percent moisture content (MC) under these conditions (Table 3). Acetylated pine and red alder (*Alnus rubra*) had the lowest EMCs under these conditions—at 3.3 and 4.4 percent MC, respectively. Thermally modified ash (*Fraxinus* spp.), furfurylated pine, and acetylated MDF equilibrated to similar EMCs of approximately 5 percent. At

Table 3.—Equilibrium moisture contents of various wood-based material stored at three different temperature and relative humidity (RH) conditions.[a]

Material	Equilibrium moisture content (%)[b]		
	20°C/65% RH	30°C/90% RH	30°C/30% RH
Acetylated radiata pine (*Pinus radiata*)	3.34 (0.14) A	5.17 (0.16) A	1.23 (0.01) A
Acetylated red alder (*Alnus rubra*)	4.43 (0.86) B	6.07 (0.32) B	1.33 (0.09) B
Radiata pine control	12.72 (0.86) H	18.91 (0.50) G	5.76 (0.01) H
Sapele (*Entandrophragma cylindricum*)	12.21 (0.27) G	18.48 (0.41) F	6.21 (0.01) I
Thermally modified ash (*Fraxinus* spp.)	5.04 (0.33) CD	8.62 (0.38) C	2.84 (0.01) D
Furfurylated pine	4.93 (0.05) C	8.72 (0.19) C	3.07 (0.01) E
Acetylated MDF[c]	5.37 (0.05) D	8.82 (0.12) C	1.68 (0.01) C
MDI MDF	9.22 (0.14) F	14.87 (0.21) E	4.94 (0.01) G
PF MDF	8.80 (0.01) E	14.01 (0.01) D	4.46 (0.01) F

[a] Values represent means of 10 replicates per material; figures in parentheses represent one standard deviation.

[b] Values in columns followed by the same letter or number do not differ significantly from one another ($\alpha = 0.05$).

[c] MDF = medium-density fiberboard; MDI = methylene diphenyl diisocyanate; PF = phenol-formaldehyde.

approximately 9 percent EMC, the phenol-formaldehyde (PF) and methylene diphenyl diisocyanate (MDI) MDF values were higher than those for the other modified materials. Interestingly, acetylated MDF had a slightly higher EMC than acetylated radiata pine from which it is made, but still lower than the EMCs for the other MDF panels. The processing conditions for the MDF panels disrupt the wood structure and may create more opportunities for wood/moisture interactions, thereby accounting for the slightly higher EMCs.

Exposing the samples to higher RH conditions resulted in a marked increase in EMC, but trends remained similar—acetylated pine and alder equilibrated to significantly lower EMCs than other materials tested; thermally modified ash, furfurylated pine, and acetylated MDF behaved similarly and equilibrated to an average EMC of just under 9 percent; the other PF and MDI MDF materials equilibrated to an average EMC of between 14 and 15 percent and the control materials (radiata pine and sapele) equilibrated to approximately 18 to 19 percent EMC.

Equilibrating samples at 30°C and 30 percent RH produced sharp drops in EMC values, but the trends observed under the other temperature/moisture conditions were similar. However, EMCs were significantly different ($P = 0.05$) for all products after equilibration at 30°C and 30 percent RH and the EMC for acetylated MDF was significantly ($P = 0.05$) lower for all materials with the exception of the acetylated pine and alder (Table 3).

Dimensional stability

As with the EMC tests, all of the acetylated samples experienced lower levels of swelling/shrinkage when immersed in water (Fig. 1 and Table 4). Untreated radiata pine and sapele samples experienced the largest increases in volume for solid wood, whereas the PF and MDI MDF samples swelled at three to four times the rate of the acetylated MDF. Furfurylated and thermally modified wood both experienced higher rates of swelling than the acetylated materials, but these levels were still less than half of those found with untreated wood, illustrating the effects of these treatments on moisture behavior in terms of interactions with available hydroxyl groups in the cellulose and hemicelluloses in the wood cell wall.

Table 4.—Volumetric shrinkage (fiber saturation point to ovendry [OD]) for solid materials; linear expansion (OD to soak) for medium-density fiberboard (MDF).

Material[a]	Volumetric shrinkage or swelling (%)[b]
Acetylated radiata pine (*Pinus radiata*)	2.11 (0.28) A
Acetylated red alder (*Alnus rubra*)	1.89 (0.26) A
Radiata pine control	11.55 (1.88) D
Sapele (*Entandrophragma cylindricum*)	10.43 (1.39) C
Thermally modified ash	4.74 (0.23) B
Furfurylated pine	4.74 (0.56) B
Acetylated MDF	2.94 (0.17) E
MDI MDF	13.28 (2.65) F
PF MDF	9.60 (1.92) G

[a] MDI = methylene diphenyl diisocyanate; PF = phenol-formaldehyde.

[b] Values followed by the same letter or number do not differ significantly from one another ($\alpha = 0.05$). Note: Solid wood and MDF panels were analyzed separately.

Hardness

Hardness decreased with increased MC for all materials except the acetylated MDF, which remained nearly identical (Table 5). Decreased hardness with increasing MC is consistent with changes in wood structure due to swelling. Acetylation of radiata pine has been shown to increase hardness substantially and our results here confirm these prior findings (Larsson and Simonson 1994, Bongers and Beckers 2003, Xie et al. 2013). Interestingly, the three acetylated products (pine, alder, and MDF) had statistically similar hardness values when at the same ambient temperature and RH. Untreated radiata pine had significantly lower hardness than other materials tested at both exposure conditions. The hardness values for radiata pine and sapele were slightly lower than those previously reported, whereas those for the thermally modified ash were higher than those reported for nonmodified wood of the same species (US Department of Agriculture [USDA] 2010). Thermally modified, furfurylated, and MDI MDF all had hardness values that were similar to sapele under both exposure conditions. Hardness of PF MDF at the lower humidity was different from all other products tested, whereas PF MDF hardness was similar to sapele under higher humidity conditions.

IB strength

Results of the ANOVA ($P = 0.05$) indicated that IB strength was significantly higher for MDI MDF than other materials tested; IB values for acetylated MDF and PF MDF were similar (Table 6).

Flexural properties

Modulus of rupture.—Untreated radiata pine had the lowest MOR of any of the solid wood materials tested,

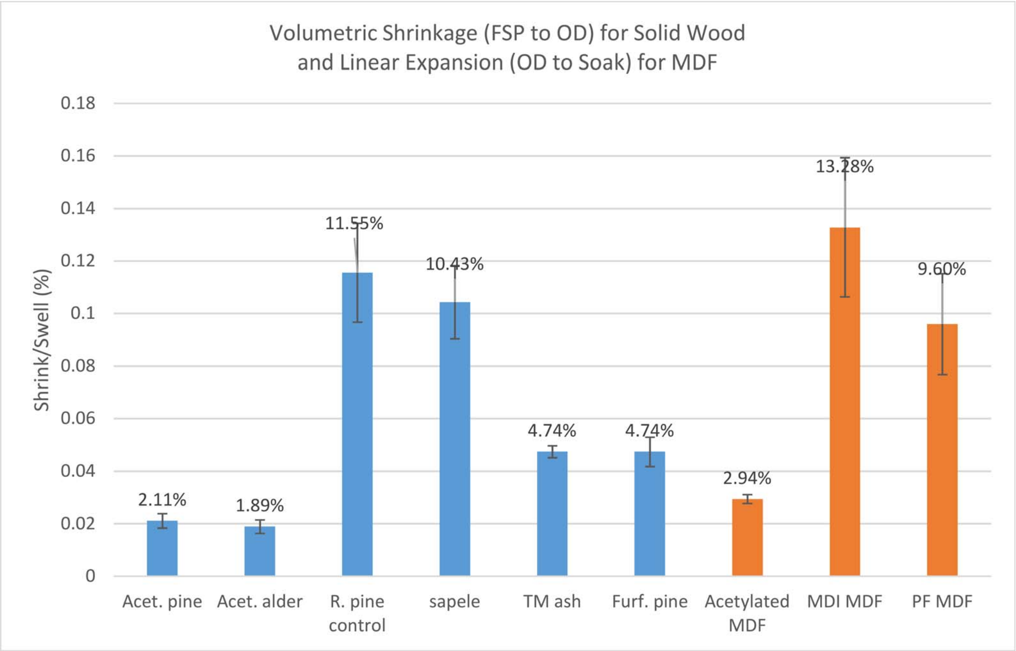

Figure 1.—Volumetric shrinkage (fiber saturation point [FSP] to ovendry [OD]) for solid wood and linear expansion (OD to soak) for medium-density fiberboard (MDF). TM = thermally modified; MDI = methylene diphenyl diisocyanate; PF = phenol-formaldehyde.

whereas sapele had the highest when the wood was conditioned at 20°C and 65 percent RH. MOR values for acetylated radiata pine and red alder were both higher than those found for the untreated radiata pine, although the differences between acetylated and nonacetylated radiata pine were slight. MOR for thermally modified wood conditioned at 20°C and 65 percent RH was similar to those for furfurylated and acetylated wood. Exposing samples to higher RH before testing was associated with lower MOR values for almost all of the samples except for the acetylated radiata pine or red alder and the thermally modified wood. Further, acetylated solid wood (pine and alder), sapele, and thermally modified wood exposed to higher humidity conditions all had similar values for MOR, whereas the value for the furfurylated wood was different from all other materials tested.

As expected, the MDF samples had lower MOR values than the solid wood. MDI MDF at 20°C and 65 percent RH had significantly higher MOR values than the other MDF materials, whereas the acetylated and PF MDF samples were similar. Acetylated MDF was still similar in MOR value to PF MDF at higher humidity levels; however, MOR values for MDI and PF MDF did not differ significantly ($P = 0.05$) from each other. Acetylation and thermal modification should both limit potential moisture interactions with cellulose microfibrils and thereby reduce flexural properties. This effect was less apparent with acetylated MDF.

Modulus of elasticity.—MOE values for radiata pine were significantly lower than those for acetylated wood of the same species as well as for the acetylated alder (Table 7). The values were also lower than those reported previously for this species (USDA 2010). Exposure of untreated wood to higher RH was associated with lower MOE values, which is consistent with differences in moisture sorption. MOE values for acetylated or furfurylated materials were similar under the two humidity regimes. MOE for furfurylated

Table 5.—Average hardness of solid wood and medium-density fiberboard (MDF) samples under two different temperature/relative humidity (RH) conditions.

Material[b]	Hardness (N)[a] 20°C/65% RH	30°C/90% RH	Difference (%)	Ovendry density (kg/m^3)
Acetylated radiata pine (*Pinus radiata*)	4,185 (318) D	3,813 (336) C	8.9	506 (54)
Acetylated red alder (*Alnus rubra*)	3,982 (295) D	3,701 (263) C	7.1	504 (41)
Radiata pine control	2,830 (361) E	2,355 (289) D	16.8	436 (69)
Sapele (*Entandrophragma cylindricum*)	5,951 (188) B	5,032 (458) AB	15.4	621 (49)
Thermally modified ash (*Fraxinus* spp.)	6,073 (304) AB	4,751 (375) AB	21.8	536 (4.5)
Furfurylated pine	6,545 (592) A	5,207 (447) A	20.4	659 (52)
Acetylated MDF	3,609 (156) D	3,602 (110) C	0.2	667 (6.7)
MDI MDF	6,167 (251) AB	4,610 (158) B	25.2	784 (18)
PF MDF	4,979 (207) C	4,598 (156) B	7.7	727 (35)

[a] Values represent means of four tests on 10 samples per material; figures in parentheses represent one standard deviation. Values in columns followed by the same letters do not differ significantly ($\alpha = 0.05$).

[b] MDI = methylene diphenyl diisocyanate; PF = phenol-formaldehyde.

Table 6.—Internal bond strength of medium-density fiberboard materials.

Material[a]	Value (MPa)[b]
Acetylated MDF	0.70 (0.12) B
MDI MDF	1.00 (0.34) A
PF MDF	0.71 (0.25) B

[a] MDI = methylene diphenyl diisocyanate; PF = phenol-formaldehyde.

[b] Values represent means of tests on 20 samples per material; figures in parentheses represent one standard deviation. Values with the same letters do not differ significantly ($\alpha = 0.05$).

material was similar to those for sapele. Thermally modified ash had higher MOE than other materials, but this would be consistent with the higher mechanical properties of this species (USDA 2010).

MOE was similar for all the composite materials when exposed to the same ambient conditions.

Decay resistance

Mass losses of blocks exposed in chambers without a fungus were generally less than 0.5 percent, indicating that any higher weight losses would be fungal associated (Table 8). Mass losses of untreated radiata pine sapwood averaged 34.75, 44.65, and 9.25 percent for *G. trabeum*, *R. placenta*, and *T. versicolor*, respectively. The weight losses for the white rot fungus were low on all but the untreated hardwood (sapele), reflecting the tendency for this fungus to produce lower weight losses on coniferous woods. The lower weight losses with *T. versicolor* may also reflect the use of a 16-week incubation period, whereas the AWPA Standard now recommends 24 weeks of exposure. In general, mass losses for the three fungi indicate that conditions were suitable for aggressive degradation of test materials.

Untreated sapele also experienced higher weight losses with *R. placenta* and *T. versicolor*. This species is classified as moderately to highly durable, depending on the source (Scheffer and Morrell 1998). The current results would classify the material tested as moderately durable on the basis of guidance provided in AWPA Standard E30 (2017c).

Acetylated radiata pine and red alder both experienced low mass losses, with most losses below 1.00 percent, except for the acetylated red alder exposed to *G. trabeum* where mass loses averaged 3.57 percent. All of these results would still classify the acetylated materials as highly durable (average mass losses <10%) according to AWPA Standard E30 (2017c). The very low durability of red alder coupled with the known tolerance of *G. trabeum* to organic materials may have accounted for the slightly higher weight losses (Scheffer and Morrell 1998, AWPA 2017a).

Results for thermally modified blocks tended to be highly variable, with standard deviations for mass losses for blocks exposed to *R. placenta* being higher than the means. This suggests some variability in relative durability of the materials. The test blocks were cut from larger materials, creating the potential for exposure of materials with differing degrees of thermal modification as a result of differences in the depth from which the materials were cut. However, this factor would also influence performance of these materials wherever cuts or holes were made that exposed wood away from the surface. The thermally modified wood would be classified as resistant to decay on the basis of these results (AWPA 2017c).

Mass losses were low (<10%) for furfurylated wood exposed to *G. trabeum* or *T. versicolor*, but higher for materials exposed to *R. placenta* and would be classified as resistant to decay.

Exposure of the three MDF materials to fungal attack resulted in average weight losses that were all below 7 percent. Acetylated MDF had the lowest average mass losses, whereas those for the other two materials were two to three times higher, depending on the fungus. Although the results indicate that these products were resistant to fungal attack, it is important to note that MDF has long been considered an interior use product (Composite Panel Association 2019*)*. The results of these tests suggest that it can perform in exterior applications out of direct soil contact.

Mold resistance

The free sugars stored in the ray cells make most wood-based materials susceptible to mold attack. These fungi do not appreciably affect the structural properties of the material, but consumers find the presence of mold objectionable. Thus, resistance to mold growth can be an important product attribute. The AWPA mold box test creates a very aggressive environment for mold growth.

Table 7.—Flexural properties of various solid wood and composite materials conditioned under three different temperature/relative humidity (RH) regimes before being tested in third-point bending.[a]

Material[b]	Modulus of rupture (MPa) 20°C/65% RH	Modulus of rupture (MPa) 30°C/90% RH	Modulus of elasticity (MPa) 20°C/65% RH	Modulus of elasticity (MPa) 30°C/90% RH
Acetylated radiata pine (*Pinus radiata*)	82.9 (12.3) B	106.3 (24.3) A	9,156 (1,316) CD	10,695 (2,083) B
Acetylated alder (*Alnus* spp.)	98.4 (18.0) A	97.0 (7.0) AB	9,362 (2,318) BC	9,930 (1,140) B
Radiata pine	67.9 (9.8) C	52.4 (9.3) D	7,497 (1,711) E	5,255 (2,281) C
Sapele (*Entandrophragma cylindricum*)	109.3 (13.2) A	87.6 (10.1) B	11,407 (1,717) B	9,408 (1,293) B
Thermally modified ash (*Fraxinus* spp.)	86.2 (26.2) B	87.9 (20.1) B	12,994 (2,398) A	13,976 (2,859) A
Furfurylated pine	88.6 (12.9) AB	74.3 (13.0) C	10,553 (1,593) B	9,897 (1,367) B
Acetylated MDF	18.2 (0.6) E	15.8 (0.7) F	2,470 (47) F	2,127 (33) D
MDI MDF	37.1 (2.7) D	27.0 (1.5) E	3,767 (199) F	2,348 (77) D
PF MDF	22.7 (1.9) E	17.7 (0.7) EF	2,497 (152) F	1,739 (27) D

[a] Values within columns represent means of 10 replicates per material; figures in parentheses represent one standard deviation. Values within the same column followed by the same letters do not differ significantly ($\alpha = 0.05$). Modulus of rupture values for radiata pine and nonmodified ash are reported as 80.7 and 103.0 MPa, respectively; modulus of elasticity values for the same species are 10,200 and 12,000 MPa (USDA 2010).

[b] MDF = medium-density fiberboard; MDI = methylene diphenyl diisocyanate; PF = phenol-formaldehyde.

Table 8.—Mass losses of solid wood and composite materials exposed to three decay fungi in American Wood Protection Association E10 soil block tests.

Material[b]	Mass loss (%)[a]		
	Gloeophyllum trabeum	*Rhodonia placenta*	*Trametes versicolor*
Acetylated radiata pine (*Pinus radiata*)	−0.07[c] (0.55) A	0.69 (0.64) A	0.06 (0.17) A
Acetylated alder (*Alnus* spp.)	3.57 (9.48) AB	0.08 (0.22) A	0.00 AB
Radiata pine	34.75 (4.96) E	44.65 (3.77) E	9.25 (1.77) D
Sapele (*Entandrophragma cylindricum*)	3.30 (0.85) C	26.42 (14.93) D	17.72 (6.54) E
Thermally modified ash (*Fraxinus* spp.)	6.45 (6.06) D	17.22 (19.75) CD	6.87 (2.27) CD
Furfurylated pine	4.43 (1.24) CD	12.27 (8.32) BC	6.25 (1.00) C
Acetylated MDF	2.68 (0.58) BC	1.80 (0.27) A	2.07 (0.56) B
MDI MDF	6.36 (0.97) D	6.28 (0.38) AB	5.80 (0.27) C
PF MDF	4.55 (0.31) CD	5.25 (0.58) AB	5.51 (1.06) C

[a] Values represent means of eight replicates per material per fungus; figures in parentheses represent one standard deviation. Values in the same column followed by the same letters do not differ significantly ($\alpha = 0.05$).

[b] MDF = medium-density fiberboard; MDI = methylene diphenyl diisocyanate; PF = phenol-formaldehyde.

[c] Negative values are common in soil block tests and reflect slight mass gains by specimens from the surrounding soil.

Mold coverage steadily increased on untreated radiata pine sapwood over the 8-week exposure period as well as on sapele, although the degree of coverage was slightly lower on the latter material (Table 9). Mold growth was most aggressive on the MDI and PF MDF samples, reaching almost complete coverage of the samples at the end of the test. The process of manufacturing MDF invariably opens wood cells, increasing access to materials stored within the wood and rendering the material more susceptible to fungal attack. Acetylated radiata pine, red alder, and MDF all experienced mold ratings that were below 1.00 at the end of the 8-week exposure period, indicating that they would be considered more resistant to mold growth.

Thermally modified wood has mold ratings that were similar to those found with untreated radiata pine or sapele, suggesting that it lacked substantial resistance to mold growth, whereas mold ratings on the furfurylated material were intermediate between the acetylated materials and the sapele, suggesting that treatment imparted some mold resistance The results indicate that all of these materials, including the acetylated woods, would benefit from some type of protective surface treatment.

Table 9.—Relative resistance of solid wood and composite materials to mold growth as assessed using an American Wood Protection Association E24 mold box test.

Material[b]	Average mold rating[a]			
	2 wk	4 wk	6 wk	8 wk
Acetylated radiata pine (*Pinus radiata*)	0.08	0.08	0.33	0.33
Acetylated alder (*Alnus* spp.)	0	0.17	0.42	0.92
Radiata pine	0.58	1.08	1.67	2.67
Sapele (*Entandrophragma cylindricum*)	0.25	0.83	1.58	2.17
Thermally modified ash (*Fraxinus* spp.)	0.25	0.75	1.58	2.42
Furfurylated pine	0.17	0.50	1.00	1.58
Acetylated MDF	0.50	0.58	0.75	0.83
MDI MDF	1.33	2.00	3.50	4.33
PF MDF	0.67	1.33	3.58	4.50

[a] Values represent means of six replicates per material on the basis of a scale of 0 (no mold) to 5 (completely covered).

[b] MDF = medium-density fiberboard; MDI = methylene diphenyl diisocyanate; PF = phenol-formaldehyde.

Conclusions

In general, modified wood products had lower moisture uptakes and degrees of shrinkage than unmodified products. In particular, acetylated pine and alder equilibrated to lower moisture contents than other materials tested. Acetylation of radiata pine has been shown to increase hardness substantially and our results here confirm prior findings. The three acetylated products had similar hardness values at the same ambient temperature and RH. Similarly, hardness for thermally modified ash was similar to that for sapele and higher than published values for unmodified white ash.

MOR values were similar for many of the modified solid wood products tested. However, the acetylated alder MOR values were similar to sapele, which had the highest test values. Flexural stiffness (MOE) values were more difficult to summarize succinctly. Thermally modified ash had higher MOE values than any other materials tested, whereas acetylated pine and alder had similar MOE values. The MOE values for the furfurylated pine and acetylated alder were similar as well. Bending properties (MOR and MOE) of composite materials were similar, with the exception that MOR for the MDI-treated MDF was higher than for the other composite materials.

IB strength was similar for the acetylated and PF-treated MDF, whereas IB of the MDI MDF was significantly higher.

All of the modified materials were more resistant to fungal attack than the control species for two of the three decay fungi tested (*R. placenta* and *T. versicolor*). However, mass losses were similar for sapele, furfurylated pine, acetylated MDF, and PF MDF when exposed to the *G. trabeum*. On the basis of these results, acetylated materials (solid wood and MDF) would be classified as highly resistant to fungal decay, whereas thermally modified and furfurylated materials would be classified as decay resistant.

All materials were susceptible to mold, although the nonacetylated moisture-resistant MDF was most susceptible. Thermally modified and furfurylated materials were similar in mold susceptibility to untreated radiata pine sapwood, whereas acetylated materials appeared to be more mold resistant.

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