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Fiberboard bending properties as a function of density, thickness, resin, and moisture content*

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Abstract

Fibers from treetop residues of lodgepole pine (*Pinus contorta*) and recycled old corrugated containers were used to fabricate wet-formed fiberboard panels over a range of densities from 300 to 1100 kg m^{-3}, a thickness range from 1.3 to 4.8 mm, and phenolic resin contents from 0% to 4.5%. The panels were then tested after conditioning in 50% and 90% relative humidity (RH) environments. Density, thickness, equilibrium moisture content, bending modulus of elasticity (MOE), and modulus of rupture (MOR) were measured for each panel. Panel apparent-density increased with thickness, but this may be due to surface effects rather than true density values. The equilibrium moisture content approximately doubled for the panels in the 90% RH environment, compared to 50% RH. At 50% and 90% RH conditions, equilibrium moisture contents decreased significantly when only 0.5% resin was added and remained essentially the same with increasing resin levels. In this study, both MOE and MOR increased with approximately the square of density. MOE increased, whereas MOR showed no clear effects as thickness and resin amount increased. This research is part of a larger program for developing an understanding of panel properties for engineered three-dimensional fiberboard products.

Keywords: bending properties; density; fiberboard; lodgepole pine; moisture content; phenolic resin; recycled fibers; small-diameter; thickness.

Introduction

In previous studies (Hunt and Supan 2005, 2006), the mechanical properties of binderless wet-formed fiberboard panels made from treetops of small-diameter lodgepole pine (*Pinus contorta*) and recycled old corrugated containers (OCC) were investigated. The type of fiber and fiber process conditions (refiner level, fiber processing temperature, and chemical pre-treatment) were shown to have significant effects on performance properties. Panels used in these studies were made with constant fiber weights, pressing conditions, and no resin so that the effects of fiber-processing variables alone could be investigated. This study continues the investigation, producing wet-formed fiberboard panels by holding fiber processing variables constant while varying fiber mass (mat thickness), pressing conditions (pressure to achieve density), and resin amounts. This paper discusses the effects of varying these conditions on bending modulus of elasticity (MOE) and modulus of rupture (MOR) for panels made from either of two types of fiber after conditioning in 50% and 90% relative humidity (RH) environments. The information will be used for modeling value-added engineered fiberboard structures.

The traditional raw material resource option for fiberboard has primarily been high-yield thermomechanical pulp made from pulp logs. However, with increasing worldwide demand for fiberboard and fiber, alternative fiber sources need to be considered, including forest residuals and recycled fibers. Each fiber type has its own characteristics that are affected by process parameters that then define subsequent performance. A long-range goal for this research program is to describe panel performance over a wide range of fiber sources, processing variables, and panel characteristics. The difficulty in developing such a program is that the variations or combinations of conditions are essentially infinite. Therefore, our research has been directed toward developing trends that could be used as a guide or to set performance boundaries. This paper describes the effects of density, thickness, resin, and moisture content (MC) on fiberboard-bending MOE and MOR. The fibers from *P. contorta* logging residuals (treetops) and OCC were the same type as used in the previous studies (Hunt 2001, Hunt and Supan 2005, 2006).

Resource utilization should be based on matching performance properties for each fiber type with desired performance characteristic(s) of the product. A broad goal of the Forest Products Laboratory composite research program is to develop value-added outlets for forest residue material and recycled fiber. In this program, empirical data from different fiber types and processes are the basis to develop performance models that can be used to optimize value-added engineered fiberboard components ranging from low-density pulp molded products to high-density structural products (Hunt 2001, Hunt and Winandy 2002).

Literature review

Most performance characteristics for wet-formed fiber-based products are compared and grouped according to low-, medium-, and high-density products. The lowest density group (200–400 kg m^{-3}) is generally described for pulp-molded products where producers focus primarily on cushioning characteristics with some need for structural performance. The medium-density (400–800 kg m^{-3}) fiberboard group could be used for any combination of cushioning, insulating, and structural performance needs for packaging, furniture, or case-good substrates. The third group, high-density (>800 kg m^{-3}), is targeted primarily for structural products in the packaging, furniture, and housing industry. Most research studies found in the literature describe performance properties of products made within one of these density groups or may evaluate a limited density range, but we are unaware of any that look at a broad range of fiberboard densities. Our study produced panels with densities spanning from 200 to 1200 kg m^{-3}. This type of data would be very useful when modeling property trends of a fiber type over a range of densities.

Thickness for many wet-formed products generally ranges from 1 to 6 mm (excluding paper, which is less than 1 mm). Wet-formed panel thickness does not generally exceed 6 mm, as drying times increase exponentially with thickness. Our study formed panels with thicknesses between 1 and 4 mm.

Resin amounts for wet-formed products generally range from 0% in some pulp-molded products to 2.0% for fiberboard (Suchsland and Woodson 1987). No resin or binderless boards can be formed with wet-formed processing, least of at all when using recycled paper fibers. Generally, a thermomechanical fiberboard-type pulp requires either resin or high density to achieve adequate fiber-to-fiber bonding. In the present study, panels were formed with 0% to 4.5% resin. Higher amounts of resin were applied than usual to inspect the possibility for significant improvements with more than 2.0% resin.

Performance characteristics of low-density fiberboard (LDF)

There are only a few publications on this topic. Pulp-molded products are uniquely developed for niche-specific three-dimensional applications, and their performance characteristics have historically been evaluated on three-dimensional geometry and systems performance rather than a material basis. Marcondes (1999) described cushioning and vibration performance characteristics correlated with the perimeter of a molded part, but no specific material properties of that molded part were mentioned. Kang (1998, 2002) measured cushioning performance of pulp-molded products and correlated them to design variables that included unit height, bottom-unit perimeter length, unit-slope angle, radius of the corners, shape-factor coefficients, and pulp thickness. These empirically determined shape factors included cone, triangle, and rectangle and the data would differ from manufacturer to manufacturer because of differences in fiber type and processing conditions. The basic material properties in his studies do not rely on standardized methods or consistent data.

Three-dimensional pulp-molded products and computer simulations for these products need reliable material properties. Gurav et al. (2003) discussed the data concerning mechanical property and thickness of low-density pulp molded parts as input variables for finite element analysis (FEA) computer simulation: both tensile and compression stress were measured and related to deformation. Their FEA model assumed that tensile and compression elastic properties were constant and isotropic at a constant density of 350 kg m^{-3}. It was difficult to determine accurately the specific properties throughout the whole shape because of thickness and property variations of the actual pulp molded part. Ma et al. (2004) also applied FEA-computer simulation to evaluate performance of three-dimensional molded pulp shapes based on manufacturing variables of geometry including basic shape, wall thickness, sidewall slope, unit height, and radius at the top. The authors assumed isotropic material properties at a density of 400 kg m^{-3}, resulting in a MOE of 100 MPa and Poisson's ratio of 0.34. There was no mention of changing the performance by varying the density. In the above articles, the products were characterized for a single density.

Performance characteristics of medium-density fiberboard (MDF)

Hunt (1998) evaluated physical and mechanical properties of wet-formed flat sheets made from several types of recycled fibers including old newspapers and OCC. MOE data were evaluated as a function of drying methods. Density for materials evaluated ranged from 300 to 700 kg m^{-3}. No resin was added to the fibers. The base relationship of the MOE data was determined as a function of density.

The Homasote Company (2007) produces a low-to-medium-density (380–640 kg m^{-3}) commercial product that is made by a wet-forming process and based on 100% recycled fibers. The company provides limited material data (MOE and tensile strength) for their products.

Performance characteristics of high-density fiberboard (HDF)

Suchsland and Woodson (1986) compiled a handbook on fiberboard manufacturing practices that summarizes numerous studies on the effects of various processing and fiber characteristics on performance properties for MDF and HDF. Studies that included the range between LDF to MDF or the utilization of recycled fibers were not summarized.

The technology of wet-formed fiberboard and hardboard based on recycled paper fibers is not new. Steinmetz (1974) investigated fibers from wax-coated corrugated containers as a partial or total replacement for virgin hardboard fibers. Adding increasing amounts of fibers from wax-coated corrugated containers in amounts up to 100% replacement resulted in improved bending strength of 10%, and stiffness increased 4%.

Kruse (1995) compared hardboard panel properties from a commercial installation that was made with and without 20% OCC fibers. The panels with or without OCC fibers had equivalent properties. It was concluded that OCC fibers could be added to the manufacturing system, but then process equipment required adjustments.

Suchsland et al. (1998) investigated recycled newsprint and kraft fibers in the manufacture of hardboard by means of a modified wet-formed process. Their results showed a beneficial effect for newsprint fibers but not for kraft fibers. The authors found no significant trends or differences for bending MOE within each fiber type with or without resin.

Yao (1978) explored properties of hardboards made from 100% municipal solid-waste paper fibers. The effects of binder type and wax treatment were investigated. In this study, just one bottom screen was applied instead of the usual two screens, one on top and one on the bottom. The effect of heat treatment was evaluated on mechanical and physical properties. The mechanical properties improved significantly if screens were used on both sides for smoothing one side-type hardboards.

A series of papers by Hunt and Vick (1999) and Hunt and Supan (2005, 2006) have demonstrated that high strength panels can be produced from recycled OCC with the wet-formed technology, if the panels are press-dried between two screens. Hunt and Supan (2005, 2006) also examined the effects of varying MC on performance characteristics and found that strength and stiffness decreased with increasing amounts of moisture.

In all the above quoted studies, the effects of panel properties over the range of densities from low-density, 200–1200 kg m^{-3}, have not been systematically explored. Density alone is not sufficient to describe fiberboard properties, but should also include thickness, resin (type and amount), and performance in static or MC conditions. These more complete investigations would enable us to develop a database of property information that describes performance characteristics of wet-formed fiberboard. An empirical model could be developed from the database that makes it possible to design wet-formed composite products that have specific performance characteristics to meet a specific performance need.

As an initial step in this process, the present paper reports the bending MOE and MOR as a function of density, thickness, resin content, and MC.

Experimental

Fiber furnish

Two fiber furnishes (*P. contorta* treetop material and OCC) were investigated. The *P. contorta* material was part of the Forest Service's National Fire Plan research program that focused on utilization of hazardous fuels, such as treetop residuals accumulating in the forest. Delimbed treetop material (the residual of a small-diameter suppressed growth logging operation) was obtained from the Bighorn National Forest, Wyoming, WY, USA. The material with a diameter around 100 mm or less was chipped with the bark. The chips were fiberized into 1-mm diameter by 12.5-mm long pin-chips in a Tornado pulper (Bolton-Emerson, Lawrence, MA, USA). The pin-chip material was pretreated with 4% NaOH and refined to produce a high freeness pulp, 650 Canadian Standard Freeness (CSF) (Tappi 2004).

The OCC material had been shown in previous studies to form well and produce composites with excellent properties (Hunt and Vick 1999; Hunt and Supan 2006). The OCC pulp was produced from commercially available corrugated paper box flats by hydropulping to an approximate freeness of 600 CSF. The OCC fiber furnished also had sufficient surface energy that allowed the production of wet-formed mats with low-density without resin ("self-bonded" mat). More recycled OCC were investigated than *P. contorta* fiber (Table 1). The reason for this is that supply of *P. contorta* fiber was limited.

Panel fabrication

All test panels were wet-formed at 1% consistency [consistency=dry fiber weight/(water+fiber weight)]. Fiber amounts for each panel were adjusted to achieve a thickness of 1.27, 1.90, 2.54, or 4.76 mm at each of the given density levels. Wet-formed phenol-formaldehyde hardboard resin was used as indicated at 0%, 0.5%, 1.5%, 3.0%, and 4.5% based on dry fiber weight. Aluminum sulfate powder was added to the pulp slurry to drop the pH to 4 to precipitate the resin onto the fibers in the pulp slurry. The slurry was blended for 15 min before forming. After forming and vacuum pressing, the formed sheets had approximately 80% MC, wet basis (400% MC dry basis). Each mat was placed between two screens and two 3.2-mm thick stainless steel cauls (0.125-in.). The wet mats were hot pressed at 175°C with continuous pressure to target densities of 400, 600, 800, 1000, and 1150 kg m^{-3} until the panels were dry (approximately 1% to 2% MC). The experimental design included 5 target

Table 1 Number of panels per target density, thickness, and resin content for the lodgepole pine and recycled old corrugated container panels.

Target density (kg m^{-3})	Hot press board pressure (kPa)	Target thickness (mm)	Lodgepole pine with resin contents of			Recycled old corrugated containers with resin contents of				
			0 (%)	1.5 (%)	4.5 (%)	0.0 (%)	0.5 (%)	1.5 (%)	3.0 (%)	4.5 (%)
400	103	1.27	–	–	–	3	3	3	3	3
400	103	2.54	–	–	–	3	3	3	3	3
600	206	1.27	–	–	–	3	3	3	3	3
600	206	2.54	–	–	–	3	3	3	3	3
800	483	1.27	–	–	–	3	3	3	3	3
800	483	2.54	–	–	–	3	3	3	3	3
1000	1380	1.27	3	3	3	3	3	3	3	3
1000	1380	1.90	3	3	3	3	–	–	–	–
1000	1380	2.54	3	3	3	3	3	3	3	3
1000	1380	4.76	3	3	3	3	–	–	–	–
1150	2070	1.27	–	–	–	3	3	3	3	3
1150	2070	2.54	–	–	–	3	3	3	3	3

Table 2 Bending span length.

Bending settings	Panel thickness			
	1.27 (mm)	1.90 (mm)	2.54 (mm)	4.76 (mm)
Span (mm)	30.5	45.7	61	114
Length (mm)	81.3	96.5	111.7	165.1
Width (mm)	50.4	50.4	50.4	50.4
Load rate (mm/min)	0.61	0.91	1.22	2.29
Number of specimens	168	24	168	24

density levels, 4 target thicknesses, and 5 resin levels (Tables 1 and 2).

Testing

After panel fabrication, four bending specimens were cut from each panel. Two from each group were placed in either a 22°C, 50% RH or 27°C, 90% RH conditioned room to reach equilibrium moisture content (EMC) (Figure 1). The samples were tested in bending according to the American Society for Testing and Materials Standard D 1037 (ASTM 1996). Bending samples of different thicknesses need to be tested with different span lengths and loading rates. The test settings are listed in Table 3 and the number of specimens for each target thickness. Thickness, length, width, and weight of specimens were determined before testing.

Results and discussion

Density

Thickness and weight were measured per unit specimen to determine specimen density. Density was affected by fiber type, panel thickness, hot press pressure, and resin content (Figure 2). Comparisons between *P. contorta* and OCCs indicate that, when pressed at the same pressure, OCC results in a higher density. Old corrugated carton pulp is a low-yield kraft pulp that conforms more easily than higher yield *P. contorta* pulp. Had the *P. contorta* pulp gone through a kraft pulping process, we would expect similar results as with OCC pulp.

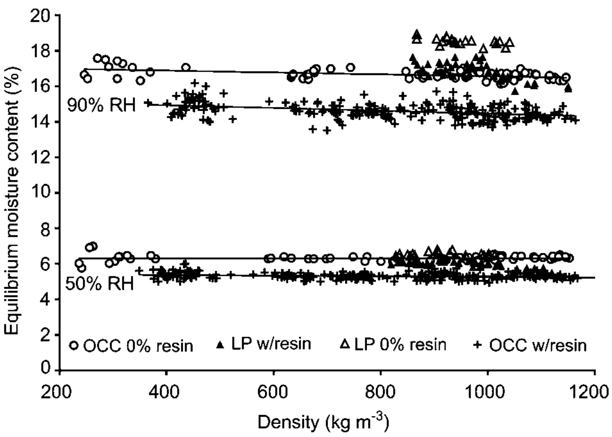

Figure 1 Equilibrium moisture content as a function of density in 50% and 90% RH conditions for panels made from lodgepole pine (*P. contorta*, LP) and recycled old corrugated fibers (OCC). Lodgepole pine and OCC resin panels include 0.5%, 1.5%, 3.0%, 4.5% resin amounts.

Table 3 Equilibrium moisture content of the lodgepole pine (LP, *Pinus contorta*) and old corrugated carton (OCC) panels after conditioning at either 50% RH and 90% RH.

Resin content (%)	Equilibrium moisture content (%) [standard deviation]			
	at 50% RH		at 90% RH	
	LP	OCC	LP	OCC
0.0	6.56 [0.11]	6.31 [0.17]	18.5 [0.20]	16.6 [0.30]
0.5	–	5.34 [0.19]	–	14.8 [0.40]
1.5	5.98 [0.16]	5.31 [0.16]	17.1 [0.41]	14.5 [0.42]
3.0	–	5.35 [0.19]	–	14.7 [0.50]
4.5	5.96 [0.17]	5.27 [0.15]	16.6 [0.46]	14.3 [0.35]

RH, relative humidity.

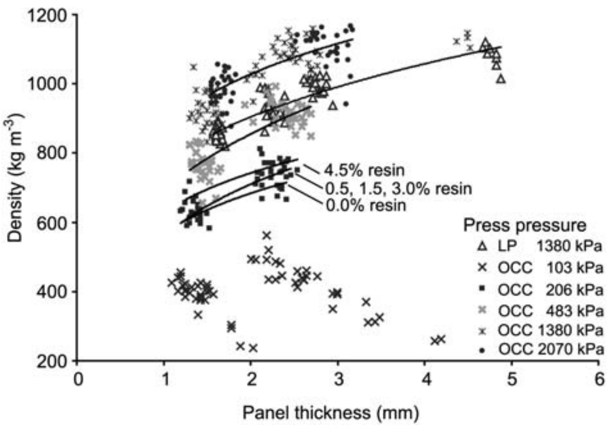

Figure 2 Density compared with thickness for lodgepole pine (*P. contorta*, LP) and old corrugated container (OCC) panels pressed at increasing press pressures.

All panels above 400 kg m^{-3} were shown to increase in density with panel thickness. Panels below 400 kg m^{-3} revealed a slight decrease in density as thickness increased. These low-density panels were nominally pressed at 103 kPa, but actual pressures may have been even lower because pressure was difficult to control at this low level. Lower press pressures would produce panels with lower densities. Even though pressures may not have been constant, these panels still provide valuable information when density or thickness is the dependent variable; these data were therefore kept in the data set for analysis.

In the first instance, it was unclear why density would increase with thickness rather than staying constant. The first hypothesis was that – if a particular fiber type were pressed at the same conditions regardless of amount – the density should not change essentially. However, because these panels were pressed with screens on both sides, screen-pattern indentations occurred on both sides of the panel. The indentations produced the same depth of low-density regions on both faces. For the thinner panels, the same depth of indentation caused a higher relative percentage of low-density regions for the total thickness. Thus as thickness increased, the relative percentage of low-density region decreased, which then

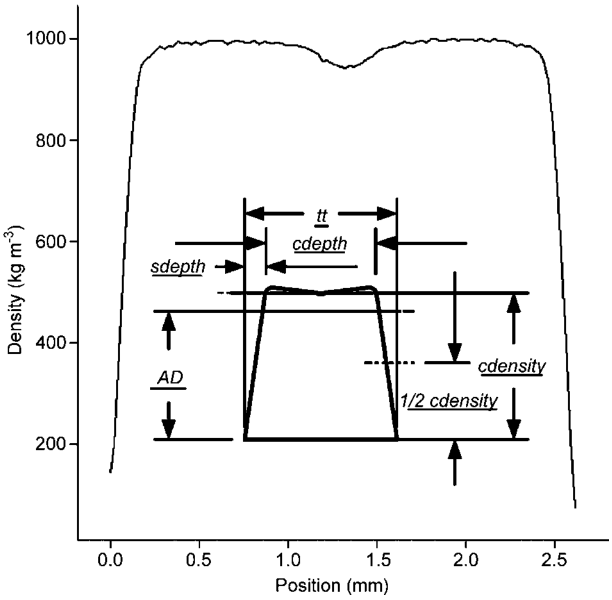

Figure 3 Typical vertical-density profile through the thickness of a panel. Apparent density is *AD*, surface depth is *sdepth*, core depth is *cdepth*, total thickness is *tt*, and core density is *cdensity*.

influenced the apparent density for the total panel. To verify this interpretation, vertical-density profiles (VDPs) were analyzed preliminarily by non-destructive X-ray densitometry (Figure 3) for a subset of *P. contorta* panels.

The VDP showed that core density was essentially uniform once past the initial density gradient on either face. As both faces were pressed with 40-mesh screens, both face density gradients were also the same. For all *P. contorta* panels, pressed at 1380 kPa, the analysis showed the face gradient accounted for 0.232 mm (±0.055 standard deviation) depth into the board. The core density (*cdensity*) for all the boards was approximately 1050 kg m^{-3} (±85.7 standard deviation) regardless of thickness. This finding verifies our initial assumption that for a given fiber the *cdensity* is the same for a given process condition. Then, it was possible to demonstrate by means of Eq. (1), that – if the surface depth (*sdepth*) stays the same – the overall apparent density (*AD*) will increase as total thickness (*tt*) increases (Figure 3). As sheet mass increases and the process is not changed, then *tt* increases and *AD* approaches the core density level. This explains why the *AD* increased as *tt* increased (Figure 2).

$$AD=2\times\left[\frac{sdepth}{tt}\right]\times\frac{1}{2}cdensity+\left[\frac{cdepth}{tt}\right]\times cdensity \qquad (1)$$

In the literature, there are numerous examples demonstrating that MOE for wood composite materials is a function of density. As illustrated in Figure 2, density distribution through the thickness of the panel changes and it is assumed that the MOE distribution through the thickness also changes. Thus, the density distribution will have an influence on bending performance. However, the standard bending equations for determining bending properties (ASTM 1996, D 1037) were developed with the assumption of a constant MOE through the thickness of the panel. For this paper, the *AD* as measured by weight and total thickness (*tt*) per unit area was assumed to be constant through the thickness, resulting in a constant MOE through the thickness of the panel. While the VDP is an important parameter when determining and predicting bending performance, the shape of the profile and its influence on bending properties is beyond the scope of this paper and will be discussed in a subsequent publication.

Press pressure is also a contributing factor to overall density. Density increased as pressure increased from 103 to 1380 kPa. However, at a pressure of 2070 kPa, density did not further increase over 1380 kPa. The minimum pressure necessary to reach maximum density may possibly be less than 1380 kPa. Old corrugated carton is a kraft pulp that easily conforms with minimal pressure. Additional research must determine the relationship between pressure and density development. By better understanding this phenomenon and then optimizing the press pressure, it should be possible to reduce pressing energy and costs associated with production.

The OCC density was marginally influenced by the resin content range observed in this study. The density data for panels pressed at 206 kPa was separated into resin levels, and trend-lines are shown at 0% resin (bottom line), at 0.5%, 1.5%, and 3.0% (middle line), and at 4.5% resin content (top line) (Figure 2). As a general trend, density increased as resin amount increased. This may be due to the higher density of resin solids compared to kraft pulp fiber. The resin also fills void spaces between fibers, contributing to increased density as well as increased fiber bonding. Similar trends were also evident for the other groupings but are not presented for clarity.

Equilibrium moisture content (EMC)

Specimens were weighed after conditioning in either 50% RH or 90% RH. After the bend test at either condition, the specimens were dried at 105°C. The dry weight for each specimen was measured and EMC determined. The EMC after conditioning in 50% RH for the *P. contorta* panels was 6.6% for 0% resin and reduced slightly to 6% with resin amounts of 1.5% and 4.5% (Table 3, Figure 1). Panels having resin and conditioned at 50% RH had similar EMC for all densities. At 90% RH, the *P. contorta* panels increased to an EMC of 18.5%, 17.1%, and 16.6% for resin contents of 0%, 1.5%, and 4.5%, respectively. Similarly, the EMC for OCC panels with no resin at 50% RH was 6.3% and 16.6% at 90% RH. It is evident that, for OCC, even 0.5% resin had an observable effect on reducing the EMC.

For panels with resin and conditioned at 90% RH, a slight trend for reduced EMC was noticeable as resin amount increased (Figure 1). The resin either blocks or inhibits the bond site from the moisture or prevents swelling and thereby limits further migration of moisture into the board. As tests were not performed above 4.5% resin, it is not clear whether the maximum amount of precipitated resin had been reached. Further additions of phenolic resin with the fiber may possibly continue to decrease EMC. Interestingly, *P. contorta* had a higher

EMC than the OCC. The opposite case could be expected because OCC fibers have more available hydroxyl groups. Panel thickness did not have a significant effect on panel EMC.

MOE and MOR

Bending MOE values for panels made from *P. contorta* and OCC fibers are illustrated in Figure 4a, and MOR values in Figure 4b. Both figures show bending test data after 50% RH and 90% RH conditioning. The OCC and *P. contorta* data is grouped to include those panels with and without resin. Both MOE and MOR were influenced most by panel density. Power curves were fitted to the OCC data to show the trends for a single fiber type, but the *P. contorta* data generally "fit" within the OCC data. These fitted curves show, on average, that MOE and MOR were both reduced by approximately 50% when boards were tested after conditioning in 90% RH, compared with those tested in 50% RH. The MCs approxi-

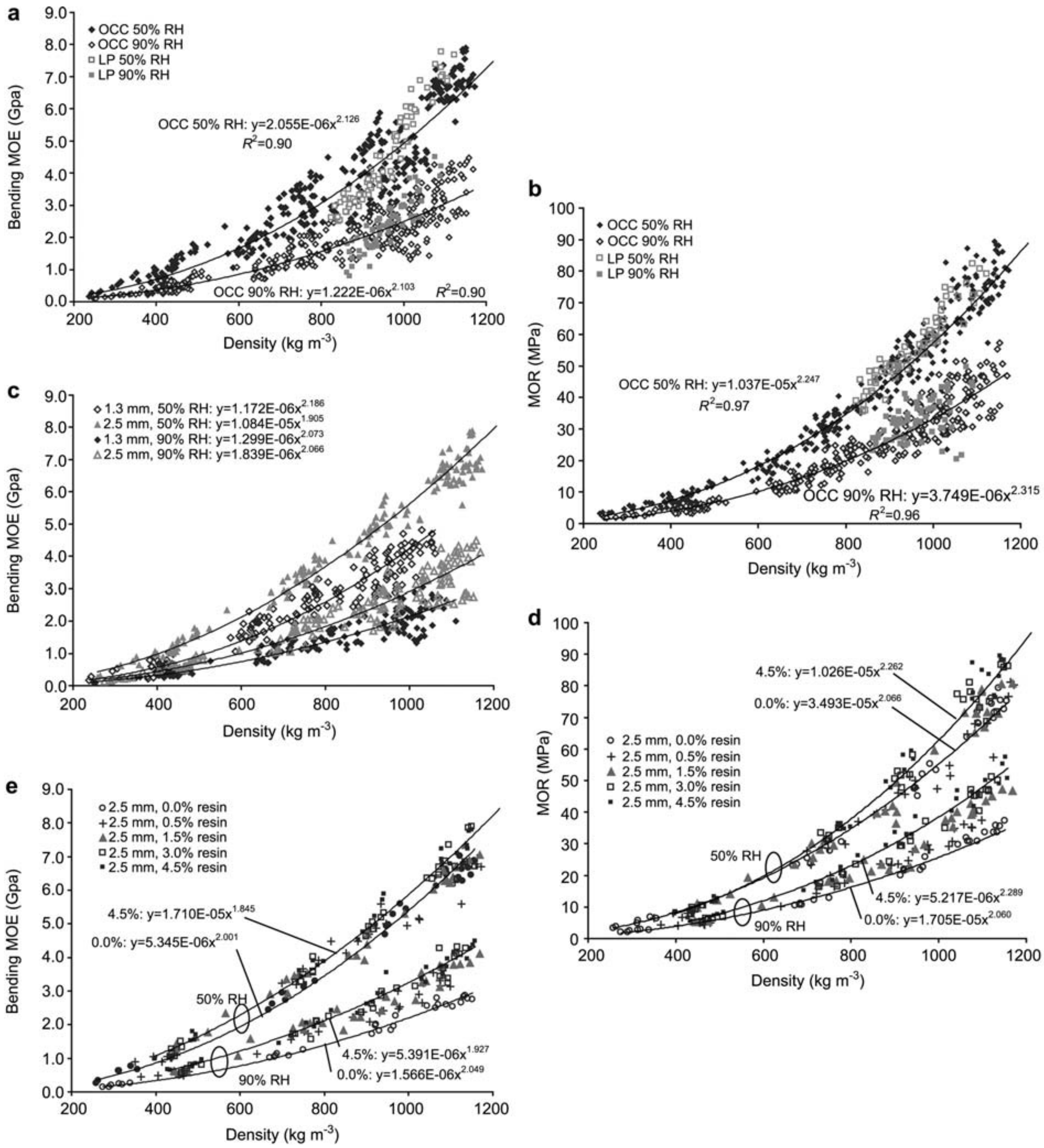

Figure 4 Bending modulus of elasticity (MOE) at 50% and 90% relative humidity (RH) shown for different groups of data for (a) panels made from lodgepole pine (*P. contorta*, LP) and recycled old corrugated containers (OCCs); (c) panel thicknesses of 1.3 and 2.5 mm made from recycled old corrugated containers (OCCs); and (e) 2.5-mm thick panels made from recycled old corrugated containers (OCCs) with increasing resin contents. Modulus of rupture (MOR) at 50% and 90% relative humidity (RH) shown for different groups of data for (b) all the panels made from lodgepole pine (*P. contorta*, LP) and recycled old corrugated containers (OCCs) and (d) 2.5-mm thick panels made from recycled old corrugated containers (OCC) at different resin contents.

mate tripling of their EMC (Table 3), if RH is elevated from 50% to 90% RH.

The effect of thickness on MOE and MOR was evaluated. The MOE data of OCCs were regrouped into nominal 1.3- and 2.5-mm thickness groups and plotted (Figure 4c) as a function of density and conditioning environment. The regrouped data included panels with and without resin. The figure illustrates that the thinner panels had lower MOE values than the thicker panels. For example, at 50% RH, MOE increased by approximately 70% as thickness increased from 1.3 to 2.5 mm at 400 kg m^{-3} and by approximately 33% at 1000 kg m^{-3}. This thickness effect was unexpected because neither the fiber type nor the process parameters had changed. As previously discussed, the VDP and thickness of the panel has an influence on MOE and may account for most of the differences presented. When MOR was similarly plotted as a function of thickness, no significant differences were noted. Because MOR is more a measure of the maximum stress on the outer face, it may be less sensitive to correlated density variation through the thickness of the panel than is MOE, which is determined by the slope of stress to strain relationship.

When MOE (Figure 4e) and MOR data (Figure 4d) were plotted as a function of increasing resin, both plots showed increasing trends as resin content increased, as expected. The trends, however, were not as pronounced as the effects of density, thickness, or MC. For panels tested at 50% RH, a MOE less positive effect was visible from resin addition than those tested at 90% RH, again, an expected observation. Resin addition partially overcame the negative effects on MOE as EMC increased. Also, panels without resin had a higher EMC than those with resin (Figure 1 and Table 3). For OCC, 2.5-mm thick panels tested at 50% RH, MOE values increased 25% at 400 kg m^{-3} and 9% at 1000 kg m^{-3}. For panels tested at 90% RH, MOE increased 65% and 48% at 400 kg m^{-3} and 1000 kg m^{-3}, respectively, when resin increased from 0% to 4.5%.

Similarly, MOR for OCC 2.5-mm thick panels tested at 50% RH did not change at 400 kg m^{-3} and only increased by 9% at 1000 kg m^{-3}. For panels tested at 90% RH, MOR increased 20% and 49% at 400 kg m^{-3} and 1000 kg m^{-3}, respectively, when resin increased from 0% to 4.5%. Panels tested at 50% RH showed a smaller increase than those tested at 90% RH, again as expected.

Similar MOE and MOR responses were observed for thinner panels (1.3 mm) as resin increased. The trend of increasing properties (MOE and MOR) was evident with as little as 0.5% resin added, and the trends continued to increase with more resin. The trend lines corresponding to the presented data points in Figure 4d and e are not depicted for clarity. Probably, the maximum resin absorption for this fiber type is not reached with 4.5% resin addition. More research is needed to clarify this. The *P. contorta* panels also exhibited similar MOE and MOR to resin relationships as OCC panels.

Conclusions

Physical and bending properties for panels made from *P. contorta* and OCC fibers over a large range of densities have been evaluated as a function of MC, density, thickness, and resin content. Panels made from *P. contorta* and OCC fibers were shown to be similar in performance. Individual curve fits reveal trends in physical and mechanical performance. Statistical trend lines indicate that mechanical properties increase approximately as the square of the density. Density vs. thickness relationships and density profile data show that “apparent” density rises as thickness (fiber amount) increases. Preliminary VDPs reveal that core density is relatively flat, but the relative percentage of low-density surface layers can have a significant effect on density and measured performance for thin panels. Further studies are needed to determine how press pressure and two-sided screens affect the relative percentage of low-density faces and how that then influences physical and mechanical properties.

As hot press pressure increased, density of the panels was elevated. Pressures above 1380 kPa did not increase density. This indicates a possible plateau in properties related to density development. Both MOE and MOR were positively correlated with density.

Panel EMC decreases with the addition of phenolic resin. Adding as little as 0.5% resin significantly diminishes EMC. Addition of more than 0.5% resin marginally decreased EMC.

The curve fits presented in this paper are simple one-parameter equations. In a later paper, statistical models will be developed that probably will better reveal the interactions between the parameters and MOE and MOR.

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