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THE EFFECT OF WET FIBRE FLEXIBILITY OF SHEET APPARENT DENSITY

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ABSTRACT

A new individual wet fibre flexibility test has been devised, and used to investigate the relationship between fines-free sheet apparent density and the wet flexibility of the constituent fibres. Linear relationships were found for a number of pulps, ranging from bleached chemical to thermomechanical, and for several different pulp treatments. It was concluded that changes in the average wet fibre flexibility of a particular pulp, caused by mechanical and/or chemical treatment, can be evaluated by measuring the apparent density of the fines-free sheet, at least over the investigated range (240-760 kg/m^3).

INTRODUCTION

Apparent density is a fundamental property of paper which has been shown or proposed to be related to several papermaking process variables, as well as to the physical properties of the sheet. For example, the linear relationship between the logarithm of refining energy and sheet apparent density has been well established, despite the recent controversy in this area (1), (2), (3). It has also been proposed that sheet apparent density is a much better indication of stock drainage on the wire than the freeness or wetness test (4). Simple relationships have also been found between the mechanical and optical properties of paper and its apparent density (5).

In keeping with the central theme of this symposium, it is highly relevant to investigate the relationship between sheet apparent density and the properties of the constituent fibres. Properties such as fibre coarseness, fibrillation, collapsibility, shrinkage on drying and pulp fines content undoubtedly influence the degree of compaction of the sheet. However, there is a widespread intuitive belief that the wet flexibility of the fibres is the controlling factor, and that a simple relationship must exist between the two variables. No experimental evidence has been published to either confirm or deny this hypothesis, probably because the existing methods for measuring wet fibre flexibility are cumbersome and time-consuming. The objectives of this study are therefore twofold; to develop a more convenient test for the measurement of wet fibre flexibility, and to use the test to investigate the relationship between wet flexibility and sheet apparent density.

The problems related to the measurement of wet fibre flexibility are mainly a consequence of the scale of the operation. A papermaking fibre, which may be only a couple of millimetres long and 30 μm across, has to be suitably supported in the wet state, and bent by a known force to a measurable deflection. Several methods have been developed to carry out such measurements, most of which involve mounting the fibre as a cantilever (6). Inevitably, such tests are tedious and time consuming. A more convenient test was developed by Tam Doo & Kerekes (7), (8), in which the fibre is mounted as a simple beam across the mouth of a submerged capillary tube, and deflected by a stream of water. This test removes a lot of the tediousness from single fibre work, but still has some important drawbacks. The minimum fibre length requirement for the test is about 2 mm, which excludes a substantial proportion of the fibres in a typical hardwood pulp. The method is also unsuitable for the testing of fibrillated fibres, because the fibrillation would increase the hydrodynamic drag forces and therefore increase the apparent flexibility of the fibre.

It was therefore decided to develop a new, more convenient test which could fulfil the following requirements:

i) Fibres should be chosen at random from the whole population, including damaged or otherwise imperfect specimens.
ii) The fibres should be deflected by forces similar to those occuring during the paper making process.
iii) The method should be applicable to short (<1 mm) fibres.
iv) No manipulation or clamping of the fibres should be required.
v) Subjective judgement should not be used at any stage of the test.
vi) The method should yield a measure of wet fibre flexibility in the appropriate engineering units, and not an arbitrary index.
vii) The time taken to test a representative sample should be reasonable, i.e. about one hour.

EXPERIMENTAL

A) Description of the Flexibility Method

I. Overview

Basically, the new test combines elements of the Mohlin test for wet fibre conformability (9) and the "contact ratio" test for fibre bondability, which was originally developed by Clarke (10), (11), (12), with a suitable theoretical treatment. A thin, tangentially-orientated fibre network is formed on a filter paper which has been placed on the wire of a standard sheet machine. The network is then pressed in contact with a 5 cm x 5 cm glass slide, which has several thin stainless steel wires attached across its surface in the form of a parallel grid. After pressing, the slide is air-dried, and is then inverted and viewed in a microscope under transmitted and incident light.

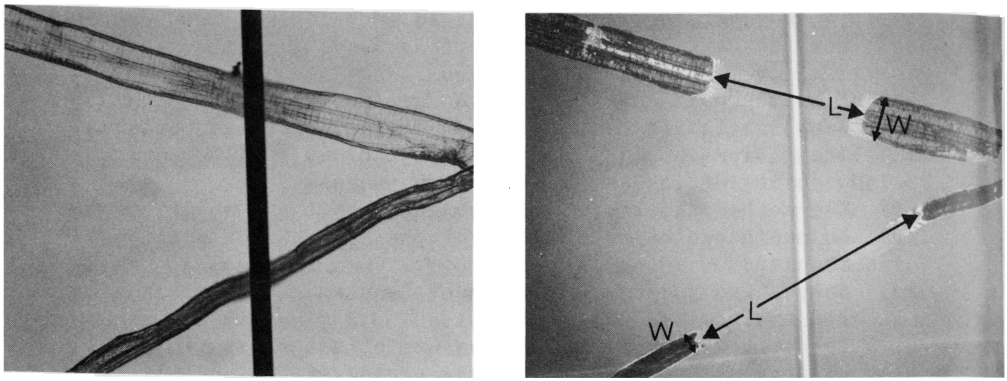


Fig 1—Detail of Two Fibres crossing the Stainless Steel Wire.
1a) Transmitted Light 1b) Incident Light

Fig. 1a) shows a view of two fibres crossing the wire under transmitted light conditions. Fig. 1b) shows the same field under incident light. In this micrograph, the areas of intimate contact between the fibres and the glass appear dark, and the area which is not in contact, i.e. as the fibre arcs over the wire, is not visible. An explanation of the incident light image, based on the theory of thin film interference, appears in the literature (13). Intuitively, it seems plausible that the no-contact length, L, is related to the flexibility of the fibre, and as the fibre becomes more flexible, this distance will decrease. From a theoretical point of view, the load on the fibre can be calculated from the pressing pressure, and its deflection is equal to the diameter of the stainless steel wire. It is therefore possible to derive an expression for the flexibility, or inverse flexural rigidity, of the fibre.

II) Theoretical Considerations

In order to obtain an expression for the flexibility of the fibre, it is necessary to treat it as a uniformly loaded, homogeneous elastic beam. The total deflection of such a beam under vertical loading is the resultant of bending and shear deformations, but since the shear component is relatively small, it will be neglected for the purposes of this analysis.

The fibre can be split in half, and treated as a statically - indeterminate cantilever beam, as indicated in fig. 2, below:

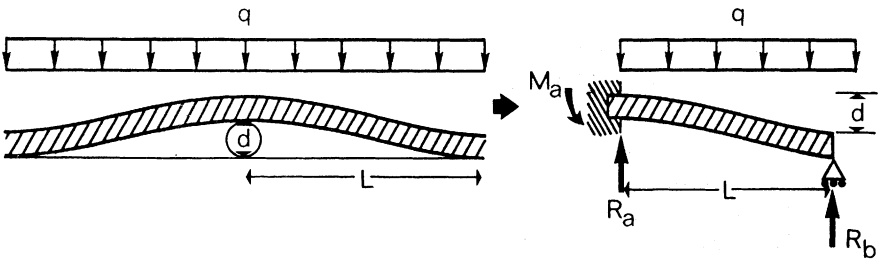


Fig 2—Theoretical Treatment of the Fibre as a Cantilever Beam.

The flexibility of such a beam can be expressed as:

$$\text{Flexibility} = \frac{1}{EI} = \frac{72\ d}{P.W.S^4}$$

where E = Modulus of Elasticity, $N.m^{-2}$
I = Moment of Inertia, m^4
d = wire diameter, m
P = pressing pressure, $N.m^{-2}$
W = projected fibre width, m
S = a mathematical estimate of the loaded fibre span, m

A full derivation of this equation, and the mathematical expression for S, appears in Appendix B.

This method was devised to obtain a measure of the flexibility of the whole pulp, rather than just the small, unrepresentative proportion of undamaged fibres. Once damaged fibres are included in the analysis, the above expression cannot be rigorously applied to obtain an expression for absolute fibre flexibility. Therefore, the definition of Tam Doo & Kerekes (7), (8) has been adopted to embrace the damaged and otherwise imperfect fibres:

"Effective Fibre Flexibility (EFF): The flexibility of a perfect fibre which deforms to the same extent as the imperfect fibre when subjected to the same loading conditions".

III) Measuring Individual Fibre Flexibility

The theoretical treatment has demonstrated that, under known press loading conditions, the flexibility of each fibre is a function of the two parameters L and W (see fig. 1b). These parameters can be measured in a variety of ways, the most simple of which is to fit a micrometer eyepiece to the microscope. This is rather tedious, and it is more efficient to digitise the parameters so that they can be handled by a microcomputer. The experimental setup at ESPRI (Empire State Paper Research Institute) is shown schematically in fig. 3.

Measuring the flexibility of a fibre simply involves touching the interactive capacitance touch screen at the two bonded points, and touching the fibre across its width. The analogue voltage signals from the screen are digitised, and the computer software then calculates and stores the flexibility for subsequent statistical analysis. The setup at STFI is rather different, but achieves the same result.

Random sampling is assured by measuring individual fibres in sequence as the moving stage of the microscope tracks along each wire. Fibres which cross the wire at angles greater than about 20^{o} from the perpendicular are rejected. The usual sample size is 300 fibres, which can be measured in about one hour.

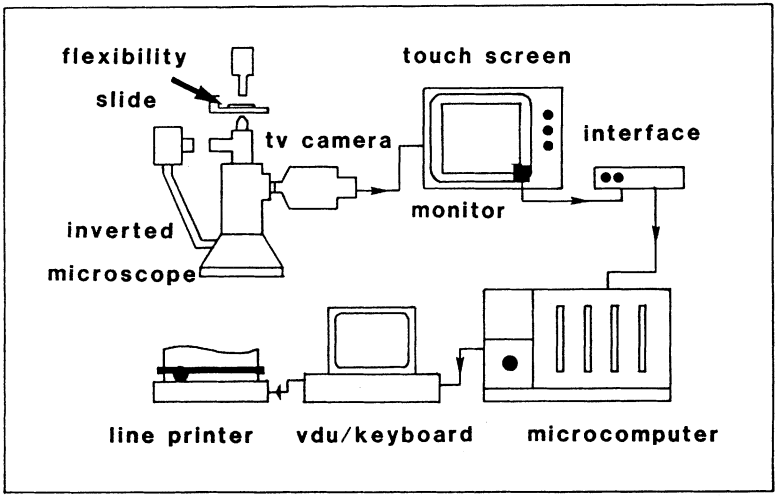


Fig 3—Flexibility Apparatus - A Schematic Diagram.

B) The Measurement of Sheet Apparent Density

The measurement of the apparent density of paper also presents well-known problems that are associated with the compressibility and surface roughness of the medium. The usual method of measuring sheet density involves using a deadweight micrometer, but several alternative methods have been proposed. These include mercury pycnometry (14), the concept of effective thickness (15), the use of soft rubber plattens (16), or small diameter, hemispherical plattens connected to an LVDT (Linear Voltage Differential Transformer) (15).

Whilst being fully aware of these alternatives, it was decided to use the deadweight micrometer method, as it is still the industry standard. In addition, the apparent density results in this study were obtained from several research institutes, all of which followed the standard method for their particular countries.

To eliminate the effect of fines, all apparent density measurements were conducted on "fines-free" sheets. For the purposes of this investigation, any fibre fraction which is retained on a screen of 200 mesh or coarser is considered "fines-free".

RESULTS

A) Comparison of Flexibility Results with a Published Method

Two unbleached, never-dried pulp samples were obtained from Dr. Peter Tam Doo at Vancouver to compare results with those obtained using the Tam Doo & Kerekes method. The results are shown in Table 1, below:

PULP	Median Flexibility Value: N^{-1} m^{-2}	
	Steadman Method	Tam Doo & Kerekes Method
BLACK SPRUCE	4.5×10^{11}	6.7×10^{10}
DOUGLAS FIR	1.7×10^{12}	2.6×10^{11}

Table 1—Result Comparison with the Tam Doo & Kerekes Method. Median Flexibility Values for Two Pulps.

As shown, our values are appreciably higher than the corresponding Tam Doo and Kerekes values, but the ratios between the two sets of results are practically identical. It should also be noted that our results were obtained from the whole pulp, including fibres shorter than 1 mm, whereas the minimum length requirement for the other test is about 2 mm. Inspection of the frequency distribution of fibre flexibility, (fig. 4), shows that the Tam Doo and Kerekes figure does fall towards the "stiff" end of the scale. This may have been a consequence of specimen selectivity, i.e. the tendency to select the longer and coarser (and correspondingly stiffer) fibres for measurement.

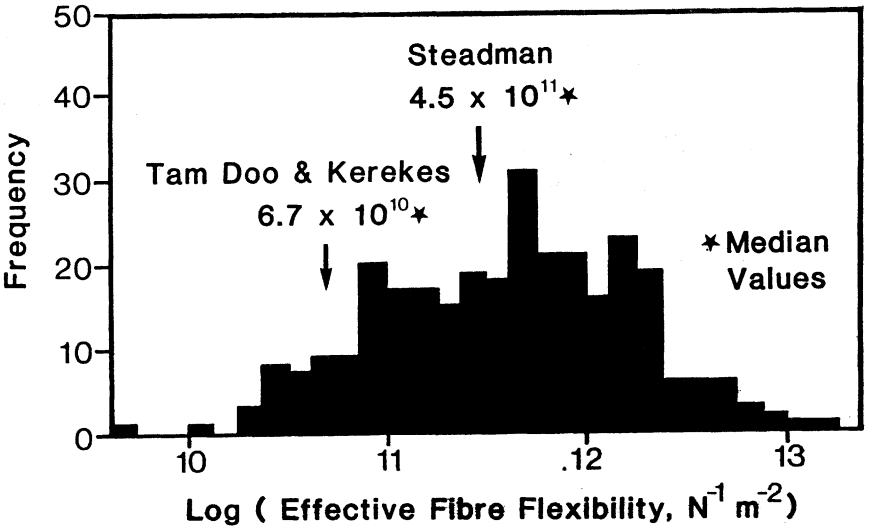


Fig 4—Result Comparison with Tam Doo & Kerekes method. Frequency Distribution for Douglas Fir.

Interestingly, when a different series of pulps were compared using the Tam Doo & Kerekes apparatus at another institute, our results indicated that the fibres were less flexible (fig. 5, below). However, the correlation between the two sets of results was very good, as indicated by the high value of the correlation coefficient.

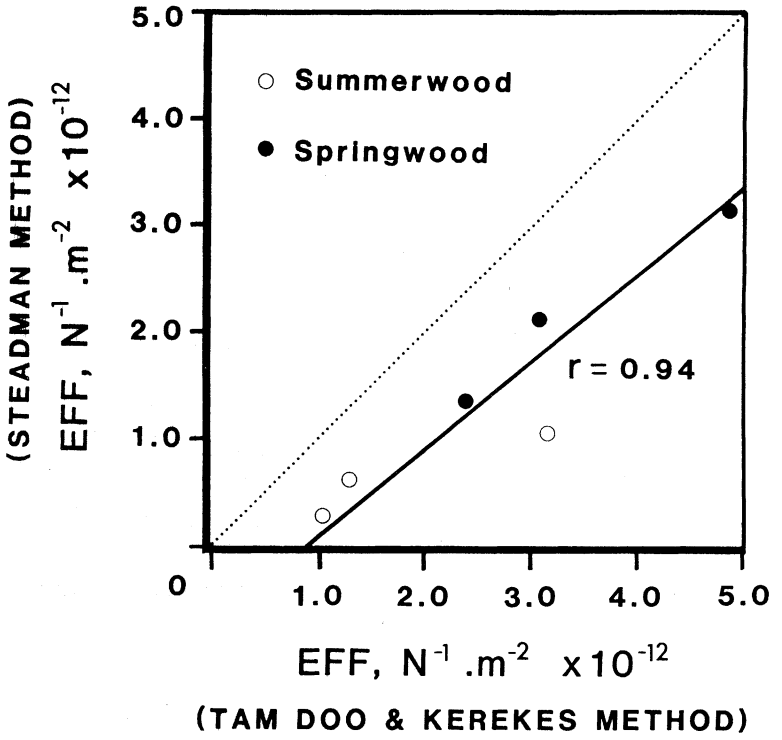


Fig 5—Result comparison with the Tam Doo & Kerekes Method. Correlation between the two tests.

Pulp: Springwood and summerwood fractions of an unbleached Finnish pine kraft pulp. Results by kind permission of Leena Paavilainen (then) Pulp Technology Dept., Helsinki University of Technology.

As a further check of the validity of the new method, the flexibility of a sample of 33 dtex collapsed viscose fibres was compared. The results are presented in fig. 6. As can be seen, the medians of the two distributions agree fairly well, but the spread of the results obtained on the Tam Doo & Kerekes apparatus, as indicated by the interquartile range, was much greater.

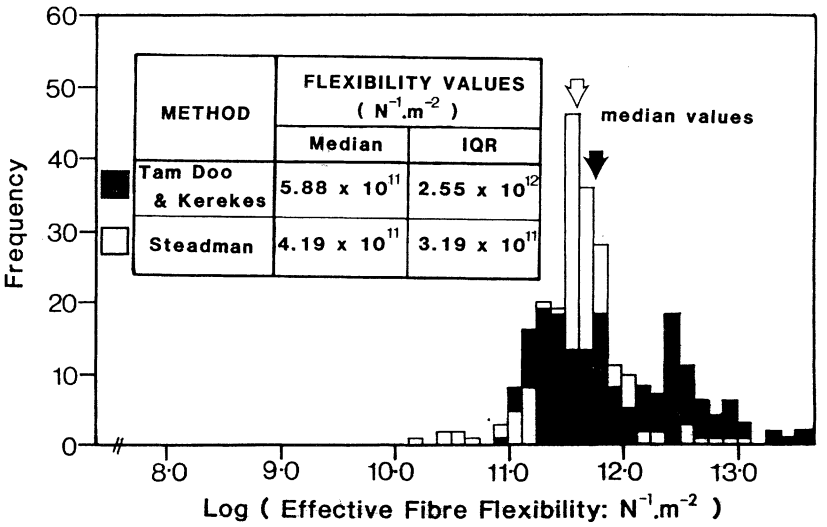


Fig 6—Result Comparison with the Tam Doo & Kerekes Method. Flexibility distributions for viscose dibres.

Comparative work is continuing between this and other fibre flexibility methods, but in conclusion it can be said that the authors are confident that the new test gives a meaningful measure of wet fibre flexibility.

B) The Relationship between Sheet Apparent Density and Wet Fibre Flexibility

A variety of pulps have been tested in co-operation with several other research institutes. The results obtained for bleached chemical pulps, an unbleached chemical pulp and TMP and CTMP are shown in figs. 7, 8 and 9 respectively.

The wet flexibility of 300 fibres and the fines-free sheet apparent density was measured for each pulp.

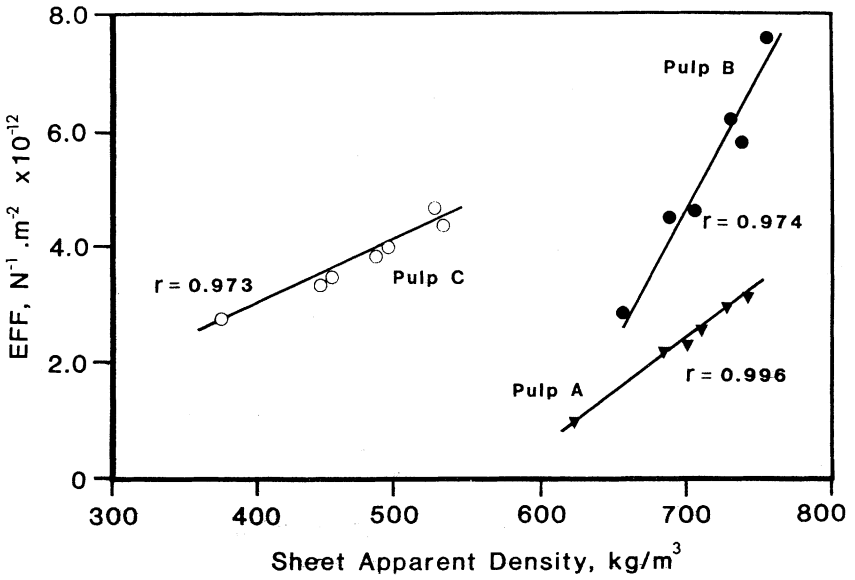


Fig 7—Wet Flexibility vs. Sheet Apparent Density - Bleached Chemical Pulps.

Pulps: A Scandinavian Pine Sulphite
B Scandinavian Birch Sulphate
C Esparto

Treatment: Up to 8 hours in a "Peerless" industrial food mixer at 20 % consistency. This particular treatment was designed to minimise fibre shortening whilst maximising fibre flexibilization. All three pulps were received in dry-lap form.

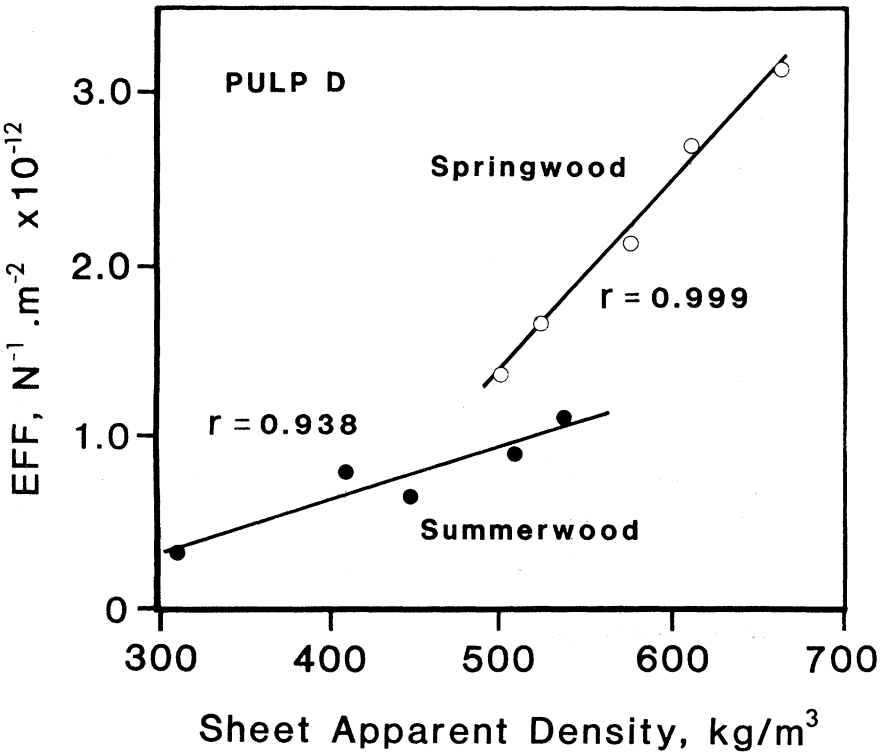


Fig 8—Wet fibre flexibility vs. Sheet Apparent Density - Unbleached Chemical pulp

Pulp D: Finnish Pine Kraft (never-dried)

Treatment: Beaten for up to 8000 revs in a PFI mill at 10 % consistency. Before beating, the pulp was separated into predominantly springwood and summerwood fractions by a centrifugal method.

Acknowledgement: Leena Paavilainen, Pulp Technology Dept., Helsinki University of Technology

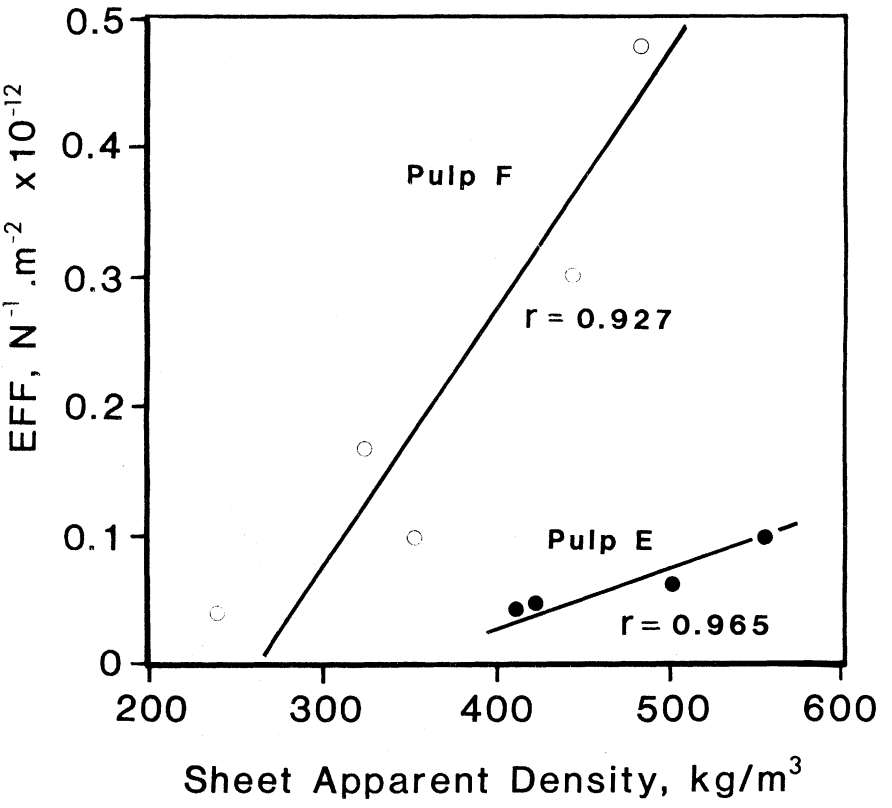


Fig 9—Wet fibre flexibility vs. Sheet Apparent Density - TMP and CTMP Pulps.

Pulp E: TMP and CTMP produced from the same wood source on the pilot plant Bauer 400 double disc refiner at PFI, Norway.

Refiner conditions: Steam temperature TMP 115°C
-"- CTMP 135°C
Retention time 300 secs.
CTMP Na_2SO_3 consumption 6.6 %
Energy consumption 1420, 1720 kWh/t (TMP)
-"- 2650, 2960 kWh/t (CTMP)

Acknowledgement: Jan Brill and Anna-Lisa Mattans, PFI, Norway

Pulp F: Swedish Commercial TMP given a sulphonation post-treatment.

Post-treatment Conditions: Consistency 5 % (+30 fraction only used)
Temperature 170°C
Initial pH 8.0
Total SO_2 2.85 mol/kg fibre
Cooking times 0, 15, 30, 130 and 180 minutes

Acknowledgement: Eva Bergman, Bill Strand, Nils Hartler of the Royal Institute of Technology, Cellulose Technology Dept., Stockholm, Sweden.

DISCUSSION

A new method to measure the wet flexibility of individual fibres has been presented. The results obtained so far look very promising, but there are still a number of questions that need to be answered.

From the nature of the test, it is clear that the measurements depend on the ability of the fibres to adhere to the glass surface. Furthermore, the adhesion must be sufficiently strong to "freeze" the maximum deflection of the fibre during the wet pressing stage, and prevent springback when the pressure is released. Dynamic observation of the bonded areas on either side of the wire during and after the pressing stage would reveal the occurence of any springback. However, the excess water in the nip would create a glass/water interface that would confuse the incident light image, and make it difficult, if not impossible, to observe single fibre behaviour.

The role that surface tension forces play in the test remains partly speculative at the moment. It is postulated that these forces have two important functions. Firstly, the strong surface tension forces between the fibre surface and the glass slide draw the two into the intimate contact that is a prerequisite for bond development. Secondly, the water

meniscus between the fibre and the wire will generate forces which counteract any tendency of the fibres to springback when the pressing pressure is released. An early experiment, conducted to evaluate the effect of surface tension per se on the measured fibre flexibility, found that the presence of a surfactant resulted in no appreciable change (5).

Quite clearly, the surface chemistry of the fibres and the glass slide is an important factor. If either surface is made hydrophobic, bonding will not occur, and flexibility will not be measurable by this method. It could be argued that this is a serious drawback, but quite the opposite may be the case. The formation of a coherent network relies on two properties of the fibres; namely the development of a bondable surface, and the development of a sufficient level of flexibility to bring neighbouring fibres into contact. The absence of either property will result in the formation of a network with very little intrinsic strength. Therefore, it is rational that a test which claims to measure the effective wet flexibility of the fibres should rely to some extent on the hydrophilicity of the fibre surface, as is the case here.

Moving on to the relationship between wet fibre flexibility and fines-free sheet apparent density, the results shown in figs. 7, 8 and 9 confirm that there are close linear relationships between the two variables for a wide range of pulps and pulp treatments. It is not suggested that this linearity would continue as sheet density increases, because the "Law of Diminishing Returns" would operate when the fibres are very flexible, because there are few inter-fibre voids available. The relationship must become asymptotic as sheet density reaches its maximum attainable value. Nevertheless, the relationship holds over a practical range of fines-free sheet density - from 240 to 760 kg/m^3.

For any single pulp which has been subjected to a particular mechanical and/or chemical treatment, it follows that fines-free sheet apparent density is indeed a measure of average wet fibre flexibility, as postulated in the past (17), (18). However, the flexibility/density relationship is not

unique. Each pulp tested produced correlation lines with a different initial (unbeaten) point and a different slope. This suggests that, while wet flexibility plays an important role in the densification of the sheet due to mechanical or chemical treatment, it does not control the apparent density of the unbeaten sheet. It seems more likely that unbeaten density is primarily dependent on the coarseness of the fibres, which will control their initial packing density, with fibre flexibility and other properties playing a secondary role.

Indeed, Claudio-da-Silva (19) proposed an empirical conformability factor in a similar study:

$$CF = S \times N$$

where S = fibre stiffness, $N.m^2$
N = No. of fibres per gram of pulp.

When he plotted fines-free apparent density against this conformability factor, the results for four very different pulps fell close to the same straight line (fig. 10).

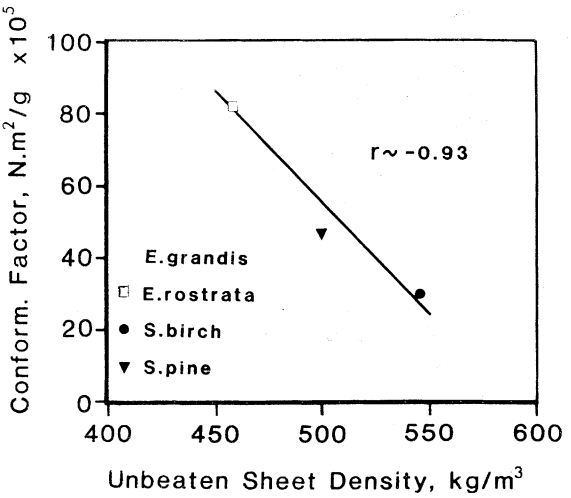


Fig 10—The Relationship betwen Sheet Apparent Density and Conformability Factor (**19**)

The number of fibres per gram of pulp is inversely related to fibre coarseness, which in turn is related to the cross-sectional area of the cell wall. This type of factor could be used to express the results in terms of flexibility per unit cross-sectional area. In turn, the "normalised" fibre flexibility of a range of pulps may be uniquely related to fines-free sheet apparent density

CONCLUSIONS

i) A new test has been formulated which gives a meaningful and reasonably fast measure of individual wet fibre flexibility.
ii) A linear, but not unique, relationship exists between sheet apparent density and average wet fibre flexibility for a number of pulps and pulp treatments.
iii) For a particular pulp treatment, fines-free sheet apparent density can be used as a measure of average wet fibre flexibility. This applies over a practical density range from 240-760 kg/m^3.

FUTURE WORK

Further investigation of the relationship between the surface chemistry of the components and the measured value of fibre flexibility will continue as a matter of high priority.

Improvements to the method itself are also in the pipeline. These include the automation of the measuring stage, and the direct deposition of a suitable grid onto the glass slides, which would dispense with the wire winding stage.

The possibility of extending the analysis to embrace other important fibre characteristics is also being considered. For example, it would be simple to include a plain glass slide in the pressing stage of the technique. By using automated or semi-automated image analysis techniques, it would then be feasible to rapidly measure fibre coarseness, length and length distribution, bondability, degree of fibrillation and curl, as well as wet fibre flexibility.

APPENDIX I.

Experimental Details of the Flexibility Method

a) Preparation of the Flexibility Slides

The glass slides used in this method are 5 cm x 5 cm x 0.1 cm photographic cover slides, which are manufactured by Kodak.

i) Slide Cleaning

The slides must be rigorously cleaned, following the procedure specified below. This cleaning procedure has two purposes; namely to remove any grease or other contaminant which might reduce the hydrophilicity of the surface, and to form a chemically-reproducible and standardized surface for the fibres to bond to. Baths containing the following solutions should be prepared:

- A 2 % solution of a commercial polyphosphate glass-cleaning detergent (eg. "Micro" or "Extran")
- Chromic-sulphuric acid ("Chromerge")
- Two cold distilled water rinses
- One hot distilled water rinse at about 90°C
- A final rinse in methanol.

The procedure is conducted more efficiently as a batch process, by using a suitable holder to clean 20 or 30 slides at a time. The holder is immersed in the detergent solution in an ultrasonic bath, and irradiated for 10 minutes. It is then removed, and immersed in the Chromerge bath for a further 10 minutes, after which it is rinsed thoroughly in the distilled water baths, and immersed briefly in the methanol bath. The slides are then dried using a hot-air blower, and stored in an airtight container until needed.

ii) Winding the Slide

This stage involves winding very thin (25 μm diameter) stainless steel around the cleaned glass slides. The objective is to end up with a parallel grid of wires attached across the face of the slide. The winding procedure consists of four stages, which are illustrated in fig. A1.

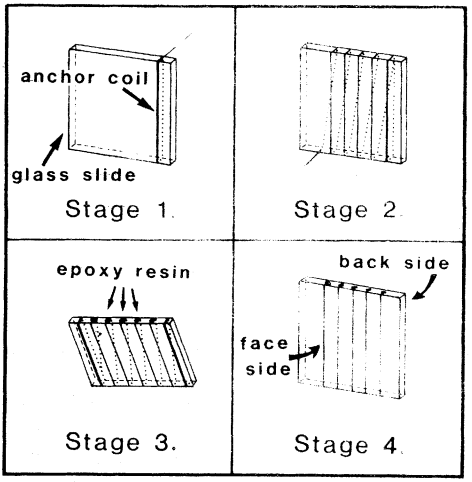


Fig A1—The preparation of a Flexibility Slide - Winding Stages.

Stage 1. Wind a few turns of wire around a position close to one edge of the slide to form an anchoring coil.

Stage 2. Carefully wind the wire around the slide in a helical fashion, keeping the wires approximately parallel and perpendicular on the face side. The spacing will depend on the application, but as a rough guide, use:

1-2 mm for hardwood chemical pulps
2-3 mm for softwood chemical pulps
3-4 mm for TMP and CTMP.

Anchor with another coil at the other edge of the slide.

Stage 3. Apply a line of epoxy resin along the top and bottom edges of the slide, and allow to set.

Stage 4. Remove the anchoring coil, and cut away the wires from the rear face of the slide. The slide is now ready for use.

b) Testing Procedure

If necessary, the pulp sample should be disintegrated following the relevant Tappi Standard Method (20), and then diluted to 0.03 % consistency. One litre of pulp at this consistency will be sufficient for about 20 flexibility determinations. Place a high speed filter paper of 18.5 cm diameter on the sheet machine wire, close the machine, and fill from the top, preferably using distilled water. Add approximately 50 ml of dilute stock, and stir as usual, but lightly swirl the pulp suspension during the last upstroke. Drain, and remove the filter paper. The fibre network is now ready for the transfer stage. Lay the filter paper on top of the three pre-wetted blotters, and place the flexibility slides face down on the fibre network in a symmetrical pattern (see fig. A2, below:)

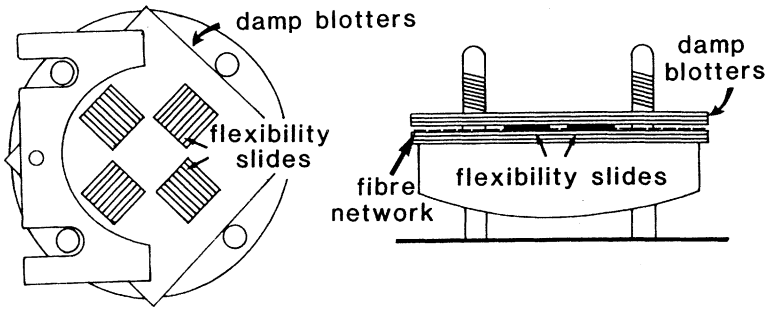


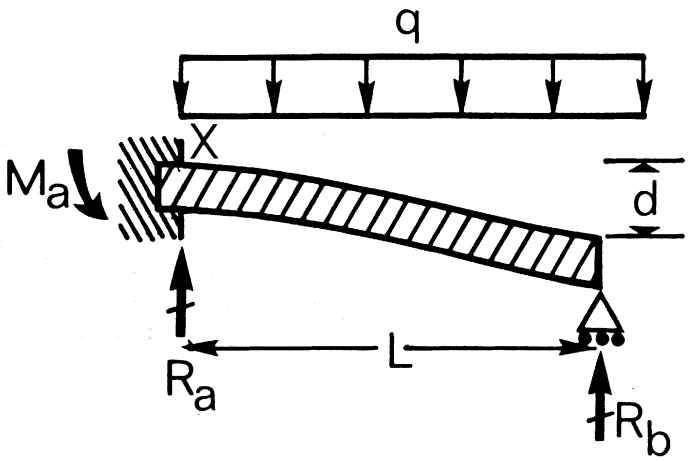
Fig A2—The Preparation of a Flexibility Slide - Pressing Stage

Place three more wetted blotters on top of the flexibility slides and press for 2 minutes at 0.4 MPa. After pressing, lift the flexibility slides from the filter paper. The slides, complete with transferred fibres, will air-dry in a matter of seconds, and can be labelled and stored until the measurement stage, which is described in the main body of the text.

APPENDIX II.

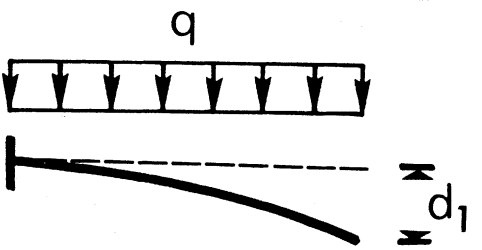
Flexibility Test - Theoretical Treatment

The fibre is treated as a statically indeterminate cantilever beam:



The method of superposition is used to evaluate the unknown reactions by following the sequence below:

i) Let R_b be the redundant reaction. The released structure then becomes an uniformly loaded and determinate cantilever beam:



$$d_1 = \frac{qL^4}{8EI} \qquad \text{(standard formula)}$$

ii) Let the redundant itself act on the released structure:

$$d_2 = -\frac{R_b.L^3}{3EI} \quad \text{(standard formula; negative by convention)}$$

iii) Place the two deflections in an equation of superposition. In this case, the total deflection of the fibre is equal to the diameter of the stainless steel wire, d.

$$d = d_1 + d_2$$

$$= \frac{qL^4}{8EI} - \frac{R_b.L^3}{3EI}$$

$$\therefore R_b = \frac{3qL}{8} - \frac{3EI.d}{L^3}$$

The reaction R_a and the moment M_a can now be found by considering the equilibrium of the beam:

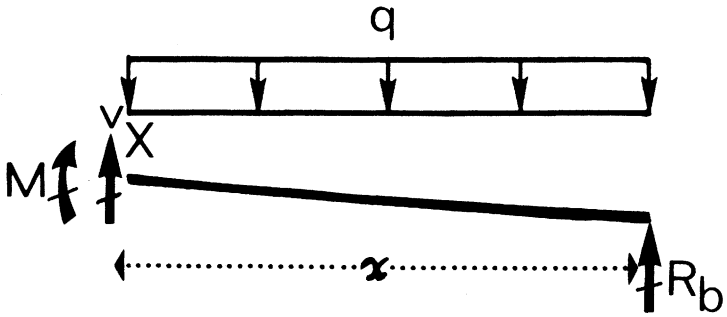
Vertical Equilibrium: $R_a + R_b = qL$

$$\therefore R_a = \frac{3EI.d}{L^3} + \frac{5qL}{8}$$

Moments about X: $M_a + R_b.L = \frac{qL^2}{2}$

$$\therefore M_a = \frac{qL^2}{8} + \frac{3EI.d}{L^2}$$

Now, considering the general expression for the bending moment of the beam, M:



Moments about X: $M = R_b x - \frac{qx^2}{2}$

By definition, $EI.v'' = -M$

$$= \frac{qx^2}{2} - R_b x$$

Multiplying each side by dx, and integrating:

$$EI.v' = \frac{qx^3}{6} - \frac{R_b x^2}{2} + C_1$$

Boundary condition: $v' = 0$ when $x = 0$, $\therefore c_1 = 0$

Integrating again: $EI.v = \frac{qx^4}{24} - \frac{R_b x^3}{6} + C_2$

Boundary condition: $v = 0$ when $x = L$, $\therefore C_2 = \frac{R_b L^3}{6} - \frac{qL^4}{24}$

$$EI.v = \frac{qx^4}{24} - \frac{R_b x^3}{6} + \frac{R_b L^3}{6} - \frac{qL^4}{24}$$

- but $v = d$ when $x = 0$ $\quad EI = \frac{R_b L^3}{6d} - \frac{qL^4}{24d}$

Substituting for R_b and rearranging:

$$EI = \frac{qL^4}{72d}$$

$$\text{Flexibility} = \frac{1}{EI} = \frac{72d}{qL^4}$$

where E = Modulus of Elasticity, $N.m^{-2}$
I = Moment of Inertia, m^4

During the flexibility test, the load exerted on the fibre has two components, namely:

- the pressing pressure
- the weight per unit length of the fibre itself

The second component is negligible when compared to the first component, so the expression for the deflecting load per unit fibre length becomes:

$$q = P.W$$

where P = pressing pressure, $N.m^{-2}$
W = projected fibre width, m

The loaded length of the fibre span S has been found by computer simulation to be very closely approximated by the following expression:

$$S = 0.01745\left[\frac{L}{8d} + \frac{d}{2}\right]\left[\text{Sin}^{-1}.\left(\frac{4Ld}{L^2 + 4d^2}\right)\right]$$

where L = no-contact length (see fig. 1b).

The final expression for fibre flexibility is:

$$\text{Flexibility} = \frac{72d}{P.W.S^4}$$

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Transcription of Discussion

The Effect of Wet Fibre Flexibility on Sheet Apparent Density
by R. Steadman and P. Luner

Jordan Since you have a function of L^4 in the equation for flexibility, the percentage error is going to be four times that of the error in the measurement of the gap. How variable is this gap and how many do you have to measure to get reproduction results?

Dr. R. Steadman The values of the no-contact length "L" typically vary from 8×10^{-4} m to about 2×10^{-4} m. We have found that a random sample of 300 fibres gives reproducible results.

Kerekes Your efforts to develop a simple test to measure fibre flexibility are very commendable. Our test is more restrictive than yours. To determine the accuracy of our test we measured the flexibility of synthetic fibres and compared these to calculated values. Have you carried out such measurements to check your test?

Steadman We intend to look at the flexibility of nylon fibres in the near future.

K.A. Cutshall Devron Hercules, Vancouver, Canada

It would seem that one of the problems of your test is the bonding of the fibres to the glass. Have you looked at the possibility of conducting this test without drying the fibres at all? Maybe similar to some of the smoothness tests?

Steadman Unfortunately the image of the contact areas between the glass and the fibre only develops as the fibre is drying, so we cannot carry out the measurement at an earlier stage.

Page A reflected light image of dyed fibres, I would have thought should provide you with a suitable image, during the pressing stage.

Steadman The problem is that we are pressing inside a TAPPI standard sheet press.

B. Radvan Wiggins Teape R & D, Beaconsfield, England

I was surprised to hear you say that surface tension forces had negligible effect. This is contrary to common experience, and is not borne out by your results with hydrophobic surfaces. It is surely these forces which determine the extent to which the fibre will spring back?

Steadman The close contact between the fibre and the glass, which is necessary to produce the contrasting image seen under incident illumination, is the result of surface tension forces. However, when these forces are averaged over the whole length of the fibre span, the influence on fibre deformation is small in comparison to the pressing pressure.

Radvan How then do you account for your results with hydrophobic surfaces.

Steadman The surface is not completely hydrophobic and some bonding is developed between the fibre and the glass. We do experience spring back to some extent.

B. Clarke UMIST, Manchester, England

Good luck with your nylon fibres but remember they are of circular cross-section and they are hydrophobic. Our own technique is to treat with oxygen plasma to make the fibres hydrophilic.

P. Howland PIRA, Leatherhead, England

When you measured the effect of surface tension alone, the fibre presumably had a large radius of curvature over the wire. In contrast after pressing the radius of curvature would be small and the surface tension forces correspondingly greater.

Steadman It would be interesting to investigate this by using some model calculations.

Dr. J. Grant Hehner & Cox, London, England

Could I ask that we bear in mind that pulp does not necessarily mean wood pulp and that when carrying out investigations the properties of rag pulp could be of interest. Dr. Page and Dr. Steadman's work could be augmented by looking at a fibre such as rag which fibrillates naturally. To what extent do they feel that rag pulp would replicate the results they have found with wood pulps.

Page We do know that microcompressions are present in fibres such as Ramie and Jute. I cannot recall looking specifically at cotton. We do know that curl-setting does occur in cotton - we call it ironing. When you put a crease in a cotton handkerchief that's what you are doing. It survives wetting and redrying.

More work in the area of curl and microcompressions in non-woody pulps should be done for the benefit of those parts of the world that are dependent on such pulps.

Steadman The effect of fibrillation is very important in determining the deformation behaviour of fibres, and so I think Dr. Grant's suggestion is an excellent one.

Dr. A.H. Nissan Westvaco, New York, USA

In the Clupac process the fibre is crimped and curled. The process can be applied to paper at about 30% moisture content but can also be applied at the wet press position. So what is the difference between compacting at 70% moisture content and compacting at 30% consistency material in the refiner? The origin of the Clupac process began with cotton in the operation of Sanforising - a non-shrinkage process. It has also been applied to paper made of non-wood pulps and non-woven materials containing cotton linters. So I would expect Dr. Seth's findings to apply also to cotton and other non-wood pulps.

Chairman I wonder if we need to draw a distinction between pre-formation curl and post-formation curl.

Page Yes we do. With regard to Dr. Nissan's comments, the change in fibre structure caused by the Clupac process is not exactly the same as is produced by high consistency refining. If you take a sheet of straight fibres and you put it though the Clupac process, you introduce microcompression, but the fibres remain straight at the gross level. If on the other hand you refine fibres at high consistency, the fibres become curled at the gross level as well as becoming microcompressed. So the two are not equivalent and the sheet properties are also different.

Nissan Microscope studies of cross sections of paper subjected to compaction by the Clupac process show the fibres to be both curled and microcompressed. The two are equivalent.

I.K. Kartovaara FPPRI, Helsinki, Finland

Dr. Steadman, when you apply pressure to your fibres you apply it through a filter paper which has a fairly rough surface. On the scale which you are observing the load applied cannot be evenly distributed over the fibre. So I cannot see the justification for using uniform loading in your theoretical work. Also, when you presented your results of surface tension you did not use pressure. How then did you calculate them?

Steadman It should be remembered that the pressing stage is carried out with an excess of water in the nip and this could even out the distribution of the pressing pressure. This is supported by the observation that the spread of the results obtained from fibres which are just draped over the wire is comparable to the spread of the results for the pressed fibres.

The effect of surface tension forces was determined by assuming a value for the flexibility of the fibre. The equation in the appendix can then be solved for the relative value of the deformation force, as given by the parameter P.