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Gross Wood Characteristics Affecting Properties of Handsheets Made From Loblolly Pine Refiner Groundwood

Specific refining energy and gross wood properties accounted for as much as 90% of the total variation in strength of handsheets made from 96 pulps disk-refined from chips of varying characteristics. Burst, tear, and breaking length were increased by applying high specific refining energy and using fast-grown wood of high latewood content but of relatively low density. To maximize sheet density, only high refining energy and high proportion of latewood were required.

Keywords: *Pinus* · *Pinus taeda* · Physical properties · Density · Summerwood · Growth rate · Mechanical pulps · Refining · Energy · Handsheets · Strength

Because refiner groundwood is manufactured essentially in one mechanical operation, continuous control of the refining process is required. Many machine and wood factors interact to affect the properties of the pulp. A broad program of research to establish interrelations between pulp quality, chemical composition, morphology of wood, and degree of fiber refining has been undertaken in our laboratory. The ultimate objective is to develop criteria useful in predicting and controlling the paper-making potential of refiner groundwood from loblolly pine (*Pinus taeda* L.). This paper discusses interrelationships between certain gross wood characteristics, refining energy, and the physical properties of handsheets. Subsequent articles will consider pulp quality, fiber morphology, and chemical composition of wood in relation to handsheet properties.

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PROCEDURE

Variables

A factorial experiment with four replications was designed with variables as follows:

Specific gravity of unextracted wood (oven-dry weight and green volume)
- Less than 0.49
- More than 0.49

Growth rate
- Less than 6 rings/in.
- More than 6 rings/in.

Rings from the pith (position in tree)
- 0 to 10 rings (core wood)
- 11 to 20 rings (middle wood)
- 21 to 30 rings (outer wood)

Specific refining energy
- Single refiner pass at 40 hp-days/air-dry ton

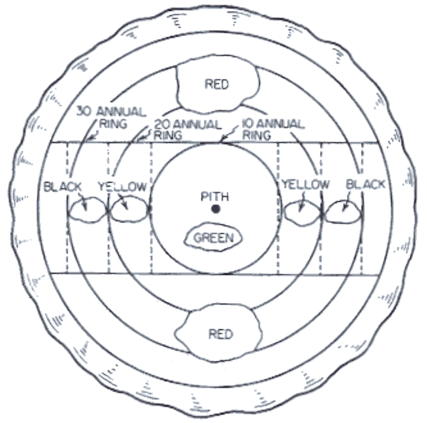

Fig. 1. Sawing diagram for recovering boards of three age classes.

Double refiner pass at 40 hp-days/air-dry ton on first pass, 30 hp-days/air dry ton on second pass

Held constant were:

Refining consistency, 20%
Actual feed rate, 21 tons of oven-dry wood/day single pass; 21 tons/day first of two passes, 26 tons/day second of two passes
Refiner, Bauer Bros. No. 410, 40-in. double-disk, 250 hp motors
Chip sample size, 25 lb, oven-dry
Refiner plate pattern, Bauer Bros. Refining Plate No. 40106
Chip solids content, 50%
Rotational speed of plates, 1200 rpm
Dilution water temperature, 130°F

The wood factors selected provided broad variation in gross characteristics. Rings from the pith was chosen as a simple means of altering morphological and chemical characteristics of the wood, which vary with radial position in the tree. Loblolly pine was used because of its moderate pitch level and its commercial importance in southern forests.

The refining energies were selected (after trial runs) to achieve fiberisation in the widely divergent wood types. Since the purpose of the study was to establish basic relationships, no attempt was made to optimise sheet properties, for example, by applying higher refining energies. In order to maintain the energies at the selected levels, nominal plate clearance was varied from 0.005 to 0.020 in. in response to changes in the physical and morphological characteristics of the raw material. This approach was followed because specific refining energy appears to largely determine the quality of the refiner groundwood and is universally used to maintain process control.

Four gross wood properties were measured: specific gravity of extracted and unextracted wood, growth rate in rings per inch, and proportion of latewood. These were correlated with four sheet properties: sheet density, burst factor, tear factor, and breaking length.

Preparation of Test Material and Refining

Fifty standing trees, 40 years or older, were selected from a natural stand in central Louisiana. After they were felled, those portions of each tree that exhibited at least 40 annual rings were bucked into 8-ft lengths; the top end of each log was marked and color-coded as shown in Fig. 1 to facilitate sawing into boards of the prescribed age class. Logs were culled if they had such defects as excessive sweep and decay or if they exhibited visible evidence of compression wood.

Two slabs (sections coded "red" in Fig. 1) were removed and discarded. The resulting pith center cant was ripped along the 10th, 20th, and 30th growth increment to form five boards of the required age classes. Thickness and width of the boards thus varied with growth rate of the tree. The boards were immediately submerged and stored in water tanks to prevent sap stain and moisture loss.

A 1-in.-wide wafer was cut from each board at mid-length. Specific gravity (oven-dry weight, green volume) and growth rate were determined. The boards were then segregated according to specific gravity, growth rate, and distance from the pith. Material with specific gravity near 0.49 or growth rate near 6 rings/in. was excluded. Bundles of 200 lb each (the green weight of material required for four refiner replications) were labelled according to material type and refining treatment. Each of the 24 bundles was dipped in water-soluble penta preservative to prevent sap stain, wrapped in polyethylene film, and sealed. The packages, crated in wooden boxes, were transported promptly by truck to the refining laboratory and processed within 5 days. No evidence of deterioration or moisture loss was visible.

The wood in each bundle was separately chipped and screened to eliminate chips larger than 1 in. Acceptable chips were randomly divided into four equal replications. A random subsample of approximately 1000 chips was taken from each replicate for measurement of wood properties.

Before refining, chip solids content was determined, and the flow rate of dilution water was adjusted for the required consistency. Concurrently, chip density was determined in order to maintain the actual feed rate at a constant oven-dry weight per unit time. The feed mechanism of the refiner was equipped with controls for obtaining consistent results with the quantities of chips used here.

As chips entered the refining chamber, plate separation was manually adjusted to maintain energy input at the predetermined level. Simultaneously, the total power demand was recorded and the run time noted. Specific refining energy in terms of horsepower days per air-dry ton was calculated from these data. Horsepower values used were total power at an assumed motor efficiency of 91.5%. Individual replications were refined in random order.

This procedure was followed for the first pass on the double-refined pulp and essentially repeated for the second pass, except that no additional dilution water was required.

All pulps were placed in polyethylene bags, sealed in barrels, and returned to the Alexandria laboratory.

Pulps can be held for extended periods if placed in cold storage with a fungicide incorporated in the slurry.[1] Accordingly, a commercial pulp fungicide was added to the dilution water, thus assuring a thorough mixture throughout the slurry. All pulps were stored at 35°F. No evidence of deterioration was observed during the experiment.

Determination of Wood Properties

Unextracted specific gravity, based on green volume and oven-dry weight, was determined on a random sample of 500 chips. Green volume of the sample chips was determined by water immersion.[2] Extracted specific gravity was calculated by reducing the observed oven-dry weight by the weight of the alcohol–benzene extractive content of a matched sample. Extractive content was determined by TAPPI Standard Method T 6 os-59.

Since growth rate and proportion of latewood cannot be determined from chips, they were measured on the cross-sectional surface of the wafers used to segregate the material before chipping. A low-power microscope with a calibrated micrometer eyepiece was employed to distinguish the characteristically abrupt transition between earlywood and latewood. Because boards varied in cross-sectional area, measurements were weighted by area in calculating the mean. The means thus calculated were assumed representative of each replicate.

Preparation of Handsheets and Determination of Properties

Pulp slurry preparation, sheet making, couching, and pressing were in accordance with TAPPI Standard Method T 205 m-58, except that sheets were made at 135 g/m² oven-dry basis weight. At least 10 sheets were formed for each pulp.

Handsheets were dried in sets of standard drying rings under 20 lb of

[1] Chilson, W., U. S. Forest Products Laboratory, Madison, Wis., personal communication.
[2] Smith, D. M., U. S. Forest Products Lab. Rept. 2209 (1961).

Table I. Wood Characteristics, Handsheet Properties, and Refining Energies[a]

Position in tree	Specific gravity: Unextracted	Specific gravity: Extracted	Latewood	Rings/in.	Sheet density, g/cm³	Burst factor	Tear factor	Breaking length, m	Specific refining energy, hp-days/air-dry ton
Core	0.431	0.398	0.237			1.76	28.2	410.8	38.3
Core	0.456	0.420	0.239			1.61	25.7	324.6	38.8
Core	0.494	0.446	0.310			2.35	35.7	451.5	38.0
Core	0.535	0.467	0.345			1.19	17.7	271.1	37.8
Middle	0.442	0.417	0.265			2.09	35.5	441.9	39.2
Middle	0.466	0.447	0.303			2.05	33.8	410.2	38.4
Middle	0.510	0.491	0.345			2.69	36.8	500.9	38.5
Middle	0.531	0.503	0.386			1.91	30.1	382.7	38.8
Outer	0.470	0.456	0.351			2.39	36.0	473.0	38.4
Outer	0.449	0.430	0.329			2.11	33.0	417.4	38.4
Outer	0.517	0.489	0.411			1.67	28.5	345.4	38.3
Outer	0.534	0.509	0.424			1.91	29.1	380.4	37.8
Core	0.427	0.400	0.171			3.34	41.7	604.3	69.1
Core	0.457	0.421	0.221			3.25	42.2	720.5	68.6
Core	0.492	0.441	0.270			3.82	48.9	761.0	67.1
Core	0.515	0.449	0.302			2.96	35.5	656.1	65.3
Middle	0.445	0.419	0.300			4.41	54.3	896.1	66.8
Middle	0.459	0.441	0.294			4.87	58.4	996.1	68.9
Middle	0.512	0.491	0.430			6.42	82.2	1264.6	70.9
Middle	0.524	0.493	0.383			3.23	41.3	724.2	69.8
Outer	0.458	0.443	0.325			5.61	67.0	1096.9	68.6
Outer	0.438	0.424	0.350			7.00	76.5	1312.4	70.8
Outer	0.534	0.519	0.431			5.49	61.3	1085.3	67.9
Outer	0.511	0.495	0.421			5.67	61.7	1129.3	68.0

[a] Each numerical value is the average of four replications except proportion of latewood and rings per inch, which are based on one observation.

pressure in a room maintained at constant 50% RH and 72°F. All sheets were dried overnight and allowed to condition at least 4 hr after removal from the drying rings. The five sheets of best formation were selected for test by visual examination.

Oven-dry basis weight, sheet thickness, and apparent density were determined as described in TAPPI Standard Method T 220. Bursting strength was measured in accordance with T 403 and results were expressed as burst factor. Tearing strength determinations conformed to TAPPI Standard T 414, and results were expressed as tear factor. Tensile strength was determined as prescribed in TAPPI standard T 404 and expressed as breaking length in meters. All tests were performed within 2 days of sheet manufacture.

In all cases, the mean strength properties were mathematically adjusted to a common basis weight (135 g/m²) by application of previously determined regression expressions relating basis weight to the property in question.

Processing the Data

Individual handsheet properties at each refining level were first plotted against wood properties to identify possible trends. In most cases, no simple relationship was apparent between a given sheet property and a single gross wood characteristic.

Analysis of variance was used to identify the factors and factor combinations to be employed as independent variables in multiple regression analysis.

The single variables were:

- UG, Unextracted specific gravity (oven-dry weight and green volume)
- EG, Extracted 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/air-dry ton)

The combinations were:

(UG)(GR)
(EG)(GR)
(HP)(LW)
(HP)(GR)

To construct the regression model, a linear relationship was assumed between total applied specific refining energy and handsheet properties. To verify this assumption, an analysis was made of de Montmorency's data relating sheet properties and specific refining energy for 1-, 2-, and 3-pass pulps of black spruce and balsam-fir.[3] In stepwise multiple regression with a curvilinear model, correlation coefficients of 0.90 to 0.95 were obtained for sheet density; 0.63 to 0.75 for tear factor; 0.90 to 0.95 for burst factor; and 0.91 to 0.94 for breaking length. All relationships proved to be either linear in all ranges or linear in the range of refining energies used in the present study.

Equations were developed by stepwise introduction of the independent variables (96 observations) in decreasing order of their individual contribution to the cumulative R^2. All were of the type $y = b_0 + b_1x_1 + b_2x_2 + \ldots$, where y is a dependent variable (e.g., burst, tear); b_i, a regression coefficient; and x_i, an independent variable (e.g., growth rate, specific refining energy). The equations were tested at the 5% level of significance, and all variables were significant at that level.

[3] de Montmorency, W. H., *Pulp Paper Mag. Can.* 66 (6): T325 (1965).

RESULTS

The 24 pulps represented in Table I exhibited a wide range of sheet properties, considering the specific refining energies employed.

Individual values for sheet density ranged from 0.190 to 0.351 g/cm³; burst factor from 1.06 to 7.93; tear factor from 15.7 to 87.7; and breaking length from 256.3 to 1342.0 m. As expected, all measured wood properties exhibited a wide range and reflected the method of specimen preparation. Unextracted specific gravity ranged from 0.421 to 0.633; extracted specific gravity from 0.393 to 0.616; latewood from 0.171 to 0.431, and growth rate from 4.11 to 12.39 rings/in.

Several of the independent variables used in multiple regression extimates of sheet properties were correlated. Correlation coefficients for all two-variable combinations are given in Table II. For the combined single- and double-pass data (96 observations), unextracted specific gravity was positively correlated with extracted specific gravity ($r = 0.917$) and proportion of latewood ($r = 0.695$). Extracted specific gravity was also positively correlated with proportion of latewood ($r = 0.820$). Growth rate and specific refining energy

Table II. Correlation (r value) Between Independent Variables Used to Estimate Sheet Properties

	Specific refining energy (HP)	*Unextracted specific gravity* (UG)	*Extracted specific gravity* (EG)	*Latewood* (LW)	*Growth rate* (GR)
Specific refining energy (HP)	1.000	−0.074	−0.033	−0.018	−0.028
Unextracted specific gravity (UG)		1.000	0.917	0.695	0.386
Extracted specific gravity (EG)			1.000	0.820	0.228
Latewood (LW)				1.000	0.220
Growth rate (GR)					1.000

Table III. Multiple Regression Equations Developed to Estimate Sheet Properties

Property	*Eq. No.*	*Variable*	*Coefficient*		*Cumulative* R^2	*Standard error of estimate*
Sheet density	1		b_0	0.2018		
		HP	b_1	0.0009	0.825	
		(HP)(LW)	b_2	0.0040	0.837	
		LW	b_3	−0.2070	0.845	0.03
Burst factor	2		b_0	−2.1295		
		HP	b_1	0.0484	0.664	
		(HP)(LW)	b_2	0.2080	0.758	
		(UG)(GR)	b_3	−1.7524	0.849	
		GR	b_4	0.9569	0.880	
		(HP)(GR)	b_5	−0.0039	0.887	0.59
Tear factor	3		b_0	−4.0995		
		HP	b_1	0.3726	0.596	
		(HP)(LW)	b_2	2.2320	0.695	
		(UG)(GR)	b_3	−19.2549	0.849	
		GR	b_4	9.8843	0.884	
		(HP)(GR)	b_5	−0.0385	0.891	5.72
Breaking length	6		b_0	−103.9859		
		HP	b_1	3.6386	0.714	
		(HP)(LW)	b_2	43.5530	0.811	
		(EG)(GR)	b_3	−357.5598	0.875	
		GR	b_4	138.3594	0.904	103.31

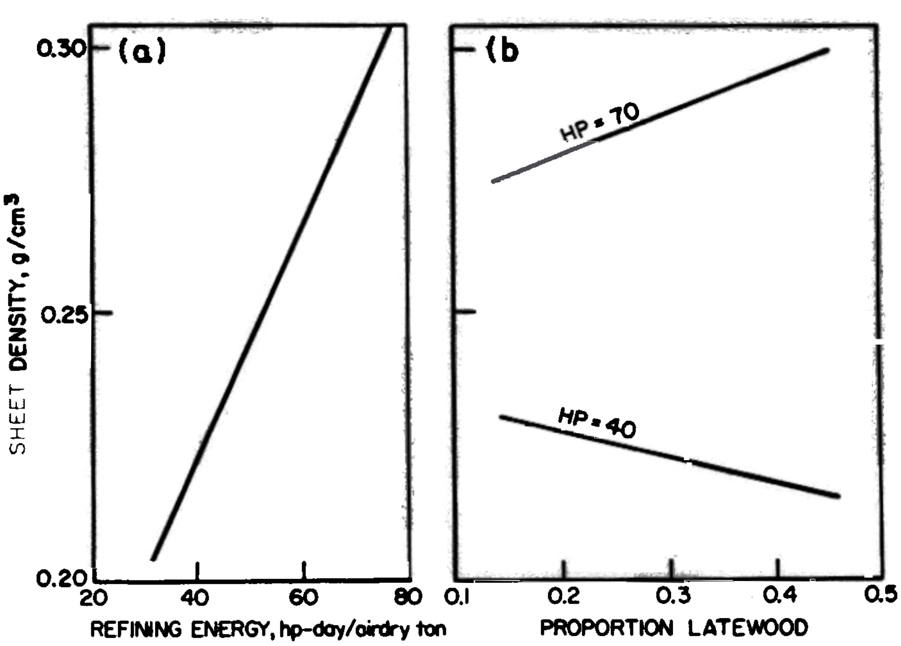

Fig. 2. Sheet density as related to refining energy and proportion latewood. The graphed lines in this and subsequent figures were obtained by substituting a range of values for the variables on the X axis and fixing the remaining variables in the regression equation at the indicated levels or at their mean values. Latewood exhibited a range of values for all levels of wood specific gravity.

were not significantly correlated with any independent variable.

Sheet properties also proved highly interrelated. Sheet density was positively correlated with burst factor ($r = 0.847$), tear factor ($r = 0.785$), and breaking length ($r = 0.875$). Burst factor was positively correlated with breaking length ($r = 0.985$) and tear factor ($r = 0.965$), while tear factor was positively correlated with breaking length ($r = 0.959$). Variance analysis showed no significant difference in refining energy within either the single- or double-pass pulps.

Table III lists multiple regression equations that most accurately describe handsheet properties in terms of refining energy and gross wood characteristics; all positions are considered. The cumulative R^2 values and the standard errors of the estimates are also given. The equations apply only to the range of data used in the study. Relationships of individual properties are discussed below.

Sheet Density

The best multiple regression equation for sheet density (Equation 1, Table III) accounted for 85% of the variation. Refining energy alone accounted for 83% of the variation. The strong positive effect of this variable is shown in Fig. 2(a).

The only significant wood factor was proportion of latewood, which interacted with refining energy as shown in Fig. 2(b). Increasing proportion latewood had a slightly negative effect on sheet density at low refining energy, while sheet density increased with increasing latewood at the higher refining energy.

For all significant variables within the range of the data, sheet density was increased by applying high refining energy and using wood containing a high proportion of latewood.

Burst Factor

The best multiple regression for burst factor (Equation 2, Table III) accounted for 89% of the total variation. Refining energy alone accounted for 66%; its positive effect on burst is shown in Fig. 3(a).

Wood characteristics of significance included proportion latewood, unextracted specific gravity, and growth rate. Proportion latewood interacted with refining energy. As shown in Fig. 3(b), burst strength increases with increasing latewood content for both levels of refining energy. The effect is slightly greater at the higher refining energy.

Figure 3(c) shows the interaction of unextracted specific gravity and growth rate on burst. Burst strength decreased with increasing specific gravity for both growth rates. The negative

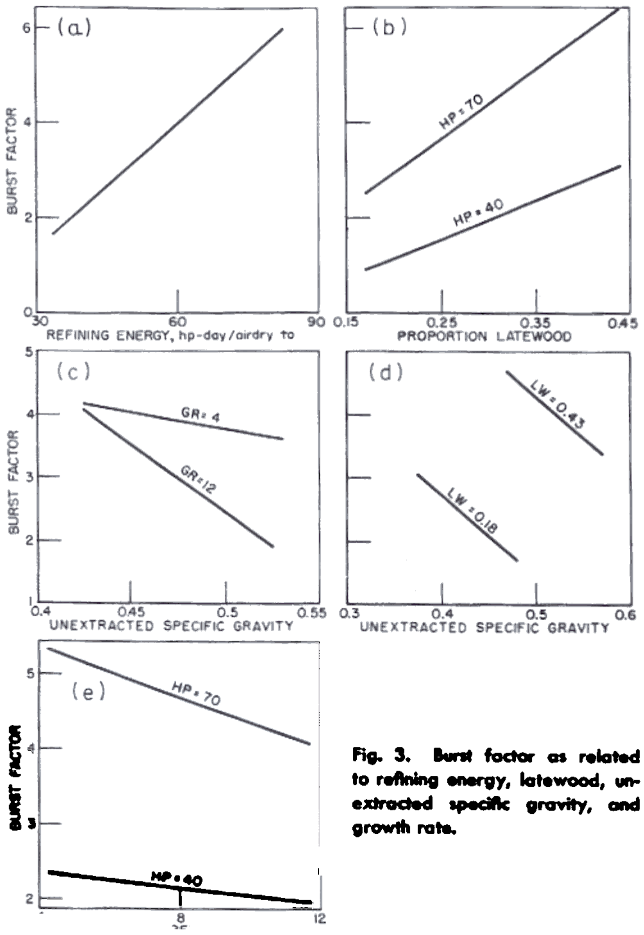

Fig. 3. Burst factor as related to refining energy, latewood, unextracted specific gravity, and growth rate.

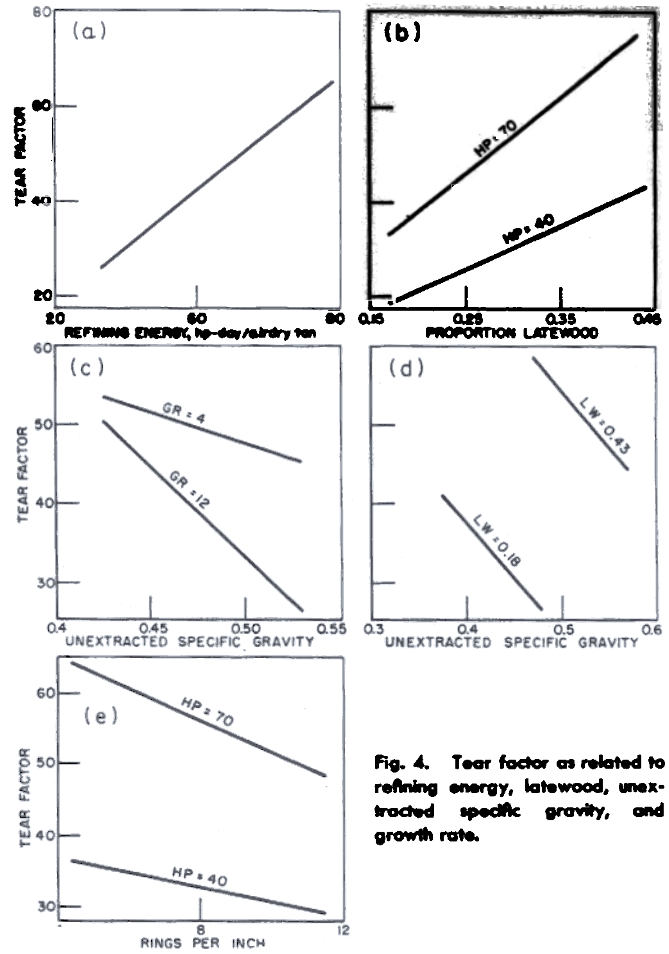

Fig. 4. Tear factor as related to refining energy, latewood, unextracted specific gravity, and growth rate.

effect is greater for wood of slow growth. For a given specific gravity, burst increased with decreasing rings per inch. The effect of unextracted specific gravity at two latewood contents is shown in Fig. 3(d). Burst decreased with increasing specific gravity and increased with increasing latewood content.

Growth rate also interacted with refining energy, as shown in Fig. 3(e). Burst strength decreased with increasing rings per inch, the negative effect being greater with increasing refining energy.

All significant variables considered, burst strength was increased by applying high refining energy and using fast-grown wood with a high latewood content and relatively low specific gravity.

Tear Factor

Equation 3 (Table III) accounted for the highest variation in tear strength: 89%.

The positive linear relationship between refining energy and tear is shown in Fig. 4(a). This variable alone accounted for 60% of the total variation.

As with burst, the significant wood factors were latewood content, unextracted specific gravity, and growth rate. The interaction of latewood content and refining energy is shown in Fig. 4(b). Tear strength increased with increasing proportions of latewood, with the rate somewhat greater at the higher refining energy.

The effect of unextracted specific gravity at two growth rates is shown in Fig. 4(c). Tear strength decreased with increasing specific gravity, the negative effect being greater for wood of slow growth. For a given specific gravity, tear increased with decreasing growth rate.

As with burst, tear strength decreased with increasing specific gravity, as can be seen in Fig. 4(d). For a given specific gravity, it increased with increasing latewood content.

Growth rate also interacted with refining energy, Fig. 4(e). Tear strength decreased with increasing rings per inch, the negative effect being greater with increasing refining energy.

For all variables considered, tear strength was increased by applying high refining energy and using fast-grown wood with a high proportion of latewood and relatively low specific gravity.

Breaking Length

This property was related to refining energy, latewood, extracted specific gravity, and growth rate. Equation 4 (Table III) accounted for 90% of the variation.

Breaking length increased with increasing refining energy, Fig. 5(a). This variable alone accounted for 71% of the total variation.

As shown in Fig. 5(b), breaking length increased with increasing latewood content, with the positive effect of latewood greater at the higher refining energy.

For reasons not clear, growth rate interacted with extracted specific gravity, while in the equation for burst and tear it interacted with unextracted specific gravity. Breaking length decreased with increasing extracted specific gravity, with the rate of decrease greater for wood of slow growth, Fig. 5(c). For a given specific gravity, breaking length increased with decreasing rings per inch. In contrast to its effect in burst and tear relationships, growth rate did not interact with refining energy.

The effect of extracted specific gravity at two latewood contents is shown in

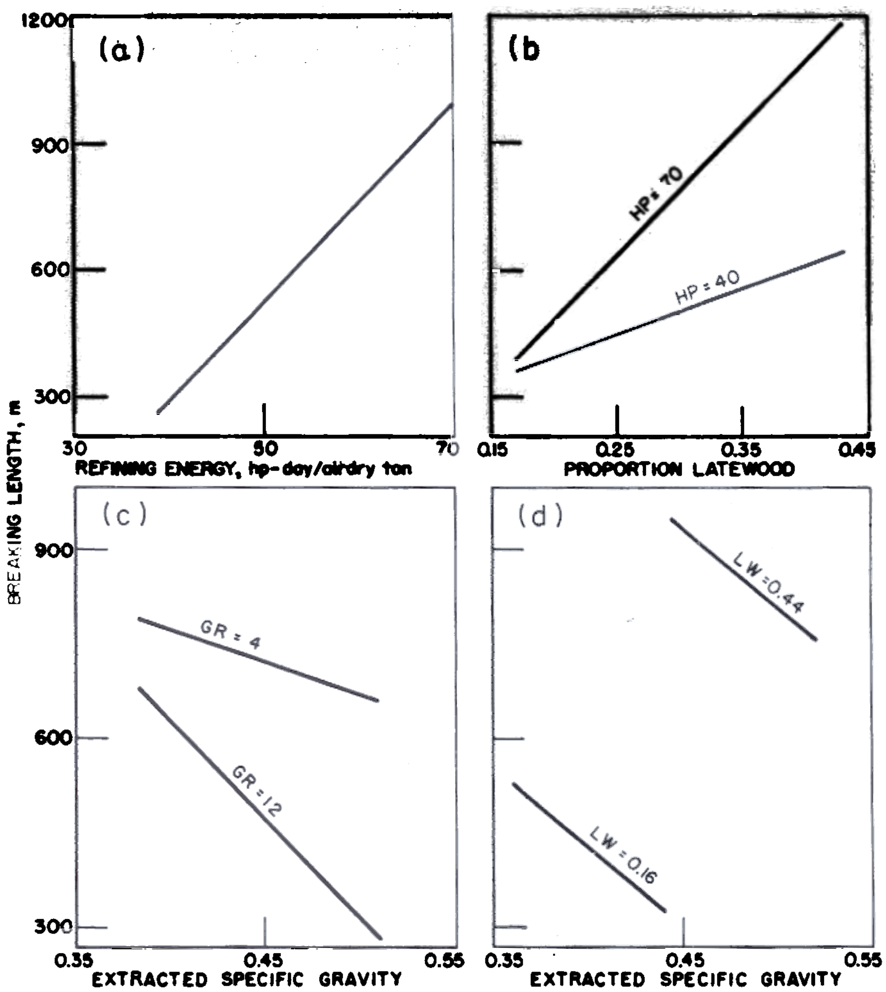

Fig. 5. Breaking length as related to refining energy, latewood, extracted specific gravity, and growth rate.

Fig. 5(d). Breaking length decreased with increasing specific gravity and increased with increasing latewood content.

All variables considered, breaking length was increased by applying high refining energy and using fast-grown wood with a high proportion of latewood and relatively low specific gravity.

DISCUSSION

Most properties considered here increased when handsheets were made from fiber refined from wood that contained a high proportion of latewood but was relatively low in specific gravity. Wood from three positions in the stem was considered: core, middle, and outer. The latewood content of loblolly pine characteristically increases with increasing rings from the pith. In the present study it increased significantly (0.05 level) from 0.262 for inner wood to 0.339 for middle wood to 0.380 for outer wood.

From this it may be surmised that fiber prepared from outer wood will yield handsheets of superior strength in accordance with the regression equations. The data in Table I confirm this observation. Thus, chips obtained from slabs and edgings of large logs would appear to be a desirable raw material from a strength standpoint. In contrast, chips from veneer cores would be expected to yield sheets of inferior strength.

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