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CURL, CRIMPS, KINKS AND MICROCOMPRESSIONS IN PULP FIBRES – THEIR ORIGIN, MEASUREMENT AND SIGNIFICANCE

D. H. Page, R. S. Seth, B. D. Jordan and M. C. Barbe*
Pulp and Paper Research Institute of Canada
570 St.John's Boulevard, Pointe Claire, Quebec, Canada H9R 3J9

ABSTRACT

The curliness of fibres and the degree of microcompression in the fibre wall strongly influence the properties of pulp suspensions, wet-webs and dry sheets. In mill operation, curl and microcompression can be induced accidentally or intentionally, by shearing at high consistency. Some pulps are highly susceptible to curling; others are more resistant. Curl is not necessarily stable; it is readily removed from some pulps but not from others. Curl can be stabilized by certain treatments, notably by heat treatment at high consistency. This can be deliberate, or it can occur accidentally during mill operation, when a pulp is stored at an elevated temperature. Both curl and microcompression are often disregarded because they cannot be easily measured. Yet in practice their effects often dominate the properties of pulp suspensions, wet webs and dry sheets. Ignoring these effects has led to costly surprises both in research and mill operation.

In this paper the literature is reviewed and new data are introduced, illustrating the importance of curl and microcompression for mechanical, chemi-mechanical and chemical pulps.

* Present address: Hymac Ltée., 2995 boul. Le Corbusier, Laval, Quebec, Canada H7L 3M3.

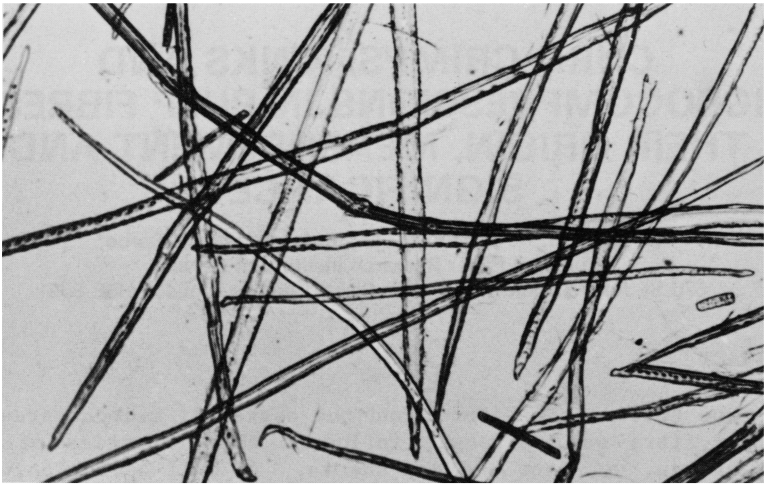


Fig 1—Straight fibres of commercial softwood bisulphite pulp of 62% yield (X60).

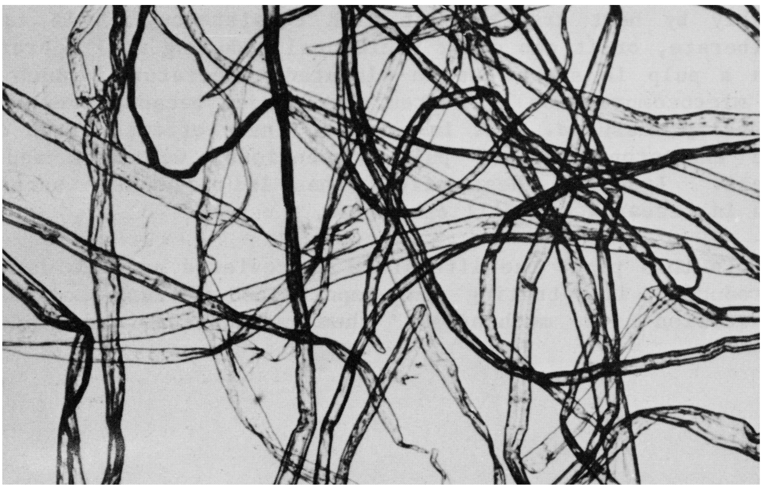


Fig 2—Moderately curly fibres of commercial dried bleached softwood kraft pulp (X60)

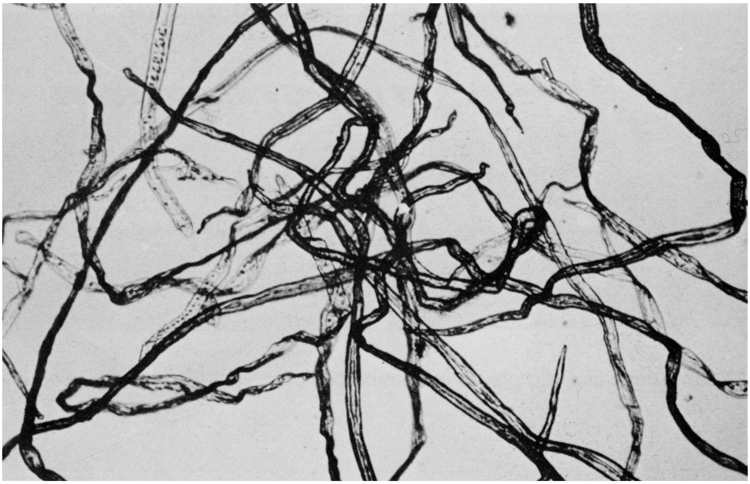


Fig 3—Highly curled fibres of commercial flash-dried bleached softwood kraft pulp (X60).

INTRODUCTION

Fibres in wood are generally straight. They deviate from linearity only enough to accommodate the interference of adjacent cells in the woody tissue. It is well established however that fibres in pulps are not straight, but deviate from their native form in a variety of ways. The first demonstration that fibres are curled in a way that is instantly apparent from low-power light microscopy, was made by Kilpper (1). In a series of seldom-referenced papers, he defined a curl factor ("Krummungsfaktor"), and showed the presence of curl in market pulps, the variability in curl from one pulp to another and the change in curl upon beating. The nature of curl of mill pulps and its variability are illustrated in Figures 1-3. The fibres of Figure 1, from 62% yield sulphite pulp, are substantially straight. Those of the bleached kraft pulp in Figure 2 are somewhat curly. The fibres of a flash-dried bleached kraft pulp shown in Figure 3 are highly curled.

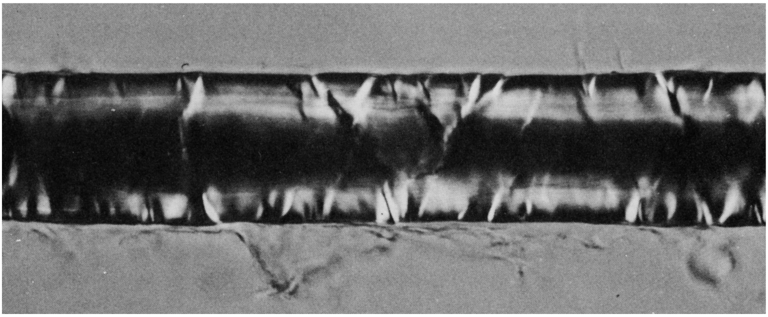


Fig 4—Dislocations and slip planes in commercial dried unbleached softwood kraft pulp (X600).

Fig 5—Node in laboratory softwood kraft pulp, unbeaten (X1,000).

At a high magnification other deviations from straightness become apparent. Regions where the alignment of the microfibrils is locally disturbed are made visible under the polarizing microscope as shown in Figure 4. These regions have been termed "dislocations" or "slip planes", by analogy with deformation in crystalline structures. Dislocations and slip planes in wood were apparently first observed by Robinson (2); the early literature was reviewed by Wardrop and Dadswell (3). The presence of dislocations and slip planes in wood pulp fibres has been subsequently studied by several authors (4-8).

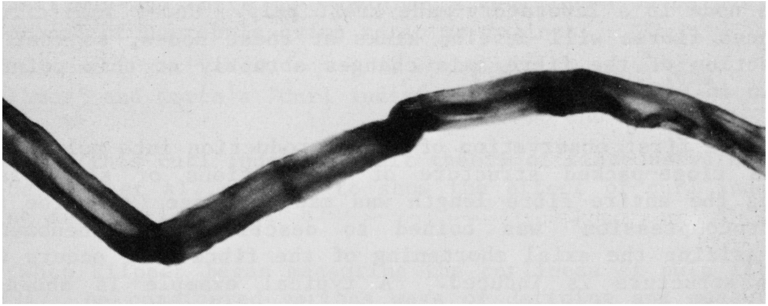


Fig 6—Kinks at nodes in commercial dried bleached sulphite pulp (X250).

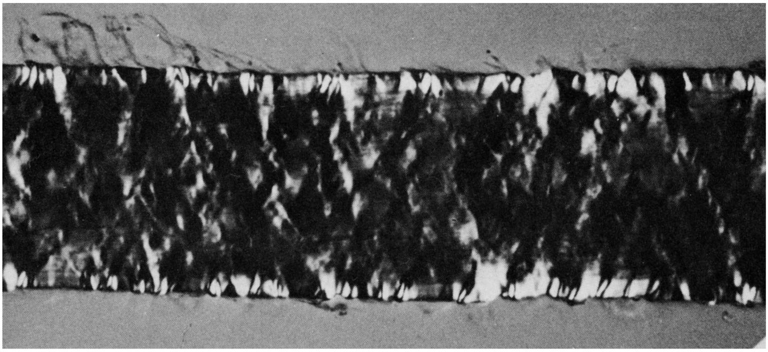


Fig 7—Microcompressions in commercial dried bleached sulphite pulp (X600).

A feature of somewhat larger magnitude is the node or crimp. A node is essentially a region of bending and compressive failure, with a highly localized compressive strain, often associated with delamination of the cell wall (8). Nodes were shown by Forgacs (4) to be preferentially sited adjacent to ray crossings, presumably because of the tendency for bends to originate there during defibering. Figure 5 shows an example of a node in a laboratory-made kraft pulp. Under some circumstances fibres will develop kinks at these nodes, so that the direction of the fibre axis changes abruptly at this point as shown in Figure 6.

The first observation of the introduction into pulp fibres of a close-packed structure of dislocations or slip planes along the entire fibre length was made by Page (9). The term "microcompression" was coined to describe this phenomenon, emphasizing the axial shortening of the fibre that occurs when this structure is induced. A typical example is shown in Figure 7.

The purpose of this paper is to discuss the measurement of both these large scale and small scale deviations from straightness, their origin and their importance for pulp and paper properties.

THE MEASUREMENT OF CURL AND MICROCOMPRESSION

Many of the studies of curl, crimp, kink and microcompression have been qualitative. Hill, Edwards and Beath (10) showed micrographs of pulps treated in the Curlator. Jones illustrated fibre straightening during latency removal by micrographs taken at a low magnification (11). De Grâce and Page studied differences between market pulps by visually ranking micrographs in order of fibre curliness (12). Some authors, on the other hand, have expended considerable effort to quantify the various forms of non-linearity and it is clear that advances in understanding are dependent on success in this endeavour.

In the textile industry, fibre curliness has been assigned a numerical value for more than fifty years. The popular "crimp ratio", introduced by Duerden in 1929 (13), is the fractional decrease in the end-to-end distance when a fibre is crimped but not compressed. Thus,

$$\text{Duerden's "Crimp ratio"} = \frac{\text{end-to-end distance}}{\text{fibre contour length}} \tag{1}$$

Kallmes and Corte (14) defined a curl index which was the reciprocal of Duerden's crimp ratio as follows:

$$\text{Kallmes' and Corte's "Curl index"} = \frac{\text{fibre contour length}}{\text{end-to-end distance}} \tag{2}$$

They used this curl index in their theory of fibre networks and Sotobayashi et al. used it to show the effect of curl induced during defibration (15).

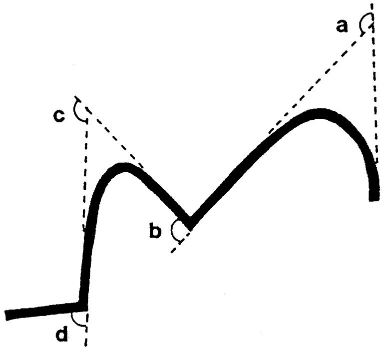
When Kilpper began measuring the curliness of pulp fibres in 1947, he considered various ways of defining and measuring curl, and decided on a "Krummungsfaktor", defined as follows:

$$\text{Kilpper's "Krummungsfaktor"} = \frac{\text{fibre contour length}}{\text{longest dimension}} \tag{3}$$

where longest dimension is the distance between the two points on the fibre that are furthest apart. He carried out these measurements manually using a projection microscope and obtained extensive data. In all, he measured some 60,000 fibres taken from 120 pulp samples (1).

Helle (16) adopted a quite different approach. He chose to measure an average curvature of fibres by measuring the angular changes between inflection points on each fibre as in Figure 8. The average angle of curvature of the sample was then calculated as the angular change in each 2.5 mm length of fibre as follows:

$$\text{Helle's "Gjennomsnittlig Vinkel"} = \frac{\text{sum of angular changes for all fibres} \times 2.5\ \text{mm}}{\text{total length of fibres sampled}} \tag{4}$$



$$\text{Curvature} = \frac{(a+b+c+d)\times 2.5\ \text{mm.}}{\text{fibre contour length, mm.}}$$

Fig 8—Definition of Helle's curvature index. Each angle is the net change in orientation of the tangent direction between inflection points, expressed in degrees. The sum of these angles per unit length of fibre is normalized to a fibre length of 2.5mm.

Kibblewhite discriminated between abrupt kink and gradual curl apparently regarding kink as more important (17). He calculated a kink index by allotting an arbitrary weight of 1 through 4 to sharp bends in the categories (10°-20°), (21°-45°), (46°-90°) and (91°-180°), respectively. Kibblewhite's kink index is the weighted sum of the number of kinks, divided by the total sampled fibre length (18).

Kibblewhite's "Kink index" =

$$\frac{N_{(10°-20°)} + 2N_{(21°-45°)} + 3N_{(46°-90°)} + 4N_{(91°-180°)}}{\text{total sample fibre length}} \qquad (5)$$

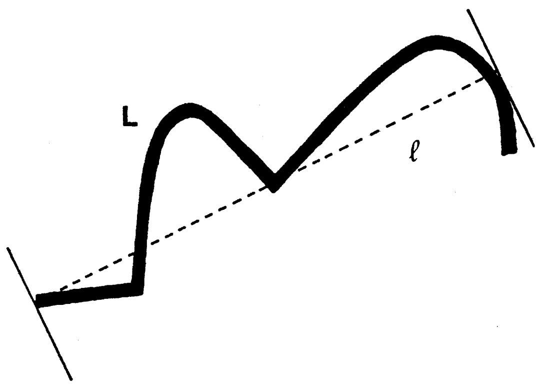
where N is the number of kinks in that angular range in the total sample.

One of the first attempts to computerize the measurement of fibre curliness in wood pulp was made by Graminski and Kirsch (19). Each fibre was traced on a digitizing tablet and read by the computer as a sequence of short straight segments. Like Kibblewhite, Graminski and Kirsch categorized the angle of bend between segments. However, they achieved this by measuring the fibre length between bends of a given magnitude. The result of this analysis is a sequence of segment length distributions for various bend angles. In a subsequent paper, Kirsch reported experiments with direct video digitization of the fibre image (20). In both papers, the emphasis was more on demonstrating algorithms on a mainframe computer than on practical procedures for pulp testing.

Amongst this assortment of definitions, Jordan and Page (21, 22) chose to return to a definition similar to that of Kilpper as follows:

$$\text{Jordan's and Page's "Curl index"} = \frac{\text{fibre contour length}}{\text{longest dimension}} - 1 \quad (6)$$

Three considerations were important in this decision. Firstly, it seemed likely that curl index defined in this way might be expected to relate directly to certain physical prop-



$$\textbf{Curl index} = \frac{L}{\ell} - 1$$

Fig 9—Definition of the curl index of Jordan and Page, as quoted subsequently in this paper. The fibre contour length (L) and "longest dimension" (ℓ) are measured with an image analyser. Longest dimension is the distance between those points within the fibre which are furthest apart.

erties of the sheet. Secondly, it was essential for the authors' purpose that the index should be measurable using available techniques of image analysis. Both fibre contour length and longest projected dimension have now been computable at high speed (1/30 sec) by commercial image analysers for a decade. Thirdly, the use of end-to-end distance in the definition of an index as in equation (2) was avoided since such an index can tend to infinity for very curly fibres.

This index is clarified in Figure 9. In the procedure used by Jordan and Page, dyed fibres are sparsely deposited onto slides and viewed through a microscope by a video camera interfaced to a computer. The computer controls stepping motors on the microscope stage, so that the entire specimen can be automatically scanned. Thus far, over 1,000,000 fibres from over 2,000 pulp samples have been measured using this method.

Using the definition of equation (6) a nearly straight fibre has a curl index of around 0 - 0.05 and a rather curly fibre has an index above 0.5. Figures 10 and 11 show typical curl distributions and micrographs from two pulps, illustrating the extremes of straightness and curliness that are found in practice. The average curl index for the straight-fibred pulp is about 0.1 and for the curly pulp about 0.2. It is clear from the nature of the distributions, that about 600 fibres must be counted to obtain a mean with a 95% confidence limit of 0.01.

The existence of several parameters designed to measure the same essential feature is an unfortunate source of confusion. In an attempt to clarify the position Jordan and Nguyen (23) measured curl index, crimp ratio, a length-normalized average curvature and kink index on a series of pulps. They found a good correlation between the first three parameters but a poor correlation with kink index. This was attributed to the importance given in calculation of the kink index to the presence of abrupt bends; the other indices are a measure of all deviations from straightness.

With the exception of the early work of Kilpper, only the kink index of Kibblewhite and the curl index of Jordan and Page have been used extensively. Because of the experience of the authors, the curl index defined by equation (6) will be the one used throughout this paper.

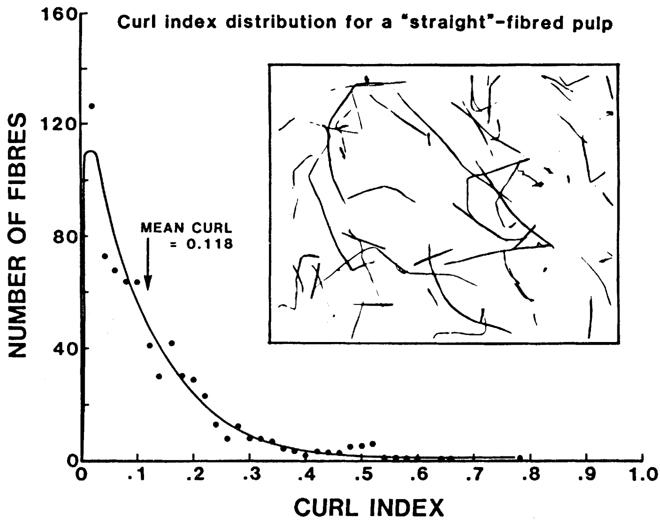


Fig 10—Typical curl index histogram of a straight-fibred pulp, inset with a micrograph of the fibres. The measurements were made on a sparser deposition of the same fibre population as that shown here. the pulp is a softwood high-yield sulphite.

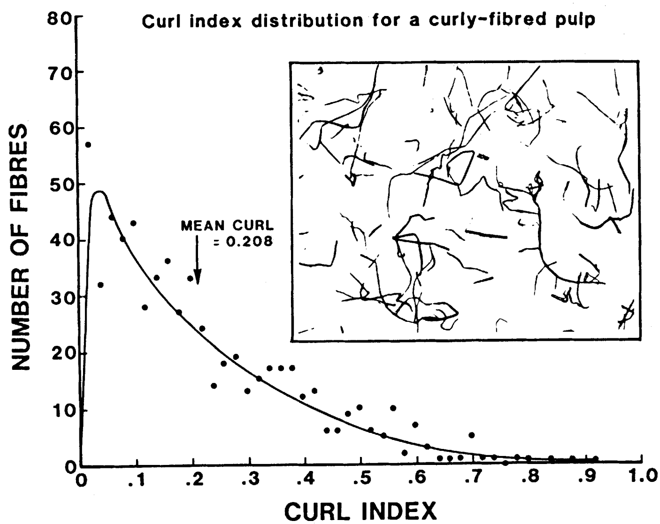


Fig 11—Typical curl index histogram of a curly pulp. This is the same high-yield sulphite pulp as in the previous figure, but curl-set by steaming for 5 min. at 160°C. Many of the fibres are still straight, but an increased fraction of the fibres have become quite curly.

It is noteworthy that there is no quantitative method for determining the degree of microcompression in a pulp. This lack is disturbing in view of the effect of microcompression on pulp and paper properties, and the fact that microcompressions can be induced separately from curl during some treatments.

INDUCTION OF CURL AND MICROCOMPRESSION

The features described earlier seem to originate from two actions, physical and chemical, which may work synergistically. It is clear however that physical processes alone can induce these features. Curl, kinks, nodes, crimps, slip planes, dislocations and microcompressions can all be the consequence of bending and compressive stresses acting upon the cell wall. Axial or hydrostatic compression can occur during the processing of chips. During defibering, fibres are subjected to bending stresses with their associated axial compressive stresses (4).

When a pulp suspension is sheared, fibres are subjected to both bending and compressive stresses (10). If the pulp consistency is higher than about 10%, the stresses are transmitted

Device	Curl index	
	Before	After
Commercial screw press discharging at 30% consistency (SUDOR)	0.126	0.152
Laboratory screw press (FRENCH)	0.149	0.171
Laboratory fluffer	0.149	0.158
Laboratory mixer operating at 20% consistency and ~0.3 MJ/kg (MICAR)	0.115	0.149

Table 1. Curl induced in low-yield unbleached softwood sulphite pulp fibres by incidental mechanical action in presses, fluffers and mixers.

directly from fibre to fibre, so that for a given shear strain rate, the stresses can be considerable. Each fibre in the pulp mass passes through many cycles of bending and compressive stress, as the pulp mass is rotated and rearranged.

In many instances, the mechanical action responsible for putting curl and microcompression into fibres is applied unintentionally. It is imparted, for example, during chipping (5, 7), during passage of chips through plug screw feeders or screw presses (24), high-consistency pumping and mixing of pulps (12), and during dewatering of pulps to high consistency in screw presses (10). Some examples of the introduction of curl by incidental mechanical action are given in Table 1.

Curl is also introduced into fibres deliberately. Over the years, fibres have been curled by employing such devices as the Kollergang (25), the Curlator (10), the Flexar (26, 27) and the Chemifiner (28). In common industrial use are the Frotapulper (29), and the high consistency refiners (30, 31) which are used for mechanical, thermomechanical, chemi-mechanical, and chemical pulps. The common feature of all these devices is the application of a mechanical shearing action on fibres held at a consistency of 15-30%. The extent of the curl induced depends on the refining energy as shown in Table 2. This mechanical treatment can be simulated conveniently in the laboratory by treating the pulp in a Hobart kitchen mixer (32, 9) or by using the PFI mill at a high consistency (9, 32-35). Examples are given in Table 3 showing the extent to which curl is introduced into fibres by various laboratory methods.

It has been suggested by Kilpper (1) that curl can be introduced by chemical means, in the caustic extraction stage of bleaching. Kerr and Kibblewhite suggest that a vapour phase ammonia treatment creates curl (36). The nonuniform reactivity of the reagent with the cell wall, enhanced by the presence of dislocations and nodes is considered to be responsible. In practice, however, it is not unusual for pulp suspensions to be subjected to simultaneous chemical reaction and mechanical shear, for example during bleaching. When fibres of such pulps emerge curled, the relative contributions of the chemical and mechanical actions are not always clear.

Pulp	Device	Refining energy, MJ/kg	Curl index
Refiner mechanical pulp of softwood prepared by refining in one stage	Double-disc refiner, 20% outlet consistency	5.61	0.113
		6.89	0.143
		9.02	0.153
Thermomechanical pulp of softwood refined in two stages	Disc refiners, 30% outlet consistency	5.33	0.121
		7.18	0.124
		7.96	0.145
92%-yield bisulphite pulp of softwood refined in one stage	Double-disc refiner, 20% outlet consistency	4.62	0.115
		6.69	0.140
		8.95	0.151
46%-yield unbleached sulphite pulp of softwood	Frotapulper, 30% consistency	-	0.152
		0.20	0.198
		0.46	0.233

Table 2. Effect of applied energy in various commercial devices on fibre curl.

Pulp	Device	Treatment	Curl index
50%-yield kraft pulp	Hobart kitchen mixer, 20% consistency	Time, min	
		0	0.141
		30	0.149
		60	0.217
		120	0.229
70%-yield bisulphite pulp	PFI mill, 20% consistency	Revolutions	
		0	0.105
		8000	0.139

Table 3. Effect of high consistency treatment in laboratory devices on curl of unbleached softwood pulps.

Curl and microcompression may be induced during the papermaking process either by drying without restraint (37) or through enforced sheet shrinkage during drying (38, 39). However, these aspects fall outside the scope of this paper.

SUSCEPTIBILITY OF FIBRES TO CURL

Fibres of different origins, pulped in different ways seem to have a different tendency to curl. Kilpper (1) first showed this in 1949, when he examined the curl factor of a range of commercial chemical pulps including sulphite, kraft and rayon pulps. He found that the curliest fibres were those with the highest α-cellulose contents. He pointed out that these differences in curl factor might not be directly related to chemical processing and may be a function of the mechanical treatment that they have received.

In a study of the effect of delignification on pulp properties, Giertz (40) showed micrographs of laboratory pulps, ranging from thermomechanical and ultra-high-yield to low-yield kraft and acid sulphite. The fibres of lower yield were seen to be more curly.

In a study of Canadian bleached kraft market pulps of papermaking grade, De Grâce and Page (12) showed a wide range of fibre curliness from pulp to pulp. No correlation was found between curl and α-cellulose content, although it was shown that the curliest pulps were those of highest coarseness and lowest viscosity. During this study it was found that hardwood and softwood fibres, pulped and bleached in the same mill were curled equally, indicating that any effect of species on curl susceptibility was overridden by the effect of the treatment given to the fibres.

It has been noted for some time that high-yield sulphite pulp fibres are, in practice, unusually straight. The micrograph shown in Figure 1 is typical of many in the literature. Values of curl index have been obtained for samples of high yield sulphite pulps used in Eastern Canadian newsprint mills (41), and are shown in Table 4. The average curl index is 0.116 indicating straight-fibred pulps.

Mill		Curl index
A		0.113
B		0.120
C		0.120
D		0.117
E		0.110
	Average	0.116

Table 4. Curl index of commercial softwood sulphite pulps in the yield range 65-75%.

While the work described above strongly suggests that the tendency of fibres to curl depends on their history of chemical treatment, the evidence is not conclusive. However certain controlled experiments have been carried out that demonstrate clearly the effect of chemical treatment on the tendency of fibres to accept curl.

Helle (16) measured, as a function of pulp yield, the curvature of fibres of sulphite pulps that had been given a mild mechanical treatment. Figure 12 shows that the higher the yield the more resistant are the fibres to the introduction of curl.

The present authors have studied the introduction of curl into ultra-high-yield sulphite pulps refined at high consistency. A plot of curl index against yield is shown in Figure 13. It seems that, for a given energy input, the pulp at 90% yield is the least curled, falling below that for both a lower yield pulp and an untreated refiner mechanical pulp. In fact, of all the pulps examined by the authors a 90%-yield sulphite seems to be the most resistant to the introduction of curl.

The evidence is convincing that the susceptibility of fibres to curl is affected by sulphite pulp yield. However, no systematic work has been done to determine the effect of other process variables such as wood source, pulping process or bleaching conditions.

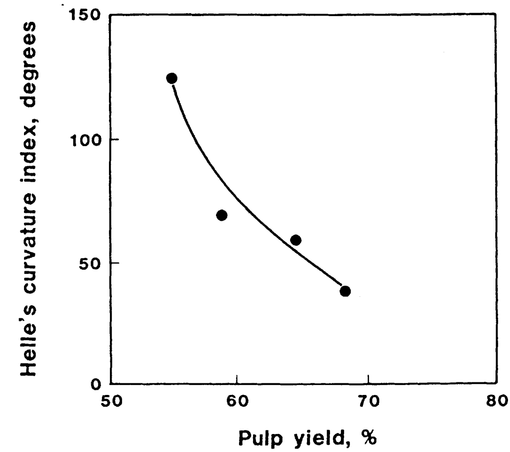


Fig 12—Data of Helle (**16**) showing the effect of pulp yield on curvature index for sulphite pulp fibres which had been given a mild mechanical treatment at high consistency.

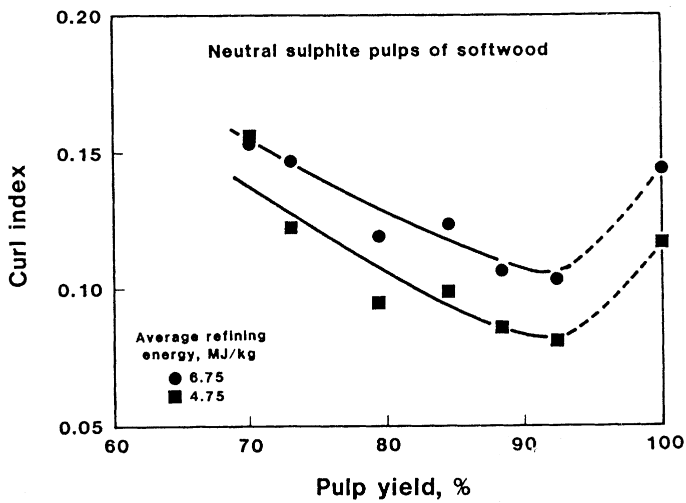


Fig 13—Plot of curl index against pulp yield for neutral sulphite pulps. the curl indices are compared at constant input of refining energy. The pulps were refined in a double-disc refiner at about 20% consistency.

STABILITY OF CURL

It may be thought that curly fibres are limp, like string, capable of taking up any form. If this were correct, curl measurement should have little value, being simply a measure of the most recent stress field that the fibre had experienced. However, this is not confirmed by experiment. Fibres, when curled, generally retain their form so that the same fibre returned to the microscope for a second examination after a mild agitation at low consistency is seen to have approximately the same form as before (42). The stability of curl does vary however from pulp to pulp, and depends on the conditions of treatment.

The phenomenon of latency removal in refiner mechanical pulps is perhaps the best known example of curl instability (11, 43). The curl put into the fibre during high-consistency refining remains if the fibres are disintegrated at low temperature, but is lost if the disintegration temperature is above 50°C. Table 5 shows the effect of hot and cold disintegrations on the curl indices of refiner mechanical and thermomechanical pulps.

Pulp	Curl index after disintegration	
	Cold	Hot
Refiner mechanical pulp of softwood prepared in one stage at 6.75 MJ/kg and 17% inlet consistency	0.204	0.143
Thermomechanical pulp of softwood prepared at 8.09 MJ/kg	0.215	0.121

Table 5. Latency removal in mechanical pulps.

Curl is even more unstable in high-yield and ultra-high-yield sulphite pulps. These fibres may be curled at a high consistency, but upon dilution they tend to straighten immediately, and even a disintegration at room temperature is enough to straighten them completely. Thus, the familiar straight form of high-yield sulphite fibres arises from the extreme instability of the curled form.

Curl in low-yield pulps is retained after either hot or cold disintegration as illustrated in Table 6.

Pulp	Curl index after disintegration	
	Cold	Hot
49%-yield kraft pulp	0.197	0.177
50%-yield sulphite pulp	0.210	0.230

Table 6. Effect of disintegration on curl of low-yield unbleached pulps after curlation for 60 minutes at 20% consistency in a Hobart kitchen mixer.

Several attempts have been made to stabilize curl, particularly in the high-yield pulps, since certain properties are enhanced by the presence of curl.

The general term "curl-setting" has been applied (41) to processes which render the curl resistant to removal by the further mechanical action that a pulp would experience in a mill. In the case of chemi-mechanical and mechanical pulps, we consider a pulp curl-set if the curl remains high after a standard hot disintegration; in the case of chemical pulps after a standard disintegration at room temperature.

It is important to note that Kibblewhite's definition of curl-setting (44) differs from ours. He regards a pulp as curl-set if the fibres in a strained wet web do not straighten before failure.

Kibblewhite suggests that drying, freezing and bleaching cause curl-setting according to his definition (45). Table 7 shows the effect of freezing on curl retention in a thermomechanical pulp and a curlated kraft pulp. The thermomechanical pulp is not curl-set by freezing, and the curlated kraft pulp shows only a small increase in curl. We conclude that freezing does not set any appreciable curl in the fibre according to our definition.

	Curl index after disintegration	
	Cold	Hot
Thermomechanical pulp of softwood		
Before freezing	0.249	0.113
After freezing	0.211	0.127
50%-yield kraft pulp of softwood		
Before freezing	0.167	-
After freezing	0.180	-

Table 7. The effect of freezing curlated pulps on curl retention.

Kibblewhite and Kerr (36, 46) demonstrated that ammonia treatment of an already curled pulp causes curl-setting. The increase in kink index obtained is shown in Table 8. Although this has not been repeated in our laboratory, it seems likely to us, from the physical test data, that such a treatment would curl-set a pulp according to our definition.

Stabilization of curl has also been achieved using the "OPCO" process (47). In this process, curled mechanical pulp fibres held at high consistency are treated to a mild delignification using sulphite liquor at temperatures in excess of 130°C. The curl in the resultant pulp is stable both to hot and cold disintegration as shown in Table 9.

Pulp	Pretreatment, revs. PFI mill	Kink index	
		Before NH_3 treatment	After NH_3 treatment
Kraft pulp of slabwood, Kappa No. 29.7	9000	1.9	3.4
Kraft pulp of corewood, Kappa No. 32.1	9000	3.9	8.2
Soda-oxygen pulp of slab-wood, Kappa No. 28.6	5000	1.7	3.6

Table 8. Effect of gaseous ammonia on fibre kink index of radiata pine unbleached pulps (46).

	Curl index after disintegration	
	Cold	Hot
Before heat treatment	0.240	0.131
After heat treatment	0.250	0.224

Table 9. Heat treatment in the presence of sodium sulphite (OPCO process). Thermomechanical pulp of softwood refined at 8.09 MJ/kg, subsequently cooked to approximately 90% yield by 10% Na_2SO_3 at 150°C for 40 minutes at 10% consistency.

Barbe, Seth and Page (41) demonstrated that curl is stabilized by a simple steam treatment of a high consistency pulp mass at temperatures in the range 120-170°C for times ranging from 2 to 60 minutes. Table 10 shows typical results on a variety of pulps. Because the temperature exceeds 100°C in this process, a pressure vessel is required. However, it has also been shown that, if a treatment time of many hours is acceptable, curl-setting can be achieved by storage in an unpressurized vessel at or below 100°C, as shown in Table 11. Curl-setting has also been achieved (48) by reacting a curled pulp mass with caustic soda at room temperature, as shown in Table 12.

	Before heat treatment, after disintegration		After heat treatment, after disintegration	
	Cold	Hot	Cold	Hot
Thermomechanical pulp of softwood refined at 8.09 MJ/kg.	0.215	0.121	0.250	0.239
Refiner mechanical pulp of softwood refined at 6.75 MJ/kg and 17% inlet consistency	0.204	0.143	0.258	0.239
89%-yield bisulphite pulp of softwood refined at 7.60 MJ/kg and 17% inlet consistency	0.159	0.102	0.220	0.205

Table 10. Curl stabilization by heat treatment at 150°C for 60 minutes at 22% consistency.

Of the various curl-setting methods, only the OPCO process has so far been commercialized (49).

Pulp	Treatment conditions	Curl index after hot disintegration	
		Before treatment	After treatment
Chemi-thermomechanical pulp of softwood, 450 mL CSF	80°C, 24 hours, 20% consistency	0.120	0.139
	100°C, 6 hours, 20% consistency	0.120	0.136
Chemi-thermomechanical pulp of softwood, 275 mL CSF	80°C, 16 hours, 20% consistency	0.095	0.122
Thermomechanical pulp of softwood, 80 mL CSF	100°C, 5 hours, 20% consistency	0.122	0.162

Table 11. Curl-setting by heat treatment at temperatures of 100°C or lower.

Pulp	Curl index after hot disintegration
Thermomechanical pulp of softwood refined at 7.82 MJ/kg	0.085
Original latent pulp sprayed with NaOH solution to 20% consistency and a weight ratio of alkali to fibre of 0.09	0.103
Original latent pulp sprayed with NaOH solution to 20% consistency and a weight ratio of alkali to fibre of 0.33	0.179

Table 12. Effect of alkali treatment on curl retention.

The stability of curl after refining or beating has been studied for chemical pulps by several authors (1, 16, 48, 50). Curl is generally reduced upon low-consistency beating as illustrated in Table 13.

Pulp	Refining conditions	Curl index
46%-yield unbleached sulphite pulp of softwood curlated at at 0.46 MJ/kg and 30% consistency in a Frotapulper	Refining energy in MJ/kg (at 3% consistency in a commercial refiner)	
	0	0.233
	0.11	0.188
	0.25	0.184
	0.36	0.163
53%-yield unbleached kraft pulp of softwood curlated for 90 minutes in a Hobart kitchen mixer at 20% consistency	Revolutions in PFI mill (at 10% consistency)	
	0	0.176
	1500	0.127
	6000	0.123
Commercial, dried bleached kraft pulp of softwood	Time in minutes in Valley beater at ~1.6% consistency	
	0	0.206
	20	0.169
	40	0.160

Table 13. Removal of curl by low-consistency refining.

When an ultra-high-yield sulphite pulp is refined and curl-set, subsequent refining diminishes the curl, as shown in Table 14. The energy split between the two stages then controls the degree of curl in the final pulp.

Second stage refining energy, MJ/kg	Freeness, mL	Curl index
-	537	0.167
0.78	405	0.140
1.98	193	0.118

Table 14. The effect of refining after curl-setting. A softwood thermomechanical pulp prepared at 5.33 MJ/kg and 46% outlet consistency, curl-set at 170°C, 70 minutes and 20% consistency in the presence of 20% sodium sulphite at pH 9, and subsequently refined at 20% consistency in a double-disc refiner.

MECHANISMS OF CURL STABILITY

An attempt has been made to explain these rather complex phenomena, in terms of the stresses within the various cell wall components (48). When a wood fibre is bent, the cellulosic fibrils are deformed, and provide a stress tending to restore the fibre to its straight form. These stresses are counteracted by the stresses in the hemicellulose-lignin matrix that tend to keep it curled. Whether the fibre straightens or remains curly depends on the stress-relaxation within these two components.

Thus, a curly refiner mechanical or thermomechanical pulp is straightened when its temperature rises above the point where stresses can relax rapidly in the hemicellulose-lignin matrix. The matrix of high-yield sulphite pulp fibres has been chemically weakened so that even at low temperatures it is incapable of maintaining a stress that will resist the straightening stresses of the cellulose. The permanently curled form of a low-yield fibres is seen to be caused by degradation of the cellulose, so that it becomes incapable of sustaining a stress tending to straighten it.

Using this model, the various known methods of curl-setting, namely heat treatment with or without sulphite liquor or treatment with caustic soda or ammonia are all seen as relaxing the stresses in the cellulose fibrils while the fibre is held curled, so that the fibre will no longer straighten upon disintegration.

An alternative explanation of curl-setting is the chemical bonding of the structure in the curled state. It is not clear however what kind of bonding would be created by these different treatments. The finding that curl-set mechanical pulps remain curl-set, even after complete delignification (48) suggests that bonding within the interfibrillar matrix cannot be responsible. Moreover direct bonding between cellulose fibrils cannot be responsible since these are separated in the wood cell wall.

THE EFFECT OF CURL AND MICROCOMPRESSION ON PULP AND PAPER PROPERTIES

Fibre curl and microcompression have a large effect on the properties of pulps and the quality of products made from them. Unfortunately it is not always possible to demonstrate the effects unequivocally, since the method of changing curl often changes other properties and the effect is masked. An attempt will be made in this section to make comparisons of pulp and paper properties in ways which vary the curl but maintain other fibre properties constant.

Pulp Properties

Drainage and Freeness

The introduction of curl into fibres reduces the drainage resistance of most pulps. While the literature contains many examples, none give measurements of the curl index. Table 15 shows the way in which curlation, latency removal and curl-setting affect curl and Canadian Standard Freeness. It is not unusual to find a difference as large as 100 mL between the freenesses of curled and uncurled pulps. It is hypothesized that drainage resistance is decreased by curl partly by the bulking of the mat, and partly by the reduced cross-section of the curled fibre that is presented to the flow.

Pulp	Treatment by which curl was changed	Curl index		Freeness, mL	
		Before	After	Before	After
Unbleached 46%-yield sulphite pulp of softwood	Dewatering by commercial screw press discharging at 30% consistency	0.126	0.152	633	664
Thermomechanical pulp of softwood refined at 9.24 MJ/kg	Latency removal	0.259	0.154	201	106
78%-yield bisulphite pulp of softwood refined at 17% consistency and 2.20 MJ/kg	Curl-setting	0.125	0.220	236	326

Table 15. Effect of curl on pulp freeness.

Fibre Length Measurement

Curl and microcompression influence the determination of fibre length. Although it is not apparent from published data, slight changes occur in the values of the Bauer-McNett fractions of refiner mechanical pulps, when curl is removed by hot disintegration. This is illustrated in Table 16 in which the data of eight fractionations have been averaged to increase the precision. The long-fibre fractions increased by about 8% upon latency removal.

Fibre length measured by other methods also seems to change as curl is changed. Table 17 shows the fibre length, measured by image analysis, of an unbleached kraft pulp after high-consistency treatment, followed by PFI mill beating. The fibres of this strong pulp are not expected to be damaged by this treatment. The fibre length is decreased by about 10% upon curlation; this result is typical of a number of experiments. The coarseness, as measured by image analysis, is proportionally increased. The fibre length is however restored upon beating. It seems that the image analyser is measuring the shortening of fibres caused by the introduction of microcompressions (9) and the removal of these microcompressions by low-consistency refining.

Bauer-McNett fractions	Disintegration Cold	Disintegration Hot	Difference	Percent difference upon hot disintegration
R14	5.77	6.26	+0.49	+ 8.49
14/28	23.64	25.62	+1.98	+ 8.38
28/48	15.76	17.00	+1.24	+ 7.87
48/100	16.87	14.44	-2.43	-14.40
100/200	7.71	7.40	-0.31	- 4.02
P200	30.30	29.29	-1.01	- 3.33

Table 16. Bauer-McNett classification of a refiner mechanical pulp of softwood with and without latency removal.

	Untreated	Curlated	Curlated + 1500 revs. PFI mill	Curlated + 6000 revs. PFI mill
Curl index	0.093	0.176	0.127	0.123
Fibre length, mm	2.41	2.16	2.34	2.43

Table 17. The effect of curl on fibre length measurement. Curl was introduced in a laboratory-made, never-dried, 53%-yield unbleached softwood kraft pulp by treating the pulp at a high consistency in a Hobart kitchen mixer. Curl removed by beating in a PFI mill. Fibre length measured by image analysis.

Wet-Web Properties

The presence of curl, kinks, crimps and microcompressions affects the wet-web strength properties of pulps. The higher the fibre curl, the higher is the stretch of the wet-web (10, 44, 51, 52). Although fibre curl tends to decrease the tensile strength of the web, the increase in stretch often more than compensates and thus the toughness of the web is increased as seen in Table 18.

The mechanisms by which curl and microcompressions increase wet-web stretch are now well understood (52). The presence of curl controls wet-web stretch at low solids, around 20%, because fibres can slide upon one another and straighten when the web is strained. At high solids, above 40%, since the fibre-fibre contacts are strong, the relative movement of fibres is prohibited and gross curl cannot be removed. The extensibility of the sheet then depends on the extensibility of the fibre between the fibre-fibre contacts, which in turn depends on the presence of crimps and microcompressions. The extent to which the potential stretch in fibres due to curl and microcompressions can be utilized depends on the degree of fibre-fibre interaction in the web, and this in turn depends on factors such as fibre flexibility, fibrillation and fines. For extremely flexible fibres there is a perfect correspondence between the value of the curl index, expressed as percent, and the value of wet-web stretch at about 25% solids, since failure occurs when the available curl in the fibre has been removed. This is illustrated in Figure 14.

Formation and Fibre Orientation

Although no data are available, conceptually the curled shape of fibres may affect the forming of a machine-made sheet. Curled fibres may entangle more easily, forming flocs, and there is comment in the literature that this occurs (28). We have confirmed that curled fibres settle more rapidly, as stated by Herbert et al. (28).

While a straight fibre has a well-defined orientation, a curly fibre does not. This is because the orientation of segments in a curly fibre is itself broadly distributed. It is conceivable that the fibre orientation of machine-made papers may be diminished by the use of curly fibres.

Pulp	Treatment	Curl index before and after treatment	Solids, %	Tensile strength, m	Stretch, %	Work-to-rupture, mJ/g
Thermomechanical pulp of softwood, refined at 8.09 MJ/kg	Latency removal	0.215	23.5	61	16.0	121
		0.121	18.9	92	6.3	69
78%-yield bisulphite pulp of softwood refined at 2.20 MJ/kg and 17% consistency	Curl-set at 150°C for 60 minutes at 22% consistency	0.125	20.6	144	6.4	116
		0.220	19.2	111	16.2	244
49%-yield unbleached kraft pulp of softwood	Curlation at 20% consistency for 60 minutes in a Hobart kitchen mixer	0.141	27.2	116	6.6	91
		0.217	28.0	100	16.7	188

Table 18. Effect of fibre curl on wet-web tensile properties. The webs were prepared following the procedure described elsewhere (53), and pressed at 60 Pa.

Thus, for a variety of reasons, curl may affect the structure of machine-made papers. Further discussion of this point is however beyond the scope of this paper.

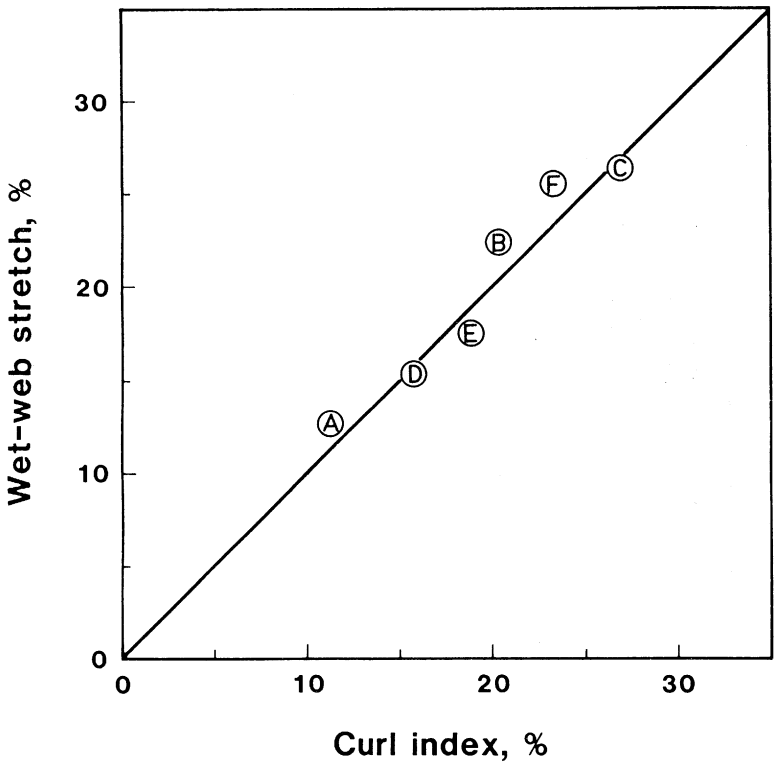


Fig 14—Plot showing the excellent correspondence between wet-web stretch at low solids and fibre curl index, expressed as a percentage, for very comformable fibres. A and B — thermomechanical pulps of solftwood, original and curl-set, followed by delignification with acidified sodium chlorite. C — commercial dried unbleached softwood kraft pulp, beaten and then curlated at high consistency. D, E and F — 46% — yield unbleached softwood sulphite pulp, curlated and refined at low consistency.

Dry Sheet Properties

Bulk

In the absence of other effects the presence of curl in fibres raises the bulk of the sheet. The most notable case is latency removal in mechanical pulps prepared at a high consistency. Curl-setting by heat treatment can raise the bulk of the sheets, provided that care is taken to avoid side reactions that may affect fibre flexibility. Mechanical curlation of chemical pulps often reduces bulk because of the concomitant increase in fibre flexibility. Examples of increased bulk in the presence of curl are given in Table 19.

Pulp	Treatment	Curl Index		Bulk, cm^3/g	
		Before	After	Before	After
Thermomechanical pulp of softwood, refined at 8.09 MJ/kg	Latency removal	0.215	0.121	3.30	2.95
Thermomechanical pulp of softwood refined at 8.52 MJ/kg	Curl-set at 150°C for 10 minutes at 19% consistency	0.106	0.177	2.79	3.10
78%-yield bisulphite pulp of softwood refined at 2.20 MJ/kg and 17% consistency	Curl-set at 150°C for 60 minutes at 22% consistency	0.125	0.220	1.54	1.66
46%-yield unbleached sulphite pulp of softwood	Dewatered by commercial screw press discharging at 30% consistency	0.126	0.152	1.65	1.68

Table 19. The effect of fibre curl on dry-sheet bulk.

Tensile Strength and Tearing Resistance

It is possible by a combination of treatments to introduce curl into pulps while keeping the bulk of the sheet approximately constant. This can be achieved either by relying on the natural counterbalancing effects of increased flexibility and increased curl or by adjusting the bulk during sheetmaking through wet-pressing pressure. The effect of curl on tensile strength is shown in Figure 15 for a series of pulps in which bulk has been maintained approximately constant.

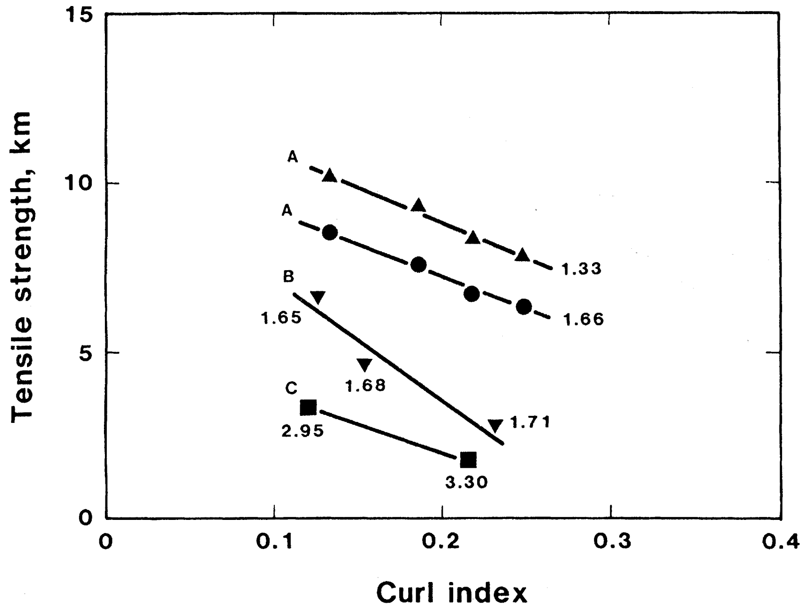


Fig 15—Plot showing the effect of fibre curl on dry-sheet tensile strength. The numbers against lines and data points indicate sheet bulks in cm^3/g. A — Tensile strengths interpolated at constant bulks of 1.33 and 1.66 for handsheets made at various pressing pressures from a 47%—yield never-dried unbleached kraft pulp of black spruce, curlated in the laboratory to different levels. B — Standard handsheets made from a 46%—yield never—dried unbleached sulphite pulp of softwood curlated in a frotapulper to various degrees. C — Standard handsheets of softwood thermomechanical pulp with and without latency.

Curl in the range 0.12 to 0.24 thus appears to reduce tensile strength by between 30 and 50%. The mechanism of this strength reduction has been discussed elsewhere (54, 55). The length along which stress is transmitted, before it is transferred to other fibres via the bonds, depends on the straightness of the fibre. For straight fibres, this length is the fibre length, but for fibres containing curls or kinks, the effective length is less, giving, according to the Page equation, a lower tensile strength (54).

The Elmendorf tearing resistance increases by about 70% as curl increases from 0.12 to 0.24, as shown in Figure 16. We attribute this increase to the uneven distribution of stress along the length of a curled fibre in the fracture zone. Thus,

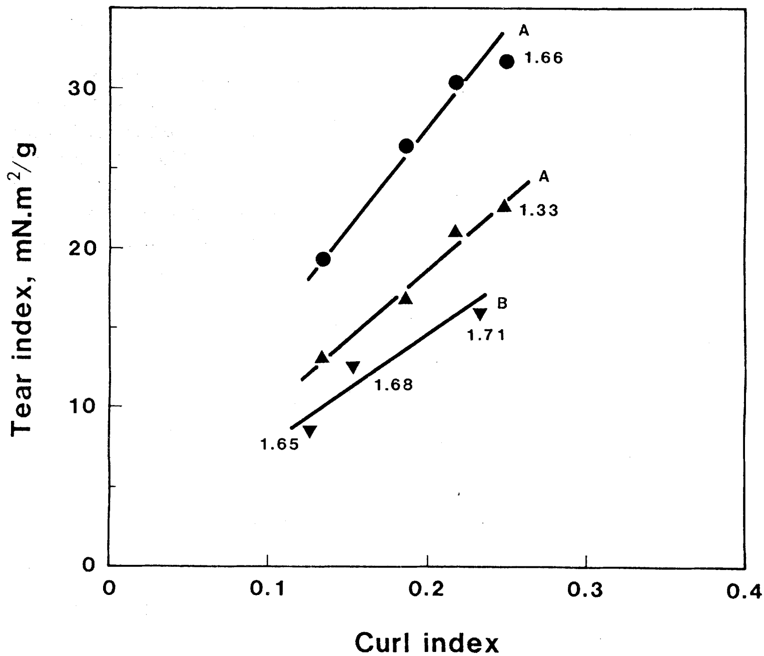


Fig 16—Plot showing the effect of fibre curl on dry-sheet tear index. The numbers against lines and data points indicate sheet bulks in cm^3/g. Experiments A and B correspond to those in Figure 15.

curly-fibred pulp transfers larger stresses to the bonds which, in breaking, consume greater energy as proposed by Van den Akker (56).

Because curl is affecting tearing resistance and tensile strength through the same mechanism, both properties cannot simultaneously be enhanced by adjusting curl.

The Stress-Strain Curve

The stress-strain curve of dry paper is influenced by both curl and microcompression. When a dry sheet is strained, few fibre-fibre bonds fail completely prior to sheet failure. Thus, grossly curled fibres cannot be straightened during straining of a dry sheet. Dislocations or microcompressions in fibres can be extended, however, since they are present in all segments, and do not require bond breakage for release.

Thus, modulus and tensile strength are reduced proportionally by fibre curl, but the overall shape of the stress-strain curve is unaffected. On the other hand, dislocations and microcompressions do change the shape of the stress-strain curve, because they change the response to stress of each fibre segment. Fibres without microcompressions have a steep, almost linearly elastic response, whereas microcompressed fibres are more extensible, and show a yield point followed by appreciable plastic deformation (57, 58).

Seth and Page (59) have concluded that the general shape of the stress-strain curve of paper is governed almost entirely by the stress-strain curve of its constituent fibres.

It follows that highly microcompressed fibres produce sheets of high extensibility; modern methods for manufacturing extensible papers exploit this effect.

Microcompression is also responsible for some of the differences between stone groundwood and refiner mechanical pulp (60). Since stone groundwoods are never treated at high consistency they contain fewer microcompressions than mechanical pulps refined at high consistency. As a result, refiner pulps have a higher stretch-to-break than stone groundwoods as shown in Figure 17.

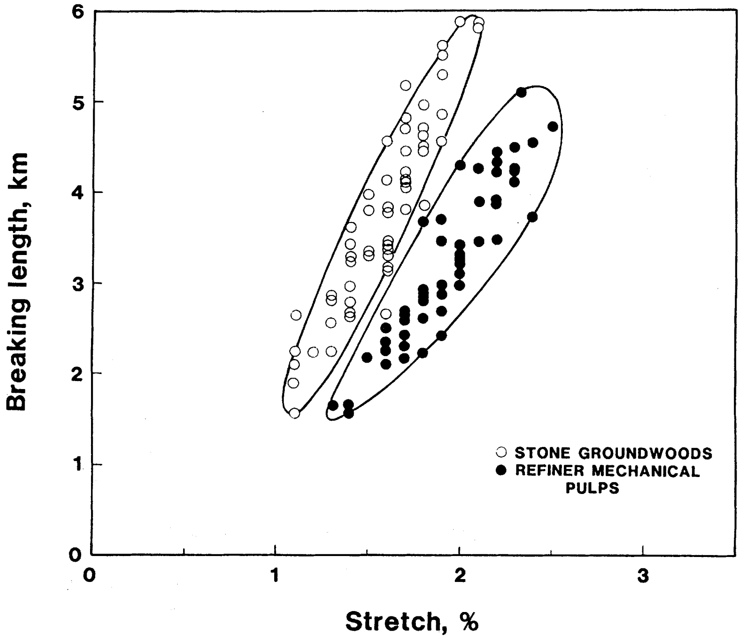


Fig 17—Breaking length against stretch for handsheets of laboratory mechanical pulps. At a given tensile strength the refiner mechanical pulps, which contain microcompressions, have a higher stretch, as shown by Page and Seth (**60**). Data of de Montmorency (**61**).

Other Properties

Curl and microcompression influence several other properties. Through the mechanism of changing the stress distribution in the sheet, curliness reduces bursting strength, folding endurance, stiffness and edgewise compressive strength. Microcompression in the absence of curl increases bursting strength, folding endurance, and the toughness of the rewetted sheet. Through the bulking mechanism and the effect on fibre cross-sectional form, they both affect porosity and water absorbency.

Other properties may also be changed by mechanisms that do not fall within the scope of this paper. These include dimensional stability, ply-bond strength, roughness, coefficient of friction, ink receptivity and other printing properties.

DISCUSSION

Curl and microcompression are either created or removed during many of the processes used in pulping and papermaking. However the role of curl and microcompression in controlling pulp properties has often gone unrecognized, doubtless because there is no simple method of measurement. As a result, processes have been changed and developments proposed, that change curl and microcompression and hence change properties in an unexpected way. This has led to unforeseen problems some of which have had major economic consequences. It appears further that process modifications will continue to be contemplated, without due regard to this phenomenon. Some examples of past problems and future pitfalls will now be discussed.

The development of refiner mechanical pulping in the paper industry was jeopardized by the unrecognized presence of curl in fresh samples of high-consistency refined mechanical pulps. It was indeed fortunate that the uncurling of such pulp fibres by a low-consistency hot disintegration was shown by Beath, Neill and Masse (43) and by Jones (11) as early as 1966. At that time the former authors stated that this phenomenon had been "a cause of obscurity and confusion in the testing of high-consistency refiner groundwoods and a cause of substantial economic losses to the industry".

The move from low-yield sulphite to high-yield sulphite as a reinforcing pulp for newsprint in Eastern Canada, in the 1960's and 1970's, was dictated by considerations of wood supply and environmental protection. An unexpected consequence was the adverse effect on wet-end runnability particularly for open-draw machines. As is now understood wet-web stretch at couch moisture contents falls rapidly with an increase in yield, because of the increasing straightness of the fibres. Thus a newsprint sheet reinforced with high-yield sulphite pulp is more brittle and prone to failure at the wet end. Barnet, Bedard and Shaw (62) explicitly state that because of this effect "increases in yield were accompanied by loss in paper machine efficiency".

Fibres of the more recently developed very high-yield pulps used for reinforcement of newsprint such as chemi-thermomechanical, chemi-mechanical and sulphonated chemi-mechanical pulp are also always straight, as evidenced by published micrographs (63, 64). However because they have been refined at high consistency, they contain microcompressions that enhance somewhat the wet-web and dry-sheet stretch. Thus in comparison with conventional high-yield (60-70%) sulphite pulps, which are generally refined at low consistency, they are more extensible. Nevertheless their extensibility does not rival low-yield sulphite or kraft pulps, and it is worth noting that in at least one Eastern Canadian newsprint operation using a very-high-yield pulp, a small percentage of the curly low-yield fibres is still added (65).

Forming of paper in air rather than water has certain attractive features, both economically and environmentally, and has been used for some specialty products. Nevertheless it has never been possible to demonstrate that dry-forming can produce sheets of high elastic modulus, stiffness and tensile strength. The mechanism for the poor strength now appears not to be, as is generally thought, inadequate fibre-fibre bonding because of the absence of water. Air-borne dry fibres of wood pulp seem to be always curled, kinked and crimped because of their method of preparation. If they are flash-dried they are curled upon drying into a contorted form; if they are dry-fluffed they are curled by the mechanical action of fluffing (66). A sheet of such fibres has a low modulus and tensile strength because the effective fibre length of a curled fibre is considerably reduced and this leads to a poor stress distribution in the sheet (54, 55). It follows that no improvement in bond strength can bring the sheet strength to that of a straight-fibred wet-laid sheet. Considerable investments have been made in research on dry-forming without appreciation of this important fact.

The importance of microcompression in mechanical pulps has not generally been recognized. Pressurized grinding provided the hope that properties similar to thermomechanical refiner pulps might be achieved at a lower energy level (67). It was not realized until later (68), however, that pressurized groundwoods are deficient in microcompression, since they have not been treated at high consistency, and therefore give sheets of lower stretch-to-break and lower tearing resistance. It is interesting to note that pressurized grinding to a high freeness, followed by high-consistency refining has been shown to give enhanced properties (69).

Curl plays an important role in the development of strength of dried bleached pulps by beating. In current theories, the increase in strength is attributed either to increased bonding, through increased fibre flexibility or fibrillation or to increased shrinkage stress. It now appears that these are not the major effects. More than half the strength improvement upon beating comes from the straightening out, during beating, of the fibres that have been curled and kinked during pulping and bleaching (70). Failure to recognize this important fact about the effect of one of the industry's major processes on one of its major products must surely have had economic consequences.

For the future, attention should always be paid to circumstances which may incidentally change curl and microcompression or which may set the curl in.

Any process that subjects wood chips to pressure may be responsible. The passage of chips through plug screw feeders prior to subsequent treatment or through screw presses for defibration, liquor impregnation, liquor extraction, washing, bleaching or brightening are examples (24, 71-76). Improved or modified properties may be claimed for such treatments, but the change may be due in part to the introduction of curl and microcompression rather than other mechanical or chemical effects that are implied. Consequent improvements in wet-web and dry-sheet extensibility should no longer be regarded as surprising.

Similarly, vapour phase chemical treatments of high-consistency fluffed pulps may result in changed properties (77, 78), but these may be partly mechanical in nature, caused by the introduction of curl during fluffing and shearing of the fluff in transport. If the chemical treatment is carried out at an elevated temperature, curl-setting may occur.

The curl-setting effect can also occur incidentally at lower temperatures. It has been shown above (Table 2) that some curl is set after 24 hours of treatment at 80°C. Lunan et al. (79) have shown appreciable effects on pulp stored for 24 hours at temperatures as low as 65°C. Similar results have been obtained by Karnis and Harris (80). This implies that lengthy high-consistency storage of a latent pulp emerging from a refiner must be avoided if curl-setting is not required.

The lesson that curl and microcompression are important variables in consideration of pulp properties seems to be a hard one for the industry and research community to learn. It has been rediscovered at regular intervals, but often as the result of a precipitated crisis. It is hoped that this paper may increase the awareness of pulp and paper research workers and mill management to these phenomena, so that such crises may be prevented in the future, and the phenomena may be exploited for the industry's benefit.

CONCLUSION

Curl and microcompression are among the most important factors affecting pulp and paper properties of all pulps. They can be created, stabilized or eliminated by incidental, as well as deliberate means. There is no way of quantifying microcompressions, and only a tedious research method exists for quantifying curl.

Major property differences occur between pulp and paper products caused by these unrecognized differences. There have been many surprises in research and production enterprises, because of failure to recognize the importance of these fibre features.

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Transcription of Discussion

Curl, Crimps, Kinks and Microcompressions in Pulp Fibres — their Origin, Measurement and Significance

by D.H. Page, R.S. Seth, B.D. Jordon and M.C. Barbe

Dr. O. Kallmes MK Systems, Danvers, USA

You have shown in one of your slides that curl of fibres seems to relate linearly with wet web stretch. Could this form the basis of a simple test for this property?

Dr. R.S. Seth Yes, it could but there is a problem. The relationship I showed applies only to very flexible fibres where you can take the curl out during straining. If the fibres are stiff, then you may not be able to fully utilize the curl and therefore that relationship would be somewhat different. Yes, the wet web stretch is a good indicator of curl in fibres, but I would prefer measuring it directly.

Prof. E.L. Back STFI, Stockholm, Sweden

I would like to ask about the effect of curl on the z direction strength?

Seth We don't have any information that I could give you on Z-direction strength and its relationship with fibre curl. Since there are so many factors involved, I would prefer not even to speculate on the relationship.

S.O. Dillen Dillen Consulting AB, Stockholm, Sweden

You described curl as being either set or non-set, I wondered whether perhaps curl could be what you might describe as partially set. There are indications in several of the mills that latency in TMP which you think has been removed turns out in fact not to have been fully removed. Could storage at high temperature induce a partial curl setting in the fibres which can later be removed by hot disintegration?

Seth For curl to be set, the conditions are that the pulp should be at high consistency, the temperature should be high and the length of time should be sufficient. The curl will be partly removed on subsequent hot disintegration but the amount of curl left will depend on the extent to which the curl had already been set.

S.U. Hossain Kimberly Clark Corpn., Neenah, USA

What is the effect of alkaline treatment of fibres on curl? How does an alkaline treatment accomplish "Curl Setting"? What is the mechanism involved?

Seth It depends what else the alkaline treatment is doing to the fibres. If it is swelling them, then of course they will bond better. Maybe Dr. Kibblewhite would like to comment.

Dr. R. Kibblewhite Pulp and Paper Research Organisation, Rotorua, New Zealand

Treatment with anhydrous gaseous ammonia should not be equated with an alkaline or caustic treatment.

Treatment of pulp with gaseous ammonia causes fibre walls to become swollen while the fibres are held in highly kinked and curled configurations because of the treatment being at high stock concentration.

Pulp treatment with gaseous ammonia has a negligible effect on pulp yield and rebonding within fibre walls occurs when they contract as the gaseous ammonia pressure is released and it is allowed to dissipate. At the same time the kinks and curls of the fibres are also set into position since they are held at high stock concentration during treatment and as the ammonia is removed.

Dr. D.H. Page While we feel that in most cases curl is caused by mechanical action, we cannot deny that there is also a chemical element to consider. In the presence of caustic soda for example one can get poral differences in swelling because of the enhanced effect of caustic on mechanically damaged retions. This action can, of itself, create curl.

Seth The mechanical and chemical actions may act synergistically.

D.B. Mutton CIP Research, Hawkesbury, Canada

You indicated that microcompressions have a somewhat different quantitative effect on fibre properties than curl but you also indicated that there is no method at present for quantitative measurement of microcompressions, so I assume that your conclusions are based on a large number of microscopic examinations, is that correct?

Seth Yes, that is correct.

Mutton Do you see any prospect for the development of a more quantitative measurement of microcompressions to be developed in the near future?

Seth At this moment I cannot foresee a simpler alternative method.

P.A. Johansson STFI, Stockholm, Sweden

I would suspect that the short fibres would be more likely to be straight than the long ones, so your curl index must be heavily influenced by the number of short fibres. How do you discriminate short fibres, and at what length?

Dr. B.D. Jordan We remove the fines. Tiny particles with very low aspect ratio like say cells tend to be straight. The curl of such particles is ill-defined and irrelevant to the web behaviour. Although, they constitute a small weight fraction, they can be quite numerous thus degrading arithmetic averages.

As long as the minimum included length is small compared to the average fibre length, the resulting curl index is reasonably insensitive to the precise value of the minimum length.