

Effects of fiber processing on properties of fiber and fiberboard made from lodgepole pine treetops

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Abstract

As a part of the National Fire Plan, the USDA Forest Service is conducting research to reduce the severity of forest fires through effective utilization of low- or no-value logging residues and forest thinnings. This report explores the effect of processing on the physical properties of the fibrous material and flat fiberboard panels made from small-diameter lodgepole pine treetops processed with the bark. Delimbed treetops were chipped and fiberized with water using commercial equipment, digested with hot water and/or small amounts of chemical additives, refined in a disk refiner, and hot-pressed to make flat panels. To observe only the effects of water and additives on fiber bonding, adhesive resin was not used. We evaluated the effects of processing variables (digester temperature, refining level, and sodium hydroxide content) on fiber length, freeness, fines content, and shive content. Fiber quality was related to mechanical properties of the flat panels. The mechanical properties of the resin-free fiberboard surpassed the minimum standards for commercial hardboard. We conclude that small-diameter lodgepole pine treetops with bark are well-suited for the production of structural boards. This research is part of a larger program for developing three-dimensional geometries for engineered fiberboard products.

The forest floor of many National and private forests in the Western United States is covered by large amounts of densely packed small-diameter material and dry residue from harvesting or thinning operations (**Fig. 1**). This material has accumulated because it has low, no, or even negative value for products given current processing or utilization technology. The dry or semiarid conditions in the West cause the material to decompose slowly, increasing the fuel load for forest fires. After decades of effective forest fire prevention and an accumulation of forest biomass, forest fires have become an increasing hazard (USDA Forest Serv. 2004). The private sector could be an outlet for this material and could reduce the fuel load if there were economical processes that could handle this material and produce value-added products.

This paper discusses the effects of processing variables on the properties of fiber made from lodgepole pine treetops and the relationship of fiber properties to fiberboard panel properties. The goal is to develop a simple and economic means to reduce forest residue into a bondable fibrous material for use in three-dimensional engineered fiberboard structural applications. This research is part of the USDA Forest Service's National Fire Plan.

Some applications, such as panel products, require maximum strength and stiffness properties. Other applications, such as packaging, can require maximum cushioning, but lower strength and stiffness. The required performance characteristics of the product influence the type of fiber processing. To convert wood chips to simple thermal mechanical pulp (TMP) for paper, an estimate for refiner energy needed to pulp wood is 2000 kWh/ton (Scott and Swaney 1998). At

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Figure 1. — Thinned timber on forest floor of Bighorn National Forest.

\$0.10/kWh the cost for only refining can be approximately \$200/ton. The cost of raw material ranges from \$60 to \$70/ton (dry metric ton) for pulp chips in the southern United States and \$60 to \$170/ton in the Northwest (Ekstrom 2008). In relative terms, to make pulp using the TMP process, the majority of the cost is for refining the fibers to a bondable condition.

Simple cost-saving approaches were used in this study to minimize total cost/ton, which requires minimal chemical or high-pressure steam processing. We chose a wet-forming rather than air-forming method for distributing the fibers for several reasons. First, a wet-forming system has the potential for being a completely resin-free system. A dry-forming method requires resin to bond the fibers together. Second, a wet-forming method usually forms a thinner mat than does dry forming for the same given weight of fiber, which is critical for forming more detailed three-dimensional engineered fiberboard. Third, water-based processing generally produces fewer fines, which improves fiber utilization. Previous research (Scott et al. 1995) has shown that panels having equal or superior performance can be obtained using continuous press-drying with less refined fibers. A process temperature of 150 °C using steam is routinely used for pretreating wood chips. Additional efforts to reduce processing costs such as lowering the pretreatment temperature prior to fiberization in an atmospheric refiner would help reduce overall costs as long



Figure 2. — Small-diameter treetop material.

as properties were equal or superior to those from commercial products. If a process could be developed that uses less energy, then that cost could be used to offset the additional cost of removing the material from the forest and transporting it to the processing facility.

Because only a single tree species was used for experimental control, the scope of the study is limited. However, results from this study will form the basis for further investigations to optimize processing of various material types and mixes that could be used to produce a number of three-dimensional engineered fiberboard products (Hunt 2001, Hunt and Winandy 2002). These applications may provide the value-added incentive to use forest residue.

Methods and materials

Material

Treetops were obtained from the Bighorn National Forest and Wyoming State Forest lands. This material is representative of residue from logging operations over much of the Intermountain West region. The treetops were delimbed, had a diameter of less than 10 cm, and were often heavily curved or knotted. The material was stacked in a clearing at the edge of the forest for 3 months, simulating storage in a log yard.

Chipping and fiberizing

Two crates of treetops, weighing 545 kg each with a solids content of 82.3 percent, were shipped to the Herty Foundation in Georgia (Fig. 2). The material was first chipped with a conventional chipper, then made into pin-chips in a Tornado pulper (Bolton–Emerson Americas, Inc., Lawrence, Massachusetts) (Fig. 3). All material passing through the chipper, Tornado pulper, and refiner was used for the study. Total processing yield was estimated at 99 percent, with minimal loss of fines during dewatering operations. Total tree yield was not determined but would be less than 100 percent because limbs and needles were left in the forest.

The chips were processed in two 450-kg batches. The Tornado processing tank was filled with 7,500 L of water, and the chips were added while the machine was running. No water or chemical pretreatment of the chips was done prior to placing the fibers into the Tornado pulper. The final consistency of the (fiber/(fiber + water)) mixture was 5.6 percent. At the Herty Foundation, the Tornado's configuration is designed to recirculate the pin-chips and water mixture past the rotor/stator at 11,250 L/min. The first batch of chips was run to qualitatively analyze the time needed to obtain a well-fiberized material. Samples were collected at 15-minute intervals. We recorded the electrical amperage as a function of processing time to

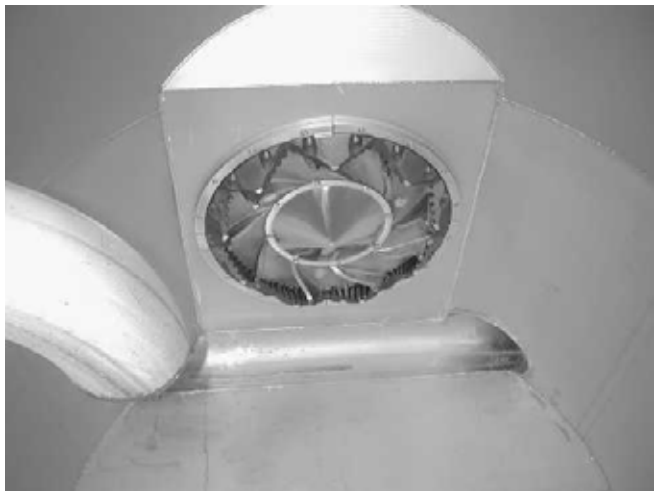


Figure 3. — Tornado 0.9-m diameter rotor and stator configuration mounted on side of 7500-L tank.

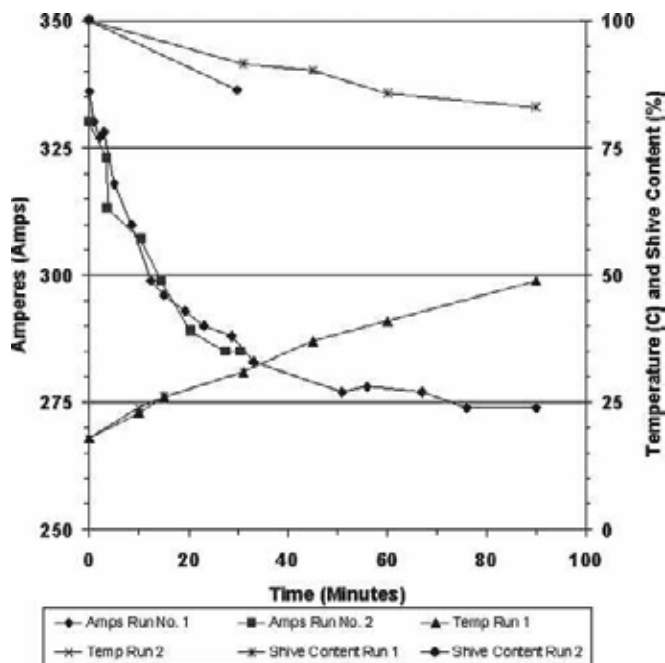


Figure 4. — Rate of electrical flow, water temperature, and shive content as function of time for processing treetop chips into pin-chips in Tornado pulper.

determine when the refiner energy had reached a steady state (Fig. 4). The power began to level out after 30 minutes of refining, indicating that most of the work to reduce the size of the chip material had been completed. The second batch of material was refined for 30 minutes.

Fiber digestion and refining

The goal for the next step in fiber processing was to reduce the pin-chip material (Fig. 5) into a bondable fibrous material with minimal reduction of freeness. Additional refining increases bonding. However, refining also increases fines and reduces freeness, which then decreases the drainage rate. The pin-chips were processed and refined at the Forest Products Laboratory in Madison, Wisconsin, using a series of tempera-

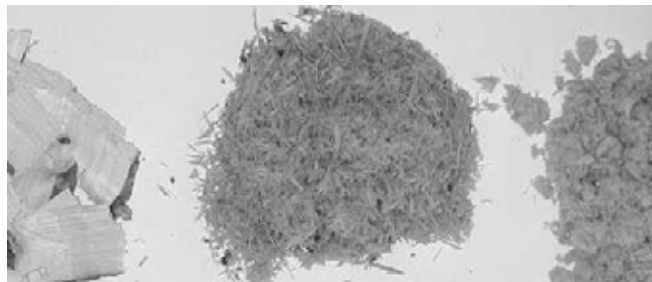


Figure 5. — Tornado-processed pin-chips (center) compared to conventional chips (left) and refined pulp fiber (right). The 0.5- to 1.0-mm-diameter by 10- to 15-mm-long pin-chips have high length-to-diameter ratio fiber bundles with minimum amount of fines.

ture, NaOH, and refining gap process parameters. A series of refiner runs were conducted after pretreating the pin-chips in 95 °C water or pressurized steam at 110 °C with or without small amounts of NaOH (Table 1). The pretreated material was run through a Sprout-Waldron atmospheric refiner (plate design #C2976, Sprout-Waldron/Koppers Co., Inc., Muncy, Pennsylvania) 1, 2, or 3 times with the plate gap set at 0.43, 0.25, and 0.25 mm, respectively. This refiner design is typically used to produce low-freeness material for papermaking. The larger gap for the first pass through the refiner was intended to help reduce pin-chip size with minimal reduction of fiber length. The second and third passes, set at smaller gaps, were intended to roughen the fiber surface and increase the number of potential bonding sites. A sufficient quantity of material was produced at each condition to wet-form two 0.5-by 0.5-m panels with a nominal thickness of 2.5 mm at a density of 1,000 kg/m³. All pin-chip material for refining was taken from the second batch of material.

Fiber analysis

The effects of processing on shive content, freeness, fiber length, and yield were measured for each fiber run. Shive content was measured using a Pulmac shive analyzer (Pulmac, Montpelier, Vermont) with a 0.1-mm slot. Material greater than 0.1 mm is considered a shive in this report. TAPPI test method T-227 (TAPPI 2000) was used to measure freeness. Pulp was produced with freeness greater than 500-mL Canadian Standard Freeness (CSF) for faster formation of thicker samples. A fiber quality analyzer (FQA) (OpTest Equipment, Inc., Hawkesbury, Ontario) was used to measure fiber length. The FQA classifies a fiber as material longer than 70 µm (0.07 mm). The length weighted average (L_w) value of detected fibers was used to compare differences between samples:

$$L_w = \frac{\sum (l_x^2 * n_x)}{\sum (l_x * n_x)}$$

where l_x is the measured fiber length and n_x are the number of fibers measured at length l_x . Fines tend to have only minor effects on a L_w .

To verify fiber quality from pin-chip material, a low-yield kraft pulp was produced to determine the effectiveness of the fiber processing methods to produce a quality fiber from pin-chips. The pin-chips were pulped using 20 percent NaOH and 25 percent sodium sulfide. The pulp was heated from 80 to

Table 1. — Fiber properties after pretreatment and refining.

Fiber process temperature	NaOH content	Refiner plate gap (first/second/third pass)	CSF	Fiber length	Total fines content	Shive content
(°C)	(percent)	(mm)		(mm)	----- (percent) -----	
95	0	0.43	710	1.002	11.1	50.49
		0.43/0.25	580	0.942	13.7	28.37
		0.43/0.25/0.25	440	0.872	15.5	20.77
		0.43	740	1.010	9.1	53.45
	0.5	0.43/0.25	600	0.906	14.5	25.88
		0.43/0.25/0.25	530	0.888	15.3	19.43
		0.43	755	0.981	11.0	49.16
	1	0.43/0.25	600	0.947	13.6	28.17
		0.43/0.25/0.25	560	0.907	13.6	23.82
		0.43	740	1.142	8.5	56.42
	2	0.43/0.25	700	1.062	11.2	29.57
		0.43/0.25/0.25	640	1.009	12.7	21.90
		0.43	780	1.251	6.8	58.21
	4	0.43/0.25	740	1.108	10.1	36.15
		0.43/0.25/0.25	705	1.120	11.0	21.83
		0.43	730	1.146	9.6	48.18
110	5	0.43/0.25	660	1.073	12.2	21.23
		0.43	755	1.227	8.1	46.87
	1	0.43/0.25	640	1.105	11.7	25.12
		0.43/0.25	670	1.297	11.7	25.17

170 °C in 60 minutes and then cooked for 70 minutes at the elevated temperature.

Flat panel pressing and testing

Two flat panels were made from fibers from each refiner run and tested for strength properties to determine the effects of refining and chemical additives on fiber bond strength. To isolate the effects of fiber processing on fiber-to-fiber bonding, no adhesives were used in the fibrous mixture. The fiber mats were formed in a 0.5- by 0.5-m forming box; the mats were placed between two screens and two stainless steel cauls and hot-pressed for 10 minutes at 163 °C with continuous application of 1,175 kPa pressure. The final target panel thickness was 3.2 mm with a density of 1,000 kg/m³. Flat panels were tested in tension and bending following ASTM D 1037 (ASTM 1996) test standards. The panels were conditioned either at 22 °C, 50 percent relative humidity, or 26.5 °C, 90 percent relative humidity, resulting in MC at the time of testing of 6.75 percent and 14.75 percent, respectively.

Results and discussion

Pin-chip and fiber properties

Processing the wood chips in the Tornado for 30 minutes reduced them to pin-chips that were 0.5 to 1.0 mm in diameter and 10 to 15 mm long. Pin-chip material greater than 0.1 mm in diameter represented 86.3 percent of the material; the remainder was a combination of fibers and fines. This was the first trial using the Tornado for this type of application. The process worked well, but improvements could be made to further reduce the material into more fibers and less pin-chip shives. Changes could include pretreatment of chips with a water-soak, enzymatic, or chemical treatment to improve pin-chip quality. Increasing the consistency of the slurry could also increase chip-to-chip abrasive and crushing interaction as

the chips pass through the Tornado, improving fiber surface fibrillation for bonding. In this study, 5.6 percent consistency was used; it is possible to double or triple the consistency in the Tornado batch tank.

The effects of processing parameters on freeness, fiber length, total fines, and shive content are listed in **Table 1** and plotted as main effects in **Figure 6**. The plots in **Figure 6** are statistical summaries of the data and are used to show the overall effect and trends for each pretreatment on fiber properties.

Temperature had no noticeable effect on freeness, slightly decreased fines and shive content, and significantly increased fiber length. Although the difference in temperature was not large (95 or 110 °C), temperature can make a significant difference in terms of processing equipment. To achieve temperatures above 100 °C requires significant additional capital investment in pressurized processing equipment. Although a higher temperature was

used for comparison, our results confirmed that suitable properties can be obtained without pressurized equipment.

Pretreatment of pin-chips with NaOH significantly increased freeness, increased fiber length, and decreased fines, three desirable fiber properties. Sodium hydroxide is a swelling and softening agent in wood that influences refiner effects. As NaOH concentration increased, the pin-chips became less brittle and compressed more easily, allowing the fibers to separate from the chips more readily rather than breaking into shorter fibers and fines. The result was an increase in fiber length and decrease in total fines. However, it is interesting to note that shive content increased with the addition of NaOH, which is counterintuitive. With increasing amounts of NaOH, the softened and flexible pin-chips are likely to compress and pass more readily through the refiner without breaking. Thus fiberization occurs, but with fewer fines and a higher percentage of pin-chips. Freeness is an indirect measure of water flow rate. Longer fiber length, fewer fines, and higher shive content all increase mat freeness for water flow. With the addition of NaOH, less refiner energy is required to separate the fibers.

Increased refining decreased freeness, fiber length, and shive content, and increased total fines. While freeness is not a single measure of a fiber property, it is a partial qualitative indicator of work done on the fibers. Passing the fibers through the refiner three times had a greater effect on all fiber-related properties than did either temperature or NaOH treatments. All processing variables had a similar effect on fiber length. Because refining effects are significant for “all” fiber properties, refining should be carefully used in combination with temperature and NaOH to obtain optimum fiber properties.

To determine the effectiveness of fiber processing methods to produce a quality fiber, a low-yield kraft pulp was produced from the lodgepole pine pin-chips. Pulp yield was 46 percent

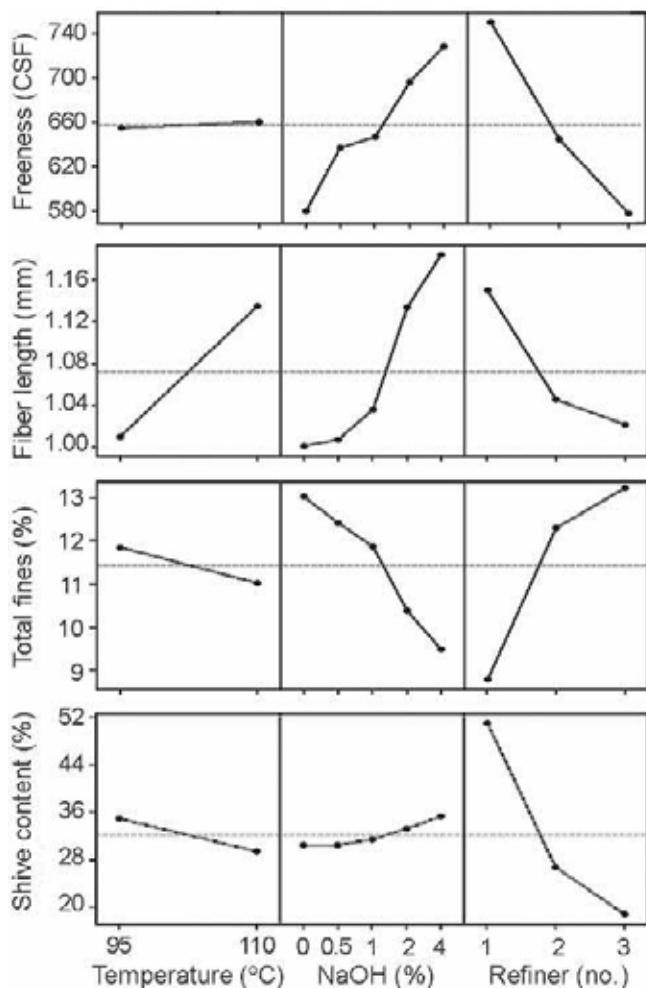


Figure 6. — Main effects of pretreatment on freeness, fiber length, total fines, and shive content. Pretreatment variables: temperature (95 °C and 110 °C), NaOH addition (0%, 0.5 percent, 1.0 percent, 2.0 percent, and 4.0%), and number of refiner passes (1 to 3).

and CSF was 740 mL. Average fiber length ranged from 1.45 to 1.50 mm. In comparison, the lodgepole pine fiber, which was processed with only 4 percent NaOH pretreatment, low processing temperatures, and multiple passes through the refiner, produced a fiber with only slightly less properties, but at potentially less cost. In addition to reducing the amount of energy needed to heat the water, these process variables lower the cost of the equipment because non-pressurized vessels can be used to pretreat the material. The exact pulp yields were not obtained for the fiber processes described in this study, but they are estimated to be above 90 percent at the 4 percent NaOH treatment level and higher for less chemical usage. Although the process uses less chemicals and lower processing temperatures, refining energy may be slightly higher because more chemicals and higher temperatures reduce the amount of refiner energy needed. However, overall costs should be lower than those incurred in the production of a low-yield high-quality pulp since the structural product that this pulp is intended for requires significantly less refined fiber. Although the processing parameters used in this study were not optimized, the results indicate it is possible to produce a good-quality pulp from low-value treetop material.

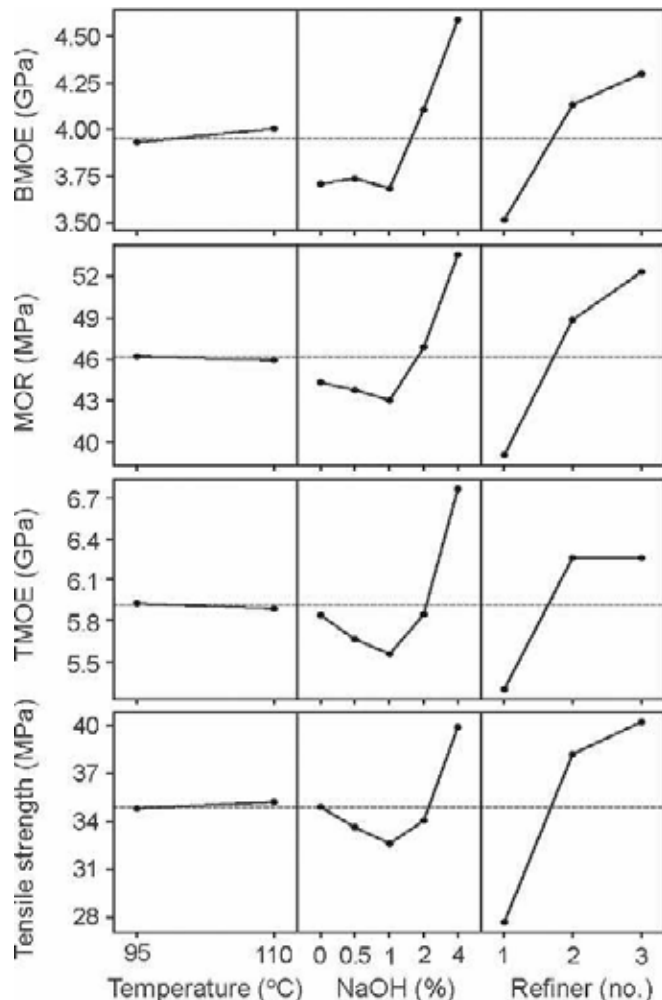


Figure 7. — Main effects of pretreatment on bending modulus of elasticity (BMOE), bending modulus of rupture (MOR), tensile modulus of elasticity (TMOE), and tensile strength.

Mechanical properties

The combined fiber processing effects on the mechanical properties of flat panels made from the fiberized treetops are shown in **Figure 7**. Processing temperature (95 or 110 °C) did not seem to have any direct effect on the measured mechanical properties. However, both NaOH level and refining had significant effects.

Small amounts of NaOH (0.5% and 1.0%) did not have a significant effect on properties and may have actually had a slight negative effect. A possible reason for the negative trend may be the generation of fines. Pin-chips not pretreated with NaOH were stiff and generated more fines than did pretreated pin-chips (**Fig. 6**). Fines fill fiber-to-fiber gaps and can actually increase total sheet bonding. As NaOH was added at the 0.5 percent and 1.0 percent levels, it reduced total fines, but not enough to significantly increase fiber-to-fiber bonding through fiberization. The addition of 2 percent NaOH increased fiberboard mechanical properties noticeably, and the addition of 4 percent NaOH had a significant effect. The addition of 2 percent NaOH markedly affected both fiber length and fines (**Fig. 6**). We are unsure of the maximum potential strength properties, but the plots in **Figure 6** suggest that these properties would continue to rise with additional NaOH pretreatment. With the addition of 4 percent NaOH, pulp yield

was around 95 percent. In contrast, papermaking processes generally use 15 to 20 percent NaOH to obtain yields between 55 and 70 percent. However, these high treatment levels require extensive water treatment. At the low level of 4 percent NaOH used in this study, relatively simple water treatment could recover much of the dissolved solids and chemicals. Studying the effects of low levels of NaOH on the yield and dissolved chemicals of pulp from whole tree pin-chips merits further investigation but is outside the scope of this research study.

Refining had a significant effect on all mechanical properties. The properties began to plateau at the third refining. The refiner plate gap settings were the same for refining runs 2 and 3. It is possible that the properties would have continued to increase at the same rate if the refiner plate gap had been decreased by a small amount. However, for this study there was the possibility of over reducing pulp freeness. At 0 percent NaOH, freeness had dropped to 440 CSF by the third refining pass (**Table 1**), and our goal was to retain freeness above 500 CSF for faster drainage times. However, even 0.5 percent NaOH softened the pin-chips to the extent that further refining caused less reduction in fiber length, less fines, and a decrease in freeness. With further addition of NaOH, the refiner plate gap possibly could have been reduced further, producing a flexible and bondable material with minimal loss of freeness.

It is interesting to note that additional refining affected fiberboard strength more than stiffness. Refining increased modulus of rupture and tensile strength by 28 percent and 42 percent, respectively. Refining had less effect on stiffness; bending and tensile modulus were reduced by 18 and 21 percent, respectively. These effects reflect fundamental properties of a fiber mat. Strength is associated with fiber bonding—increased refining enhances surface-to-surface bonding, resulting in higher overall strength. Elasticity is more a combination of a fiber property and stress transfer property through the fiber matrix. Refining decreases the cellulose chains within the fibers, which decreases individual fiber stiffness. However, with increased refining the fiber-to-fiber bonds increase, which results in a bonded fiber matrix with higher stiffness. The net effect of these counteracting tendencies is nevertheless an increase in stiffness properties, albeit a lower increase than that in strength properties. With the increasing addition of NaOH, which softens fibers, the negative effects of broken cellulose chains are minimized, but refining has the beneficial effect of roughening the surface. A balance of these fiber processing factors is necessary for obtaining optimum mechanical properties.

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 specimens made from the fiberized small-diameter material exceeded the hardboard minimum standard requirements (**Fig. 7**). This was achieved without the use of resin. Adding resin would only improve panel properties, especially in humid or wet environments.

Conclusions

The objectives of this study were to evaluate the effects of processing variables on the properties of fiber from small-diameter lodgepole pine treetops and on the bending and tensile properties of flat panels made from this fiber. An increase in process temperature had a significant positive effect on all measured fiber properties except freeness. Temperature had no signifi-

cant effect on the mechanical properties of the panels. Consequently, a lower process temperature could be sufficient to produce a fibrous material for structural panels. A lower temperature system could also lower initial installation and operating costs because high-pressure steam and related equipment would not be necessary to process the fibrous material.

The addition of sodium hydroxide had a significant positive effect on both fiber properties and panel mechanical properties. Even with the addition of 4 percent NaOH, strength properties had not reached their maximum. Further improvements in both fiber and mechanical properties are possible with additional NaOH pretreatment and optimization of the refining process. Further research needs to be done to determine at what point maximum mechanical properties are reached and also to evaluate the environmental impact of increasing NaOH in processing.

All strength properties increased significantly with increased refining. All fiber properties decreased with each additional refining pass. The overall effect, however, is positive, for the mechanical properties of the panels would not have reached their full potential if the fiber had not been refined.

These data show that lodgepole pine small-diameter treetop logging residues can be used to produce a bondable fibrous material at non-steam pressure conditions, with or without low levels of NaOH; a value-added structural panel product can be produced from this material through refining. Current technology and equipment could be used or adapted and applied to commercial production of structural fiberboard from small-diameter treetop material. Additional work is necessary to more accurately determine the overall cost and environmental impact of production using low-value material processed with less chemicals and more refining. Subsequent research will also focus on processing issues related to producing a value-added three-dimensional molded product using this type of fiber. Using forest thinnings for value-added products can reduce the fire hazard in overcrowded tree stands, improve forest health, and enhance rural economies.

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