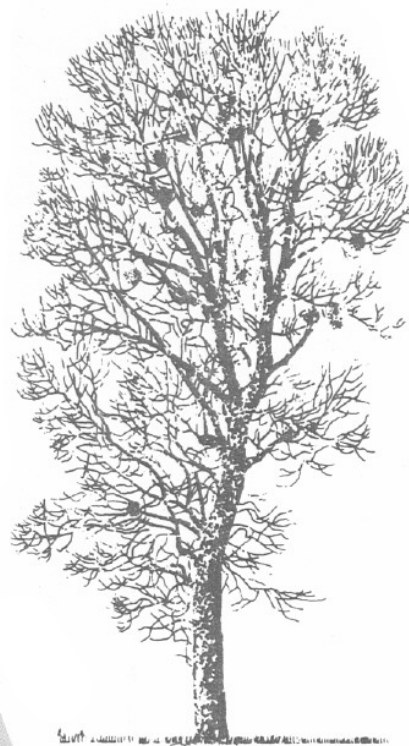


**MORPHOLOGY
OF
PULP
FIBER
FROM
HARDWOODS
AND
INFLUENCE
ON
PAPER
STRENGTH**



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SUMMARY

The results of this investigation showed that physical properties of sheets made from hardwood fiber are very dependent upon fiber morphology. Chemical variation of pulp fibers did not exhibit an influence on sheet strength. Of the morphological characteristics investigated, those contributing the most were fiber length, L/T ratio, and fibril angle. Hardwood fines (parenchyma cells) were detrimental to bursting and tensile strength. Vessel elements, in amounts found originally in typical hardwood furnishes, had no effect on tensile strength.

MORPHOLOGY OF PULP FIBER FROM HARDWOODS AND INFLUENCE ON PAPER STRENGTH

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INTRODUCTION

Although sheet strength properties are dependent upon process variables—e.g., fiber orientation and bond formation between fibers—an earlier investigation on softwood species clearly showed that sheet strength was influenced most by the original properties of the pulp fiber (9).^{2/} The objective of this investigation was to examine similarly the influence that the original morphological characteristics of wood pulp fibers from hardwood species have on sheet strength.

It is apparent from the literature that opinions differ on the relative importance of particular fiber properties and their practical effects on paper properties (7, 17, 18).

Early research on the effect of fiber properties on paper strength (3, 4, 6) led to the general belief that paper with desirable strength properties could only be made from long-fibered wood species—i.e., softwood pulps. Subsequent studies have shown that fiber length possibly is not the overriding factor in producing paper with acceptable strength (1, 2, 9).

Wood-fiber characteristics that have often been associated with paper strength—in particular, paper made from hardwoods—are the length to diameter ratio (L/D), and Runkel Ratio—twice the cell wall thickness/lumen diameter ($2w/l$). Both are fiber parameters

which, by the very nature of their required measurements, should be associated with wood fiber and not with pulp fiber. The L/D ratio has been shown to be unreliable in providing basic information on strength properties dependent upon fiber bonding (19). The Runkel Ratio is a microscopic extension of the wood density in that wall thickness and lumen width are the basic factors used in their determination. Therefore, it should not be expected to provide much more basic information than the measured wood density. It is important to reflect on this in that differences in performance of fiber-based products are traced to the pulp fiber. Consequently, performance can only be assessed by measuring morphological parameters of the pulp fiber because existing data clearly demonstrate that wood fiber undergoes internal dimensional changes under conditions of kraft pulping (15, 16).

There continues to be concern for more complete utilization of the tree. In the future, it will be necessary for the paper industry to rely much more on currently less-desirable hardwood species for their products. To advance their utility, it is essential that those fiber properties which provide for optimum performance in paper manufacture be known.

^{1/}Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

^{2/}Italicized numbers in parentheses refer to literature cited at the end of this report.

EXPERIMENTAL

Wood from ten hardwood species was used in this study: paper birch (*Betula papyrifera* Marsh.), American elm (*Ulmus americana* L.), sugar maple (*Acer saccharum* Marsh.), quaking aspen (*Populus tremuloides* Michx.), American beech (*Fagus grandifolia* Ehrh.), red alder (*Alnus rubra* Bong.), white oak (*Quercus alba* L.), sweetgum (*Liquidambar styraciflua* L.), blackgum (*Nyssa sylvatica* Marsh.), and shagbark hickory (*Carya ovata* (Mill.) K. Koch).

Trees with little or no lean were selected from their common growth ranges at two sites. A 5-foot bolt was cut from each tree at the 5- to 10-foot interval (ground as base). A diameter of 8 to 12 inches was required.

The bolts were chipped in a Norman-type chipper that produced 1/2-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 comparable grade of pulp by the kraft process (Kappa number range of 18 to 22).

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 400 ml. All pulp handsheets were prepared according to TAPPI Standard procedures.

Data on the modulus of elasticity (MOE) and tensile properties were obtained on a Universal constant elongation-rate testing machine (10). The effects of fiber morphology on bursting strength, tensile strength, and MOE were analyzed after correcting for sheet density. All correlation coefficients shown in this report are significant to at least the 0.01 probability level.

Table 1.—Morphological properties of unbeaten, unbleached pulp fibers

Species	Morphological properties								
	Specific gravity ^{1/}	Fiber length ^{2/}	Fibril angle ^{3/}	Cell wall thickness ^{4/}	Cross-sectional area ^{5/}	Length/thickness ratio (L/T)	Pulp fiber coarseness ^{6/}	Fibers/gram ^{7/}	Fibers/cubic centimeter
		<u>mm</u>	<u>deg</u>	<u>μ</u>	<u>μ²</u>		<u>mg/100 m</u>	<u>10⁵</u>	<u>10⁶</u>
Red alder	0.380	1.25	7.8	3.54	183	353	12.38	81.60	5.47
Aspen	.391	1.05	9.4	3.20	149	328	8.59	118.90	8.09
Sweetgum	.454	1.65	14.3	6.40	353	258	24.60	24.20	1.40
American elm	.500	1.35	15.5	4.20	156	322	9.53	108.30	6.39
Blackgum	.507	1.85	15.8	6.32	350	293	25.40	22.35	1.34
Paper birch	.531	1.51	14.7	3.75	180	403	13.08	76.12	5.10
American beech	.579	1.16	9.9	5.60	181	207	13.10	75.96	4.33
Shagbark hickory	.582	1.29	19.4	4.10	141	315	10.59	97.50	5.36
Sugar maple	.588	.85	6.3	4.05	140	210	7.86	127.90	7.29
White oak	.627	1.25	13.7	5.80	130	216	14.08	68.91	3.79

^{1/} Oven-dry weight and green volume, unextracted.

^{2/} Based on measurement of 50 whole, unbeaten fibers.

^{3/} Method from Page (12).

^{4/} Average of four measurements per fiber of 35 fibers.

^{5/} By planimetry measurements on same fibers as footnote 4.

^{6/} Method from Britt (5).

^{7/} Method from Horn (8).

DISCUSSION

Evidence Indicates that interpretation of fiber-paper relationships must be made with reference to whether hardwood or softwood pulps are used (7). Hardwoods are much more heterogeneous in their anatomical makeup than are softwoods. This heterogeneity complicates analysis of fiber morphology effects on properties of paper made from hardwoods. In this Investigation, it was generally found that the relationship developed from even the most Influential hardwood fiber parameter to a given paper property was not as clearcut as in the case of softwood fibers (9).

Tear Strength

The results of this investigation show that tearing strength of sheets made from either unbeaten ($r = 0.817$) or beaten ($r = 0.832$) hardwood fiber is principally dependent upon fiber length (figs. 1 and 2). This contrasts with paper made from softwood pulps in which

cross-sectional area and cell wall thickness are the dominant variables (9).

in addition to fiber length, tearing strength shows, too, a positive and significant relation to fibril angle In unbeaten pulps ($r = 0.730$). With unbeaten pulps, fibril angle is the only secondary factor that exhibits a significant influence on tearing strength.

The positive correlation of fibril angle with tearing strength would indicate that fiber extensibility contributes more to tearing strength than does fiber strength. Page (13) has shown that fiber strength is dependent upon fibril angle, regardless of species or fiber type. Therefore, If fiber strength were a dominant factor it would be expected that fibril angle would show a negative correlation with tearing strength. This is especially evident in unbeaten pulps in that the extensible properties (stretch) of the sheet show a very high correlation with tearing strength ($r = 0.913$). Multiple regres-

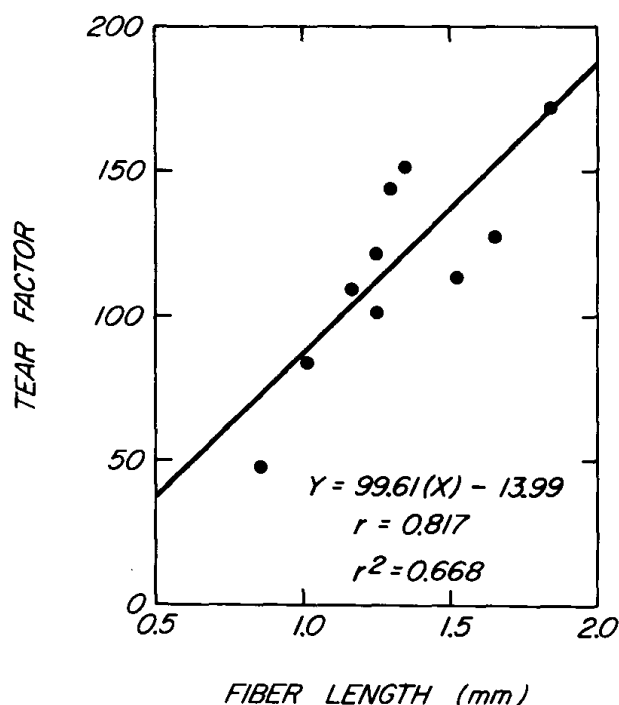


Figure 1.—Influence of fiber length on the tearing resistance of pulp sheets made of unbeaten, unbleached kraft pulp fibers.

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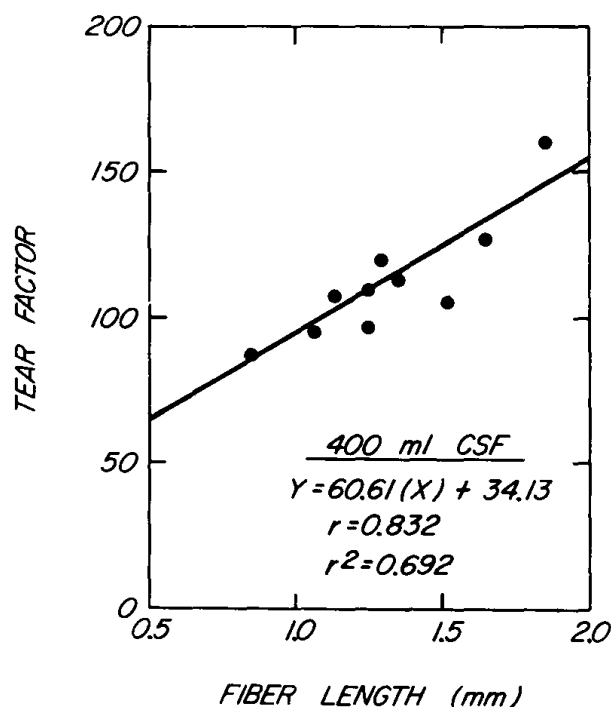


Figure 2.—Influence of fiber length on tearing resistance of pulp sheets made of unbleached kraft pulp fibers beaten to 400 ml CSF.

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sion analysis showed that 76 percent of the variation in tearing strength in unbeaten pulps could be accounted for by fiber length and

fibril angle. Multiple regression equations developed for the measured paper properties are shown in table 2.

Table 2.—Regression models of fiber data to sheet properties.

Sheet property	Canadian Standard	Equation	$1/r^2$
	<u>ml</u>		
Tear factor	Unbeaten	-13.99 + 99.61 (fiber length)	0.668
		34.18 + 6.60 (fibril angle)	0.571
		-16.67 + 68.81 (fiber length) + 3.43 (fibril angle)	0.758
	400	34.13 + 60.61 (fiber length)	0.692
		45.87 + 3.29 (fibril angle) + 0.14 (cross-sectional area)	0.860
Stretch	Unbeaten	0.16 + 1.42 (fiber length)	0.776
		0.87 + 0.09 (fibril angle)	0.704
		-0.44 + 2.47 (fiber length) - 0.06 (fiber coarseness)	0.923
	400	2.97 + 0.08 (fibril angle)	0.447
		2.09 + 3.03 (fiber length) - 0.15 (fiber coarseness)	0.745
Burst factor	Unbeaten	-18.94 + 37.50 (fiber length)	0.694
		7.56 + 0.15 (L/T) - 0.25 (fiber/gram)	0.973
	400	25.29 + 0.17 (L/T)	0.642
		17.31 + 81.84 (fiber length) - 3.62 (fiber coarseness)	0.736
Tensile strength	Unbeaten	1465 + 19.10 (L/T)	0.634
		4686 + 22.31 (L/T) - 28.35 (fiber/gram)	0.979
		- 148.94 (fibril angle)	
	400	5400 + 23.68 (L/T)	0.694
		4862 + 16809 (fiber length) - 503 (fibril angle)	
		- 605 (fiber coarseness)	0.899
Modulus of elasticity	Unbeaten	1594 (10 ³) - 1560 (specific gravity)	0.533
		269 (10 ³) + 1.80 (L/T)	0.439
		526 (10 ³) + 2.26 (L/T) - 30.84 (fibril angle)	0.889
		668 (10 ³) + 2.39 (L/T) - 36.10 (fibril angle) - 1.39 (fiber/gram)	0.952
	400	421 (10 ³) + 2.34 (L/T)	0.596
		1936 (10 ³) - 1620 (specific gravity)	0.462
		678 (10 ³) + 2.80 (L/T) - 30.65 (fibril angle)	0.954

1/ Significant to the 0.01 probability level.

The secondary factor exhibiting the most influence on the tear strength of beaten pulps is fiber cross-sectional area ($r = 0.764$). Although fibril angle in itself does not account for as much of the variability in tearing strength of beaten pulps ($r = 0.698$) as it does with unbeaten pulps ($r = 0.730$), it appears that tearing strength is a manifestation of both fibril angle and fiber cross-sectional area. Multiple regression showed that these two properties were the most influential multiple factors and could account for 86 percent of the variation in tearing strength ($r = 0.927$) of beaten pulps.

Stretch

The stretch properties of sheets made from unbeaten fibers are influenced primarily by fiber length ($r = 0.881$) and fibril angle ($r = 0.838$).

After beating, the effect of fiber length becomes negligible. Fibril angle becomes the dominant single variable. Although dependence is lessened, it accounts for 45 percent of the variation in stretch of sheets made from beaten fiber. No other single variable exhibited any significant influence on the stretch properties of sheets made from beaten pulp fiber.

For unbeaten pulps, multiple regression revealed that 92 percent of the variation in stretch could be accounted for by fiber length and fiber coarseness. The same two fiber properties accounted for 75 percent of the variation in beaten pulps.

Burst and Tensile Strengths

Bursting and tensile strengths of pulps are two properties highly dependent upon fiber-to-fiber bonding. Generally, bursting and tensile strengths of handsheets made from hardwoods respond to the same fiber morphological effects as do softwoods. This was especially true after the pulps had been beaten. Although statistically significant at the 1 percent probability level, the primary morphological factors influencing these sheet properties were not as dominant as in the softwoods (9).

Fiber length was the dominant factor in bursting strength of unbeaten pulps ($r = 0.833$, fig. 3). The second variable showing the most significant influence was the length-to-thickness ratio (L/T) ($r = 0.709$). The primary factor in the tensile strength of unbeaten pulps

was L/T ($r = 0.798$). After beating, the L/T ratio is the dominant factor for both bursting strength ($r = 0.801$, fig. 4) and tensile strength ($r = 0.833$, fig. 5). This most probably reflects the greater degree of fiber collapse which results from beating. The fibers become more flexible and conformable which in turn provides for more area to be developed for bonding along the fiber's length. Therefore, bursting and tensile strength, being dependent upon the formation of fiber-to-fiber bonds, is greatly influenced by fiber length and cell wall thickness.

The results of this and a previous investigation on softwood pulp fibers (9) have shown the L/T ratio to be the most effective single fiber parameter in estimating a pulp's potential bursting and tensile strengths. The L/T ratio, however, does not apply to hardwood furnishes as strongly as to softwood pulps. This is most probably due to the presence of relatively large amounts of nonfibrous fines (parenchyma and vessel element parts) not found in softwoods.

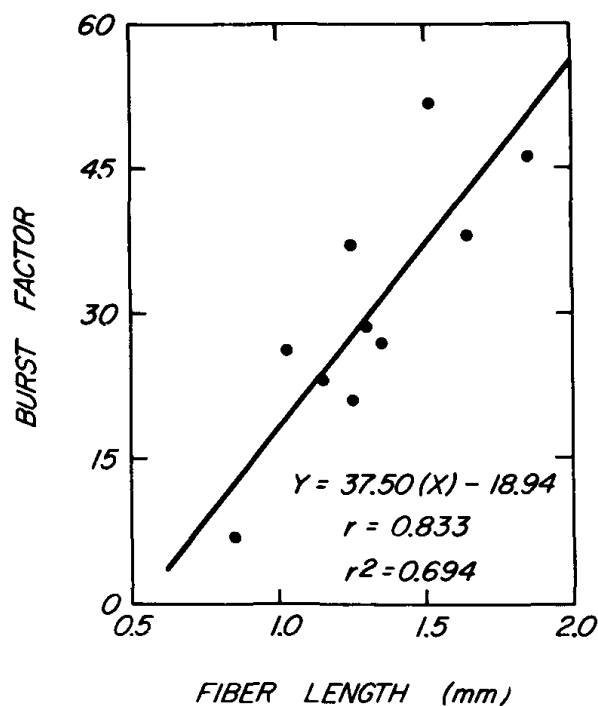


Figure 3.—Relationship of burst to fiber length of pulp sheets of unbleached, unbeaten kraft pulp fibers.

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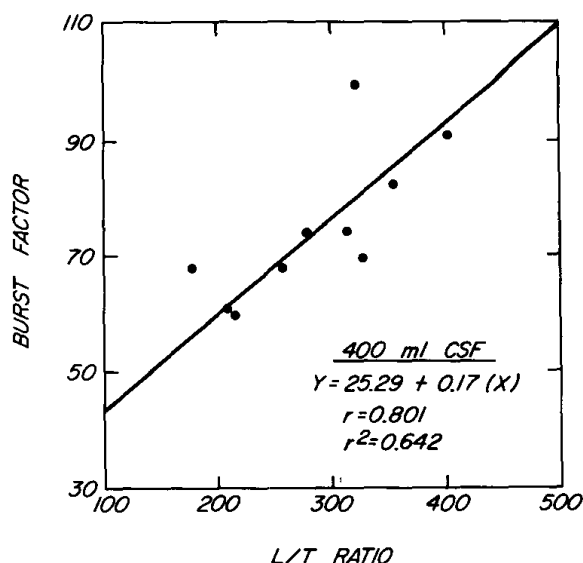


Figure 4.—Relationship of burst to L/T ratio (fiber length to cell wall thickness) of pulp sheets made of unbleached kraft pulp fiber beaten to 400 ml CSF.

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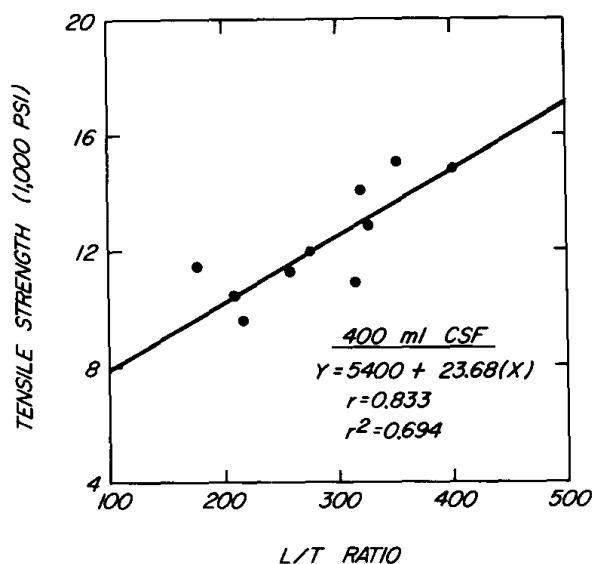


Figure 5.—Relationship of tensile strength to L/T ratio (fiber length to cell wall thickness) of pulp sheets made from unbleached and beaten kraft pulp fiber (400 ml CSF).

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Parenchyma cells.—The lesser effect of the L/T ratio in hardwood pulps can be observed in the effect of parenchyma cells (fines) on bursting and tensile strengths of red alder and white oak before and after fractionation (table 3).

In the case of white oak, very little improvement in strength is noted by the removal of parenchyma cells. This can be attributed to the thick cell wall of the oak fiber. If, however, those same parenchyma cells removed from the oak are added to a "clean" red alder furnish, the result is a lowering of the bursting and tensile strengths. This reduction occurs even though the cell wall thickness of red alder is considerably less than that of oak.

Effect of vessels.—Another anatomical factor which must be considered in hardwood pulps is the effect of vessel elements on pulp strength.

Using a method of separation developed by Marton (11), red alder and white oak vessel elements were obtained from their respective unbeaten furnishes. The white oak contained 1.9 percent vessel elements by weight and the red alder, 3.7 percent by weight—confirming the low percentage of vessel elements by weight as reported by Marton (11).

Table 4 shows the effect of vessel elements, at the weight fractions actually present in the furnish, on tensile strength. The presence or absence of vessel elements at the percentages found in the original pulp furnish has little influence on the ultimate tensile strength of the pulp.

Modulus of Elasticity

Regression analysis showed that the best single factor for predicting modulus of elasticity (MOE) of unbeaten pulps was unextracted specific gravity ($r = -0.730$). The second best was L/T ($r = 0.663$). Multiple regression revealed that, of the fiber parameters, fibril angle and L/T could account for 89 percent of the variation in MOE for unbeaten pulps.

For beaten pulps, the best indicator for MOE was the L/T ratio ($r = 0.772$). The second best was unextracted specific gravity ($r = -0.680$). Multiple regression revealed that 95 percent of the variation in MOE of beaten pulps could be accounted for by fibril angle and L/T ratio.

Explicit in these results is the dependence of MOE upon parameters which promote the

development of fiber bonding, i.e., fiber flexibility, collapse, conformability.

It is of interest to note that the two parameters most influencing MOE are also major determining factors in sheet density. For unbeaten pulps the coefficient of correlation values are -0.771 for unextracted specific gravity and 0.737 for L/T. For beaten pulp, however, cell wall thickness ($r = -0.851$) and L/T ($r = 0.713$) are predominant.

It has been shown that MOE is highly dependent upon sheet density (14). Regression analysis from data in this study confirms this dependence. The results show that sheet density could account for 92 percent of the variation in MOE of unbeaten pulps and 82 percent in beaten pulps.

Therefore, these results strongly indicate that the attainment of good stiffness properties in paper made from hardwoods is greatly dependent upon fiber characteristics that promote fiber bonding.

Chemical Properties

Chemical properties of the pulps used in this investigation were also determined. They included percent holocellulose, hemicelluloses, and lignin. At the pulp Kappa number used, chemical properties varied little between species. No discernible influence of chemical properties on physical properties was observed. The low degree of variation between species could possibly account for this lack of significance.

Table 3.—Variation in bursting and tensile strength due to fines content

Species	Fines ^{1/}	Burst	Tensile	Fiber length	Cell wall thickness
	pct		psi	mm	μ
White oak	2/0	65	9,500	1.25	5.80
	3/18.8	56	8,950		
Red alder	2/0	97	16,650	1.25	3.54
	4/18.8	77	13,700		

^{1/} Defined as that portion of furnish passing 200-mesh screen. This fraction comprised primarily of parenchyma cells plus a small amount of short fiber segments and vessel element fragments.

^{2/} Fines removed and fiber fraction beaten to 400 ml CSF.

^{3/} Fractionated furnish beaten to 400 ml CSF and fines added.

^{4/} Fractionated furnish beaten to 400 ml CSF and fines from oak added.

Table 4.—Effect of vessel elements on tensile strength of unbeaten and beaten furnishes

Species ^{1/}	Vessel elements ^{2/}	Tensile strength		
		Unbeaten	Beaten 400 ml CSF	Beaten ^{3/} 400 ml CSF
	pct	psi		
White oak	4/0	4,150	9,350	—
	1.9	4,200	9,500	9,400
Red alder	4/0	8,500	16,300	—
	3.7	8,350	16,650	15,900

^{1/} Pulp fraction used was as in table 3; contained 0 percent fines.

^{2/} By weight of original pulp.

^{3/} Fiber fraction beaten separately and unbeaten vessels added to furnish.

^{4/} Vessel element separation not 100 percent, but fractions beaten were fairly free of vessel elements.

CONCLUSIONS

Physical properties of sheets made from hardwood pulp fibers are very much dependent upon fiber characteristics. The results of this study have demonstrated that those fiber characteristics most involved in developing fiber-to-fiber bond potential are most important in hardwood pulps. In the pulp properties examined, fiber characteristics contributing the most were fiber length, L/T ratio (a measure of pulp fiber flexibility), and fibril angle.

Generally the relationships of fiber characteristics to hardwood pulp properties are not as strong as those for softwood pulps. This can most possibly be attributed to the greater heterogeneity of the hardwoods—i.e., especially the higher parenchyma (fines) content of hardwood pulps. The presence of a high percentage of fines was detrimental to bursting and tensile strengths. Vessel elements, on the other hand, based on amounts actually found in a typical hardwood furnish, had little effect on tensile strength.

Tear strength of both unbeaten and beaten pulps was influenced primarily by fiber length. Fibril angle also showed a significant correlation in unbeaten pulps and multiple regression showed that the interaction of fiber length plus fibril angle could account for 76 percent of the variation in tearing strength for unbeaten pulps. The results indicate that

tearing strength is influenced more by fiber extensibility than fiber strength. This is shown by a positive rather than negative correlation of fibril angle to tearing strength. After beating, fiber length remains the dominant factor in tearing strength of hardwood pulps.

Fibril angle and fiber length were found to be factors also in the stretch properties of hardwood pulps. In unbeaten pulps, fiber length accounted for 78 percent of the variation in stretch. After beating, fiber length became negligible and fibril angle became the dominant variable, although its influence was not as strong as in unbeaten pulps.

Burst and tensile strengths were influenced primarily by a combined effect of fibril length and cell wall thickness as measured by the pulp fiber flexibility ratio index L/T.

Modulus of elasticity was also influenced by fiber characteristics which increased fiber-to-fiber bonding. An increasing L/T ratio contributes to improved stiffness properties in papers made from hardwood pulps.

Chemical properties of the hardwood pulp fibers did not show any significant relationship to strength properties. At the Kappa range of the pulps studied in this investigation, variability in morphological characteristics of the fibers is considerably more important to sheet strength than are chemical variables.

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