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Summary

Pulp quality, in terms of a fiber shape factor S and a fiber length factor L, was determined for 96 pulps disk-refined from chips of varying characteristics. S was evaluated in terms of the Canadian Standard Freeness of the 48/100 fiber length fraction and is a parameter inversely proportional to specific surface. L is the percentage, by weight, of pulp retained on a 48-mesh screen and reflects the distribution by weight of fiber length in the whole pulp. S and L accounted for as much as 83 percent of the variation in handsheet properties. Properties were improved by using pulps displaying low values of S and relatively high values of L. Both S and L were related to specific refining energy and wood quality. S increased with increasing unextracted chip specific gravity and rings per inch of growth rate but decreased with increasing latewood content and refining energy. L decreased with increasing refining energy, rings per inch of growth rate, and unextracted chip specific gravity but increased with increasing latewood.

Zusammenfassung

Die Qualität von 96 verschiedenen Zellstoffarten, alle im Scheiben-Refiner aus Hackschnitzeln unterschiedlicher Art hergestellt, wurde mit Hilfe des Faser-Form-Faktors S und des Faser-Längen-Faktors L bestimmt. S wurde in Einheiten des Mahlgrades nach Canadian Standard Freeness der 48/100 Faser-Längen-Fraktion bestimmt. S ist als Parameter umgekehrt proportional zur spezifischen Oberfläche. L ist der gewichtsmäßig bestimmte Anteil an Zellstoff, der ein 48-Mesh-Sieb nicht mehr passiert und gibt gleichzeitig gewichtsmäßig die Verteilung der Faserlängen in der Gesamtmenge des Zellstoffes an. Durch S und L werden 83% der Eigenschaftsschwankungen innerhalb der Prüfblätter erklärt. Diese Eigenschaften konnten durch Zellstoff mit niedrigeren S-Werten und relativ hohen L-Werten verbessert werden. Sowohl S als auch L wurden mit der spezifischen Refiner-Leistung und mit der Holzqualität korreliert. S nahm mit ansteigender Dichte der unbehandelten Hackschnitzel und mit ansteigender Jahrringzahl je Zuwachseinheit zu, fiel dagegen mit ansteigendem Spätholzanteil und Refiner-Leistung ab. Dagegen nahm L mit ansteigender Refinerleistung, Jahrringzahl je Zuwachseinheit und Dichte der unbehandelten Hackschnitzel ab, stieg jedoch mit zunehmendem Spätholzanteil an.

Introduction

Three previous papers [MCMILLIN 1968b, 1969a, 1969b] have examined interrelations between gross wood characteristics, fiber morphology, degree of refining wood chemical composition, and the physical properties of handsheets made from loblolly pine (*Pinus taeda* L.) refiner groundwood.

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These studies revealed that variations in wood quality and refining energy are immediately reflected in handsheet properties. For example, burst, tear, and breaking length were improved by applying high specific refining energy and by using fast-grown wood having high latewood content but of relatively low density. As another example, high extractive contents adversely affected burst and tear strengths after the effects of fiber morphology had been considered.

This final paper discusses the interrelationships between refining energy, gross wood characteristics, handsheet properties, and pulp quality.

Procedure

The detailed procedures for selection and preparation of samples, refining, wood property determinations, and handsheet testing have all been described previously [McMILLIN 1968b]. All pulp characteristics were determined from samples used in the earlier studies and were correlated with the previously determined gross wood characteristics, refining energies, and handsheet strengths.

Wood was selected and stratified into 12 categories in each of two blocks. Two growth rates, two specific gravities, three radial positions in the tree, and two refining energies were considered in a factorial design. The wood in each category was chipped, and the chips were randomly divided into four within-sample replications and refined to fiber. Thus, a total of 96 pulps were evaluated.

The 48 samples from one block were refined in a single pass at 40 hp days per air-dry ton. The 48 samples from the second block were refined in a double pass; energies were 40 hp days per air-dry ton on the first pass and 30 on the second pass.

Determination of Pulp Quality

The method of characterizing the quality of mechanical pulps reported by FORGACS [1963] was adopted here. It was selected because it predicts with a high degree of accuracy the properties of handsheets made from mechanical pulps.

In this method, the structural composition of pulp is defined in terms of two numerical factors—the distribution by weight of fiber length (L), and a particle-shape factor (S). The shape factor S, as defined by FORGACS, is the hydrodynamic specific surface of the fiber length fraction that will pass a 48-mesh screen but will be retained by a 100-mesh screen. It is indirectly measured by the Canadian Standard Freeness of the 48/100-mesh fraction. FORGACS [1963] interpreted S in terms of specific surface, since specific surface exhibits a close negative correlation with the Canadian Standard Freeness of the 48/100 fiber length fraction.

It should be carefully noted that in the present study the shape factor was interpreted directly in terms of the Canadian Standard Freeness of this fraction. Hence, S in this study is a parameter inversely proportional to specific surface. Accordingly, low values of 48/100 Canadian Standard Freeness, i.e., S, denote pulps with high specific surface.

L is defined as the percentage, by weight, of pulp retained on a 48-mesh screen. It is a parameter that reflects both the distribution by weight of fiber length and the weighted average fiber length of the whole pulp. In pulps having high L, the major portion of the weight is composed of long fibers.

Ten grams of oven-dry fiber from each pulp were first processed in a Bauer fiber length classifier in accordance with TAPPI standard method T 223 su-64. The screen mesh sizes were 28, 48, 100, and 200. After being processed, the fiber in each fraction was collected on tared filter pads, oven-dried, and weighed. The results were expressed as a percentage of the oven-dry weight of the unfractionated pulp (10 g). The sum of the weight percentages obtained for the retain-28 and pass-28-retain-48 fractions were taken as the length factor L. Duplicate determinations were made and the results averaged.

A minimum of 3 g of oven-dry fiber passing a 48-mesh screen and retained on a 100-mesh screen is required for determination of S. Since each 10-g classification yielded approximately 1 g of the fiber, several runs were necessary. The number of runs required was determined by the previously calculated 48/100-mesh weight percentage. The total oven-dry weight of fiber collected was assumed equal to the weight percentage times the number of runs. The collected fiber was then reslurried and sufficient water at 20° C added to make 1000 ml. The volume of the resulting slurry containing 3 g of oven-dry fiber was computed, transferred to a second beaker, and made up to 1000 ml.

The Canadian Standard Freeness of the resulting sample was then determined in accordance with TAPPI standard method T 227 m-58. The volume of overflow in milliliters was taken as the measure of S. The pulp and water then were carefully re-collected, a duplicate freeness determination made, and the two results averaged. After the second freeness determination, all fiber was collected on a tared filter pad and the actual oven-dry weight of pulp determined. The observed freeness values were corrected to a 3-g sample by use of a regression equation relating freeness to sample weight. In no case did the weight of fiber differ from the required 3 g by more than ± 0.2 g. No correction for temperature was required.

The procedure was repeated for each of the 96 sample pulps.

Processing the Data

The previously determined handsheet properties were first related to the pulp characteristics S and L by multiple regression analyses. Equations were developed by stepwise introduction of the independent variables in decreasing order of their individual contribution to the cumulative R^2. All were of the type $y = b_0 + b_1x_1 + b_2x_2 + \cdots$, where y is a dependent variable, e.g., burst factor, tear factor; b_i, a regression coefficient; and x_i an independent variable, e.g., S or L. The square of S, the square of L, and the product of S and L were also considered.

In a second analysis, S and L were separately related to gross wood properties and specific refining energy by stepwise multiple regression analysis of the pooled data (96 observations). Equations of the same form as above were developed where y was a dependent variable, e.g., S or L, b_i, a regression coefficient; and x_i, an independent variable. The single independent variables were:

UG	unextracted chip specific gravity (oven-dry weight and green volume)
LW	proportion of latewood (expressed as a decimal fraction)
GR	growth rate (rings per inch)
HP	specific refining energy (hp-days per air-dry ton)

The combinations were:

$(UG)^2$
LW/UG
GR^2
(UG) (GR)

All equations were tested at the 95-percent level of probability and all variables included were significant at that level.

Results

Table 1 summarizes wood characteristics, refining energy, handsheet properties and pulp quality determinations for single- and double-pass pulps. The 96 pulps represented in this table exhibited a wide range of properties, considering the specific refining energies employed.

Table 1. *Wood Characteristics, Handsheet Properties, Refining Energies, and Pulp Characteristics*[1]

Position in tree (rings from pith)	Unextracted specific gravity			Sheet density g/cm^3	Burst factor	Tear factor	Breaking length, m	Specific refining energy, hpd/adt	*S*	*L*
Single-pass refining										
0 ... 10	0.431	0.237	4.75	0.236	1.76	28.2	410.8	38.3	777.5	57.2
0 ... 10	.456	.239	10.13	.222	1.61	25.7	324.6	38.8	782.3	53.8
0 ... 10	.494	.310	4.47	.224	2.35	35.7	451.5	38.0	771.8	58.5
0 ... 10	.535	.345	12.39	.241	1.19	17.7	271.1	37.8	794.3	46.2
11 ... 20	.442	.265	5.52	.224	2.09	35.5	441.9	39.2	777.5	60.7
11 ... 20	.466	.303	6.84	.226	2.05	33.8	410.2	38.4	775.5	62.1
11 ... 20	.510	.345	4.78	.217	2.69	36.8	500.9	38.5	775.3	63.6
11 ... 20	.531	.386	8.34	.223	1.91	30.1	382.7	38.8	790.3	57.5
21 ... 30	.470	.351	5.21	.233	2.39	36.0	473.0	38.4	774.0	62.8
21 ... 30	.449	.329	8.15	.208	2.11	33.0	417.4	38.4	773.0	65.2
21 ... 30	.517	.411	6.30	.210	1.67	28.5	345.4	38.3	787.3	60.3
21 ... 30	.534	.424	9.86	.222	1.91	29.1	380.4	37.8	784.8	59.3
Double-pass refining										
0 ... 10	.427	.171	4.11	.289	3.34	41.7	604.3	69.1	754.8	42.0
0 ... 10	.457	.221	7.59	.281	3.25	42.2	720.5	68.6	754.0	43.8
0 ... 10	.492	.270	4.80	.266	3.82	48.9	761.0	67.1	748.5	45.4
0 ... 10	.515	.302	11.83	.293	2.96	35.5	656.1	65.3	767.8	42.0
11 ... 20	.445	.300	5.53	.287	4.41	54.3	896.1	66.8	750.3	48.0
11 ... 20	.459	.294	7.08	.293	4.87	58.4	996.1	68.9	744.3	50.3
11 ... 20	.512	.430	5.30	.318	6.42	82.2	1264.6	70.9	733.3	53.0
11 ... 20	.524	.383	12.38	.292	3.23	41.3	724.2	69.8	768.5	41.5
21 ... 30	.458	.325	4.91	.291	5.61	67.0	1096.9	68.6	731.5	50.3
21 ... 30	.438	.350	8.27	.319	7.00	76.5	1312.4	70.8	720.7	50.6
21 ... 30	.534	.431	5.53	.302	5.49	61.3	1085.3	67.9	740.3	49.7
21 ... 30	.511	.421	8.27	.299	5.67	61.7	1129.3	68.0	743.5	51.8

[1] Each numerical value is the average of four replications except that values for proportion of latewood and rings per inch are based on one observation apiece.

Individual values for sheet density ranged from 0.190 ... 0.351 g/cm^3, burst factor from 1.06 ... 7.93, tear factor from 15.7 ... 87.7; and breaking length from 256.3 ... 1342.0 m. The shape factor ranged from 801 ... 699, and the length factor ranged from 39.0 ... 66.7.

There was considerable variation in all measured wood properties. Unextracted specific gravity ranged from 0.421 ... 0.633, proportion of latewood from 0.171 to 0.431, and growth rate from 4.11 ... 12.30 rings per inch.

Variance analysis showed no significant difference in refining energy within either the single- or double-pass pulps.

Table 2 lists multiple regression equations that most accurately relate sheet properties to functions involving S and L for the combined single- and double-pass pulps (96 observations). The cumulative R^2 values and the standard errors of the estimates are also given. The correlation between S and L for these data was low ($r = 0.38$).

Table 2. *Multiple Regression Equations Developed to Estimate Sheet Properties for Single- and Double-pass Pulps*

Eq. No.	Property	Variable	Coefficient	Cumulative R^2	Standard error of estimate
	Sheet density		b_0 0.7642		
		$(S)^2$	b_1 $-0.0655(10^{-5})$	0.615	
		$(S)(L)$	b_2 $-0.0303(10^{-4})$	0.790	0.018
2	Burst factor		b_0 60.0024		
		(S)	b_1 -0.0743	0.833	0.70
3	Tear factor		b_0 332.7173		
		$(S)^2$	b_1 $-0.4790(10^{-3})$	0.809	7.41
4	Breaking length		b_0 6071.9567		
		$(S)^2$	b_1 $-0.9270(10^{-2})$	0.815	140.8

These and subsequent equations apply only for loblolly pine and for the refiner and plate pattern employed. Additional tests would be required to develop similar relationships for other situations.

The best multiple regression equation for sheet density (Eq. (1), Table 2) accounted for 79 percent of the variation in this property with a standard error of the estimate of 0.018. Both the square of S and the product of S and L were significant. From Eq. (1) and Fig. 1 A, sheet density decreased with increasing S. For a given S it increased with decreasing L. All pulp characteristics considered, sheet density was improved by using pulps displaying low values of S—i.e., high specific surface—and low values of L.

The best equation for burst factor (Eq. (2), Table 2) accounted for 83 percent of the variation with a standard error of 0.70. The only pulp characteristic of significance was S. As shown in Fig. 1 B, burst factor decreased with increasing S. All pulp factors considered, burst strength increased when pulps displayed low values of S.

Tear factor was significantly related to the square of S. Equation (3), Table 2, accounted for 81 percent of the variation in this property with a standard error of

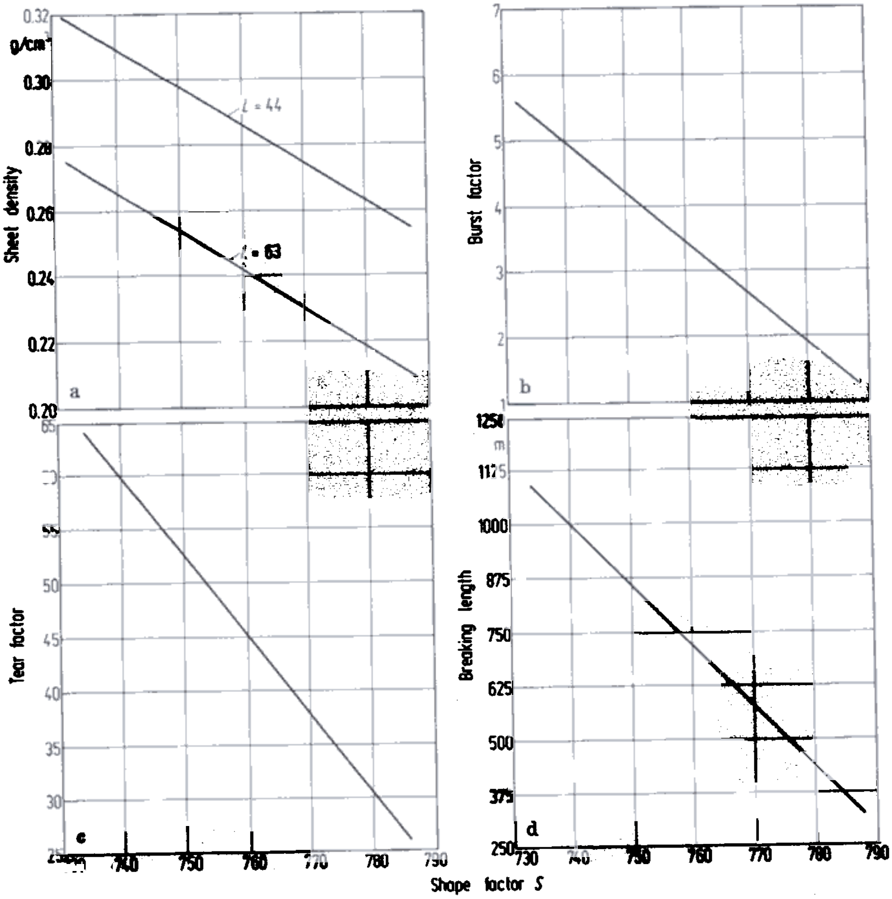

Fig. 1. Effect of S and L on sheet properties. The graphed lines in this figure and in Figs. 3 through 5 were obtained by substituting a range of values for the variable on the X axis and fixing the remaining variables in the regression equations at the indicated levels. The range of S plotted is contained within all plotted levels of L.

7.41. Tear factor decreased with increasing S; the curvilinear effect of S on tear was small (Fig. 1 C).

The relationship of breaking length to pulp quality was similar to that obtained for tear (Eq. (4), Table 2, and Fig. 1 D). The equation accounted for 82 percent of the variation with a standard error of 140.8. All pulp characteristics considered, tear factor and breaking length were improved by using pulps displaying low values of S.

Figure 2 shows the relationship of S on L for single- and double-pass pulps separately and for the pooled data. As previously noted, S exhibited a positive relationship with L for the pooled data (dashed regression line in Fig. 2). However, it displayed a negative relationship with L when the single- and double-pass pulps were analyzed separately (the solid regression lines in Fig. 2). The respective correlation coefficients were $r = -0.582$ and $r = -0.663$.

The level and slope of the relationship of S on L is higher for the single-pass than for the double-pass pulps. From Fig. 2, S and L decrease with increasing specific refining energy; e.g., the specific surface increases and the fiber length distribution decreases with increasing refining energy. In the present experiment, the range of values observed for S and for L at a given specific refining energy must be a function of wood quality, since no significant difference in refining energy was detected within either the single- or double-pass pulps.

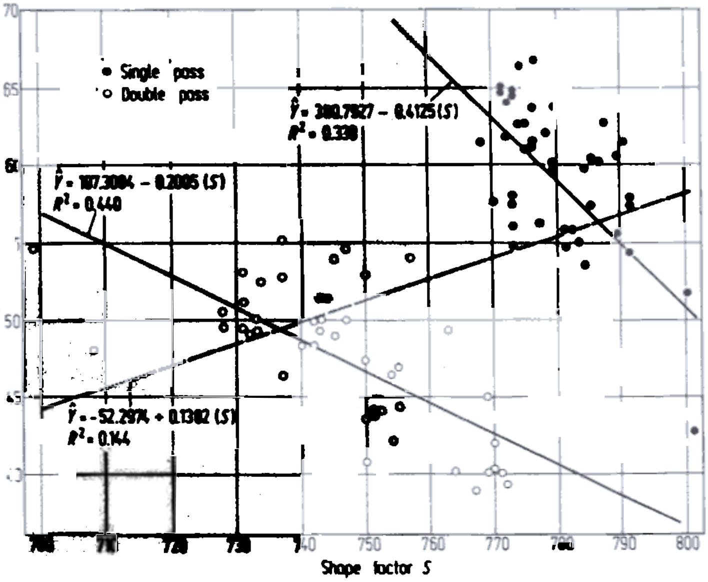

Fig. 2. Relationship of the fiber length distribution factor L to the shape factor S. The dashed regression line plots the relationship for the combined single- and double-pass pulps. The solid regression lines plot the relationship for single-pass and double-pass pulps separately.

This result indicates that the fiber-length distribution L and the quality of the adhesive components S in refiner groundwood pulps can independently change with changes in wood quality or pulping parameters, e.g., refining energy.

Table 3 lists multiple regression equations for the pooled data (96 observations) which describe the relationship of S and L on specific refining energy and gross wood properties. A linear relationship was assumed between the two pulp characteristics and specific refining energy. For these data, unextracted chip specific gravity was positively correlated with proportion of latewood ($r = 0.695$). Growth rate and specific refining energy were not significantly correlated with any independent variable.

S was significantly related to refining energy, unextracted chip specific gravity, rings per inch of growth rate, and proportion of latewood (Eq. (5), Table 3). The equation accounted for 86 percent of the total variation in S with a standard error of the estimate of 8.2.

Specific refining energy alone accounted for 68 percent of the variation in S. From Eq. (5), Table 3, and Fig. 3A, S decreased with increasing refining energy. Figure 3B shows the effect of unextracted chip specific gravity on S at two

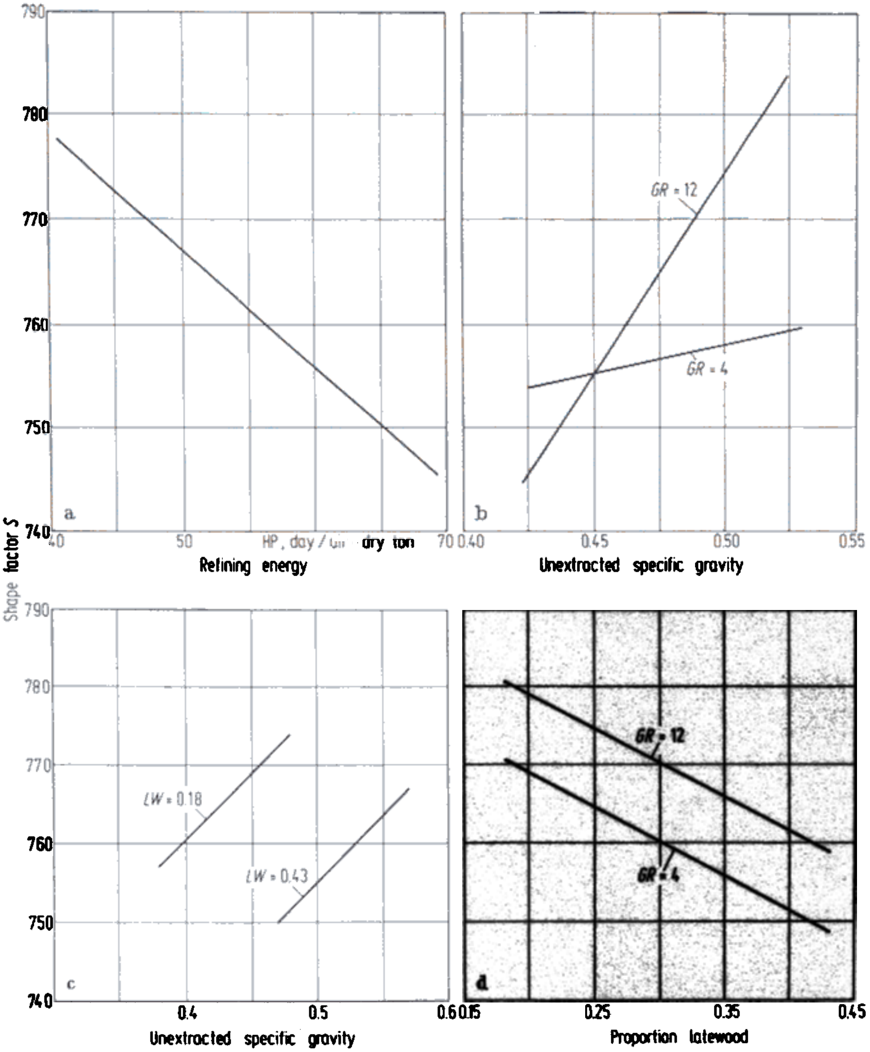

Fig. 3. Effect of refining energy, unextracted specific gravity, rings per inch, and proportion of latewood on the shape factor *S*. The range of specific gravity plotted is contained within the plotted levels of latewood content.

growth rates. *S* increased with increasing specific gravity for both wood of fast growth (4 rings per inch) and wood of slow growth (12 rings per inch). The rate of increase was greater for the slow-grown material. For specific gravities greater than 0.45, *S* increased with increasing growth rate.

Figure 3C shows the effect of unextracted chip specific gravity on *S* at two latewood contents. *S* increased with increasing specific gravity for all levels of latewood. For a given specific gravity, it increased with decreasing proportion of latewood.

Figure 3D charts the interaction of proportion of latewood and growth rate. *S* decreased with increasing latewood for all levels of growth rate. For a given latewood content *S* increased with increasing growth rate.

Table 3. *Multiple Regression Equations Used to Estimate S and L for Pooled Single- and Double-pass Pulps*

Eq. No.	Property	Variable	Coefficient	Cumulative R^2	Standard error or estimate
5	(*S*)		b_0 878.8570		
		(HP)	b_1 −1.1020	0.683	
		(UG) (GR)	b_2 37.8480	0.776	
		(LW)/(GR)	b_3 −42.4000	0.825	
		(GR)	b_4 −17.0430	0.848	
		$(UG)^2$	b_5 −164.0250	0.856	8.2
6	(*L*)		b_0 51.3170		
		(HP)	b_1 −0.3746	0.536	
		$(GR)^2$	b_2 −0.2077	0.681	
		(LW)/(GR)	b_3 24.2980	0.817	
		(GR)	b_4 4.3060	0.843	
		(UG) (GR)	b_5 −3.7822	0.854	3.0

It has been shown that low values of *S* are required to improve sheet properties (Table 2). All factors considered, *S* was reduced by applying high specific refining energy and by using wood of fast growth displaying a high proportion of latewood but of relatively low specific gravity. High refining energy and the same combination of gross wood characteristics were shown in an earlier study [McMillin 1968b] to result in sheets of improved strength and density.

L was significantly related to refining energy, growth rate, unextracted chip specific gravity, and proportion of latewood (Eq. (6), Table 3). The equation accounted for 85 percent of the total variation in *L* with a standard error of 3.0.

Specific refining energy alone accounted for 54 percent of the variation in *L*. From Eq. (6), Table 3, and Fig. 4A, *L* decreased with increasing refining energy. Figure 4B shows the effect of growth rate on *L* at two unextracted specific gravities. *L* first increased slightly with increasing rings per inch, then decreased. The rate of decrease became greater with increasing rings per inch. For a given number of rings per inch, *L* decreased with increasing specific gravity.

Figure 4C shows the effect of unextracted chip specific gravity on *L* at two latewood contents. *L* decreased with increasing specific gravity for all levels of latewood. For a given specific gravity it increased with increasing proportion of latewood.

Figure 4D charts the interaction of proportion of latewood and growth rate. *L* increased with increasing latewood for all levels of growth rate. For a given latewood content *L* increased with decreasing growth rate.

As previously noted, *S* exhibited a stronger relationship with sheet properties than did *L*. When the high refining energy required to obtain the desired level of *S* is applied, the overall level of *L* is simultaneously reduced. For single-pass pulps, *L* averaged 58.9; for double-pass pulps, 47.6. Furthermore, in specifying the gross wood characteristics conducive to low values of *S*, the gross wood characteristics affecting *L* are also specified. Examination of Fig. 4 suggests that after high refining energy is specified, and after selection of fast-grown wood having a high latewood content but a relatively low density, *L* should be as high as possible.

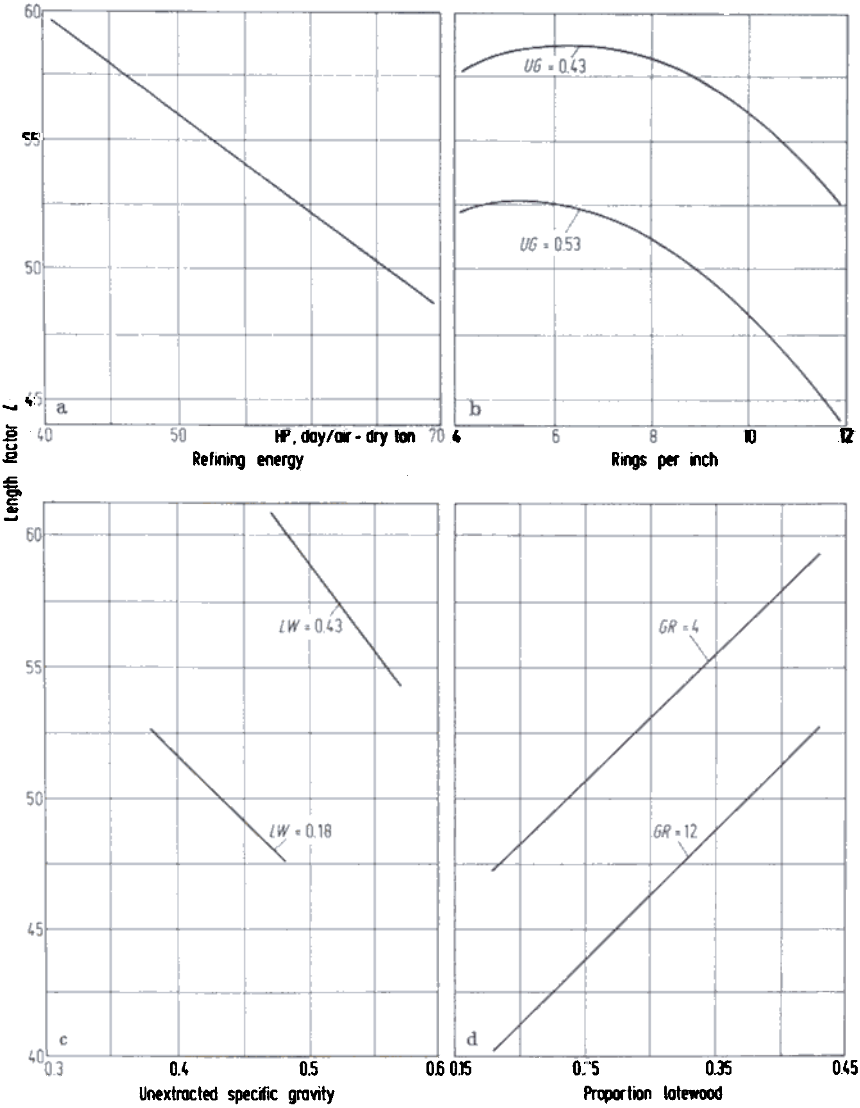

Fig. 4. Effect of refining energy, unextracted specific gravity, rings per inch, and proportion of latewood on the fiber length distribution factor L. The range of specific gravity plotted is contained within the plotted levels of latewood content.

Table 4 lists multiple regression equations that relate handsheet properties in terms of S and L for the double-pass pulps (48 observations). S was significantly correlated with L ($r = -0.663$).

The best multiple regression equation for sheet density (Eq. (7), Table 4) accounted for only 9 percent of the variation in this property with a standard error of the estimate of 0.020. The only significant factor was S. From this equation and Fig. 5A, sheet density decreased with increasing S. It should be noted that for the pooled data (single- and double-pass pulps), the square of S alone accounted

Table 4. *Multiple Regression Equations Developed to Estimate Sheet Properties for Double-pass Pulps*

Eq. No.	Property	Variable	Coefficient	Cumulative R^2	Standard error of estimate
7	Sheet density		b_0 0.5947		
		(S)	b_1 0.0004	0.092	
8	Burst factor		b_0 17.0607		
		$(S)^2$	b_1 0.0032 (10^{-2})	0.621	
		(L)	b_2 0.1142	0.793	
9	Tear factor		b_0 209.8028		
		$(S)^2$	b_1 −0.0330 (10^{-2})	0.617	
		$(L)^2$	b_2 0.0135	0.710	8.09
10	Breaking length		b_0 −259.2430		
		(L)	b_1 129.9974	0.548	
		$(S)(L)$	b_2 −0.1407	0.653	148.60

for 62 percent of the total variation and sheet density decreased with increasing S. Furthermore, 68 percent of the total variation in S was accounted for by specific refining energy. Hence, in specifying a high level of refining energy, most of the variation in sheet density is accounted for. This finding is confirmed by the earlier study [McMillin 1968b], in which sheet density was principally related to specific refining energy and was relatively unaffected by wood characteristics; i.e., wood characteristics accounted for only 2 percent of the total variation beyond the 83 percent accounted for by refining energy.

The best multiple regression for burst factor (Eq. (8), Table 3) accounted for 79 percent of the variation with a standard error of the estimate of 0.77. Both L and the square of S were significant. As shown in Fig. 5B, burst factor decreased with increasing S for all levels of L. For a given S, burst increased with increasing values of L. Both tear factor and breaking length displayed a similar behavior (Eqs. (9) and (10), Table 3, and Figs. 5C and 5D). From these results it may be concluded that, when refining energy is high, handsheets of improved strength and density are associated with pulps displaying low values of S and relatively high values of L.

Discussion and Conclusions

The four studies explored several aspects of refiner groundwood pulp. It seems appropriate to synopsize the results in this final report.

It was hypothesized early in the research that the physical properties of handsheets are related to certain distinguishable basic pulp characteristics and that these characteristics are determined by interrelationships of refining variables and wood properties. Thus knowledge of the factors that control the quality of pulp and an understanding of the interaction of these factors should provide a means for predetermining the suitability of wood types for refiner groundwood and for more rational operation and design of disk refiners.

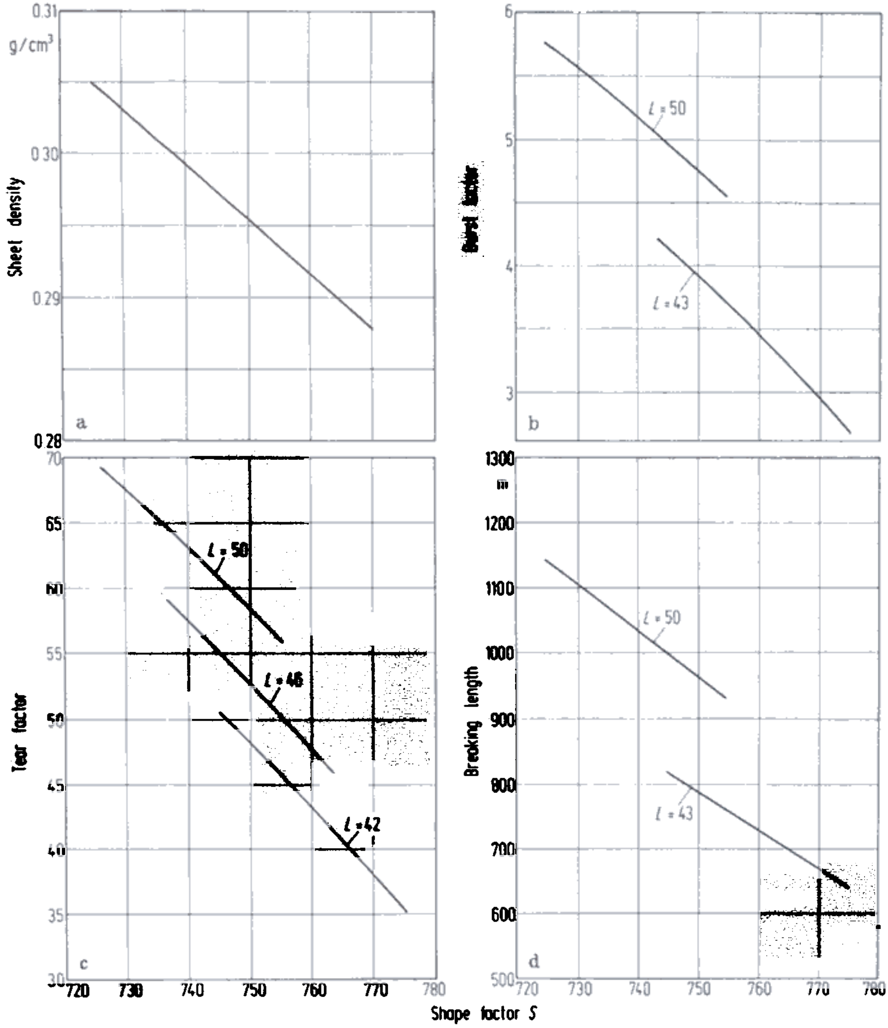

Fig. 5. Effect of S and L on sheet properties. The range of S plotted is contained within all plotted levels of L.

Accordingly, the research considered loblolly pine wood characteristics, pulp properties, and refining energy in relation to the strength and density of handsheets manufactured from pulps produced by double-disk refining of untreated wood chips. The influence of wood physical and chemical properties was studied by varying the specific gravity, growth rate, and age from the pith. Concurrently, the interaction of one processing variable was studied by varying specific refining energy. The experiment is unique in that the factorial design permitted isolating the independent effects of each variable on sheet strength and pulp quality.

Conspicuous by their absence from the list of variables considered were such factors as consistency, dilution water temperature, plate pattern, refiner speed and type, chip pretreatment, and latency. Inclusion of all such factors would have rendered the data complicated beyond hope of useful analysis.

The strength and density of handsheets proved related to specific refining energy and gross wood characteristics [McMillin 1968b]. Burst, tear, and breaking length were increased by applying high refining energy and by using wood of fast growth displaying a high proportion of latewood but of relatively low specific gravity. Only high refining energy and high latewood content were required to improve sheet density.

Characteristically the latewood content of loblolly pine increases with distance from the pith. It was therefore concluded that wood from the outer portion of the stem would result in sheets of improved properties. Variance analysis confirmed this observation; e.g., sheet properties increased with increasing distance from the pith independently of specific gravity and growth rate.

Because sheet properties proved responsive to changes in gross wood characteristics, it seemed likely that sheet strength could also be interpreted in terms of fiber morphology and wood chemical constituents, which again independently vary with specific gravity, growth rate, and distance from the pith [McMillin 1968a, 1968c].

The results indicated that fiber prepared from wood having long, slender tracheids with thick walls formed sheets of improved strength and density [McMillin 1969a]. For any specified fiber morphology, extractives adversely affected burst and tear strengths [McMillin 1969b]. Breaking length and sheet density were unaffected by extractives. A range of extractives was considered at all levels of morphological characteristics.

A theoretical stress analysis indicated that long, slender tracheids with thick walls fail by diagonal tension or parallel shear, depending on the fibril angle, while under torsional stress during refining. These failures result in ribbon-like fragments, which research elsewhere [Forgacs 1963] has demonstrated to provide the coherence necessary for strength development in mechanical pulps.

Analysis revealed that the amounts of these ribbon-like particles in the pulps increase with decreasing specific gravity and growth rate and increasing latewood content. Accordingly, a high proportion of ribbons is associated with wood of fast growth displaying a high proportion of latewood but of relatively low density.

Thus, the bonding potential of refiner groundwood pulps and the strength of sheets made from the pulps vary in an identical manner with changes in gross wood properties. It seems unlikely that extractives themselves can affect the ability of fibers to form ribbons. Morphological characteristics and their relationship to torsional stresses induced during refining appear to provide a more reasonable explanation of the mechanisms by which the ribbon-like particles are formed. Extractives, however, seem to exert a secondary negative influence on sheet strength. This effect is attributable to lessened bond strength caused by reduced surface tension forces and blocking of reactive sites on the fiber surfaces.

As has just been noted, pulps prepared from loblolly pine wood having thick-walled tracheids produced sheets of improved properties. It is known that pulps from species having an average wall thickness less than that of loblolly pine may result in sheets of even greater strength than obtained here.

The two results are not inconsistent. In species with thin walls, the correspondingly thin ribbon-like particles would be expected to be more conformable than those of the thicker loblolly pine ribbons. Hence, conditions for improved surface contact exist, and result in a greater number of hydrogen bonds and improvement in strength. In very thin-walled species conformability may be good without unwinding, since such fibers tend to collapse.

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