Binderless fiberboard: Comparison of fiber from recycled corrugated containers and refined small-diameter whole treetops

John F. Hunt*
Karen Supan

Abstract

Whereas many research activities focus on developing value-added processes that use forest residues, scientists must also investigate the mechanical properties of products made from recycled fiber resources. This study compared the tensile and bending properties of binderless panels made from recycled corrugated containers with properties of panels made from lodgepole pine treetop residues. The properties were measured after reaching equilibrium moisture contents in 50 and 90 percent relative humidity environments. The results show panels made from recycled corrugated containers at both humidity levels were 10 to 20 percent stronger and stiffer than those made from lodgepole pine. Tensile energy absorption was also measured and showed that panels made from old corrugated containers could absorb about 200 percent more energy than the lodgepole pine panels. Tensile stress and strain plots graphically show the difference between the fiber types and processing methods, especially the higher strain at failure for the recycled corrugated container panels. Panels from both fiber sources surpassed minimum commercial hardboard standards. The results showed alternative fibers could be used to produce strong and stiff panels. This research is part of a larger program for developing an understanding of panel properties for engineered three-dimensional fiberboard products.

A previous paper (Hunt and Supan 2005) discussed in detail the properties of binderless fiberboard panels made from the whole treetops of small-diameter lodgepole pine. That study on the development of panel properties used whole treetops for value-added three-dimensional (3D) engineered fiberboard structures as part of a larger study sponsored through the National Fire Plan (NFP) of the USDA Forest Service. The goal of our NFP research is to develop economical outlets for forest residue material. The reality in many locations is that logging residuals or thinnings from National Forests may not always be readily available because of administrative or litigation reasons. Many potential commercial entrepreneurs are reluctant to invest in these rural opportunities if the availability of fiber is not guaranteed long-term. Alternative fibrous resources must be investigated and their properties determined in case supplies from the forests are interrupted or diminished.

Many alternative raw-material resource options are available for use in structural products, including agricultural and recycled fibers. However, each fiber type has its own characteristic parameters that define its potential use. Rather than describing the specific differences in the fiber types, this paper will show that both virgin and recycled fiber have unique and slightly different properties, and each can be used to produce binderless panels with properties like hardboard. These differences must be analyzed and understood to appropriately determine what type of processing should be used to produce a fiber with specific mechanical properties. Wood fibers that are processed differently will most likely respond differently when exposed to various moisture conditions. For example, high-yield hardboard fibers are significantly less chemically processed and contain higher contents of lignin (23% to 33% lignin) compared with low-yield kraft pulped fibers that may contain much lower lignin contents (15% lignin). The effects of moisture content (MC) on the mechanical properties of panels made from different fiber types needs to be determined. The reason for producing a high-density hardboard-like product that meets the American

The authors are, respectively, Research Mechanical Engineer, USDA Forest Products Lab., Madison, WI (jfhunt@fs.fed.us); and Graduate Student, Dept. of Mechanical and Aerospace Engineering, Univ. of Florida, Gainesville, FL (ksupan@ufl.edu). This paper was received for publication in April 2005. Article No. 10033.
*Forest Products Society Member.

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Society for Testing and Materials (ASTM) Standard D 1554 (ASTM 2001) is not necessarily to produce hardboard as an end product but to develop a database of material properties for binderless panels. The fundamental-material property database will be used to develop future design and analysis for value-added 3D engineered fiberboard products (Hunt and Winandy 2002).

A good alternative fiber source could be old corrugated containers (OCC) because 1) this material is a readily available recycled fiber resource available most anywhere in the country; 2) it is relatively low-priced compared with office waste paper; 3) it is a relatively clean source of fiber without significant fillers or plastic contaminants; and 4) it has been shown in previous studies to form well (a critical property for future 3D engineered fiberboard) and produce composites with enhanced properties (Hunt and Vick 1999).

Research efforts to recycle paperboard fibers into hardboards are not new. Steinmetz (1974) investigated fibers from wax-coated corrugated containers as a partial or total replacement for virgin hardboard fibers in wet process hardboards. He found that adding increasing amounts of fibers from wax-coated corrugated containers up to 100 percent increased bending strength 10 percent and stiffness 4 percent but decreased drainage rates 110 percent. Kruse (1995) reported equivalent hardboard properties from a commercial trial where 20 percent recycled OCC fibers were added to virgin hardboard fibers. Adding OCC fibers reduced drainage rates and caused fractures in the mat during wet pressing. Kruse concluded that OCC fibers could be added to the manufacturing system with minor adjustments to the process equipment. Yao (1978) explored the properties of hardboards made from 100 percent municipal solid waste paper fibers. He investigated the effects of binder type, heat treatment, wax treatment, and one compared with two screens, and he found that hardboards met or exceeded the commercial requirements for tensile strength, modulus of rupture (MOR), internal bond, and thickness swell. He also found that properties improved if screens were used on both sides rather than on only one side of the panel during drying.

This study compared the properties of flat panel high-density binderless fiberboards made with OCC with those made of virgin lodgepole pine treetops and the mechanical tensile and bending properties of each material are described. The properties were measured after reaching equilibrium MCs in 50 and 90 percent relative humidity (RH) environments. The study by Hunt and Vick (1999) used 1.5 percent resin. No resin, however, was used for the present study because the goal was to determine the effects of processing and pulping time for natural fiber-to-fiber bonding potential.

Experimental

Fiber furnish

The OCC pulp was produced from commercially available corrugated paper box flats obtained from a local box maker. The boxes did not have any labels or hot-melt adhesive, and their recycled fiber content was unknown. Six different batch samples of hydropulped OCC were made using a high-consistency laboratory hydropulper. The start temperature of the hydropulper water was 45°C, the batch OCC dry-weight was 4.5 kg, and batch consistency was 10 percent. The processing time for each batch varied, starting at 20 minutes and increasing to intervals of 40, 60, 120, 180, and 240 minutes.

Small-diameter (less than 10 cm [4 in]) lodgepole pine treetops were used as the virgin raw material for this study (Hunt 2001). The treetops were obtained from the Bighorn National Forest and Wyoming State Forest. The de-limbed treetops were chipped with the bark but without limbs or needles and fiberized into pin-chips using a Tornado, which wet-fiberizes

Table 1. — Fiber properties at each of the conditions for OCC refined at different time intervals. The fiber processing temperature was 45°C, and no NaOH was used.

Trial no.	Hydropulping time	Freeness	Fiber length	Total fines	Shives
	(min)	(CSF)	(mm)	----------(%)-----------	
1	20	710	1.560	8.2	5.33
2	40	670	1.360	12.4	1.81
3	60	640	1.428	10.1	1.62
4	120	610	1.403	9.5	1.60
5	180	553	1.343	12.0	1.64
6	240	593	1.483	9.0	1.57

Table 2. — Fiber properties at each of the conditions for refining the lodgepole pine Tornado pin-chip fibers.

Trial no.	Fiber processing temperature	NaOH	Refiner plate gap (1st/2nd/3rd pass)[a]	Freeness	Fiber length	Total fines	Shives
	(°C)	(%)	(mm)	(CSF)	(mm)	----------(%)----------	
1	90	0	0.43	710	1.002	11.1	50.49
2	90	0	0.43/0.254	580	0.942	13.7	28.37
3	90	0	0.43/0.254/0.254	440	0.872	15.5	20.77
4	90	0.5	0.43	740	1.010	9.1	53.45
5	90	0.5	0.43/0.254	600	0.906	14.5	25.88
6	90	0.5	0.43/0.254/0.254	530	0.888	15.3	19.43
7	90	1	0.43	755	0.981	11.0	49.16
8	90	1	0.43/0.254	600	0.947	13.6	28.17
9	90	1	0.43/0.254/0.254	560	0.907	13.6	23.82
10	90	2	0.43	740	1.142	8.5	56.42
11	90	2	0.43/0.254	700	1.062	11.2	29.57
12	90	2	0.43/0.254/0.254	640	1.009	12.7	21.90
13	90	4	0.43	780	1.251	6.8	58.21
14	90	4	0.43/0.254	740	1.108	10.1	36.15
15	90	4	0.43/0.254/0.254	705	1.120	11.0	21.83
16	110	0.5	0.43	730	1.146	9.6	48.18
17	110	0.5	0.43/0.254	660	1.073	12.2	21.23
18	110	1	0.43	755	1.227	8.1	46.87
19	110	1	0.43/0.254	640	1.105	11.7	25.12
20	110	4	0.43/0.254	670	1.297	11.7	25.17

[a]Some trials completed only one or two passes.

woody biomass (Bolton-Emerson, Lawrence, MA). These pin-chips, which were approximately 1 mm in diameter and 12.5 mm long, were used as fiber furnish to investigate 20 variations of wet-refining with and without sodium hydroxide (NaOH) pulping treatments to produce a bondable fibrous material. A sufficient quantity of material was produced at each trial condition to wet-form two 0.5- by 0.5-m panels at each variation. Fifteen trials were run at an elevated temperature of 90°C at atmospheric pressure and five trials were run at 110°C in a pressurized digester. Both fiber furnishes were evaluated using pulp test methods to determine freeness (TAPPI 2004), fiber length (OpTest FQA 2006), and shive content (Pulmac International 2005). A more detailed description of fiber processing is provided in a previous article (Hunt and Winandy 2002).

Panel fabrication

All test panels were wet-formed at 1 percent consistency (consistency = dry fiber weight/water weight). After forming and vacuum pressing, the formed sheets had approximately 80 percent MC (wet basis, or 400% MC on a dry basis). Each mat was placed between two screens and two stainless steel cauls and hot-pressed at 163°C with continuous 1175 kPa pressure for 10 minutes to near 0 percent MC. The target thickness was 3.2 mm, and target density was 1000 kg/cm^3. For this study, only the effects of the processing variables on fiber-to-fiber bonding were to be determined; therefore, no adhesive was used to influence bonding. The fibers bonded together naturally under heat and pressure.

Testing

Test specimens were cut from the flat panels to evaluate their bending and tensile properties as outlined in ASTM Standard D 1037 (ASTM 1996). Four bending and four tensile specimens were cut from each panel. Two from each group were placed in a 22°C, 50 percent RH conditioned room. The other two specimens were placed in another conditioned room held at 27°C, 90 percent RH.

Results and discussion

Fiber furnish

The only processing variation for the OCC was time mixing in water (hydropulping). The most significant changes occurred when the hydropulping time went from 20 to 40 minutes, when freeness, fiber length, and shive content all greatly decreased (**Table 1**). Most notably, the shive content went from 5.33 percent at 20 minutes to 1.81 percent at 40 minutes. Shive content for this fiber type is unpulped paper flakes, compared with fiber bundle shives for the processed lodgepole pine. Shive content described here is defined as any material not able to pass through a 0.10-mm-wide slotted screen. Additional hydropulping time imparts mechanical action onto the fiber, which slightly decreases freeness and reduces fiber length. Additional hydropulping after 40 minutes did not have any noticeable effects on any of the fiber properties.

Variations of fiber preparation and their effect on fiber properties for the whole treetop trial have been discussed in other articles (Hunt and Supan 2005, Hunt et al. 200_). Those studies found significant effects on fiber properties for all parameters investigated: treatment temperature, NaOH addition, and refining time. **Table 2** lists the fiber property data for the lodgepole pine.

Minimal differences for water flow through the sheet (freeness) or fines content between the two fiber types were found. Fiber length and shive content, however, are significantly different. The fiber-length difference can be attributed to the kraft chemical-pulping used to obtain fibers for the linerboard used in corrugated containers. High chemical pulping pro-

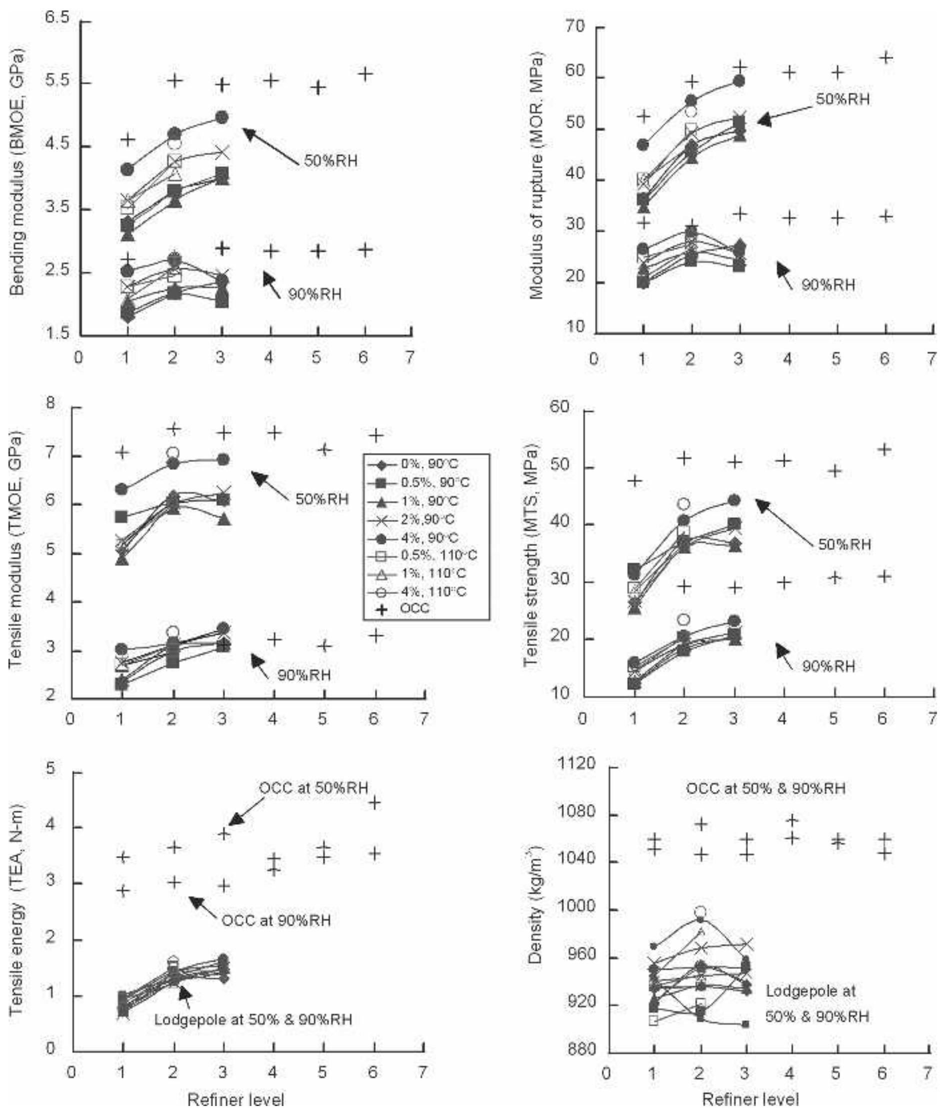

Figure 1. — Bending and tensile modulus, strength, and density properties for OCC panels compared with lodgepole pine panels at 50 and 90 percent RH. OCC panels were made from hydropulped fibers after 20, 40, 60, 120, 180, and 240 minutes, represented as refiner levels 1, 2, 3, 4, 5, and 6, respectively.

vides higher fiber length retention. When OCC is recycled, much of this fiber length is maintained. The lodgepole pine's 4 percent NaOH chemical treatment is much lower than the concentration of chemical used to make kraft fiber. Nonetheless, the pine still produced a fiber length of 1.2 mm, which begins to approach that of the OCC fiber length of 1.5 mm. To determine the maximum potential fiber length from the pin-chip material, a separate high-chemical kraft pulping of the lodgepole pine pin-chips was conducted, producing pulp with an average fiber length of 1.46 mm. The shive content for lodgepole pine is higher than for OCC. If additional amounts of NaOH were used, it would be expected to improve the fiber properties with further increases in the average fiber length and reduced shives content. The specific fiber effects and interactions have broad implications and should be fully investigated but are beyond the scope of this paper.

Physical panel properties

The MCs for the OCC panel specimens were 6.2 percent after conditioning in 50 percent RH and 12.8 percent after 90 percent RH, less than the MCs of 7.0 and 14.8 percent for the lodgepole pine panel specimens. The overall MC gain was doubled for both fiber types going from 50 to 90 percent RH conditions. The OCC specimens were higher in density at 1043 kg/m^3, compared with an average of 925 kg/m^3 for the lodgepole pine specimens (**Fig. 1** and **Tables 3** and **4**). All panels were pressed with the same pressure and temperature press conditions. The differences in properties would then be due to the different fiber types. The OCC fiber is a more highly chemically treated fiber, and the process removes a significant portion of lignin and hemicellulose components, rendering the fiber much more flexible and bondable, as in the paper-making process. During hot-pressing, the more flexible OCC fibers easily conform, yielding a higher density panel with more surface area in contact for higher fiber-to-fiber bonding potential. It is possible that the higher fiber-to-fiber bonding also affects available bond sites for water as seen with the lower equilibrium MCs for the OCC panels. Further research is needed to determine the total effects of pulping yield and resulting fiber bonding potential.

Mechanical properties

Panel mechanical properties from OCC at both MC levels are shown in **Figures 1** and **2** and listed in **Tables 3** through **6**. A two-independent-sample student's t-test with a Type I error rate of $\alpha = 0.05$ was used to verify statistical differences in the averages for all measured properties. Refining levels 1, 2, 3, 4, 5, and 6 correspond to hydropulping times of 20, 40, 60, 120, 180, and 240 minutes, respectively. The refining levels also refer to the number of passes through the refiner used for the lodgepole pine fiber. For specimens conditioned at 50 percent RH, the bending modulus of elasticity (MOE) and MOR, and tensile modulus of elasticity (TMOE) all show a slight increase but insignificant difference going from 20 to 40 minutes in hydropulping. These specimens showed no increases with hydropulping beyond 40 minutes. Tensile strength and tensile energy absorption (TEA) do not show any differences with hydropulping time. Mechanical properties of the specimens conditioned at 90 percent RH showed no significant differences for all hydropulping times.

The effect of different fiber preparations on panel properties for the lodgepole pine treetop material has been previously discussed (Hunt and Supan 2005, Hunt et al. 200_). These studies found that improvements in strength properties start to increase at 2 percent NaOH addition for bending properties and at 4 percent NaOH for tensile properties. Each step in refining improved strength properties for bending and tension, which are shown in **Figures 1** and **2**.

Comparing the "lower yield" OCC panels with the "higher yield" lodgepole pine specimens shows that OCC produces a stronger and stiffer panel at 50 and 90 percent RH and similar tensile MOE properties at 90 percent RH (**Fig. 1**). TEA for OCC panels, however, is significantly higher. The significant differences between the panels were evident from the two fiber types at both MC levels. As mentioned previously, a possible major reason for this difference is the fundamental fiber characteristic differences. The OCC fibers are lower yield chemical pulp. Generally low-yield pulps are highly flexible and conformable. For high-density panels, these characteris-

Table 3. — Bending MOE and MOR of OCC panels refined at different time intervals at 50 and 90 percent RH.

Trial no.	Hydropulping time	Bending MOE		Bending MOR	
		50% RH	90% RH	50% RH	90% RH
	(min)	----------(GPa)----------		----------(MPa)----------	
1	20	4.62	2.73	52.44	31.58
2	40	5.55	2.77	59.18	31.25
3	60	5.48	2.89	62.15	33.48
4	120	5.55	2.84	61.06	32.70
5	180	5.44	2.86	61.21	32.59
6	240	5.66	2.86	63.99	33.08

Table 4. — Bending MOE and MOR of binderless fiberboard panels made from lodgepole pine at 50 and 90 percent RH.

	Bending MOE		Bending MOR	
Run no.	50% RH	90% RH	50% RH	90% RH
	------------(GPa)------------		-----------(MPa)-----------	
1	3.31	1.80	36.47	19.80
2	3.81	2.17	46.75	25.38
3	4.00	2.37	49.72	27.31
4	3.23	1.87	36.21	19.89
5	3.79	2.17	45.55	23.96
6	4.07	2.05	51.10	23.09
7	3.10	2.05	34.70	22.79
8	3.65	2.26	44.50	26.00
9	4.00	2.26	48.90	24.39
10	3.65	2.29	39.20	23.81
11	4.26	2.56	49.10	28.12
12	4.41	2.46	52.30	25.78
13	4.14	2.52	46.70	26.48
14	4.69	2.70	55.30	29.92
15	4.96	2.38	59.20	26.00
16	3.52	2.27	39.90	24.77
17	4.27	2.45	49.60	27.37
18	3.65	2.08	40.00	20.89
19	4.07	2.58	46.90	26.61
20	4.55	2.72	53.19	29.04

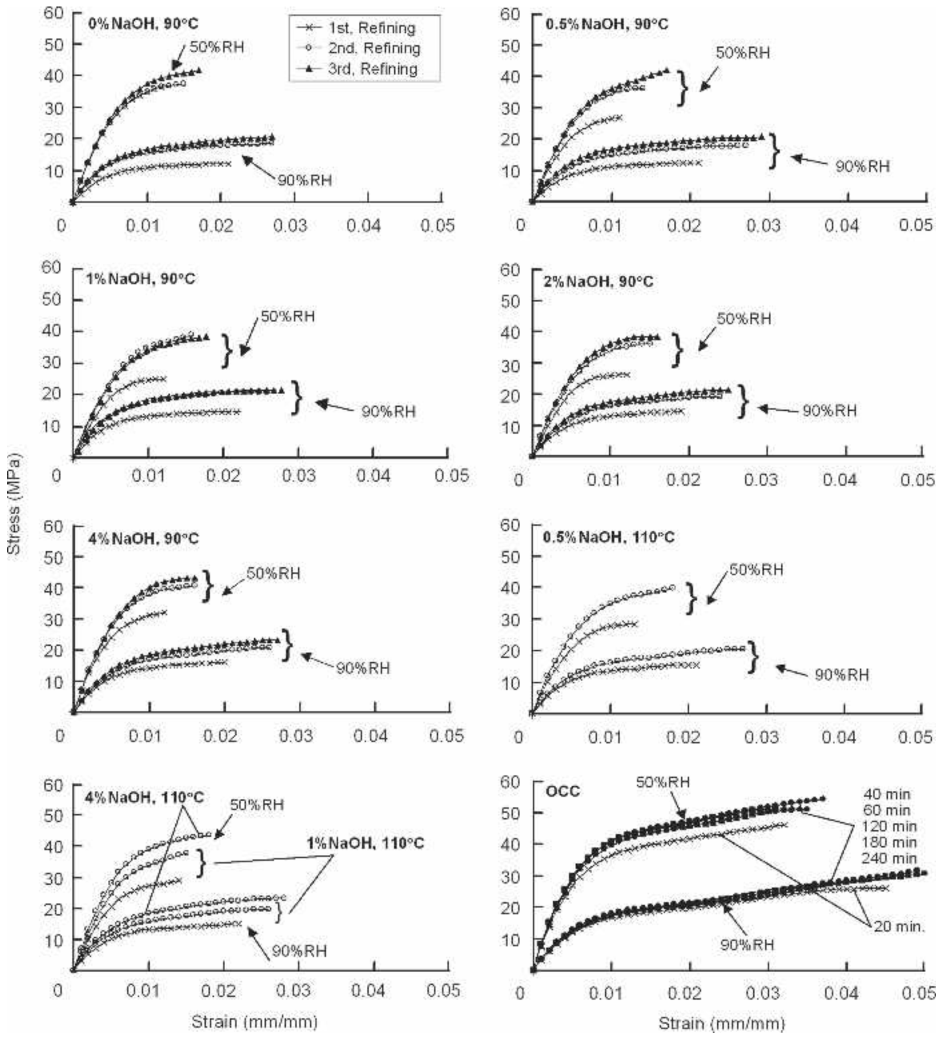

Figure 2. — Tensile stress compared with strain plots for press-dried binderless fiberboards made from lodgepole pine at three refining levels (1, 2, and 3) at various chemical pulping conditions. The bottom right graph shows OCC curves at hydropulping times of 20, 40, 60, 120, 180, and 240 minutes. The RH levels at the time of testing were 50 and 90 percent.

Table 5. — Tensile modulus of elasticity (TMOE), maximum tensile stress (MTS), and tensile energy absorption (TEA) of OCC panels refined at different time intervals after conditioning in 50 and 90 percent RH environments.

		TMOE		MTS		TEA	
Trial no.	Hydropulping time	50% RH	90% RH	50% RH	50% RH	90% RH	50% RH
	(min)	----------(GPa)----------		----------(MPa)---------		---------(N-m)---------	
1	20	7.07	2.90	47.77	26.76	3.47	2.87
2	40	7.55	3.14	51.56	29.28	3.66	3.04
3	60	7.46	3.12	50.92	29.10	3.88	2.96
4	120	7.47	3.22	51.21	30.06	3.44	3.26
5	180	7.13	3.10	49.39	30.75	3.65	3.47
6	240	7.41	3.31	53.26	31.04	4.44	3.55

tics provide for higher fiber-to-fiber contact and bonding, thus achieving higher properties. At 50 percent RH, the strength properties of the lodgepole pine panels increased and began to approach those from OCC as the chemical (NaOH) treatment and refining increased. The addition of NaOH chemically softens the fibers so they are more conformable when pressed. Refining helps to separate shives into individual fibers that are more flexible than the fiber-bundle shives. Refining also improves surface roughness and surface energy for improved bonding.

The tensile stress-strain diagrams for OCC and the lodgepole pine specimens are shown in **Figure 2**. All the OCC panels had essentially the same stress-strain behavior except for the panels made from fibers hydropulped for only 20 minutes. The lowest curve represents the average for panels made after 20 minutes of hydropulping. The effects of increased panel MC on the stress-strain relationships are apparent in **Figure 2**. Note that while the TMOE and maximum tensile stress decrease with increasing MC, TEA remained essentially the same. This same trend is well documented for solid wood and many resin-bonded wood composites (USDA 1999).

The lodgepole pine panels underwent 1, 2, or 3 refining passes with a gap thickness of 0.43 mm for the first pass and 0.254 mm for the second and third passes (**Table 2**) at each level of NaOH pretreatment (0%, 0.5%, 1%, 2%, and 4%) and processing temperature (90°C and 110°C). The effect of refining is evident in the stress-strain plots. For each pretreatment level and processing temperature, the first refining level is exhibited in the lowest stress-strain relationship, and the stiffness (slope), maximum stress, and maximum strain increased with the second refining. At the third refining level, the stress-strain curve is the greatest, showing the highest stiffness, strength, strain, and area under the curve or TEA. The tensile strains for OCC panels are nearly twice those of lodgepole pine panels (**Fig. 2**). The significantly higher strain for OCC panels and slightly higher maximum strength resulted in two to three times the TEA (**Tables 5** and **6** and **Fig. 2**). This increased strain and strain energy for the OCC panels could be attributed to a higher content of individual fibers compared with a higher content of large and less-flexible shives in the lodgepole pine panels. As mentioned previously, when refining increased (reduced shives and increased surface roughening) and NaOH increased (longer fibers), the lodgepole pine panels increased in strength, strain, and TEA. With further pretreatment and refining of the lodgepole pine

Table 6. — Tensile modulus of elasticity (TMOE), maximum tensile stress (MTS), and tensile energy absorption (TEA) of binderless fiberboard panels made from lodgepole pine after conditioning in 50 and 90 percent RH environments.

Run	TMOE		MTS		TEA	
no.	50% RH	90% RH	50% RH	90% RH	50% RH	90% RH
	--------(GPa)--------		---------(MPa)---------		---------(N-m)---------	
1	5.03	2.36	26.47	12.36	0.77	0.72
2	6.19	3.00	37.21	18.28	1.27	1.37
3	6.06	3.15	36.85	20.22	1.31	1.43
4	5.72	2.29	32.09	12.25	1.02	0.78
5	6.02	2.76	36.95	17.97	1.30	1.42
6	6.07	3.07	40.00	20.64	1.41	1.55
7	4.88	2.41	25.55	12.57	0.75	0.73
8	5.93	3.10	36.04	19.04	1.23	1.31
9	5.71	3.15	36.35	20.01	1.47	1.48
10	5.26	2.76	26.68	14.35	0.70	0.81
11	6.03	3.12	36.17	19.25	1.24	1.25
12	6.24	3.36	39.38	21.10	1.50	1.40
13	6.29	3.02	31.26	15.89	0.89	0.92
14	6.83	3.15	40.74	20.44	1.33	1.43
15	6.91	3.43	44.24	23.16	1.62	1.67
16	5.17	2.71	28.77	15.26	0.90	0.94
17	6.00	2.96	38.75	20.27	1.53	1.50
18	5.17	2.69	28.46	14.71	0.94	0.87
19	6.07	3.12	36.72	20.63	1.22	1.41
20	7.03	3.36	43.52	23.29	1.60	1.49

treetop material, the properties could possibly reach or surpass those obtained from the OCC fibers. Note that for both fiber types, the TEA is essentially the same within the same fiber type for either MC level. In other words, it takes about the same amount of energy to reach failure regardless of the MC for a given fiber type. The benefits for higher strength and stiffness are more commonly understood for most engineering applications. However, the benefits for higher TEA are a little more abstract. A possible benefit could be impact-energy absorption for packaging products. Having constant or near constant TEA over a range of MCs would be an important performance characteristic when a packaging product would be exposed to various humidity conditions yet required to protect the packaged goods.

Although it was not the intent for this study to make a hardboard replacement, hardboard is useful for comparison as a point of reference. Minimum strength standards set by the American Hardboard Association (AHA 1995) are 15.2 MPa for tension and 31 MPa for bending for standard ANSI 135.4 hardboard. All panels made from OCC and lodgepole pine fiber exceeded the minimum high-density hardboard standard requirements. This was achieved without the use of resins. Adding resin would only increase the panel properties and would also help to improve moisture resistance properties. The effects of resin on mechanical properties have been studied and will be reported in later publications.

Conclusions

The following are summary findings from this study.

- Binderless fiberboards made from recycled low-yield pulp fiber (OCC) produced higher density panels than did high-yield virgin pulp fibers at the same pressing conditions.
- Panel properties increase as chemical processing and refining of the higher-yield pulp increases.
- Moisture contents are different for fiberboard made from the two fiber types conditioned at the same RH.
- Moisture contents doubled within panels for both fiber types when going from 50 to 90 percent RH conditions.
- Mechanical properties decrease by approximately one-half with a doubling of the MC, except for tensile energy absorption.
- Tensile stress/strain curves show significant differences between OCC and high-yield lodgepole pine processed fibers.
- A high-strength binderless fiberboard panel made from fiber derived from forest residues obtained from lodgepole pine treetops and OCC both exceed minimum high-density hardboard standards.

These results indicate that fibers from OCC or forest residues could both be used as a fiber resource to produce a high-strength product if a production facility using wet-forming technology was considering switching fiber sources. Additional research will investigate what effects different recycled fiber types, resin type, resin amount, and pressing conditions have on physical and mechanical properties of panels.

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