MORPHOLOGY OF WOOD PULP FIBER FROM SOFTWOODS AND INFLUENCE ON PAPER STRENGTH

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ABSTRACT

To achieve full utilization of each harvested tree, interest centers on use of all of the tree components. Here the objective was to determine the influence of the morphological characteristics of pulp fiber from 12 western U.S. softwood species, representative of a wide range of fiber.

The effect of the morphology of the wood pulp fiber as distinguished from that of the wood fiber is emphasized because differences in performance of fiber-based products are traced to the pulp fiber. Interrelationships of fiber morphology and pulp sheet properties are discussed. The results indicate that it is not possible to fully characterize the performance of a pulp by a single morphological characteristic and that the morphological characteristics significantly influence strength properties of sheets.

MORPHOLOGY OF WOOD PULP FIBER FROM SOFTWOODS AND INFLUENCE ON PAPER STRENGTH

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The successful conversion of pulp into a marketable product depends on a combination of original fiber properties (fiber morphology) and the response of the fibers to processing variables. Because of the great variety of wood types within the softwood genera, the physical properties of a piece of paper from one species will often vary markedly from a similar piece from another species although processing conditions may have been identical.

Investigations of relationships between the morphology of fibers and paper properties began in the early 1900's (7).[2] However, results have often been contradictory.

One of the first fiber properties related to paper strength properties was fiber length. Several investigators found that fiber length directly affects the tensile strength of paper (3,4,8). This led to the conclusion that hardwood pulps are lower in paper strength properties because the fibers of hardwoods are shorter than those of softwoods.

Several investigators have found contradicting evidence that suggests fiber length does not have a great influence on paper properties, especially on tensile strength (1,2).

Tearing resistance is another paper property with correlations established to one or more of the morphological properties of fibers (4,6,20,21). Again, contradictory evidence on importance of fiber length and other properties has been presented (2,15,18).

However, a fiber property that has received little attention is the effect of fibril angle on paper properties. Watson and Dadswell (22) showed a relationship between the micellar angle of wood fiber and stretch properties of paper. They found that other properties measured, such as bursting strength and tensile strength, were not influenced to any appreciable extent.

More recently, a comprehensive study by Page et al. (17) has clearly shown that fiber strength of wood pulp fibers is controlled by fibril angle regardless of species or fiber type.

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[1] *Maintained at Madison, Wk., in cooperation with the University of Wisconsin.*

[2] *Numbers in parentheses refer to Literature Cited at the end of this paper.*

From the literature it is apparent that opinions differ on the relative importance of particular fiber properties and their affects on paper properties. Comprehensive reviews of investigations in this field have been published (9,19).

Because of the present concern for full utilization of each harvested tree, emphasis has been increased on using all of the tree components. Therefore, the objective here was to determine the influence on sheet properties of morphological characteristics of the pulp fiber from a wide range of available fiber type regardless of species.

EXPERIMENTAL

Wood from the following 12 softwood species was used in this study: Lodgepole pine *(Pinus contorta* Dougl.), western larch *(Larix occidentalis* Nutt.), Douglas-fir *(Pseudotsuga menziesii* var. *menziesii),* western white pine *(Pinus monticola* Dougl.), Port-Orford-cedar *(Chamaecyparis lawsonia* (A. Murr.) Parl.), Alaska-cedar *(C. nootkatensis* (D. Don) Spach), grand fir *(Abies* grandis (Dougl.) Lindl.), western hemlock *(Tsuga heterophylla* (Raf.) Sarg.), Sitka spruce *(Picea sitchensis* (Bong.) Carr.), western redcedar *(Thuja plicata* Donn), ponderosa pine *(Pinus ponderosa* var. *ponderosa),* and redwood *(Sequoia sempervirens* (D. Don) Endl.).

Trees were selected randomly from their common growth ranges at two sites in the western United States. A 5-foot bolt free of compression wood was cut from the 5- to lo-foot interval (ground level as base) of a tree. A diameter of 8 to 12 inches at breast height was required.

The bolts were chipped in a Norman-type chipper that produced 5/8-inch chips. A composite sample of the separate sites was prepared from the chips for each of the species. For comparative purposes, all species were cooked to a bleachable grade of pulp by the kraft pulping process (Kappa number range of 30 to 33).

Morphological measurements of pulp fiber were made before beating (table 1), and the physical properties of the pulps were determined before and after beating to a Canadian Standard Freeness (CSF) of 500 milliliters. All pulp handsheets were prepared according to TAPPI Standard procedures. Data on the modulus of elasticity and tensile properties were obtained by a universal constant elongation-rate testing machine (13). The effects of fiber morphology on sheet properties were analyzed after correcting those properties for sheet density.

DISCUSSION OF FIBER-SHEET RELATIONSHIPS

The extensible properties of sheets of unbeaten fiber show a strong positive correlation with fibril angle (fig. 1). Quantitatively, the results show that 79 percent of the variation in stretch is associated with fibril angle in unbeaten pulps.

After beating, this dependence on fibril angle is lessened, but fibril angle remains the dominant variable. After beating, only 40 percent of the variation in stretch is associated with fibril angle. Therefore, after beating, interaction between morphological properties occurs. Multiple regression analysis showed that 75 percent of the variation in stretch could be accounted for by fibril angle and by the number of fibers per cubic centimeter of sheet. Interpreting this finding to sheet performance is as follows: For a sheet of unbeaten fibers, the stretch is controlled almost exclusively by the extensibility of fiber segments between fiber-to-fiber bonded areas. That is, in the unbeaten sheet the bonded areas formed are fewer and weaker than those formed in a sheet from beaten fibers. The bonds are, however, sufficient to hold the fibers while the fibers themselves stretch by an amount dependent on fibril angle to a point at which the load can no longer be maintained by the bonded network.

In a beaten sheet a greater number of bonded areas and bonds are formed than in an unbeaten sheet. Under these conditions it is plausible that the extensibility of a given bonded area will not be controlled primarily by the respective fibril angles of the overlapping fibers, but that, the extent of fiber-to-fiber bond formation will be critical.

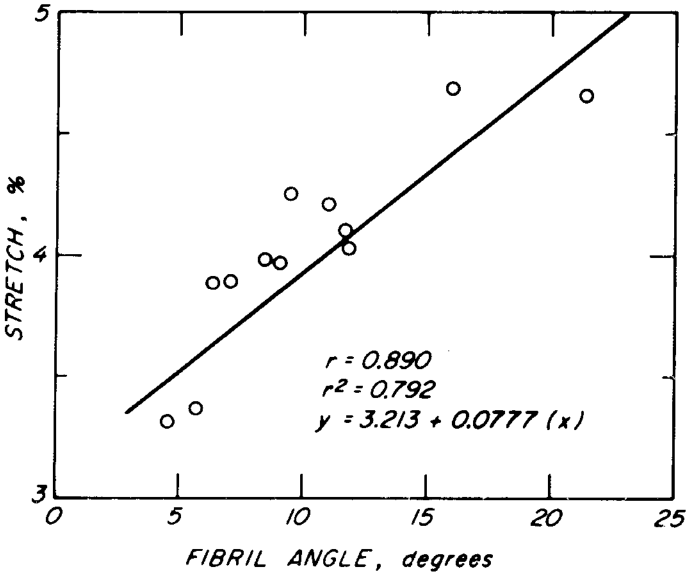

Figure 1.—Relationship of stretch to fibril angle of pulp sheets from unbeaten, unbleached kraft pulps.

(M 141 720)

That the effect of fibril angle, per se, on sheet extensibility is reduced and that the number of fibers per cubic centimeter of sheet (implies number of bonds per cubic centimeter) and fibril angle are shown to be interacting variables support this hypothesis. Therefore, it is concluded that sheet extensibility is not only the result of stretching fiber segments but also of network distortion that comes into play only if bonding is sufficiently strong.

In analyzing the effects of fiber morphology on sheet properties, it becomes apparent that some degree of interaction occurs between morphological characteristics that affects certain paper properties differently, that is, variations in strength cannot be fully explained by a single variable. This is further emphasized when assessing the effect of fiber morphology on bursting and on tensile strength properties of paper.

Visually, it is easy to grasp the significance of cell wall thickness on paper properties in particular, to those in which bonding is important (fig. 2). The results of this study show quantitatively that cell wall thickness does indeed exert considerable influence (fig. 3). For tensile strength it was found that 82 percent of the variation is associated with cell wall thickness for the unbeaten fiber and 76 percent for the beaten fiber (fig. 3).

Although fiber length, per se, did not show a significant correlation with tensile or bursting strength, the correlation of fiber length to cell wall thickness was quite high, a correlation coefficient of 0.853. Consequently, it is reasoned that the significance level of the cell wall thickness in terms of sheet strength included part of the influence of fiber length. Multiple regression analysis of fiber length and cell wall thickness on tensile strength did show some influence of fiber length. Of the variation in tensile strength, 88 percent was associated with the two variables for the unbeaten pulp fiber and 80 percent for the beaten pulp fiber. Similar values were obtained for bursting strength; 78 percent for the unbeaten fiber, 84 percent for the beaten pulp fiber.

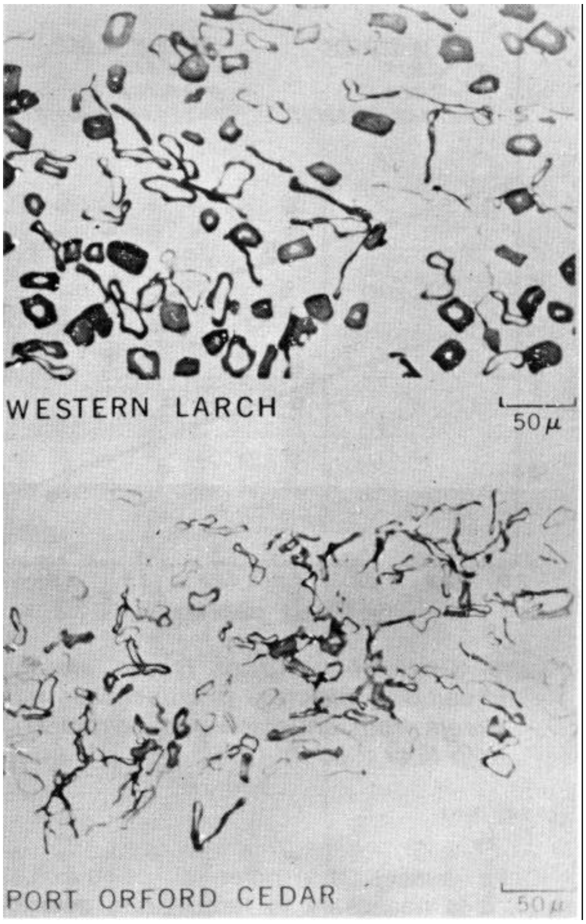

Figure 2.—Cross-sections of western larch fibers and of Port-Orford-cedar fibers.

(M 141 732)

From these results a quantitative index to fiber flexibility, consequently to pulp strength, could be obtained by determining the ratio of fiber length to cell wall thickness, L/T.

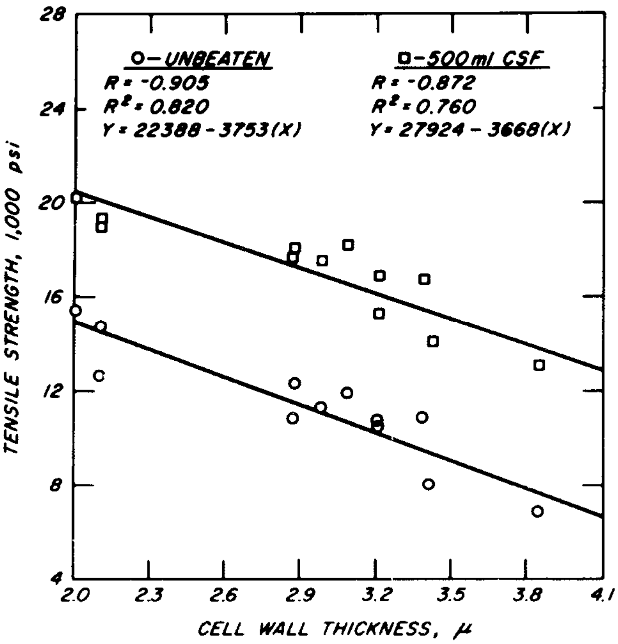

Figure 3.—Relationship of tensile strength to cell wall thickness of unbleached pulp sheets from unbeaten and beaten kraft pulp fiber (500 ml CSF).

(M 142 026)

To assess the potential of the L/T ratio, it is necessary to remove the overriding effect that wood density may sometimes contribute to pulp sheet properties. It is apparent from this study and other studies (10,23,24) that wood density is a factor in the ultimate performance of fiber as a raw material for pulp.

Figures 4 and 5 show graphically the effect of L/T on bursting and tensile strength of unbeaten fiber. In each figure two points are decidedly lowest in strength. The results show that, with the exception of tearing strength, paper strength properties were adversely affected when wood density was higher than 0.450 gram per cubic centimeter. The lowest two points represent two wood species, western larch and Douglas-fir, each with density greater than 0.450 gram per cubic centimeter (table 1). Therefore, if these two species are omitted from the analysis, an r^2 value of 0.917 is obtained between tensile strength and L/T for the unbeaten fiber and 0.837 for the beaten fiber (fig. 5). No comparable improvement in r^2 is obtained when these two dense species are omitted from the regression between tensile strength and cell wall thickness. This means that the L/T ratio is a better indicator than cell wall

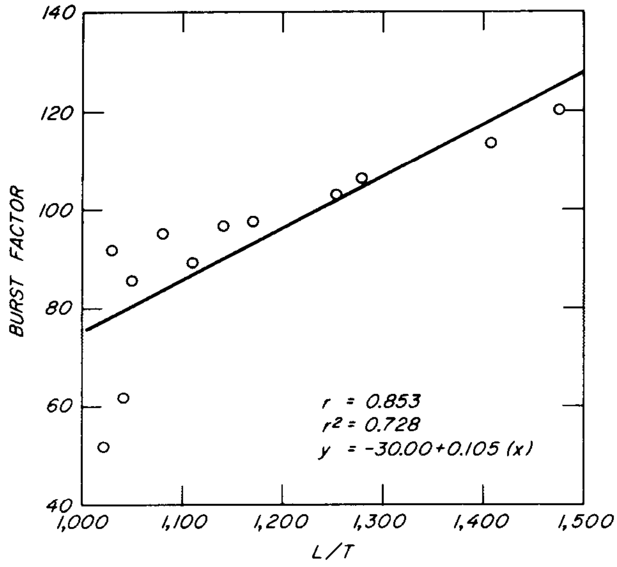

Figure 4.—Relationship of burst to L/T ratio (fiber length to cell wall thickness) of pulp sheets of unbeaten, unbleached kraft pulp fibers.

(M 141 723)

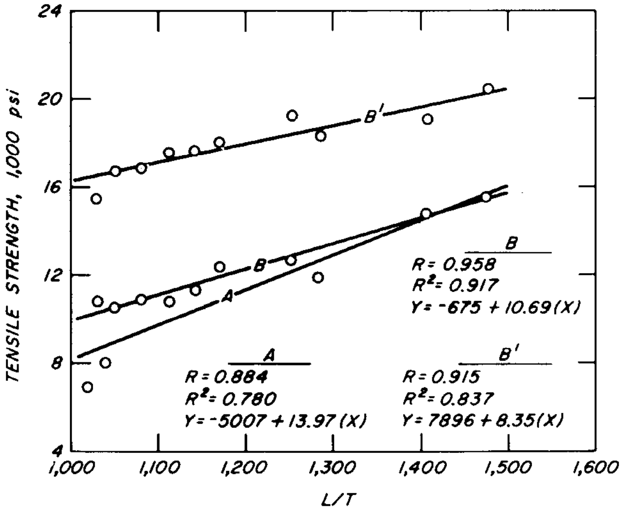

Figure 5.—Relationship of tensile strength to L/T ratio (fiber length to cell wail thickness) of (A) pulp sheets of unbeaten, unbleached kraft pulp fibers; (B) pulp sheets from unbeaten, unbleached kraft pulp the wood density of which was less than 0.450 gram per cubic centimeter; and, (B') same as (B) after beating to 500 milliliters Canadian Standard Freeness.

(M 142 027)

Table 1.--Morphological properties of unbeaten, unbleached kraft pulp fibers

Species	Morphology properties								
	Measured					Derived			
	Wood density[1]	Fiber length[2]	Cell wall thickness[3]	Fibril angle[4]	Cross-sectional area[5]	Ratio of length/thickness (L/T)	Pulp fiber coarseness[6]	Fibers/gram[7]	Fibers/cubic centimeter
	(g/cm^3)	(mm)	(μ)	(°)	(μ^2)		(mg/100 m)	(10^5)	(10^5)
Lodgepole pine	0.426	3.45	3.02	4.5	181	1,142	23.1	14.65	8.64
Western larch	.527	3.96	3.87	5.9	250	1,020	32.5	8.65	4.50
Douglas-fir	.458	3.50	3.41	6.3	220	1,040	30.8	9.51	5.52
Western white pine	.383	3.40	2.88	7.0	148	1,170	24.1	13.13	8.66
Port-Orford-cedar	.367	2.98	2.12	8.5	110	1,406	15.0	23.08	15.23
Alaska-cedar	.373	2.67	2.13	9.0	98	1,254	15.8	22.06	15.00
Grand fir	.390	3.33	3.23	9.5	147	1,030	24.3	13.70	8.22
Western hemlock	.449	3.39	3.23	10.9	202	1,050	29.0	10.52	6.52
Sitka spruce	.341	3.19	2.87	11.7	131	1,111	21.7	15.90	10.34
Western redcedar	.312	2.95	2.00	11.8	100	1,475	15.4	22.56	15.79
Ponderosa pine	.406	3.65	3.38	16.0	190	1,080	26.0	12.45	7.85
Redwood	.406	3.98	3.10	21.5	173	1,285	26.8	11.90	7.62

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[1] Based on weight when ovendry and green volume.

[2] Based on measurement of 50 whole, unbeaten pulp fibers.

[3] Average of 4 measurements per fiber of 35 fibers.

[4] Method from Page (16).

[5] By planimetry measurements on same fibers as in footnote 3.

[6] Method from Britt (5).

[7] Method from Horn (11).

thickness for the strength potential of a pulp in the range of wood densities below 0.450 gram per cubic centimeter. This means, too, that using L/T as a measure of fiber flexibility for species less dense than 0.450 gram per cubic centimeter provides the best available index between fiber morphology and pulp strength.

The direct relationship between wood density and cell wall thickness (fig. 6) and the number of fibers per cubic centimeter of sheet (fig. 7) has several implications, not only to paper strength but to economic considerations. For instance, papers from fibers with thick cell walls are lower in bursting and tensile strength. As shown, cell wall thickness has a positive correlation with wood density and it is those species with thick-walled fibers that contain fewer numbers of fibers per sheet volume. Therefore, papers of fiber from high-density woods will have fewer fibers for the same weight of paper than paper from species of low density. Because paper is commonly made on a weight basis, the importance of the number of fibers per unit volume is evident. For instance, increasing wood density to increase fiber yield per acre or yield per digester or to increase both may not always be most advisable. If the resultant fiber has to be refined at greater power consumption or the paper produced at higher-than-normal basis weights to obtain adequate strength properties, it would seem that the effects of fiber morphology on the manufacture of paper should be part of the overall considerations for obtaining optimum performance.

Tearing resistance is also a property of paper important to the industry. For years the greatest variance in results in establishing effects of fiber morphology has related to this property. Here the results for unbeaten pulps strongly suggest that tearing resistance is primarily influenced by fiber cross-sectional area (fig. 8) and secondly, by cell wall thickness. With beaten pulps, however, cross-sectional area and cell wall thickness, individually, are not the primary factors; fiber coarseness accounts for the greatest amount of variation in tear (fig. 9).

The explanation of these results again reflects fiber-to-fiber bonding or the lack of it. In the theory of tear as proposed by Van den Akker (12), differences in tearing strength are related to changes in fiber length (no difference is assumed in fiber strength). In this investigation, individual fiber strength was not measured, and no significant effect of fiber length on tearing strength was

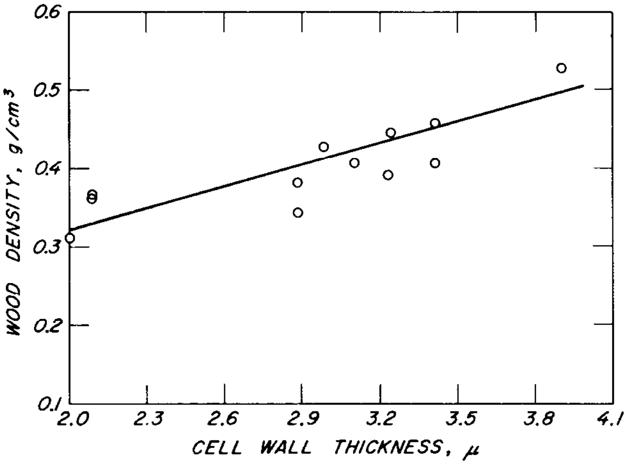

Figure 6.—Relationship of cell wall thickness to the wood density of the 12 western U.S. softwoods used in this investigation.

(M 141 726)

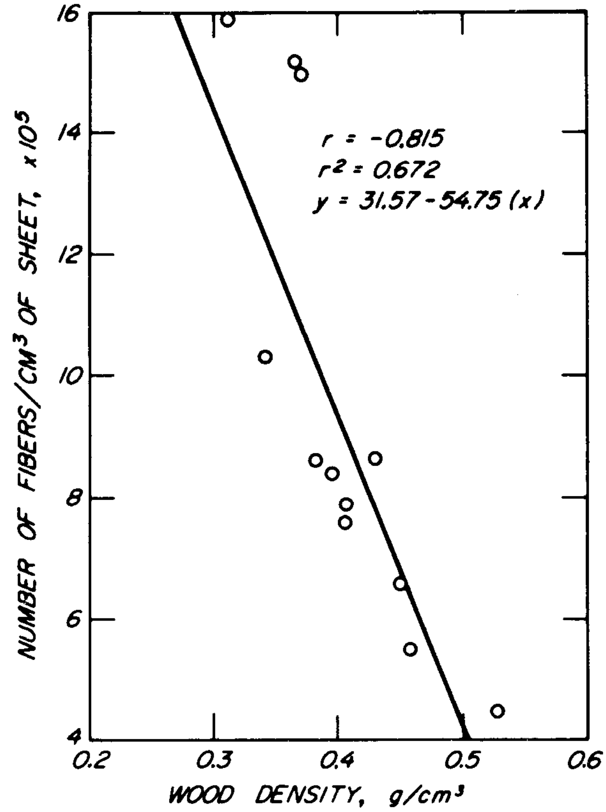

Figure 7.—Relationship of number of fibers per cubic centimeter of pulp sheet to the wood density of the 12 western U.S. softwoods.

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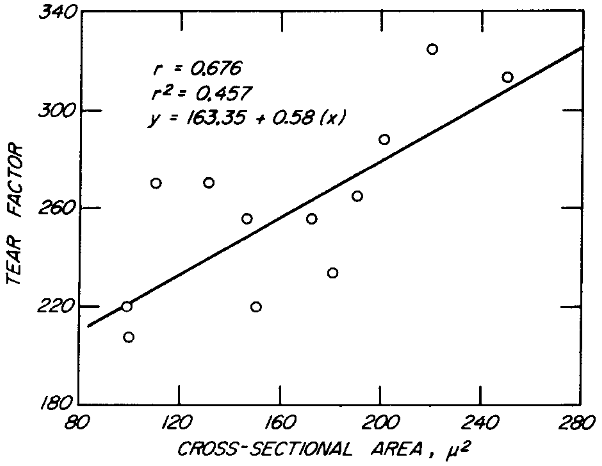

Figure 8.—Influence of fiber cross-sectional area on tearing resistance of pulpsheets made of unbeaten, unbleached kraft pulp fibers.

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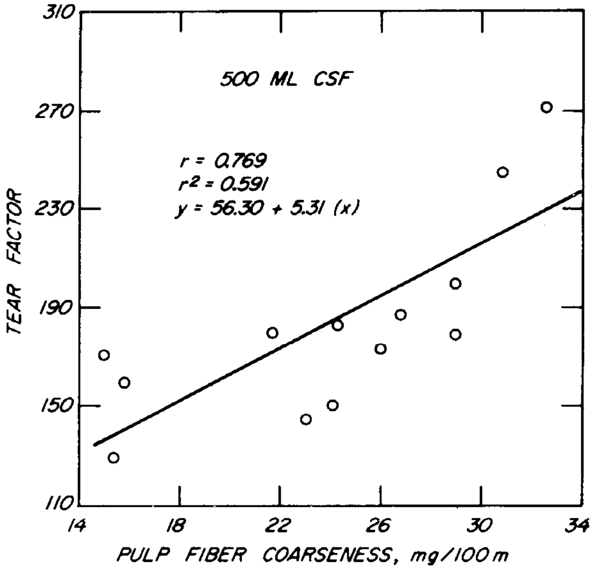

Figure 9.—Influence of pulp fiber coarseness on the tearing resistance of pulp sheets made of unbleached kraft pulp fibers beaten to 500 milliliters Canadian Standard Freeness.

(M 141 728)

observed. However, the results here can be explained based on the principles of the theory of tearing strength as proposed by Van den Akker.

As stated, in this investigation fiber cross-sectional area accounted for the greatest variation in tearing strength in the unbeaten pulps (fig. 8). Because the unbeaten sheet does not have sufficient bonding capabilities, an increase in cross-sectional area necessarily will increase the resistance of the fiber to rupture. Consequently, an increase in cross-sectional area should increase the number of fibers pulled out: thereby the frictional drag work will be increased and tear will be increased.

Whereas bonding is inadequate in unbeaten pulps for optimum tensile strength properties, this is not true for tearing resistance. The beating process optimizes fiber properties to create increased bonding that in softwoods usually gives rise to a decrease in tear. Therefore, the influence of fiber bonding increases and fiber length, as a function of fiber coarseness, apparently has the most influence on the tearing strength of beaten pulps (fig. 9). Fiber length is important for its effects on the total length available for bonding, and cross-sectional area and cell wall thickness provide the mass at any given point along the length of fiber.

Coarseness entails the entire spectrum of these variables because it is a measure of that mass per unit length. The high-value fiber coarseness pulps not only required more beating than do the flexible, low-value coarseness pulps, but at any given point in beating, the ability of these coarse pulp fibers to form strong fiber-to-fiber bonds is considerably less than pulps with lower coarseness values. Therefore, due to the greater number and the stronger bonds formed with the flexible fiber, the number of fibers pulled out will decrease and the proportionate number of fibers ruptured will increase. This results in lowering the tearing strength of beaten pulps.

Little is known about the effects of fiber morphology on modulus of elasticity (MOE), a measure of paper stiffness. Logically, fibril angle, shown to cause profound changes in the elastic modulus of individual wood fibers (14), would be expected to exhibit some influence on the elastic modulus of paper. However, the results here show no significant effect of fibril angle on the elastic properties of paper.

No one fiber property demonstrated itself to be a sensitive indicator of paper stiffness. However, the results show the MOE of unbeaten pulps is negatively correlated with fiber cross-sectional area, cell wall thickness, and coarseness. Fiber cross-sectional area gave the highest correlation coefficient (-0.723) and accounted for 53 percent of the variation in MOE (fig. 10).

After beating, these same morphological factors influence paper stiffness. However, fiber coarseness gave the highest correlation coefficient (-0.676) and accounted for 46 percent of the variation in MOE (fig. 11),

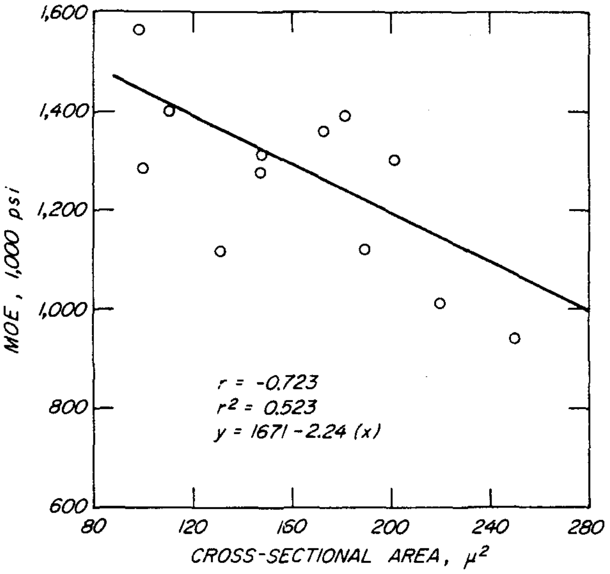

Figure 10.–Influence of fiber cross-sectional area on the MOE (modulus of elasticity) of pulp sheets made of unbeaten, unbleached kraft pulp fibers.

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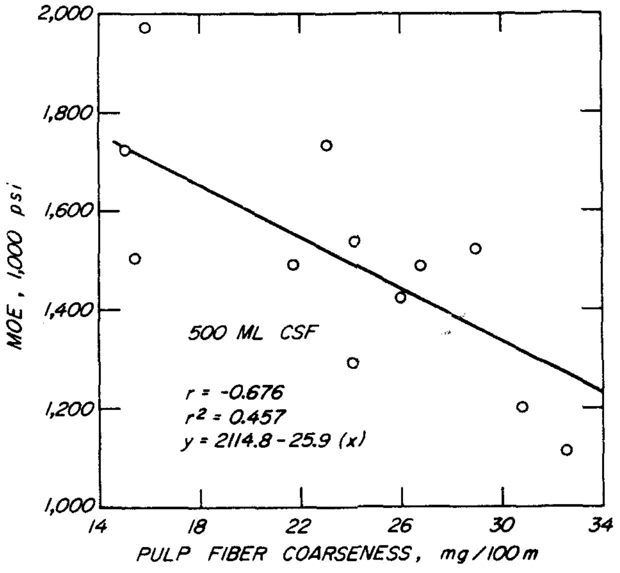

Figure 11.–Influence of pulp fiber coarseness on the MOE (modulus of elasticity) of pulp sheets made of unbleached kraft pulp fibers beaten to 500 milliliters Canadian Standard Freeness.

(M 141 730)

CONCLUSIONS

The results of this work show that the morphology of fiber significantly influences sheet strength properties. and that it is not possible to fully characterize the performance of a pulp by a single morphological factor.

Fibril angle was the factor that had the greatest influence on stretch properties of a sheet from unbeaten fibers. Although this influence was less after beating, it remained the single most important factor. Multiple regression analysis showed that after beating, variation in the stretch properties of paper could be accounted for by fibril angle and by the number of fibers per cubic centimeter of sheet.

Tensile and bursting strength were influenced primarily by cell wall thickness. Fiber length was important insofar as a minimum length is required for bonding and stress distribution. Because of the significant combined effect of cell wall thickness and fiber length, a new index of pulp fiber flexibility was introduced, the ratio of fiber length to cell wall thickness (L/T).

Tearing strength of unbeaten pulps was influenced primarily by fiber cross-sectional area and cell wall thickness; fiber cross-sectional area had slightly greater influence than wall thickness. With beaten pulps, fiber coarseness was found the dominant factor. No experimental evidence was obtained to show that fiber length, per se, had any significant effect on tearing strength. This can be interpreted to indicate either fiber length is not really important or there is a critical range of fiber length not present in the range studied here.

In sheets from unbeaten fibers, the modulus of elasticity was mostly dependent on fiber cross-sectional area, whereas in sheets from beaten pulps, the modulus showed dependence on fiber coarseness.

The results show that wood density, although not a pulp fiber property, can be considered a general indicator for assessing the potential of a wood species for use as fiber in papermaking. These results strongly indicate there may be a critical point in wood density at which pulp quality, in terms of tensile strength properties, deteriorates rapidly.

It can be concluded that the conversion of wood into marketable paper products is dependent on both the initial, or morphological, characteristics of the pulp fiber and on the response of this fiber to processing variables. Without question, processing variables such as beating will affect sheet strength. However, under the conditions of this investigation, sheet strength was influenced most by the original properties of the pulp fiber.

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