Chemical and mechanical pulping of aspen chunkwood, mature wood, and juvenile wood*

GARY C. MYERS, RODGER A. AROLA, RICHARD A. HORN, AND THEODORE H. WEGNER

ABSTRACT

Chunking is a comminution technology developed at the Forestry Sciences Laboratory in Houghton, MI, to enhance the economics and subsequent utilization of harvesting small-diameter trees from noncommercial or poor-quality stands. Chunkwood, the product of chunking, has previously been evaluated for fuel, forest road building, and flake products and as a lightweight aggregate for concrete. The objective of this study was to explore the technical feasibility of using chunked small-diameter aspen, high in juvenile wood content, as a raw material for chemical and mechanical pulps.

Blocky chunkwood particles were destructured by crushing prior to chemical pulping by the kraft and neutral sulfite semichemical (NSSC) processes and mechanical pulping by the thermomechanical pulping(TMP) and chemithermomechanical pulping (CTMP) processes. Conventional 19-mm chips, prepared from mature and juvenile wood aspen, were pulped by the same chemical and mechanical pulping processes for comparison purposes. Chunkwood yielded pulps lower in quality to chipped mature wood for kraft, NSSC, TMP, and CTMP, but better in quality to that obtained from chipped juvenile wood. Chunkwood consumed more energy in producing TYMP and CTMP than chipped mature and juvenile woods.

Application:
This paper presents laboratory pulping results for a different comminution technology that could be used to harvest underutilized or nonconventional forests.

SMALL-DIAMETER TREES FROM noncommercial or poor-quality stands and residues are generally not used for solid-wood products. This material has also been underutilized as a fiber source for pulping and papermaking, primarily because of marginal economics and process and product problems associated with its use. Small-diameter trees have generally been harvested using whole-tree chipping technologies. Whole-tree chipping converts the trees in the woods into chips without prior debarking. Consequently, bark, dirt, and grit are dispersed throughout the chipped material and are difficult to remove without losing 15% or more of the wood itself. The presence of bark, dirt, and grit causes increased chemical consumption during pulping, greater wear on processing equipment, reduced wet web strength, more web breaks during papermaking, and cleanliness problems in the final sheet. Chip washing at the mill, prior to pulping, can remove some of these contaminants.

Another problem with small-diameter trees is the high juvenile wood content, which can be as high as 76% in 15-year-old pine *(1)*. Larger-diameter, and presumably older, pine trees may contain only 15% juvenile wood. Juvenile wood in general has thinner cell walls, is higher in lignin content, and is less dense than mature wood. This translates into higher chemical consumption during chemical pulping, lower digester throughputs, and lower paper tear strength. Most research on juvenile wood has been conducted on softwoods, because they have been the predominate raw material source for structural lumber and wood pulp. Zobel and van Buijtenen *(2)* reported that hardwood juvenile wood, in comparison with mature hardwood, has slightly lower specific gravity and slightly shorter fiber length. Pulp yields are slightly affected, but pulp or paper quality from hardwoods is not influenced enough by age to have an important effect. Hardwoods are generally more homogeneous from the pith outward and from base to tree top than are softwoods.

Scientists at the Forestry Sciences Laboratory in Houghton, MI, have developed a new technology and the machinery for comminuting small whole trees into an alternative particle to wood chips, called ***chunkwood*** ***(3,*** *4)*. Chunkwood is a blocky wood particle, much larger in size and of different shape than the traditional plate-shaped wood chip. Chunkwood has been evaluated for fuel wood processing *(5)*, as an intermediate raw material for producing composite flakewood products *(6)*, as a road-building material for low-use forest roads *(7)*, and as aggregate in concrete *(8)*. The potential for chunkwood as a raw material for pulping is unexplored.

Harvesting small-diameter trees via the chunking approach produces chunkwood particles 50-100 mm in length along the fiber direction, whereas chips are typically in the 16-25 mm length range. Therefore, the larger chunkwood particle contains fewer severed fibers, which could translate into improved pulp properties. It is also believed, but not yet shown, that the larger particle size may make it easier to devise processing procedures to remove bark and accompanying dirt and grit without losing substantial amounts of wood.

Another aspect, besides bark, dirt, and grit removal, that may require investigation is size reduction, or ***destructuring,*** of the chunkwood particle. Because of their larger size, chunkwood particles may not be as conducive to pulping liquor as the traditional pulp chip. Bryce and Lowe *(9)* reported the results of chip-crushing mixed dense hardwood chips followed by kraft pulping. Their research showed that effective alkali charge could be reduced 2%, and the resultant pulp contained less screen rejects. Puri and Higgins *(10)* showed that roll restructuring of hardwood and softwood chips reduced the fiberization energy required for refiner mechanical pulp (RMP), chemimechanical pulp (CMP), and chemithermomechanical pulp (CTMP).

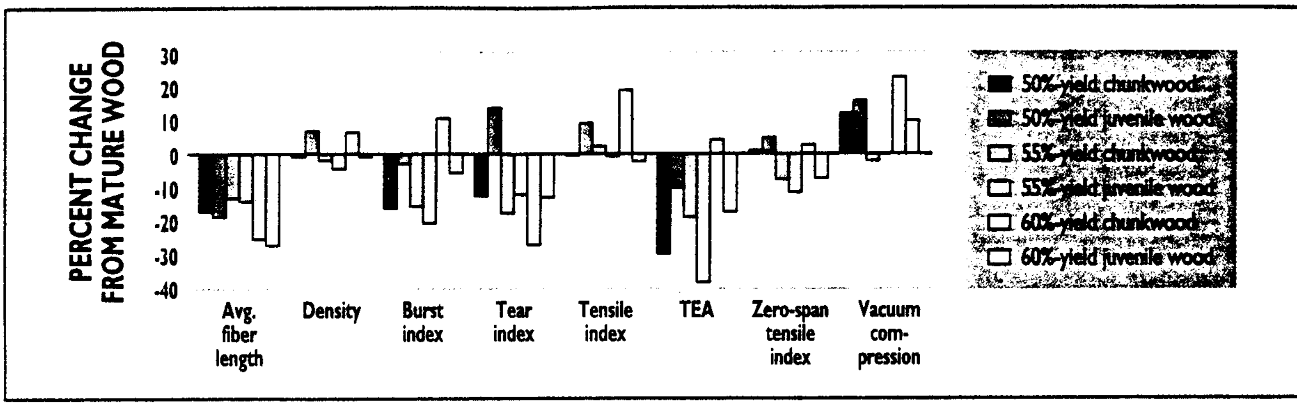
The objective of this study was to determine the

Raw material	Total extractives, %	LIGNIN Klason, %	LIGNIN Acid soluble, %	Glucose, %	Xylose, %	Galactose, %	Arabinose, %	Mannose, %	Ash content, % mm	Avg. fiber length,
Chunkwood	5.5	21.2	3.5	49.4	20.8	2.3	1.1	1.6	0.6	1.1
Mature	3.9	17.2	2.9	56.5	18.6	2.0	0	2.7	0.3	1.3
Juvenile	6.1	20.7	3.4	51.7	22.5	Trace	0	1.7	0.5	1.0

I. Characteristics of aspen raw materials used in study

Raw material	FIBER ANALYSIS Average length, mm	FIBER ANALYSIS Fines <0.2 mm, %	Drainage time, s	Apparent density, kg/m³	Burst index, kPa·m²/g	Tear index, mN·m²/g	Tensile index, N·m/g	Stretch, %	TEA, J/m²	Zero-span tensile index, N·m/g	Vacuum comp., kN/m
Values for 50%-yield pulps											
Chunkwood	0.67	2.8	5.8	675	3.1	5.9	73.9	1.2	35.9	127.0	5.6
Mature	0.81	1.9	6.1	678	3.7	6.7	74.3	1.6	50.6	126.3	5.0
Juvenile	0.66	2.8	8.9	722	3.6	7.6	80.5	1.3	45.4	132.2	5.8
Values for 55%-yield pulps											
Chunkwood	0.72	2.5	9.0	713	3.4	6.3	80.5	1.4	46.5	123.4	5.7
Mature	0.83	1.6	9.0	725	4.0	7.6	79.2	1.7	57.2	133.7	5.8
Juvenile	0.71	2.5	9.0	696	3.2	6.7	78.1	1.1	35.3	118.7	5.8
Values for 60%-yield pulps											
Chunkwood	0.69	2.4	6.4	727	4.2	5.8	94.9	1.4	56.7	128.1	6.5
Mature	0.92	1.3	9.0	684	3.8	7.9	80.1	1.6	54.7	124.8	5.3
Juvenile	0.67	2.8	8.8	681	3.6	6.9	78.2	1.4	45.4	115.9	5.8

II. Kraft pulp and handsheet properties at 500 mL CSF



I. Kraft properties at 500 mL CSF

Raw material	FIBER ANALYSIS Average length, mm	Fines <0.2 mm, %	Apparent density, kg/m³	Burst index, kPa·m²/g	Tear index, mN·m²/g	Tensile index, N·m/g	Stretch, %	TEA, J/m²	Vacuum comp., kN/m	Ring crush, kN/m	Corrugating medium test, N
Chunkwood	0.89	3.5	748	4.8	5.7	94.7	1.9	139.4	3.2	1.70	340
Mature	1.12	1.7	733	5.1	7.0	94.9	2.2	165.2	3.3	1.65	330
Juvenile	0.91	3.5	714	4.6	6.1	91.5	1.8	128.7	3.1	1.67	321

III. NSSC pulp and handsheet properties at 500 mL CSF

feasibility of using chunked, small-diameter aspen ***(Populus tremuloides*** Michx.) as a raw material source for kraft, neutral sulfite semi-chemical (NSSC), TMP, and CTMP pulping. Pulping trials were conducted on (a) chunkwood particles that had been restructured by crushing and sawing and (b) conventionally chipped wood containing high proportions of juvenile wood. Pulping process parameters and paper strength properties from these materials were compared with pulps prepared from conventionally chipped mature pulpwood.

RESULTS AND DISCUSSION

Destructuring chunkwood

Chunkwood pieces were very large (50-100 mm long and 100-600 mm across the fiber direction) when compared with the conventional wood chips traditionally used in pulping. Some type of restructuring was required to open the large particles along the fiber length to facilitate pulping liquor penetration. It was determined that chunkwood could be restructured by compression in a laboratory platen press. This not only fractured the wood chunks extensively along the fiber length, but it separated some of the bark from the wood. Most of the remaining bark was removed by hand. Restructured particles intended for the small pressurized refiner were sawed in half across the fiber length to enable passage through the feed screw.

Raw material characteristics

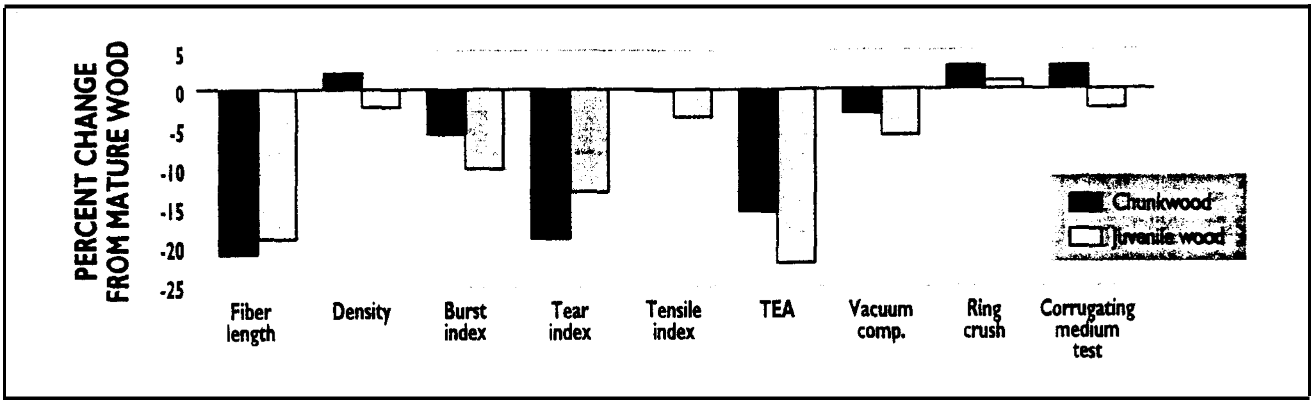
Several chemical analyses were run on the raw materials, and the results are presented in **Table I.** The slightly higher ash content of the chunkwood is due to incomplete bark removal during the restructuring process. Chunkwood values were more closely aligned with juvenile than with mature wood. This alignment was anticipated, because trees harvested and processed by the chunking operation had a small diameter, increasing the probability of a high juvenile wood content.

Kraft pulping

Concern about liquor penetration prompted the use of restructured chunkwood for kraft pulping trials. Pulping and handsheet results imply no apparent problems with liquor penetration into the restructured chunkwood particles.

Properties of the chunkwood pulps are close and, in a few instances, better than pulps from the other wood types when the data for each pulp yield are compared at 500 mL CSF (see **Table II** and **Fig.** 1).

At 50% pulp yield, chunkwood was better than mature wood in compression strength. In all other strength test categories, chunkwood was equal to or weaker than pulp from mature wood. Chunkwood was inferior to juvenile wood for all handsheet properties. Juvenile wood was higher than mature wood in tear index, tensile index, zero-span tensile index, and compression strength. At



2. NSSC properties at 500 mL CSF

55% pulp yield and 500 mL CSF, chunkwood was barely higher than mature wood in tensile index but was inferior to mature wood in all other properties. Chunkwood was also better than juvenile wood for burst index, tensile index, stretch, tensile energy absorption (TEA), and zero-span tensile index. At 60% pulp yield and 500 mL CSF, chunkwood was higher than mature wood in burst index, tensile index, TEA, zero-span tensile index, and compassion strength. Chunkwood was also better than juvenile wood in burst index, tensile index, TEA, zero-span tensile index, and compression strength. Note that the tear index of chunkwood was lower than either the mature or juvenile wood, regardless of pulp yield.

All pulps from mature wood had longer fiber lengths and more frees **(Table II** and **Fig. 1).** Average fiber length and frees contents of the chunkwood pulps were essentially the same as those of juvenile wood pulps. This probably reflects the high juvenile wood content in the chunkwood material.

NSSC *pulping*

Concern about liquor penetration also prompted the use of destructured chunkwood for the NSSC pulping trials. Pulping and handsheet results imply no apparent problems with liquor penetration into the restructured chunkwood particles. The chemical consumption and cooking conditions of chunkwood were between that of mature and juvenile wood to reach nearly identical pulp yields.

As with kraft pulping, paper properties were compared at 500 mL CSF **(Table III** and **Fig. 2).** Properties of the chunkwood pulps compared favorably and, in many instances, better than pulps from the other wood materials. At 500 mL CSF, chunkwood was greater than mature wood only in ring crush and corrugating medium test. Chunkwood was better than juvenile wood for all handsheet properties except tear index. Note that the tear index Of, chunkwood was 19% less than mature and 7% less than juvenile woods.

Average fiber length was shorter and fines content greater for the chunkwood pulp than for the mature and juvenile pulps **(Table III** and **Fig. 2).**

Thermomechanical pulping

Chunkwood material, as originally received, was too large to pass through the feed screw mechanism of the pressurized refiner. As previously discussed, to pass the material through the pressurized refiner, it was necessary to restructure and shorten the chunkwood material. Hoekstra *et al. (11)* had shown that chip thickness is an important parameter in mechanical pulping, which was not evaluated in this study.

Mechanical pulps must be refined to very low freeness levels (about 100 mL CSF) to reduce or eliminate shives and to develop paper strength properties *(12).* For comparison purposes, chemical pulps develop maximum strength properties, while maintaining suitable drainage rates, when refined to a 450-500 mL CSF range. Energy consumption can often be used as a guide to strength development of mechanical pulps. Generally, the greater the energy input, the better the fiber development. However, too much energy input can cause excessive fiber damage and fiber shortening, which would reduce strength properties.

Although not shown, freeness decreased as energy consumption increased. At 100 mL CSF, chunkwood consumed more energy than mature and juvenile woods, probably due to the larger particle size **(Table IV** and **Fig. 3).** Chunkwood was inferior to mature wood in all strength and most optical properties. Chunkwood was superior to juvenile wood in most properties, except for being lower in burst index.

Chemithermomechanical pulping

As with TMP, shortened, destructured chunkwood was also used in the CTMP pulping trials. In the

Raw material	FIBER ANALYSIS Energy consumed, W·h/o.d. kg	Average length, mm	Fines <0.2 mm, %	Drainage time, s	Apparent density, kg/m³	Burst index, kPa·m²/g	Tear index, mN·m²/g	Tensile index, N·m/g	Stretch, %	TEA, J/m²	Bright-ness (ISO), %	Printing opacity (ISO), %	Scattering coeff. (ISO), m²/kg
Chunkwood	2835	0.49	13.4	12.9	417	0.4	1.6	18.7	1.1	8.8	44.5	99.6	69.1
Mature	2661	0.55	11.5	13.4	433	0.6	2.1	22.0	1.3	12.2	48.5	99.2	72.3
Juvenile	2396	0.48	15.7	13.9	422	0.5	1.3	16.9	1.0	7.3	44.6	99.7	75.4

IV. TMP pulp and handsheet properties at 100 mL CSF

Raw material	FIBER ANALYSIS Energy consumed, W·h/o.d. kg	Average length, mm	Fines <0.2 mm, %	Drainage time, s	Apparent density, kg/m³	Burst index, kPa·m²/g	Tear index, mN·m²/g	Tensile index, N·m/g	Stretch, %	TEA, J/m²	Bright-ness (ISO), %	Printing opacity (ISO), %	Scattering coeff. (ISO), m²/kg
Chunkwood	3072	0.52	10.7	11.8	490	1.09	2.0	28.0	1.0	10.8	54.3	98.0	72.6
Mature	2450	0.61	9.1	16.4	482	1.08	2.5	25.9	1.1	12.0	54.0	98.2	77.0
Juvenile	1895	0.52	14.4	11.2	426	0.67	1.5	17.7	0.9	6.6	46.3	99.5	74.1

*CTMP prepared with 1.2% NaOH and 1.6% H_2O_2.

V. CTMP* pulp and handsheet properties at 100 mL CSF

CTMP process, chemical solutions injected into the pressurized refiner were mixed with the passing steamed wood particles about six seconds before entering the refiner plates, where the presoftened wood was fiberized. During fiberization, the chemicals interacted with the fibers and fiber bundles. Because of the extremely short residence time, there was relatively little chemical penetration into any wood prior to fiberization. Adding chemicals to the wood during pulping may increase energy consumption but should improve sheet properties when compared with TMP.

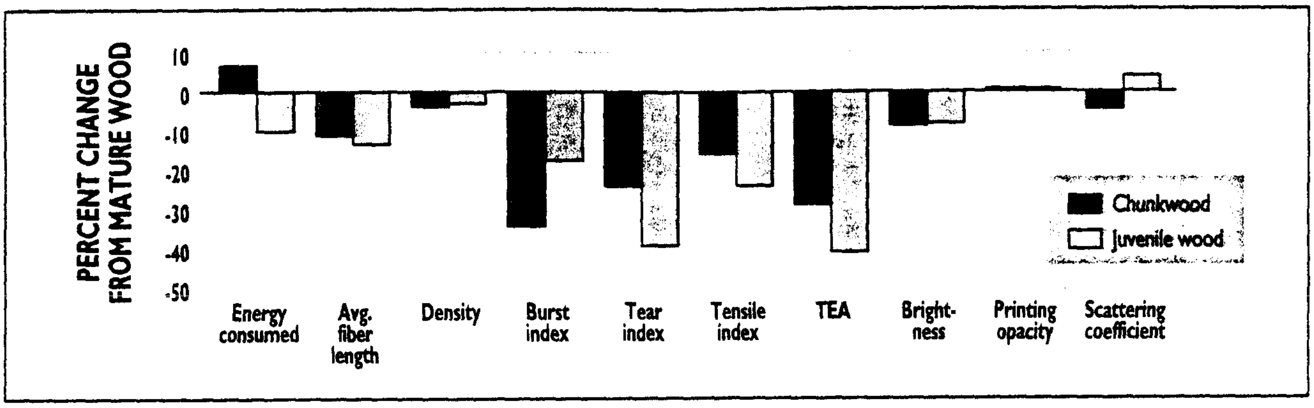
Although not shown, freeness decreased as energy consumption increased with the chemical treatment. The results of the CTMP trials using approximately 1.2% NaOH and 1.6% H_2O_2. showed that, at a constant freeness of 100 mL, chunkwood consumed more energy than mature and juvenile woods, probably due to the larger particle size **(Table V** and **Fig. 4).** Chunkwood was better than mature wood in tensile index but nearly the same in burst index and brightness. Chunkwood was better than juvenile wood in most strength and optical properties.

EXPERIMENTAL

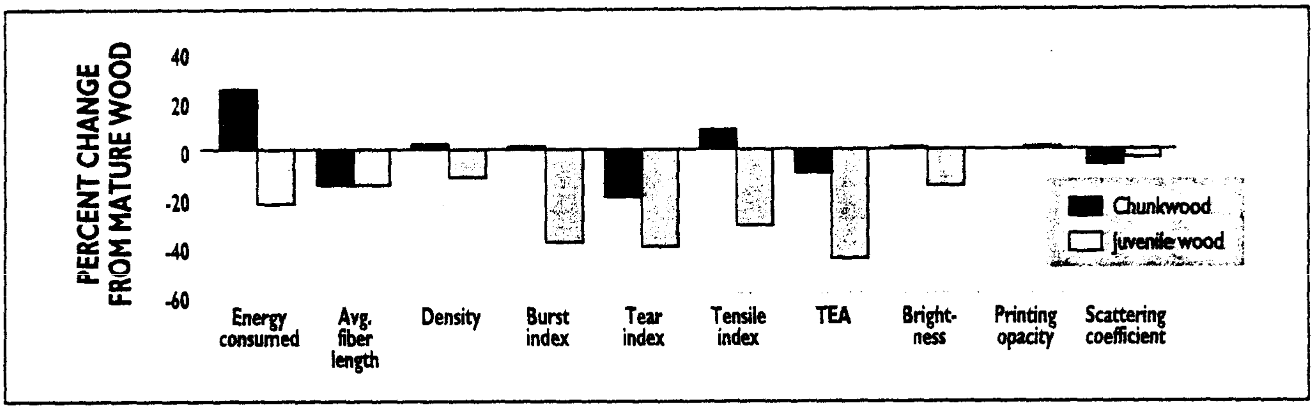
Raw material acquisition and preparation

Aspen *(Populus tremuloides* Michx.) was the species chosen for this study. AU trees were harvested near Houghton, MI. Aspen from small-diameter trees (50-mm-diam. minimum size) was chunked in prototype equipment at the Forestry Sciences Laboratory in Houghton. Wood of the same size obtained from the same site, along with conventional-diameter pulpwood (100-500-mm-diam.), was also shipped to the Forest Products Labotatory in Madison, WI. The small- and conventional-diameter trees were hand peeled to remove all bark and were chipped to a 19-mm chip length in a four-knife commercial-size chipper.

Chipped wood was screened to remove all particles greater than 38 mm and less than 6 mm in length. Screened wood chips and the chunkwood pieces were placed in polyethylene-lined barrels and stored in a 4°C room until needed for additional preparation or pulping. The chunkwood was destructured in a hydraulic platen press, crushing the particles until they had a spongy texture, and the particles were clearly opened along the fiber length. Bark remaining after restructuring was removed by hand. Destructured chunkwood intended for TMP and CTMP trials was sawed in half across the fiber length to reduce particle size and to avoid problems with the pressurized refiner's 76-mm-diam. feed screw.



3. TMP properties at 100 mL CSF



4. CTMP properties at 100 mL CSF

KEYWORDS

Chemical pulping, chemithermomechanical pulping, chips, comminution, juvenile wood, kraft pulping, mature wood, mechanical properties, mechanical pulping, NSSC pulping, optical properties, paper properties, populus, thermomechanical pulping.

Kraft pulping

A 23-L digester was used to prepare kraft pulps ranging in kappa numbers from 9 to 45 for the three raw materials. The following range of pulping conditions was used to reach pulp yields of 50, 55, and 60%: 14-24% active alkali, 4:1 liquor-to-wood ratio, 25% sulfidity, 30-90 min time from room temperature to 170°C, and 20-90 min at 170°C. After pulping, the cooked chips were partially washed inside the digester with hot water and then disintegrated in a stainless steel mixing tank with a stirrer and hot water. Disintegrated pulps were dewatered before determining yield and kappa numbers. Each pulp was beaten in a laboratory-size Valley beater to obtain three different freeness levels. One replicate was prepared for each yield of the three raw materials.

NSSC pulping

A 23-L digester was used to prepare 74± 1% -yield pulps from the three raw materials. The following range of pulping conditions was used: 10-13.5% Na_2SO_3, 4.5% Na_2CO_3, 4:1 liquor-to-wood ratio; 90 min time from room temperature to 170°C, and 30-100 min at 170°C. After pulping, the cooked chips were partially washed inside the digester with hot water. Pulped chips were fiberized in a 305-mm-diam. Sprout-Waldron refiner and dewatered before determining yield. Each pulp was beaten in a laboratory-size Valley beater to obtain three different freeness levels. One replicate was prepared for each yield of the three raw materials.

TMP preparation

An Andritz Sprout-Bauer Model 12-lCP 305-mm-diam. pressurized refiner, fitted with plate pattern D2B505, was used for fiberization. All saw materials were steamed for 10 min at 69 kPa before fiberization with a 0.254-MM plate gap, Raw material feed rate through the pressurized refiner varied from 259 to 817 g ovendry (o.d.) raw material per min. Flberized raw materials were refined in a Sprout-Waldron Model

105-A 305-mm-diam. atmospheric refiner, also fitted with plate pattern D2B505. Plate gap was 0.152-0.305 mm. A constant volume of shredded pulp was delivered to the refiner inlet by a constant-speed belt conveyor, and dilution water added to the shredded pulp adjusted to approximately 15% Consistency in the refiner. Multiple passes were necessary to reduce pulp freeness to 100 mL CSF or less.

Energy consumed during fiberization and refining was measured using an Ohio Semitronic Model WH30-ll195 integrating watt-hour meter attached to the power supply of the 44.8-kW electric motor, measuring amperes, volts, and power factor. Energy consumption values for fiberizing and refining were reported as watt-hours per kilogram (o.d. weight basis), with the idling energy subtracted. Latency was removed from the pulp after fiberization and each refining step by soaking the pulp in 90°C water for a minimum of 30 min, with occasional stirring. Three replicates were prepared for the mature and juvenile woods, and four replicates were made for the chunkwood.

CTMP preparation

The pressurized and atmospheric refiners described under TMP preparation, fitted with plate pattern D2B505, were also used for CTMP preparation. All raw materials were steamed for 10 min at 69 kPa before fiberization at a 0.254-0.305-mm plate gap. During the fiberization procedure, a positive displacement metering pump delivered solutions composed of sodium hydroxide, hydrogen peroxide, sodium silicate, diethylenetriamine pentamethylene acid, and magnesium sulfate to the horizontal feed screw housing at a point approximately 20 cm before the eve of the pressurized refiner. Refining procedures, energy consumption measurements, and latency removal were the same as previously described under TMP preparation. Three replicates were prepared for each raw material.

Pulp testing, handsheet formation, and testing

Freeness was measured according to TAPPI Test Method T 227. Shive contents of the mechanical pulps were determined with a Pulmac shive analyzer, using a disc with 0.10-mm slot openings. Fiber analysis was performed using a Kajaani FS-100 analyzer. Handsheets weighing 60 g/m^2 were made according to TAPPI Test Method T 205. Drainage time was measured according to TAPPI Test Method T 221 as the pulps were formed into handsheets. Burst and tear indexes were measured according to TAPPI Test Methods T 403 and T 414, respectively. Tensile properties were measured according to a procedure described by Setterholm and Kuenzi *(13).*

Vacuum compression was measured on the equipment and by the procedure described by Gunderson *(14).* Flat crush of corrugating medium, or the CMT test, was measured according to TAPPI Test Method T 809, and ring crush of paperboard was measured according to TAPPI Test Method T 818. Brightness, printing opacity, and light-scattering coefficient were measured with a Technidyne Corp. Technibrite Model TB-1 diffuse brightness apparatus (New Albany, IN) according to TAPPI Test Method T 525.

Each chemical and mechanical pulp was processed to freeness levels above and below the respective 500 and 100 mL CSF targets, and 10 handsheets were made and tested for each pulp. These results were regressed, and values at 500 mL CSF for chemical pulps and 100 mL CSF for mechanical pulps are estimated and reported in this paper. No additional statistical analysis was performed on the results.

CONCLUSIONS

Destructured chunkwood yielded pulps of lower quality than those obtained from chipped mature wood for kraft, NSSC, TMP, and CTMP pulps. Pulps produced from chipped juvenile wood were of somewhat lower quality than those from chunkwood and mature wood.

Chunkwood consumed more energy than mature and juvenile woods in producing TMP and CTMP.

Chunking is an interesting comminution technology that needs additional pulping trials on larger-scale equipment using a nondestructured chunkwood to fairly assess its suitability for pulping. **TJ**

Myers is a research forest products technologist, Wegner is assistant director, and Horn is retired from the USDA Forest Service, Forest Products Laboratory, One Gifford Pinchot Dr., Madison, WI 53705-2398. Arola is retired from the USDA Forest Service, Forestry Sciences Laboratory, 410 MacInnes Dr., Houghton, Ml 49931-1199.

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LITERATURE CITED

1. Thomas, R. J., *Proceedings of Symposium on Utilization of the Changing Wood Resource in the Southern United States*, N.C. State University, Raleigh, NC, 1984, p. 40.
2. Zobel, B. J. and van Buijtenen, J. P., *Wood Variation, Its Causes and Control*, Springer-Verlag, Berlin, 1989, pp. 82–100.
3. Arola, R. A., Radcliffe, R. C., Winsauer, S. A., *et al.*, Research Paper NC-211, USDA, Forestry Sciences Laboratory, North Central Experiment Station, St. Paul, MN, 1982.
4. Barwise, R. D., Arola, R. A., and Matson, E. D., U.S. pat. 4,431,039 (Feb. 14, 1984).
5. Anon., General Technical Report NC-145, USDA, Forestry Sciences Laboratory, North Central Forest Experiment Station, St. Paul, MN, 1991.
6. Haataja, B. A., Adams, R. D., and Arola, R. A., *Proceedings of the 1984 Council on Forest Engineering and International Union of Forest Research Organizations*, University of Maine, Orono, ME, and University of New Brunswick, Fredericton, NB, Canada, p. 157.
7. Arola, R. A. and Sturos, J. A., *1990 Proceedings of the 13th Annual Meeting of the Council on Forest Engineering*, N.C. State University, Raleigh, NC, p. 196.
8. Arola, R. A., *Proceedings of the 88th Annual Meeting of the American Wood Preservers' Association*, American Wood Preservers' Association, Woodstock, MD, 1993, p. 126.
9. Bryce, J. R. G. and Lowe, R. W., *Pulp Paper Can.* 88(9): T326(1987).
10. Puri, V. P. and Higgins, H. G., *Appita* 37(6): 496(1984).
11. Hoekstra, P. L., Veal, M. A., and Lee, P. F., *International Mechanical Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, 1983, p. 185.
12. Leask, R. A. and Kocurek, M. J., Eds., *Pulp and Paper Manufacture, Vol. 2*, TAPPI PRESS, Atlanta, 1987, p. 138.
13. Setterholm, V. C. and Kuenzi, E. W., Report 2066, USDA, Forestry Sciences Laboratory, Forest Products Laboratory, Madison, WI, 1956.
14. Gunderson, D., *Appita* 37(2): 137(1983).