Distinguishing characteristics of biomechanical pulp

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ABSTRACT *In the laboratory, biomechanical pulping has been shown to use substantially less energy than conventional pulping and to increase paper strength. However, to ascertain whether biomechanical pulping is feasible on a commercial scale requires an understanding of the mechanisms involved and of the papermaking properties of biomechanical pulp fiber. We qualitatively compared biomechanical pulps with conventional mechanical and chemical pulps using scanning electron microscopy. We observed more fibrillation on biomechanical pulp than on refiner mechanical pulp. The biomechanical pulp fiber appeared more woolly, looser, and more uniform in length than conventional mechanical and chemimechanical pulp fibers. Fiber bonding in handsheets produced from biomechanical pulp was visually similar to that observed in handsheets produced from chemical pulps.*

KEYWORDS
Biomechanical pulping
Biopulping
Biotechnology
Electron microscopy
Mechanical pulp
White-rot fungi

Certain white-rot basidiomycetes are capable of extensively and selectively degrading lignin in wood (*1—3*). The fungi penetrate and colonize the wood cells, secreting degradative enzymes that diffuse through the cell lumen and through the cell wall layers (*4*). However, the rate of producing cellulose pulps through fungal delignification of wood (*5*) is presently too slow for commerical processes.

Tests with a high-yield, bench-scale, biomechanical pulping process suggest that pretreating aspen wood chips with white-rot fungi prior to refiner mechanical pulping can result in both substantial energy savings (*6, 7*) and increased sheet strength properties (*8, 9*). By requiring less pulping chemicals, biomechanical pulping has the potential to be less polluting than chemimechanical and chemical pulping processes (*10*). Little wood is lost in biopulping (*6, 9*); about 96% is recovered. In chemical kraft pulping, about 50% wood is lost. Although biomechanical pulping seems promising, the mechanism of this process and the resulting papermaking properties of the pulp remain to be determined.

Previous research established how the fungus colonizes and partially degrades aspen wood chips (*11*). Wood chips were pretreated with *Phanerochaete chrysosporium* BKM-F-1767 and were examined by scanning electron microscopy. The major findings were:

1. The degradative enzymes of the organism brought about overall softening and swelling of the wood cell walls as well as localized wall fragmentation (*11*).
2. The fungal enzymes that attacked the cell walls appeared to be secreted preferentially from the cell lumen (*4, 11*).

Mechanical and chemical pulping are distinguished functionally on the basis of physical or chemical dispersion of fibers from the wood matrix (*12*). Mechanical pulping produces high yields and ruptures the fiber walls during fiberizing (*13*). In addition, mechanical fiberizing consumes large amounts of energy (*14*). Fiberizing is much less energy-intensive in chemical pulping because substances of the middle lamella are chemically removed (*14*). In our tests with biopulping, the enzymes of *P. chrysosporium* BKM-F-1767 did not separate fibers by dissolving lignin in the compound middle lamella but swelled and softened the fiber walls, often releasing ribbons of fibrils. When fiberized, the pulp appeared woolly, with loose (less compact) fibers.

The objective of our research was to determine the characteristics of pretreated biomechanical pulp (BMP). Using scanning electron microscopy, we compared BMP fiber and handsheets to aspen pulps and handsheets made by conventional pulping methods.

I. Comparison of aspen biomechanical pulp with pulps produced by conventional methods

Pulping process	Apparent fiber length	Fiber shape	Debris	Fibrillation	Compressibility and conformability	Collapsed fibers
SGW	Varied	Different width	Yes	Reduced	Poor	No
RMP	Shorter than SGW	Thinner than SGW	Yes	Moderate	Poor	No
TMP	Longer than RMP	Thinner than SGW, twisted fibers	Yes	Reduced	Poor	No
CTMP	Longer than RMP	Thinner than SGW, twisted fibers	Yes	Reduced	Poor	No
NSSC	Longer than CTMP	Various widths, not twisted	Moderate	Reduced	Moderate	Yes
Kraft	Longest fibers, fairly uniform	Not twisted	Reduced	Abundant	Good	Yes
BMP	Moderate length, fairly uniform	Not twisted	Reduced	Abundant	Good	Yes

II. Comparison of yield and handsheet data for different pulping processes

			Handsheet properties*						Bauer-McNett screen analysis for pulp					
									Retained,				Passed,	
Pulping process	Yield, %	Freeness, mL	Burst index, kPa• m²/g	Tear index, mN• m²/g	Tensile index, N•m/g	Scattering coef., N•m/g	Opacity, %	Density, kg/m³	0.595-mm screen	0.297-mm screen	0.149-mm screen	0.075-mm screen	0.075-mm screen	Fiber length index
SGW	95	115	0.91	1.9	28	77	97	421	0.70	7.15	2.15	48.05	41.95	0.062
RMP	95	110	0.92	2.0	30	57	92	389	6.45	27.90	24.00	17.65	24.00	0.101
TMP	95	111	1.0	3.8	28	59	92	417	8.40	25.10	25.60	8.60	32.20	0.088
CTMP	94	120	2.1	6.7	47	41	84	499	22.15	28.00	20.00	8.85	21.00	0.120
NSSC	76	230	5.5	4.8	106	14	62	717	9.20	34.50	28.10	8.10	19.80	0.120
Kraft	56	315	7.1	6.4	116	18	82	773	9.20	45.90	24.90	6.75	13.25	0.154
BMP	95	100	2.0	4.6	52	40	95	402	5.30	60.00	24.00	7.25	3.45	0.243

*Properties for 60-g/m² handsheets.

Our observations suggest that conformability of BMP in handsheets is similar to that of chemically prepared pulps; BMP shows good compressibility and fiber-to-fiber conformability. In contrast, handsheets prepared from conventional mechanical and chemimechanical pulping methods produce stiff fibers that do not compress readily and that result in poor conformability, which reduces the bonding strength between fibers.

Results and discussion

Comparison of aspen BMP and conventional pulp fibers

We compared aspen pulps and sheets produced by biomechanical pulping with those produced by several different pulping methods: stone groundwood (SGW) pulping, refiner mechanical pulping (RMP), thermomechanical pulping (TMP), chemithermomechanical pulping (CTMP), neutral sulfite semichemical (NSSC) pulping, and kraft pulping. These pulping methods produce fibers with generally well-known and accepted morphological characteristics (*12, 13, 15–23*).

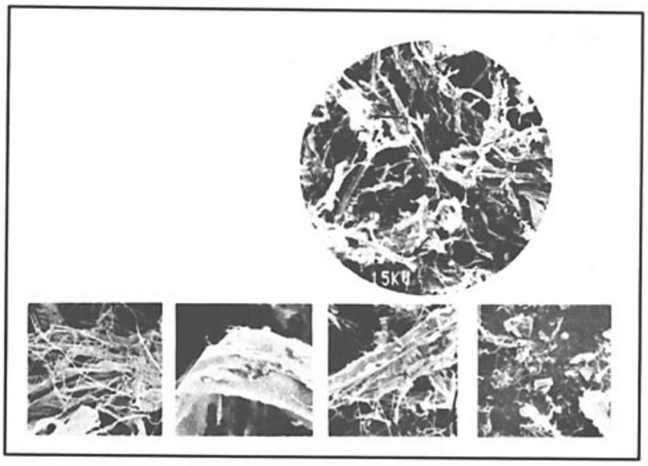
The BMP fibers showed clear qualitative differences in length, width, compressibility, and conformability (**Tables I and II**). Our observations (Table I) of the various conventional pulps were in general agreement with those reported by others.

The BMP fibers (**Fig. 1**) were woolly and loose; these fibers were of more uniform length and had more abundant fibrillation than the RMP fibers (**Fig. 2**). The RMP fibers were substantially thinner and shorter than the BMP fibers and had moderate fibrillation. Both the TMP (**Fig. 3**) and SGW pulp (**Fig. 4**) contained stiff fibers and debris; these pulps had less fibrillation than the BMP. The BMP fibers were less twisted than the TMP and CTMP fibers (Fig. 3 and **Fig. 5**).

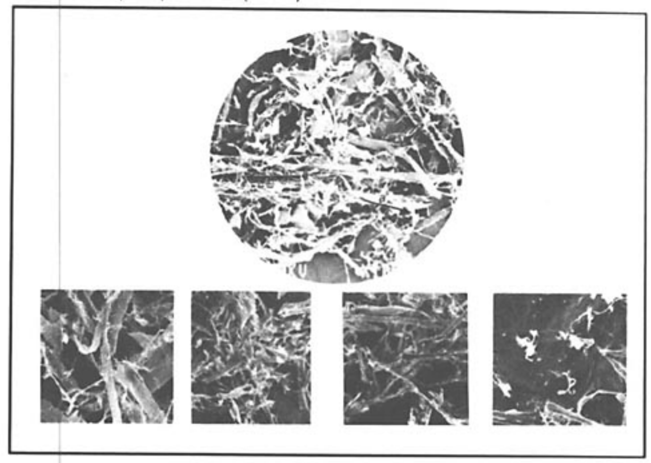
On the whole, chemical pretreatment of chips before thermomechanical (Fig. 5) and NSSC (**Fig. 6**) pulping resulted in stiffer fibers of various lengths and widths with reduced fibrillation and much wood cell wall debris compared to kraft pulp and BMP.

Of the pulps studied, those produced by kraft pulping showed the most uniformly separated and collapsed fibers and the highest degree of conformability (**Fig. 7**). The BMP

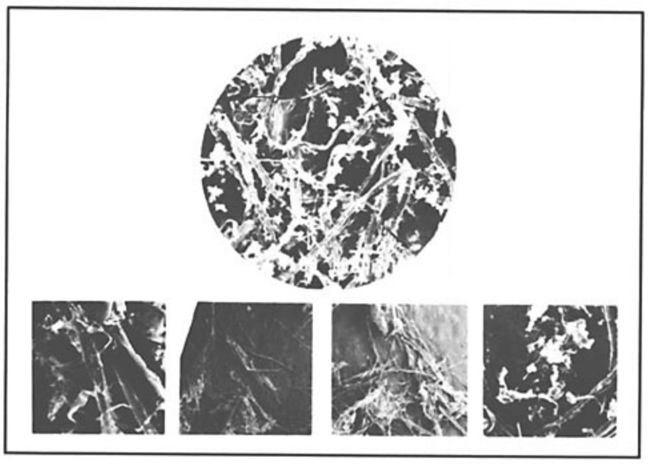
1. Biomechanical pulp (BMP) fibers are fairly uniform in length (X170), with abundant fibrillation (a, X100 and X2200), and good compressibility and conformability, i.e., flat fibers (X1200). Debris (X110).



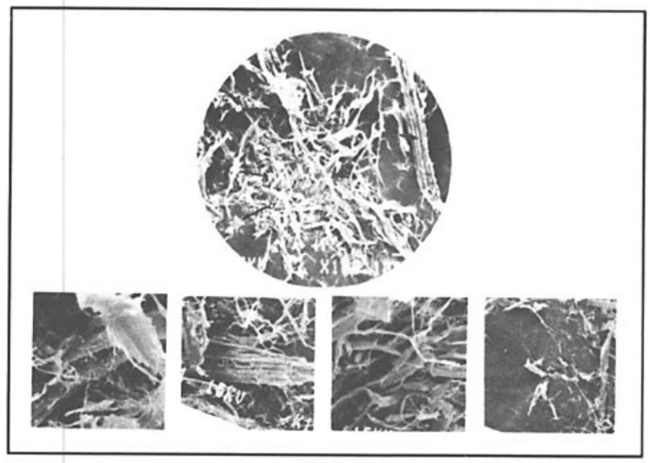
2. Refiner mechanical pulp (RMP) fibers are thin and short with little fibrillation (a, X100), they are stiff (X90), and they have various lengths and widths (X90). Debris (X160).



3. Thermomechanical pulp (TMP) fibers are of various lengths and widths (a), and have less fibrillation (b) than fibers of BMP and RMP (X100 and X430). Fibers are stiff (X22) and of various lengths and widths (X22). Debris (X150).



4. Stone groundwood pulp (SGW) fibers (a) are of various lengths and widths (c), and have less fibrillation (b) than fibers of BMP and RMP (X100 and X850). Fibers are stiff (X170) and are of various lengths and widths (X400). Debris (X170).



resembled kraft pulp because of the uniform length and collapsed fibers plus the excellent bonding of fibers, which in part may have resulted from the release of fibril ribbons by *P. chrysosporium* enzymes.

Comparison of handsheets from BMP and conventional pulping methods

Compared to handsheets made from BMP, handsheets prepared from pulps produced by mechanical pulping methods (RMP, TMP, SGW, CTMP; **Figs. 8—11**) had more noncompressed fibers that lacked conformability, indicating a reduction of bond strength. The NSSC (**Fig. 12**) and kraft (**Fig. 13**) handsheets exhibited good fiber collapse and conformability. The BMP (**Fig. 14**) handsheets bore a strong similarity to kraft handsheets.

Table II shows values for physical properties of handsheets produced from aspen pulps at selected freeness levels.

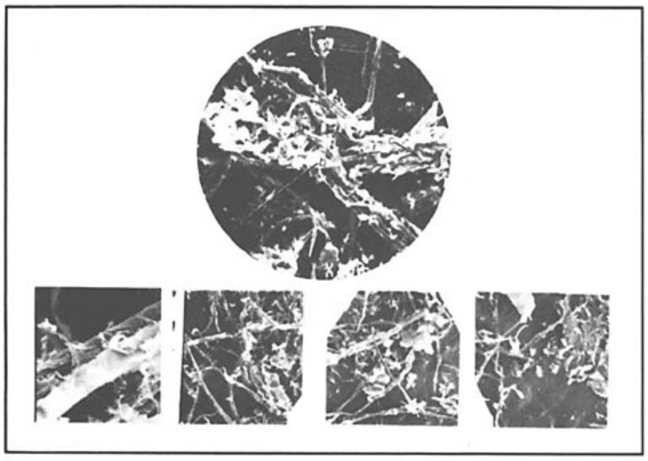
Overall, tensile indexes of the handsheets produced from the aspen BMP were much higher than those produced from SGW, RMP, and TMP and were within the range of the indexes of CTMP handsheets. The handsheet tensile index of NSSC pulp was much higher than that of BMP. The low-yield kraft pulp gave the highest handsheet tensile index.

Tear indexes of handsheets produced from TMP were higher than those of handsheets from RMP and SGW pulp. Handsheets from BMP had a much higher tear index than that of handsheets from TMP; the tear index of BMP handsheets was equivalent to that of handsheets made from NSSC. The CTMP pulp yielded handsheets with the highest tear index.

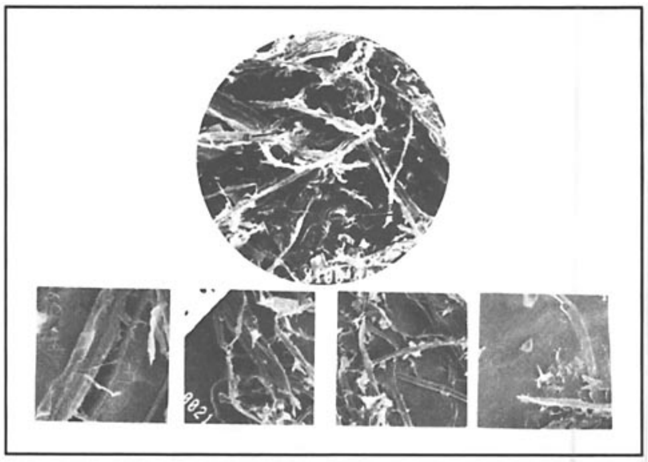
Handsheets produced from SGW, RMP, and TMP pulps had the lowest burst indexes. Handsheets produced from CTMP and BMP had essentially equivalent values; the burst index values of these handsheets were higher than those of handsheets made from SGW, RMP, and TMP pulps. Handsheets from NSSC and kraft pulps had the highest burst indexes.

The results show that BMP produced a stronger pulp than SGW, RMP, and TMP pulps (Table II). Handsheets from BMP were most similar in strength properties to handsheets produced from CTMP.

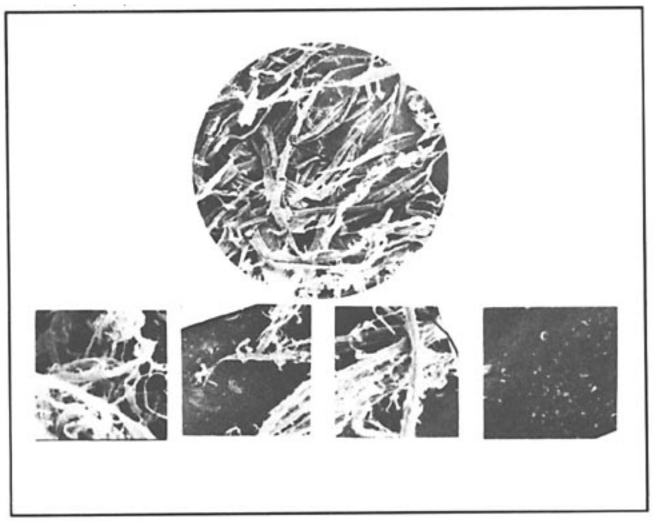
5. Chemithermomechanical pulp (CTMP) fibers (a) are of various lengths and widths (c), and show some twisting (e) and much cell wall debris (b) (X100). Reduced fibrillation (X850). Various lengths and widths and stiffness of fibers are also shown at lower magnification (X55). Debris (X55).



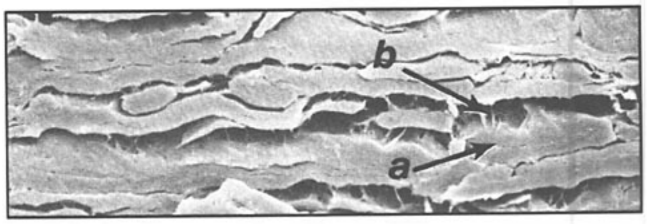
6. Neutral sulfite semimechanical pulp (NSSC) fibers are stiff and of various lengths and widths. Reduced fibrillation (a) and cell wall debris (X100). Reduced fibrillation, stiffness, and various lengths and widths are also shown at higher magnification (X750, X110, and X110 respectively). Debris (X170).



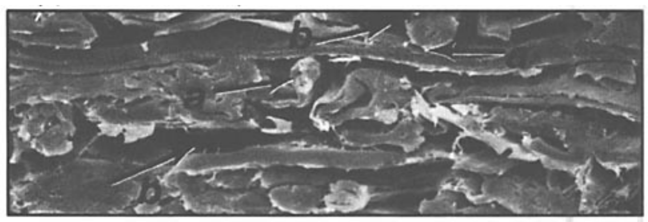
7. Kraft pulp fibers (a) are quite uniform in length and are usually separated; many are collapsed (X100). Abundant fibrillation (X600). Collapsed and conforming fibers (X180). Uniform fiber length (X180). Debris (X170).



8. RMP handsheet fibers (a) are stiff, they show little flexibility (resulting in less conformability compared to BMP handsheets), and they contribute to poor bonding (b) (cross section X100).



9. TMP handsheet fibers (a) exhibit poor bonding (b) and conformability (cross section X200).



Compared to handsheets produced by mechanical pulping, semichemical pulping, and BMP, handsheets produced by kraft pulping were far superior in strength properties.

Concluding remarks

During biomechanical pulping (BMP), the enzymes of *P. chrysosporium* BKM-F-1767 promote the release of fibril ribbons. By contrast, chemical pulping methods separate fibers by dissolving the lignin in the compound middle lamella. Our results show significant differences between BMP and mechanical pulps and fewer differences between BMP and chemical pulps. When fiberized, BMP emerged more woolly, looser, and more regular and had more uniform fiber length than pulps produced with conventional mechanical and semichemical methods (**Fig. 15**). The BMP fibers were also more flexible. Consequently, handsheets from BMP were more conformable and had greater strength properties than handsheets from mechanical pulps. The BMP appears to bond fibers in the handsheets in a fashion similar to that of kraft pulping. However, the nonoptimized biomechanical process studied here resulted in handsheets with less strength than handsheets produced from kraft pulping. The strength properties of BMP handsheets were similar to those of CTMP handsheets. Burst, tear, and tensile strength properties were greater than those in handsheets produced from mechanical pulping methods. Despite the differences in density, the cross-sections of BMP handsheets were more similar to handsheets from chemical pulps than handsheets from mechanical pulps.

Experimental procedures

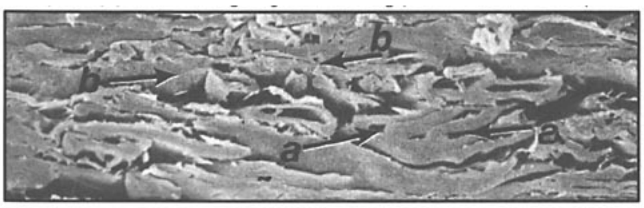
Pretreatment of chips

P. chrysosporium Burds. (syn. *Sporotrichum pulverulentum*) strain BKM-F-1767 was maintained on potato

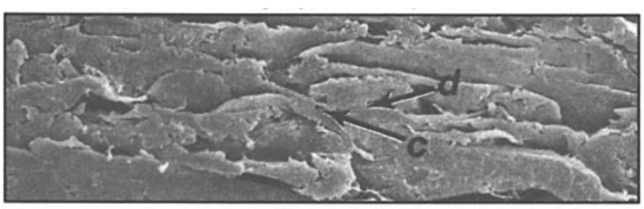
10. In an SGW handsheet, fibers (a) are stiff and show much cell wall debris. Many fibers are not collapsed, contributing to poor bonding (b) (cross section X200).

11. In a CTMP handsheet, fibers (a) are stiffer and do not collapse as well as those in BMP handsheets, contributing to poor bonding (b) (cross section X200).

12. In an NSSC handsheet, fibers (a) are stiffer and do not collapse as well as those in BMP handsheets. However, many fibers are collapsed (d), contributing to good bonding (cross section X200).

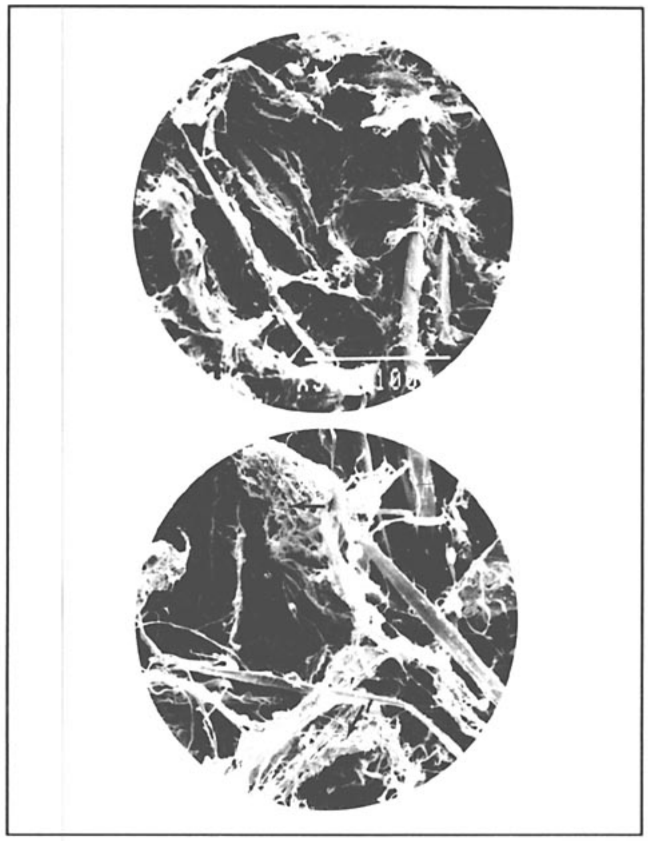


13. In a kraft handsheet, fibers collapse well and exhibit excellent conformability (d) contributing to good bonding (c) (cross section X200).



14. In a BMP handsheet, fibers exhibit excellent compressibility and conformability (d), contributing to good bonding (c). In cross section, BMP handsheets bear strong visual similarity to kraft handsheets. This is a distinguishing characteristic of BMP pulp (cross section X200).

15. Biomechanical pulp (BMP) fibers appeared woolly (f), when viewed at lower (X100) and higher (X1000) magnification. This is a distinguishing characteristic of BMP pulp.



dextrose agar slants. The fresh 19-mm aspen (*Populus tremuloides* Michx.) wood chips, nutrient supplements, inoculation method, aeration with humidified air, three-week incubation in stainless-steel rotating drum bioreactors, and the method for determining chip yield were described previously (*9*).

Pulp preparation

The pulps were obtained from the study of Myers *et al.* (*8*). All aspen pulps, with the exception of TMP, CTMP, and SGW pulp, were prepared at the Forest Products Laboratory (FPL). Refiner mechanical pulp and BMP were prepared in a 305-mm-diameter, rotating, single-disc refiner at atmospheric pressure. Chips were fiberized during the first pass, the coarse pulp slurry was caught in a container, and the pulp was dewatered in a bag-lined vacuum crock to retain all the fines material. The pulp freeness was carefully reduced by utilizing multiple passes (approximately five) through the single-disc refiner, each time reducing the clearance between the refiner discs. The pulp slurry was dewatered after each pass. The freeness levels of the pulps were as follows: 110 mL for RMP, 100 mL for BMP, and 115 mL for SGW.

The TMP and CTMP were produced at a commercial pilot plant facility. The TMP was produced at 138-kPa steam pressure in a 914-mm-diameter pressurized refiner followed by atmospheric refining in a 914-mm-diameter refiner to 111 mL CSF. The CTMP was produced by impregnating aspen wood chips with 4.6% Na_2SO_3 and 2.0% NaOH followed by pressurized refining at 138 kPa and atmospheric refining to 120 mL CSF. The aspen SGW pulp was obtained from a commercial Midwest source. The NSSC pulp was prepared in a 0.023-m^3 pulping digester at the FPL. A pulping liquor consisting of 13.5% Na_2SO_3 and 4.5% Na_2CO_3 was added to the wood chips in a liquor-to-wood ratio of 4 to 1. The digester temperature was raised from 80°C to 170°C in 90 min and was held at the higher temperature for 170 min. The partially delignified chips were fiberized in a 203-mm-diameter, single-disc, atmospheric refiner and were refined in a Valley beater to 230 mL CSF. The yield of the semichemical pulp was 75.5%. Kraft pulp was prepared in a 0.023-m^3 pulping digester. A pulping liquor consisting of 15% active alkali and 25% sulfidity was added to the wood chips in a liquor-to-wood ratio of 4 to 1. The digester temperature was raised from 80°C to 170°C in 60 min and was held at the higher temperature for another 60 min. The yield was 55.8%. The delignified chips were fiberized in a 203-mm, single-disc, atmospheric refiner and were refined in a Valley beater to 315 mL CSF.

Paper production, paper testing, and chemical analysis

Test methods were followed as described previously (*8*, *9*). Paper handsheets of a basis weight of 60 g/m^2 were produced according to TAPPI T 205. Tests run to determine handsheet properties included those for density, burst index (T 403), tensile index (T 404), tear index (T 414), opacity, brightness, and scattering coefficient. Values for paper properties made from fungal-treated chips were for 100-mL-CSF pulps extrapolated by regression from a series of three or four pulps refined for each treatment. (Note: Values for each pulp series produced from BMP gave the near-linear relationships typically observed for nontreated chips.)

Sample preparation for scanning electron microscopy

Dehydration, critical point drying, mounting of dried pulp and 60-g/m^2 sheet specimens on aluminum stubs, and vacuum coating with approximately 100 angstroms of gold were described previously (*11*). Samples were examined with a JOEL 840 scanning electron microscope using 20 kV.□

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Correction

On p. 200 of the May issue, in the paper by Leatham, Myers, and Wegner of the Forest Products Laboratory, the paper cited in Ref. 23 was not in press but had been published in the March issue on p. 249.