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MECHANICAL TREATMENT OF PULP FIBERS FOR PAPER PROPERTY DEVELOPMENT

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ABSTRACT

Some fundamental aspects of mechanical actions on wood pulp fibers have been studied. Specifically, the objectives of the study were to produce internal fibrillation in pulp fibers, evaluate its influence on paper properties, and establish its importance relative to external fibrillation and fines in terms of paper property development.

An apparatus was constructed that subjected pulp fibers (in the form of a wet handsheet) to repeated compressive loading cycles. Pulp was also treated in an experimental apparatus designed to promote external fibrillation, and in a Valley beater. Several fiber and paper properties were measured.

The results showed that internal fibrillation could be produced with the repeated compressive action of the apparatus. The effect of internal fibrillation on paper properties caused a threefold increase in breaking length, from 2 km to 6 km. This level was 75% of the highest breaking length achieved with the Valley beater, which was 8 km. The reason for the difference in breaking length between the samples is due to the (calculated) differences in fiber-fiber bond shear strength. By adding external fibrillation to internally fibrillated fibers and forming the sheet, no change in breaking length was achieved. However, adding fines to a suspension of internally fibrillated fibers increased the sheet breaking length, almost to the level produced by Valley beaten fibers.

From these results, it was concluded that internal fibrillation in pulp fibers plays the largest part in improving sheet breaking length. Also, fines are a necessary supplement in the fiber network to improve interfiber bonding. The effect

of external fibrillation had no apparent influence on improving breaking length, but its importance may lie elsewhere in the sheet forming process. Internal fibrillation and fines can be produced in separate steps, indicating an additive approach to developing sheet properties through refining is possible.

INTRODUCTION

Wood pulp fibers are unsuitable for direct use on the paper machine. A sheet of paper made from unbeaten fibers is characterized by its low tensile strength, its bulkiness, and its open, irregular surface. For most commercial papers, these characteristics are undesirable but they can, to a large extent, be suitably altered by mechanical refining processing. The refining operation is, therefore, a necessary step in the papermaking process. There are, however, some undesirable aspects to the current refining operations. Considerable quantities of energy are used in refining. Published estimates of refining energy consumption suggest that the process, when viewed as a mechanical operation, is inefficient (1-4). These reports show little agreement regarding the actual efficiency of the operation (from 0.1% to 50%), but the one point on which most investigators agree is that the total amount of energy consumed is excessive.

The design of refiners has changed considerably during the past 50 years. Development has moved the equipment from a batch to a continuous operation, and to equipment capable of treating ever-increasing process flows. Despite the changes in the configuration, size and mode of operation of refining equipment, refining is still accomplished by mechanical treatment of a pulp slurry between the edges and closely spaced faces of rapidly moving bars. And, as some would agree, this is easier said than properly done.

The purpose of this study was to contribute to our understanding of the refining process by studying in depth only one of the many complex actions of the refiner. Pure compression was selected because it was thought to be one important factor contributing to internal fibrillation without the generation of fines. We found that it does, and is quite effective in the early stages of refining, but also that it is not sufficient to develop the full strength potential of the pulp. The effects of external fibrillation and of addition of fines were studied in separate experiments on the treated fibers. Addition of fines to the compression-refined fibers was found to be quite effective.

BACKGROUND

Conventional refining processes have many effects on fibers. In this review, Ebeling's (5) summary is used to categorize the effects as follows:

- Internal structural changes - internal fibrillation; caused by breaking intrafiber hydrogen bonds and replacing the bonds with water molecules.

- External structural changes - external fibrillation, which is defined as pulling fibrils out of the outer walls of the fiber and primary wall removal; fines formation, due to the removal of parts of the outer walls and breaking off of the fibrils.

- Fiber shortening or cutting.

Internal Structural Changes

The forces of any applied action, whether classified as stressing, pressing, bending, flexing, curling, bruising, kneading, rubbing, twisting, crushing, etc., may be absorbed by the fiber and cause breakage of internal bonds. The bonds in question may be between cellulosic fibrils, between fibrils and hemicellulose, between cellulose and lignin and between hemicellulose and lignin. Mechanical action on the fiber of such intensity that bonds will be broken will usually result in swelling. Swelling of the fiber takes place mainly in the amorphous hydrophilic hemicellulosic interfibrillar material (6). However, partial crystallization and hydrogen bonds will limit swelling, as will the presence of lignin (7). The primary wall and the S_1 layer of the secondary wall will also restrain the swelling during the earliest stages of refining due to their hydrophobic nature and the high fibril angle of the S_1 layer (6,7).

McIntosh (8), Page and DeGrace (9), Kibblewhite (10-12), and Stone and Scallan (13) add to the theory of bond clevage by observing delamination of the wet fiber walls into many lamella upon refining. As mentioned previously, desirable papermaking properties should result from these internal structural changes.

External Structural Changes

Removal of the outer parts of the cell wall will expose the S_2 layer. By removing these regions of the fiber, which act as swelling restraints, the fiber may become more flexible through increased swelling. Steenberg (14) stated that fiber flexibility, both wet and dry, is the second most important item (after fiber length) in strength development. Giertz (15) reported that, at least very early in the beating process, the fraction of fiber surface free from the primary wall can be directly correlated with tensile strength. Therefore, as more hydrophilic hemicelluloses in the S_2 are brought to the surface, they replace the greater number of hydrophobic lignin molecules in the P and S_1 layers, and promote interfiber bonding.

Another reason for causing external surface changes is the amount of surface area that is generated for fiber bonding. Throughout his book (16), and more recently (17), Clark emphasizes the importance of external fibrils as the main entity in interfiber bonding. There has never been much denial that the larger fibrils developed from a well beaten pulp will enhance the cohesiveness of the fibers in a wet sheet (18). Many researchers, however, (19-21) do not emphasize external fibrillation as much as Clark.

External fibrillation may be caused by direct mechanical action in a refiner and by other means, such as agitation or ultrasonic radiation (22). The ultrasonic techniques are very energy intensive, and to keep energy consumption to a minimum, use of this method was disregarded. Higgins (23) reported that large amounts of external fibrillations could be achieved by treating pulp fibers between two rotating abrasive parallel disks. By varying the surface roughness of the disks, different levels of external fibrillation could be obtained. However, the external changes in the fiber were achieved at the expense of reductions in fiber length.

As a consequence of most refining actions, fines are generated. In this paper, fines are defined by the method by which they are made. They are generated by cutting fibers, detachment of large parts of the lamellar structure of the fiber and peeling off of external fibrils. Many reports center around the influence of fines on flow characteristics of the fiber suspensions (24,25), and the influence of fines on paper properties (26-29). The presence of fines is detrimental to drainage characteristics of the pulp because of the additional surface area and their high water holding capacity.

Fiber Shortening

If the strain on a fiber is great enough, it will break or be deformed. The mechanism of fiber shortening has been studied with Cottral (30) stating that two of the mechanical effects of refining cause transverse subdivision of the fibers. Accordingly, fibers may be cut by direct shearing forces of the passing refiner bars or they may fail when pulled from a network of other fibers. Steenberg's theories on cooperative process (31) tend to favor the idea of stress failure due to network forces rather than by direct shear of the passing bars.

The previously mentioned changes in the fibers usually translate into a reduction in the rate of water drainage from the stock on a forming wire, an increase in density, an increase in interfiber bonded area, and an increase in the tensile strength of the resulting sheet. The improvements are not necessarily proportional to the duration of refining or the amount of work done on the stock. Since each product requires a different balance of properties, and since refining, in general, is the only way to achieve tensile strength (burst, etc.), many of the undesirable components of a conventional refining process are tolerated.

Page's (32) description of the parameters affecting the tensile strength of a sheet was used as a convenient guide for designing the refining process for this study. To increase tensile through refining, the refining actions should 1) preserve fiber length, 2) preserve zero-span breaking length and 3) provide either a high bond shear strength per unit area or a large relative bonded area (RBA). Choosing refining conditions to preserve fiber length and fiber strength are not as difficult as producing high bond shear strength or high RBA. In fact, using many conventional refiners at mild operating conditions could probably satisfy the first two criteria. Mechanical treatments to improve bond strength and RBA involve additional considerations.

In discussing the bond shear strength and how to influence it, Van den Akker (33) pointed out that the architecture of the fiber-fiber bond is important. There are basically three classes of fiber-fiber bonds in a sheet of paper; S_1 - S_1, S_1 - S_2, and S_2 - S_2. It follows that there will at least be three levels of what he calls "intrinsic bonding strength". Therefore, a method to vary the bond shear strength in terms of the tensile equation would be to produce fibers with uniform amounts of S_1 and S_2 present on the fiber surfaces, and then form them into sheets. Unfortunately, no reliable method is available to control, or even measure, such parameters. On the other hand, the reliability of methods for determining RBA is better than that of bonding strength.

The RBA of a sheet of paper has been considered in principle as important to all the mechanical characteristics of paper (34). The optical technique for measuring RBA, originated in the work of Parsons (35), is favored by a number of investigators because it is direcly correlated to unbonded fiber area (36) and the test may be performed quickly without destroying the sheet.

By increasing the RBA, one would expect the strength to increase accordingly, and this can be done through making the fibers more flexible. The increase fiber flexibility will allow the fibers to deform under the surface tension forces during drying, and create a dense, well bonded sheet.

In summary then, one objective of this investigation was to isolate a refining action that would produce internal fibrillation in pulp fibers. By striving for only the internal fibrillation effect, fiber length and fiber strength could be preserved and the fibers should become more flexible, all of which should improve the tensile strength of the final sheet. This was done by subjecting pulp fibers to multiple compression/decompression cycles. A second objective was to determine how internal fibrillation caused by this action actually influences paper properties. Finally, an attempt was made to establish the relative importance of internal fibrillation, external fibrillation, external fibrillation and fines addition.

EXPERIMENTAL

Bleached spruce sulfite pulp was used in the main part of this investigation. It was obtained from Mr. Jan-Erik Levlin of Keskuslaboratorio Centrallaboratorium (KCL) in Helsinki, Finland. This particular pulp was chosen because a sample was available from the pulp used in their refining studies (37,38) with the Escher Wyss conical refiner. The pulp was received in dry lap form. Prior to use, it was soaked overnight and defibered for 50 counts in a British disintegrator.

A schematic of the roll refiner is shown in Fig. 1. The basic components of the apparatus are the vertical support columns, A; the horizontal support beam, B; the refining roll (60 mm diameter), C; the support roll (160 mm diameter), D; the oscillator motor and eccentric, E; the loading mechanism, F; the support roll bearing, G; and the drive mechanism, H. Refining involves fiber transport, usually temporary immobilization, and the actual treatment. This was done by treating the fibers in the form of a thin, moist sheet. The width of the sheet effectively refined was 150mm.

The refining roll has grooves machined into its surface to break up the line contact between the two rolls into discrete segments. Subdividing the refining roll and oscillating it along its axis approximately the distance of one groove width (1.2 mm) ensured even treatment and allowed new configurations of fibers to be refined with each revolution of the support roll. The amount of slippage between the two rolls with fibers in the nip was less than 0.1%. With this small amount of macroscopic shear in the nip, the major stress applied to the fibers was one of compression-decompression.

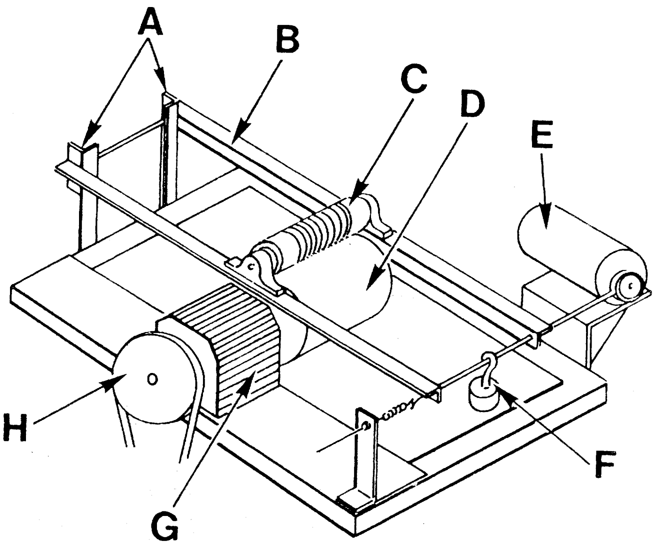

Fig 1—Schematic of roll refiner

The pulp was formed into handsheets on a Formette Dynamique handsheet machine (39,40). The operating conditions of the Formette were adjusted to obtain a 30 g/m^2 (dry basis) handsheet with approximately 5 to 1 MD to CD tensile strength orientation. The nozzle used was H 1/8 U2504. The wire, 84 x 64 mesh/inch and intended for light weight tissue applications, was operated at 1100 m/min. Once formed, the laboratory sheet was couched onto a wet blotter (at 30% consistency), the wire was removed, and another wet blotter was added to make a wet blotter/wet sheet/wet blotter sandwich.

The full size of a Formette sheet is 21 x 91 cm. To fit the roll refiner format, the sheets were trimmed to a size of 10 x 50 cm. The blotters were removed after trimming and the sheets were placed in two layers on the support roll of the roll refiner. This configuration gave a final basis weight of 60 g/m^2 around the complete circumference of the support roll. The consistency was maintained at 28-30% during refining by means of a continuous and controlled flow of water mist.

A number of preliminary experiments indicated that, for any one of several differently grooved refining rolls, the range of useful nip loads was limited to about 3:1. At higher loads the fibers would be cut, and at lower loads the effects of refining on paper properties became too small to be of interest. These observations are consistent with a hypothesis that fibers will yield when they are subjected to a certain level of transverse stress (41). Variations of the refining energy level were obtained by running the fibers through the nip up to 4000 times.

In separate experiments, pulp was abraded between rotating parallel disks to promote external fibrillation. A schematic of this abrasion refiner developed by Higgins (23) is shown in Fig. 2. The stainless steel rotor was driven at 1000 rpm by a 1/2-hp variable speed motor. The stator, made from Plexiglas to aid flow visulization, was threaded into a steel housing which was loaded against the rotor throught a Teflon seal. The internal diameter of the chamber so formed was 102mm. The threads in the housing allowed the clearance between the rotor and stator to be adjusted. For these experiments a clearance of 4 mm was used. The roughness of the disk surfaces could be altered by attaching silicone carbide sandpaper with various grit sizes. All results reported here used a 120 grit surface roughness.

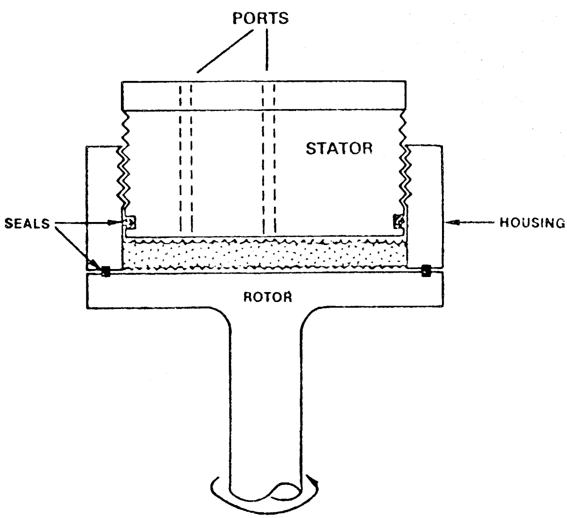

Fig 2—Schematic of abrasion refiner

One gram samples of unrefined bleached spruce sulfite pulp were treated for five minutes. A second set of samples were first refined for 500 cycles in the roll refiner and then treated in the abrasion refiner at the same operating conditions. The consistency during abrasion treatment was approximately 3%.

Fines were generated by refining the bleached spruce sulfite pulp for 21 hours in a Valley beater. The quality of the fines was evaluated with a light microscope to ensure that no fiber fragments were present. Freeness of the final product was 720 mL (all material passed through the screen of the tester). The fines generated in this manner were added to an unrefined pulp sample and to a sample that had been roll refined for 500 cycles. As a basis of comparison, the sulfite pulp was also treated in the Valley beater, following TAPPI Standard T 200.

After each refining experiment, the fibers were formed into handsheets using TAPPI standard conditions. Small samples of wet fibers were collected and the following tests were made: Fiber length distribution, scanning and transmission electron microscopy (the SEM samples were critical-point dried to minimize fiber collapse), polarization microscopy, Canadian Standard Freenes, and a centrifugal water retention test. All handsheet testing was performed in a controlled environment of 23°C and 50% relative humidity.

RESULTS & DISCUSSION

The first objective of this work was to isolate a refining action that would produce internal fibrillation in pulp fibers. In previous papers (42,43), it was shown that the major effect of the roll refiner on the fiber cell wall was interval fibrillation. This was documented by transmission electron micrographs of fiber cross sections and by polarization microscopy of the cell wall. Also, an increase in the water retention value over unrefined samples indicates the presence of water in the newly formed internal surface region. Furthermore, the action of the roll refiner did not appreciably shorten the fibers or cause external fibrillation. Once these desired changes (or lack thereof) were achieved, the second objective was to determine the influence different levels of roll refining had on paper property development.

Effect Of Internal Fibrillation

Breaking length is plotted against density in Fig. 3 for pulps treated in the roll refiner and Valley beater. Compared at a constant density level, sheets made from roll refined pulp have lower breaking lengths than sheets made from Valley beaten pulp. For roll refined pulps, the highest breaking length achieved is 5.8 km. This represents nearly a three-fold increase in breaking length over the unrefined pulp. For the Valley beaten pulp, breaking length increases from 2 to 8 km.

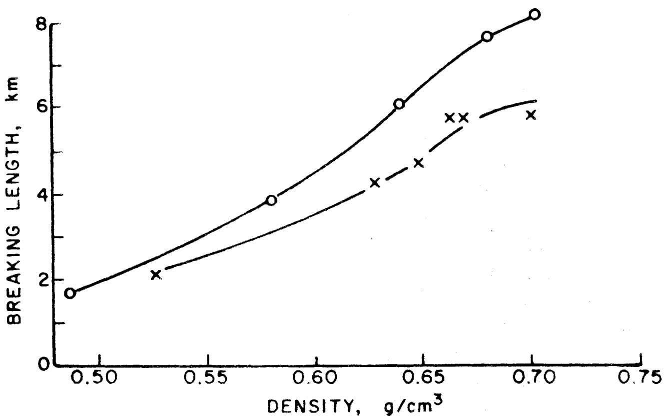

Fig 3—Breaking length vs density
x = roll refined, o = Valley beaten

In his theory for the tensile strength of paper, Page (32) states that tensile strength is a function of seven variables which may be combined into two groups. The first group of variables is related to the strength of individual fibers and the second is related to the nature of bonds holding the fibers in the network. These relationships can be expressed by the following equation:

$$\frac{1}{T} = \frac{1}{F} + \frac{1}{B} \tag{1}$$

where T = the tensile strength of the sheet
F = an index that describes only the resistance of the fibers to breakage, and
B = an index that describes only the resistance of bonds to breakage.

If formation of the sheet of paper is uniform, so that the number of fibers crossing the rupture line is the same as the number crossing any other line in the strip, then the zero span breaking length test can be used to obtain F (32). A plot of zero span breaking length, Z, vs. sheet density for roll refined and Valley beaten pulps is presented in Fig. 4. The data illustrate, first of all, that the zero-span breaking length increases from 12 km to about 16 km as refining levels increase.

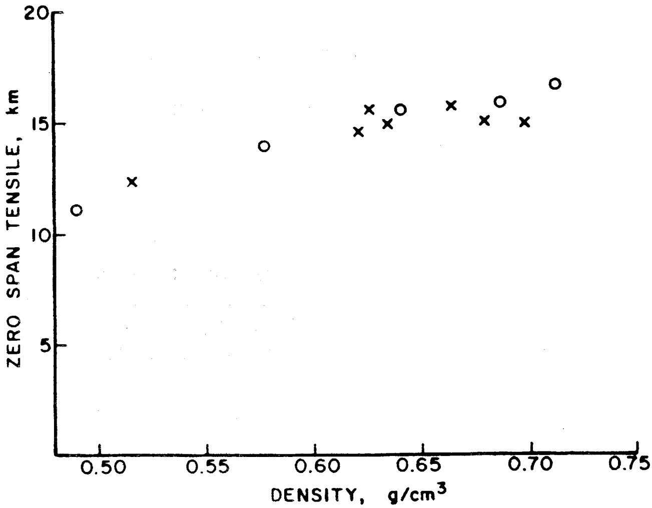

Fig 4—Zero span tensils vs density
x = Roll refined, o = Valley beaten

Strengthening of the fibers during the early stages of refining has been reported (16,44) and is probably due to removal of kinks and microcompressions in the cell wass during straining (45). The second, and more important, point to make about the results in Fig. 4 is the zero span breaking length development is the same for each refining treatment. This means that, over the range of refining levels considered, neither refining action is damaging the fibers in terms of fiber strength. The value F is also a function of the density of the fiber wall, ρ, the gravitational constant, g, and the average fiber cross sectional area, A. Assuming 1) any difference in fiber cross-sectional area between the two refining methods is not large enough to entirely account for any difference in breaking length that may be observed in the sheets, and, 2) because ρ, g, and Z are the same for each sample, then any differences in breaking length between the two refined samples are most likely related to variables influencing interfiber bonding.

The variables that affect the resistance of bonds to breakage, B, are given by:

$$B = f\ (b,\ P,\ L/4,\ RBA) \qquad (2)$$

where b = bond shear strength per unit bonded area

P = perimeter of the fiber cross section

L = fiber length

RBA = relative bonded area

The relative bonded area of pulp fibers in a sheet has been studied (33,46-48), and a method for determining RBA was given by Swanson and Steber (36). By plotting breaking length versus specific scattering coefficient for pulp treated in each refiner (Fig. 5), and extrapolating the regression lines to zero breaking length, a value for the specific free surface area for an unbonded sheet is found. The scattering coefficient at a finite breaking length was determined and both values were used to obtain the RBA at the chosen breaking length. The RBA values for both samples over a range of breaking lengths are presented in Table I.

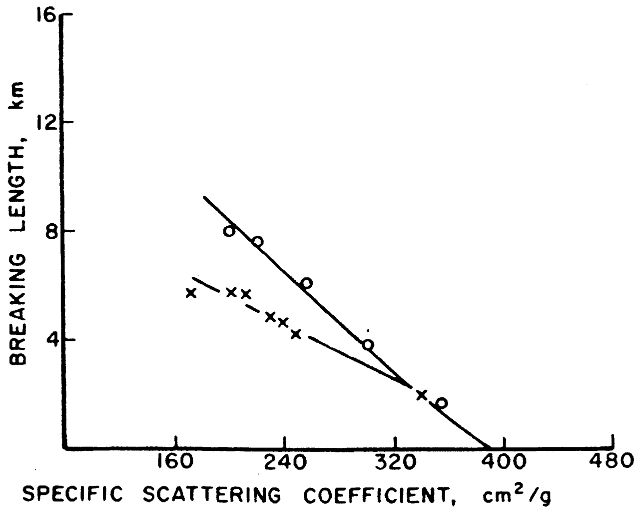

Fig 5—Breaking length vs specific scattering coefficient
x = roll refined, o = Valley beaten

TABLE I

RELATIVE BONDED AREA FOR ROLL REFINED AND VALLEY BEATEN PULP

Breaking Length, km	0	3	4	5	6
Spec. scattering co., cm^2/g					
Roll refined	390	304	263	221	181
Valley refined	390	316	294	272	251
RBA, %					
Roll refined	0	22.0	32.6	43.3	53.5
Valley refined	0	19.0	24.6	30.2	35.6

From Table I, it is clear that roll refined fibers have higher RBA's than Valley beaten fibers at a constant breaking length. In order for the sheets made from roll refined fibers to have higher RBA values than the sheets from Valley beaten pulp, one of the other factors that influence bond strength must be correspondingly lower. Rearranging Page's original equation for the tensile strength of paper,

$$\frac{1}{T} = \frac{9}{8Z} + \frac{12\ A\rho g}{bPL\ (RBA)} \qquad (3)$$

where T = the finite-span tensile strength of paper (expressed as breaking length)

Z = the zero-span tensile strength expressed as breaking length (a measure of fiber strength)

A = the mean fiber cross sectional area

ρ = the density of the fibrous material

g = the gravitational constant

b = the shear strength per unit area of the fiber-fiber bonds

P = the perimeter of the average fiber cross section

L = the mean fiber length

RBA = the fraction of fiber surface that is bonded in the sheet

to find the bond shear strength per unit bonded area, b, we obtain the following:

$$b = \frac{96A\ \rho g\ Z\ T}{(8Z-9T)\ P\ L\ (RBA)} \qquad (4)$$

Values for Z, T, RBA and L were measured in this study. To complete the calculation of bond shear strength, the following values of A, ρ, and P for a spruce sulfite pulp were used (49):

$$A = 2.4 \times 10^{-6} cm^2$$

$$\rho = 1.56\ g/cm^3$$

$$P = 9.0 \times 10^{-3} cm^2$$

	Roll Refined	Valley Beaten
T	6.0 km	6.0 km
Z	15.5 km	15.5 km
L	0.22 cm	0.17 cm
RBA	0.535	0.356
b	4.42×10^7 dynes/cm^2	8.59×10^7 dynes/cm^2

Assuming A and P are the same for each type of refined fiber, then the difference in b is almost a factor of two, which is substantial. If the roll refined fibers are assumed to be flattened out after refining and the Valley beaten fibers remain constant in cross section, then the difference in the calculated bond shear strength between the two samples becomes even greater. The perimeter of the flattened fibers has a stronger influence on the A/P ratio than cross-sectional area. As the fibers become flatter, P increases faster than A, and the resulting value for b decreases.

Regardless, the results suggest that the difference in tensile development between roll refined fibers and Valley beaten fibers is due to differences in interfiber bonding characteristics. Specifically, roll refined fibers require a larger relative bonded area to attain a given breaking length because of lower bond shear strength values per unit bonded area.

The breaking length values of sheets from roll refined pulps were found to be lower than the values from Valley beaten pulps, with the probable reason being differences in bond shear strength. One obvious question is, therefore, what can be done to increase the bond shear strength of roll refined fibers? The refining effects not found in roll refined fibers are external fibrillation and generation of fine material. It seemed reasonable that, by roll refining pulp fibers to a moderate level and then adding fines or a treatment to promote external fibrillation (being careful not to alter fiber strength or length), the inter-fiber bonding characteristics would change. The addition of a refining effect to internally fibrillated fibers may improve bond strength enough to increase the breaking length to levels achieved in the Valley beater. Moreover, by treating unrefined fibers to promote external fibrillation and by adding fines to the unrefined fibers, the relative importance of the three refining effects could be obtained.

Effect Of External Fibrillation

The operating conditions of the abrasion refiner were chosen to provide changes in the external fiber surface without decreasing fiber length or fiber strength (42,43). The effect of abrasion refining on fiber length and zero span breaking length is shown in Fig. 6. Small changes in the shape of the histograms and no significant change in the weighted average fiber length are the result of roll refining, abrasion refining and their combination. Zero span breaking length data indicate the various mechanical treatments did not degrade fiber strength. The operating conditions chosen for the abrasion apparatus, therefore, produced fibers that differed from the untreated samples mainly in the relative amount of external fibrillation.

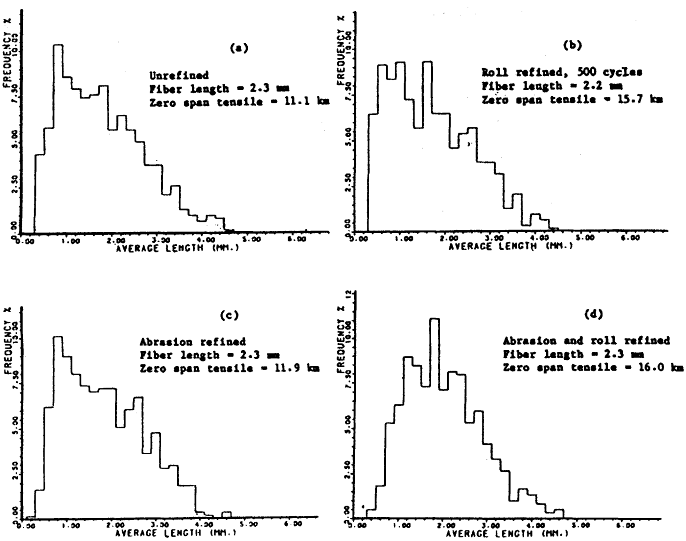

Fig 6—Fibre length distributions for different refining treatments

Figure 7 shows the effect of adding external fibrillation to pulp samples that were unrefined and previously roll refined for 500 cycles. By adding external fibrillation to these pulps, the breaking length and density relationship altered only in density. The density of the handsheets increases approximately seven percent without an increase in tensile. Because this change was accomplished without decreasing fiber length or fiber strength, interfiber bonding is again at the center of the question.

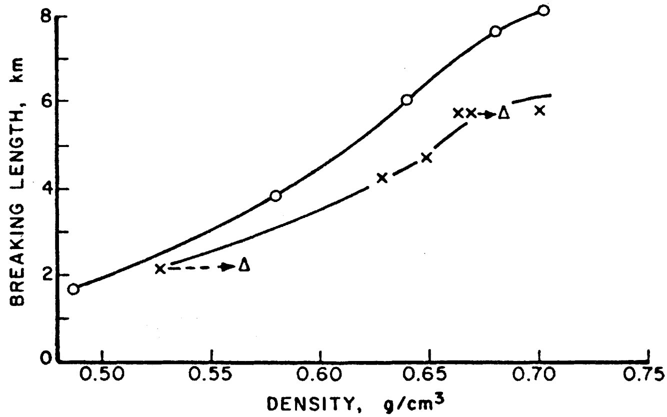

Fig 7—Breaking length vs density
x = roll refined, o = Valley beaten, △ = effect of abrasion refining

The relationship between breaking length and light scattering coefficient after abrasion refining is presented in Fig. 8. The results indicate the amount of free surface in the sheets of both samples increases following abrasion, however, no increase in breaking length was observed. External fibrillation developed in conventional refining represents a large amount of surface area while the fibers are in suspension. On drying, however, the large amount of external fibrils are expected to aid in bonding (16), thus lowering the scattering coefficient and increasing the breaking length. This was not observed. The abrasion refiner, therefore, might produce a different kind of fibrillation; one that keeps the fibers from coming into optical contact with each other. Or, it might be that the influence of external fibrillation in interfiber bonding is not as important as previously reported (16). The real importance of external fibrillation may lie in the sheet forming operation (18), or, in the idea that the existence of external fibrillation is important only because it is a precursor to fines (50).

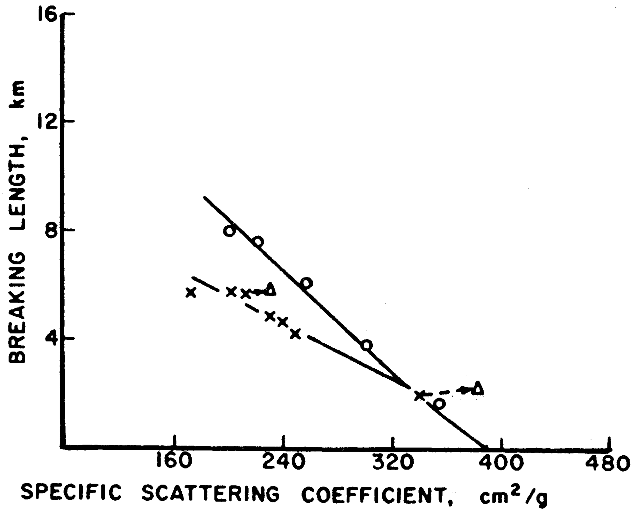

Fig 8—Breaking length vs specific scattering coefficient
x = roll refined, o = Valley beaten, △ = effect of abrasion refining

Effect Of Fines Addition

Figure 9 illustrates the influence of adding fines to an unrefined pulp suspension and a suspension that was roll refined for 500 cycles, and forming them into a sheet. The amount of fine material in the final sheet was 16% on an o.d. basis. This figure illustrates increases in both breaking length and density occur as a result of fines addition. The new paper property levels obtained by adding fines were close to the levels developed in the Valley beater.

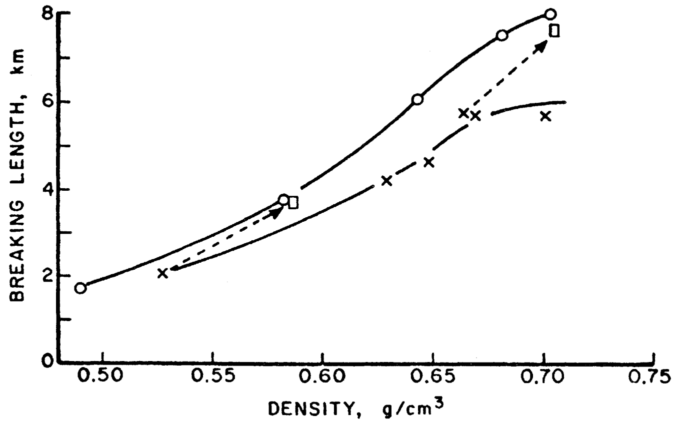

Fig 9—Breaking length vs density
x = roll refined, o = Valley beaten, □ = fines addition

A plot of breaking length vs. specific light scattering coefficient (Fig. 10) shows the influence of fines; 1) increases both light scattering and breaking length when they are added to unrefined fibers and 2) increases the breaking length to the level of the Valley beaten pulp when they are added to the roll refined pulp.

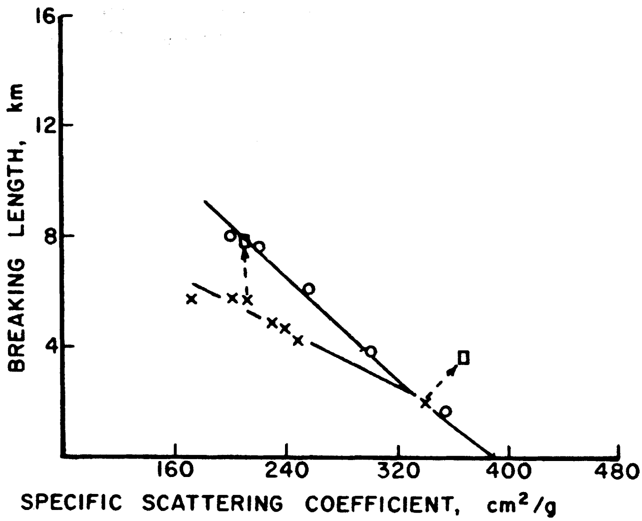

Fig 10—Breaking length vs specific scattering coefficient
x = roll refined, o = Valley beaten, □ = fines addition

The fines used in this experimental work were produced by highly refining pulp fibers. They were not screened or classified, so they include both primary and secondary fines fractions (26,27). Primary fines are free particles associated with the unbeaten pulp and secondary fines are the free particles generated in refining. Although there is belief that the chemical nature of the fines is no different from the longer fibers (52), evidence suggests that, for properties of concern in papermaking, the chemical reactivity of fines is quite different from the fibers (27). In the present case, there are no differences in the macroscopic chemican nature per se because the same fibers that were ground up were used in sheet forming. However, the fact that the fibers were ground up to a material resembling a gel suggests that different chemical entities (hemicelluloses in particular), formerly inside the fiber, became more accessible. The fines' ability to influence bonding, therefore, increases greatly.

A second point to consider is how fines influence the sheet forming process. Figure 11 is a simplified model of two idealized fiber crossings in dry paper in three alternate cases (26). In Fig. 11 (A), the sheet has been made from unbeaten fibers without fines present. The fibers are stiff and only partly collapsed. The number of bonds is low and the bonded area per bond is small. As a consequence, the sheet has low strength.

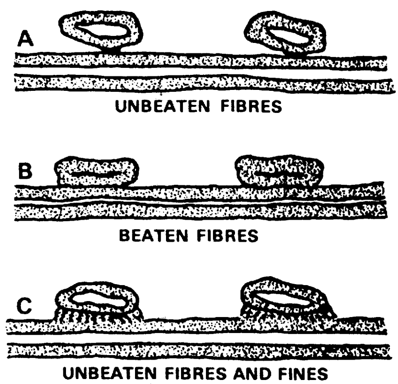

Fig 11—Models of interfibre bonding (**26**)

Figure 11 (B) represents the corresponding situation in a sheet of roll refined fibers without fines present. As the RBA values have indicated, interfiber bonding increases with refining, which in turn increases the breaking length and density.

Figure 11 (C) depicts the influence of fines addition to unbeaten fibers, which increases the fiber to fiber contact area. The characteristics of the fine material in this situation are important for two reasons; their influence in sheet consolidation and their influence in a dry sheet under tensile stress. Their size, form, and their large specific surface are important in consolidation. It has been observed that the last free water in a drying web exists as menisci held in fiber crossings (52). Some degree of fines concentration may thus occur in the fiber crossings if the fines have some mobility to follow the water phase (53). On this basis, it is assumed that the fines increase the effective contact area of the bonded fiber crossings and, in the case of unrefined fibers, possibly also help establish contacts between fibers which would have been unbonded if fines were not present. This assumption is supported by the increase in density which occurs when fines were added to unbeaten fibers (Fig. 9 & 10).

In a dry sheet, fines reduce local stress concentrations in the bonded fiber crossings (52). This allows for a more uniform stress distribution when a load is applied to the sheet. To explain the low tensile strength obtained with internally fibrillated fibers followed by the improved tensile strength achieved by adding fines, consideration was given to the work of Button (54). He has shown that when two strips of cellophane are bonded, the resulting structure is still weak. The explanation given was as the ends of the strips are loaded stresses build up at the edges of the bond. The stress and the bond behaves as if it were brittle. This may be analogous to the case of using only roll refined fibers to form a sheet. The pulp develops substantial breaking length and the fibers in the sheet appear to be bonded well, as indicated by decrease in light scattering coefficient (Fig. 10). However, the bonds still behave in a brittle fashion for large strain levels. When fines are added, they will be present at the fiber-fiber interfaces (53) and impart a different quality to the bonds. Instead of bonding two S_1-S_1 layer surfaces together, a pseudo- S_2-S_2 architecture may result because of the fines. This S_2-S_2 architecture provides a means for allowing large local strains (at the microscopic level) to occur, thus distributing the stress over the whole surface of the bond. Thus, fines in the bonded region help increase the tensile strength of a sheet and, based on such an interpretation, this should be the major effect for the behavior of the observed results.

Figure 11 (B) helps to illustrate why the fines may contribute less to the paper properties when added to conventionally beaten long fibers than when added to unbeaten fibers. In several studies (26,28,52,55), the relative importance of the fines, both in consolidation and in the dry sheet under load, was de-emphasized because of the modifications in the properties of the fibers due to beating. They reasoned a smaller fraction of the fines in the sheet are active in the bonded regions because of fiber collapse. Also, the mobility of the fines may be lower in the wet sheet of collapsed, swollen and externally fibrillated fibers compared to the more open structure in a wet sheet of unbeaten fibers.

However, the results of the fines addition experiments in this work show the same effect whether the fines are combined with unrefined or roll refined pulps. The reasoning here is because the external surfaces of the fiber cell wall of the roll refined fibers are very similar to unbeaten fibers - both in physical components and chemical makeup. Therefore, the magnitude of the effect of fines addition should be the same on unrefined and roll refined samples, which it is.

To provide a qualitative comparison of the sheets under discussion in the results section, a series of photomicrographs of the following treatments is presented in Fig. 12; A, unrefined; B, abrasion refined; C, roll refined; D, roll refined with 16% fines added; E, combination roll refined and abrasion refined; and F, Valley refined for 40 minutes.

A summary of the results of the different refining actions on fiber and sheet properties is presented in Appendix I.

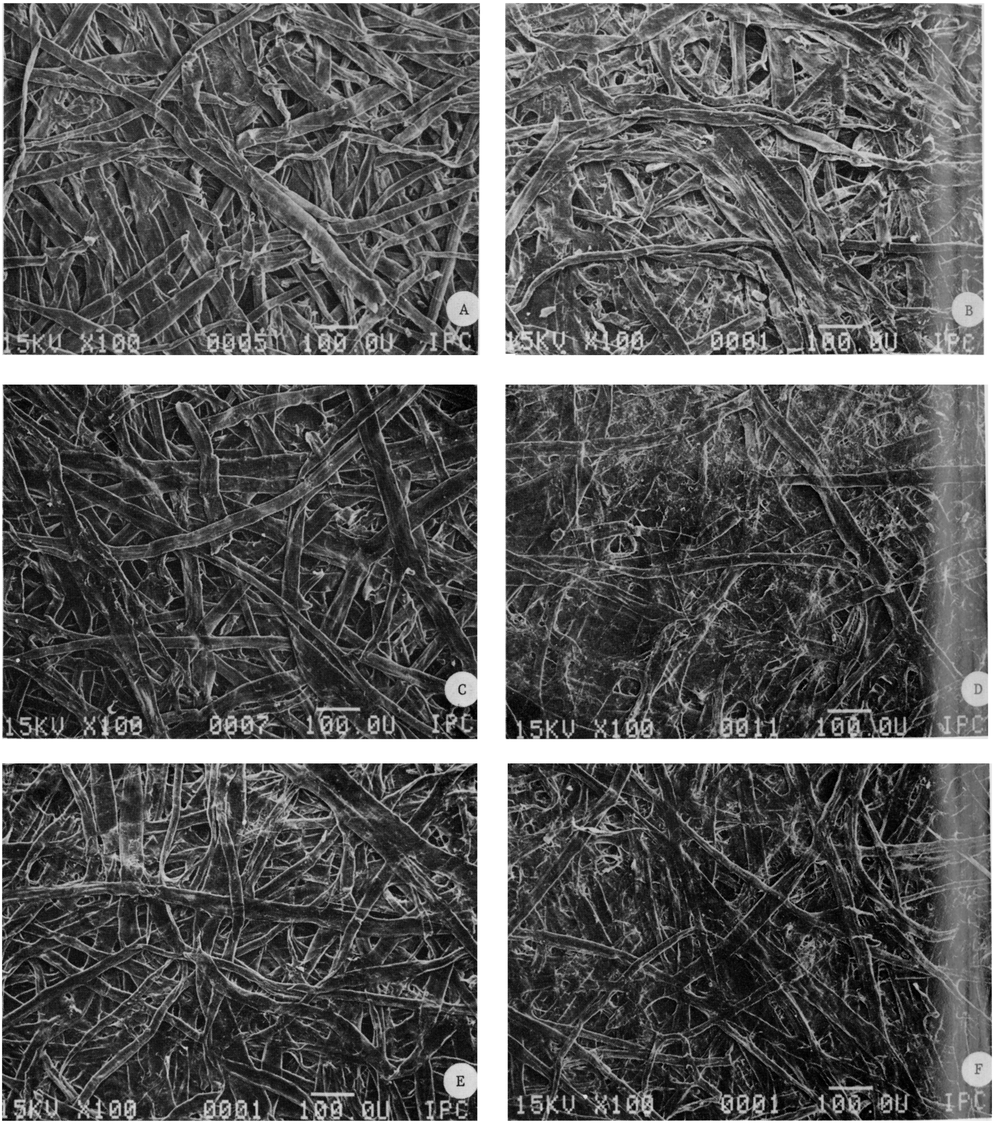

Fig 12—Scanning electron micrographs of the sheet surfaces: A, unrefined; B, abrasion refined, 5 min., 1000 rpm; C, roll refined, 500 revolutions; Dm roll refined, 500 revolutions plus fines addition; E, roll refined, 500 revolutions, abrasion refined, 5 min., 1000 rpm; F, Valley refined, 40 min.

CONCLUDING REMARKS

There are three direct conclusions that were drawn from the results of this study. First, the primary effect on pulp fibers of the repeated compressive action of the roll refiner is internal fibrillation. Second, internal fibrillation appears to be the single most important effect on fibers to make dense, strong sheets. Significant paper strength development (75% of the breaking length achieved in the Valley beater) is possible with internally fibrillated fibers. Third, additional effects of refining are necessary (i. e., fines addition), if we desire to develop the full strength potential of the pulp. Fines are a required supplement to internally fibrillated fibers in order to achieve Valley beaten pulp strength levels. There is apparently no advantage to externally fibrillating the roll refined spruce fibers in terms of breaking length improvement.

Beyond these direct conclusions, however, of other remarks can be made about these findings. From a macroscopic viewpoint, external fibrillation and fines both increase the specific surface of the pulp, yet the properties they develop are quite different. The data illustrates that interfiber bonding is the central issue in understanding strength development in a fiber network.

Another issue resulting from this study is the fact that the effects of refining on pulp fibers are additive. With the proper equipment, it could be possible to impart only the desired effects of refining in pulp fibers. The advantages (unique combinations of pulp properties never achieved before, possible energy savings) might possibly outstrip the disadvantages (capital costs). Regardless, more work would be necessary to determine the optimuim order of the treatment steps and the best mechanical designs.

In summary, I feel that current refiner designs are not adequate as far as paper property development is concerned. However, the results from this study can lend direction to future research, if the impetus to improve the refining process is large enough.

APPENDIX I

RESULTS OF REFINING EXPERIMENTS ON PRIMARY PROPERTIES

Property	Un-refined	Roll Refined	Abrasion	Roll and Abrasion	Roll and Fines	Valley	Escher Wyss Low Intensity
Internal fibrillation	-	Y	-	Y	Y	Y	Y
External fibrillation	-	N	Y	Y	N	Y	Y
Fines	-	-	-	-	Y	Y	Y
Shortening	-	N	N	N	N	Y	Y
Zero-span breaking length km	12.3	15.7	11.9	16.0	13.8	16.6	-
Breaking length km	2.01	5.77	2.28	5.75	7.62	8.02	6.45
TAPPI density g/cu cm	0.527	0.702	0.556	0.685	0.728	0.702	0.693
Spec. scattering co. cm^2/g	339	171	375	232	289	199	246

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Transcription of Discussion

Mechanical Treatment of Pulp Fibres for Paper Property Development
by R.R. Hartman

E. Strazdins Fairfield, U.S.A.

On discussing the role of fines in strength development, we cannot leave out the fact that all mill systems use some sort of a polymer for strength improvement, drainage or retention. A cationic polymer will coagulate the solubilised hemi celluloses and coagulate the small fines. The high molecular weight retention aids will flocculate the fines on long fibres, rendering such fines more immobile, so that they cannot be drawn into the fibre cross overs by the surface tension of water. Other fines will be retained by mechanical filtration. How would this affect the fines/colloidal matter contribution to strength? Secondly, since fines have much larger surface area, most of the added strengthening resins will be on the fines. (50 - 90%). How would you visualise the strength effects of these resins in the light of these several retention mechanisms of the resin rich fines?

Dr. R.R. Hartman The work did not involve polymers or additives, but I would think that according to the papers I have read about fines and their migration, if there is any mobility at all, in other words, whether or not this floc of fines is able to move about, it should be able to move into that fibre crossing area. But if it is such a large body, it might not get trapped into the zone between the fibres.

Kartovaara The beater or Hollander is one of the oldest devices for beating pulp. Now you have designed various devices where you can create specific types of beating action and then you have combined this. Have you ever found a combination of treatments that would have been better than the conventional Valley beating?

Hartman No, I wish we had.

Kerekes In your last slide, you state that the refining effect of your roll refiner was achieved at low energy. Could you tell us what the specific energy was?

Hartman Part of the equipment was designed to allow measurement of energy consumption more easily than with existing methods. Using this equipment, the net energy consumption was one tenth of that required to reach the same strength level as in a conventional conical refiner. We referred to the work of Jan-Erik Levlin, where he has a conical refiner equipped to measure net specific energy input. That is what I compare my energy consumption data to.

Prof W. Scott Miami University, Oxford, U.S.A.

Following up on E. Strazdins' question, how did you put the fines in the sheet?

Hartman In the sheet mould. The fines were generated by grinding up the same fibre source as used in the main experiments in a Valley beater. The material was beaten to a level where no whole fibres were discernible. Portions of that material were added into the sheet mould as the standard handsheet was being formed.

Ebeling Did you carry out a negative fines experiment? Did you remove fines from your Valley beaten pulp and see the effect on breaking length, e.g. in Figure 9, what would be the magnitude of the arrow the other way? Adding 16% of slime would be similar to adding 16% of mannogalactan. I think this addition bears little relation to the fines normally found in papermaking.

Hartman To answer your first question, I didn't remove the fines from the Valley beaten pulp. It was difficult to decide on the level of fines. We calculated the amount of fines passing through a 100 mesh screen in a normally refined pulp and used this to calculate the fines addition level. However, the level is probably higher than you find in normal practice.

Dr. R.S. Seth PPRIC, Pointe Claire, Canada

I am surprised to find, on page 428, that the specific bond strength from Page's equation for roll refined pulp is 4.42×10^7 dynes/cm^2 which is half the Valley beaten value. We have worked on the effect of beating on specific bond strength which was calculated by the Nordman bond strength method. We have not seen an increase of this kind. Dr. Nordman and Dr. Mohlin have also shown that beating has little effect on specific bond strength. So, I find your results surprising. I do not think you are justified using Page's equation in the way you have. The equation works for straight fibres, but not for kinked fibres. What is in fact happening is that in the Valley beaten pulp the fibres are straight, whereas in the roll refined pulp, the fibres are kinked. Since the stress cannot be transferred across a kink, the effective fibre length for roll refined pulp is probably half that for the Valley beaten pulp. If you take this into account, this will reconcile the results on specific bond strength.

Hartman I didn't measure the amount of curl in the fibres. However, we are comparing two separate refining methods and I don't see why I cannot use the Page equation to calculate bond strength when two different types of fibre surfaces are brought together.

Seth You are using a dried pulp which is full of kinks. A Valley beater straightens the fibres, whereas a roll refiner would not.

Hartman The Valley beater may indeed straighten the fibres but it also changes the fibre external structure, whereas the roll refiner changes only the internal structure. There is really no external fibre change in roll refining. Effectively, the S_1 layer is intact, resulting in a different fibre-fibre bond architecture. I was aware of the bond strength values you calculated when I carried out these experiments, and for my Valley beaten results, we are in good agreement.

Chairman In the original paper, in which I developed this equation, I specifically stated that L is not equal to fibre length. It is only equal to the fibre length if the fibres are straight. For curly fibres or kinked fibres, it is equal to the straight length of the fibre. If you had used this, you would have found that this effective fibre length increases after Valley beating since you started with a curly dried pulp and Valley beating straigtens fibres out. After inserting the effective fibre length into my equation, I think you would then have found that bond strength did not change with beating.

Prof R.H. Atalla IPC, Appleton, U.S.A.

At the same time that this work was carried out, we were using Raman spectroscopy to study the effect of refining on the threshold for mercerisation. One of the puzzling aspects of the work was that the refining method which Dr. Hartman used did not affect the threshold for mercerisation and a piece of work by Dr. Platt also on spruce pulps did not show that effect. We have since discovered that with loblolly pine pulps, there is that effect in the Raman spectral measurement of the threshold for mercerisation. Also using NMR studies of bound water, there is a significant difference between loblolly pine and spruce pulps, suggesting that in the refining of spruce pulps, the new surfaces which are created are of similar energy to those pre-existing. Whereas in loblolly pine, the new surfaces are of higher energy than those pre-existing.

Dr. F. El-Hosseiny Albany International, Dedham, U.S.A.

Your work showed that fines are beneficial to the strength of chemical pulps and we know that they enhance the optical properties of the sheet. I would also like to add that fines are beneficial to the wet web strength and hence to machine productivity.

Dr. H.G. Higgins CSIRO, Clayton, Australia

One should not take energy efficiency calculations made in the past too seriously, but I would agree that refining is a very energy intensive process. I wonder if the effects you find with your apparatus are in any way analogous to the effects which were observed originally by de Choudens and Monzie, when they put chips through parallel rolls. One of the effects we have noticed is that refining energy can apparently be reduced on subsequent treatment in a disc refiner. With respect to the effect of fibre length and fibre strength on tensile strength, common experience with hardwoods suggests that these are not important factors as they are with tear. I would like to ask D. Page what is the sensitivity of tensile strength to the various parameters listed on page 427 of Volume 1? Doesn't the relative bonded area have an overwhelming effect if L is the straight part of the fibre and not the fibre length? My difficulty is that fibre length and fibre strength do not seem to have a very big effect on tensile strength. Can you explain this in terms of the Page equation?

Chairman I do not think it is appropriate for me, as Chairman, to respond to this question in the detail that is necessary. The problem is that the sensitivity of tensile strength to fibre strength and fibre length varies depending on the values of other parameters. I will leave Dr. Hartman to respond to the first part of your question.

Hartman D. Attack did some work on the relevance of energy input to chip de-structuring and I had this work in mind when the equipment was designed. I also considered the simple concepts of calendering and pressing as energy input mechanisms.