# Mechanical properties for a wet-processed fiberboard made from small-diameter lodgepole pine treetop material

John F. Hunt*
Karen Supan

## Abstract

Many federal, state, and private forests, especially in the western part of the United States, have an overabundance of fire-prone small-diameter trees, forest thinnings, and residual material. These materials are not being fully utilized as a fiber resource because there are few economical options for their use. This report looks at using treetop material to produce a structural fiberboard-like product by varying several pulping and refining conditions. The treetop material with bark was processed using a wet processing method. Resin-free experimental panels were formed and press-dried. Mechanical properties were obtained at both 50 and 90 percent moisture conditions. These panels were tested in bending and tension to determine the effects of processing on structural properties. General trends show an increase in properties with an increase in sodium hydroxide pulping and refining level. In comparison, strength properties were equal to or surpassed minimum standard hardboard properties. Results from this study will be used to design value-added three-dimensional engineered structural fiberboard panels. Three-dimensional panels are currently being developed at the USDA Forest Service, Forest Products Laboratory, and will provide a potential outlet for the underutilized small-diameter fiber resource.

It is estimated that more than 73 million acres in the National Forests are at risk due to overcrowded stands (Bosworth 2001) that need to be thinned to reduce the fire hazard and practice good forest management. However, because much of this material is too small for structural lumber, contains defects, or is too costly to transport or process (Barbour 1999), the thinned material is left to decompose on the forest floor. Many forests in the western United States experience dry conditions that prevent decomposition of woody debris, thus leaving a significant fire hazard (**Fig. 1**). Traditional logging operations also often leave significant residue after the merchantable logs have been harvested. The amount of this fiber resource is extremely large. For example, according to USDA Forest Service Forest Inventory Analysis data (USDA 2002), in the combined forested areas of Colorado, Idaho, Montana, and Wyoming, there are more than $29.7 \times 10^6$ metric tons ($32.8 \times 10^6$ tons) (ovendry basis) of unmerchantable material less than 10 cm (4 in.) in diameter. This amount of material could provide an abundant fiber supply for use in value-added products.

The data presented here are part of a larger study funded through the USDA Forest Service National Fire Plan (NFP) to investigate using thinnings and residual material for an adhesive-free three-dimensional engineered fiberboard material. To fully utilize this small-diameter material in a structural fiberboard, the material was fiberized with the bark on. Care was taken during fiberization to maintain fiber length and still abrade the surface for increased fiber-to-fiber bondability. Economically, it is important to develop a product that provides value-added qualities in function or performance, or both. The USDA Forest Service Forest Products Laboratory (FPL) is developing a three-dimensional engineered fiberboard (Hunt and

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The authors are, respectively, Research General Engineer, USDA Forest Service, Forest Products Lab., One Gifford Pinchot Dr., Madison, WI 53726-2398; and Graduate Engineering Student, Univ. of Florida, Gainesville, FL. This paper was received for publication in August 2003. Article No. 9746.
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*Figure 1. — Residual thinnings left on forest floor about 10 years after cutting. A significant amount of material is left that is now very dry and an extreme fire hazard.*

*Table 1. — Fiber size distribution for the Tornado fiberizing equipment.*

| Sieve no. | | | | | | |
|---|---|---|---|---|---|---|
| +8 | -8/+12 | -12/+16 | -16/+20 | -20/+35 | -35/Pan | Total |
| (%) | | | | | | |
| 13.0 | 16.7 | 28.4 | 18.5 | 14.5 | 9.0 | 100 |

*Figure 2. — Tornado pin-chips (center) have high length-to-diameter ratio fiber bundles (0.5- to 1.0-mm diameter by 10- to 15-mm length) with a minimum amount of fines. Conventional chips (left) and refined pulp fibers (right) are for reference.*

Winandy 2002) that should be capable of achieving these requirements. However, to design three-dimensional composite products, it is important to understand how processing affects stiffness and strength properties of the press-dried material. The processing methods and the resulting engineering data developed in this study are sufficient to develop a preliminary design for a three-dimensional engineered structural fiberboard product. Possible applications for this product include office furniture, structural panels, and packaging. The fiberboard should be manufactured with full three-dimensional forming for final or near-final shape and form, thus eliminating many secondary operations. The three-dimensional engineered fiberboard would thus provide a high-value outlet for no- or low-value thinned or forest residue.

## Experimental

This study summarizes the basic material properties of flat panels made from the fiber of treetop material. After cutting small-diameter trees on the Bighorn National Forest for another research study, the remaining pile of treetops represented maybe 10 to 20 percent additional material that would normally be left in the forest. Once fully developed, this three-dimensional engineered fiberboard could potentially utilize much, if not all, of this type of residual material. In this study, the effects of various refiner conditions and the use of chemical treatments on the panel properties were measured. The wet processing method was used because it maximizes overall fiber length, minimizes fines, and maximizes fiber-to-fiber (i.e., adhesive-less) bonding compared with dry processing. Simplified methods and processes need to be developed to help small- to moderate-sized companies and smaller rural communities use local forest resources to produce economically viable value-added products. The Tornado fiberizing equipment used in this study produces a very uniform pin-chip with minimal fines without any chip pretreatment. A sieve analysis (**Table 1**) showed that less than 10 percent of the material passed through a 500-micron (0.020-in.-diameter or 35-mesh) screen. One goal for this study was to refine the pin-chips with minimal loss in fiber length and freeness while still maximizing strength. The purpose of this study was to determine the initial range of mechanical properties possible using various processing methods.

### Fiber furnish

Small-diameter lodgepole pine treetops with diameters less than 10 cm (4 in.) were used for this study. The treetops were obtained from the Bighorn National Forest and Wyoming State Forest lands. The de-limbed treetops were chipped with the bark included but without limbs or needles. Then they were fiberized into pin-chips (**Fig. 2**) using a Tornado pulper (Bolton-Emerson Americas, Inc., Lawrence, Massachusetts). The 0.5- to 1.0-mm- (0.02- to 0.04-in.-) diameter by 10- to 15-mm- (0.4- to 0.6-in.-) long pin-chips were used as fiber furnish to investigate 20 variations of wet refining without and with sodium hydroxide (NaOH) pulping treatments

*Table 2. — Fiber properties at each of the conditions for refining the Tornado pin-chip fibers. For trials 1 through 15, the fiber processing temperature was 90°C. For trials 16 through 20, the fiber processing temperature was 110°C.*

| Trial no. | NaOH | Refiner plate gap (1st/2nd/3rd pass) | Freeness (CSF)[a] | Fiber length | Shive content |
|---|---|---|---|---|---|
| | (%) | (mm) | | (mm) | (%) |
| 1 | 0 | 0.43 | 710 | 1.002 | 50.49 |
| 2 | 0 | 0.43 / 0.254 | 580 | 0.942 | 28.37 |
| 3 | 0 | 0.43 / 0.254 / 0.254 | 440 | 0.872 | 20.77 |
| 4 | 0.5 | 0.43 | 740 | 1.010 | 53.45 |
| 5 | 0.5 | 0.43 / 0.254 | 600 | 0.906 | 25.88 |
| 6 | 0.5 | 0.43 / 0.254 / 0.254 | 530 | 0.888 | 19.43 |
| 7 | 1 | 0.43 | 755 | 0.981 | 49.16 |
| 8 | 1 | 0.43 / 0.254 | 600 | 0.947 | 28.17 |
| 9 | 1 | 0.43 / 0.254 / 0.254 | 560 | 0.907 | 23.82 |
| 10 | 2 | 0.43 | 740 | 1.142 | 56.42 |
| 11 | 2 | 0.43 / 0.254 | 700 | 1.062 | 29.57 |
| 12 | 2 | 0.43 / 0.254 / 0.254 | 640 | 1.009 | 21.90 |
| 13 | 4 | 0.43 | 780 | 1.251 | 58.21 |
| 14 | 4 | 0.43 / 0.254 | 740 | 1.108 | 36.15 |
| 15 | 4 | 0.43 / 0.254 / 0.254 | 705 | 1.12 | 21.83 |
| 16 | 0.5 | 0.43 | 730 | 1.146 | 48.18 |
| 17 | 0.5 | 0.43 / 0.254 | 660 | 1.073 | 21.23 |
| 18 | 1 | 0.43 | 755 | 1.227 | 46.87 |
| 19 | 1 | 0.43 / 0.254 | 640 | 1.105 | 25.12 |
| 20 | 4 | 0.43 / 0.254 | 670 | 1.297 | 25.17 |

[a] CSF = Canadian Standard Freeness.

to produce a bondable fibrous material. A sufficient quantity of material was produced at each trial condition to wet-form two 50- by 50-mm (20- by 20-in.) panels, 3.24-mm thick, at each variation. Fifteen trials were run at an elevated temperature of 90°C (194°F) at atmospheric pressure, and five trials were run at 110°C (230°F) in a pressurized digester. A more detailed description of the fiber processing is provided in a previous publication (Hunt and Winandy 2002).

### Panel fabrication

After forming and vacuum dewatering down to around 80 percent moisture content (MC) (wet basis), each mat was placed between two screens and two stainless steel cauls and hot-pressed at 163°C (325°F) with continuous 1.175 MPa (170 psi) pressure for 10 minutes. The target thickness and density were 3.2 mm (0.125 in.) and 1000 $kg/m^3$ (62.4 pcf), respectively. The boards were dried to near 0 percent MC. To determine the effects of the processing variables on fiber-to-fiber bonding, no adhesive was used to enhance fiber-to-fiber bonding. The fibers bonded together naturally under heat and pressure.

### Testing

The flat panels were evaluated for their bending and tensile properties as outlined in the American Society for Testing and Materials Standard D-1037 (ASTM 1996). Four bending and four tensile specimens were cut from each panel. Two from each group, oriented perpendicular to one another, were placed in a conditioned room at 22°C (72°F) and 50 percent relative humidity (RH). The other two specimens, also oriented perpendicular to one another, were placed in a conditioned room at 26.5°C (80°F) and 90 percent RH. Specimen MCs at the time of testing were 6.75 and 14.75 percent, respectively.

## Results and discussion

### Fiber furnish

The basic fiber physical properties (fiber freeness, fiber length, and shive content) of the refined pulp were measured after each trial (**Table 2**). Freeness is an index of water flow through a fiber matrix measured in units of Canadian Standard Freeness (CSF) or mL of water. Higher freeness values equate to higher water flow rates. **Table 2** shows that additional refining generally reduced freeness, fiber length, and shive content. Freeness for trials without NaOH (trials 1 to 3) decreased from 710 to 440 CSF while trials with NaOH (trials 13 to 15) decreased from 780 to only 705 CSF. Fiber length for both trials 1 to 3 and 13 to 15 decreased by an average of 0.13 mm (0.005 in.). However, the trials with NaOH had a longer average fiber length, as expected. Preconditioning with NaOH helped to soften the lignin in the pin-chips, allowing for improved fiber separation with less damage to the individual fibers. Longer fibers in the furnish can increase freeness values. The goal was to maintain freeness above 500 CSF for faster drainage rates, which then relates to potentially faster production times. Longer fibers also entangle more than short fibers; this provides for a tougher, less brittle failure mode.

Shives in the paper industry are small fiber bundles that have not been fully fiberized into individual fibers. Shives are measured as material that does not pass through a slotted screen; in our analysis, we used a Pulmac shive analyzer (Pulmac Instruments International, Montpelier, Vermont) with slots of 0.10 mm (0.004 in.). Shive content decreased with increased refining. After the first pass through the refiner, all trials showed a high percentage of shives, between 45 and 60 percent. The shive content decreased to around 21 percent after the third refiner pass. There was no significant difference in shive content between the two processing temperatures of 90°C and 110°C (194°F and 230°F). Individual shives were evident on the surfaces of the panels.

A thicker three-dimensional structural material can tolerate a higher percentage of shives, whereas paper cannot tolerate even a small percentage of shives. This is because the three-dimensional structural components are thicker (~10 times thicker than paper) and can therefore tolerate larger thickness variations (shives) in forming and pressing. The thicker panels are also used when structural performance is the primary concern and surface uniformity and appearance is not critical. Because we were interested in using whole log chips, the bark remained in the material mix. Visual inspection showed that our refining method did a good job of breaking up the bark, leaving only small bark pieces evident on the surface of the panels. Comparisons between panels made with and without the bark were not made as

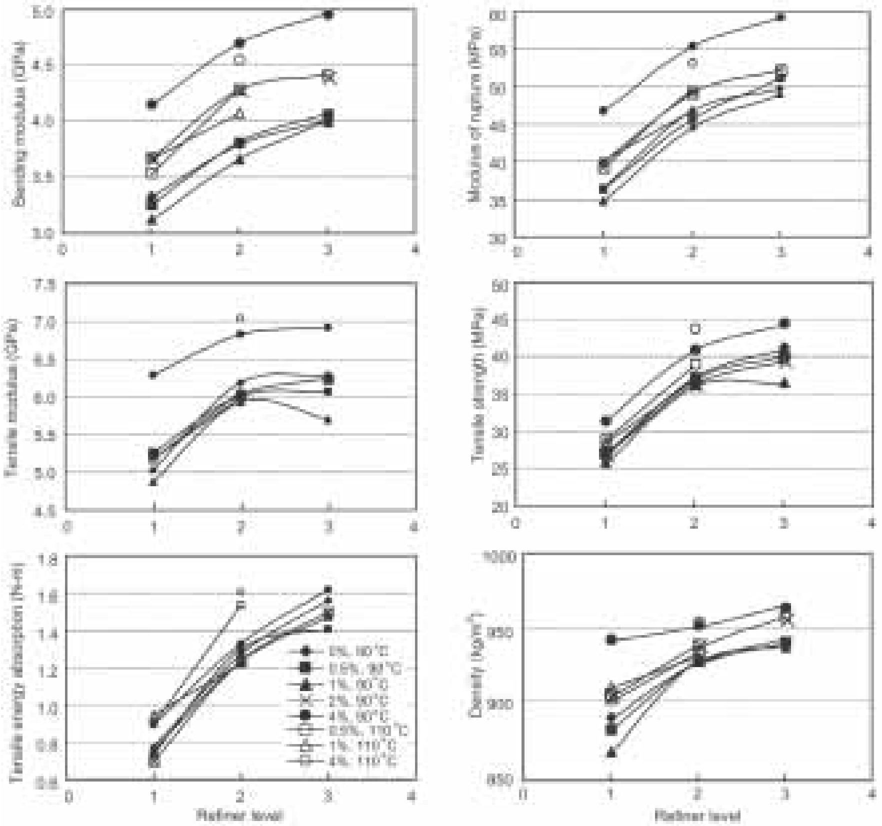

*Figure 3. — Bending and tensile modulus, strength, and density properties of the experimental panels at three levels of refining and at 6.75 percent MC. Legend shows panel forming conditions of RH and temperature.*

*Table 3. — Bending modulus of rupture (MOR) and modulus of elasticity (MOE) of hardboard panels at 6.75 and 14.75 percent MCs.*

| Panel forming conditions[a] | Refining level 1 | Refining level 2 | Refining level 3 | Refining level 1[b] | Refining level 2[b] | Refining level 3[b] |
|---|---|---|---|---|---|---|
| | Bending MOR, 6.75% MC | | | Bending MOR, 14.75% MC | | |
| | - - - - - - - - - - - - - - - - - - - - - - - | | | (MPa) - - - - - - - - - - - - - - - - - - - - - - - | | |
| 0%, 90°C | 36.5 | 46.8 | 49.7 | 19.8 (0.54) | 25.4 (0.54) | 27.3 (0.55) |
| 0.5%, 90°C | 36.2 | 45.6 | 51.1 | 19.9 (0.55) | 24.0 (0.53) | 27.4 (0.54) |
| 1%, 90°C | 34.7 | 44.5 | 48.9 | 19.2 (0.55) | 25.4 (0.57) | 27.2 (0.56) |
| 2%, 90°C | 39.2 | 49.1 | 52.3 | 21.0 (0.54) | 27.1 (0.55) | 28.2 (0.54) |
| 4%, 90°C | 46.7 | 55.3 | 59.2 | 23.8 (0.51) | 29.3 (0.53) | 30.0 (0.51) |
| 0.5%, 110°C | 39.9 | 49.6 | -- | 22.6 (0.57) | 27.4 (0.55) | -- |
| 1%, 110°C | 40.0 | 46.9 | -- | 20.9 (0.52) | 26.6 (0.57) | -- |
| 4%, 110°C | -- | 53.2 | -- | -- | 29.0 (0.55) | -- |
| | Bending MOE, 6.75% MC | | | Bending MOE, 14.75% MC | | |
| | - - - - - - - - - - - - - - - - - - - - - - - | | | (GPa) - - - - - - - - - - - - - - - - - - - - - - - | | |
| 0%, 90°C | 3.31 | 3.79 | 4.00 | 1.79 (0.54) | 2.21 (0.58) | 2.34 (0.59) |
| 0.5%, 90°C | 3.24 | 3.81 | 4.07 | 1.86 (0.57) | 2.14 (0.56) | 2.34 (0.58) |
| 1%, 90°C | 3.10 | 3.65 | 4.00 | 1.86 (0.60) | 2.21 (0.60) | 2.41 (0.60) |
| 2%, 90°C | 3.65 | 4.27 | 4.41 | 2.07 (0.57) | 2.55 (0.60) | 2.55 (0.58) |
| 4%, 90°C | 4.14 | 4.69 | 4.96 | 2.41 (0.58) | 2.69 (0.57) | 2.76 (0.56) |
| 0.5%, 110°C | 3.52 | 4.27 | -- | 2.14 (0.61) | 2.48 (0.58) | -- |
| 1%, 110°C | 3.65 | 4.07 | -- | 2.07 (0.57) | 2.55 (0.63) | -- |
| 4%, 110°C | -- | 4.55 | -- | -- | 2.69 (0.59) | -- |

[a] Percentages indicate amount of NaOH concentration used in the pulp furnish.

[b] Values in parentheses indicate the relative property retention compared with a value at 50 percent RH.

part of this study. There are some benefits of being able to use material with higher shive content and material that contains bark: 1) less energy is used to process the material; 2) mat freeness is higher, which increases production rates; and 3) using material with bark can simplify material handling and processing.

It is also well known in the paper industry that refining significantly improves fiber bonding (Danforth 1986), but too much refining can cause slower drainage rates in the forming process, thus slowing production rates. Because our goal is to use this material to fabricate thicker three-dimensional wet-formed structures, it is important to balance the forming properties with performance characteristics.

## Mechanical properties

Bending and tensile properties were measured on all the specimens. Increased refining and addition of NaOH tended to increase bending and tensile properties. **Figure 3** shows the trends and properties at 6.75 percent MC. The graphs indicate properties were still increasing, except tensile modulus, for which maximum values leveled off after two refining passes. The trends indicate that further increases in properties could be obtained from this material.

Similar trends to those shown in **Figure 3** are also present for all the properties at the higher 14.75 percent MC (**Tables 3** and **4**). The differences, however, are that stiffness and strength retention at 14.75 percent MC are only about half those at 6.75 percent MC (relative property retentions are provided in parentheses in **Tables 3** and **4**). These reductions are critical information when designing any three-dimensional engineered fiberboard where high humidity conditions are present. These specimens were formed without any resin or sizing-coating additives. We anticipate that the reduction from higher humidity environments might be minimized with these additions.

Stress vs. strain plots were obtained for all tensile specimens. **Figure 4** shows the average MC of four specimens for trials 1 to 3 and 13 to 15 at 6.75 and 14.75 percent, respectively. Commercial hardboard standards were used for comparison. Minimum strength standards set by the American Hardboard Association (AHA 1995) are 15.2 MPa for tension and 31 MPa for bending for standard

*Table 4. — Tensile MOE, maximum tensile stress (MTS), and tensile energy absorption (TEA) of hardboard panels at 6.75 and 14.75 percent MCs.*

| Panel forming conditions[a] | Refining level 1 | Refining level 2 | Refining level 3 | Refining level 1[b] | Refining level 2[b] | Refining level 3[b] |
|---|---|---|---|---|---|---|
| | Tensile MOE, 6.75% MC | | | Tensile MOE, 14.75% MC | | |
| | - - - - - - - - - - - (GPa) - - - - - - - - - - - | | | | | |
| 0%, 90°C | 5.04 | 6.19 | 6.29 | 2.4 (0.48) | 3.0 (0.48) | 3.2 (0.51) |
| 0.5%, 90°C | 5.26 | 6.02 | 6.07 | 2.3 (0.44) | 2.8 (0.47) | 3.1 (0.51) |
| 1%, 90°C | 4.88 | 5.93 | 5.71 | 2.4 (0.49) | 3.1 (0.52) | 3.2 (0.56) |
| 2%, 90°C | 5.26 | 6.04 | 6.24 | 2.8 (0.53) | 3.1 (0.51) | 3.4 (0.54) |
| 4%, 90°C | 6.29 | 6.83 | 6.91 | 3.0 (0.48) | 3.2 (0.47) | 3.4 (0.49) |
| 0.5%, 110°C | 5.17 | 6.00 | -- | 2.7 (0.52) | 3.0 (0.50) | -- |
| 1%, 110°C | 5.17 | 6.07 | -- | 2.7 (0.52) | 3.0 (0.49) | -- |
| 4%, 110°C | -- | 7.03 | -- | -- | 3.4 (0.48) | -- |
| | MTS, 6.75% MC | | | MTS, 14.75% MC | | |
| | - - - - - - - - - - - (MPa) - - - - - - - - - - - | | | | | |
| 0%, 90°C | 26.5 | 37.2 | 41.1 | 12.4 (0.47) | 18.3 (0.49) | 20.2 (0.49) |
| 0.5%, 90°C | 26.9 | 37.0 | 40.0 | 12.2 (0.45) | 18.0 (0.49) | 20.6 (0.51) |
| 1%, 90°C | 25.5 | 36.0 | 36.3 | 12.6 (0.49) | 19.0 (0.53) | 20.0 (0.55) |
| 2%, 90°C | 26.7 | 36.2 | 39.4 | 14.3 (0.54) | 19.2 (0.53) | 21.1 (0.54) |
| 4%, 90°C | 31.3 | 40.7 | 44.2 | 15.9 (0.51) | 20.4 (0.50) | 23.2 (0.52) |
| 0.5 %, 110°C | 28.8 | 38.7 | -- | 15.3 (0.53) | 20.3 (0.52) | -- |
| 1%, 110°C | 28.5 | 36.7 | -- | 14.7 (0.52) | 20.6 (0.56) | -- |
| 4%, 110°C | -- | 43.5 | -- | -- | 24.1 (0.55) | -- |
| | TEA, 6.75% MC | | | TEA, 14.75% MC | | |
| | - - - - - - - - - - - (N-m) - - - - - - - - - - - | | | | | |
| 0%, 90°C | 0.772 | 1.272 | 1.559 | 0.716 (0.93) | 1.369 (1.08) | 1.435 (0.92) |
| 0.5%, 90°C | 0.733 | 1.300 | 1.405 | 0.781 (1.07) | 1.417 (1.09) | 1.548 (1.10) |
| 1%, 90°C | 0.754 | 1.233 | 1.472 | 0.732 (0.97) | 1.315 (1.07) | 1.475 (1.00) |
| 2%, 90°C | 0.696 | 1.235 | 1.499 | 0.808 (1.16) | 1.247 (1.01) | 1.400 (0.93) |
| 4%, 90°C | 0.893 | 1.331 | 1.619 | 0.919 (1.03) | 1.430 (1.07) | 1.670 (1.03) |
| 0.5 %, 110°C | 0.897 | 1.534 | -- | 0.944 (1.05) | 1.501 (0.98) | -- |
| 1%, 110°C | 0.945 | 1.221 | -- | 0.869 (0.92) | 1.290 (1.06) | -- |
| 4%, 110°C | -- | 1.603 | -- | -- | 1.561 (0.97) | -- |

[a] Percentages indicate amount of NaOH concentration used in the pulp furnish.

[b] Values in parentheses indicate the relative property retention compared with a value at 50 percent RH.

American National Standards Institute (ANSI) 135.4 hardboard. All specimens made from the fiberized small-diameter material exceed hardboard minimum standard requirements. This again was achieved without the use of resins. Adding resin would only improve the panel properties.

For most panel products, an increase in density signifies an increase in fiber bonding and improved stiffness and strength. In this study, the panel densities increased with the level of refinement and NaOH addition (**Table 5**), indicating similar trends to those for the strength properties. The panels were also within density ranges similar to commercial hardboard.

Compared with other processing conditions, the addition of 4 percent NaOH significantly improved all the panel properties. The 4 percent addition level is significantly lower than commercial paper pulping conditions of 15 to 20 percent NaOH addition. Processing costs are minimized when only 4 percent NaOH is used, and steam energy use is also less, because at 90°C (194°F), simple nonpressurized equipment can be used instead of pressure vessels. At the 2 percent NaOH level, minimal increases were evident and results were still similar to the control at 0 percent NaOH. Even at 0 percent NaOH, the properties were above the AHA minimum standard for commercial hardboard. Evaluation of the costs for this process will be evaluated in another publication.

For future work, studies will be initiated to help determine the potential strength properties through a variety of means, including density, fiber processing, and press conditions, to produce predictable three-dimensional engineered fiberboard structures. In addition, performance evaluations of a three-dimensional engineered fiberboard will include shape and geometrical considerations.

## Summary

A process was developed to convert small-diameter lodgepole pine treetop material into a resinless structural fiberboard by first fiberizing then pulping and refining. The data indicate that the maximum potential of the fiber was not reached and that improvements in fiber processing, improvements in press drying, or addition of resin could further improve the engineering properties. The data show that a structural material can be made from a low-value material. It is possible that other similar fibrous materials considered low- or no-value could be used to make value-added products, such as three-dimensional engineered fiberboard.

The next step in developing the three-dimensional engineered fiberboard is to use the flat-panel engineering data presented here to design several molds that will be used to form the fiberboard. We will then test the fiberboard to determine if the structure meets the design specifications.

The economic feasibility of constructing panels from these materials is also being assessed and will be reported in future articles. If these panels prove structurally and economically successful, viable products could be produced from a wide range of lignocellulosic fibers such as forest undergrowth, forest residues, and underutilized small-diameter timber. The proposed technology shows promise in the construction of pallets, bulk bins, heavy-duty boxes, shipping containers, packaging supports, wall panels, roof panels, cement forms, partitions, displays, reels, desks, caskets, shelves, tables, and doors. Assuming the value-added products provide economic incentive, private-sector companies could then develop these products using the otherwise little value, fire-prone material, thus helping to reduce the cost to the federal government for fire mitigation and, at the same time, improving forest health and creating rural economic development.

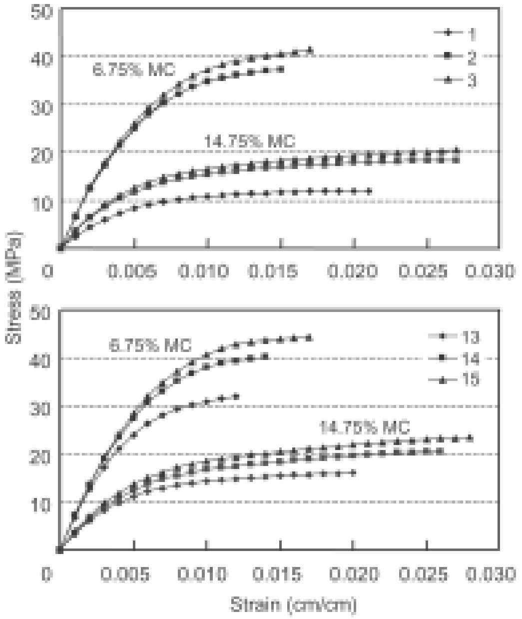

*Figure 4. — Tensile stress vs. strain plots for trials 1, 2, and 3, which were run at 0 percent NaOH, and trials 13, 14, and 15, which were run at 4 percent NaOH. MCs at time of testing were 6.75 and 14.75 percent.*

*Table 5. — Density values for the hardboard panels at 6.75 and 14.75 percent MCs.*

| | 6.75% MC | | | 14.75% MC | | |
|---|---|---|---|---|---|---|
| Panel forming conditions[a] | Refining level 1 | Refining level 2 | Refining level 3 | Refining level 1 | Refining level 2 | Refining level 3 |
| | (kg/m$^3$) | | | | | |
| 0%, 90°C | 888 | 925 | 939 | 884 | 938 | 949 |
| 0.5%, 90°C | 880 | 925 | 942 | 876 | 915 | 940 |
| 1%, 90°C | 865 | 926 | 937 | 868 | 932 | 939 |
| 2%, 90°C | 903 | 937 | 958 | 895 | 939 | 950 |
| 4%, 90°C | 942 | 951 | 965 | 932 | 950 | 952 |
| 0.5 %, 110°C | 900 | 933 | -- | 890 | 927 | -- |
| 1%, 110°C | 908 | 929 | -- | 898 | 924 | -- |
| 4%, 110°C | -- | 954 | -- | -- | 953 | -- |

[a] Percentages indicate amount of NaOH concentration used in the pulp furnish.

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