A STUDY OF LOBLOLLY PINE GROWTH INCREMENTS—PART IV. PAPERMAKING PROPERTIES

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(Received 8 July 1980)

ABSTRACT

Loblolly pine growth increments were divided into five fractions: two earlywood, a transition, and two latewood growth zones. Each fraction was kraft digested to four different time schedules, Valley beaten, made into handsheets, and tested for tear, tensile strength, and bulk properties. Differences in these physical properties were related to inherent characteristics of individual fibers.

Tear factor was highly correlated with the relative position of wood from which the pulps were prepared, with respect to the growth ring. Earlywood pulps produced sheets of low tear values, whereas latewood pulps produced high tear factors. Variation in specific volume, or bulk, of handsheets showed trends similar to those of tear factor. However, intra-increment variation in tensile strength of handsheets was the opposite of those in tear and bulk. For all three physical characteristics of handsheets, most of the variations could be accounted for by relative position of tracheids within the growth rings of loblolly pine.

The extent of digestion and refining of the pulps affected tear and bulk adversely but improved tensile strength of handsheets. However, by far the most important single variable affecting sheet properties was inherent intra-increment tracheid morphology.

Keywords: Loblolly pine, kraft pulp, intra-increment, handsheet, tearing resistance, tensile strength, bulk, earlywood, latewood, papermaking, pulp.

INTRODUCTION

Knowledge obtained during the last twenty-five years indicates that proper application of silvicultural practices and careful consideration of genetic influences may lead to a reasonable control of wood quality of southern pine species. One of the most important changes that may be induced by such manipulations is that of the relative amount of latewood in individual trees of these species. In terms of pulping and stock refining characteristics of southern pines, earlywood and latewood have been reported to be more different from one another than are two entirely different species of wood (Ifju and Labosky 1972; Labosky and Ifju 1972; Gladstone and Ifju 1975; Ifju et al. 1975).

The objective of this study was to determine the papermaking properties of tracheids obtained from various growth zones within growth rings of loblolly pine. In addition, the objective was to relate bulk, tensile, and tear characteristics of the papers made from the intra-incremental growth zones to kraft pulp yield and freeness.

Wood and Fiber, 13(2), 1981, pp. 120–137

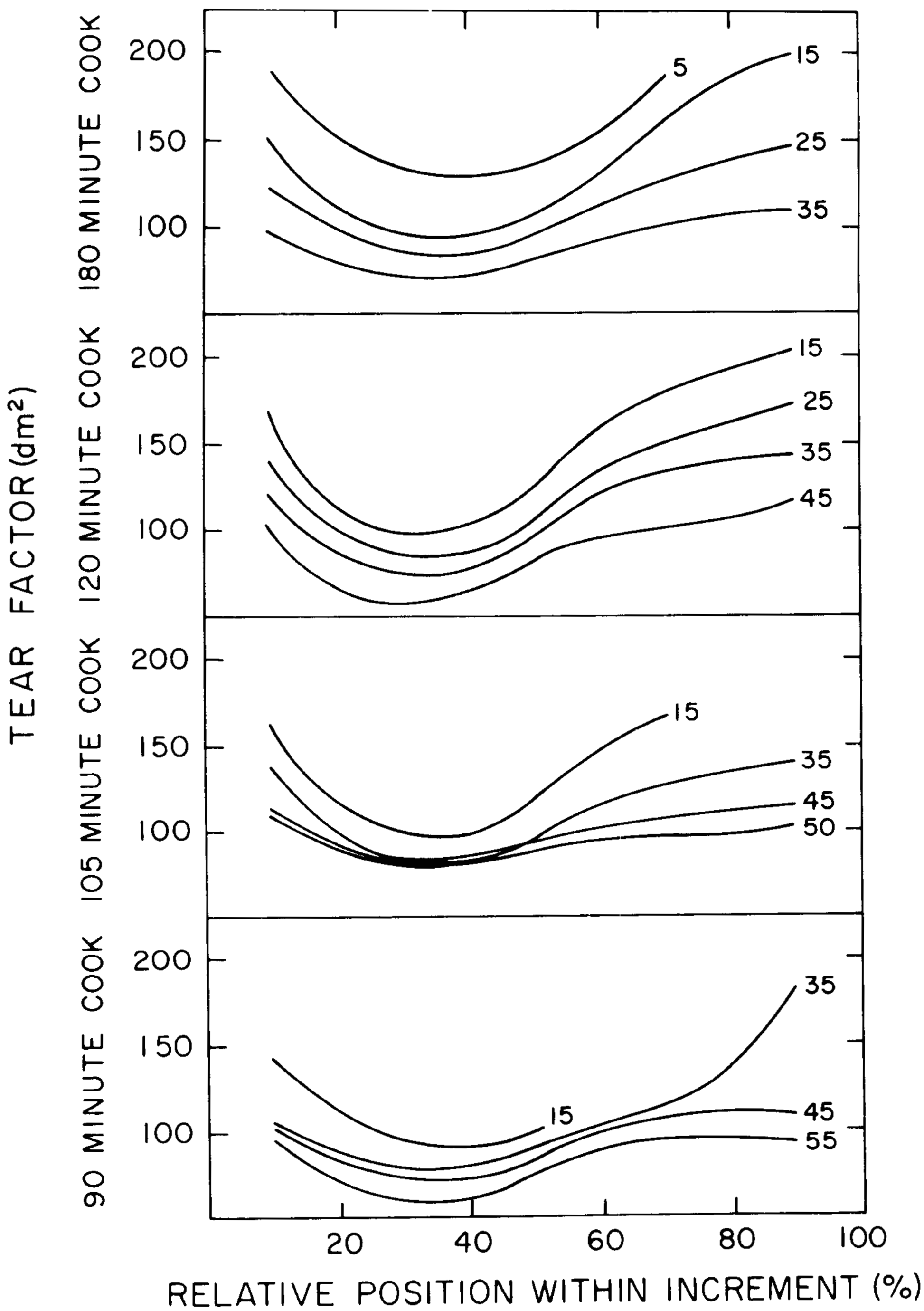


FIG. 1. Tear factor of handsheets made from tracheids originating from various relative positions within growth increments of loblolly pine and related to cooking time and beating time. Numbers in the diagrams represent beating times in minutes.

TABLE 1. *Regression models and corresponding coefficients for the variations in tearing resistance of handsheets made from pulps from intra-increment growth zones of loblolly pine.*

Cook time (minutes)	Beating time (minutes)	Replicates	Tear factor (dm²)					
			$Y = a + bx + cx^2 + dx^3$ (where x = position)					
			a	b	c	d	R	See
90	15	30	155.5	−0.38	−0.11	0.0019	0.852	14.62
	35	50	111.8	−0.78	0.01	−0.0000	0.663	17.42
	45	50	156.5	−5.77	0.12	−0.0007	0.941	5.32
	55	50	131.8	−4.52	0.10	−0.0006	0.886	5.27
	all	180	112.1	−0.78	0.01	−0.0000	0.360	21.77
105	15	40	252.7	−11.26	0.24	−0.0014	0.970	7.50
	35	50	192.6	−7.06	0.14	−0.0008	0.929	8.30
	45	50	150.1	−4.08	0.08	−0.0004	0.756	10.09
	50	50	138.7	−2.95	0.05	−0.0002	0.605	12.87
	all	190	186.5	−6.75	0.14	−0.0008	0.587	20.89
120	15	50	265.2	12.00	0.26	−0.0014	0.944	13.40
	25	50	212.7	−9.28	0.20	−0.0011	0.959	9.56
	35	50	184.4	−8.08	0.18	−0.0010	0.964	7.18
	45	50	136.9	−0.492	0.11	−0.0006	0.964	4.44
	all	200	197.5	−8.35	0.18	−0.0010	0.721	26.20
180	5	40	241.5	−6.64	0.11	−0.0004	0.895	14.76
	15	50	221.4	−9.17	0.19	−0.0010	0.984	6.84
	25	50	178.0	−6.63	0.13	−0.0007	0.952	8.06
	35	50	133.9	−4.36	0.09	−0.0005	0.954	4.79
	all	190	204.1	−7.98	0.17	−0.0010	0.590	31.83
Total		760	122.9	−1.06	0.02	−0.0000	0.435	30.42

EXPERIMENTAL PROCEDURES

Loblolly pine growth rings extracted from the mature portion of a fast-grown stem were divided into five growth zones: early springwood (fraction 1), late springwood (fraction 2), transition wood (fraction 3), early summerwood (fraction 4), and late summerwood (fraction 5). These positions expressed as percentages based on the total width of the rings were 12, 36, 57, 76 and 91%. The procedure used for separating the growth rings into the five incremental fractions has been described earlier (Ifju and Labosky 1972). In another paper, the procedures used for producing four kraft pulps from each of the five intra-incremental zones were reported (Labosky and Ifju 1972). The four cooking times were 90, 105, 120 and 180 min. Each of the twenty kraft pulps so obtained was subjected to four beating periods in a standard Valley beater, and Canadian Standard Freeness was determined (Ifju et al. 1975). Five Tappi Standard handsheets were prepared from each pulp after each beating time (Tappi Standard T205m-58 1958). This resulted in a total of 400 handsheets for physical tests (5 growth zones × 4 cooking times × 4 beating times × 5 handsheets). The total number of physical tests performed was 760 each for tensile strength, sheet bulk and tear (Tappi Standard T220-60 1960).

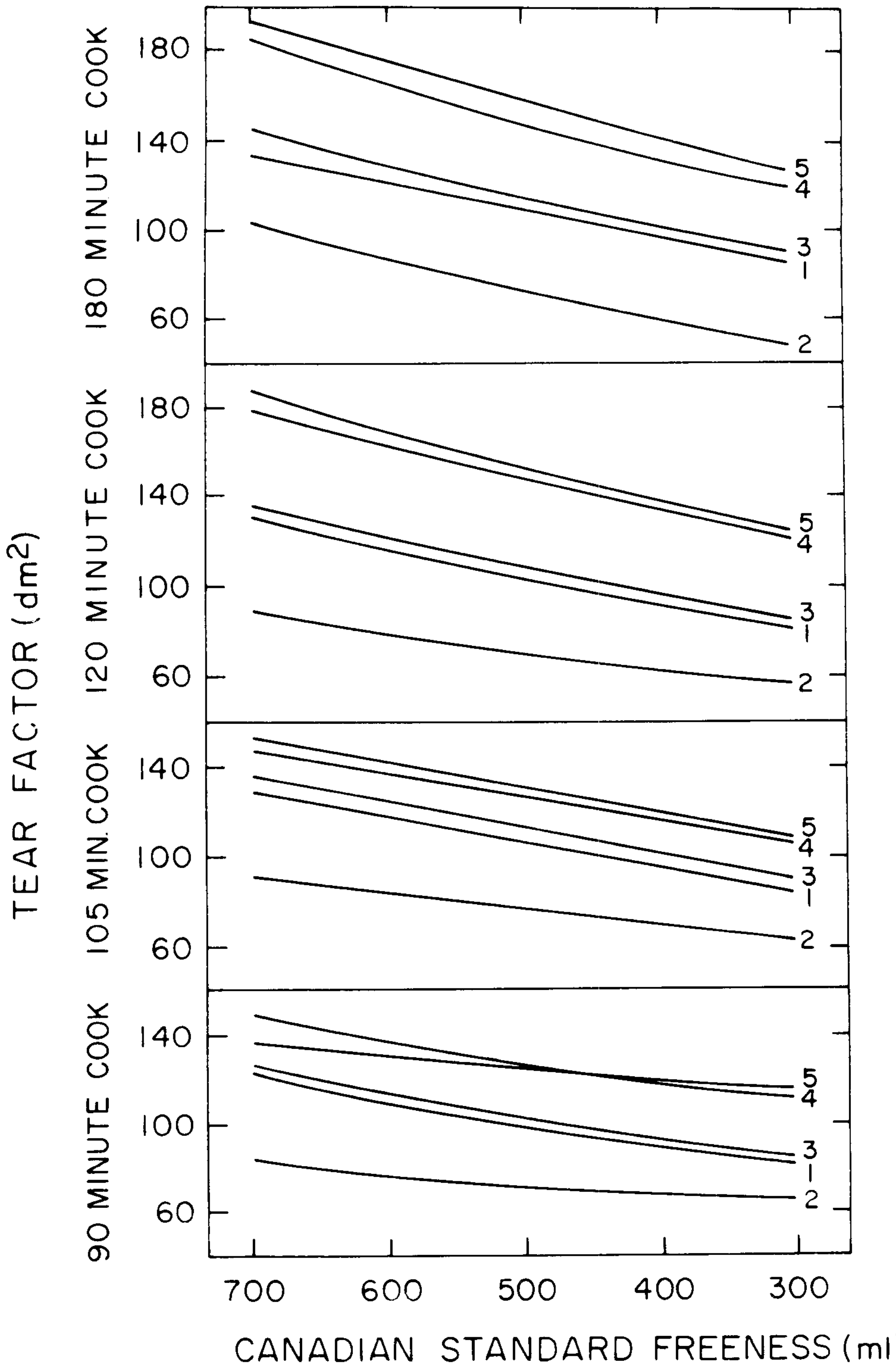


FIG. 2. Influence of pulp freeness on tearing resistance of four kraft pulps after refining. The numbers in the diagrams represent intra-increment growth zones from early earlywood (1) to late latewood (5).

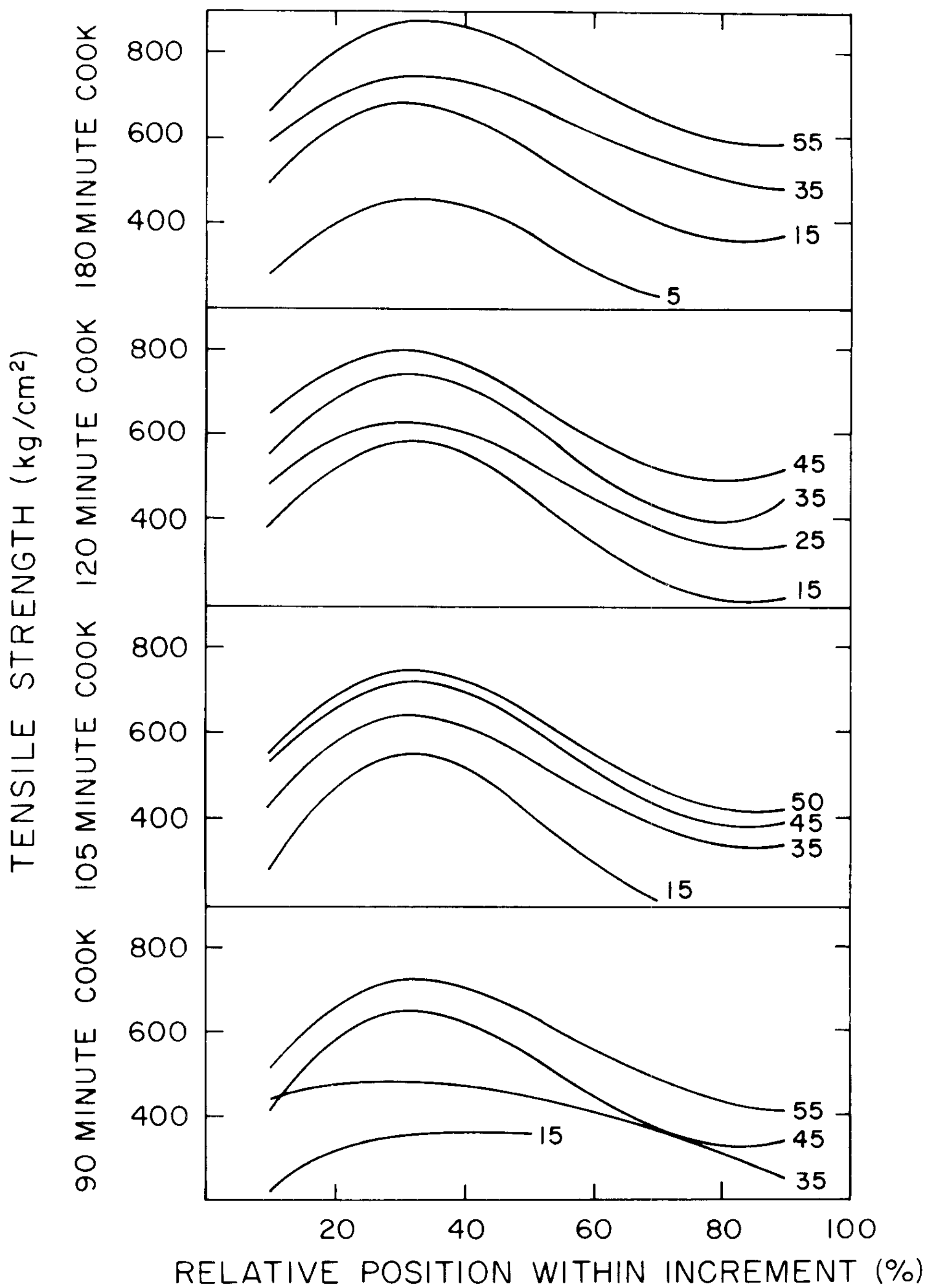


FIG. 3. Tensile strength of handsheets made from tracheids originating from various relative positions within growth increments of loblolly pine and related to cooking time and beating time. Numbers in the diagrams represent beating times in minutes.

TABLE 2. *Regression models and corresponding coefficients for the variations in tensile strength of handsheets made from pulps from intra-increment growth zones of loblolly pine.*

Cook time (minutes)	Beating time (minutes)	Replicates	Tensile strength (kg/cm^2) $Y = a + bx + cx^2 + dx^3$ (where x = position) a	b	c	d	R	See
90	15	30	170.3	2.45	0.266	−0.0005	0.949	22.03
	35	50	195.5	5.54	−0.090	0.0001	0.832	65.90
	45	50	48.3	44.43	−0.964	0.0056	0.981	24.19
	55	50	273.1	34.92	−0.719	0.0039	0.974	27.30
	all	180	388.2	6.05	−0.083	0.0001	0.484	123.53
105	15	40	−164.0	55.53	−1.293	0.0082	0.984	23.22
	35	50	111.6	38.44	−0.834	0.0048	0.965	30.71
	45	50	251.2	36.07	−0.812	0.0048	0.981	24.45
	50	50	257.9	36.11	−0.784	0.0045	0.962	34.89
	all	190	129.0	40.16	−0.900	0.0054	0.758	94.59
120	15	50	79.9	38.90	−0.886	0.0052	0.968	35.03
	25	50	271.5	27.89	−0.636	0.0037	0.963	30.95
	35	50	273.0	36.78	−0.835	0.0049	0.986	22.83
	45	50	408.7	30.72	−0.718	0.0044	0.945	35.73
	all	200	268.9	32.58	−0.747	0.0044	0.751	102.98
180	5	40	2.1	34.84	−0.798	0.0050	0.984	15.13
	15	50	221.3	34.76	−0.781	0.0046	0.977	25.36
	25	50	389.9	25.20	−0.530	0.0029	0.906	44.37
	35	50	413.0	32.03	−0.672	0.0038	0.897	52.20
	all	190	248.3	32.94	−0.737	0.0044	0.500	149.16
Total		760	510.8	3.68	−0.066	0.0001	0.482	138.19

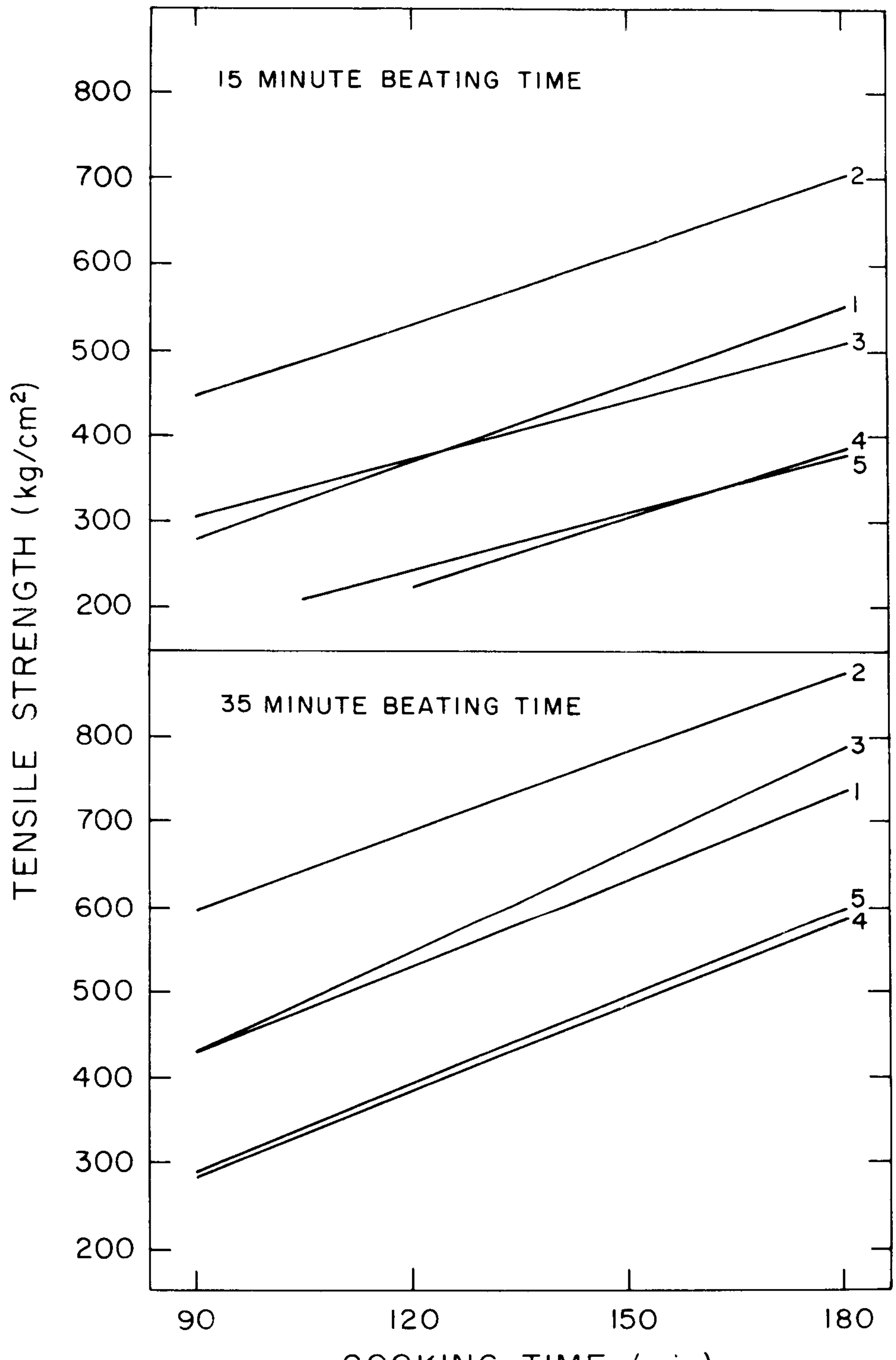
RESULTS AND DISCUSSION

Studies on intra-increment variations in pulping and related properties of loblolly pine showed large differences between growth zones (Ifju and Labosky 1972; Labosky and Ifju 1972; Gladstone and Ifju 1975; Ifju et al. 1975). On the basis of these early results, it was reasonable to expect that handsheet characteristics would also be affected.

Tear factor

Tearing resistance of paper has been shown to be related directly to fiber length and inversely to fiber-to-fiber bonding. Tracheid length measurements on the experimental material for this study showed small but significant differences with respect to growth zones in the growth rings (Ifju and Labosky 1972). The large variations in cell-wall thicknesses also reported earlier by Ifju and Labosky (1972) appeared to influence fiber flexibility, thereby affecting fiber-to-fiber bonding capacity of tracheids from the five growth zones.

The results of the tear strength measurements are given in Fig. 1. Tear factor is related to relative position of the wood source in the growth ring and also to cooking and beating times in the figure. The curves given in Fig. 1 were constructed on the basis of regression lines fitted to the experimental points. The form of the equations and the corresponding coefficients are given in Table 1.



15 MINUTE BEATING TIME
35 MINUTE BEATING TIME
TENSILE STRENGTH (kg/cm²)
COOKING TIME (min.)
800
700
600
500
400
300
200
90
120
150
180
1
2
3
4
5

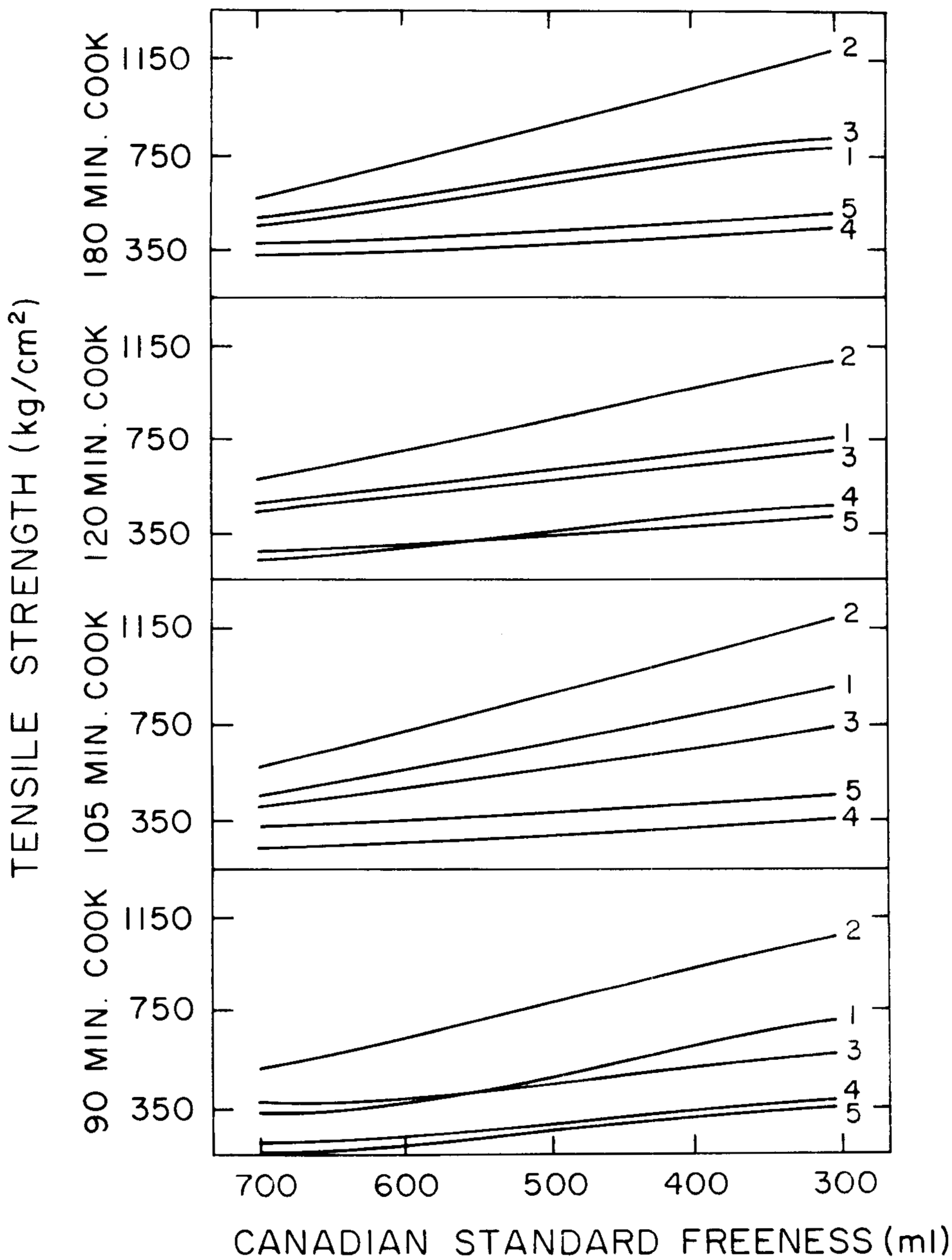


FIG. 5. Influence of pulp freeness on the tensile strength of four kraft pulps after refining. The numbers in the diagrams represent intra-increment growth zones from early earlywood (1) to late latewood (5).

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FIG. 4. Effect of cooking time on the tensile strength of handsheets refined for two time periods in a Valley beater. Numbers in the diagram represent intra-increment growth zones from early earlywood (1) to late latewood (5).

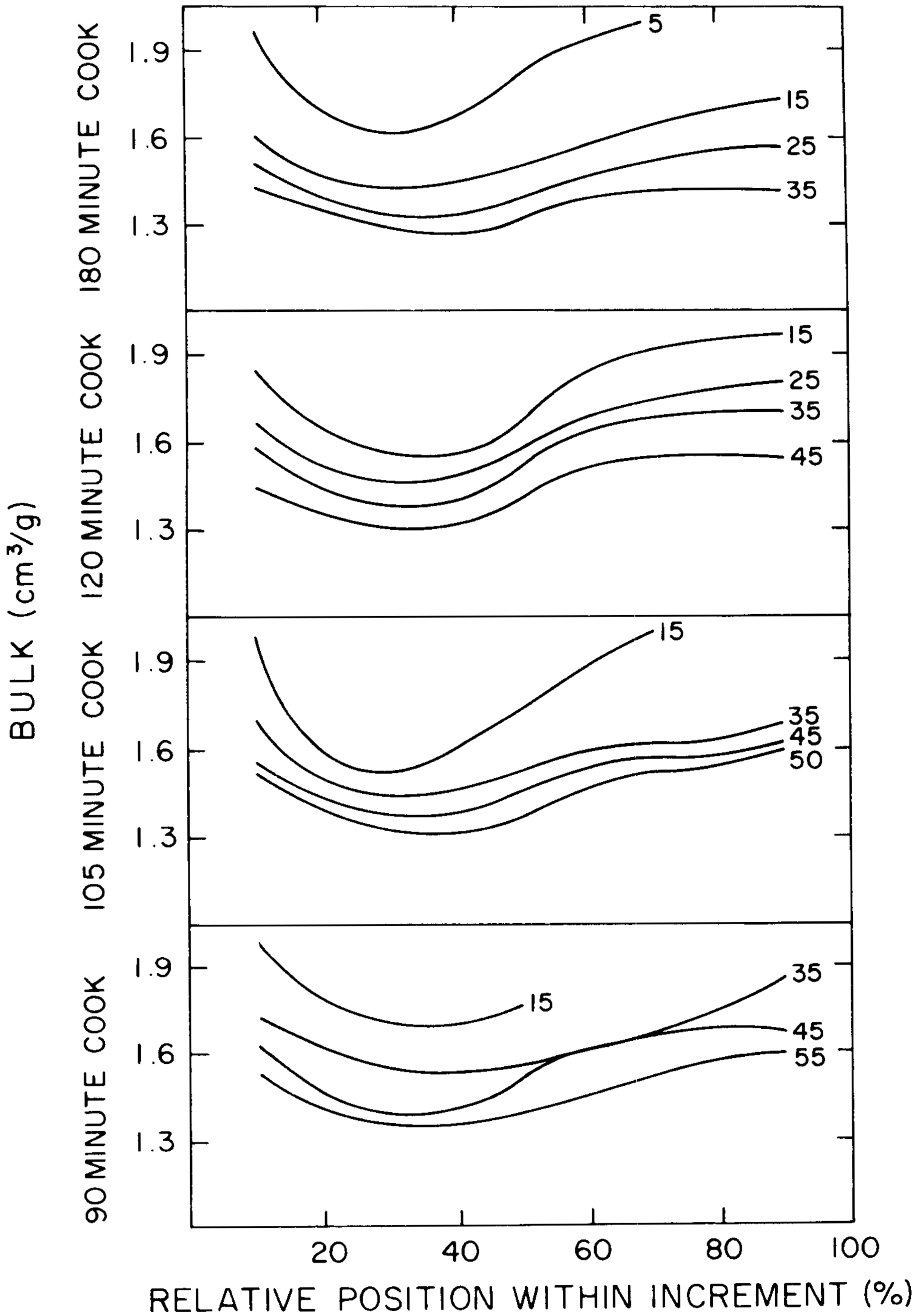

FIG. 6. Sheet bulk handsheets made from tracheids originating from various relative positions within growth increments of loblolly pine and related to cooking time and beating time. Numbers in the diagrams represent beating times in minutes.

TABLE 3. *Regression models and corresponding coefficients for the variations in bulk of handsheets made from pulps from intra-increment growth zones of loblolly pine.*

Cook time (minutes)	Beating time (minutes)	Replicates	Bulk (cm^3/g)					
			$Y = a + bx + cx^2 + dx^3$ (where x = position)					
			a	b/1,000	c/1,000	d/1,000	R	See
90	15	30	2.25	−20.60	−0.0539	0.0055	0.974	0.032
	35	50	1.72	−7.21	0.1091	−0.0001	0.831	0.072
	45	50	1.95	−37.66	0.8218	−0.0047	0.990	0.015
	55	50	1.67	−17.51	0.3190	−0.0015	0.976	0.019
	all	180	1.73	−6.81	0.0843	−0.0001	0.349	0.160
105	15	40	2.80	−98.08	2.2523	−0.0143	0.996	0.021
	35	50	2.03	−39.25	0.7966	−0.0044	0.954	0.036
	45	50	1.78	−26.97	0.5665	−0.0022	0.897	0.046
	50	50	1.74	−24.48	0.4725	−0.0024	0.912	0.041
	all	190	2.08	−46.85	1.0244	−0.0062	0.552	0.160
120	15	50	2.27	−54.56	1.1944	−0.0069	0.978	0.036
	25	50	1.95	−34.78	0.7678	−0.0044	0.982	0.023
	35	50	1.92	−41.13	0.9297	−0.0055	0.964	0.038
	45	50	1.68	−26.78	0.6226	−0.0038	0.973	0.019
	all	200	1.94	−37.94	0.8481	−0.0050	0.682	0.130
180	5	40	2.67	−78.99	1.8079	−0.0116	0.990	0.022
	15	50	1.85	−28.96	0.5989	−0.0035	0.955	0.033
	25	50	1.71	−23.64	0.4676	−0.0025	0.983	0.015
	35	50	1.60	−21.53	0.4472	−0.0025	0.923	0.024
	all	190	1.96	−38.77	0.8548	−0.0052	0.389	0.192
Total		760	1.64	−4.93	0.0725	−0.0001	0.341	0.179

It should be noted in Table 1 that each cooking time and beating time was handled separately; therefore, the only factor influencing tear factor in each equation is relative position of the wood source within the growth rings. The correlation coefficients (R) and the standard errors of estimate (See) shown in Table 1 indicate very high levels of association between the variables. If the coefficients of determination are calculated from the correlation coefficients, it may be seen that up to 97% of the variation in tear factor could be accounted for by the relative position of the tracheids in the growth ring alone.

For all cooks and for all beating levels, earlywood tracheids produced handsheets of lower average tear values than did latewood tracheids. Early springwood, however, and transition wood gave similar intermediate tear values, whereas latewood fractions had high tear properties.

As cooking time was increased for a given growth zone, the tear factor increased slightly or remained relatively unaffected. This indicates that removal of lignin by increasing the cooking time beyond a certain level does not have an important effect on sheet tearing resistance. Apparently, morphological and physical factors have greater importance in determining tearing resistance of paper sheets than do chemical factors.

It may also be observed that as beating time increased, the tear factor decreased. This inverse relationship was most apparent for handsheets prepared

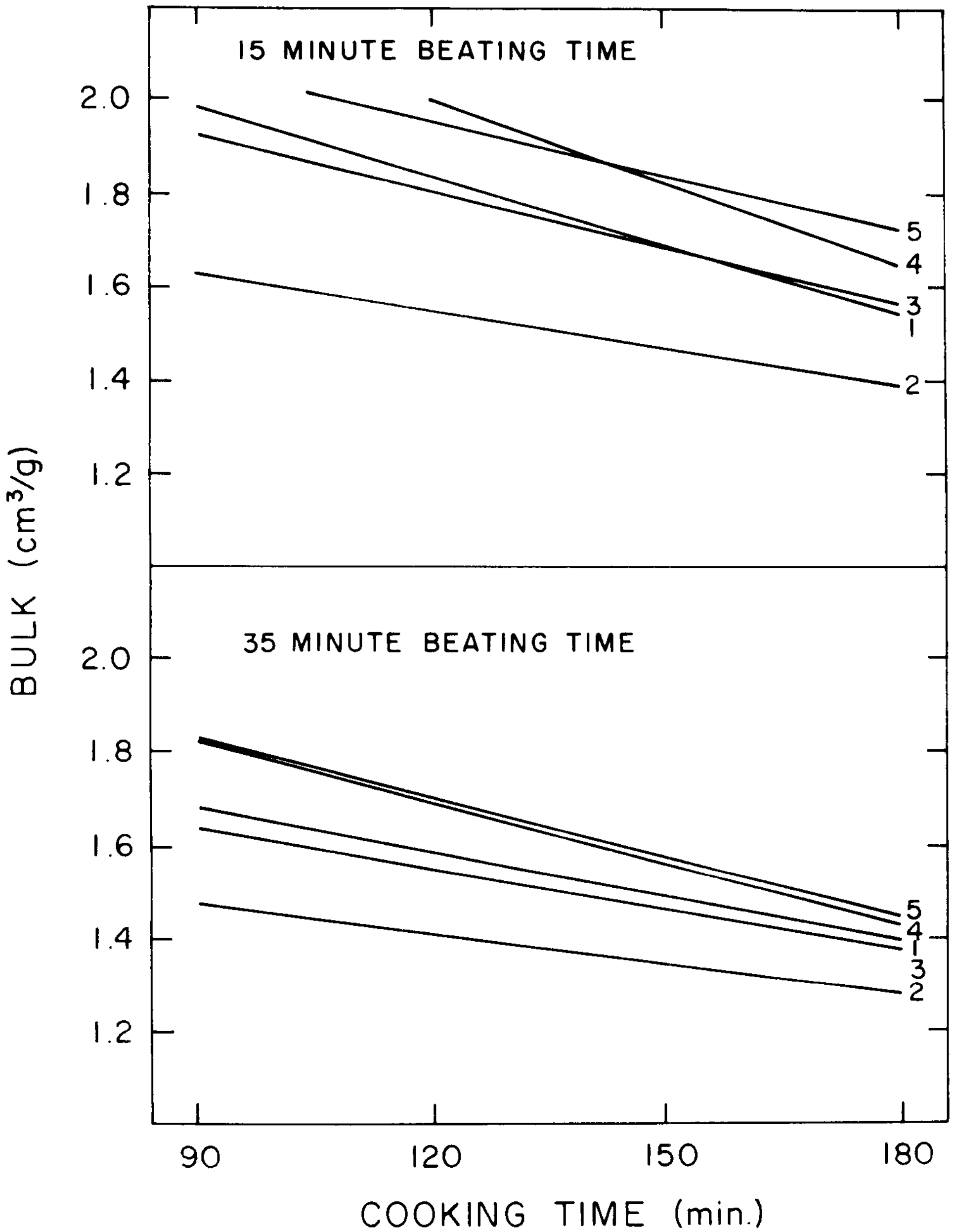

FIG. 7. Effect of cooking time on the bulk of handsheets refined for two time periods in a Valley beater. Numbers in the diagram represent intra-increment growth zones from early earlywood (1) to late latewood (5).

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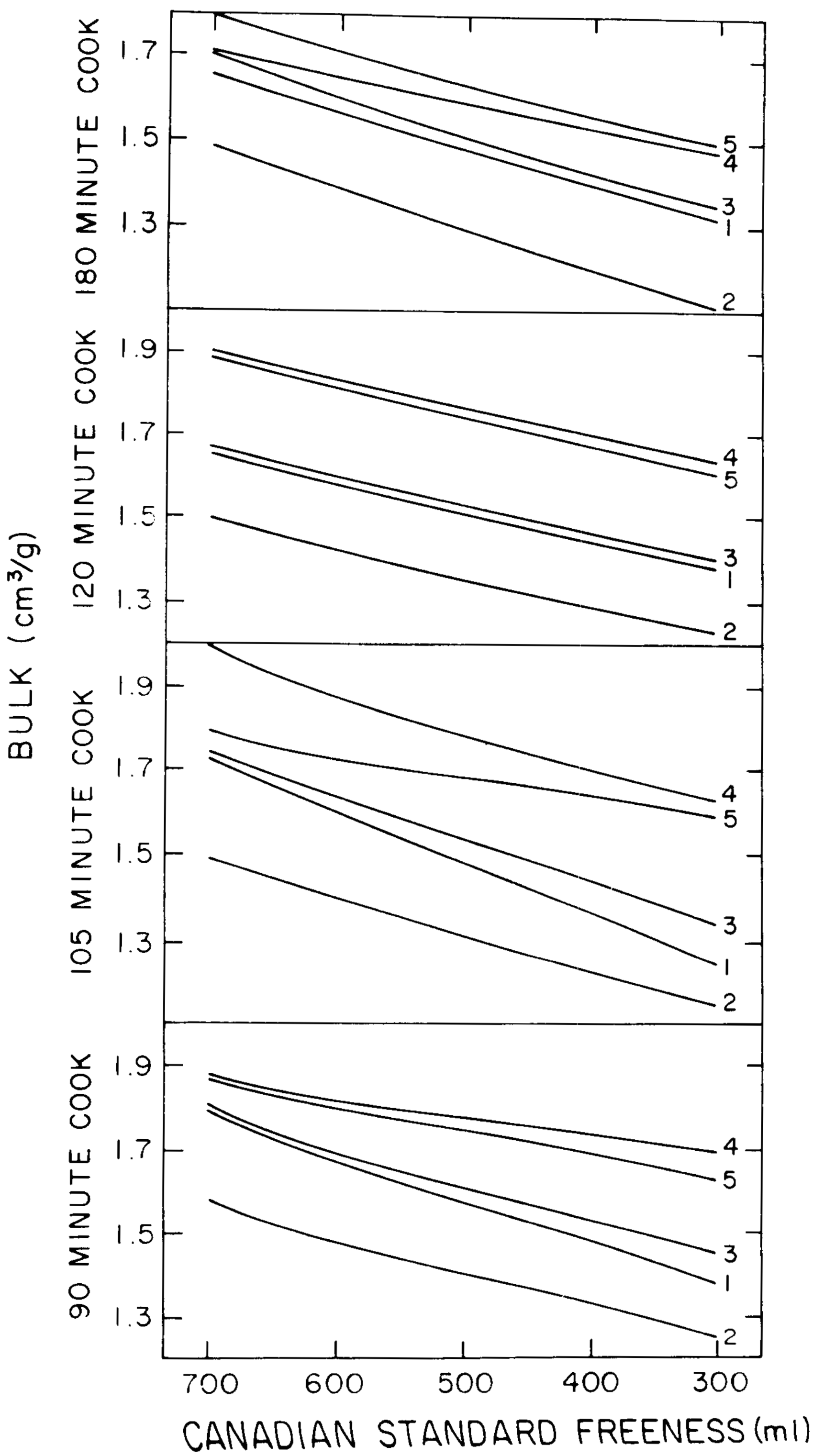
FIG. 8. Influence of pulp freeness on the bulk of handsheets made from four kraft pulps after refining. The numbers in the diagrams represent intra-increment growth zones from early earlywood (1) to late latewood (5).


BULK (cm³/g)
180 MINUTE COOK
120 MINUTE COOK
105 MINUTE COOK
90 MINUTE COOK
1.3
1.5
1.7
1.9
1
2
3
4
5
700
600
500
400
300
CANADIAN STANDARD FREENESS (ml)

from the 180-min cook. The relationship may be shown by plotting tear factor against Canadian Standard Freeness (Fig. 2). The slopes of the lines, representing each intra-incremental zone, are significantly steeper for the 180-min cook than for the 120-min cook, and so on down to the 90-min cook. As has been reported in an earlier publication, pulps delignified to a greater degree respond to refining treatments more readily than the higher yield pulps (Ifju et al. 1975).

In general, tear factor determined for handsheets made from the five growth zones of loblolly pine growth rings may be ranked to increase from earlywood to latewood with early springwood and late springwood changing relative positions in the ranking. This pattern of property change within loblolly pine growth ring has been found for tracheid morphology as well (Ifju and Labosky, 1972). The results of handsheet tests are thus consistent with those of anatomical and morphological measurements, further indicating a strong correlation between tracheid and paper sheet characteristics.

Tensile strength

Sheet tensile strength in this study was expressed in kg/cm^2 rather than as breaking length in km more conventional in the pulp and paper industry. This was done so that the influence of sheet thickness or bulk on tensile strength could be taken into consideration. Breaking length is insensitive to sheet thickness variations. Figure 3 shows the relationship of tensile strength of handsheets to the intra-incremental position of wood source for the pulps as well as to cooking and beating times. The curves in Fig. 3 were drawn on the basis of regression equations tabulated in Table 2. The high correlation coefficients show that the relative position of tracheids in the growth rings was by far the most important single variable affecting tensile strength of paper.

It is important to note that the curves themselves and their relative locations in Fig. 3 are very close to being the mirror images of those in Fig. 1. This indicates that the anatomical and morphological characteristics inherent in the origin of the tracheids with respect to the growth ring have the opposite effect on tensile vs. tear properties. Indeed, the thin-walled earlywood tracheids produced papers with high tensile strength but low tear values. On the other hand, handsheets made from thick-walled, rigid latewood tracheids had high resistance to tearing but low tensile strength. These results are in agreement with the early findings of Watson and Hodder (1954) and Watson and Dadswell (1962), who reported that an increase in wall thickness reduced bursting strength and breaking length, the two strength properties related to tensile strength. However, tearing resistance of those same handsheets showed the reverse response to changes in cell-wall thickness. It is well known that latewood tracheids have significantly thicker cell walls than earlywood tracheids. And these thick-walled latewood tracheids are more rigid and would therefore resist bending and intertwining during the papermaking process (Schniewind et al. 1965).

The extent of digestion had a direct effect on tensile strength. The longer the cooking time, the higher the tensile strength. This result may be explained on the basis of tracheid flexibility enhanced by extensive chemical treatment. In addition, removal of more lignin effected by longer cooking times exposed more of the carbohydrates on tracheid surfaces available for fiber-to-fiber bonding. The tensile strength–cooking time relationship shown in Fig. 4 illustrates this relationship for two beating times. It should be noted in Fig. 4 that early springwood (fraction 1) and transition wood pulps (fraction 3) behaved very similarly with respect to digestion time as did pulps from the two latewood zones. Here again, as in the case of tearing resistance, the late springwood zone and not the early springwood zone produced pulps most significantly different in terms of tensile strength.

Beating also increased handsheet tensile strength as was expected. As Canadian Standard Freeness (CSF) decreased with increasing beating time, tensile strength of the handsheet increased (Fig. 5). It should be noted that although CSF of latewood pulps dropped more significantly with beating time (Ifju et al. 1975), tensile strength of the handsheets improved more markedly for the earlywood pulps when compared at the same freeness level. The significantly greater slopes of earlywood pulps (fraction 2) in Fig. 5 show this trend.

Bulk

Bulk, or specific volume of paper (cm^3/g), is an important property. It has an influence on opacity as well as on printability of papers. Dense sheets having low bulk are less opaque but have superior surface characteristics and printability as opposed to low-density, bulky sheets. Figure 6 shows the relationship between bulk and relative position of tracheids within growth rings. This figure also shows the influence of cooking time and beating time on bulk. The curves in Fig. 6 were fitted to the experimental data using the least squares method. The regression model and the associated coefficients are given in Table 3.

The high levels of correlation between bulk and growth zones within growth increments may be observed in Table 3 as indicated by the correlation coefficients (R) and the standard errors of estimates (See). The relationships are similar to those for tear factor shown in Fig. 1 and appear to be opposite to those for tensile strength. Latewood tracheids with thick cell walls produced sheets of high bulk as opposed to thin-walled earlywood tracheids that produced sheets with low bulk.

As expected, cooking time was inversely related to sheet bulk (Fig. 7) as was beating time (Fig. 8). The relationships in Fig. 7 indicate that delignification promoted tracheid flexibility resulting in low bulk. However, as Canadian Standard Freeness decreased with beating time, bulk was proportionately reduced.

Bulk, or the reciprocal of sheet density, may be used as an independent variable influencing strength properties. Hatton and Samkova (1972) examined relationships between strength properties and bulk for spruce kraft pulps made from stem, branch, stump, and root woods. They found that the slopes of the lines fitted to their data points could be used for characterizing the paper sheets. Kellog and Thykeson (1975) found that breaking length, bursting strength, and tear factor were not linearly related to bulk of commercial western hemlock kraft pulps. The relationships could be used for characterizing machine-made papers.

Figures 9 and 10 show the influence of bulk on the tensile strength and tearing resistance, respectively. The relationships shown in the figures are lines fitted to the experimental data. The regression equations with the corresponding coefficients are shown in Table 4. If the slopes of the regression lines are useful in characterizing the pulps, as suggested by Hatton and Samkova (1972), the regression coefficients (b) should be compared. For the tensile strength relationships,

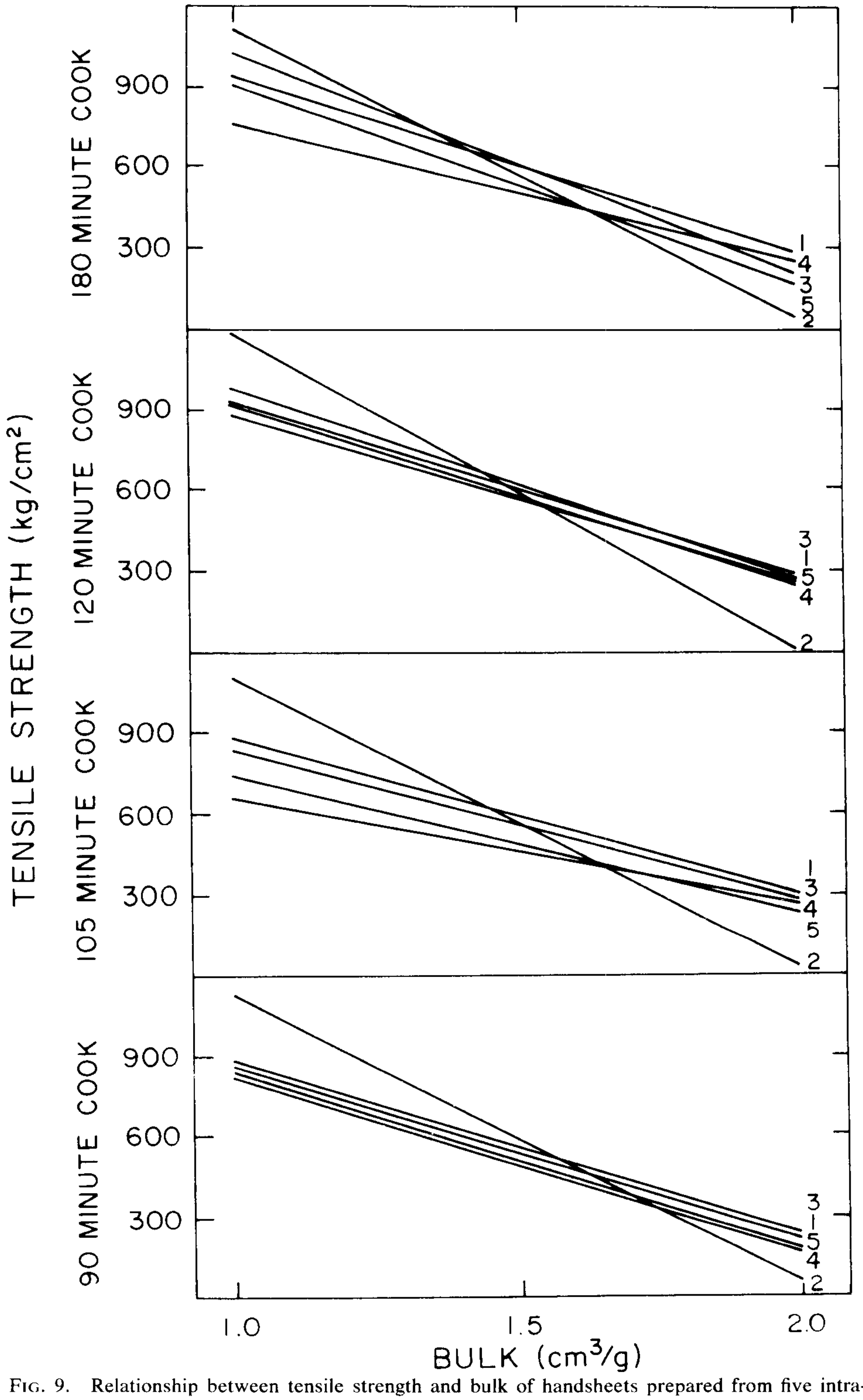


FIG. 9. Relationship between tensile strength and bulk of handsheets prepared from five intra-increment growth zones of loblolly pine kraft digested to four different time periods. Numbers in the diagrams represent within-ring growth zones from early earlywood (1) to late latewood (5).

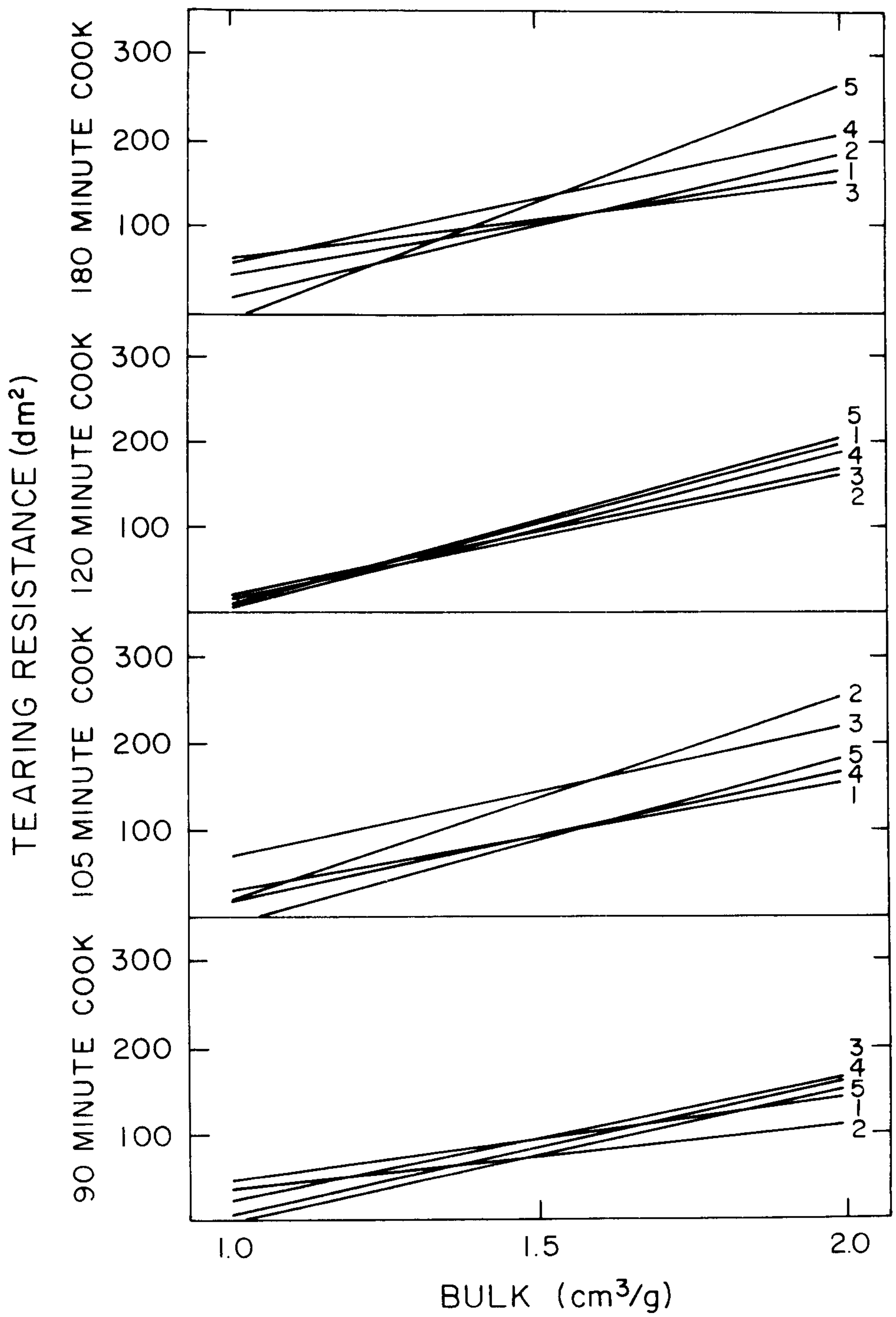


FIG. 10. Relationship between tearing resistance and bulk of handsheets prepared from five intra-increment growth zones of loblolly pine kraft digested to four different time periods. Numbers in the diagrams represent within-ring growth zones from early earlywood (1) to late latewood (5).

TABLE 4. *Tear factor and tensile strength related to sheet bulk for handsheets made from pulps from intra-increment growth zones of loblolly pine.*

Cook time (minutes)	% position	Replicates	Tear factor (dm²)				Tensile strength (kg/cm²)			
			Y = a + bx (where x = bulk (cm³/g))							
			a	b	R	See	a	b	R	See
90	12	40	−44.05	91.64	0.921	7.52	1,429.8	−598.5	0.972	27.94
	36	40	−41.56	78.54	0.908	4.54	2,221.6	−1,087.3	0.975	30.91
	57	40	−66.47	107.62	0.893	9.79	1,491.3	−631.0	0.962	32.37
	76	30	−153.76	158.69	0.939	7.28	1,468.9	−658.3	0.969	21.11
	91	30	−155.28	154.37	0.910	6.50	1,479.1	−656.7	0.948	20.41
	all	180	−96.87	121.94	0.893	10.46	1,712.4	−772.5	0.934	50.09
105	12	40	−25.49	91.16	0.922	6.68	1,482.5	−600.0	0.968	27.02
	36	40	−49.36	94.02	0.792	5.63	2,289.0	−1,142.7	0.961	25.63
	57	40	−2.90	74.64	0.920	5.15	1,398.0	−569.7	0.960	26.96
	76	40	−125.95	144.66	0.978	7.42	1,111.0	−435.0	0.976	23.27
	91	30	−233.44	214.45	0.957	3.99	1,268.6	−526.6	0.851	19.84
	all	190	−87.45	125.08	0.932	9.29	1,588.9	−685.6	0.910	59.82
120	12	40	−171.82	183.56	0.950	7.74	1,734.9	−735.6	0.962	26.82
	36	40	−125.79	143.90	0.897	5.16	2,489.3	−1,252.1	0.920	38.94
	57	40	−137.77	158.33	0.960	5.48	1,625.8	−690.5	0.960	23.77
	76	40	−195.57	195.91	0.873	16.57	1,649.8	−720.8	0.891	55.57
	91	40	−187.07	195.58	0.920	13.67	1,541.7	−661.9	0.982	20.62
	all	200	−204.13	201.69	0.950	11.77	1,869.3	−836.5	0.955	45.92
180	12	40	−92.01	138.93	0.948	10.19	1,645.5	−683.6	0.966	40.21
	36	40	−149.98	171.29	0.984	4.31	2,177.9	−1,061.6	0.966	38.95
	57	40	−42.59	104.47	0.932	8.41	1,892.0	−840.8	0.944	60.82
	76	40	−100.56	154.86	0.869	21.17	1,327.5	−549.2	0.949	43.87
	91	30	−292.18	282.48	0.964	9.58	1,659.2	−740.8	0.933	34.84
	all	190	−127.87	164.63	0.871	19.29	1,731.7	−759.7	0.920	67.18
Total		760	−112.67	143.26	0.805	19.99	1,725.2	−763.2	0.919	61.96

the late springwood fractions appear to show greater slopes than the other four growth zones. However, for the tear-bulk relationships, no significant differences among the slopes may be found. Therefore, the value of these relationships to characterize the pulps obtained from five growth zones of loblolly pine growth rings is questionable.

CONCLUSIONS

From the results of this study of within-growth ring variation in the papermaking properties of loblolly pine tracheids, the following conclusions may be drawn:

1. Physical properties of paper are highly dependent on the inherent intra-increment characteristics of tracheids in loblolly pine. The relationships are such that thick-walled latewood tracheids promote high bulk and increased resistance to tear, but thin-walled earlywood tracheids improve tensile strength.
2. Although digestion and refining have significant influence on paper sheet properties, by far the most important source of variation is caused by inherent tracheid characteristics in kraft pulps.

3. Tree improvement programs aimed at assisting the southern pulp and paper industry should focus on wood and fiber (tracheid) quality of superior trees in addition to volume or weight (specific gravity) production.

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