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DEPENDENCE OF SHEET PROPERTIES ON FORMATION AND FORMING VARIABLES

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Synopsis—An investigation of the effect of forming variables on handsheet strength properties showed that stock dilution, shear gradients and controlled initial drainage are factors that have major effects on sheet structure and properties. A better understanding of the causes of changes in paper strength properties resulted from the introduction of a new concept of basic sheet properties.

One basic property is the specific tensile strength. This represents the average tensile strength throughout a sheet, in contrast with the standard tensile strength, which is generally a measure of strength in the weakest part of the test samples. The well-known loss of tensile strength that occurs when handsheets are formed from stock at higher concentrations is shown to be caused mainly by small-scale substance variability, since the specific tensile strength is essentially constant over the same range of concentrations.

The effect of substance variability on other strength properties was examined by means of uniform base layer sheets with superimposed substance spots. The spots were used to obtain a known and reproducible pattern of substance variability. Notwithstanding the increased substance of the spotted sheets, they were found to be physically weaker in all properties except tearing strength. Substance variability was found also to be responsible for the reciprocal dependence of tearing strength on bursting and tensile strengths.

As a test of the practical importance of dilution and shear gradients, Fourdrinier machine trials were run in which the water removal capacity was increased considerably by the application of fan-produced vacuum under the forming zone. Sheet properties were found to be still improving up to the maximum flow box dilution or speed set by other machine limits such as drying and stock pumping.

Introduction

THE STRUCTURE of a sheet of paper is usually defined to be the spatial distribution and orientation of the various fibre fractions comprising the sheet, but the microstructure of the sheet describes more particularly the degree of fibre interlacing and the manner and extent to which the smaller fibre fractions are packed into the available voids. These latter aspects may be called the forming consolidation, since they influence the fibre density of the forming web. The wet web forming consolidation and the compression the sheet receives in subsequent pressing operations both have an effect in the final sheet on the apparent sheet density—a property held by Giertz[1] to be perhaps the most basic property of paper.

In what follows, it will become apparent that there is a property of paper that is perhaps even more basic than its density—its variability. The main variability considered here is the non-uniform distribution of fibres in the plane of the sheet—that is, substance non-uniformity. It will be convenient to subdivide this substance non-uniformity into small-scale and large-scale categories. Small-scale substance non-uniformity has dimensions approximating 1 in or less. Paper in which this small-scale non-uniformity is least is referred to by papermakers as having a good formation or good look-through. In contrast with large-scale non-uniformities, which increase the scatter of physical test figures but not the average value, small-scale non-uniformities in substance are responsible for reducing bursting and tensile strength averages, because they introduce localised weaknesses into the test area. The small-scale substance non-uniformity of the sheet is determined by the condition in which the papermaking fibres are held in suspension before drainage commences and by the conditions under which the suspending liquid is withdrawn.

This paper is primarily concerned with the influence that formation and forming variables have on sheet properties, with particular reference to those variables that lead to improved utilisation of potential pulp strengths.

Sheet structure and properties

STANDARD handsheets are frequently taken as the yardstick against which the performance of machine-made paper and thus the performance of the machine itself is measured. Consequently, they become an aim for the development of potential pulp strengths. The Fourdrinier machine usually develops burst factors and breaking lengths within the range 60–80 per cent of those for standard handsheets. Although the standard handsheet represents a convenient laboratory reference, it should not be considered to be the ultimate in sheet structure, since it represents neither the most uniform arrangement of fibres possible nor that having the highest utilisation of potential pulp strengths. Non-standard handsheets that have superior uniformity and considerably increased burst factor and breaking length may be formed by using better dispersed stock and by maintaining comparatively light shear gradients over the zone of formation. When such modest departures from the standard forming method as these can result in breaking length and burst factor values up to 20 per cent above those for standard handsheets, it is clear that the strength properties of the standard are considerably below the optimum.

The structure of a standard handsheet is almost completely determined during the period of free water drainage on the wire; but, for a machine-made sheet, small changes in structure occur that arise from transport tensions and the pressing and drying operations. Although the properties of a Fourdrinier sheet are closer to those of the handsheet than are those of other machine forming processes, notable differences still exist between the physical properties of the two sheets. When wet web samples are removed from the Fourdrinier wire and thereafter receive a treatment parallel to handsheets, the differences between handsheet and machine-made sheet properties remain

TABLE 1—UNIT PROCESSES OF FORMATION OF HANDSHEET AND FOURDRINIER-MADE SHEET

Unit process	*Sheetmachine*	*Fourdrinier machine*
Stock dispersion	Well dispersed	Poorly dispersed and flocculated stock
Stock dilution	High, stock concentration 0.017 per cent	Low, stock concentration 0.3–1.0 per cent
Shear gradients in forming zone	Almost nil	Considerable shear gradients arise from— (*a*) jet/wire speed ratio (*b*) turbulence in jet (*c*) machine shake (*d*) table roll suction (*e*) dandy roll action
Wire mesh	Very fine	Relatively coarse
Drainage characteristic	Continuous and steady	Intermittent high suction, high initial drainage rate
Drainage time	Long	Short

essentially unaltered. These differences in sheet properties must then be attributed only to differences between the forming conditions on the wires. Forming characteristics for both handsheet and Fourdrinier machines can best be considered in terms of the unit processes leading to their individualised sheet structure; these processes are outlined in Table 1.

The British sheetmachine forms a sheet slowly on a very fine mesh wire from a well-dispersed fibre suspension. On the other hand, the Fourdrinier machine forms a sheet quickly on a relatively coarse mesh wire from a poorly dispersed fibre suspension under conditions of strong and sharply pulsating drainage forces. As a direct result of these differences in forming conditions, the two sheets have characteristic structures as set out in Table 2.

From an examination of Tables 1 and 2, it is clear that the superior substance uniformity of the handsheet is due, in no small measure, to the much improved dispersion of fibres in the suspension from which the sheet is formed. That small-scale substance non-uniformities in a machine-made sheet do introduce localised weaknesses has been inferred from tensile strength measurements, for which the values obtained have been found[2, 3] to decrease with increasing sample length or decreasing sample width and demonstrated by Tydeman & Hiron,[4] who found that failure occurred across low substance areas.

The structure of a sheet of paper, however, embraces much more than just the uniformity of substance over the plane of the sheet: other factors known to be of importance include fibre orientation effects and fines distribution. Nevertheless, it will be convenient to subdivide paper structure into two

TABLE 2—COMPARISON OF STRUCTURE OF HANDSHEET AND FOURDRINIER SHEET

Property	*Handsheet*	*Fourdrinier sheet*
Small-scale substance uniformity	Comparatively uniform	Non-uniformities are large flocs
Retention of fines	High	Medium
Fines distribution	Highest near wire side	Fines usually have a maximum concentration near top side, but may even be near wire side, depending on forming conditions
Fibre distribution	Uniform through depth of sheet	Wire side usually has highest long-fibred content
Fibre orientation	Not oriented	Oriented, on wire side in particular
z-direction structure	Uniform apart from distribution of fines	Usually two-sided, with flocculated top side and oriented wire side
Forming density	High	Medium to high

aspects. The first of these is small-scale substance variability, which is the meaning given here to the term *formation.* This interpretation is consistent with the traditional papermaking use of the word in so far as the small-scale substance variability of a sheet is inferred from its optical transparency or look-through. All other facets of sheet structure have been lumped together and are referred to hereafter as the *forming consolidation.*

Effect of formation on sheet properties

THE NARROW strip of paper used for the standard tensile strength test can be likened to a paper chain, in which the high substance parts represent the strong links and the low substance parts the weak links. When such a paper chain is strained to failure, as with any other type of chain, failure occurs always at the weakest link. The standard tensile strength measurement, reflecting as it does the strength of the weakest link or group of links, is therefore biased towards the strength of the low substance areas and has a value less than the average paper strength in the test strip. The average strength of the paper in the strip can be obtained only by averaging the strength of all the links—or at least by averaging the strength of a random selection of links.

Specific tensile strength

This average strength property throughout a sheet of paper is designated the specific tensile strength or specific breaking length. It is equal to the tensile strength or breaking length that the paper would have had in the event of complete substance and strength uniformity. The specific breaking length of paper has been measured by making tests in randomly selected positions on areas of paper sufficiently small to have substance and strength uniformity within them. The requirement of strength uniformity within the test area can be met by reducing the dimensions in both length and width of that part of the sheet being subjected to test. When the test area is reduced to a dimension below which complete uniformity exists in that area, so the inferred value for specific tensile strength will rise to a maximum and remain there. Such testing could be done either by using narrower specimens and a small span across the clamping jaws, which is roughly comparable with a zero-span tensile test or by using necked or waisted samples as is commonly done in tensile testing of metals. The waisted sample technique was chosen mainly because of clamping difficulties associated with zero-span tensile testing, but waisted samples always fail at lower tensile loads than would be expected from the waist dimension, because of stress concentrations that occur along each edge of the waist because of the necking-in. The ratio of strength obtained to that expected from the minimum dimension across the waist is the form factor and it is always less than unity. Complete substance uniformity is required in the paper being used for the form factor determination, because any substance non-uniformities within the test area would introduce additional stress concentrations and thereby introduce a form factor of their own. Glassine proved to be the most uniform of the papers tested and was used for the form factor determinations. The ratio of breaking length obtained with a particular waist width to that obtained with the standard 15 mm tensile strip is the form factor for that waist width. The dimensions and form factors for samples with two different waist widths are given in Fig. 1; sample *A* has a $\frac{1}{8}$ in waist and form factor of 0.936, sample *B* has a $\frac{3}{16}$ in waist and form factor of 0.900.

Unless otherwise specified, only the $\frac{1}{8}$ in waisted samples have been used, in order to minimise substance non-uniformity effects that may enter with sheets having a poor formation. The waisted samples were positioned centrally between the jaws of the tensile test instrument, which were set to a span of 1 cm and the straining rate was adjusted to have the same time to failure as the standard test procedure requires.

The specific breaking length was obtained by dividing the breaking length of samples with a certain waist width by the form factor for that width. The

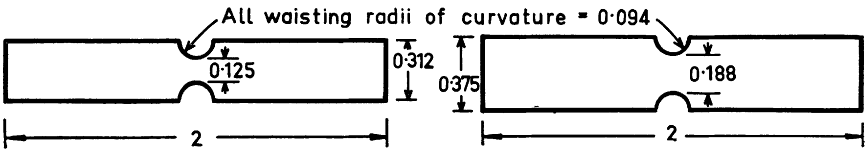

Fig. 1—Dimensions (inches) and form factors for waisted test specimens

specific breaking length or, more particularly, the deviation in specific breaking length from the standard handsheet value, is used subsequently as a measure of the forming consolidation of the sheet.

Tensile strength and breaking length

Both standard and specific breaking length measurements were made on handsheets formed in a British sheetmachine over a wide range of stock concentrations from liner stock, which consisted of a 70/30 mixture of softwood and eucalypt kraft pulps beaten to 450 CSF and 150 CSF, respectively. The results graphed in Fig. 2 show that in contrast to the standard breaking length, which falls quickly with increasing stock concentration, the specific breaking length is constant. This result is of considerable importance, since it shows that the average tensile strength throughout the area of a sheet is independent of the stock concentration from which it was formed.

That a twentyfold change instock dilution has had so little apparent influence on the microstructure of the sheet, as far as this may be inferred from the stability of the specific breaking length, is perhaps surprising. The implication is either that the microstructure of the sheet is determined before drainage commences and is independent of stock dilution or that the microstructure varies with stock dilution, but in such a way as to have no effect on sheet strength. At a particular stock concentration, the difference between the specific and the standard breaking lengths represents the strength loss that is due to formation alone. This loss is seen to exceed 40 per cent for sheets formed from stock at concentrations above 0.2 per cent. The advantages in forming a sheet from stock at high dilution would thus appear to be limited to the improved formation that results from the improved fibre dispersion.

A specific breaking length determination based on $\frac{3}{16}$ in waist specimens from handsheets made at standard dilution is also shown in Fig. 2 as an open circle. Within the limits of error, this value is in agreement with the value inferred from the use of the smaller waist. For stock concentrations of 0.12 per cent and above, the estimates from the use of the larger waist specimens fall below the values obtained from the smaller waist specimens. This shows that for these concentrations the substance non-uniformities are sufficient to enter the $\frac{3}{16}$ in waist failure zone. At a stock concentration of 0.3 per cent in sheets made entirely from long-fibred pulp, the substance or strength non-uniformities were sufficient to influence the results from the $\frac{1}{8}$ in waisted samples as could be inferred from the nature and position of the breaks. At standard handsheet concentrations, the line of the break was almost straight

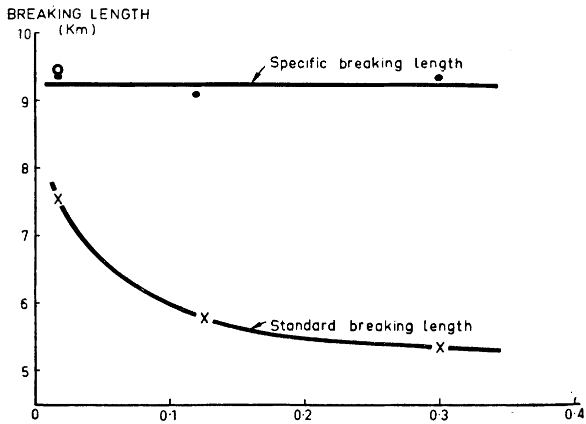

Fig. 2—Effect of forming stock concentration on the standard and specific breaking lengths

and across the narrowest part of the waist; at progressively increasing sheet forming concentrations, the failure line became more and more devious and moved away from the narrowest part of the waist. Since the sample in these latter cases had not failed at the narrowest part, the strength of this position was not given by the test value and the only conclusion to be drawn is that the specific breaking length had been underestimated at concentrations of 0.3 per cent and above by this type of measurement. It is probable that the choice of a specimen waist width smaller than $\frac{1}{8}$ in would give higher values for the specific breaking length at 0.3 per cent concentration, but smaller widths were not used because of possible complications caused by fibre length considerations.

It may be noted in Fig. 2 that at standard handsheet dilution the standard breaking length is approximately 20 per cent below the specific breaking length. This does not mean that weak spots occurring across the standard 15 mm test strips are, on the average, 20 per cent below the mean substance level. The presence of a low substance area anywhere across the standard test strip, but more particularly at its edge, is sufficient to cause stress concentrations that will produce a premature failure. As an extreme example, a cut or notch that reduces the standard test strip to 96 per cent of its original width, reduces the tensile strength to 40 per cent of the original value. Such a notch has a form factor less than 0.5. The same notch may be considered also to be an example of the substance being reduced to zero for 14 per cent of the width. Form factors thus arise whenever stress concentrations are produced. Stress concentrations are introduced by skewing or tilting the clamping jaws, by a change in shape as in notched or waisted specimens or by substance and strength non-uniformity across the width of the test sample. Consequently, the weakest links in the test strips are not necessarily located at the lowest substance positions, but at positions where the product of substance and form factor is a minimum. Moreover, the onset of failure causes a gross reduction in form factor, which may allow the fracture line to pass occasionally through high substance areas. It is possibly for these reasons that Tydeman and Hiron[4] were unable to show that the failure line in tensile tests always passed through the lowest substance route. In the circumstance of the nick or cut in particular—and to a lesser extent for all tensile test samples as well—the strength of the paper chain is *weaker* than might be expected from the substance of the weakest link. Thus, the 20 per cent difference between standard and specific tensile strengths or breaking lengths, for standard dilution handsheets, could be explained in terms of a lesser variability in small-scale substance level. This concept is supported by the scatter of test results for specific tensile strength, which is a direct measure of the small-scale strength and substance variability. The substance variability of the standard handsheets, which is inferred from the scatter of specific tensile strength test results, is able to account for only a small fraction of the difference between standard and specific breaking length test results. The standard tensile strength is therefore lower than the average tensile strength across the weakest part of the sheet.

Standard and specific breaking length measurements were then made on handsheets formed at various stock concentrations from softwood kraft, softwood bisulphite semi-chemical, eucalypt kraft and from 70/30 and 30/70 blends of softwood and eucalypt kraft pulps. Softwood and eucalypt pulps were beaten to freenesses of 450 and 85 CSF, respectively. Formation measurements were made on all sheets with a light transmission formation recorder,[5] which gives an indication of substance non-uniformity in terms of a formation number increasing with the root mean square variation in light transmission. A sheet of poorer formation had a higher formation number.

The ratio of standard to specific breaking length measurements on a particular sheet, when expressed as a percentage, is referred to as the breaking length retention. The loss in breaking length is thus the percentage by which the standard is below the specific breaking length. A sheet of complete substance uniformity has a breaking length retention of 100 per cent, reducing

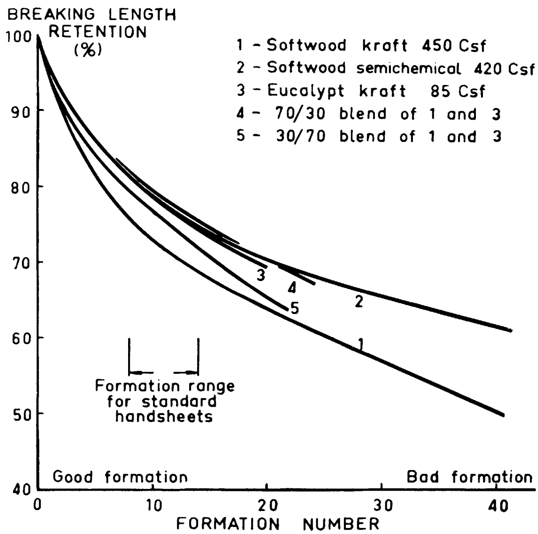

Fig. 3—Effect of formation of breaking length retention

progressively as the substance variability is increased. The breaking length retention of sheets made from various stock concentrations and pulp types is graphed against their respective formation numbers in Fig. 3.

The breaking length retention is seen to fall quickly with increasing formation number (increasing substance variability), the loss ranging 20–30 per cent for standard handsheets of eucalypt and softwood kraft pulps, respectively. Sheets formed at 0.3 per cent stock concentration from softwood pulps have higher formation numbers and lower breaking length retentions than those from the eucalypt kraft pulp. Curves 4 and 5 in Fig. 3, which represent the 70/30 and 30/70 respective blends of softwood and eucalypt krafts, appear to have exchanged positions and curve 5 (70 per cent eucalypt kraft content) moves closer to curve 1 (representing 100 per cent softwood kraft pulp). This effect could be produced by an unknown characteristic of the formation recorder or by a variation in the substance against strength relationship for blended pulps. This latter aspect raises the question of whether blended pulps behave as homogeneous or, to some extent, as heterogeneous suspensions.

That the breaking length retention in Fig. 3 falls quickly with increasing formation number indicates that breaking length retention is itself a sensitive measure of substance variability. In this regard, a very convenient and reproducible measure of formation is given by the tensile strength ratio of the standard 15 mm test strip to the $\frac{1}{8}$ in waist specimen. This ratio ranges from 5.0 for a very uniform material like glassine to 3.6 for a standard handsheet of softwood kraft pulp, becoming progressively smaller with deterioration in formation.

Burst, tear and stretch

The concept of basic sheet properties may be extended to include properties such as stretch and tear factor. The specific stretch, for example, would be the stretch obtained under conditions of complete substance uniformity. The use of very small test areas is not a practical method for evaluation of these test properties, but it is possible by a completely different approach to obtain an indication of the direction and extent to which they are affected by formation.

Any part of a sheet that has a higher substance can usually be shown to have a higher strength. A sheet having a cloudy or flocculated appearance may thus be considered to consist of a uniform strength base layer having random substance and strength reinforcement scattered over its area. The concept that disorderly strength reinforcement could, through the introduction of localised stress concentrations, produce a sheet that was actually weaker than the lower substance base sheet from which it was composed has already been shown to apply in the tensile strength test. Since it was not practicable to measure the burst, tear or stretch properties of the uniform base-layer part of a flocculated sheet, a special type of sheet was constructed from separate components. A sheet having random strength reinforcement over its area was assembled from a comparatively uniform strength base layer upon which was wet-pressed a random distribution of base-layer substance spots. The latter was prepared by punching $\frac{5}{16}$ in diameter holes, the centres of which were randomly distributed about a preferred spacing of $\frac{5}{8}$ in, in a thin plastic sheet, which was then placed over the wire of a British sheetmachine and sufficient stock at standard handsheet dilution used to produce 60 g/cm^2 substance spots in the open areas of the plastic sheet. A standard 60 g/cm^2 handsheet prepared immediately beforehand was then wet-pressed on to the spots and the combination couched from the handsheet wire and pressed and dried with other standard handsheets. The spots were used to obtain a known and reproducible pattern of substance and strength variability.

Both randomly reinforced and standard handsheets made from each of three pulps were tested for bursting, stretch, tensile and tearing strengths (Table 3).

TABLE 3—EFFECT OF SUBSTANCE NON-UNIFORMITY ON TEST STRENGTHS

Values listed are percentage changes away from standard handsheet values, given by the randomly reinforced sheets (+ is an increase)

Pulp	*Stretch*	*Tensile*	*Burst*	*Tear*	*Breaking length*	*Burst factor*	*Tear factor*
Eucalypt kraft	−30	−5	−15	+42	−28	−35	+8
Softwood kraft	−28	−5	0	+40	−28	−22	+9
Softwood semi-chemical	−28	−3	0	+48	−25	−25	+15

Note—Standard handsheet tensile strengths are already 22–28 per cent below the tensile strength of a sheet with complete substance uniformity—see Table 5

In forming the spots in the perforations of the plastic sheet, only the long-fibred pulps tended to bridge the land areas and a correction for this increase in weight has been applied to the tensile and bursting strengths, breaking lengths and burst factors. A most noticeable characteristic of the randomly reinforced sheets was the way in which the line of failure in both tensile and bursting strength tests avoided the high substance areas. In not one instance did the failure line pass through a high substance area, in contrast to the tearing strength test, for which the presence of such areas seemed to have no influence on the direction of the tear line.

It might be expected that a particular type and degree of substance non-uniformity such as that of the spotted sheets would cause similar changes to the physical properties regardless of the pulp type; this seems to hold for all properties, except bursting strength and burst factor. A possible reason for this discrepancy could be found in the level of substance variability already existing in the standard handsheets that were used as the uniform base layer. The substance variability in standard handsheets is greatest for the softwood pulps, as shown later in Table 5 by the strength losses from formation. The random strengthening provided by the substance spots on a sheet of varying substance tends on the one hand to strengthen the weak spots and on the other to weaken the sheet further by introducing stress concentrations. It should be noted, too, that the stress concentrations introduced by a $\frac{5}{16}$ in spot are not very great and should not produce as low a form factor as that caused by the smaller radius of curvature of the waisted samples in Fig. 1.

Formation was found also to be partly responsible for the well-known variation of breaking length with handsheet weight. The results in Fig. 2 show that specific breaking length is independent of the stock concentration at which standard weight handsheets are formed. Measurements on handsheets formed over a range of weights showed that, between 120 and 300 g/m^2, the specific breaking length was constant. Below 120 g/m^2, both the standard and the specific breaking lengths fell quickly with decreasing sheet weight, the loss in specific breaking length accounting almost entirely for the loss in standard breaking length. From 120 down to 15 g/m^2, where the loss of breaking length amounts to 50 per cent, all results can be corrected to the same breaking length as the heavier sheets, if it is assumed that one fibre layer contributes nothing to breaking length and the effective substance is calculated on the basis of the number of fibre layers minus one.

Interdependence of test properties

Another very interesting aspect of the results in Table 3 is that here again we have the seemingly inevitable reciprocal dependence of tear factor on burst factor, breaking length and stretch—an effect that is well known to papermakers and researchers alike.[6] Just why the tear factor should increase when substance is made variable is not clear, but the appearance of the reciprocal relationship for all three pulps in this experiment, in which substance non-uniformity is the only variable, suggests that its origin is the substance non-uniformity itself. Additional support for this suggestion is given by the similarity in pattern of change in these strength properties, regardless of the type

TABLE 4—EFFECT OF SUBSTANCE NON-UNIFORMITY ON PATTERN OF CHANGE IN TEST STRENGTH PROPERTIES

Values listed are percentage changes from standard handsheet figures for long-fibred kraft pulp—see Table 3 (+ is an increase)

Type of substance non-uniformity	*Stretch*	*Tear factor*	*Breaking length*	*Burst factor*
Flocs from forming at 0.12 per cent s/c	−21	+11	−18	−19
Standard handsheet plus laminated spots	−28	+9	−28	−22

of substance non-uniformities. The percentage changes in test properties from standard handsheet values are given in Table 4 for two softwood kraft handsheets of essentially different construction; one has been formed at 0.12 per cent stock concentration and has flocculated, the other has been formed at standard handsheet concentration, but has been provided with base layer substance spots randomly distributed over its surface.

Notwithstanding large differences in the type of substance non-uniformity in the two sheets, there is a considerable similarity in the pattern of changing test properties, which again implies that small-scale substance non-uniformity is responsible for the pattern of change, thus for the interdependence between these test properties. The pattern of change may be less clear with machine-made products, however, because of fibre orientation effects.

Forming consolidation

FORMING consolidation has been defined as all those aspects of sheet structure apart from small-scale substance variability and it is loosely interpreted to mean the forming density of the wet web. A high forming consolidation has therefore been defined as one that leads to a high specific breaking length in the dried sheet. When, as a result of a change in one of the forming variables such as stock dilution the standard breaking length is caused to change, it is impossible to develop a meaningful explanation for that change, unless the contributions from formation and from forming consolidation can be separated. The specific breaking length was found to be independent of forming stock concentration for the particular stock blend used to obtain the results shown in Fig. 2. This does not usually occur, however, and it is of interest to determine in what circumstances a variation in furnish or forming stock concentration can improve the forming consolidation and, thereby, the specific breaking length.

Effect of furnish and dilution

Measurements of both standard and specific breaking lengths were made on handsheets formed at various concentrations from softwood kraft, softwood bisulphite and eucalypt kraft pulps, separately and in combination. Whereas the specific breaking length was found to be independent of stock concentration for the particular furnish used in Fig. 2, it is apparent from the results shown in Fig. 4 that this is not the usual behaviour.

For sheets made from each pulp type used separately, the specific breaking length is seen to decrease with increasing stock concentration. Such a result is to be expected if added dilution acts not only to improve formation because of better fibre dispersion, but also to improve the forming consolidation because of better fibre packing. To show more clearly the effect of the variables on forming consolidation, the results have been rearranged in the following way. The specific breaking length values from standard handsheets of each stock used has been chosen as a reference point for that stock and has been assigned a forming consolidation value of 100 per cent. The reference thus represents the breaking length that a standard handsheet would have had in the event of complete substance uniformity. Specific breaking length measurements for each stock, expressed as a percentage of their own reference, are graphed as forming consolidation against sheetforming stock con-

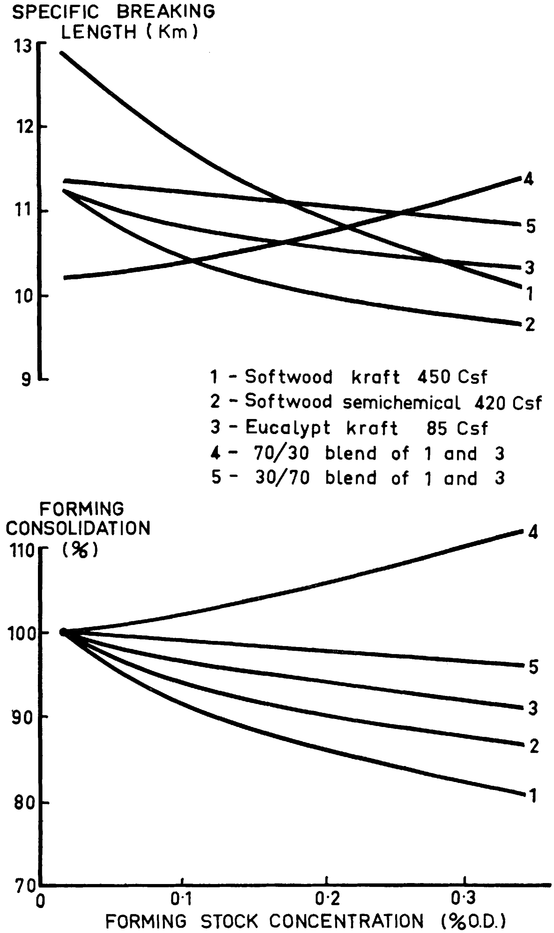

Fig. 4—Effect of forming stock concentration on specific breaking length and on forming consolidation

centration as well in Fig. 4. The deterioration in forming consolidation with increasing stock concentration is most marked for the softwood kraft and implies that this pulp has the least chance of fibre rearrangement in forming a sheet. Yet blended stocks in general—and the 70/30 blend of softwood and eucalypt krafts in particular—do not exhibit the same behaviour and the forming consolidation of the 70/30 blend increases with forming stock concentration up to the maximum value used. The specific breaking length and forming consolidation values for this blend at standard handsheet dilution are lower than would be expected from the blend proportions of the parent pulp properties, but the values at 0.3 per cent stock concentration are higher than would be expected and even exceed the strength of the parent softwood

TABLE 5—LOSSES IN BREAKING LENGTH FROM FORMATION AND FROM FORMING CONSOLIDATION

(*Specific breaking length at 0.017 per cent s/c is reference for each pulp*)

Forming concentration (oven-dry), per cent	*Stock*	*1 Softwood kraft*	*2 Softwood semi-chemical*	*3 Eucalypt kraft*	*4 70/30 blend of 1 & 3*	*5 30/70 blend of 1 & 3*
0.017	Formation number	11	15	12	12 (11)	9 (12)
	Percentage losses from—					
	(*a*) Formation	28	27	22	23 (26)	22 (24)
	(*b*) Forming consolidation	....	Reference .	....	....	....
0.12	Formation number	26	26	15	22 (22)	16 (18)
	Percentage losses from—					
	(*a*) Formation	40	32	23	32 (35)	31 (28)
	(*b*) Forming consolidation	10	9	4	3 gain	0
0.30	Formation number	40	42	19	26 (34)	24 (25)
	Percentage losses from—					
	(*a*) Formation	50	40	32	47 (45)	39 (37)
	(*b*) Forming consolidation	20	13	8	10 gain	3

Note—Values in brackets calculated from blend proportion of parent stock

kraft. A possible implication from this result is that the eucalypt kraft fibres, being shorter, maintain a higher mobility within the matrix of the forming web.

It is possible now to separate the losses in standard breaking length into two components—the loss from formation and the loss or gain from forming consolidation. For a given stock and sheetforming concentration, the percentage loss from formation is the percentage by which the standard is below the specific breaking length. The percentage loss or gain from forming consolidation is the percentage by which the specific breaking length of sheets formed at a given stock concentration is respectively below or above the specific breaking length of sheets formed from the same stock at standard handsheet dilution. These percentage losses in breaking length are given in Table 5 for the various pulp types and blends and for different sheetforming stock concentrations.

The percentage losses in breaking length from formation can be calculated with reasonable accuracy for the blended stock handsheets as the sum of the blend proportions of parent stock losses. These figures, together with formation number estimates calculated in a similar way, are bracketed in Table 5. The actual formation number for the 70/30 blend at 0.3 per cent stock concentration appears to be significantly below and therefore to have a better formation than would be expected from the estimate. The heavy losses suffered by the softwood kraft pulp at high stock concentrations, owing to deficiencies in both formation and forming consolidation, serve to highlight the difficulties in realising the very high strength potentials of these pulps.

Effect of shear gradients

Some effects of shear gradients on sheet properties are reported in a later section *Machine trials*. In laboratory experiments with the British sheetmachine, a particular type and level of shear gradient was found to improve forming consolidation or specific breaking length for pulp blends, but had little effect when each of the three different pulp types was used separately. This may be because shear gradients have no effects on the forming consolidation of unblended pulps or because the level and type of shear gradients used was not appropriate. In another laboratory experiment described in the appendix, however, in which shear gradients were applied to a stock blend deposited at 0.12 per cent stock concentration by a moving flow box, the sheet produced had properties comparable with the standard handsheet. This result shows that shear gradients become of considerably greater importance at the higher stock concentrations and is presumably the reason for the development of flow boxes with high turbulence levels in the slice jet, such as that reported by Gustafson and Parker.[8]

Likewise, an improved mill to laboratory ratio for breaking lengths was found to occur at either higher dilutions or higher speeds in machine trials. This is described more fully in a later section: the improvement was found in both instances to be due primarily to increased forming consolidation. The machine stock used was a 70/30 blend of softwood and eucalypt kraft pulps.

Effect of forming variables on sheet properties

An experiment in which the effects of forming variables on sheet properties were investigated is described in detail in the appendix: the main results are summarised below.

Wire mesh

Changing from a 150 × 150 mesh handsheet wire to a 44 × 60 mesh Fourdrinier wire has a significant effect on strength properties either for conditions of fast initial drainage or for a well-beaten eucalypt kraft pulp. When both conditions exist simultaneously, losses of 20–25 per cent occurred in bursting strength, breaking length and stretch, together with a loss of 50 per cent in air resistance—which indicates that high drainage rates produce a fines-depleted sheet structure.

Drainage time or rate

Drainage rates were maintained at approximately constant values throughout the drainage cycle. Shortest drainage time for a 2 in stock depth was approximately $\frac{1}{3}$ sec, which corresponds with a machine speed in excess of 4 000 ft/min for a 25 ft forming table. Although this average drainage rate is considerably above the average rate on production machines, it is not improbable that the initial drainage rate on some commercial machines would exceed the average rate used in these experiments. At drainage rates in excess of 7 in/sec, great difficulty was experienced in couching the wet web from the Fourdrinier wire because of the manner in which the fibres project down through the openings in the wire.

The change from low to high drainage time had no significant effect on the physical properties of the sheet made from the long-fibred kraft. A possible explanation of this result may be found in terms of fibre length and fibre flexibility. The longer fibres will more readily bridge the openings in the wire mesh and quickly establish a fibrous filter bed on the wire. In addition, the flexible nature of the kraft fibres will impart a high compressibility to the forming mat. A high drainage rate thus causes a compression and closing up of the forming mat and so allows a greater retention of shorter fibre fractions. This action would be inevitable with increasing drainage rate and should cause a longer drainage time for kraft pulp than for semi-chemical pulps under fast drainage conditions. Such a trend can be seen in Table 7 of the appendix: as drainage rate increases, the long-fibred kraft stock takes progressively longer to drain than the semi-chemical pulp, even though it drained in a shorter time on the British sheetmachine.

The very considerable losses in strength properties accompanying the use of the higher initial drainage rates with short-fibred pulps on the relatively open Fourdrinier wire were mentioned earlier. From an examination of the drainage times for eucalypt kraft pulp in Table 7, it is evident that it is the initial drainage rate that causes the strength losses rather than the average rate.

Significant strength losses occur also at the higher drainage rates for the semi-chemical pulp, which remains more open during the drainage cycle because of the greater fibre rigidity. The greater rigidity and lower compressibility of the semi-chemical fibres is reflected in the ratios of drainage times (Table 7). The necessity to prevent very high drainage rates on a bare wire, which is possibly the only place where they can occur, is a well-recognised Fourdrinier requirement and is met by restricting or preventing breast roll drainage when the rate would be excessive, also by using plain or slotted forming boards to reduce slice jet impact drainage.

Dilution

The variation in stock concentration over the range 0.017–0.12 per cent has sweeping effects on sheet properties. This change in stock concentration produces important decreases in bursting and tensile strengths, stretch, air resistance—and the expected increase in tearing strength.

The influence of dilution on sheet properties found in this investigation is not directly applicable to commercial papermaking machines for two reasons. Firstly, the top end of the stock concentration range investigated barely reaches the lower end of the range used on commercial machines and, secondly, all commercial sheets are formed with shear gradients present in the stock, which have a pronounced effect on sheet properties through the intermediaries of formation and forming consolidation. Some idea of the trend that the physical properties will follow, provided shear gradients are slight, can be gained from the tensile strength/forming consistency graph (Fig. 11). This clearly shows the extent of the change in tensile strength over the consistency range of interest. Because of the interdependence between the physical properties noted earlier, one would expect comparable changes in burst, stretch and air resistance in the same direction as for tensile strength and perhaps a lesser change in the opposite direction for tearing strength.

Shear gradients

The importance of shear gradients in sheetforming cannot be overstressed. The improvement in strength recovery with shear gradients present is most marked at the higher consistencies as shown by the experiment with a travelling flow box, but it is still of importance even at standard handsheet dilutions. The appropriate type and level of shear gradients improve both formation and forming consolidation and, in the former respect, have effects similar to dilution on sheet structure. Shear gradients might to some extent be considered to be interchangeable with dilution, except that a sustained undirectional shear gradient leads to strong fibre orientation effects and to fibre fractionation effects, too, as occurs in vat machines.

Machine trials

THE RESULTS of laboratory experiments (described in the appendix) show that high strength recoveries could be achieved in the laboratory either at high dilution as used for standard handsheets or at lower dilutions, provided shear gradients were present over the forming zone. On the Fourdrinier machine, shear gradients in the zone of formation can be produced by the flow box or by the wire section. The flow box perforated roll at the slice position produces turbulence within the slice jet; the speed differential between the slice jet and the moving wire is an important source of shear gradients during the early part of sheet formation. On the wire, shear gradients are produced by the wire shake mechanism, by the table roll suction that causes considerable disturbances in the stock on the wire, by whitewater re-entering the table roll nips, even by the dandy roll riding on the nearly formed wet web.

Following on the handsheet experiments, methods of implementing the findings on a Fourdrinier machine were considered. Since various types of shear gradient are already present, a trial was held in which efforts were concentrated on increasing flow box dilution. Whenever dilution is increased on a Fourdrinier machine, the dry line moves progressively towards the couch. A greater proportion of the sheet is then drained over the vacuum boxes, where different shear gradient conditions are present and any improvement from the increased dilution could be offset by the change in shear. Therefore, it is necessary to increase the drainage capacity of the forming table by other means than the application of more vacuum to the existing boxes or by adding more vacuum boxes.

The drainage time for a given quantity of stock was determined at various heads. To a first approximation, the drainage time (T) is proportional to the inverse square root of the head (H)—that is, $T\sqrt{H}=$constant—in which the root head relationship does not necessarily imply that the flow is turbulent. This relationship shows that the water removal most efficient in power is obtained by using as low a head as practicable to maintain water flow; it shows also that the drainage capacity of the wet end should be increased by a redistribution of vacuum over the forming length rather than by extending the wire. As a test of the distributed vacuum hypothesis on drainage capacity and as a test of the effect of increasing dilution on machine-made paper properties, trials were carried out on a 201 in Fourdrinier machine having a wire length of 100 ft.

A 15 ft section of the forming table adjacent to the main suction boxes was boxed in around the table rolls and 3–4 in water gauge of fan-produced vacuum was applied over this area. The test was made on linerboard grades, since the machine was always at its drainage limit on such high substance and, in this case, comparatively low freeness stock. The wet end configuration from the slice was table rolls for the first 12 ft, table rolls and a vacuum of 3–4 in wg for the next 15 ft, followed by eight vacuum boxes.

Trial results

Tests were carried out both with and without vacuum on the boxed in section (which is termed a fan-box to distinguish it clearly from the standard vacuum boxes) over a range of stock concentrations extending down when the fan-box was operating to nearly half the standard concentration. The

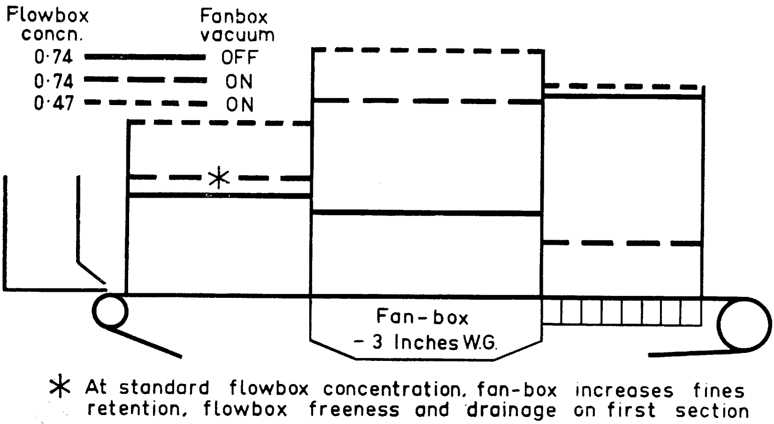

Fig. 5—Drainage increase and redistribution with fan-box

machine was making a 42 lb/1 000 ft^2 kraft linerboard from a 70/30 mixture of long-fibred and eucalypt kraft pulps prepared to freenesses of 500 and 150 CSF, respectively. Flow box freeness varied 310–450 CSF, reaching the higher levels when vacuum was on the fan-box, which demonstrates the improved fines retention of the sheet formed. The application of higher dilution and the distributed vacuum concept led to the following changes—

1. Increased drainage capacity and redistribution of drainage. With 3 in wg applied to the fan-box, the flow box stock concentration had to be reduced from 0.75 to 0.47 per cent so that the solids content of the sheet entering the main vacuum boxes could reach the original value. Drainage volumes through the various sections of the wire are shown diagrammatically as areas in Fig. 5.

In these trials, the total drainage obtained with the fan-box operating proved to be equivalent to that from a wire length of at least 190 ft. Solids content of the sheet leaving the couch and presses remained unchanged as flow box dilution was varied over a 2:1 range, and indicates that these units were operating under equilibrium conditions. The drainage resistance of the wet web was found also to be higher with fan-box operating. This is believed to be due to the higher fines retention in the wire side of the sheet.

2. *Strength properties of the sheet.* The increase in flow box dilution (shown as a long-dash broken line in Fig. 5) resulted in the changes in strength properties listed in Table 6.

TABLE 6—EFFECT OF INCREASED DILUTION ON FOURDRINIER SHEET PROPERTIES

Product is 42 lb/1 000 in² kraft linerboard (+ is an increase)

Property	*Breaking length*		*Burst factor*	*Tear factor*		*Toughness (T.E.A.)*		*Stretch*		*Ring crush*		*Density*
	MD	CD		MD	CD	MD	CD	MD	CD	MD	CD	
Change, per cent	+11	+12	+23	+10	+14	+23	+31	+10	+14	0	0	+3

3. *Speed and dilution effects.* At a constant speed, the ratio of mill to laboratory bursting strength varied with dilution as shown in Fig. 6, with no evidence of a maximum having been passed in the dilution range covered in the trial. The variation of mill to laboratory ratio with speed at a constant dilution of 130 (0.75 per cent consistency) is shown also in Fig. 6.

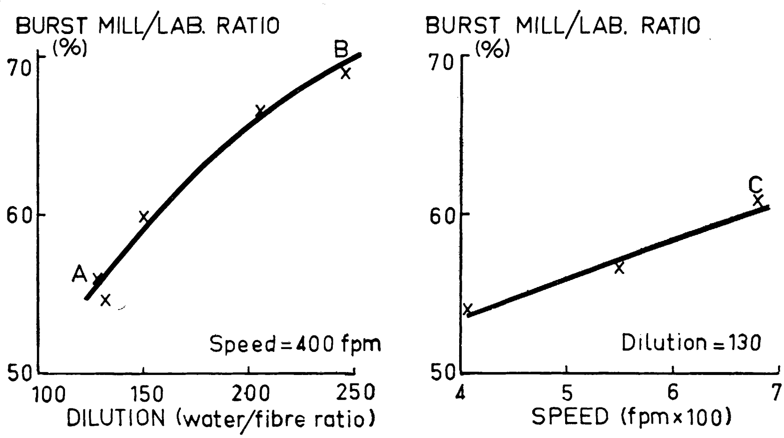

Fig. 6—Effect of dilution and speed on mill/laboratory burst ratio

The formation numbers of both high speed and high dilution samples, which are shown as points *C* and *B* respectively on the curves in Fig. 6, were equal and below that of the control shown as point *A*, meaning that they were more uniform in substance. In the dilution trial, for which flow box stock concentration was reduced from 0.74 to 0.47 per cent, the breaking length was found to increase by 12 per cent, a change that is greater than would have been expected from the handsheet dilution results shown in Fig. 4 and 11. From measurements on waisted samples, it was found that three quarters of the 12 per cent improvement in standard breaking length result was due to an increase in specific breaking length, thus forming consolidation. This finding is consistent with the increases in sheet density and stretch recorded in Table 6 and shows that the improved formation has produced only a minor improvement in breaking length.

It is presumed that the improved forming consolidation was produced either by the increased shear gradients existing in the stock fed to the forming zone or by the increased stock disturbances on the wire—both of which increase inevitably with increasing dilution. Alternatively, it could have been produced by the continuous drainage characteristic of the fan-box, which was known from other work to improve the fines retention of the sheet. The view that shear gradients are responsible for some of the improvement is in accord with the explanation offered by Gustafson & Parker(7) that the probable reason for the strength losses found by Wrist(8) to occur when Fourdrinier table rolls were replaced by suction boxes was due to the loss of shear gradients previously induced by the table rolls.

Conclusion

THE MICROSTRUCTURE or forming consolidation achieved in a sheet of paper establishes an upper limit of strength that is realised only by a sheet having perfect substance uniformity. How closely this limit is approached in practice depends entirely upon the small-scale substance variability. Substance variability is detrimental to strength development for two reasons. Firstly, the areas of low substance constitute definite weak spots that have lower than average strength. Secondly, substance variability introduces stress concentrations that cause a serious additional weakening everywhere; in consequence, the failure load is considerably lower than the average strength of the weak spot.

Forming consolidation can be increased with blended pulps by the use of suitable shear gradients and higher forming concentrations; but, for each pulp type used individually, better results are achieved by forming the sheet from stock at higher dilutions. In the stock concentration range appropriate to Fourdrinier machine operation, stock blends of long and short fibred pulps are found to have a higher forming consolidation and a higher strength than either component used separately.

Although a small gain in tear factor accompanies an increase in small-scale substance variability, this gain would appear to be heavily outweighed by the losses that occur in stretch, in breaking length and in burst factor. Since in these latter tests—ultimately, in field performance, too—small to large areas of paper are probed by the applied loads for a single weak spot, the strength of the whole assemblage is no greater than that of the weakest part and the strength of the weakest part is lower than would be inferred from the substance of the lightest part. The results therefore show that, for papers with a strength requirement, the attainment of a high degree of substance uniformity should be the principal structural objective.

Acknowledgement

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Appendix—Effects of forming variables on sheet properties

THERE ARE many factors that can be varied in making handsheets. To obtain some idea of the effectiveness and interdependence of the various factors affecting formation and strength, a statistically designed experiment was carried out with the following variables—

1. Type of stock.
2. Freeness of stock.
3. Sheetforming dilution.
4. Drainage time and characteristic.
5. Type of wire.

Shear gradients were excluded, because of the difficulty in simulating anything approaching machine conditions on the handsheet wire, but they are treated separately later. To minimise the number of possible combinations, three different pulp types were chosen and Valley beaten to freeness levels commonly used in the mill for these pulps. Unbleached Ljusnan long-fibred kraft, unbleached *Eucalyptus regnans* kraft and *Pinus radiata* bisulphite semi-chemical pulps were used at freenesses of 450, 100 and 450 CSF, respectively. Formalin was added at the rate of 2 ml/litre of 2 per cent stock and the stock stored at low temperature to control freeness drift. Twelve sets of sheets were made from each pulp, with ten sheets in each set. The twelve sets were made in random order in two rounds, five sheets of each set being made in each round.

Experimental

A British sheetmachine was used to make the standard handsheets. Another sheetmachine was connected to an 18 gal reservoir through a $2\frac{1}{2}$ in quick-opening valve. The reservoir could be evacuated down to 25 in mercury by means of two water jet pumps connected to the main water supply and the vacuum level was indicated by a gauge.

If drainage of the fibre suspension is carried out with a constant drainage pressure across the forming web and wire, the drainage rate starts at a very high value and falls quickly with time; when drainage takes place at a constant rate, drainage pressure across the forming web starts at a very low value and quickly builds up as the web forms. Handsheets formed by constant drainage pressure were found to be extremely difficult to couch from the wire. Even with pressure differentials as low as 5 in mercury, the web was very effectively anchored to the Fourdrinier mesh wire by the fibres projecting down through the wire openings. This effect is presumed to be caused by the high initial flow rates associated with constant pressure drainage, since it becomes more serious either with increasing pressure or with the more open wire.

A constant drainage rate technique was employed, because the main objective was to vary the total drainage time rather than to reproduce the drainage cycle of the Fourdrinier machine. This was accomplished by inserting orifice plates between the vacuum reservoir and the wire, as well as by operating the reservoir at a high vacuum to minimise the vacuum loss as whitewater displaced air from the reservoir. The vacuum head was kept at 20 in mercury and an additional vacuum reservoir was fitted to reduce this displacement effect. Intermediate and fast drainage rates were obtained by using $\frac{5}{8}$ in and 1 in diameter orifice plates, respectively. With this arrangement, a relatively even drainage rate was secured throughout the drainage cycle, provided the pressure drop across the forming mat was always small compared with the reservoir vacuum. It should be noted that the drainage rate on a handsheet machine is stabilised to a large extent also by a flow-restricting discharge line. As a test procedure, handsheets were made both on the standard and on the modified handsheet machines, with vacuum on the latter reduced to give the same drainage time as the former. Since both lots of handsheets were found to have identical properties, any variation in properties accompanying shorter drainage times on the modified machine must be due to those shorter drainage times.

Furnish, dilution, wire mesh and drainage rate

All handsheets were made to 60 g/m². The stock concentrations used were the standard 0.017 per cent (7 litres) and 0.12 per cent (1 litre). The latter was the highest concentration that could be agitated and stilled satisfactorily in the sheet-machine and is just below the range of Fourdrinier machine operation. Two different wire meshes were used: one was a 150 × 150 as used on handsheet machines and the other was a 44 × 60 mesh Fourdrinier wire. Drainage times to the appearance of the 'dry line' for the 7 litre dilutions are given in Table 7. When only 1 litre was used, the drainage times were roughly one seventh of the times required at standard dilution.

TABLE 7—DRAINAGE TIMES IN SECONDS FOR 7 LITRES OF STOCK (14 in DEPTH)

Furnish	*British sheetmachine wire*		*Modified sheetmachine*			
			Slow drainage		*Fast drainage*	
	Hand-sheet	*Fourdrinier*	*Hand-sheet*	*Fourdrinier*	*Hand-sheet*	*Fourdrinier*
Softwood semi-chemical	5.8	5.7	3.8	3.9	2.0	1.9
Eucalypt kraft	12.8	12.8	7.0	6.8	6.2	5.3
Softwood kraft	5.6	5.5	4.1	4.1	2.5	2.4

The highest drainage rate was chosen to approximate to a 2 sec drainage time to dry line. Since this rate would be equivalent to draining a 14 in stock depth on a 50 ft forming table at 1 500 ft/min, it must be regarded as representative of a very high average drainage rate. The intermediate drainage rate is between the high rate and that of the standard sheetmachine. Since the same orifice size was used regardless of pulp type and freeness, the fast (2 sec) drainage time is only nominal. For the well-beaten eucalypt kraft pulp, very little change in the drainage time accompanies the increased orifice size, which shows that a pressure difference of nearly 20 in of mercury must exist across the wet web for a considerable part of the drainage cycle, even with the smaller orifice in place. Because of this effect with the eucalypt pulp, it should be noted that the slow and fast drainages apply to the initial drainage rates only for this pulp. The pattern of reducing drainage times for the semi-chemical pulp in Table 7 shows that this is the least compressible of the three pulps and that its forming web remains more open throughout the drainage cycle than do the others.

Standard tests were made on each set of handsheets for tear factor, burst factor, breaking length, stretch, bulk and air resistance. For each of the three different pulps, handsheets were prepared at three different drainage rates, two different wire meshes and two different dilutions. The key to the test results is given in Fig. 7 and the test results for softwood bisulphite semi-chemical, for unbleached eucalypt kraft and for unbleached softwood kraft pulps are presented as three-dimensional charts in Fig. 8–10, respectively. The main points from the results in these charts are summarised in Table 8. The least significant difference (at 95 per cent level of significance) between 2 of the 12 data is about 0.7 (approximately 8 per cent), although this figure would be reduced further when averaging over two or more sets of data, also when the interdependence of the physical properties is taken into account.

TABLE 8—SUMMARY OF EFFECTS OF FORMING VARIABLES ON PHYSICAL PROPERTIES

Figures are percentage changes, averaged over all other forming variations

Pulp type	*Change in forming method*	*Burst factor*	*Breaking length*	*Tear factor*	*Stretch*	*Air resistance*
Softwood semi-chemical	Low drainage rate + low dilution	−3	−6	+7	0	−6
	Medium to high drainage rate + low dilution	−12	−18	+11	−26	−22
Eucalypt kraft	Low diluton	−8	−9	+5	−14	−18
	High drainage rate + open wire + low dilution	−21	−23	+7	−24	−49
Softwood kraft	Low dilution	−19	−18	+11	−21	−20

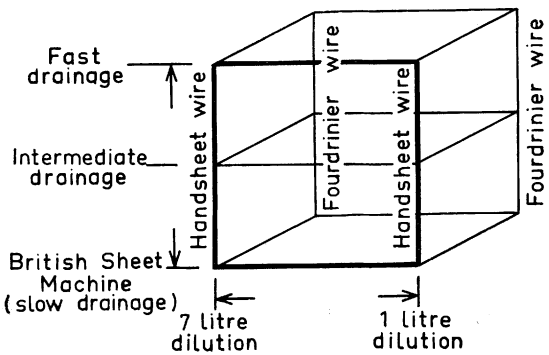

Fig. 7—Key to test results in Fig. 8–10

Effect of extended dilution range on strength properties

The major changes in physical properties of handsheets have been found in the preceding experiments to be caused by the increase in stock concentration from 0.017 to 0.12 per cent. As a guide to the direction and extent of the changes in physical properties that would occur at concentrations closer to those used on Fourdrinier machines, breaking length measurements were made on handsheets

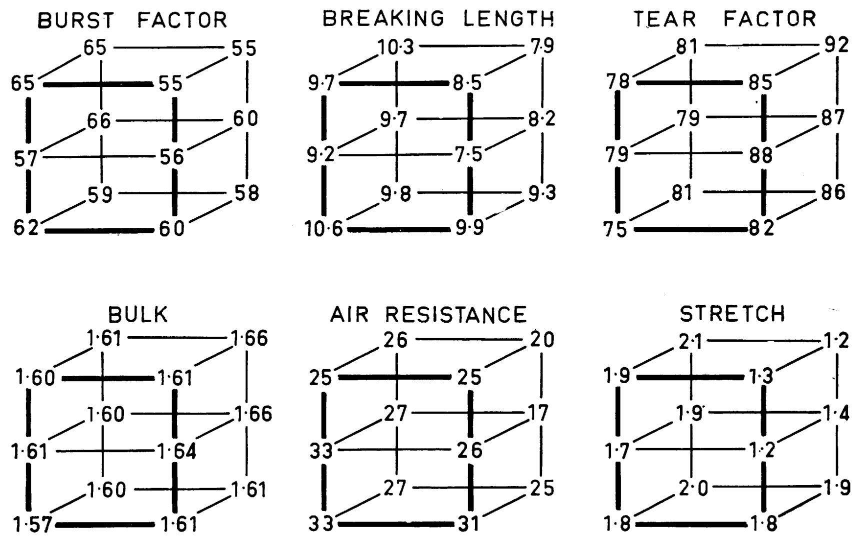

Fig. 8—Test results for softwood semi-chemical pulp

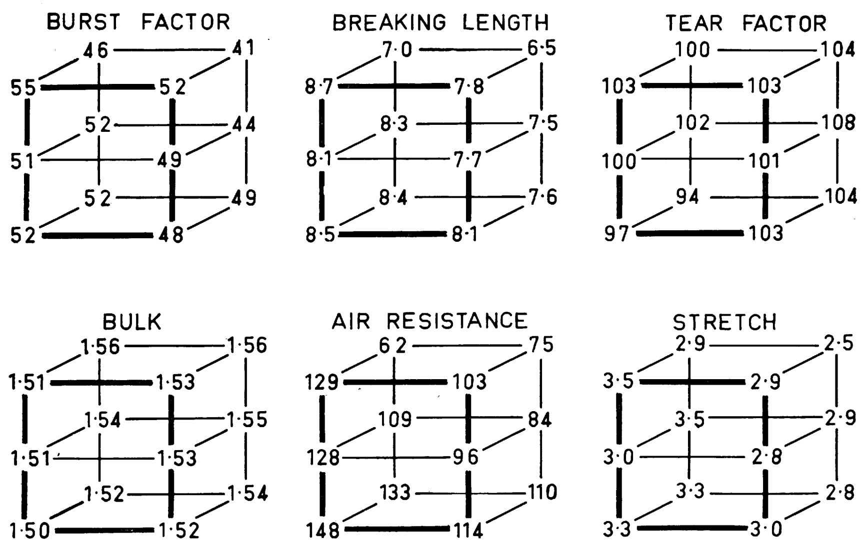

Fig. 9—Test results for eucalypt kraft pulp

formed from stock at concentrations up to 0.70 per cent. The results for the three different pulp types are graphed in Fig. 11.

Rough predictions of the changes in the other strength properties can be made on the basis of the change in breaking lengths over the extended dilution range and the interdependence between test properties shown in Fig. 3, 4, 8–10. In Fig. 11, softwood kraft pulp has the greatest loss in breaking length over the stock concentration range 0.12–0.70 per cent, softwood semi-chemical pulp has a smaller loss and the well-beaten eucalypt kraft pulp has the smallest loss of the three

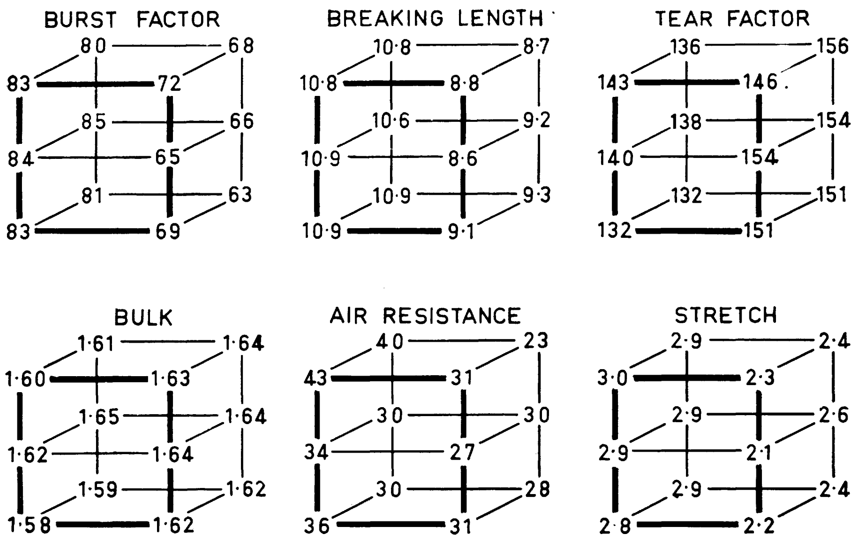

Fig. 10—Test results for softwood kraft pulp

pulps. Consequently, the losses in burst factor over the extended range are expected to be similar to or perhaps a little greater than the respective losses in breaking length found for the three pulps. Losses in stretch are expected to be in the same proportions, but lower than the respective breaking length losses, whereas small increases in tear factor are expected. It should be noted, however, that the reciprocal dependence of tear factor on breaking length and burst factor is not infallible and an example occurs in Table 6 for which all three properties have moved in the same direction.

Shear gradients

Handsheets formed from the same concentration of stock as is used in the flow box usually have inferior formation to that of the normal Fourdrinier sheet. This could occur because the fibre suspension is delivered to the forming zone in a better dispersed condition, for shear gradients present on a Fourdrinier wire cause dispersion of fibres while formation is in progress—or for both reasons. To test the effects of shear gradients on sheet properties, handsheets from the three pulps were prepared in the standard way, except for the presence of shear gradients. These were produced over the forming zone by rotating a paddle back and forth at a height of 4 in above the wire. The sheets were tested for formation and for both standard and specific breaking lengths. The effect of the particular type and level of shear gradient used was to improve the formation and standard breaking length of sheets made entirely from long-fibred kraft or semi-chemical pulps, but there was no improvement in the specific breaking length. The effect on sheets made

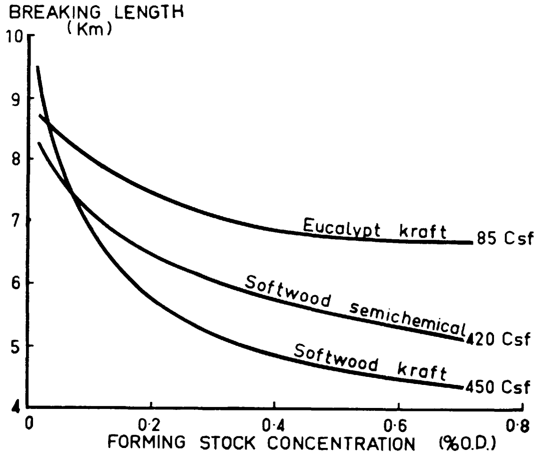

Fig. 11—Effect of forming stock concentration on breaking length

entirely from eucalypt was to cause a slight deterioration in formation, a slight improvement in specific breaking length and no change in standard breaking length.

The results were quite different, however, for sheets made from blended pulps in general and from a 70/30 blend of softwood and eucalypt kraft pulps in particular. Here, the use of similar shear gradients caused a slight loss of formation, but a 10 per cent increase in both standard and specific breaking lengths and a 19 per cent increase in burst factor. Sheet density was slightly higher than standard, a change that is consistent with the conception that an increase in sheet density will increase the forming consolidation, thus the specific breaking length. The precise nature of the changes in sheet structure that have occurred as a result of the presence of shear gradients is, of course, not known.

In some circumstances, the shear gradients have improved formation, in others they have improved the forming consolidation and, to this extent, they produce effects that approach those produced by an increase in dilution. To test the extent to which shear gradients could be substituted for dilution, a sheetforming device was constructed in which a travelling flow box moved across a stationary wire part supplied with adjustable vacuum on its underside. Shake, of adjustable amplitude and frequency, could be applied to the wire part in order to obtain the required level of shear gradients. Preliminary experiments with this new sheetmachine have shown that sheets formed from a 70/30 stock blend at a consistency of 0.13 per cent, with shake applied throughout the drainage cycle, had bursting and tensile strengths comparable with those of standard handsheets formed from 0.017 per cent stock. Although the resulting sheets did not have as uniform formation as the standard handsheet, they were considerably better than those produced without shake. In the present experiments, the investigation of effects produced by shear gradients has been very superficial; nevertheless, it has shown that significant gains in sheet properties can be secured from the application of these gradients over the forming zone.

An important side effect, in the drainage of some stocks with shear gradients present, is the increase in drainage resistance. It would appear that all those factors that tend to increase the forming consolidation such as dilution, shear gradients and, of course, beating also tend to increase the drainage resistance. A convincing demonstration of this effect can be obtained by gently swirling the stock in a sheetmachine. Drainage times of 10 sec or so with an unswirled sheet can easily be doubled and, in some cases, trebled by swirling the stock while drainage proceeds.

Discussion

Mr B. Radvan—How is the forming consolidation derived? If I understood correctly, what happens is that, if one measures the breaking length against increasing consistency, the conventional breaking length decreases; but, if an allowance is made by using a notched specimen, then the breaking length remains constant and can be derived as a specific breaking length. This is not always so and, when not, this departure is called forming consolidation. Is it not possible that this departure arises simply from the fact that, for example, different form factors apply to flocculated sheets or something similar? Is there any independent information that consolidation takes place, for instance, from measurements of density?

Dr R. J. Norman—Yes, there are in fact small but significant density changes, which reflect that there has been a change in the consolidation of the sheet.

Dr O. J. Kallmes—Could you enlarge on how you reinforce sheets? I find it difficult to believe that to add more substance, the sheet becomes weaker. How did you characterise the structure of these sheets? Are you sure you have a lower degree of bonding in these sheets than those you started with?

Dr Norman—Spotted handsheets were constructed, firstly by making a standard handsheet and couching this from the machine. Then, after inserting a thin perforated plastic sheet over the wire and forming substance spots that had the standard substance, these were wet couched on to the first sheet. Thereafter, the spotted sheet received the same treatment as the standard handsheets, also the same treatment as a sheet formed at perhaps 0.12 per cent consistency and that was a flocculated sheet. It is clear that the type of substance variability present is very different in the spotted handsheet from that in the sheet formed at high consistency. Yet the similar pattern of change in test properties suggests that the substance variation alone has been the major factor.

Dr Kallmes—Would you say that, in wet pressing the sheet, the spots were under greater pressure than the thinner remainder of the sheet? Therefore, the thin parts of the reinforced sheet might be weaker than a sheet with the thickness of the thinner parts over its entire area.

Dr Norman—We attempted to clarify this point, firstly, by using the standard pressing technique, then using a greater number of blotters so that there would be a greater cushioning effect and a more uniform pressure. We found this made no difference to the results. In any case, the differential pressing would have taken place equally as much on the flocculated handsheet as it does on the spotted sheet.

Mr P. A. Tydeman—Firstly, to comment on Kallmes' points, I think the real significance of Norman's work on the effects of substance spots is that it emphasises the importance that formation has upon paper properties. To what extent the spots are bonded and of precise simulation is not of great relevance. Was the specific breaking length calculated by using the substance in the waist itself or the average substance of the paper?

Dr Norman—The specific breaking length is calculated from the average substance. The use of a constant value for the substance is the main reason for the wide scatter in test results.

Mr Tydeman—Presumably, the individual values of specific breaking length vary according to the amount of material in the waist. If you happen to have selected a waist with a high amount of material in it, it is going to be somewhat stronger. Is there a distribution of values and can any information be derived by comparison with the distribution of conventional breaking length?

Dr Norman—Yes, there is quite a wide distribution of specific breaking length values. As one might expect, the breaking load values are spread over the entire range of strength and substance variations within the sheet for this type of test, but the scatter of values that one has with the standard breaking length is very much less, since they represent a scatter about the weaknesses in the sheet.

Dr J. A. Van den Akker—Have you attempted to rationalise your results with regard to the shortness of span and flocculation by means of the Peirce*

* Peirce, F. T., *J. Textile Inst.*, 1926, **17**, T 355–T 368

weak-link theory? I believe this theory generally accounts for the dependence of the tensile strength of paper on the variance of the material.

Mr G. F. Underhay—Firstly, my immediate reaction to Norman's very interesting presentation was to be a little worried by the straight line obtained by using the waist-line method of testing. On reflection, however, one realises that the marked difference between the straight line and the dropping curve as the consistency goes up is one that has revealed the inadequacy of our testing and not one that discounts the desirability of dilution.

I am reminded that under the direction of Arthur Baker (whom we are delighted to see here), the original sheetmachine grew in height from 8 in to about 16 in entirely from such experimentation to find out how much better sheet uniformity can be by diluting the stock to the standardised consistency of 0.017 per cent.

My second comment concerns some information that Wrist gave us on a slide (I think, in Oxford), the implications of which I regarded as rather shattering. He showed that, if fibres could be distributed in a completely random manner, as calculated by statistical methods, the look-through of the sheet would be extremely disappointing.

To ask an omnibus question, how far are we getting in this symposium in finding out (if, indeed, a statistical distribution fails to give a good sheet of paper) how to produce a good sheet of paper? We have been talking a great deal about factors that affect uniformity of dispersion: even if we achieve an ideal distribution of fibres in paper, according to the statistical information of four years ago, we end up with a sheet that still has a poor look-through.

My last point is that, at the British Association meeting only a fortnight ago here, in Cambridge, Sir Cyril Hinshelwood, in his presidential address, emphasised the great importance of fundamental research. He also brought in the old story of the lack (in this country, at any rate) of nearly enough technological application of fundamental research. Here, I suggest, is an urgent need for us to combine this work on dispersion with the practical objective of producing much improved sheet formation. Personally, I do not yet know how to do it.

Dr N. Hartler—During the discussion, our chairman brought up the question of the relationship between stiffness and nodes. Some fundamental facts are known and I would like to call your attention to them. From Fig. B, we can discuss the fibre stiffness (as measured by bending) and the quantity of kink-bands (as measured in polarised light) as distortions of fibrils in the fibre wall (kink-band is a better word than node). Fibres that have been very carefully removed from delignified, undamaged woodchips contain no kink-bands and would therefore have appeared at the extreme left in the graph. Such fibres are so sensitive, however, that they cannot be mounted and measured by bending. Therefore, no data is available for the interval to the left in the graph. (My articles in *Svensk Papperstidning*, 1963 could be consulted for further information.) As the right of the graph shows, in the early stage of

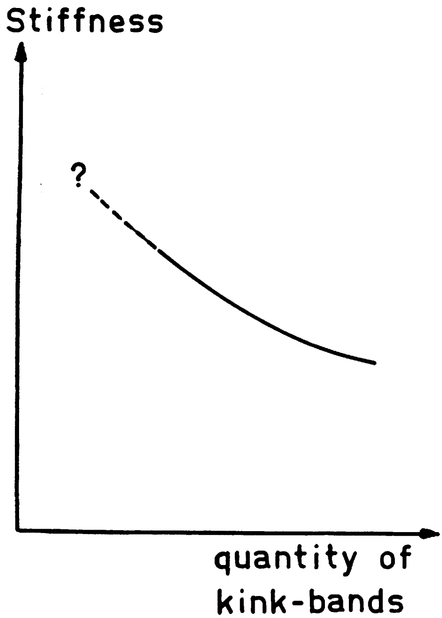

Fig. B

beating, the stiffness decreases with an accompanying increase in kink-bands. Whether or not the flexibilisation of fibres during mechanical handling and beating is a result of preferential banding in the kinks is an open question. During bending, the fibres assumed the shape of a continuous curve, not that of the circumference of a polygon. (Observations were made using only low magnifications.)

Dr J. Grant—I was very struck by Jacquelin's flocs, because they bear a striking resemblance to the phenomenon known as ricing, a property peculiar to esparto pulp, in mill usage at any rate. One associates it with overdigestion and overagitation by pumping or beating. It appears therefore that esparto pulp is an excellent material for further work, if he wishes to pursue his experimentation. My immediate question is do the known properties of esparto pulp fibres support his theory of the flexible and rigid constituents of a pulp slurry?

Mr G. Jacquelin—We have compared the ability of many pulps to give that kind of floc and have seen that esparto pulp very easily gives a high yield of these flocs. This is probably correlated with the special morphology of these fibres, giving them a certain rigidity. We have compared pulps originating from the same plant material, but with different kinds of cooking. It is the cooking that gives more flexible fibres, which in turn provide the lower yield of flocs. I think it is not only a question of morphology, but also one of degree of cooking of the fibres.

Dr L. J. Groen—I made a small calculation, which might be a bit overdone. We learned from this paper that, in testing handsheets, one should rather use the specific breaking length, which turns out to be roughly 10 per cent higher than the usual average breaking length. The non-ideal formation of machine-made paper gives about another 10 per cent loss in strength values, owing to flocculation (generally accepted experience corroborated by Higgins' paper). According to Schwalbe, the use of alum and rosin size decreases the strength values by roughly 20 per cent. If we take into account that the anisotropy of machine-made paper introduces another 10 per cent strength loss compared with isotropic paper, the paper strength would be about 50 per cent of the pulp (stock) strength potentialities. I do not believe this and I do not think that I am the only one. It means that we have to be very careful in describing the different effects independently and we must be realistic in trying to apply our knowledge to practice, which in fact is our ultimate object.