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Title: Relationships between Properties of Pulp-Fibre and Paper

Authors: J. Lee [1,2], D.N. Roy [2], M. Hong[3], and P. Whiting [1,2]

Address:

1 Abitibi-Price Inc.
Sheridan Park
2240 Speakman Dr.
Mississauga, Ontario
Canada L5K 1A9

2 University of Toronto
Faculty of Forestry
33 Willcocks St.
Toronto, Ontario
Canada M5S 3B3

3 University of Toronto
Department of Engineering
200 College Street
Toronto, Ontario, M5S 1A4

ABSTRACT

In order to produce papers with differing qualities, papermakers use pulps with varying fibre and fines characteristics. Since the early 1900's, numerous studies have been conducted to investigate the relationships between pulp-fibre and paper properties. However, a common weakness was that previous investigations focused on relationships within restricted ranges of properties of pulp-fibre and paper. For this reason, the main goal of this investigation was to examine and to characterize a broad scope of fibre-paper relationships. In order to achieve this goal, a statistical approach was taken. This technique explained much of the total variation in paper properties by investigating a large number of pulp-fibre types, including fines, with a broad range of characteristics. It was discovered that robust and orthogonal non-linear multiple regression models could be developed to predict various paper properties. The multiple curvi-linear regression models reported here (based on the PhD thesis of the first author of this paper) could explain, on the average, 85 ± 10% of the

variance (R^2)in the paper properties. Although the models generated are empirical, and thus lack fundamental interpretative meaning, they do clearly rank those fibre properties most important for a given paper property and allow prediction of the "form" of the relationship. These relationships confirm the expectation that there are no universally optimum fibre paper properties. Instead, compromises must be made to achieve an acceptable balance of properties. Such interactions are described in more detail in the paper.

INTRODUCTION

In the pulp and paper industry, there are several standard tests for paper properties (Elmendorf four-ply tear, breaking length, density, and scattering). The relationships between pulp-fibres and the above standard paper properties have been well established over the years. However, these paper properties have been characterized only in terms of chemical pulp-fibres. Thus, the relationships between paper properties and many of the new mechanical pulp-fibre properties are not well understood. In this report, only the four-ply tear and breaking length results are discussed. Density and scattering results are reported in the Ph.D. thesis of the first author of this paper (1).

There are also numerous non-standard paper properties that have not been studied extensively and therefore not well understood (one-ply Elmendorf tear, fracture toughness, tensile energy absorption [TEA], stretch, roughness, static friction, calendering response, and porosity). Among these, only the fracture toughness, roughness, and porosity are discussed in this report. The rest of these paper properties are reported in (1). The fracture toughness (determined by the elastic region of the J-integral method [$J_{elastic}$]) (2,3) is defined as a measure of the energy required to propagate a crack (mode I fracture) that has been initiated within a sheet of paper. Since fracture toughness measures in-plane tear strength, it is representative of mill or press-room paper breaks. (4). Roughness is defined as the inconsistent physical attributes of the paper surface that promote deviation from a completely smooth paper surface. It plays a vital role in determining printability of a sheet of paper. Porosity is defined as the amount of holes or inter-fibre pores found in a sheet of paper. Thus, any fibre property that affects the structure of the sheet could influence porosity.

Since the early 1900's, there have been hundreds of studies investigating the relationships between pulp-fibre and paper properties. A detailed literature review can be found in the Ph.D. thesis of the first author of this paper (1). The common weakness of all the past studies was that they focused on the relationships between a limited number of properties of pulp-fibre and paper. Most examined kraft pulp-fibres exclusively but even when various mechanical pulp-fibres were investigated, they were based on a small number of tree-species. For this reason, there was a need to develop models that described the relationships between the widely diversified properties of pulp-fibres and paper that are present in today's market. Thus, this investigation's main overall goal was to attempt to elucidate the whole space of fibre-paper relationships.

In order to achieve this goal, a "statistical" experimental approach was chosen. This approach took advantage of the power of multivariate data analysis and multiple regression statistical methods. In this investigation, the overall picture or the "population" is defined as the complete relationship between every pulp-fibre and paper property. If enough samples that are representative of the "population" could be collected, then these samples could statistically predict the parameters of the "population". Now, the next logical question was "how to gather a sufficient number of the best representative samples?". First, the larger the sample size the better the properties of the "population" could be predicted. Thus, it was decided to choose the largest number of samples that could be handled within the time frame of this project (three to four years). Secondly, the best representative sampling method would encompass as much of the independent and dependent "variable spaces" as possible. This would translate to sampling as wide a range of pulp-fibre characteristics and paper properties as possible. This step is essential because in any model, but particularly in empirical statistical models, extrapolation has limited validity. Statistical models are built to predict dependent variables by interpolating within the realm of the independent variables measured, not beyond them.

In addition to the statistical approach, the scope of this investigation incorporated two other experimental goals. First was to assimilate into the models not only the standard pulp-fibre and paper properties of the industry, but also others that have not been researched in detail. Second was to integrate into the models the effect of the quantity and quality of the fines in a sheet of paper. It was clearly recognized by the authors that this approach would not produce models that, on their own, explain the causal reasons for how any fibre property affects any paper property. However, it is possible to determine which fibre properties are important, their relative importance, and in what way that effect is manifested (eg. is the effect linear, curvi-linear, etc.).

OBJECTIVES

The scope and approach of this investigation are summarized in the following objectives:

i. To prepare a sufficient number of pulp samples to derive statistically meaningful results over a wide range of properties.

ii. To measure relevant pulp-fibre properties.

iii. To measure relevant properties of paper (made reproducibly with fines retention).

iv. To use statistical techniques to deconvolute the data-set to produce empirical models.

v. To test the models for their statistical validity and robustness.

vi. To interpret, wherever possible, the results in light of available knowledge.

vii. To determine which fibre-properties account for most of the variation in paper properties and to characterize the form of these interactions.

METHODOLOGY

The detailed methodology of this investigation can be found elsewhere (1). An abbreviated version will be presented in this report.

Experimental

Most of the pulps were prepared at Abitibi-Price Inc. Sheridan Park Technology Centre in Mississauga, Canada. Exceptions are SGW, which was made at the Pointe Claire branch of the Pulp and Paper Institute of Canada (PAPRICAN); solvent pulps, which were provided by Repap Enterprises; CTMP, which was supplied by Temcell Inc. SGW was made using the pilot plant scale grinder (fully conditioned 61 cm diameter pulpstone with silicon carbide abrasive segments). Grinding was done at a constant foot pressure (241 kPa) to maintain a uniform condition for all the species. TMP was made with the pilot scale Sunds defibrator cone disk refiner (CD 300). UHYS pulps were made by cooking the wood chips in two pilot scale digesters. The cooking liquor consisted of 16% sodium bisulphite ($NaHSO_3$), based on oven-dried wood. The liquor to wood ratio was 4:1. Refining of the cooked chips was carried out using a 30.5 cm Sprout atmospheric discharge refiner. Kraft pulps were made in two small cooking digesters with the sulphidity and active alkali charge of the cooking liquor at 30% and 18% (based on oven-dried wood) respectively. The liquor to wood ratio was 5:1.

In addition to all the pulps mentioned above, two samples at the opposite extremities in terms of their pulp-fibre characteristics (black spruce kraft and eastern larch SGW), were selected to test for reproducibility of all the measurements made in this study. Table 1 presents a synopsis of all sixty-two pulps plus two replications used in this investigation.

Handsheets were formed according to CPPA standard C.4 with one exception. In order to retain fines in the handsheets, the white-water passing through the sheet-forming screen was recirculated and used to make the next handsheet. Preliminary test handsheets were made until a constant sheet mass was achieved. Once fines content in the white-water reservoir and that in the handsheet maker tank were in equilibrium, approximately 60 g/m^2 basis weight sheets were made for testing.

Pulp	Species	Description	Freeness (ml)					
TMP	Black spruce (picea mariana)	Mature/juvenile	127	165	278	350	216	176
	Jack pine (pinus banksiana)	Mature/juvenile	196	318	118	159	214	102
	Eastern white cedar (thuja occidentalis)	Mature/juvenile	254	437	564	421	321	592
	Western red cedar (thuja plicata)	Juvenile	385		327		198	
	Douglas fir (pseudotsuga menziesii)	Mature	342		123		86	
UHYS	Black spruce	Mature/juvenile	491	299	180	569	352	188
	Jack pine	Mature/juvenile	434	324	144	506	386	177
	E. white cedar	Mature/juvenile	524	392	163	579	342	169
	W. red cedar	Juvenile	530		353		164	
	Douglas fir	Mature	612		391		370	
Kraft	Black spruce	Mature/juvenile	723 , 713			689		
	Jack pine	Mature/juvenile	691			710		
	E. white cedar	Mature/juvenile	609			597		
	W. red cedar	Juvenile	629					
	Douglas fir	Mature	738					
SGW	Black spruce		60					
	E. white cedar		95					
	Eastern larch (larix laricina)		76 , 96					
Solvent	Mixed hardwood (betula, acer, populus spp.)	Unbleached	595					
	Mixed hardwood (betula, acer, populus spp.)	Bleached	576					
CTMP	Paper birch (betula papyrifera)	Bleached	539					

Table 1 Summary of the 62 Pulps

Once all the pulps were prepared, various pulp-fibre characteristics as well as the paper properties were measured. Tables 2 and 3 list the techniques, the instruments, and the references used to measure the properties of paper and pulp-fibre respectively.

Paper Properties	Measure-ment units	Techniques/ Instruments	References
Breaking length	m	Instrom #1130	CPPA standard D.6H
4-ply Tear index	N•m²/kg	Elmendorf tester	CPPA standard D.9
$J_{elastic}$	J/m	Instrom #1130	(5) & (6)
Porosity	Ml/min	Parker print-surf	Instrument manual
Roughness	μm	Taylor-Hobson Surtronic 3P	Instrument manual

Table 2 Paper Properties

Pulp-Fibre Properties	Measurement Units	Techniques/ Instruments	References
Length	mm	Kajaani FS100	Instrument Manual
Coarseness	mg/m	Kajaani FS100	Instrument manual
# fibres / g	g^{-1}	Kajaani FS100	Instrument manual
Width	μm	Image analysis	(7)
Density	g/cm³	calculated	coarseness / width²
Freeness	ml	CSF tester	CPPA standard C.1
Zero-span breaking length	km	Pulmac	Tappi standard T231
Wet fibre flexibility	10^{12} $N^{-1}m^{-2}$	EFF method (conformability)	(7)
Fibre saturation point	%	Solute exclusion technique	(8)
Long, medium & fine fractions	%	Bauer-McNett classifier	Tappi standard T233
Fines Turbidity	Nephelometric turbidity units	LOV-100B Turbidity meter	Instrument manual
Surface free energy	mN/m	Capillary rise method	(9)

Table 3 Pulp-Fibre Properties

Statistical Methods

First, basic statistics (mean, standard deviation, skewness, kurtosis, minimum, maximum, range, variance, standard error of the mean, sum, and coefficient of variation) were performed to describe the original data-set.

Second, preliminary analyses (correlation matrix, paired scatter-plots, and principal component analysis) were done to reduce the size of the original data-set so that the multivariate data analysis could be executed on only those statistically meaningful independent and dependent variables.

Third, multiple regression models were built for each dependent variable (paper property) by using a stepwise regression method. These models incorporated not only the linear term (x) but also the curvi-linear terms (x^2, $x^{1/2}$, x^{-1}, log(x)) of the independent variables. Furthermore, two-factor interaction terms of the selected independent variables were included.

Fourth, once the regression models were completed, coefficient of determination (R^2) and standard error of the estimate were calculated to evaluate how much of the variation in the dependent variable could be explained by the model. In addition, partial R^2, standardized coefficients, and the standard errors of the coefficients were used to determine the relative importance of each independent variable in the models.

Finally, each model had to be tested for its authenticity and robustness. Authenticity of the models was confirmed by satisfying the four assumptions associated with model building: 1. The expected value of the error term in the model is 0 for all cases, 2. The variance of the errors for each case is constant, 3. The error terms are normally distributed, 4. All independent variables are indeed orthogonal. The robustness of the models was repeatedly tested by comparing the R^2 calculated with all the pulp samples and that determined with all but one randomly removed pulp sample. The results from this work confirmed that these models were robust.

More details about the statistical approach can be found elsewhere (1).

RESULTS

Table 4 shows that on the average, 85 ± 10% of the variance in the paper properties were explained by the models. Also, Table 4 displays the standard errors of estimate (as a percentage of the mean predicted values of paper properties). This calculation is also known as the standard deviation of the residuals. Therefore, it depicts how dispersed the actual data points are away from the predicted line. In all cases, the standard errors are quite reasonable considering the diversified pulp samples that were studied. On the average, the standard error of estimate was 12.5 ± 3% of the mean predicted values.

To give a visual picture of the relationships between individual pulp-fibre properties and paper properties one pulp-fibre property was varied from the minimum to the maximum of its measured value while holding the other pulp-fibre properties constant at their mean values. In this way, sets of predicted values for the five paper properties were calculated. Then, these predicted paper properties were individually plotted against individual pulp-fibre properties (See Figures 1 to 18).

Table 5 lists the quantitative changes in each paper property caused by each pulp-fibre property. The ranges of individual pulp-fibre properties could explain almost all of the total variance in the paper properties, confirming that the relationships established in this study do describe most of what is happening.

During this project, hundreds of experiments were conducted which produced thousands of results. This predictably culminated in an extremely large data-set that could not be presented in this paper. However this information will be made available to the readers, upon request, by contacting the first author of this paper.

Paper Properties	Multiple Regression Model	Adjusted R^2	Stand. ϵ of estimate
Breaking Length	$19374 - 107269\, l_o^{-1} - 77t + 672\, G^{-1} - 110462\, D^{-1} - 40156\, t^{-1} + 274702\, CSF^{-1} - 1724\, FINE^{-1} - .01\, t*NG - 32\, l_o*WFF + 3\, FSP$	95.12%	11.10%
4-ply Tear	$-5.354 + 0.012\, CSF * l + 0.963\, l_o * G + 0.018\, t * l_o + 59.97\, t^{-1} - 6.68 * 10^{-6}\, CSF$	90.31%	13.11%
$J_{elastic}$	$1.335 + 5.561*10^{-6}\, CSF * FSP - 6.261*10^{-5}\, NG$	68.08%	17.22%
Average Rough-ness	$9.609 + 6.895 \log(h) + 2.711*10^{-4}\, CSF * t - 0.097\, WFF * t + 0.001\, D * t + 0.045\, WFF * D - 0.001\, WFF * CSF$	87.23%	10.53%
Porosity	$961.041 + 0.004\, CSF^2 - 151.786\, h^{-1} - 1411881.629\, NG^{-1} + 34.541\, WFF^{-1}$	84.36%	10.41%
Average R^2		85 ± 10%	12.5 ± 3%

Table 4 Multiple regression models, adjusted coefficient of determination, and standard error of estimate of each paper property

where,

where,	l_o =	Zero-span breaking length
	l =	Average fibre length
	D =	Fibre width
	G =	Fibre coarseness
	FSP =	Fibre saturation point
	t =	Fines turbidity
	h =	Fibre density
	CSF =	Canadian standard freeness
	NG =	Number of fibres per gram
	FINE =	Fines fraction (%)
	WFF =	Wet fibre flexibility

Paper Properties (Range studied)	Pulp-fibre Properties	Range studied	Change in Paper Properties	Change/Range [±(%)]* in Paper Properties
Breaking length (8,051 m)	zero-span breaking length	7.4 - 18.5 km	8456.0 m	+105 %
	fibre coarseness	0.08 - 0.93 mg/m	-7,679.8 m	-95.4 %
	# of fibres/g	1,329 -23,810	-6,022.6 m	-74.8 %
	fines turbidity	5 - 54 NTU	4 km & -6 km	+50% & -74.6%
	C.S.F.	60 - 738 ml	-4,206.1 m	-52.2%
	fines content	0.6 - 62.2 %	2,654.1 m	+33.0%
	wet fibre flexibility	.07 - 4.11 $[N*m^2]^{-1}$	-1,499.0 m	-18.6%
	fibre width	21.7 - 46.5 μm	2,718.8 m	+33.8%
	fibre saturation point	93.9 - 363.5 %	813.4 m	+10.1%
4-ply tear index ($19.8\ N*m^2/kg$)	fibre coarseness	0.08 - 0.93 mg/m	$9.37\ N*m^2/kg$	+47.3%
	zero-span breaking length	7.4 - 18.5 km	$7.68\ N*m^2/kg$	+38.8%
	fibre length	0.27 - 1.54 mm	$5.55\ N*m^2/kg$	+28.0%
	fines turbidity	5 - 54 NTU	$-6\ \&\ 5\ N*m^2/kg$	-30.2% & +26.3%
	C.S.F.	60 - 738 ml	$4.32\ N*m^2/kg$	+21.8%
Fracture toughness ($J_{elastic}$) (2.6 J/m)	# of fibres/g	1,329 -23,810	-1.40 J/m	-53.8%
	C.S.F.	60 - 738 ml	0.71 J/m	+27.3%
	Fibre saturation point	93.9 - 363.5 %	0.55 J/m	+21.1%
Profilometer average roughness (9.3 μm)	gross fibre density	.06 - .52 g/cm^3	6.52 μm	+70.1%
	C.S.F.	60 - 738 ml	4.48 μm	+48.2%
	wet fibre flexibility	.07 - 4.11 $[N*m^2]^{-1}$	-5.03 μm	-54.1%
	fines turbidity	5 - 54 NTU	2.46 μm	+26.4%
	fibre width	21.7 - 46.5 μm	1.54 μm	+16.6%
Porosity (1,976 ml/min)	C.S.F.	60 - 738 ml	2,164.1 ml/min	+109.5%
	gross fibre density	0.06 - 0.52 g/cm^3	910.7 ml/min	+46.1%
	# of fibres/g	1,329 -23,810	519.0 ml/min	+26.3%
	wet fibre flexibility	.07 - 4.11 $[N*m^2]^{-1}$	-514.9 ml/min	-26.1%

Table 5 Change in Paper Properties caused by Pulp-Fibre Properties (Note: "+" symbol indicates direct & "-" symbol indicates indirect relationships)

DISCUSSION

One of the main goals of this study was to present an overall picture of the relationships between pulp-fibre and paper properties. This approach, although empirical, would help in identifying and comprehending the underlying fundamental pulp-fibre properties from which the various paper properties could be predicted. In order to achieve this objective, exploratory work was conducted with the most diverse data-set possible. Unfortunately this methodology did sacrifice some details. For example, a more focused approach would have made causal interpretation of the relationships between pulp-fibre and paper properties more reliable. However at the same time, that approach would have confined any conclusions to a much more limited variable space. It would not have provided information on the wide range of pulp-fibre and paper properties about which little is known.

Because our approach generates only empirical models the published literature had to be consulted to assist the interpretation of the predicted relationships. Whenever possible, the known characteristics of both chemical and mechanical pulps were used to interpret the models built in this study.

Some cautionary notes for the reader must be made at this point with regards to the relationships shown in Figures 1 to 18. First, these graphs are calculated, based on the predictions of the models. They are intended only to show the magnitude of the effect of the fibre-properties on paper properties, as well as the shape of the effect curve. Of particular importance is that one must constantly keep in mind that <u>all</u> of the other fibre properties are held constant as the fibre property of interest is varied. Thus, one cannot interpret, say, a freeness effect as a change in fibre length since fibre length was independantly measured and "factored-out" of the freeness effect by being held constant.

Breaking Length

Breaking length was discovered to be most strongly correlated to zero-span breaking length, coarseness, number of fibres per gram, fines turbidity, and freeness (See Table 5 and Figures 1 to 5). There are several types of relationships between these pulp-fibre properties and breaking length.

- The positively-sloped curvilinear function of zero-span breaking length indicates that fibre strength is important for breaking length; especially when the paper contains fibres that are inherently weak.

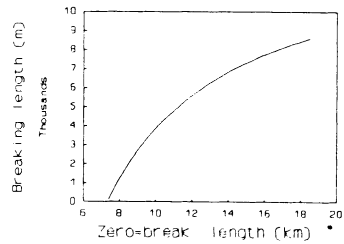

Figure 1 Change in breaking length caused by zero-span breaking length

- Coarseness has a 1/x relationship with breaking length. As fibres become coarser, there is initially a sharp drop in breaking length. One possible explanation is that the bonding potential of the fibres is decreasing rapidly due to fibres becoming less collapsible. However, beyond a certain coarseness, the fibres no longer collapse very much and thus breaking length levels off.

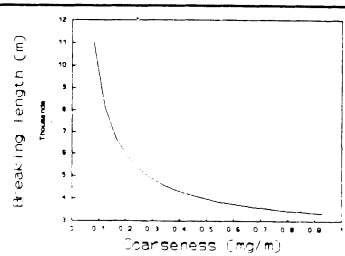

Figure 2 Change in breaking length caused by coarseness

- Freeness also shows a 1/x relationship with breaking length. Remember that fibre length, fines quality, etc. arguments cannot be used to explain this effect since these are accounted for in the breaking length model. It thus appears that in this case it is fibre fibrillation which is causing the effect. Below a freeness of about 200 mL, fibrillation develops and increases fibre to fibre bond strength. This could acount for the rapid increase in breaking length at lower freeness.

- The number of fibres per gram can be affected by the length factor (shorter fibres increase the number of fibres in a given mass) and/or by the mass factor (coarser fibres occupy more mass per unit length). Since coarseness is accounted for in this model, it appears that the fibre length effect is represented here. As the number of fibres per gram increases, fibres in the sheet become shorter; thus the number of bonds/fibre decreases.

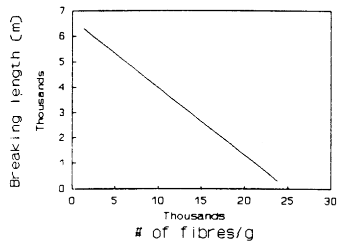

Figure 4 Change in breaking length caused by number of fibres/g

- Fines turbidity is a measure of fines quality. As fines quality increases, there is initially a rapid increase in strength, presumably due to improved bonding. However at some critical point, strength decreases, possibly due to a change in the fracture mechanism during failure. It is interesting to note that fines turbidity has a similar effect on paper stretch. At high turbidity, stretch is lower. This could prevent stress relaxation during the test, causing more stress localization and a decreased force required for initiation of failure.

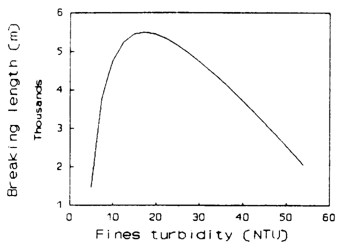

Figure 5 Change in breaking length caused by fines turbidity

The results of this work generally agree with those of the past studies. It has been illustrated above that fibre-to-fibre bonding (governed by hydrodynamic specific volume, coarseness, and number of fibres per gram [length factor]) and fibre strength (zero-span breaking length) are important for breaking length.

One important observation should be made here. It has been known for a long time that fibre strength, fines quality, etc. are important in breaking length. One of the unique contributions of this work is that these effects have been quantified and their interactions have been shown to hold over a wide range of pulps (from SGW to kraft).

4-ply Out-of-Plane Tear

Four pulp-fibre properties were found to be strongly correlated to 4-ply tear strength (See Table 5 and Figures 6 to 9). The first two (coarseness and zero-span breaking length) describe fibre strength while the last two (fibre length and fines turbidity) illustrate bonding strength of the fibre-network.

- Coarseness is positively and linearly related to 4-ply tear. Coarseness, as discussed earlier, is a measure of the cell wall thickness. One might expect that these thicker fibres would be stronger, thus accounting for the effect on tear. This argument cannot be used since, in this calculation, zero-span breaking length was held constant. An alternative explanation is that coarser fibres absorb more energy during deformation in the out-of-plane test than do thin-walled fibres.

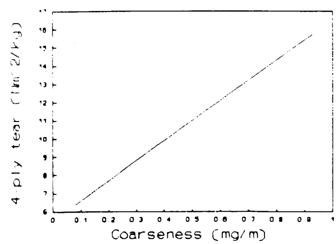

Figure 6 Change in 4-ply tear caused by coarseness

- Zero-span breaking length is also positively and linearly related to 4-ply tear. Zero-span breaking length is a measure of inherent fibre strength. It seems self-evident that stronger fibres would result in higher tear, all other factors being equal.

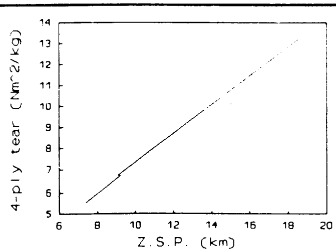

Figure 7 Change in 4-ply tear caused by zero-span breaking length

- Fibre length has a positive linear relationship with 4-ply tear strength.. Longer fibres have more bonds per fibre. This increase for longer fibres increases the 4-ply tear strength, as is well known to occur.

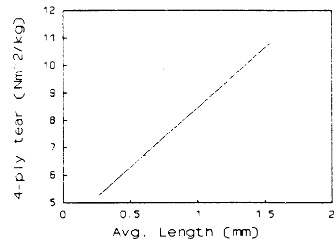

Figure 8 Change in 4-ply tear caused by average length

- There is a complex "V"-shaped relationship between fines turbidity and 4-ply tear strength. This is opposite of the inverted "V"-shaped relationship found between fines turbidity and breaking length. The first phase of the "V" curve shows that for those fines with low turbidity (< 15 NTU), as fines quality increases 4-ply tear strength decreases. This contradicts the conventional wisdom. We are currently unable to explain their initial drop in the curve. The second phase of the "V" curve shows that for those fines with higher turbidity (>15 NTU), as fines quality increases 4-ply tear strength also increases. This simply means that fines quality improves bonding potential; thereby increasing 4-ply tear strength.

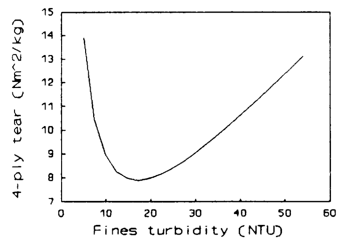

Figure 9 Change in 4-ply tear caused by fines turbidity

Most of the results from this work agree with those of those past investigations. It was discovered that fibre strength and bonding strength indeed dictate the relationships between pulp-fibre properties and 4-ply tear strength. On the other hand, it was also discovered that fines quality has an effect on 4-ply tear strength, only part of which can be explained, and that a possible energy-absorption effect occurs with coarse fibres.

Fracture Toughness ($J_{elastic}$)

$J_{elastic}$ was found to be significantly affected by 3 pulp-fibre properties (number of fibres per gram, freeness, and fibre saturation point) (See Table 5 and Figures 10 to 12).

- $J_{elastic}$ is strongly related to the number of fibres per gram in a negatively linear way. Changes in number of fibres/gram can be caused by changes in either fibre length or coarseness or both. Because neither are included in the model (ie they did not produce significant effects) it is impossible to eliminate either so one must assume that both interact in some way to produce this effect. It thus appears that to increase $J_{elastic}$, increasing the number of fibres per gram could be accomplished by changing either fibre length or coarseness with the same effect.

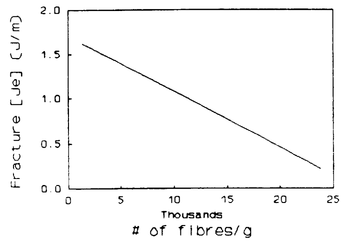

Figure 10 Change in $J_{elastic}$ caused by number of fibres/g

- $J_{elastic}$ has a positive linear relationship with freeness; i.e. a negative linear relationship with hydrodynamic specific volume. This is puzzling at first because one might imagine that as freeness decreases, bonding potential would increase and subsequently fracture toughness would increase. An alternative explanation exits, however. Remember that we are discussing toughness in the elastic region only. It thus appears that high freeness pulps are more difficult to deform elastically and thus gives a higher $J_{elastic}$. This observation requires further investigation to be adequately understood.

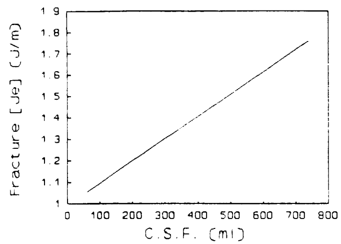

Figure 11 Change in $J_{elastic}$ caused by freeness

- The relationship between $J_{elastic}$ and fibre saturation point is positive and linear. This indicates that the swelling potential of the cell walls of the pulp-fibres (predominantly the long fraction) is important for $J_{elastic}$. High swelling potential is caused by fibre development. Chemical and/or mechanical treatment of fibres cause cell walls to become more fibrillated and to have higher affinity for water. Thus, such fibres would be able to form stronger inter-fibre hydrogen bonds and thereby improve the elastic portion of fracture toughness.

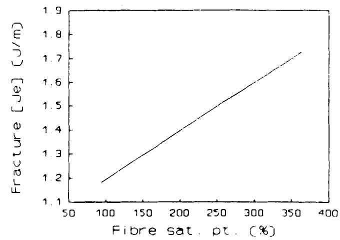

Figure 12 Change in $J_{elastic}$ caused by fibre saturation point

Interpretation of the individual fibre effects on $J_{elastic}$ is difficult and it is readily apparent that more work is needed to elucidate the true causal effects. However, combining all 3 fibre-properties does produce at least one plausible explanation. To get high $J_{elastic}$ one needs a pulp at high freeness and with relatively few fibres/gram (not unusual) but with a high fibre saturation point; an unusual pulp indeed. An interesting test of this prediction would be to create a high freeness pulp from coarse fibres and add to it a strong bonding agent; basically what is done in the production of many fibre boards. It is not known if such materials have high $J_{elastic}$ properties, as would be expected from these predictions.

Roughness

In this work, gross fibre density, freeness, wet fibre flexibility, and fines turbidity were found to have the strongest relationships with roughness (See Table 5 and Figures 13 to 16).

- Gross fibre density has a positive log function relationship with roughness. As fibres become denser, cell walls become thicker, bonding potential decreases, paper becomes bulky and less uniform, paper surface becomes uneven, and roughness increases.

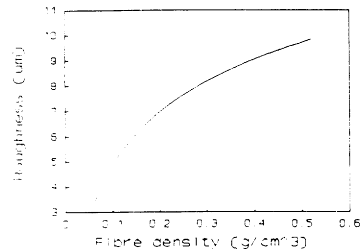

Figure 13 Change in roughness caused by fibre density

- Freeness has a positive linear relationship with roughness. As freeness increases, the hydrodynamic specific volume of the pulp decreases (due to decrease in fibrillation of the long fibre fraction and/or due to decrease in fines content). Since fines content was not selected as a factor in this model, one cannot eliminate the possibility that, in this case, the freeness effect is a fines effect. That is, as freeness decreases the amount of fines increases. Fines will fill in holes and pores in the sheet, presumably decreasing roughness.

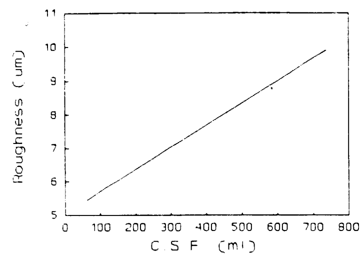

Figure 14 Change in roughness caused by freeness

- Wet fibre flexibility was found to have a negative linear relationship with roughness. That is expected because flexible fibres tend to conform better and thus promote a more even paper surface.

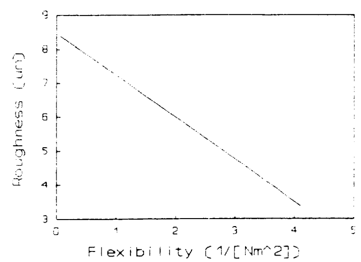

Figure 15 Change in roughness caused by wet fibre flexibility

- Fines turbidity has a positive linear relationship with roughness. Since fines turbidity appears three times in the regression model as interaction terms, fines turbidity seems to be an integral part of determining roughness. This relationship once again contradicts initial expectations. As fines quality improves, paper might be expected to become smoother, not rougher. An explanation could be that to improve roughness, what is needed is a "filler" type fine; ie. one that fills in voids only. A good bonding fine will increase inter-fibre bonding, perhaps deforming the long fibre and increasing its deviation from linearity - ie. increased roughness. Roughness is most sensitive to large deviations (big "holes") and it could be that this phenomenon causes more big holes.

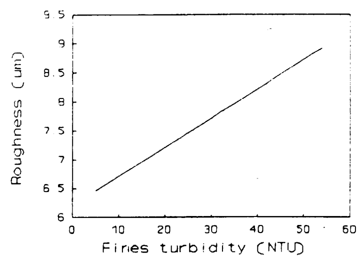

Figure 16 Change in roughness caused by fines turbidity

In the relationships between roughness and pulp-fibre properties it was found that less dense and flexible fibres with a large specific surface area produced smoother paper. Assuming the freeness effect is caused by fines quality, then both quantity and quality of fines play a role in determining roughness.

Porosity

Freeness and fibre density were most strongly related to porosity (See Table 5 and Figures 17 to 18).

- Freeness has a positive squared function relationship with porosity. As freeness increases (hydrodynamic specific volume decreases), porosity increases. In other words, the well fibrillated fibre fraction and/or larger amount of fines fraction cause better bonding and/or more voids between long fibres to be filled; subsequently reducing the holes in the sheet structure and decrease in porosity. Since it seems reasonable to expect fines to be important in porosity, and fines do not appear in the model, it is plausible to once again suspect fines quantity as the explanation for the freeness effect.

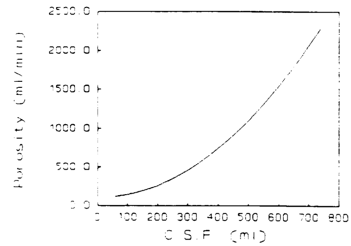

Figure 17 Change in porosity caused by freeness

- Fibre density has a negative inverse function (looks like a positive log function) relationship with porosity. This indicates that as fibres become denser, cell walls become thicker, bonding potential decreases, there is more inter-fibre spaces) and hence a sheet of paper becomes more porous.

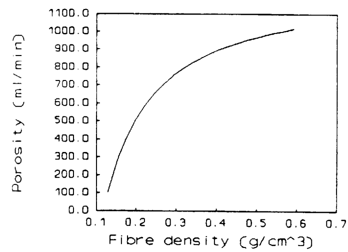

Figure 18 Change in porosity caused by fibre density

The results from the present study, seem plausible; particularly if one accepts that the freeness effect is primarily derived from the inverse relationship between freeness and fines quantity.

CONCLUSIONS

i. Using sixty-two different pulps of a wide range of pulp-fibre properties, robust and orthogonal curvi-linear multiple regression models can be developed to predict various paper properties.

ii. The pulp-fibre properties (independent variables) of the five regression models could explain, on the average, 83 ± 10% of the variance in the paper properties (dependent variables).

iii. 95% of the variance in breaking length could be explained by (in order of importance) inherent fibre strength, fibre coarseness, number of fibres per unit mass (fibre length factor), fines quality, freeness(hydrodynamic specific volume), fibre width, fines content, flexibility, and fibre wall swelling potential.

iv. 90% of the variance in four-ply-tear index could be explained by (in order of importance) fibre coarseness, inherent fibre strength, fibre length, fines quality, and freeness.

v. 68% of the variance in the elastic portion of fracture resistance could be explained by (in the order of importance) number of fibres per unit mass, freeness and fibre wall swelling potential.

vi. 87% of the variance in surface roughness could be explained by (in order of importance) gross fibre density, freeness, flexibility, fines quality, and fibre width.

vii. 84% of the variance in porosity could be explained by (in order of importance) freeness, gross fibre density, number of fibres per unit mass, and flexibility.

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Transcription of Discussion

RELATIONSHIPS BETWEEN PROPERTIES OF PULP-FIBRE AND PAPER

J Lee, P Whiting & D N Roy
(Paper presented by A Chatterjee)

P Mangin, PAPRICAN, Canada

The roughness that you are actually presenting which parameter are you using? Is it $\mathbf{R_a}$ or $\mathbf{R_q}$?

A Chatterjee

It is R_a.

Prof J Lindsay, IPST, USA

I've got two suggestions for the next stage of the work. The work that would be convincing to people on the success of the model is how well it predicts new pulp types or other pulp types to those in the data set. You can always add more terms in a regression model to get a higher square. If you take some new pulps and make those measurements and plug them into the existing model and see how well they fit then this would be a very important piece of evidence. And also I would like to suggest at least introducing a class variable for the type of pulp, whether it is mechanical or kraft, because it seems it would be very difficult to force fit all those properties for any type of pulp into any one equation unless there is something in there that takes account of the type of pulp. The mechanisms tend to be different.

A Chatterjee

As to the second part of your comment I think I would like to say it is not possible to extrapolate if we look at one type of pulp but it is possible to intrapolate if we look at the overall picture. It is not possible if we have a smaller data set for one pulp type to look at a range from kraft to stone groundwood but here we looked at the overall picture and maybe the correlations were not perfect but it answers the overall shape of the variations and that's what we're attempting to do. I agree with the first part wholeheartedly.

Prof D Wahren, Stora Teknik AB, Sweden

I think the data would be worth re-examining with proper statistical methods to give us an indication of which terms are important and which are not and how the significance would change - possibly using a factor analysis - to give an indication of which terms are important and which are just co-variations that merely cancel them.

Dr D Page, PAPRICAN, Canada

I guess if there was a strong feeling about this we could persuade those who are preparing volume 3 to include all the tables of data which I am inclined to agree would be most interesting. Would this be possible? Douglas do you think this would be a good idea.

[Yes particularly if it is on disk.]

Prof C T J Dodson, University of Toronto, Canada

The interest is very welcome but the mass of data is formidable. I sat on the examination of this thesis and there is a lot of data you would not wish to publish as it is. Provision in perhaps Lotus spreadsheet form on a disk I am sure could be arranged for anyone who wished to have it and who would be prepared to analyse it and would send us what they find.

Dr S Loewen, Abitibi-Price, Canada

Did you use recirculated handsheets for your tests?

A Chatterjee
Yes.

Prof D Wahren, Stora Teknik AB, Sweden
What is fibre density?

A Chatterjee
The way that J Lee calculated it was he looked at the fibre width and when we found the coarseness he could assume that they are completely collapsed and we looked at the fibre width and weight and also the length so that he could calculate the density of the collapsed fibres.

Dr D Page
Is it the density of the cell wall that was being calculated?

A Chatterjee
It is the overall fibre density.

Prof D Wahren
The values were very low - the densities were down to a range of 0.1-0.5 whereas the fibre wall density is 1.5.

A Chatterjee
They are not measuring the actual wall density it is possible that they are not fully collapsed.

Prof J Lindsay, IPST, USA
The equation for breaking length does not include a fibre length term and the discussion in the text implies the fibre length is somehow incorporated by the inclusion of the term NG, the number

of fibres per gramme. Perhaps in volume 3 there could be some discussion as to why fibre length itself doesn't appear in breaking length. Also, the form of that equation is somewhat curious - the relations to zero span and inverse zero span and a negative term, a -32 I_0* WFF. Why did that particular term evolve and also why is not fibre length included? D Wahren's suggestion of having a table showing the statistical significance of each term might help us understand some of that.

A Chatterjee

I left out a few slides as to how J Lee decided on each term. He did the principal component analysis and scatter plots as well as looking at individual R^v values. He then screened out some of the less statistically significant terms from the model building because there are so many of them we had to do preliminary selections. Based on those he came up with those terms. This is the best explanation I can give.