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Title: PULPING CHARACTERISTICS OF DOUGLAS-FIR SAWDUSTS

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A kraft pulping study has been conducted on Douglas-fir sawdust of two different particle sizes. The coarse sawdust was produced by a Swedish gang saw with a blade thickness of .18-.20", and the fine sawdust was produced by a Quad headrig with a blade thickness of .12-.13". Pulp mills have been accustomed to using the coarse sawdust, whereas the fine sawdust is just recently becoming available as sawmills are converting to the use of fine bladed saws, in an effort to conserve raw material and produce more lumber. Additionally, a similar pulping study was made on individual fractions of the coarse sawdust, which were obtained by screening with 1/4", 6, 10, and 20 mesh screens.

The different sawdust samples were each pulped separately with 15%, 20%, 25%, and 30% active alkali, based on the sawdust weight. Otherwise, the pulping conditions were constant. The pulps were processed by normal laboratory techniques, made into

handsheets, and tested by TAPPI Standard methods. The test data were analyzed by a variety of statistical methods, including analysis of variance, paired "t" test, and a combination of analysis of variance with multiple regression analysis.

The coarse sawdust had more material retained on the 1/4" mesh screen, and less on the 20 mesh screen, both significant at the .001 level. Similarly, the coarse sawdust pulps had 9% more long fibers than the fine sawdust pulps. The yields of the coarse sawdust pulps were about 1.5% higher and the Kappa numbers were about 6.5 ml higher than the corresponding values of the fine sawdust pulps.

Coarse sawdust pulps required about 6 minutes longer to reach a given freeness level and produced handsheets that were .06 g/cc lower in apparent density than fine sawdust pulps. The higher density of the fine sawdust handsheets partially explains the higher average values for breaking length, stretch, bursting strength, and folding endurance, which are, respectively, 1450 m, 0.20%, 8 m^2/cm^2, and 90 double folds greater than the corresponding values for coarse sawdust handsheets. The shorter average fiber length of the fine sawdust pulps explains their higher densities. By contrast, the average tearing strength of the coarse sawdust handsheets is 6 dm^2 higher than that of the fine sawdust handsheets, a reflection of the longer fibers in the former handsheets.

Values for the coarse and fine sawdust handsheet properties were predicted from the values of the corresponding properties of pulps made from fractionated sawdust. Linear and log-log relationships were tested in a weighted average formula, and the log-log model was able to predict strength properties of the whole sawdust pulp handsheets within an average 5% deviation of the true value.

Both coarse and fine sawdust pulps produce weaker paper than does pulp from chips. Utilization of the fine sawdust, however, should not prove detrimental to strength properties of those grades where sawdust is presently used, with the exception of tearing strength.

Pulping Characteristics of Douglas-fir Sawdusts

by

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INTRODUCTION

Sawdust comprises a substantial amount of the raw material requirements for many of the kraft pulp mills in the Pacific Northwest. Harkin (1969) stated that approximately 2.3 million oven-dry tons of wood residues were processed into paper products, and the western states have the major outlets for the material. Recently, utilization of sawdust in southern pulp mills has begun to develop. Sawdust has now become generally acceptable for pulping so that this may represent the best long-term outlet for such a residue.

Many sawmills are converting their equipment to narrow kerf saw blades. The reason for this changeover is that the narrow blades waste less material during lumber production, thus increasing production efficiency. These saws cut kerfs about 0.13" vs. 0.18" wide for older Swedish gang saws. Utilization of these narrow blades produces a finer sawdust with smaller average particle size. Thus, it seems evident that the Northwest pulp industry must begin to cope with increasing amounts of this finer particle size material in their operation, and a knowledge of its pulping characteristics seems essential to successful utilization.

The objective of this study was to compare the kraft pulping properties of coarse and fine Douglas-fir sawdusts, and also to establish the correlation between the particle size and pulp properties. The next step was to determine whether the pulping properties of the original sawdust samples could be predicted from a knowledge of the pulping properties of the different particle size fractions of the samples. The results should be of substantial help in the operations of the pulp and paper industry.

LITERATURE REVIEW

Kraft Pulping

The kraft or sulfate process is the most common process used to pulp Douglas-fir wood, since the presence of the extractive taxifolin limits the use of the calcium base sulfite pulping process (Casey 1961).

The literature reveals a modest amount of pulping research on Douglas-fir sawdust, including articles by Samuels (1962), Anon. (1964), Wilkie (1965), Hackett (1967, 1968), and Sullivan (1970). These articles will be further discussed. However, in all this work, no one has fractionated sawdust and performed pulping experiments on the individual fractions.

Advantages and Uses of Sawdust Pulp

One of the major characteristics of sawdust pulp is its shorter fiber length, which usually means lower strength properties. However, there are numerous uses for pulp in which strength and fiber length are not of paramount importance, and in fact there are some cases in which some short fiber is necessary. By blending variable amounts of sawdust pulp with chip pulp, the former can be used to advantage in many grades of paper.

Harkin (1969) reported that the finer fibers from sawdust pulps are used in place of hardwood pulps that have been found to improve the printing characteristics of papers. Hackett (1967) reported that Longview Fiber Co., Longview, Wash., used Douglas-fir sawdust and shavings pulp to replace hardwood kraft pulp in the manufacture of special converting paper grades.

It was reported that blending 10-15% of Douglas-fir sawdust pulp into a regular kraft furnish will improve formation, opacity, and printability (Anon. 1964). Blackerby (1967) also reported that 10-15% of the kraft pulp used for the manufacture of bag and wrapping papers as well as linerboard, consists of sawdust and shavings pulps. Sullivan (1970) noted that the short fiber pulp in limited quantities has filling properties which improve both surface smoothness and printability of the finished sheet. Dyck (1965) reported that the Crown-Zellerbach Elk Falls mill in British Columbia was using up to 10% sawdust pulp in the chemical pulp portion used in the manufacture of newsprint. Sullivan (1970) reported that kraft pulp from 100% sawdust is used for tissue paper which is converted into bathroom tissue, towels, and napkins. Harkin (1969) reported that minor amounts of sawdust pulp produced from continuous digesters are blended with normal chip pulp and used in a variety of products, ranging from newsprint and tissue to bag and business papers.

Sawdust and shavings are also an important raw material for refiner groundwood manufacture. Bell (1963), Service (1967), Morkved and Larson (1968), Harkin (1969), and Nystrom and Okell

(1969) noted that these materials can be used in addition to chips for making refiner groundwood, which finds uses in newsprint, tissue, towels, etc.

General Characteristics of Sawdust Pulping

Sawdust, because of its small particle size, behaves very differently in a digester than chips do. Martin (1959) noted that coarse sawdust materials were slightly easier to pulp than standard chips, whereas the fines were less readily pulped.

Sutherland (1965) stated that the small particles of sawdust mat together and present fewer voids for liquor circulation than in the case with chips. Further, the small particle size presents an immense increase in surface area. Therefore, sawdust has an enormous increase in the ability to absorb cooking liquor which contributes to quick impregnation. This tendency for the particles first exposed to liquor to absorb chemicals may deplete the amount of chemicals available for impregnation of the balance of the mass. In addition, sawdust has a great tendency to mat and acts as an insulator to itself, causing nonuniform liquor penetration and poor heat transfer. This effect may cancel the basically rapid liquor impregnation quality of the small particles of wood.

The following are some characteristics of sawdust from Sutherland (1965):

1. Small particle size--large surface area.
2. Lack of normal chip circulation voids.
3. Rapid absorption of liquor.
4. High packing characteristics.
5. Self-insulating.

These peculiarities of sawdust are inter-related and combine to present unique problems in pulping. The problem, then, is to accomplish the essential pulping steps of uniform liquor distribution, absorption, and uniform heat transfer which is essential to a controlled end product.

However, with the pulping systems developed within the past 10-15 years, coarse sawdust and shavings can be delignified on a continuous basis using short (approximately 30 min) cooking cycles, in contrast to the 2.5- to 6-hour cycles used for cooking normal chips (Harkin 1969). This has opened the field for the conversion of these wood wastes to paper products.

Particle Size Distribution of Coarse and Fine Sawdusts

Simmon and Hiller (1960) studied particle size distribution of various types of sawdust. The results showed that the fiber length of sawdust pulp tended to decrease with a decrease in sawdust particle size, but the fiber length of pulp from hardwood sawdust did not vary with sawdust particle size. In Table 1 the particle size distributions of some commercial Douglas-fir sawdusts are given.

Table 1. Screen classification of Douglas-fir sawdust (Simmon and Hiller 1960).

Saw or planer	Screen fractions (%)				Total
	-2 +4	-4 +8	-8 +16	-16	
Band headsaw	0. 2	32. 1	45. 4	32. 3	100. 0
Band resaw	0. 7	19. 4	37. 8	42. 1	100. 0
Gangsaw	0. 4	24. 2	38. 2	37. 2	100. 0
Edger	1. 8	19. 8	41. 5	36. 9	100. 0

Note: The symbol -2 +4 means that the fraction passed through the 2 mesh screen but was retained on the 4 mesh screen.

Effects of Sawdust on Paper Properties

Sawdust pulps generally have shorter fiber lengths than conventional chip pulps. The effects of the sawdust pulps on paper properties have been examined by many researchers who have shown significant correlations between certain fiber dimensions and physical properties of paper.

Wilkie (1965) concluded that strength loss due to sawdust blending is linear with the amount of sawdust, and bleached paper-grade (filler-type) sawdust kraft pulp has only approximately 70% of the strength properties of chip pulp produced from hemlock and/or Douglas-fir. Cross (1966) revealed that the strength of sawdust pulp is 20-30% lower than that of comparable chip pulp. Chao and Laver

(1959) pulped sawdust from barked logs of loblolly pine and mixed hardwoods by the kraft process. The results revealed that the pulps obtained were inferior to those from regular mill chips. It also indicated that sawdust pulps have a relative high lignin and a low pentosan content and give a high proportion of fines after defibration. It has been indicated that blending 10-15% of Douglas-fir sawdust into a regular kraft furnish has resulted in only slight reductions in mechanical properties (Anon. 1964). Martin (1959) pulped "sawdust chips" produced by a coarse feed saw, and found little loss in strength properties of the resulting pulp.

In the following discussions, results obtained from chip pulp will be identified thus: ______________ (chips). Otherwise the discussion concerns results of sawdust pulping.

Freeness

Dinwoodie (1966) reported that the freeness in Sitka spruce (*Picea sitchensis* (Bong) Carr) was determined primarily by fiber length and secondarily by fiber density, while the beating time to a given freeness was inversely related to average cell wall thickness, and to the Runkel ratio (chips). Barefoot *et al.* (1964) reported that the cell wall thickness accounted for 78% of the variation in beating time of loblolly pine (*Pinus taeda* L.) and that the Runkel ratio would account for 85% of the variation (chips). Blackman (1970) reported that beating time is directly correlated to fiber length (chips). Wilkie (1965) stated that sawdust pulp freeness drops faster with beating than chip pulps do.

Yields

Nolan (1963) reported that the variation in size distribution of shredded chips has a minor effect on total yield but a very marked effect on screened yield. Nolan (1968) also studied the yields from shredded chip fractions and concluded that as the chip cross section decreases, a definite increase in screened yield and slightly diminished total yield are found. Wilkie (1965) noted that low yield is to be expected from the finer material in a sawdust sample.

Sheet Density

Barefoot _et_ _al._ (1964) reported that within the range of variables considered, high sheet density is obtained from low specific gravity wood with thin summerwood cell walls, low Runkel ratio, and short fiber length (chips). Blackman (1970) noted that sheet density is inversely correlated to fiber length (chips).

Bursting Strength

Barefoot _et_ _al._ (1964) found the fiber length was directly related to bursting strength, but at a low level of significance (chips).

Dinwoodie (1966) stated that the principal factors determining the bursting strength are fiber density and fiber length (chips). Horn (1972) reported that a high ratio of pulp fiber length to cell wall thickness value indicated high bursting strength (chips).

Martin (1959) reported that sawdust chips from a new, coarse-feed saw gave kraft pulp with bursting strength of 80-85% of that for regular-chip pulp, and also concluded that the bursting strength decreased as the wood particles became smaller. Samuels (1962) studied the NSSC pulps prepared from Douglas-fir sawdust and red alder chips, and the results indicated that the burst values were lower for sawdust pulps than for red alder pulps under all pulping conditions. Mixtures of the two materials produced pulps with burst values intermediate between those of pulps from either material alone.

Simmonds and Hiller (1961) indicated that the bursting strength of kraft pulp from screened fractions of southern yellow pine sawdust was 60-85% of that of kraft pulp from 5/8'' chips, and softwood sawdust pulps had equal bursting strength compared with hardwood kraft pulps. Nolan (1968) reported that the pulps from the 16-mesh fraction were 19.6% lower in bursting strength than those from the 2 to 8-mesh fraction (shredded chips).

Stretch

Dinwoodie (1966) reported that fiber length was directly related to stretch in Sitka spruce. A similar relationship was noted by Clark (1958). Blackman (1970) concluded, however, that stretch is inversely correlated to fiber length.

Tensile Strength

Barefoot et al. (1964) reported that tensile strength was inversely related to both the latewood cell wall thickness and to the Runkel ratio. A lesser degree of significance was found for a direct relationship to fiber length. These relationships were confirmed in Sitka spruce by Dinwoodie (1966), and in slash pine by Einspahr (1964). Horn (1972) concluded that as the fiber length and cell wall thickness ratio increases, the tensile strength of handsheets increases (chips).

Nolan (1968) reported that the pulps from the 16-mesh fraction were 14.8% lower in tensile strength than those from 2 to 8-mesh fraction in the freeness range of 300-700 ml (shredded chips). When comparing the pulps from the 10-mesh fraction to the 2 to 8-mesh fraction, there is no clearcut difference in tensile strength.

Folding Endurance

Folding endurance was reported as being directly related to fiber length by Clark (1942), Hentschel (1958), and Wangaard (1962) (chips).

Tearing Strength

Dinwoodie (1966) reported that cell wall thickness was directly related to tearing strength in Sitka spruce (chips). The relationship was confirmed in works by Jayme (1958) and Dadswell (1962) (chips). Blackman (1970) noted that internal tearing resistance is directly correlated to fiber length (chips). Barefoot *et al.* (1964) reported that there is no relationship of tearing strength to fiber length (chips).

However, many researchers have shown a significant effect of sawdust pulps on tearing strength. Martin (1959) reported that the tearing strength decreased as the wood particles became smaller. Owen (1962) indicated that sawdust pulps had low tearing strength, and he concluded that the low tearing strength resulted from lack of a normal percentage of longer fibers. Nolan (1968) reported that the presence of the 10-mesh fraction in the shredded chips leads to about a 10% loss in tearing strength. The pulps from the 16-mesh fraction were 21% lower in tearing strength than those from the 2 to 8-mesh fraction in the freeness range of 300-700 ml. He concluded that when the fibers of the resultant pulp are severely cut, low tearing strength results. Simmonds and Hiller (1961) indicated that the tearing strength of kraft pulp from screened fractions of southern yellow pine sawdust was 60-85% that of kraft pulp from 5/8" chips. They also reported that softwood sawdust pulps had longer fibers and higher tearing strength than hardwood kraft pulps.

In summary, paper properties have been shown to be functions of fiber characteristics. Beating time, bursting strength, and tensile strength are inversely related to both the latewood cell wall thickness and the Runkel ratio. Freeness, stretch, folding endurance, and tearing strength are directly related to fiber length. Due to the shorter fiber length, sawdust pulp has lower strength, yield, and freeness than chip pulp.

EXPERIMENTAL PROCEDURE

Sample Selection and Preparation

The sawdusts used in this project were obtained from the Hobin Lumber Co., Philomath, Oregon, on October 19, 1971. This mill obtains its logs from the coastal range area west of Philomath, and is processing Douglas-fir exclusively. The coarse sawdust was obtained from the production line which utilizes a Swedish gang saw for rough dimensioning of lumber from the logs. The blades of this type of saw are about .18-.20" thick. The fine sawdust obtained came from the production line which utilizes a new type of saw, the Quad Headrig, manufactured by the Albany International Industries, Inc., of Albany, Oregon. This is a modern high capacity headrig utilizing narrow kerf bandsaw blades about .125" thick. The two production lines utilize essentially the same type of logs, except that the Swedish rig can handle logs up to 24" in diameter while the Quad Headrig is limited to logs not more than 16" in diameter.

The bark, knots, and other debris were removed by hand from the sawdusts. The sawdusts were packed in polyethylene bags, and stored in a cold room maintained at 4°C.

Part of the regular coarse sawdust was fractionated on a Tyler vibrating screen using various mesh sizes. The top deck was equipped with a screen with 1/4" opening, followed by 6-, 10-, and 20-mesh screens. The sawdusts retained on the above various screens were collected and packed in plastic bags respectively, and also stored in a cold room maintained at 4°C.

The solids content of each batch was measured using the following formula:

$$\text{Percent solids} = \frac{\text{Oven dry weight of sawdust at } 110^{\circ}\text{C}}{\text{Wet weight of sawdust}} \times 100\%$$

The percent solids was checked for each sample to assure that the correct amount of wood was used for each pulping experiment.

Screen Analysis of Douglas-fir Sawdusts

Both coarse and fine sawdusts were analyzed on the Tyler Rotap sifter, using the 8" diameter Tyler standard screen. In a typical screening procedure, the top screen of a nest of four screens was filled about 3/4 full of sawdust. The nest was placed in the Rotap sifters and the machine was operated for exactly 15 min. At the end of this period, the sawdusts on each screen and in the bottom pan were weighed and the screen analysis calculated. Three samples of each sawdust were screened in order to obtain a reliable analysis.

Pulping Procedures

Each kind of sawdust was pulped by the kraft process under comparable cooking conditions of time and temperature. These cooks were performed in a stainless steel digester of 12 liter capacity. Liquor was circulated continuously and heated with steam in an external heat exchanger. The digester temperature was measured with a thermocouple and controlled by a Honeywell Electronic 15 cam controller, which regulated the amount of steam entering the heat exchanger. The white liquor for the cooks was formulated from concentrated stock solutions of sodium sulfide and sodium hydroxide. A predetermined amount of the stock solution was measured and diluted with distilled water to give a final liquor to wood ratio of 8:1. In order to obtain different yields and study the sawdust response, variable amounts of active alkali (sodium hydroxide and sodium sulfide) of 15, 20, 25, and 30% were used for pulping each of the samples. The cooking plan is shown in Figure 1.

Individual sawdust charges of 1000 grams (O. D. basis) were placed in a fine mesh wire basket and sealed in the digester for each cook. The cooking conditions are shown in Table 2.

The unscreened yield for each cook was calculated by weighing the entire batch of freshly cooked sawdust and measuring the percent solids of an aliquot sample of the pulp. The unscreened yield was determined by the following formula:

$$\text{Unscreened yield } (\%) = \frac{(\%\text{ solids}) \times \left(\begin{array}{c}\text{cooked sawdust}\\ \text{wet weight}\end{array}\right)}{\text{Uncooked sawdust dry weight}} \times 100\%$$

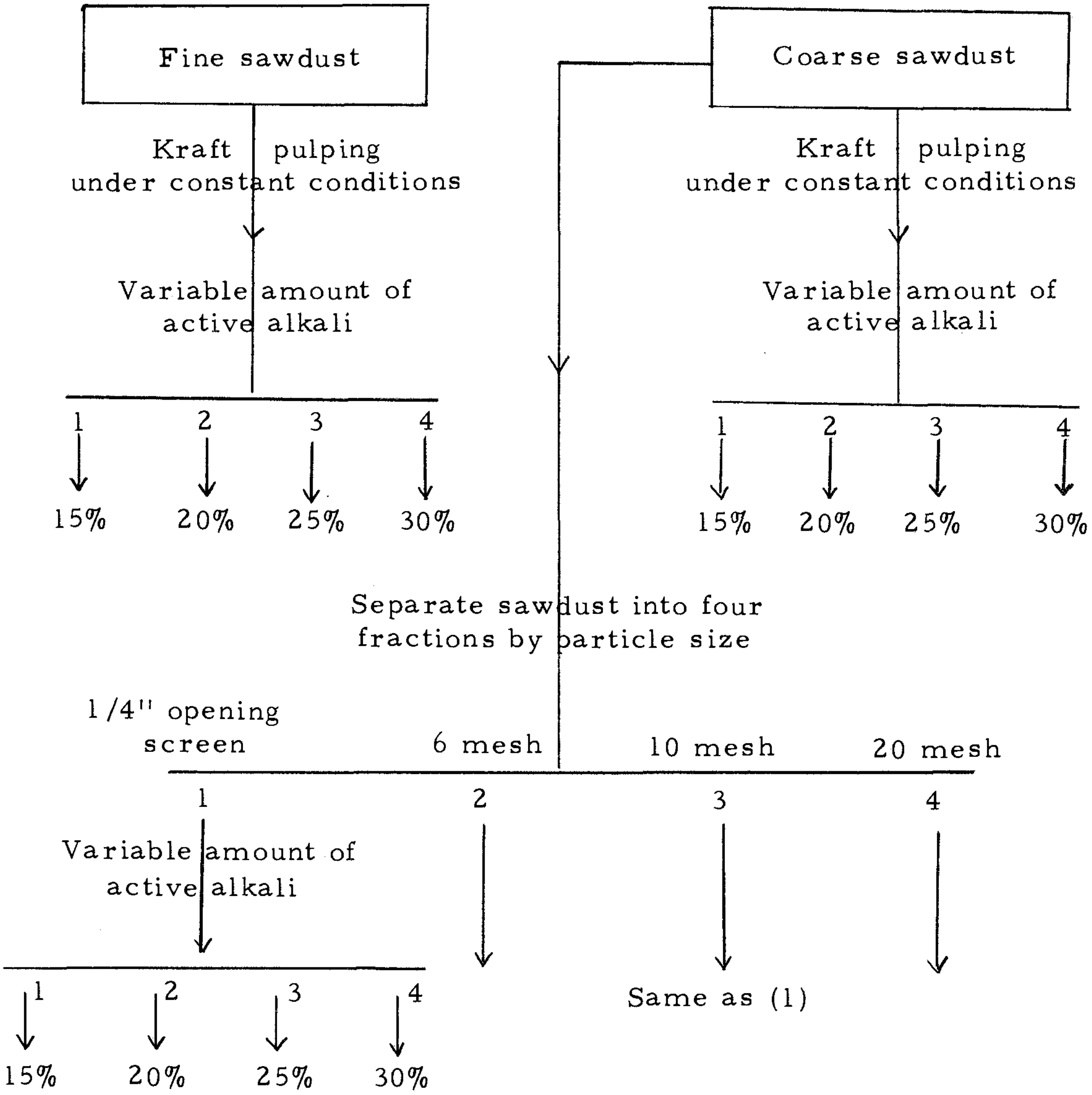

Figure 1. Sawdust cooking plan.

Table 2. Kraft pulping conditions.

Chemical	
Active alkali (as Na_2O) based on O. D. wood	15% 20% 25% 30%
Sulfidity	20%
Liquor to wood (O. D.) ratio	8:1
Schedule	
Impregnation time	45 min
Cooking time	120 min
Digester Conditions	
Final temperature	340°F (171. 1°C)
Final pressure	105 psi (7. 5 kg/cm)
Wood Input	
Total sawdust weight per cook (O. D.)	1000 g

A black liquor sample was taken when each cook was blown, and after cooling to room temperature it was analyzed for active and total Na_2O by potentiometric titration of 5 ml of black liquor with HCl. Active and total Na_2O concentrations were determined by the following formulae:

$$\text{Active } Na_2O \text{ (g/l)} = (\text{Volume HCl to pH } 7.5) \times (\text{Normality HCl}) \times 6.2$$

$$\text{Total } Na_2O \text{ (g/l)} = (\text{Volume HCl to pH } 4.0) \times (\text{Normality HCl}) \times 6.2$$

Pulp Preparation

The cooked sawdusts needed only a small amount of mechanical action to defiber them into pulp. A batch of cooked sawdust was equally divided into two 5-gallon buckets and diluted to about 4 gallons total. Each suspension was agitated for 15 min with a stirrer manufactured in accordance with TAPPI Standard T200ts-66.

The pulp slurries were screened through a Valley Laboratory Pulp Screen fitted with 0.018'' wide slots. Pulp which passed through the screen was accepted for further work.

The screening rejects were removed, oven dried, and weighed for screened yield calculations. Screened yield was calculated using the following formula:

$$\text{Screened yield (\%)} = \frac{\left(\text{Calculated unscreened pulp dry weight}\right) - \left(\text{Screenings dry weight}\right)}{\text{Uncooked sawdust dry weight}} \times 100\%$$

The screened pulp was collected, dewatered, sealed in plastic bags containing a few drops of formaldehyde, and stored in a cold room maintained at 4°C.

Fiber Classification

From each of the two replicated cooks per sawdust sample, 7.5 g (O. D.) of pulp were removed and combined for one fiber classification test in the Bauer-McNett fiber classifier. Screen sizes were set at 20, 35, 65, and 150 mesh. This test was performed in accordance with TAPPI Standard T233su-64.

Kappa Number Determination

A Kappa number determination was made on a random sample of each pulp in accordance with TAPPI Standard T236m-60. Two determinations per sample were made and averaged to give the value reported for each cook.

Pulp Refining and Handsheet Formation

Pulp refining was performed in a Valley Beater in accordance with TAPPI Standard T200ts-66. For each sample, a total of 360 g (O. D.) of pulp obtained equally from each replicated cook was charged for one beater run, and each sample was refined to a Canadian Standard Freeness below 200 ml.

Sufficient stock for one Canadian Standard Freeness evaluation and seven handsheets were taken at suitable intervals for further testing. Canadian Standard Freeness evaluations were made in accordance with TAPPI Standard T205m-28. The handsheets were conditioned for 48 hours in a TAPPI Standard room at 73°F and a relative humidity of 50%.

Handsheet Testing

Five of the seven handsheets were selected for physical tests at each beater interval, with the remaining sheets being saved for reference purposes.

Prior to physical testing, average sheet weight, caliper, and density were determined in accordance with TAPPI Standard T220m-60.

Brightness was determined with an Elrepho Colormeter at filter position number 8, by averaging five readings taken from each sheet.

Physical testing of handsheets was performed in accordance with TAPPI Standard T220-60, with the exception of sheet divisions.

Each of the five handsheets per beater interval was prepared for physical testing by cutting to the plan shown in Figure 2. At each beater interval, 10 burst, 5 tensile, 5 fold, 5 stretch, and 4 tear tests were performed.

For the tensile and stretch measurements, the Instron testing machine was set at a crosshead speed of 1 cm/min and the chart speed was 10 cm/min. Bursting tests were performed on a Perkins Model C Mullen Tester in accordance with TAPPI Standard T403ts-63. Folding endurance was measured on an MIT Fold Tester in accordance with TAPPI Standard T420-50. A summary of these test methods is given in Table 3.

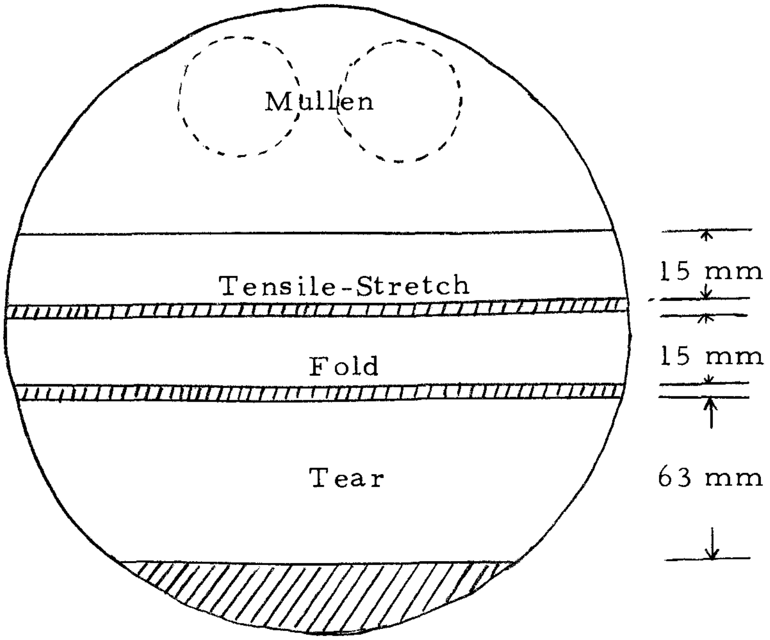

Figure 2. Cutting diagram for handsheet testing.

Table 3. Summary of physical tests.

Test	TAPPI Standard Method	Test Instrument	Unit of Measurement
CSF	T227m-58	Freeness Tester	ml
Sheet density	T220m-60		g/cm^3
Brightness	E. -1p[a]	Elrepho Colorimeter	% reflectance at 457 nm
Breaking length	T404ts-66	Instron TT-BLM	m
Stretch	T457m-46	Instron TT-BLM	%
Mullen factor	T403ts-63	Perkins Model C Mullen tester	m^2/cm^2
Tear factor	T414ts-65	Elmendorf tearing tester	$dm^2 \times 10^2$
MIT fold	T511su-66	MIT fold tester	No. double-folds

[a] Canadian Standard Method

Statistical Analysis

A forward stepwise, multiple linear regression analysis (OSU program-01) was used to determine the correlation between pulp and paper properties, and the following independent variables: (1) different kinds of sawdust and fractions, (2) percent active alkali, (3) total yield, (4) Kappa number, (5) Canadian Standard Freeness, and (6) sheet density.

The regression equations were generated in the form:

$$Y_i = b_0 + b_1 X_{1i} + b_2 X_{2i} + \ldots + b_6 X_{6i} + e_i \qquad i = 1, 2, 3, \ldots, n$$

where

Y = value of the dependent variables

b_0 = constant overall mean

$X_1, X_2, \ldots, X_6$ = actual value of the independent variables

$b_1, b_2, \ldots, b_6$ = regression coefficients of the independent variables

e = deviation of actual value from expected value under the model

The data for the coarse-fine sawdusts and fractionated sawdusts were analyzed separately.

In the case of the coarse-fine sawdust comparison, the fitted regression equation for the coarse sawdust in a given condition could be written as:

$$\hat{Y}_c = b_0 + a + b_1 X_1 + \ldots + b_6 X_6 \qquad (1)$$

while for the fine sawdust is

$$\hat{Y}_f = b_0 + b_1 X_1 + . . . + b_6 X_6 \qquad (2)$$

By difference:

$$(1) - (2) \quad \hat{Y}_c - \hat{Y}_f = a \qquad (3)$$

Equation (3) indicates that the average difference between the coarse and fine sawdusts for a given property at certain conditions is equal to the constant "a." Therefore from the value "a" the difference of a given property between coarse and fine sawdusts could be determined. The Student's "t" value (the ratio of the regression coefficient to its standard error) was used to demonstrate if there was a significant correlation between a given dependent pulp property and any independent variable.

A combination of analysis of variance and multiple regression was used to analyze the data for the fractionated sawdusts. Where independent variables can be quantified, as in the case of yield and amount of cooking chemical used, multiple regression techniques are applicable. Analysis of variance calculations must be used, however, where similar independent variables cannot be quantified, but only classified, yet are important to the analysis of the data and an understanding of the problem. To combine the two techniques, the following multiple regression scheme is used (Table 4).

The complete matrix is shown only for the first category, 1/4" opening screen sawdust pulped with 15% active alkali, and the

Table 4. Scheme of statistical analysis.

Sawdust fraction	Amount of chemical (%)	Beating interval (min)	Dummy variables			Independent variables			
			X_5	X_6	X_7	X_1	X_2	X_3	X_4
1/4" opening	15	1	1	0	0	-	-	-	-
		2	1	0	0	-	-	-	-
		3	1	0	0	-	-	-	-
		4	1	0	0	-	-	-	-
	20	1-4 etc.	1	0	0	-	-	-	-
	25	"	1	0	0	-	-	-	-
	30	"	1	0	0	-	-	-	-
6 mesh	15-30 etc.	1-4 etc.	0	1	0	-	-	-	-
10 mesh	"	"	0	0	1	-	-	-	-
20 mesh	"	"	-1	-1	-1	-	-	-	-

remainder of the total matrix is suggested below, following the same scheme. Variables 5-7 are called "dummy variables" and are used in the regression analysis to identify the sawdust fractions. Note that $\Sigma X_5 = \Sigma X_6 = \Sigma X_7 = 0$. The actual numerical values for the independent variables are entered in the analysis, and the complete set of data used are given in Appendix Table 4.

Two separate regressions were run with these data, a reduced regression and a full regression. In the first case, only variables 1-4 inclusive were entered, whereas in the second case, all variables, 1-7, were entered. The purpose of the reduced analysis was to study the effects of variables 1-4 (pulping parameters) on pulp quality, independent of sawdust particle size. The full regression equation in addition brought in the effect of sawdust particle size. The results are given in Table 6 of the Appendix. Note that the F value denotes the significance of only the particle size on the particular property, whereas the "t" value of variables 1-4 indicates the significance of these variables.

The mathematical model is as follows for the two regression analyses:

$$Y_{ji} = b_0 + a_j + b_1 X_{1ji} + . . . + b_6 X_{6ji} + e_{ji}$$

$$\text{with } \sum_{j=1}^{4} a_j = 0, \quad j = 1, 2, 3, 4 \text{ (full regression equation)}$$

$$Y_{ji} = b_0 + b_1 X_{1ji} + . . . + b_6 X_{6ji} + e_{ji}$$ (reduced regression equation)

The use of the regression equations can be explained as follows: If the breaking length at a certain pulp yield, Kappa number, pulp freeness, and sheet density is desired, the chosen values of these four independent variables are inserted into the full regression equation multiplying each factor by its respective β given in Table 6 for breaking length. Next, the particle size is chosen, and its parameter estimate given in Table 6 is multiplied by the value of the dummy variable given in the regression plan already shown. The other particle size parameter estimates are not included since the dummy variables are zero for those particle sizes not in question. In effect, calculating a dependent variable value using independent variables X_1 to X_4 establishes a grand average for those conditions, and the addition of the dummy variable to the calculation is equivalent to adding a constant value to this average which accounts for the effect of the particular sawdust particle size.

The correlation coefficient (r^2) was employed to explain the amount of variation contributed by a given variable. In the discussion to follow, the average r^2 of the single most important estimator is given. Also, (+) is used to indicate a direct correlation between an individual variable and a given property, while (-) indicates an inverse correlation.

For the test of the results of the Bauer-McNett fiber classification and of the total and active Na_2O in the spent black liquors, two and three factors analysis of variance tests were made respectively. The two factors are (1) sawdust fractions and (2) percent active alkali. The third factor, screen mesh, was included in the three factorial analysis.

An F-test based on an analysis of variance was employed in testing the hypothesis that the means are all equal. When this hypothesis is rejected as a result of statistical testing, the conclusion is reached that there is a significant difference between the means. When there is a significant difference between means, it can be concluded that a given factor or combination of factors has an effect on a given property. The acceptance or rejection of a hypothesis was determined by the magnitude of the F-value in the analysis of variance.

The Student's "t" test was used to determine the relative significance of difference between coarse and fine sawdust particle size distribution. In addition, the paired "t" test was used to analyze the data from the testing of the pulps and handsheets.

RESULTS AND DISCUSSIONS

Sawdust Particle Sizes

The results of screening of both the coarse and fine sawdusts are shown in Table 5.

The "t" test indicated that only the fractions retained on the 1/4" opening screen and the 20 mesh screen were significantly different. The amount of the coarse sawdust particles retained on the 1/4" opening screen was higher than the amount of the fine sawdust, while more of the fine sawdust particles was retained on the 20 mesh screen than of the coarse sawdust.

Pulping Results

Throughout this study, each sawdust sample was cooked at constant pulping conditions, except for the percent active alkali used. The time-temperature relationship was monitored and maintained to a maximum deviation of 5°F from the schedule. If the pulping temperature deviated from these limits, the cook was rejected.

Liquor Analysis

The simulated white liquor was prepared with goals of 15, 20, 25, and 30% (as Na_2O) active alkali based on O. D. wood. Appendix Table 1 tabulates the average values of percent active alkali and sulfidity.

Table 5. Particle size analysis of Douglas-fir sawdusts.
Description of columns:
1. Percent of sample held on 1/4" square opening screen
2. Percent of sample held on 6 mesh screen
3. Percent of sample held on 10 mesh screen
4. Percent of sample held on 20 mesh screen
5. Percent of sample passed through 20 mesh screen

	1	2	3	4	5
			Coarse sawdust		
	12.84	9.22	30.93	32.77	14.24
	11.92	10.40	29.87	34.77	13.05
	12.05	4.88	32.82	35.28	14.96
Ave.	12.27	8.17	31.20	34.27	14.08
			Fine sawdust		
	1.20	4.50	28.67	49.10	16.52
	0.58	3.80	28.02	48.30	19.26
	0.68	4.92	27.85	48.43	18.12
Ave.	0.82	4.40	28.18	48.61	17.97
"t"	33.11***	2.20	3.37*	17.81***	4.00*

*Significant at 0.05 level

**Significant at 0.01 level

***Significant at 0.001 level

DF = 4

The total Na_2O and active Na_2O contents of the spent black liquor for each cook were analyzed, and are tabulated in Appendix Table 2. An F-test based on two factor analysis of variance was used to test the means of both total and active Na_2O. Analysis of variance data are tabulated in Tables 6 and 7.

Table 6. Analysis of variance of black liquor total Na_2O.

Source	DF	SS	MS	F
Fractions (A)	5	3.06	0.61	0.60
Active alkali % (B)	3	920.92	306.97	301.13***
(A) x (B)	15	15.29	1.02	1.00
Total	23	939.28	--	--

***Significant at 0.001 level

Table 7. Analysis of variance of black liquor active Na_2O.

Source	DF	SS	MS	F
Fractions (A)	5	13.85	2.77	0.90
Active alkali % (B)	3	670.37	223.46	72.24***
(A) x (B)	15	46.40	3.09	1.00
Total	23	730.62	--	--

***Significant at 0.001 level

The analysis shows that only the amount of active alkali used had any significant effect on the total and active alkali in the black liquor. The sawdust particle size had no significant effect here.

With respect to the fractionated sawdusts, the co-variance analysis indicates that the total yield of the cook is the most significant variable influencing the Kappa numbers, and that the fraction size is next. Again the same trend is seen, and the Kappa numbers of the pulps made from the larger sized fractions are higher than those from the smaller sized fractions. In all cases, it appears that the larger the average sawdust particle size, the less complete is the pulping action under comparable pulping conditions. The basic reason is probably the slower rate of penetration of cooking liquor, and the subsequent retarded diffusion of dissolved lignin and other decomposition products out of the larger particles during the cooking process.

Total Yields

The average total yield of the coarse sawdust was higher than that of the fine sawdust, the difference being significant at the 0.01 level. Both the percent active alkali (-), and Kappa number (+) were significantly correlated to the total yield at the 0.001 level. About 94% of the total variation could be explained by the above variables. Once again, the sawdust fractions significantly contributed to the variation in total yield.

Screened Yields

There was no significant difference in average screened yield between the coarse and fine sawdusts. In the coarse-fine sawdust category, neither percent chemical (-) nor Kappa number (-) was significantly correlated to screened yield. The sawdust fractions, however, were significantly correlated to screened yield.

Kappa Number

The Kappa number data (Appendix Table 3) were analyzed by two methods, the co-variance analysis and a conventional factorial analysis of variance. The data for the former are given in Appendix Table 6, and this analysis indicates no significant difference between the Kappa numbers of the coarse and fine sawdust pulps. Examination of the basic data in Table 3 suggests, however, that the coarse sawdust pulps have higher Kappa numbers than the fine sawdust pulps. The reason that this difference does not show up in the co-variance analysis is that the data for the coarse sawdust pulps are pooled (and the same for the fine sawdust pulps), and this pooling ignores the effect of active alkali on the resultant Kappa numbers of the pulps. It is obvious that the amount of chemical used will greatly affect the yields and Kappa numbers of the pulps, perhaps even more so than particle size of the sawdusts, and this factor must be considered in the analysis. An analysis of variance for a factorial design resolves this dilemma nicely, as shown in Table 8.

Table 8. Factorial ANOVA for Kappa numbers of coarse and fine sawdust pulps.

Source	Level	Treatment SS	Treatment DF	Treatment MS	Error MS	F Value
Sawdust particle size (A)	2	170.95	1	170.95		33.20***
Active alkali % (B)	4	3982.33	3	1327.60		257.00***
(A) x (B)	8	4.52	7	0.65	5.15	0.13
Total	14	4157.80	11	--	--	--

***Significant at 0.001 level

This analysis clearly shows that the difference between the Kappa numbers of the coarse and fine sawdust pulps is significant. If, however, a simple analysis of variance is run comparing the effect of particle size only, the F value for this factor is only 0.6. The reason is that the error MS term, which is the denominator in the F value, is quite large in this case, 287.7, as opposed to only 5.15 used in the factorial analysis above. The latter analysis is the more appropriate tool to be used here, although an analogous result is obtained by using the paired "t" test. In this case, a "t" value of 11 is obtained with 3 DF, and this is significant at the 0.001 level. These two statistical tests substantiate the difference in Kappa numbers of the coarse and fine sawdust pulps.

Refining

The various Douglas-fir sawdust pulps were refined in a Valley Beater to a freeness below 200 Canadian Standard Freeness

(CSF). The data are shown in Appendix Table 4.

The average freeness of the coarse sawdust pulp at constant beating time was about 58 ml higher than that of the fine sawdust pulp, the difference being significant at the 0.05 level. Beating time was the most important single estimator of freeness, and contributed about 81% of the total variation. The sawdust fractions showed no significant correlation to freeness.

Bauer-McNett Classification Test

This test separates the pulp into different fractions according to fiber length by passing the dilute stock through a series of graded screens, ranging from 20 to 150 mesh. The pulp collected on each screen is dried and weighed, and a frequency distribution by weight can thus be calculated. The data are given in Appendix Table 5.

1. Coarse-fine Sawdust Comparison

If an ANOVA is run for this comparison, by pooling all the coarse sawdust pulp data (and pooling all the fine sawdust pulp data), no significant difference will be found between the two sawdust fractions (F = 0.01). As was true for the Kappa number, this is due to the wide range of values within both categories which results in large values for the error SS and MS terms. In this case, either the paired "t" test or ANOVA for individual Bauer-McNett screen sizes provides more meaningful data (Table 9).

Table 9. Analysis of variance and "t" test for fiber length distribution of coarse and fine sawdust pulps.

Bauer-McNett mesh	Paired "t" value	F Value (ANOVA)	Comparison
20	4.1*	2.3	8.7% (+)[a]
35	5.1**	33.7***	5.5% (-)
65	3.0	1.1	2.7% (-)
150	6.8**	1.5	2.9% (-)
< 150	2.8	5.0*	2.9% (+)

[a] (+) means that the coarse sawdust pulp is larger for this screen size than the fine sawdust pulp by the amount given, and (-) means the reverse.

*Significant at 0.05 level.

**Significant at 0.01 level.

***Significant at 0.001 level.

The paired "t" test is probably the most meaningful, since it compares pairs of values in the coarse and fine categories that are connected by common amounts of cooking chemical. The major difference in the fiber length distributions of the two classes of sawdust pulp lies in the 20 mesh fraction, with a difference of 8.7% in favor of the coarse sawdust pulp. In general, the amounts of coarse sawdust pulp collected on the smaller screens are smaller, as would be expected, but rather unexpected is the greater fraction of coarse sawdust pulp passing through the 150 mesh screen, all relative to the fine sawdust pulp fractions.

2. Fractionated Sawdust Comparison

A standard factorial ANOVA for the fractionated sawdusts shows an F value for the effect of sawdust size of 3×10^{-5}, an infinitesimally small value. Again, this is due to the wide range of values within each size category. A paired "t" test cannot be used here, but a standard ANOVA comparing values within Bauer-McNett screen size categories yields meaningful results (Table 10).

Table 10. Analysis of variance for fiber length distribution of fractionated sawdust pulps.

Bauer-McNett mesh	F Value (ANOVA)	Comparison
20	46.3***	(+)[a]
35	75.0***	(-)
65	44.2***	(-)
150	26.2***	(-)
< 150	0.9	(+)

[a] (+) means that values for coarser sawdust pulp are higher than those for finer sawdust pulp, and (-) means the reverse.

*** Significant at 0.001 level

Again, significant differences are seen in the fiber length distribution of the different fractions of sawdust pulp, with the coarsest sawdust pulp having the greatest amount of long fibers. The difference between the high and low value for the 20 mesh Bauer-McNett screen is over 35% of the total weight, which is a major factor. The increased < 150 mesh fraction for the coarser sawdust is analogous to the situation for the coarse-fine sawdusts, and cannot be explained at present.

Handsheet Properties

Evaluations of paper strengths were performed on handsheets prepared at various beating intervals, depending on the sawdust particle sizes and percent chemical used in pulping. The results are shown in Appendix Table 4.

The regression analysis previously discussed was used to determine the degree of correlation between the independent variables and the dependent handsheet properties. Table 6 of the Appendix tabulates the regression equations and allied data used in this analysis.

Sheet Density

1. Coarse-Fine Sawdust Comparison

The average density of the coarse sawdust papers was .06 g/cc lower than that of the fine sawdust papers. This difference was significant by the paired "t" test (t = 10.2***).

Analysis of the regression equations indicated that freeness (-) was the most important single estimator of sheet density, which accounted for 70% of the total variation. Kappa number (-) was also significantly related to the sheet density, contributing an additional 11% to the r^2.

2. Fractionated Sawdust Comparison

Analysis of the fractionated sawdusts shows that the particle size was highly significantly correlated to the sheet density in the reduced regression analysis. The freeness was the most important estimator of sheet density in the full regression, explaining about 75% of the total variation, and the particle size was the next most important estimator. It explained an additional 8% of the variation.

Tensile Strength

Tensile strength, as expressed in breaking length in meters, is one of the most important pulp properties to paper makers.

1. Coarse-Fine Sawdust Comparison

The average tensile strength of the fine sawdust papers was higher than that of the coarse sawdust papers, 7940 vs. 6500 m. The multiple regression analysis (Appendix Table 6) indicates that the particle size is not significantly related to the breaking length, but examination of Figure 7 suggests a significant trend, if the two sawdusts are compared on the basis of common cooking chemical. For this case, the paired "t" test was employed to analyze the data, and this test shows a significant difference in tensile strength between the two types of sawdust pulps ($t = 5.3^{***}$).

2. Fractionated Sawdust Comparison

The sawdust particle sizes contributed significantly to the tensile strength. In the full regression equation, the sheet density (+) was the most important single variable, accounting for 88% of the total variation.

Stretch

1. Coarse-Fine Sawdust Comparison

The average stretch values developed by coarse sawdust papers were lower than those of fine sawdust papers, and this difference was significant by the paired "t" test (t = 2.0*).

The sheet density (+) was the most important single estimator of stretch. It accounted for about 78% of the total variation. Strong correlations with total yield (+), Kappa number (-), and freeness (-) were also noted. From 78-89% of the total variation could be explained if all of the above variables were included stepwise in the regression equation.

2. Fractionated Sawdust Comparison

The sawdust particle size had a significant relationship to stretch. Again, sheet density was the most important variable in the full regression equation, alone accounting for 81% of the total variation.

Bursting Strength

The bursting strength or Mullen strength is an important paper strength property, particularly in such grades as linerboard and bag paper, both products made from unbleached kraft.

1. Coarse-Fine Sawdust Comparison

The average Mullen factor of the fine sawdust papers was higher than that of the coarse sawdust papers, 37.7 vs. 29.7 m^2/cm^2. As was true for tensile strength, the multiple regression analysis failed to indicate a significant difference between the two classes. Once again the paired "t" test disclosed a significant difference when the matched pairs of data were compared on the basis of common cooking chemical. The paired "t" value was 6.1^{***}.

2. Fractionated Sawdust Comparison

The sawdust particle size contributed significantly to the bursting strength in both regressions. Sheet density was the first variable in the full regression equation, explaining 78% of the total variation.

Folding Endurance

1. Coarse-Fine Sawdust Comparison

The average folding endurance of the coarse sawdust papers was about 93 double folds less than that of the fine sawdust papers.

This difference was significant at the 0.05 level by the regression analysis, and at the 0.01 level by the paired "t" test ($t = 3.2^{**}$).

The total yield (+) and freeness (-) were correlated to the folding endurance, and about 77% of the total variation could be explained by freeness alone.

2. Fractionated Sawdust Comparison

The particle size of the sawdusts contributed significantly to the folding endurance. The sheet density (+) was the first variable in this regression, explaining 52% of the variation.

Tearing Strength

1. Coarse-Fine Sawdust Comparison

The average tearing strength of the coarse sawdust papers was 17.54 dm^2 higher than that of the fine sawdust papers. This difference was significant at the 0.01 level by both the regression analysis and paired "t" test.

In this category, the sheet density (+) was the most important single estimator of tearing strength, but accounted for only 27% of the total variation. A correlation with Kappa number (-) was also noted.

2. Fractionated Sawdust Comparison

The sawdust particle size was significantly correlated to the tearing strength. There were strong correlations with freeness as well as sheet density, but the correlation coefficient was rather low in this comparison, only .62 after all variables were entered compared to .8 to .9 for many other factors.

Brightness

1. Coarse-Fine Sawdust Comparison

The average brightness of the coarse sawdust papers was 0.12% higher than that of the fine sawdust papers, but this difference was not significant by the regression analysis. Again the paired "t" test showed a significant difference ($t = 3.2^{***}$).

The total yield (-) was the most important single estimator of brightness. It accounted for 82% of the total variation. The Kappa number (-), and sheet density (+) were also significantly correlated to brightness. From 82-96% of the total variation could be explained by the above two variables.

2. Fractionated Sawdust Comparison

The sawdust particle size was not significantly correlated to the brightness. The first variable entered was the Kappa number (-), which was significant at the 0.001 level and accounted for 75% of the variation. Total yield (-) and freeness (+) were significant at the 0.05 level.

Implications of Test Results

In summary, significant differences have been found between certain properties of the coarse and fine sawdusts, and even more significant differences between certain properties of the various classes of fractionated sawdust. These differences, which are significant from a statistical standpoint, should have industrial significance. They can be determined both from the statistical tables and from the graphs (Figures 3 to 12).

Yields and Kappa Numbers

The easier pulping quality of the fine sawdust is demonstrated by the lower yield and Kappa number, at constant active alkali charge, of the fine sawdust pulp. The explanation is the greater specific surface of the fine sawdust, which allows quicker access and penetration of the cooking liquor. Commercially, this suggests that fine sawdust would require shorter residence time in the digesters for the same yield (Kappa number), or a reduction in chemical charge to the digester. In either instance, utilization of the fine sawdust could represent an economical saving for the mill, although the two sawdusts might have to be pulped separately.

Beating Time

The fine sawdust pulp requires less beating time (energy) to a

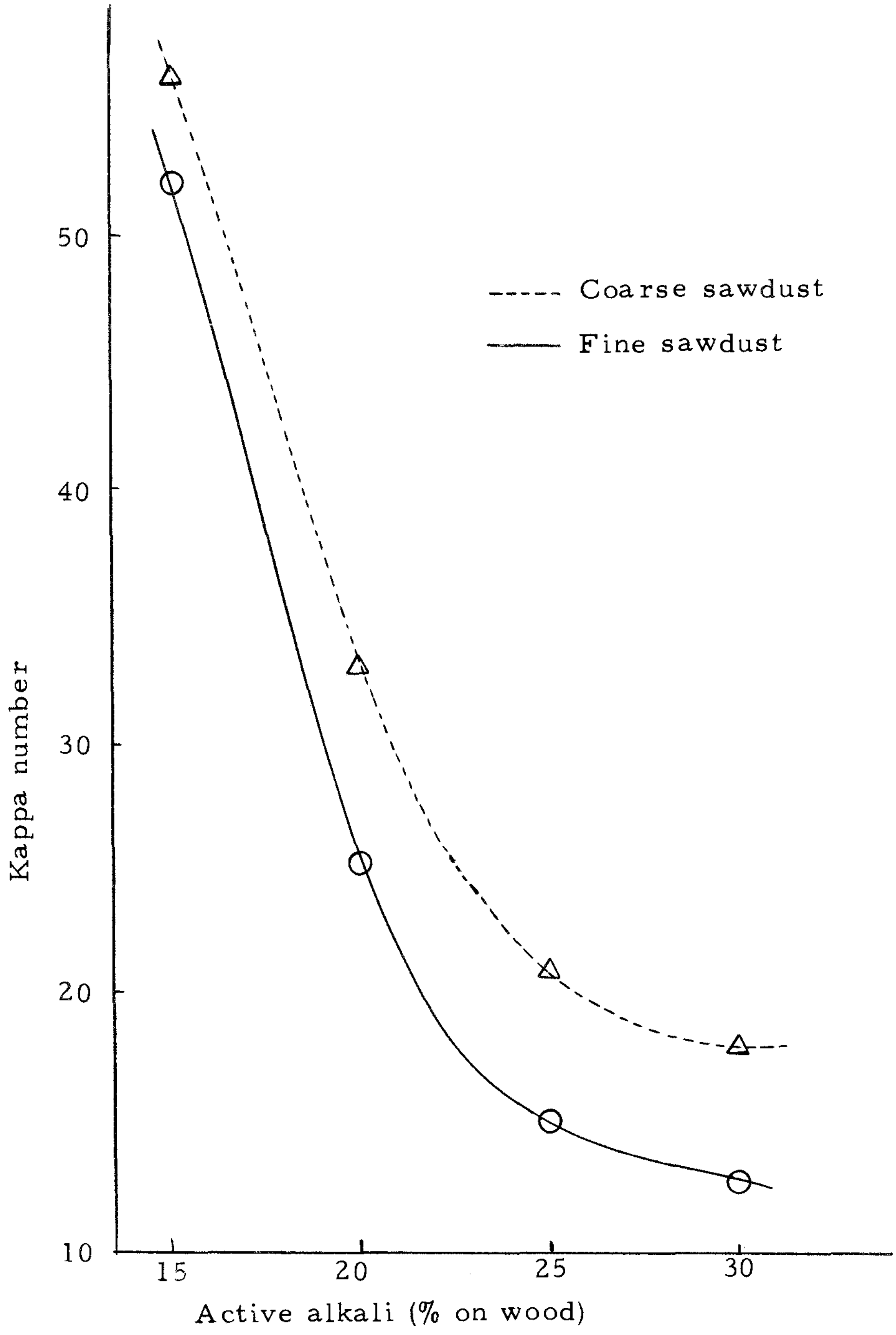

Figure 3. Comparative Kappa numbers of coarse and fine sawdust pulps.

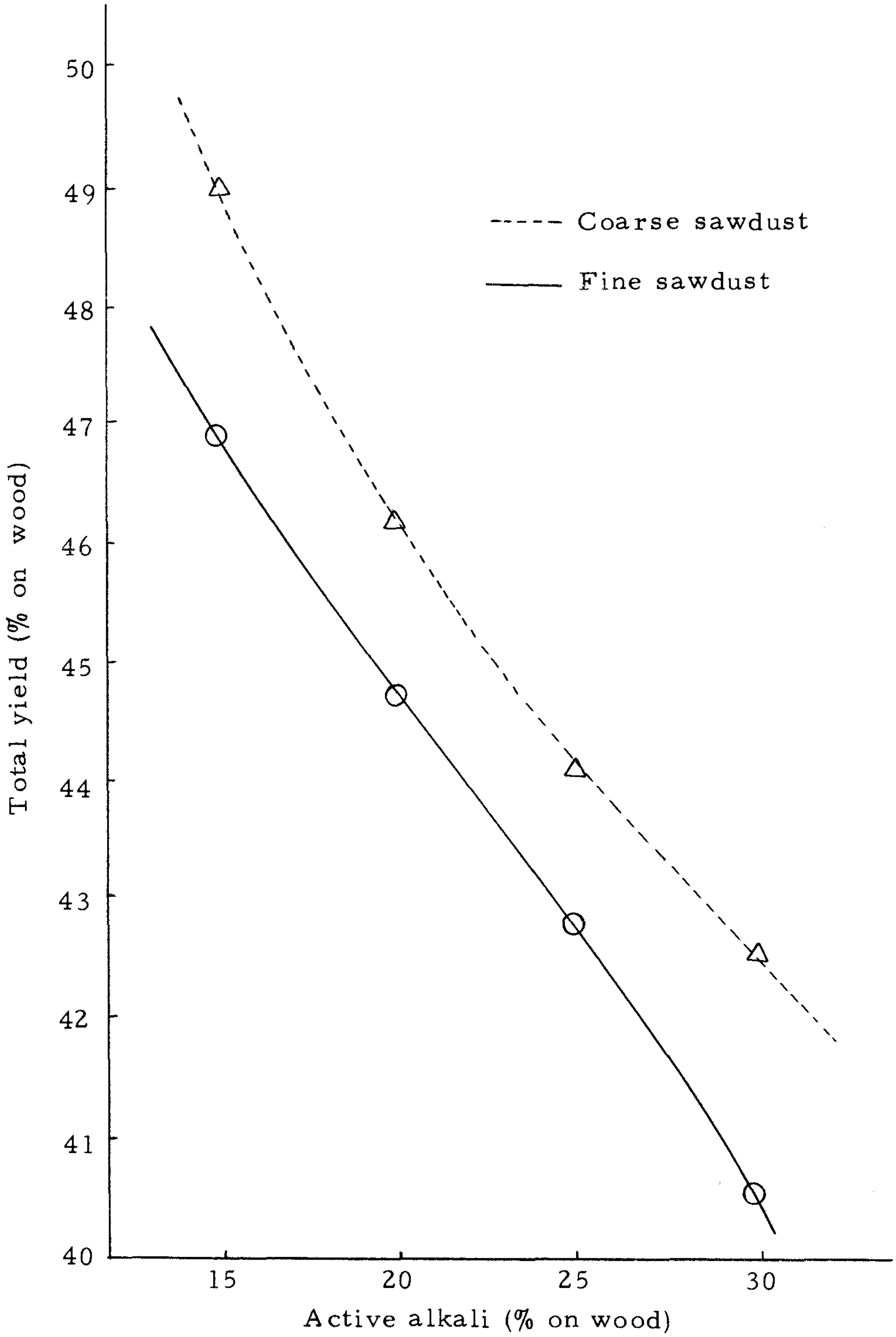

Figure 4. Comparative total yield of coarse and fine sawdust pulps.

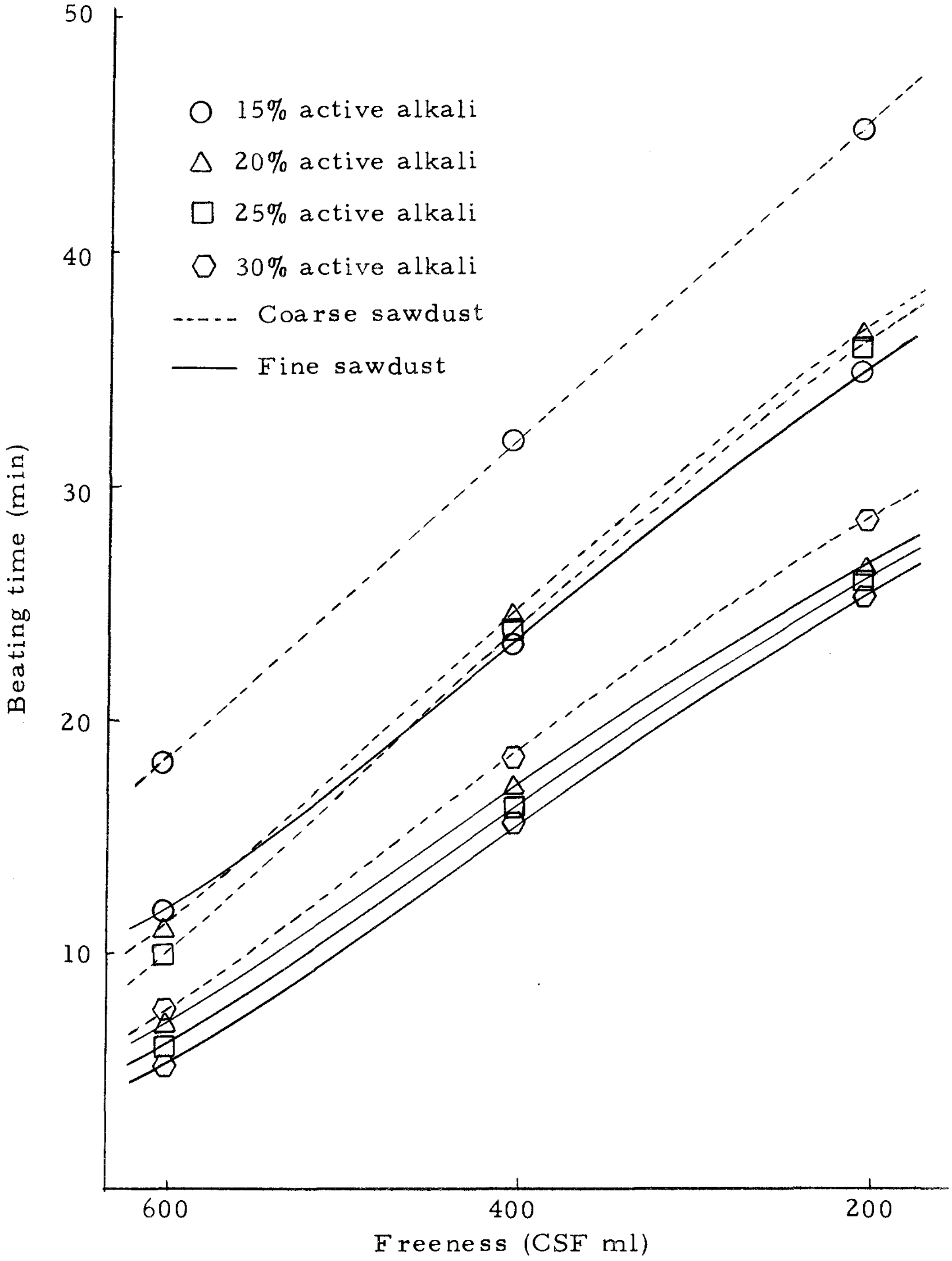

Figure 5. Comparative beating time of coarse and fine sawdust pulps.

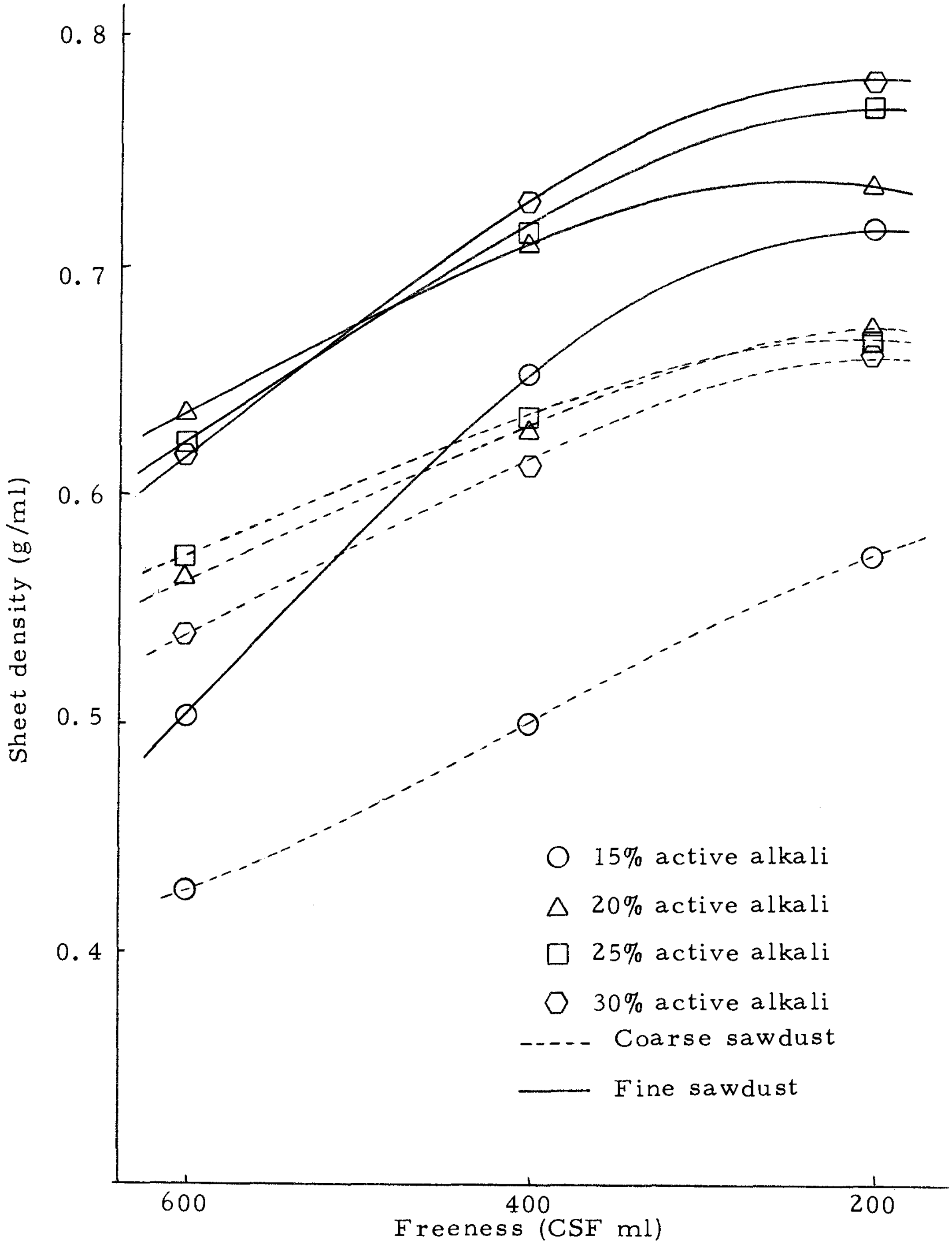

Figure 6. Comparative sheet density of coarse and fine sawdust pulps.

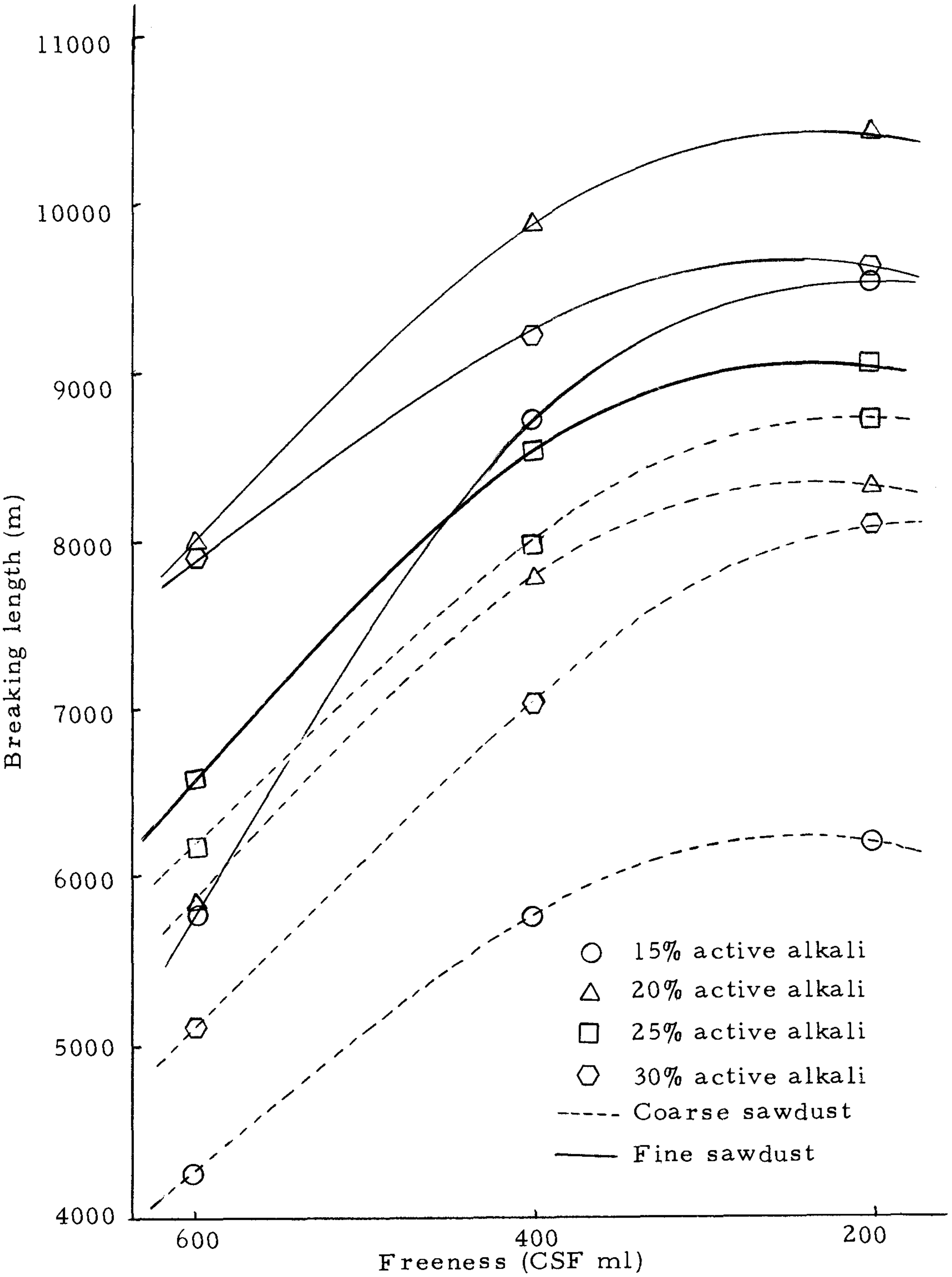

Figure 7. Comparative breaking length of coarse and fine sawdust pulps.

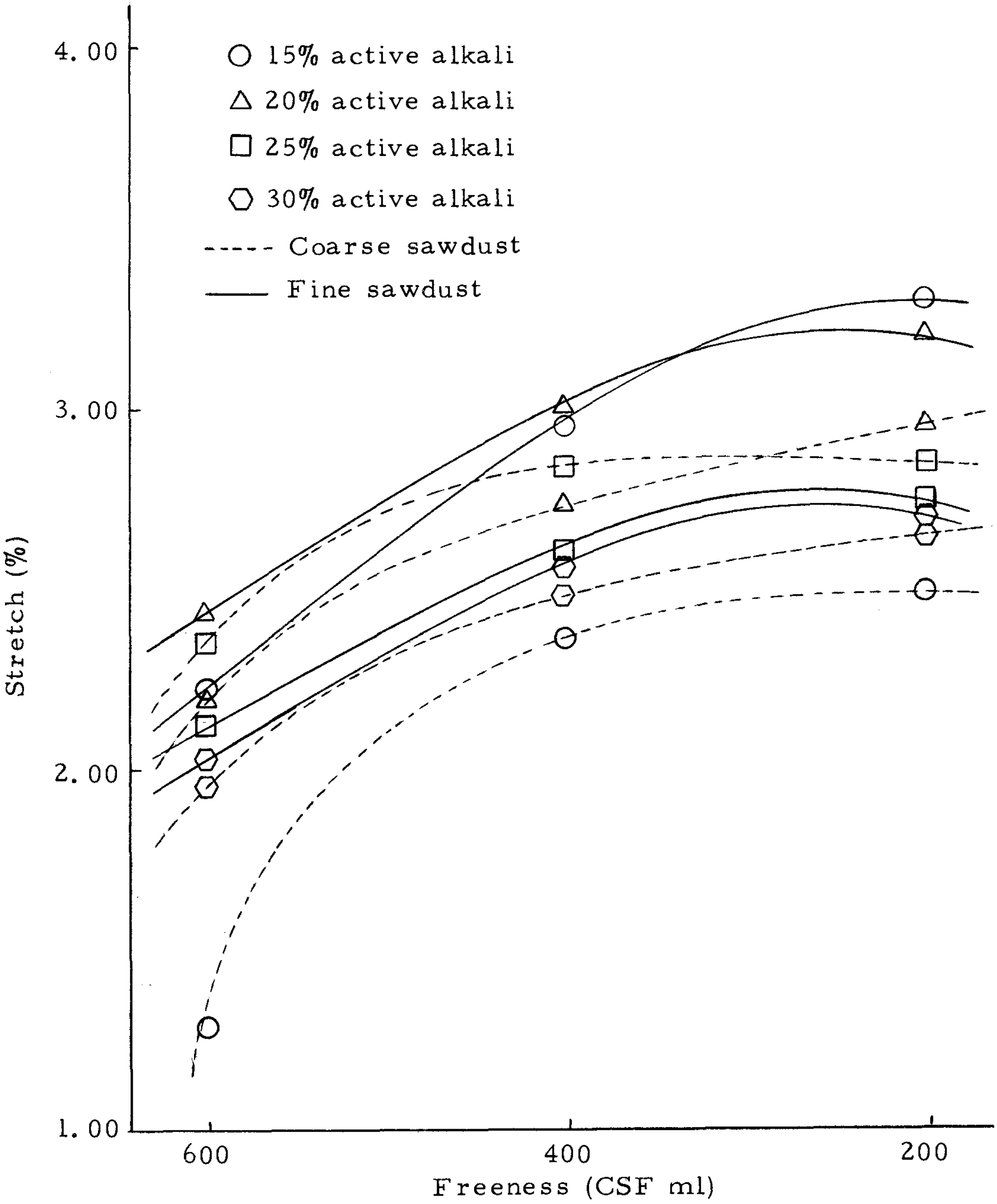

Figure 8. Comparative stretch of coarse and fine sawdust pulps.

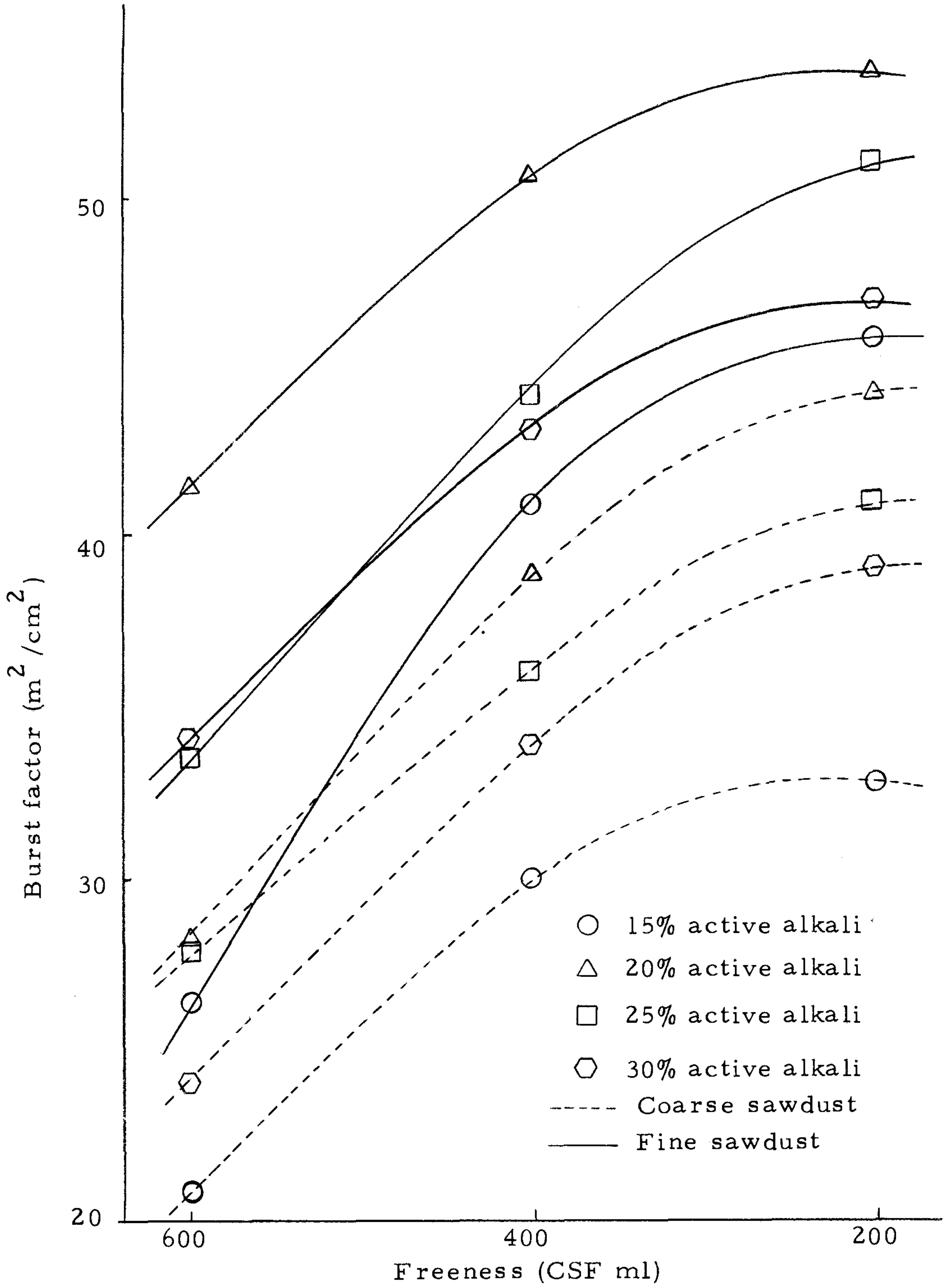

Figure 9. Comparative bursting strength of coarse and fine sawdust pulps.

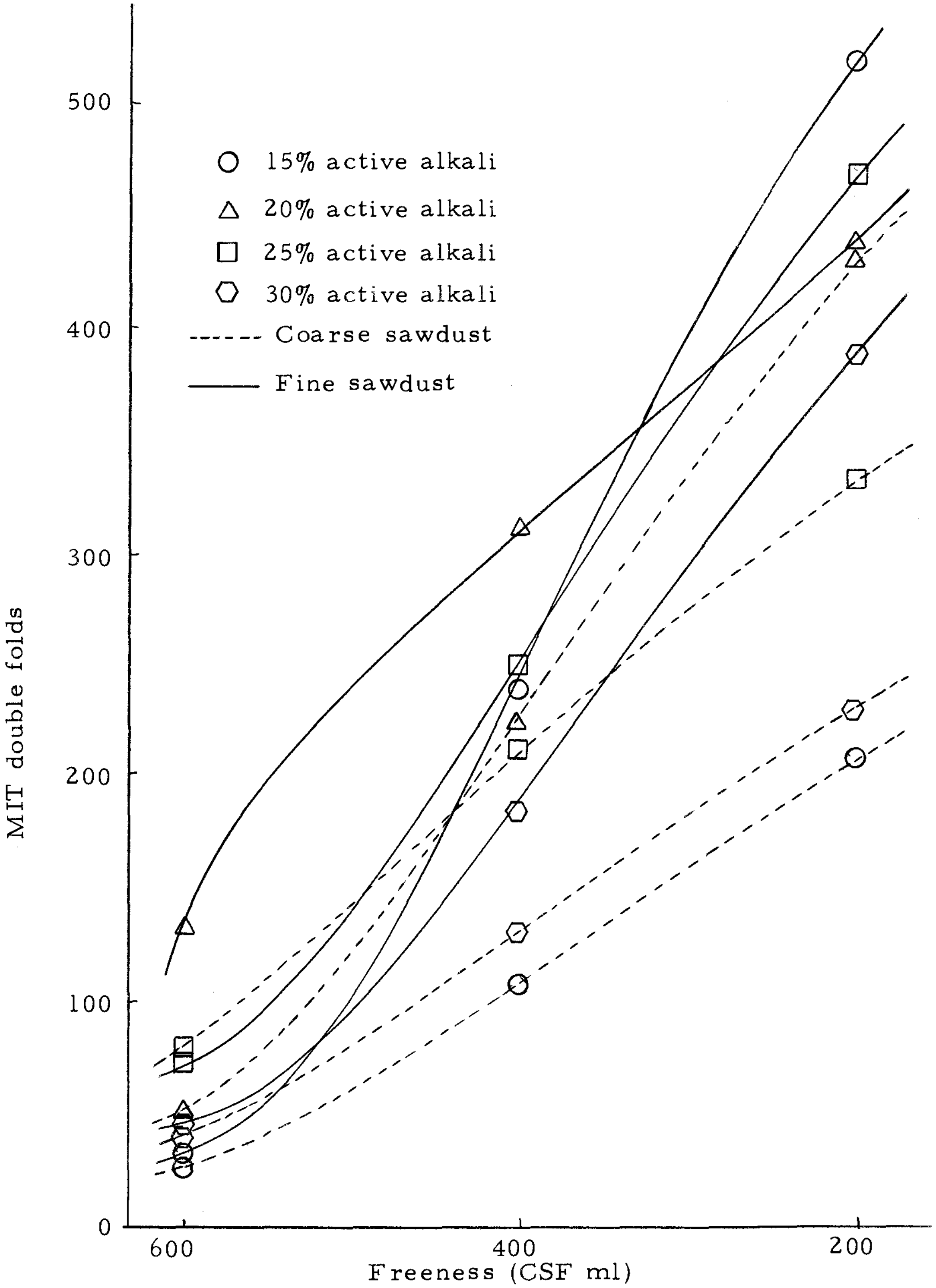

Figure 10. Comparative folding endurance of coarse and fine sawdust pulps.

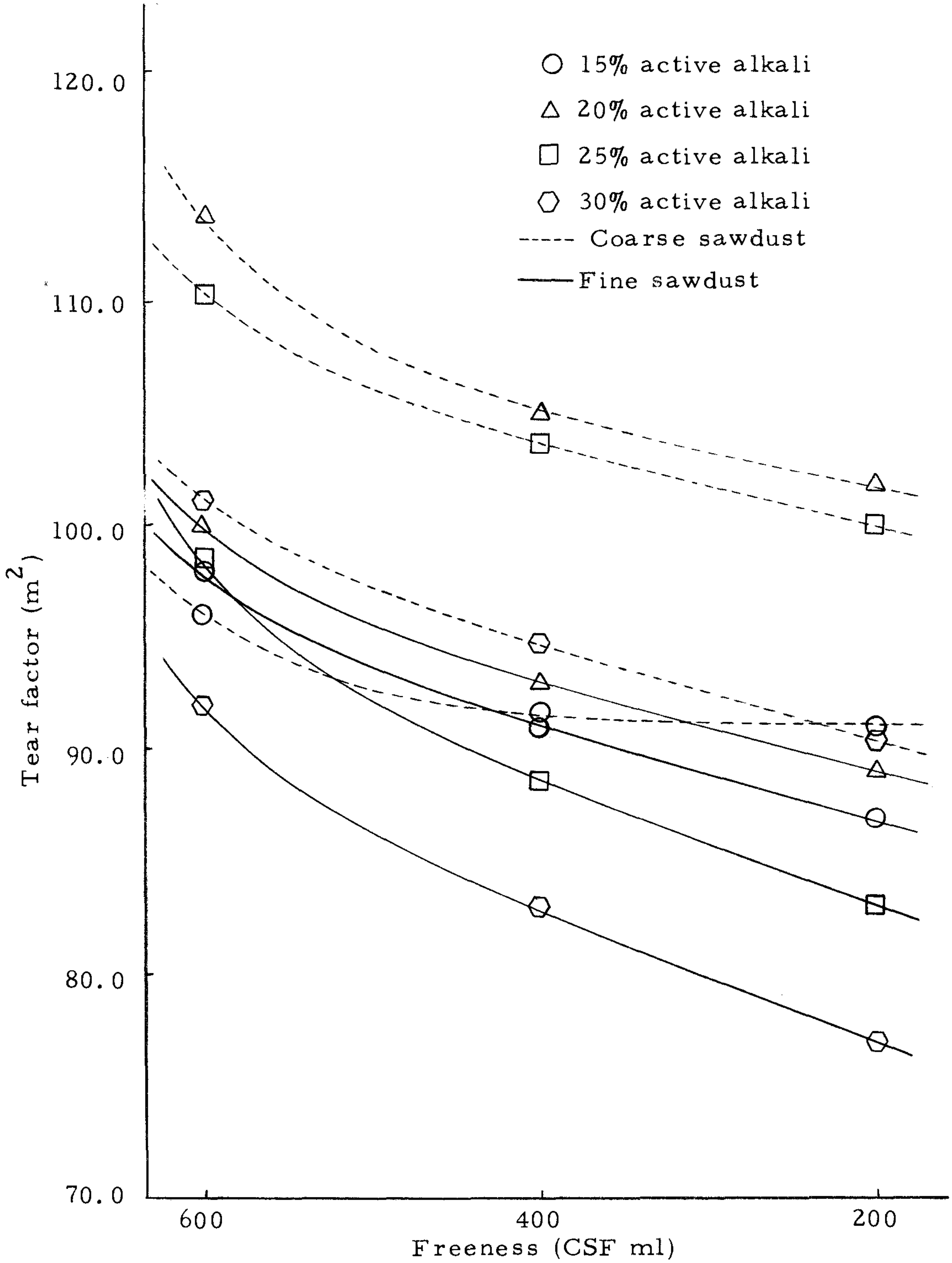

Figure 11. Comparative tearing strength of coarse and fine sawdust pulps.

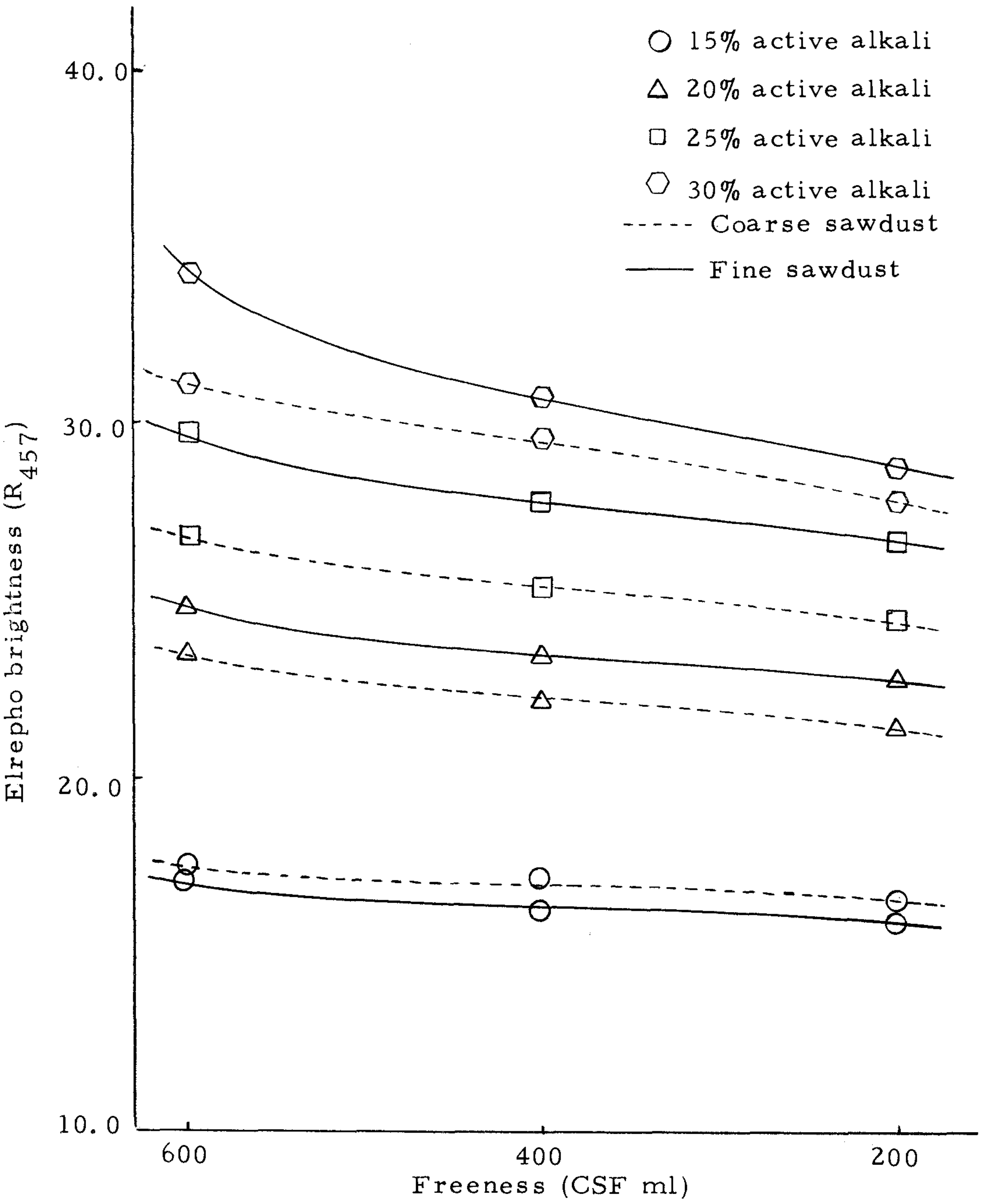

Figure 12. Comparative brightness of coarse and fine sawdust pulps.

given freeness than the coarse sawdust pulp, and this is in part due to fewer long fibers in the fine sawdust pulp (20 mesh fraction). The average initial freeness of the fine sawdust is 707 ml CSF as opposed to 741 ml CSF for the coarse sawdust, and refining to any given lower freeness would require less time for the fine sawdust for this reason also. The rates of freeness drops are quite similar in both cases, as shown in Figure 5 by the parallelism of the curves. Again, from an industrial standpoint, the reduced beating time represents a plus for the fine sawdust. The differences in the averages of beating times for coarse and fine sawdust pulps are 4.2, 6.5, and 8.3 min respectively to the discrete freenesses of 600, 400, and 200 CSF, with the fine sawdust pulp being faster beating in each case. Relatively speaking, fine sawdust pulp needs only 65-75% as much time to refine to a given freeness as does the coarse sawdust pulp.

Significantly Different Handsheet Properties

The following handsheet properties show statistically significant differences between the coarse and fine sawdust classes:

Sheet Density***
Breaking Length**
Stretch*
Mullen Factor***

Tear Factor**
Folding Endurance**
Brightness**

*, **, and *** represent significance at the 0.05, 0.01, and 0.001 probability levels, respectively.

Examination of the data indicates that most of the differences in the strength properties can be related to the difference in fiber lengths of the coarse and fine sawdusts. The longer fibers of the coarse sawdust pulps enhance the tearing strength of the papers, relative to fine sawdust pulp and paper, but also tend to produce sheets with lower density. Sheet density is closely connected with fiber bonding, which in turn strongly influences the tensile, stretch, burst, and fold strengths of paper. Hence the superiority of the fine sawdust papers over coarse sawdust papers can be explained in part by the higher density of the former.

These differences, while statistically significant, are relatively small compared to the difference between chip paper and sawdust paper (Table 11). For example, the difference in breaking length between coarse and fine sawdust pulps at 400 CSF is 600 m, but between the strongest sawdust pulp and the chip pulp is nearly 2200 m. Similar relationships exist for other properties.

Whether the differences between the properties of the two different sawdust pulps could be detected in a typical mill operation is questionable. Laboratory conditions are generally much better controlled than large scale mill operations, and it is common experience to be able to detect variations in the laboratory that cannot be duplicated in the mill. Differences in yields of 1-2% are extremely difficult to substantiate on a large mill scale, for example, because of difficulties of accurately measuring the weights, volumes, or moisture contents of large tonnages of pulp. Similarly, differences in strength properties can be hidden by variations in raw material supply, refining variables, and machine variables, to mention only some of the more obvious factors. Hence it is questionable whether a mill could detect a difference between the utilization of coarse or fine sawdusts.

In summary, it appears that there is only one disadvantage to the utilization of fine sawdust, a loss of tearing strength. Fine sawdust can be pulped faster or with less chemical to a given yield of Kappa number, and produces pulps that are somewhat stronger in those properties dependent on fiber bonding, namely tensile, stretch, burst, and fold. The shorter fiber length of the fine sawdust pulp accounts for its weaker tearing strength. If this latter factor is secondary in importance, as in the case of linerboard, then the increased tensile and bursting strengths, especially the latter, of the fine sawdust pulp would be an advantage to the mill using the material. The greatest benefits would result to a mill which could segregate the two types of sawdust through the production process up to the paper machine. Then full advantage could be taken of the shorter cooking time, shorter beating time, and improved strength properties of the fine sawdust pulp. Conversely, its use would be restricted in those grades where tearing strength is a significant paper parameter. There are, however, no compelling technical reasons for such segregation, and it would have to be left to the individual mill's discretion as to the wisdom of such a policy.

The data described above should not be extrapolated beyond the limits that have been presented. The comparisons cited are valid only for the coarse and fine sawdusts actually tested, and neither sample can be considered completely representative of both classes of sawdust. For example, there may be larger-sized "coarse" sawdusts available, and smaller-sized "fine" sawdusts available. If such a comparison were thus made, greater differences in strength properties might be found than were found in this study. Analysis of the strength data for the fractionated samples shows that almost all strength properties decline as the particle size of the fraction decreases. From this, one could infer that a major shift in particle size distribution toward the smaller size fractions would cause definite decreases in strength properties of sawdust pulps. For sawdust samples with the particle size distributions similar to the two described herein, the strength differences should be minor.

The Mathematical Model for Estimating Sawdust Pulp Properties

From the fractionated sawdust pulping data, the following mathematical models were used to estimate the pulp properties:

(1) Linear relationship

$$P = p_1 f_1 + p_2 f_2 + p_3 f_3 + p_4 f_4$$

(2) Log-log relationship

$$\text{Log } P = f_1 \text{ Log} p_1 + f_2 \text{ Log} p_2 + f_3 \text{ Log} p_3 + f_4 \text{ Log} p_4$$

where

P = The estimated value of certain pulp properties of a given sawdust

f_1, f_2, f_3, f_4 = Percentage by dry weight of different particle size fractions of a given sawdust

p_1, p_2, p_3, p_4 = The actual value of the fractionated sawdust pulp properties

The estimated values calculated from the above two models were compared to the actual values of the given sawdust pulp properties. The value (estimated value - actual value) / (actual value) x 100%) was used to indicate how close the estimated value came to the actual value. These data are given in Appendix Table 7.

For the coarse sawdust pulp, the data calculated by the above two models showed that the averaged estimated values were greater than the actual values in all of the pulp properties. The pulp properties, time to freeness, density, breaking length, tearing strength, and brightness were relatively better estimated than stretch, bursting strength, and folding strength. As far as the mathematical model is concerned, the log-log relationship gave a better estimate than the linear relationship.

In the case of the fine sawdust pulp, the log-log relationship model underestimates the following properties: time to freeness, stretch, tearing strength, and brightness. The linear relationship model underestimates the density, breaking length, bursting, and folding strength.

There is some tendency for greater deviations for the pulps prepared with 15% active alkali, and lower values for those pulps cooked with greater amounts of alkali. This is most evident in the case of the coarse sawdust, and the explanation may lie in the relatively raw cooks obtained in this instance. One might expect greater variation in properties for pulps poorly cooked as compared to pulps completely cooked.

The predictability of the fold test is the worst of the group, particularly with the linear model for the coarse sawdust. This reflects the well-known variability of the test. The predicted values for the tearing strength, brightness, and sheet density respectively are quite uniformly close to their actual values. By contrast, the bursting strength, tensile strength, stretch, and time to freeness (fine sawdust) are somewhat more variable so far as predictability is concerned.

Overall, however, the ability to predict pulp properties within an average deviation of 3-7% should be of commercial value. The importance of this model lies in the application to mill operation. If a mill fractionates its sawdust and determines the pulping and pulp properties of the fractions, then they should be able to estimate the pulping properties of any future batch of sawdust merely by making a particle size analysis of the new material. Using the weight percent of the various fractions in the previous equations, with their respective pulp properties, the mill would be able to estimate rapidly and without further pulping experiments the quality of the new sawdust.

Comparisons of Handsheet Properties of Douglas-fir Chip Pulp with Coarse and Fine Sawdust Pulps

The Douglas-fir coarse and fine sawdust pulps cooked with 25% of active alkali (based on wood) were chosen as representative pulps and are compared to Douglas-fir regular chip pulp (Blackman, 1970). The comparisons between these different pulps are based on the values at the 600, 400, and 200 freeness level. The data are shown in Table 11.

The Douglas-fir chip pulp has higher total yields and Kappa numbers, and also has higher mechanical properties. All of the above results were expected, because the chips are less impregnated by chemical, and have much greater fiber length. However, the density development of fine sawdust pulp during refining was greater than the regular chip pulp, and coarse sawdust pulp. The sheet density of regular chip pulp increased by 0.062 g/cm^3, the coarse sawdust pulp increased by 0.097 g/cm^3, while the fine sawdust pulp increased by 0.156 g/cm^3 during the refining from 600 to 200 CSF. This is because the fine sawdust pulps had shorter fiber lengths, and the sheet density was inversely related to the fiber length.

Table 11 shows the strong degradation of pulp properties that can be expected with sawdust pulps as compared to pulps from chips. This degradation, as is well known, occurs as a result of the severe cutting action experienced during the production of sawdust, resulting in shorter and more damaged fibers on the average compared to fibers from chips.

Table 11. Comparisons of the handsheet properties of Douglas-fir chip pulp (24% active alkali, Blackman 1970) with Douglas-fir coarse and fine sawdust pulps (25% active alkali).

Freeness	Total yield (%)	Kappa number	Density (g/cm^2)	Breaking length (m)	Mullen factor (m^2/cm^2)	MIT fold (double fold)	Tear factor ($100\ dm^2$)
				Coarse sawdust			
600	44.7	21.1	0.574	6575	28.1	78	110
400			0.638	8300	36.1	214	104
200			0.671	9055	41.1	334	100
				Fine sawdust			
600	41.7	15.0	0.624	7200	33.6	75	98
400			0.712	8850	44.2	250	89
200			0.770	9600	51.0	470	83
				Regular chip			
600	44.9	21.6	0.668	10824	68.4	1162	222
400			0.709	11030	70.1	1146	180
200			0.730	10862	69.6	1201	155

CONCLUSIONS

1. The particle size distributions of coarse and fine sawdusts differed significantly only for the fractions retained on the 1/4" opening screen and the 20 mesh screen. The coarse sawdust contained more particles retained on the 1/4" opening screen, but fewer particles retained on the 20 mesh screen; and vice versa for the fine sawdust.
2. The particle size of sawdust has no effect on the concentration of total and active residual alkali in the black liquor.
3. Under comparable pulping conditions, the Kappa numbers of the coarser sawdust pulps were significantly higher than those of the finer sawdust pulps.
4. The average total yield of coarse sawdust was higher than that of fine sawdust under comparable pulping conditions. The difference was significant at the 0.01 probability level. However, the screened yields of both kinds of sawdust were not significantly different.
5. The average original freeness of the coarse sawdust pulps was higher than that of the fine sawdust pulps.
6. The average sheet density of the coarse sawdust papers was lower than that of the fine sawdust paper.

7. There were significant differences between the average tensile strength (0.01 level) and stretch (0.05 level) of the coarse and fine sawdust pulps, and the coarse sawdust pulp is weaker in both properties.
8. The Mullen or bursting strength of the fine sawdust pulp was higher than that of the coarse sawdust pulp, and the difference is significant at the 0.001 level.
9. The average folding endurance of the coarse sawdust handsheets was lower than that of the fine sawdust handsheets, and the difference is significant at the 0.01 probability level.
10. The average tearing strength of the coarse sawdust handsheets was higher than that of the fine sawdust handsheets, and the difference is significant at the 0.01 probability level.
11. The particle size of the fractionated sawdust was significantly correlated to the folding endurance, breaking length, bursting strength, tearing strength, stretch, sheet density, Kappa number, and the total and screened yields of the papers.
12. The particle size of the fractionated sawdust was not significantly correlated to the pulp brightness.
13. The predicted values for the tearing strength, brightness, and sheet density respectively were quite uniformly close to their actual values. By contrast, the bursting strength, tensile strength, stretch, and time to freeness (fine sawdust) were

somewhat more variable. The predictability of the fold test was the worst of the group, particularly in the case of the linear model for the coarse sawdust.

14. The sawdust pulps had lower total yields and Kappa numbers, and also had lower mechanical properties than pulps from chips prepared under similar conditions. This degradation, as is well known, occurs as a result of the severe cutting action experienced during the production of sawdust, resulting in shorter and more damaged fibers, on the average, compared to fibers from chips.

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APPENDIX

Appendix Table 1. Percent active alkali and sulphidity of white liquor.

Description of columns:
N. Kinds of sawdust fraction
1. 15% active alkali white liquor (based on wood)
2. Percent sulphidity of 15% active alkali white liquor
3. 20% active alkali white liquor (based on wood)
4. Percent sulphidity of 20% active alkali white liquor
5. 25% active alkali white liquor (based on wood)
6. Percent sulphidity of 25% active alkali white liquor
7. 30% active alkali white liquor (based on wood)
8. Percent sulphidity of 30% active alkali white liquor

N	1	2	3	4	5	6	7	8
Coarse	15.50	21.28	20.76	20.09	26.01	20.46	29.73	20.10
Fine	15.59	20.98	20.82	20.03	26.18	20.13	31.19	19.34
1/4" opening	15.63	20.75	20.98	20.40	26.38	19.11	31.07	19.08
6 mesh	15.48	20.42	20.66	19.73	26.02	19.86	31.11	19.13
10 mesh	15.30	19.88	20.23	18.65	25.70	19.68	31.06	19.50
20 mesh	15.54	19.59	20.20	20.66	25.94	19.36	31.12	18.97
Average	15.51	20.48	20.61	19.93	26.04	19.77	30.88	19.35
Std. Dev.	0.11	0.89	0.20	0.64	0.21	0.45	0.52	0.38

Appendix Table 2. Average of total and active Na_2O (g/l) in black liquors.

Description of columns:

N. Identification of sawdust
1. Total Na_2O in black liquor of 15% white liquor
2. Active Na_2O in black liquor of 15% white liquor
3. Total Na_2O in black liquor of 20% white liquor
4. Active Na_2O in black liquor of 20% white liquor
5. Total Na_2O in black liquor of 25% white liquor
6. Active Na_2O in black liquor of 25% white liquor
7. Total Na_2O in black liquor of 30% white liquor
8. Active Na_2O in black liquor of 30% white liquor

N	1	2	3	4	5	6	7	8
Coarse	11.67	7.14	16.69	11.25	22.31	16.47	27.23	20.98
Fine	11.43	5.94	17.74	11.76	21.87	16.33	28.15	20.84
1/4" opening	11.96	8.00	16.29	12.25	23.59	17.80	27.00	20.60
6 mesh	12.93	8.73	15.80	11.39	21.03	14.99	29.83	24.74
10 mesh	12.50	7.89	16.27	11.91	23.71	10.19	29.14	20.39
20 nesh	10.00	5.43	16.67	11.91	22.59	16.50	27.93	22.51
Average	11.58	7.19	16.58	11.75	22.52	15.38	28.21	21.68

Appendix Table 3. Unscreened yields, screened yields, and Kappa numbers of cooks.

Description of columns:

N. Active alkali (%)
1. Unscreened yield (%)
2. Average unscreened yield (%)
3. Screened yield (%)
4. Average screened yield (%)
5. Kappa number of pulp
6. Average Kappa number of pulp

N	1	2	3	4	5	6
			Coarse sawdust			
15	49.5	48.6	34.5	32.4	61.3	58.5
	47.7		30.4		55.8	
20	46.3	46.2	46.2	46.0	35.3	33.4
	46.0		46.1		31.6	
25	43.6	44.7	43.5	43.6	19.4	21.1
	45.7		43.8		22.7	
30	41.8	42.6	41.8	42.4	17.2	18.1
	43.2		43.0		19.0	
			Fine sawdust			
15	49.2	49.7	46.3	46.9	50.4	52.0
	50.3		47.6		53.7	
20	43.7	44.8	43.6	44.7	24.8	25.2
	45.9		45.7		25.6	
25	41.2	41.7	41.1	41.7	13.5	15.0
	42.3		42.2		16.6	
30	40.3	40.5	40.3	40.5	11.8	12.7
	40.6		40.6		13.6	
			1/4" Opening			
15	51.4	52.3	48.3	48.7	58.7	60.0
	53.2		49.0		61.0	
20	47.4	47.5	47.3	47.4	31.0	31.2
	47.7		47.5		31.4	
25	46.3	46.8	46.0	46.4	15.9	16.8
	47.4		46.8		17.6	

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Appendix Table 3. (Continued)

N	1	2	3	4	5	6
30	40.2 40.8	40.5	40.2 40.7	40.5	12.8 13.5	13.2
			6 Mesh			
15	51.0 51.9	51.4	41.2 41.9	41.5	49.8 52.0	50.9
20	46.2 47.5	46.9	46.0 46.7	46.3	28.3 29.4	28.9
25	43.4 44.3	43.8	42.0 42.3	42.1	15.9 17.2	16.6
30	42.1 42.5	42.3	41.8 42.4	41.7	15.4 16.0	15.9
			10 Mesh			
15	54.2 54.0	54.1	45.8 44.6	45.2	55.9 57.8	56.9
20	46.7 46.4	46.6	46.5 46.1	46.3	30.0 29.7	29.9
25	45.3 44.9	45.1	45.3 44.9	45.1	17.1 16.5	16.8
30	41.8 43.0	42.9	41.8 43.0	42.9	12.2 13.5	12.9
			20 Mesh			
15	52.6 53.3	53.0	49.4 49.9	49.7	44.0 44.2	44.1
20	48.3 48.7	48.5	48.3 48.1	48.5	31.4 31.7	31.6
25	45.6 45.7	45.7	45.6 45.7	45.7	16.0 16.3	16.2
30	44.8 45.1	45.0	44.8 45.1	45.0	13.9 14.5	14.2

Appendix Table 4. Beating, CSF, and handsheet properties.
Description of columns:
N. Percent active alkali
1. Beating time (min)
2. Canadian Standard Freeness (ml)
3. Sheet density (g/ml)
4. Breaking length (m)
5. Stretch (%)
6. Mullen factor (m^2/cm^2)
7. Tear factor (100 cm^2)
8. Fold endurance (double folds)
9. Elrepho brightness (% reflectance)

N	1	2	3	4	5	6	7	8	9
				Coarse sawdust					
15	0	790	0.27	622	0.72	4.55	21.4	0	17.76
	20	580	0.44	4271	1.82	21.62	87.3	27	17.48
	35	347	0.52	6113	2.44	31.70	94.1	152	16.63
	48	164	0.58	6263	2.46	32.58	91.9	208	16.37
20	0	730	0.44	4309	1.68	14.09	91.4	7	26.19
	15	600	0.54	7075	2.62	30.24	108.9	63	24.30
	25	420	0.64	8040	2.46	37.84	101.6	248	22.32
	40	200	0.68	9154	2.98	43.37	103.7	513	21.82
25	0	720	0.43	3770	1.74	13.97	88.9	6	29.89
	15	580	0.63	7042	2.02	32.51	107.6	106	26.79
	25	410	0.65	8276	2.82	37.27	104.6	200	25.77
	40	190	0.69	9162	2.90	41.65	99.7	333	24.39
30	0	725	0.40	3519	1.32	12.07	76.9	4	34.28
	15	410	0.62	7759	2.24	36.47	90.7	106	29.65

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Appendix Table 4. (Continued)

N	1	2	3	4	5	6	7	8	9
30	25	170	0.68	9164	2.98	40.66	84.9	267	28.73
	30	90	0.71	9603	3.06	45.02	82.6	308	27.94
					Fine sawdust				
15	0	740	0.33	2564	1.40	5.72	47.1	2	19.82
	15	570	0.56	7484	2.44	31.52	95.9	61	16.95
	25	390	0.66	8445	2.64	41.90	90.1	248	18.22
	35	200	0.72	9566	3.30	46.24	86.8	521	16.91
20	0	710	0.45	4719	1.90	17.04	74.1	7	28.75
	15	450	0.70	9607	2.92	47.60	93.6	244	23.78
	20	340	0.71	10069	2.94	54.21	92.7	355	23.46
	28	170	0.74	10571	3.22	53.91	89.0	642	21.92
25	0	700	0.48	4770	1.72	18.07	76.3	10	33.62
	10	540	0.67	8762	2.50	38.70	91.0	167	29.18
	20	320	0.73	8902	2.40	47.35	87.6	299	27.70
	30	150	0.79	9923	2.70	53.61	81.5	534	26.52
30	0	680	0.47	5014	1.58	16.26	81.9	9	36.74
	10	525	0.68	7456	2.22	39.29	87.3	94	32.21
	20	310	0.75	9781	2.80	44.52	81.0	269	29.82
	30	130	0.78	9362	2.66	47.25	74.9	476	28.34
					1/4" Opening				
15	0	755	0.32	2022	1.34	7.22	105.7	4	18.85
	25	577	0.58	7576	3.38	43.56	159.2	361	17.22
	40	309	0.03	8264	3.78	59.23	132.9	659	16.36
	50	176	0.69	8659	3.66	63.21	121.2	886	15.91

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Appendix Table 4. (Continued)

N	1	2	3	4	5	6	7	8	9
20	0	738	0.36	3209	1.64	16.66	155.5	10	26.87
	20	527	0.61	7825	2.90	50.57	156.0	423	22.73
	35	242	0.65	8572	3.32	65.57	139.0	605	21.54
	45	134	0.69	8167	3.40	63.59	130.2	737	21.04
25	0	722	0.43	4281	1.92	20.50	146.4	13	33.31
	20	507	0.64	8406	3.22	47.90	128.0	440	28.19
	35	292	0.68	8862	3.06	56.68	118.6	614	27.25
	45	171	0.72	9062	3.16	52.48	113.5	674	26.37
30	0	727	0.43	3988	1.94	21.42	170.1	39	35.14
	20	524	0.61	7687	2.90	44.66	136.9	338	30.49
	35	270	0.66	8116	3.12	49.09	119.3	461	29.12
	45	146	0.69	8392	3.20	48.09	111.7	587	28.58
					6 Mesh				
15	0	750	0.32	2926	1.72	10.55	72.3	9	21.20
	25	584	0.62	8555	3.04	45.37	100.7	378	17.34
	40	383	0.68	9591	3.86	64.18	95.2	754	16.07
	60	155	0.72	10114	3.42	66.12	84.5	1057	14.10
20	0	698	0.50	5192	2.18	25.26	116.1	44	28.45
	15	569	0.66	8419	3.00	50.57	109.0	379	23.21
	30	332	0.71	8821	3.22	58.42	99.1	666	21.47
	40	180	0.74	9314	3.48	62.71	95.5	914	20.45
25	0	723	0.49	4787	2.08	22.69	119.1	28	32.45
	20	480	0.65	7984	2.76	46.90	107.1	285	26.43
	35	365	0.70	8638	2.88	52.45	99.4	453	24.76
	45	150	0.73	8505	3.14	54.03	74.3	501	24.22

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Appendix Table 4. (Continued)

N	1	2	3	4	5	6	7	8	9
30	0	691	0. 52	5645	2. 54	28. 25	104. 1	37	36. 51
	15	514	0. 69	7969	2. 94	48. 74	88. 3	319	31. 01
	25	340	0. 73	8677	3. 22	47. 10	85. 9	459	29. 35
	35	142	0. 76	8253	3. 06	56. 12	76. 5	613	26. 94
					<u>10 Mesh</u>				
15	0	755	0. 31	1851	1. 48	5. 64	59. 0	2	20. 47
	20	575	0. 59	7042	3. 16	41. 00	113. 5	148	17. 80
	35	321	0. 67	8378	3. 40	52. 00	102. 8	445	16. 52
	45	170	0. 72	9034	3. 50	55. 61	93. 0	605	15. 45
20	0	729	0. 48	3702	1. 74	14. 78	98. 4	7	26. 33
	20	483	0. 63	7533	2. 74	41. 06	115. 7	252	22. 66
	35	226	0. 71	8249	3. 18	48. 59	126. 9	560	21. 02
	45	123	0. 74	8744	3. 42	47. 95	102. 5	549	20. 46
25	0	707	0. 46	4404	1. 90	18. 95	100. 2	10	33. 76
	15	533	0. 65	7745	2. 88	49. 51	99. 2	197	29. 44
	25	341	0. 71	8416	3. 08	56. 11	101. 6	403	28. 06
	35	184	0. 74	8961	3. 28	58. 16	98. 5	522	26. 33
30	0	720	0. 44	3906	1. 96	15. 77	89. 6	8	37. 73
	15	523	0. 67	7208	2. 98	38. 88	92. 2	155	33. 60
	25	319	0. 70	7728	3. 00	45. 18	86. 9	233	32. 05
	35	165	0. 74	7836	3. 28	44. 16	79. 2	284	30. 60
					<u>20 Mesh</u>				
15	0	784	0. 29	400	0. 46	3. 90	31. 4	0	18. 55
	20	562	0. 49	4201	2. 22	18. 25	94. 8	15	18. 74

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Appendix Table 4. (Continued)

N	1	2	3	4	5	6	7	8	9
15	40	231	0.60	5905	2.82	30.03	97.0	88	17.73
	50	136	0.64	6563	3.02	36.56	99.5	173	17.31
20	0	740	0.40	2217	1.18	4.96	56.4	2	25.06
	20	510	0.61	5586	2.25	23.34	97.1	41	22.49
	30	380	0.64	5355	2.12	33.11	99.9	97	21.61
	45	160	0.68	6855	3.06	38.83	101.2	196	21.52
25	0	740	0.38	2011	1.32	3.26	57.9	1	31.99
	20	439	0.59	5337	2.34	24.37	95.5	26	29.01
	35	246	0.64	6112	2.58	29.28	95.2	80	28.12
	45	137	0.65	6162	2.78	30.90	97.2	103	27.06
30	0	725	0.39	2731	1.32	9.29	67.0	2	37.47
	15	485	0.62	6399	2.88	34.21	95.7	75	33.37
	25	267	0.68	7342	2.86	41.10	92.1	183	31.92
	35	132	0.73	7789	3.40	45.13	91.4	327	30.49

Appendix Table 5. Average Bauer-McNett fiber classification results.

Description of columns:

N. Percent of active alkali
1. Percent of fibers on 20 mesh
2. Percent of fibers on 35 mesh
3. Percent of fibers on 65 mesh
4. Percent of fibers on 150 mesh
5. Percent of fibers through 150 mesh

N	1	2	3	4	5
			Coarse sawdust		
15	56.38	22.14	15.91	3.39	2.18
20	35.82	22.76	25.02	10.68	5.72
25	40.23	19.52	24.12	11.31	4.83
30	37.18	20.24	24.28	10.48	7.82
Ave.	42.4	21.2	22.3	9.0	5.1
			Fine sawdust		
15	43.24	25.03	21.01	7.35	1.17
20	32.48	27.43	25.90	12.74	1.46
25	29.27	27.25	26.18	13.72	3.58
30	29.69	26.89	26.90	13.78	2.74
Ave.	33.7	26.7	25.0	11.9	2.2
			1/4" Opening		
15	61.60	13.07	9.55	2.27	13.50
20	65.46	11.86	11.23	3.92	7.54
25	68.00	11.91	12.04	4.95	3.10
30	75.03	9.38	10.03	3.71	1.85
Ave.	67.5	11.6	10.7	3.7	6.5
			6 Mesh		
15	67.26	15.91	12.09	3.17	1.57
20	60.76	15.14	14.72	5.87	3.51
25	58.35	16.14	15.11	6.05	4.36
30	56.86	14.78	14.29	6.32	7.75
Ave.	60.8	15.5	14.1	5.4	4.3

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Appendix Table 5. (Continued)

N	1	2	3	4	5
			10 Mesh		
15	56. 53	18. 57	14. 27	4. 91	5. 73
20	53. 03	21. 17	18. 77	6. 73	0. 29
25	52. 09	19. 10	17. 20	7. 33	4. 28
30	54. 23	18. 30	17. 50	8. 02	1. 95
Ave.	54. 0	19. 3	16. 9	6. 7	3. 1
			20 Mesh		
15	27. 38	29. 42	28. 53	11. 47	2. 20
20	29. 55	28. 34	28. 33	11. 43	2. 36
25	33. 46	26. 24	26. 47	10. 62	3. 21
30	38. 58	24. 46	21. 89	9. 91	5. 16
Ave.	32. 2	27. 1	26. 3	10. 9	3. 2

Appendix Table 6. Regression equation data.

Description of columns:

1. Variables entered in regression equation
2. Regression coefficients (β)
3. Ratio of the regression coefficient with its standard error (t)
4. Simple correlation coefficient (r^2)

*, **, *** indicate coefficients are significant at 0.05, 0.01, and 0.001 probability level or greater from the "t" test analysis

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Coarse-Fine Sawdust

	Sheet density			Breaking length		
1	2	3	4	2	3	4
Constant	0.27	0.38	--	-15800.00	3.46	--
Coarse sawdust	- 0.06	2.50	0.877	178.41	0.75	0.963
Total yield	0.02	1.32	0.975	330.59	2.61**	0.957
Kappa No.	- 0.007	3.17**	0.810	-57.02	2.11*	0.962
Freeness	- 0.0005	11.62***	0.700	- 0.75	0.69	0.964
Sheet density	--	--	--	1716.80	8.70***	0.950
	Stretch			Bursting strength		
Constant	- 5.63	2.97	--	-46.61	1.81	--
Coarse sawdust	- 0.04	0.38	0.893	- 0.44	0.33	0.964
Total yield	0.17	3.16**	0.860	0.43	0.60	0.963
Kappa No.	- 0.03	2.26*	0.87	0.04	0.28	0.960
Freeness	- 0.001	2.12*	0.89	0.003	0.54	0.9634
Sheet density	2.93	3.59**	0.78	102.90	9.26**	0.940
	Folding endurance			Tearing strength		
Constant	-1100.50	1.61	--	-210.86	2.17	--
Coarse sawdust	-92.99	2.60*	0.81	17.54	3.45**	0.41
Total yield	42.53	2.26*	0.82	3.74	1.39	0.61
Kappa No.	- 8.07	2.00	0.85	-0.48	0.83	0.62
Freeness	- 0.74	4.58***	0.77	-0.06	2.75*	0.54
Sheet density	2.38	0.01	0.84	178.62	4.26***	0.27
	Brightness			Canadian Standard Freeness		
Constant	78.57	7.72	--	140.91	0.25	--
Coarse sawdust	- 0.12	0.23	0.965	58.72	2.42*	0.920
Total yield	- 0.89	3.17**	0.817	11.24	0.79	0.910
Kappa No.	- 0.22	3.57**	0.963	1.80	0.64	0.924
Freeness	0.002	0.84	0.965	--	--	--
Sheet density	13.78	3.14**	0.935	--	--	--
Beating time	--	--	--	-15.60	17.91***	0.81
	Total yield			Screened yield		
Constant	46.81	24.95	-	62.80	5.55	--
Coarse sawdust	0.85	3.12**	0.960	-0.88	0.54	0.080
% chemical	-0.24	4.13***	0.943	-0.57	1.60	0.190
Kappa No.	0.11	4.93***	0.928	-0.25	1.90	0.110
	Kappa number					
Constant	-188.51	16.85	--			
Coarse sawdust	- 1.34	0.86	0.930			
Total yield	4.86	19.28***	0.928			

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Appendix Table 6. (Continued)

		Fractionated Sawdust		
Source of variation	Parameter estimate	Null hypothesis	Test statistic	
		Sheet density		
Constant	0.71	--	--	
Screen size				
1/4" opening	- 0.02	$B_5 = B_6 = B_7 = B_8 = 0$	F = 6.67***	d.f. = 3,56
6 mesh	0.04			
10 mesh	0.02			
20 mesh	- 0.04			
Total yield	0.001	$B_1 = 0$	t = 0.19	
Kappa no.	- 0.0006	$B_2 = 0$	t = 0.44	d.f. = 56
Freeness	- 0.0005	$B_3 = 0$	t = 16.0***	
		Multiple $r^2 = 0.84$		
		Breaking length		
Constant	-10574.00	--	--	
Screen size				
1/4" opening	7339.30	$B_5 = B_6 = B_7 = B_8 = 0$	F = 30.61***	d.f. = 3,56
6 mesh	4280.08			
10 mesh	157.15			
20 mesh	-11776.45			
Total yield	112.91	$B_1 = 0$	t = 2.42*	
Kappa no.	- 8.35	$B_2 = 0$	t = 0.74	d.f. = 56
Freeness	1.45	$B_3 = 0$	t = 2.52*	
Sheet density	19186.00	$B_4 = 0$	t = 18.09***	
		Multiple $r^2 = 0.97$		
		Stretch		
Constant	- 0.89	--	--	
Screen size				
1/4" opening	0.22	$B_5 = B_6 = B_7 = B_8 = 0$	F = 6.54***	d.f. = 3,56
6 mesh	- 0.01			
10 mesh	- 0.02			
20 mesh	- 0.19			
Total yield	- 0.003	$B_1 = 0$	t = 0.14	
Kappa no.	0.01	$B_2 = 0$	t = 1.95	d.f. = 56
Freeness	0.0002	$B_3 = 0$	t = 0.54	
Sheet density	5.58	$B_4 = 0$	t = 1.01	
		Multiple $r^2 = 0.91$		
		Bursting strength		
Constant	-86.86	--	--	
Screen size				
1/4" opening	7.71	$B_5 = B_6 = B_7 = B_8 = 0$	F = 26.05***	d.f. = 3,56
6 mesh	4.04			
10 mesh	- 2.19			
20 mesh	- 9.56			

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Appendix Table 6. (Continued)

		Fractionated Sawdust		
Source of variation	Parameter estimate	Null hypothesis	Test statistic	
		Bursting strength (cont'd)		
Total yield	0.98	$B_1 = 0$	t = 1.92	
Kappa no.	- 0.015	$B_2 = 0$	t = 0.11	d.f. = 56
Freeness	0.005	$B_3 = 0$	t = 0.55	
Sheet density	130.59	$B_4 = 0$	t = 11.22***	
		Multiple $r^2 = 0.94$		
		Folding endurance		
Constant	-447.13	--	--	
Screen size				
1/4" opening	134.54	$B_5 = B_6 = B_7 = B_8 = 0$	F = 16.07***	d.f. = 3,56
6 mesh	116.53			
10 mesh	-46.27			
20 mesh	-204.80			
Total yield	11.77	$B_1 = 0$	t = 0.89	
Kappa no.	1.30	$B_2 = 0$	t = 0.004	d.f. = 56
Freeness	0.07	$B_3 = 0$	t = 3.06**	
Sheet density	702.48	$B_4 = 0$	t = 2.34*	
		Multiple $r^2 = 0.82$		
		Tearing strength		
Constant	1.73	--	--	
Screen size				
1/4" opening	32.79	$B_5 = B_6 = B_7 = B_8 = 0$	F = 25.64***	d.f. = 3,56
6 mesh	-13.44			
10 mesh	- 8.63			
20 mesh	-10.72			
Total yield	0.36	$B_1 = 0$	t = 0.626	
Kappa no.	0.19	$B_2 = 0$	t = 0.625	d.f. = 56
Freeness	0.005	$B_3 = 0$	t = 0.590	
Sheet density	130.59	$B_4 = 0$	t = 11.22***	
		Multiple $r^2 = 0.63$		
		Brightness		
Constant	54.54	--	--	
Screen size				
1/4" opening	- 0.09	$B_5 = B_6 = B_7 = B_8 = 0$	F = 1.99	d.f. = 3.56
6 mesh	- 1.03			
10 mesh	0.81			
20 mesh	0.31			
Total yield	- 0.46	$B_1 = 0$	t = 2.09*	
Kappa no.	- 0.25	$B_2 = 0$	t = 4.72***	d.f. = 56
Freeness	0.007	$B_3 = 0$	t = 2.60*	
Sheet density	- 5.88	$B_4 = 0$	t = 1.88	
		Multiple $r^2 = 0.90$		

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Appendix Table 6. (Continued)

		Fractionated Sawdust		
Source of variation	Parameter estimate	Null hypothesis	Test statistic	
		Canadian Standard Freeness		
Constant	541.23	--	--	
Screen size				
1/4" opening	22.13	$B_5 = B_6 = B_7 = B_8 = 0$	F = 2.72	d.f. = 3,57
6 mesh	13.49			
10 mesh	-25.60			
20 mesh	-10.02			
Total yield	2.77	$B_1 = 0$	t = 0.53	
Kappa no.	2.33	$B_2 = 0$	t = 1.84	d.f. = 57
Beating time	-13.00	$B_3 = 0$	t = 35.40***	
		Multiple $r^2 = 0.96$		
		Total yield		
Constant	50.66	--	--	
Screen size				
1/4" opening	- 0.49	$B_5 = B_6 = B_7 = B_8 = 0$	F = 12.98***	d.f. = 3,58
6 mesh	- 0.88			
10 mesh	0.08			
20 mesh	1.29			
% chemical	- 0.32	$B_1 = 0$	t = 5.10***	d.f. = 58
Kappa no.	0.12	$B_2 = 0$	t = 5.58***	
		Multiple $r^2 = 0.94$		
		Screened yield		
Constant	58.87	--	--	
Screen size				
1/4" opening	0.63	$B_5 = B_6 = B_7 = B_8 = 0$	F = 16.33***	d.f. = 3,58
6 mesh	- 2.09			
10 mesh	- 0.33			
20 mesh	1.79			
% chemical	- 0.49	$B_1 = 0$	t = 4.90***	
Kappa no.	- 0.09	$B_2 = 0$	t = 2.50*	d.f. = 58
		Multiple $r^2 = 0.65$		
		Kappa number		
Constant	-156.57	--	--	
Screen size				
1/4" opening	2.78	$B_5 = B_6 = B_7 = B_8 = 0$	F = 11.10***	d.f. = 3,59
6 mesh	3.23			
10 mesh	0.01			
20 mesh	- 6.02			
Total yield	3.94	$B_1 = 0$	t = 23.61***	d.f. = 59
		Multiple $r^2 = 0.91$		

Appendix Table 7. Data calculated from the mathematical model for estimating sawdust pulp properties.
1. Linear relationship
2. Log-log relationship

Active alkali (%)	Time to freeness		Sheet density		Breaking length		Stretch		Bursting strength		Tearing strength		Folding strength		Brightness	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Coarse Sawdust																
600 CSF																
15	-0.2	-1.2	25.0	19.6	23.9	15.2	109.4	51.3	41.3	23.1	20.2	16.0	330.8	30.0	5.7	5.1
20	26.5	19.3	3.9	3.6	-6.4	-8.7	3.2	2.1	1.8	-3.8	4.6	3.4	116.7	36.5	-3.0	-3.5
25	0.6	0.4	2.3	2.0	-1.1	-1.4	4.3	2.9	9.3	-5.0	-1.2	-1.4	29.5	-49.6	10.5	9.5
30	25.6	19.3	10.2	9.0	16.6	13.4	33.7	24.4	26.9	19.9	4.8	3.7	159.0	43.9	9.3	8.4
400 CSF																
15	0.1	-0.2	20.0	16.4	25.2	18.2	32.1	23.4	42.0	24.6	16.6	13.5	175.9	37.3	1.2	1.3
20	8.5	7.8	1.7	1.7	-7.9	-9.7	1.5	0.7	11.0	7.0	7.0	5.7	20.9	-8.9	-4.0	-4.5
25	-3.4	-3.7	2.5	2.3	-5.2	-5.7	1.8	0.5	16.8	8.6	-2.2	-2.6	17.3	-45.8	11.0	9.8
30	17.1	13.9	8.9	8.2	5.8	5.3	22.5	18.6	26.6	20.7	0.3	-0.6	73.1	35.9	7.8	7.4
200 CSF																
15	0.2	-0.2	16.4	13.9	27.7	20.6	31.7	23.9	48.2	29.8	8.2	7.2	115.2	36.8	-0.6	-0.8
20	8.9	8.1	3.1	-7.5	-9.6	3.4	2.8	8.4	5.9	5.9	5.3	-5.7	-27.1	-4.3	-4.3	-4.5
25	3.4	2.9	3.3	3.0	-4.9	-4.3	8.8	7.3	12.7	7.5	-1.8	-2.1	6.6	-33.0	9.8	8.9
30	14.3	12.1	7.7	7.1	-2.8	-3.0	21.1	17.5	17.4	14.7	-1.1	-1.9	43.7	26.9	6.7	6.3
Ave.	8.5	6.5	8.8	7.5	5.3	2.5	22.8	14.6	21.9	12.7	5.1	3.9	90.3	6.9	4.2	3.6

Grand Average: 1. Linear model 20.9%
2. Log-log model 7.3%

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Appendix Table 7. (Continued)

Active alkali (%)	Time to freeness		Sheet density		Breaking length		Stretch		Bursting strength		Tearing strength		Folding strength		Brightness	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
									Fine Sawdust							
									600 CSF							
15	51.0	-50.4	-2.0	-1.6	-22.4	25.0	12.3	-10.1	-8.4	14.6	10.4	-10.2	69.7	46.0	8.1	-8.1
20	3.6	-99.2	-8.3	8.1	-37.2	37.7	-12.5	13.3	-41.0	43.7	10.6	-10.3	-26.9	47.2	-10.9	10.9
25	66.2	-66.2	-7.9	8.1	1.2	-0.9	9.0	-7.4	-24.8	36.0	5.9	-5.9	-8.7	61.6	0	0.1
30	63.9	-62.8	-5.3	5.3	-28.7	-23.3	23.7	-23.3	-17.1	18.1	10.3	-10.2	43.2	-2.9	0.6	-0.7
									400 CSF							
15	31.3	-31.1	-10.2	10.5	-23.4	25.2	-1.5	2.3	-12.3	15.4	10.2	-10.1	-19.3	57.2	9.8	-9.4
20	55.2	-55.0	-10.0	9.9	-31.8	32.5	-12.4	12.7	-24.6	26.2	13.3	-13.1	-38.2	53.2	-10.2	10.4
25	38.6	-38.5	-9.9	10.0	-1.0	1.1	3.9	-2.7	-6.7	12.5	10.4	-9.7	-35.6	65.0	2.2	-2.2
30	29.4	-29.2	-8.7	8.7	-21.3	21.5	18.6	-18.5	-4.9	5.2	9.9	-9.7	-5.4	11.6	5.5	-5.4
									200 CSF							
15	25.7	-25.5	-18.9	9.2	-21.8	23.0	-4.6	5.0	-6.7	10.0	9.9	-9.9	-38.9	56.1	5.0	-4.9
20	53.4	-53.3	-15.9	6.0	-30.3	31.1	-9.2	9.4	-19.0	19.9	15.9	-15.5	-30.5	41.3	-10.5	10.5
25	40.6	-40.2	-11.9	12.0	-3.5	3.5	8.0	-7.2	-18.3	21.9	15.8	-15.7	-46.3	63.9	1.5	-1.5
30	20.9	-20.7	-8.3	8.2	-19.4	9.4	18.4	-8.4	-4.3	4.4	12.9	-13.2	-7.5	29.0	7.3	-7.3
Ave.	40.0	-47.7	-9.8	7.9	20.0	15.5	4.5	-2.9	-15.7	19.0	11.3	-11.1	-12.0	44.1	2.5	0.6

Grand average:
1. Linear model 5.1%
2. Log-log model 3.2%

Appendix Table 8. Paired "t" test comparisons of pulp properties.

Test property	Mean test value		Difference in means $\bar{X}_1-\bar{X}_2$	$\sigma_{\bar{X}_1-\bar{X}_2}$	Paired "t" value
	Coarse sawdust- X_1	Fine sawdust- X_2			
	At Constant Freeness				
Time to freeness	24.4	18.0	6.4	3.0	7.2***
Sheet density	0.59	0.68	-0.09	0.03	10.2***
Breaking length	6900	8500	-1600	1326	4.2**
Stretch	2.43	2.66	-0.23	0.37	2.1*
Mullen factor	33.1	42.7	-9.6	2.5	13.2***
Tear factor	99.2	90.0	9.2	8.1	3.9**
Folding endurance	174	258	-84	90	3.2**
Brightness	23.7	24.9	-1.2	1.3	3.2**
	Degrees of freedom = 11				
	At Constant Beating Time				
Freeness, CSF	445	432	13	73	0.68
Sheet density	0.56	0.64	-0.08	0.04	8.0***
Breaking length	6500	7940	-1440	1080	5.3***
Stretch	2.27	2.46	-0.19	0.38	2.0*
Mullen factor	29.7	37.7	-8.0	5.2	6.1***
Tear factor	89.8	83.2	6.6	11.7	2.2*
Folding endurance	159	246	-87	93	3.7**
Brightness	24.4	25.9	-1.5	1.2	4.8***
	Degrees of freedom = 15				

*, **, and *** indicate statistical significance at the 0.05, 0.01, and 0.001 probability levels, respectively.