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FLOW RESISTANCE OF ROTATING DILUTE FIBRE SUSPENSIONS

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Abstract

The relationship between the torsional and flexural rigidity of single fibres, and the flow resistance of pulp suspensions was investigated from the view point of the flocculation process.

The torsional and flexural properties of wetted single pulp fibres were measured by the torsional pendulum method and by the bending method respectively, for chemical pulps. A new experimental apparatus to measure the flow resistance of dilute fibre suspensions to rotary motion was developed in our laboratory.

A good correlation between torsional rigidity and the flexural property of single pulp fibres was observed, and the flexibililty of fibres was found to increase intensely during the early stages of beating.

It was found that wall-shear stress, motion decay times, and the shapes of the motion decay curves of fibre suspensions depended on the flexural properties of the fibres, their length, and the concentration and temperature of the suspension.

Introduction

Both the flexibility of wetted fibres and the visco-elastic properties of fibre suspensions play an important role in flocculation processes. About twenty years ago, Mason and his co-workers investigated the correlation between flexibility of wood pulp fibres and their hydrodynamic behaviour by analysing the distribution of the types of rotational orbit (of the fibres) in laminar flow of fibre suspensions and by measuring the network and flow properties of suspensions in pipes[1,2,3].

However, since then there have been few published references to work on the flow properties of suspensions which consider the flexibility of wetted fibres. Recently, further investigations of flow properties of pulp suspensions have been carried out by Giese[4], Thalen and Wahren[5], and Duffy et al.[6]. Almost all the studies on the suspension flow have been performed in pipes. Such experiments require a large amount of pulp and large scale apparatus, especially if the effects of various pulp types, fibre length, beating degree, temperature, etc. are to be investigated.

In regard to the mechanical properties of single fibres, the rigidity has been studied by many workers. Samuelsson[7], Schniewind[8] and Haugen and Young[9] determined the flexural rigidity of the fibres by bending methods. On the other hand, only a few reports have been published on the torsional properties of paper-making fibres though the properties are thought to be an important index of the bending stiffness of fibrous materials[10,11]. It is widely accepted that the rigidity of pulp fibres must have some effects on the properties of fibre suspensions and dried sheets.

The above mentioned view points suggest that it is significant to measure both the bending and torsional properties of single pulp fibres prepared under various conditions. The relationship between the flexural properties of wetted single pulp fibres and the flow properties of pulp suspensions should also be clarified. Therefore, two experiments are presented in this paper: in one measurements of the torsional and bending properties of wetted single fibres are presented: while the other relates to the flow properties of a rotating dilute suspension.

Flexural Properties of Wetted Pulp Fibres

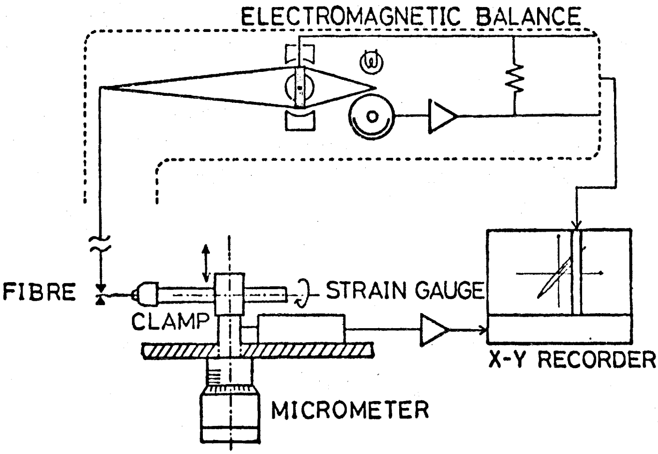

Fig 1—Schematic drawing of apparatus for measuring flexural rigidity for single fibres.

1. Bending Apparatus

A schematic drawing of the measuring apparatus is shown in figure 1. A single fibre is horizontally supported at one end with a clamp that is mounted along with a strain gauge on the micrometer head. The free end of the fibre is connected to the arm of the electromagnetic balance through a very fine metal wire. Small deflections of the fibre can be detected with the strain gauge and the deflection force can be measured with the electromagnetic balance. Consequently, the load-deformation curve obtained by bending individual fibres can be recorded on an X-Y recorder. The cross sections of pulp fibre are so irregular that the flexural rigidity is measured at four directions with respect to the fibre axis, and the obtained values are averaged. This apparatus has an accuracy of 1μg.

2. Torsional Pendulum apparatus

A torsional apparatus corresponding to type A in ASTM-D2236 was developed in our laboratory. The details of this apparatus have been published elsewhere[11], where it was shown that the torsional rigidity of wetted pulp fibres almost corresponded to that of the solvent-exchange dried fibre, as shown in figure 2. Therefore, solvent-exchange dried fibres were used (instead of wetted fibres) for the measurement of bending force.

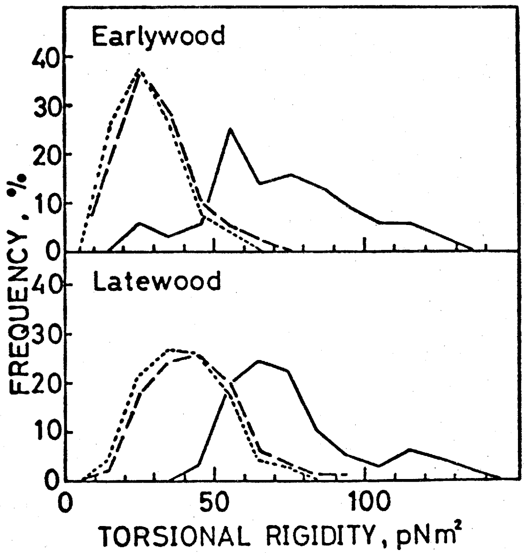

Fig 2—Frequency distribution of torsional rigidity for red pine kraft fibres.

Key: ———— Dried from water
– – – – – – Solvent—exchange dried
- - - - - - - - - - Rewetted

3. Results and discussion

The relation between torsional rigidity and flexural rigidity for wetted fibres is shown in figure 3 for softwood fibres. This result supports the idea that the flexibility of wetted single fibres can be represented by the torsional rigidity.

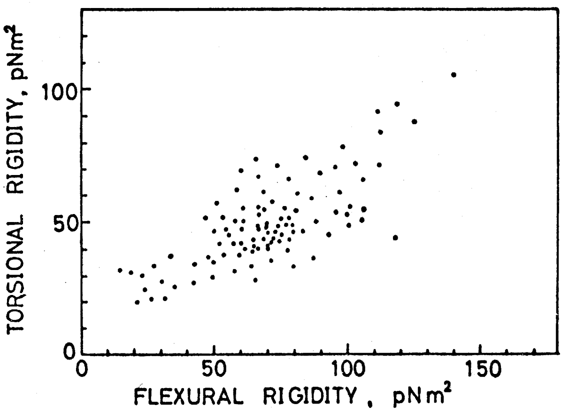

Fig 3—Relation between torsional rigidity and flexural rigidity for latewood kraft fibres of 69% yield.

For a pulp fibre with length l and bending rigidity B, the bending moment is given by the formula aB/l^3, where a is constant. A measure of fibre flexibility can be represented by the quantity

$$(\text{Fibre length})^3 \,/\, \text{Torsional rigidity}$$

as the torsional rigidity corresponds to the bending rigidity. According to this definition, the flexibility of softwood fibres is higher than that of hardwood fibres in the pulp yield range 40 to 70%, as shown in figure 4.

Figure 5 shows the relation between flexibility in the wet state and revolution numbers in a PFI mill for the long fibre fraction of pine kraft pulp.

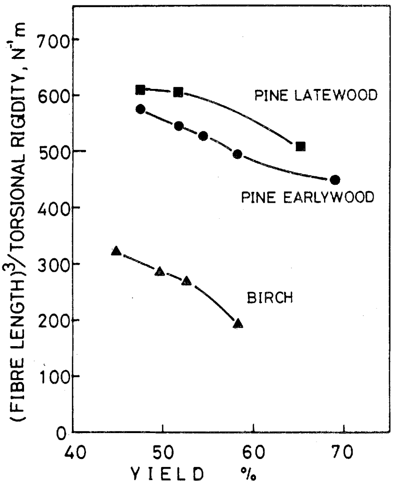

Fig 4—Variation of flexibility with yield for kraft fibres.

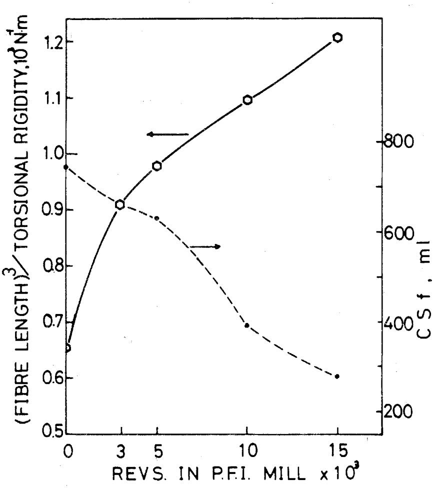

Fig 5—Variation of flexibility with beating for pine kraft fibres.

It can be seen that the fibre flexibility increases and that the rate of increase diminishes, as the beating advances.

Visco-elastic properties of fibre suspensions

1. Experimental procedure

A three-litre glass beaker containing a fibre suspension was placed on a disc which can rotate freely, supported on a ball bearing as shown in figure 6. A concentric propeller was used to disperse the suspension continuously, thus preventing it from sedimenting and at the same time creating a shearing action.

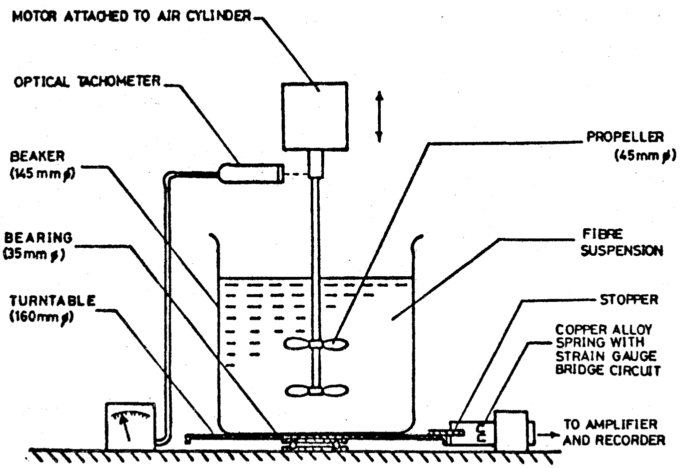

Fig 6—The experimental apparatus for measurements of the wall shear stress and the motion decay time.

The rotation speed in revolutions per minute was measured using an optical tachometer. As the suspension is stirred, the shear forces are borne at the beaker wall and hence a torque is created at the wall causing the rotation of the disc. In order to measure these shear forces, a copper-alloy flat spring with four strain gauges connected in a bridge circuit is fixed to the base of the apparatus. The resulting output signal from the bridge circuit is amplified and then recorded against time. Investigations of the effects of concentration of the fibre suspension, speed of rotation, fibre type, degree of beating, and temperature on the suspension resistance were reported in a previous paper(12). It was found that the flow resistance of the suspension to rotary motion is strongly affected by the fibre concentration and the length and flexibility of fibres. It is also affected by suspension temperature, rotation speed, degree of beating and type of fibre.

As has been mentioned above, the electric signal from the strain gauges is proportional to the wall force. Therefore, when the propeller is suddenly pulled up with a pneumatic device out of the suspension, the change of the electric output voltage versus time should display the corresponding decay of the wall forces, i.e., the decay of rotational motion with time. The time that elapsed from the moment of pulling the propeller up till the approach of the wall forces to a constant value, almost zero, was defined as the motion decay time at the corresponding propeller speed. Figure 7 shows a typical example of the recorder output signal.

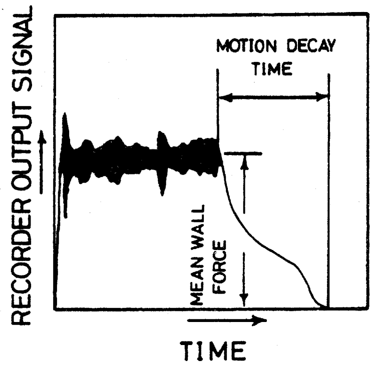

Fig 7—A typical sample of the recorder output signal.

The present experiments were performed on three types of cellulose fibres, namely, hardwood bleached kraft, softwood bleached kraft, and two sizes of viscose rayon fibre of diameter 12μm and lengths 3 and 5 mm. The experimental conditions and the fibre characteristics are given in Table 1.

The effects of type of fibre, mean fibre length, fibre concentration, degree of beating, and suspension temperature on both the motion decay time, and the decay process starting at the level of wall force generated by a pre-determined rotating speed were investigated.

2. Results and discussion

Although the principal purpose of this experiment was the measurement of the motion decay time, the process of the decay of the wall force with time was found to be of some significance in itself. Therefore, the wall force-time decay curves were examined and analysed as will be described below.

Fibre type	Freeness CSF, ml	Concentration range,%	Speed range Revs/min
Hardwood bleached kraft pulp	674 (unbeaten)	0.2-2.0	850 - 1800
	577	0.6,1.0,1.5	-
	513	-	-
	397	-	-
	300	-	-
Softwood bleached kraft pulp	738 (unbeaten)	0.2-1.8	850 - 1700
	672	0.4,0.6,1.0	1000 - 1400
	463	-	-
	308	-	-
	222	-	-
Rayon model fibres (1.5 denier) Fibre length			
l = 3 mm		0.4 - 0.6	850 - 1400
5 mm		-	-
7 mm		-	-

Table 1
Types of fibres and conditions of the experiments

2.1 Analysis of the wall force-time decay curves

The effect of fibre concentration on the shape of the wall force-time decay curves is demonstrated in figures 8 and 9 for unbeaten hardwood- and softwood-kraft fibres, respectively. These figures show that at relatively low concentrations the decay curves are smooth and do not differ much from that for water. This result indicates clearly that strong fibre networks are only formed in suspensions with higher pulp concentrations.

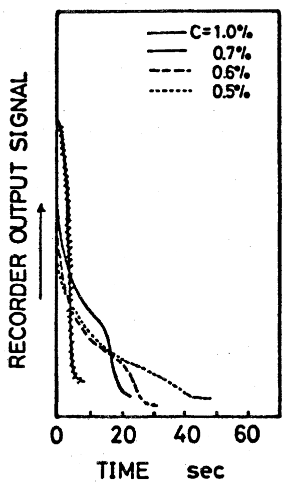

Fig 8—The wall force-time decay curves for unbeaten hardwood kraft.

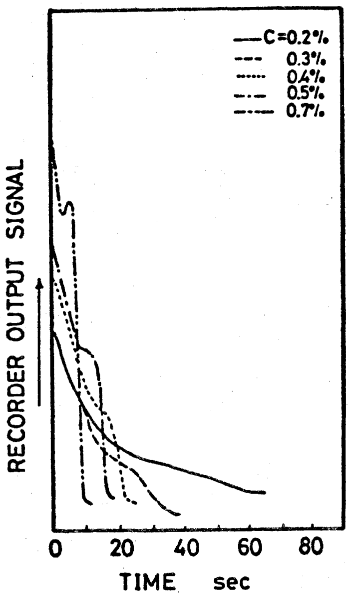

Fig 9—The wall force-time decay curves for unbeaten softwood kraft.

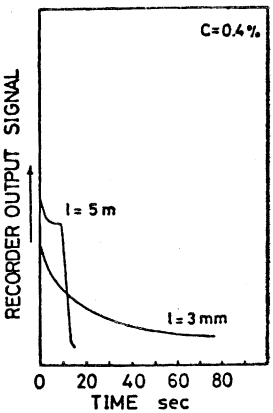

Fig 10—The wall force-time decay curves for two types of rayon fibres.

The effect of the mean fibre length on the decay curves involved in the network formation is clearly demonstrated in figure 10 for model fibres. This figure compares the curves obtained with different fibre lengths, 5 and 3 mm, but of the same diameter. It can be seen that a strong fibre network is developed for the rayon with the greater aspect ratio (fibre length to diameter) at a lower concentration than is the case for the rayon of the smaller aspect ratio.

Figure 11 shows the effect of variation of the suspension temperature in the case of unbeaten hardwood bleached kraft pulp at 0.8 % concentration. The temperature was varied from 14 to 60^{0}C. Figure 12 demonstrates the effect of beating, for the same pulp at a concentration of 0.6%. When all these decay curves in figures 8 to 12 are examined, an interesting phenomenon can be observed, viz. that in the case of some types of fibres, at certain consistencies and/or certain temperatures, the decay curves show an approximately horizontal portion or plateau that contributes to the increase of the total motion decay time. This seems to indicate that the process of formation of fibre networks depends on the length and flexibility of the fibres, and the concentration and temperature of the suspension. When the decay curves were redrawn on semi-logarithmic scales they

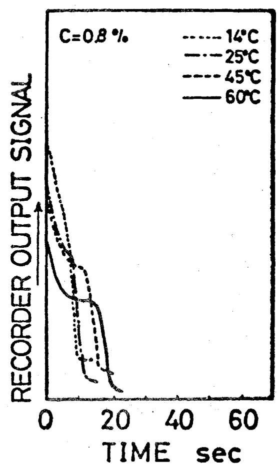

Fig 11—The wall force-time decay curves for unbeaten hardwood kraft at different temperature.

showed linearity. Consequently, the decay process conforms to an exponential equation of the following form;

$$P = P_o \exp(-t/\lambda)$$

where P is the wall force at any time during the decay process, P_o is the wall force at the beginning of each stage of the decay process, and λ is a numerical constant for the process, its value depending upon the type of fibre, its concentration, temperature, degree of beating, etc.

The curve for water can be expressed with a single constant value, while for a fibre suspension the equation has two or more constants corresponding to the initial and final stages of motion decay. The constants are denoted here by λ_i.

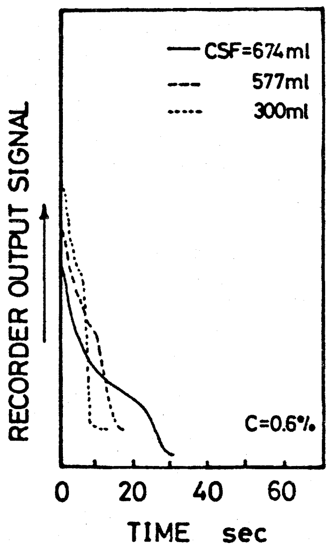

Fig 12—The wall force-time decay curves for hardwood kraft at different degree of beating.

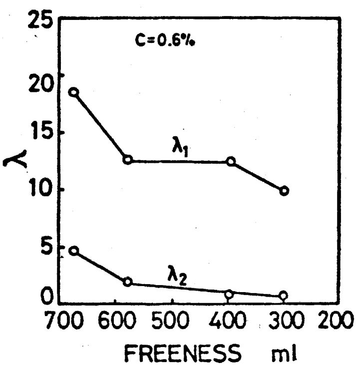

Fig 13—The variation of λ_1 and λ_2 with the degree of beating for hardwood kraft.

Figure 13 is concerned with the variation of the two constants for hardwood kraft pulp suspension with beating.

2.2 The motion decay time

The motion decay time was measured with the same apparatus for several kinds of pulp suspension as shown in figure 14.

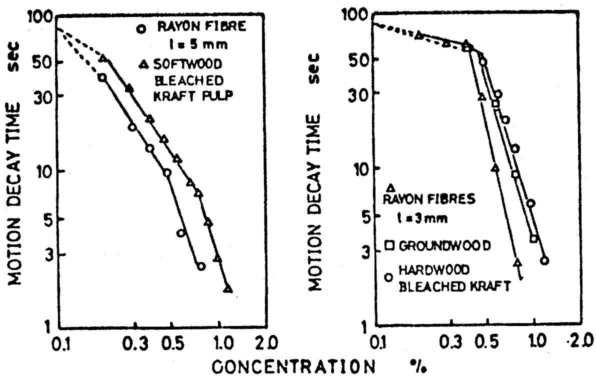

Fig 14—The motion decay time as a function of concentration for different types of fibres.

The effects of fibre concentration, fibre type, fibre length, degree of beating, and temperature of suspension on the motion decay time were investigated(13). This figure shows that the motion decay time decreases exponentially with an increase in the concentration. However, this exponential relationship holds only above a certain fibre concentration, below which the motion decay time is not much different from that of water. It was recognised that this critical concentration appeared clearly with short-fibred pulps at around 0.4%, while with the long-fibred pulps it appeared at 0.2%.

This exponential behaviour agrees with what has previously been reported by Bugliarello et al.(14).

The present experiments have covered a wide range of variables including fibre type, fibre concentration, etc. Under these different conditions, the shear stress at the beaker wall during stirring and the time required for the dissipation of the mechanical energy imparted to the suspension spread widely. Examination of the results suggests that some relation might exist between the shear stress at the moment of pulling the propeller out of the suspension and the corresponding motion-decay time. This suggestion is in line with the comment by Wrist[15] who attributed the rapid increase of energy dissipation with increase in concentration to the increase in the wall shear stress.

In order to examine the above mentioned suggestion, the time for the angular speed to decay from 1,000 revs/min to zero was plotted as a function of the initial wall shear stress in figure 15 for bleached hardwood and softwood kraft pulps and two types of rayon fibres. The data presented in this figure present the results obtained with suspensions of different concentrations, temperatures, and degree of beating. Although the experimental conditions are considerably different, it was found that the data for each type of fibre belonged to one or other of two master curves. This means that for a certain type of fibre the motion decay time is determined only by the value of the initial

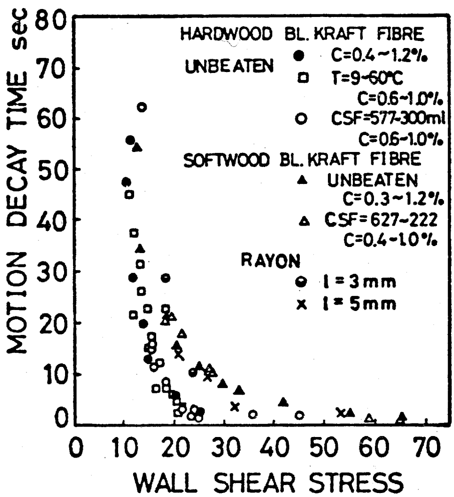

Fig 16—The relation between the motion decay time and the corresponding wall shear stress at various conditions.

shear stress induced by a given rotation speed, irrespective of other experimental conditions.

The data shown in figure 15 are separated into two groups: the first one is for the results from the short-fibred hardwood kraft pulp while the second is composed of the results from the long-fibred softwood kraft pulp and the two types of rayon fibre. This difference might be related to the appearance of the plateau in the wall-force time-decay curve for long-fibred suspensions discussed in the preceeding section.

Conclusion

It was confirmed that a significant correlation exists between the bending properties of wetted single pulp fibres and the flexibility defined as (Fibre Length)^3/Torsional Rigidity, and that the flexibility depends on the degree of beating, the fibre length, and the pulp yield. From the experimental results on the visco-elastic properties of pulp suspensions using the new apparatus, the following conclusions could be drawn.

The wall force-time decay curves for the fibre suspension proved to show characteristic shapes different from that for pure water. These shapes depend upon the concentration, mean fibre length, and the type of fibres. The temperature of the suspension and the degree of beating also were found to have effects on the shapes of the decay curves. Consequently, the wall force-time decay curves seem to show the formation process of the fibre network in pulp suspensions. And it was understood that the flexibility of the fibre, along with its length, concentration, and temperature, are important factors in the formation process and the strength of the network.

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Transcription of Discussion

Discussion following paper given by Dr. T. Kadoya

Dr. D. Wahren, IPC: Chairman

What is the significance of the decay constant? It must be a function of both the size of the beaker and the network strength. Can you explain what determined the size of beaker you used?

Mr. M. Iwasaki (for Dr. Kadoya, University of Tokyo, Japan)

The size of the beaker was governed by the need to maintain temperature uniformity and to achieve good fibre dispersion.

Prof. K.I. Ebeling, Helsinki University of Technology, Finland.

In figure 12 you show that the wall stress increases as the degree of refining increases. For how far would you expect this trend to continue? It presumably can't continue to increase indefinitely, so there must be some limit of refining, beyond which it will have no further effect on the wall stress. Have you any ideas when this limit might occur?

Dr. D. Wahren

Yes, we know too that the network strength drops as the freeness increases. But we don't know if that effect continues indefinitely. Your results might have some bearing on that.

Mr. M. Iwasaki (for Dr. Kadoya)

Yes, I agree with you about the network strength, but we do not know about the refining limit.

Dr. J.R. Parker, Bowater Technical Services Ltd., UK

Would you please explain why, in figures 3 and 4, you plot the cube of fibre length divided by torsional rigidity?

Mr. M. Iwasaki (for Dr. Kadoya)

Because there is a theoretical relationship between these two quantities.