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INFLUENCE OF THE MORPHOLOGY OF WOODPULP FIBRES ON PAPER PROPERTIES

H. E. DADSWELL AND A. J. WATSON

DIVISION OF FOREST PRODUCTS, COMMONWEALTH SCIENTIFIC AND
INDUSTRIAL RESEARCH ORGANISATION, MELBOURNE, AUSTRALIA

Synopsis

The present knowledge of the manner in which pulp strength properties and papermaking are influenced by the fibre morphology of the original wood is discussed.

Fibre length has been shown to be particularly important for tearing resistance; it is of less importance for properties more related to fibre bonding. The thickness of the cell wall has an important bearing on most paper properties. Fibres with a thick cell wall give bulky, coarse surfaced sheets, whereas those with a thin wall give dense, well-formed sheets. The thick-walled fibres adversely influence bursting strength, tensile strength and particularly folding endurance, but they enhance tearing resistance, particularly when they are long. Basic density of the wood, which is indicative of cell wall thickness, may be used for assessing the value for papermaking of wood from within any one tree, from within a species or from the many species of one genus, the lower the basic density the better the general papermaking properties. In hardwoods, the vessel elements contribute little towards strength and cause trouble in printing. There is little evidence that cell diameter or the cell length/diameter ratio, in themselves, have any significant influence. The organisation of the cell wall in the individual fibres can influence paper properties. This is shown quite clearly when reaction wood fibres, which possess a markedly different organisation from that of normal wood fibres, are considered.

L'influence de la morphologie des pâtes de bois sur les propriétés du papier

On expose les connaissances actuelles sur la façon dont les caractéristiques de résistance des pâtes et la fabrication du papier sont influencées par la morphologie de la fibre du bois. Bien que la longueur de la fibre soit d'une importance particulière en ce qui concerne la résistance au déchirement, elle a moins d'influence sur les caractéristiques plus directement liées à la liaison entre fibres. L'épaisseur de la paroi des trachéides a une grande influence sur la plupart des propriétés du papier. Les fibres à parois épaisses donnent des papiers bouffants à surface rugueuse, tandis que les fibres à paroi mince fournissent des feuilles denses et uniformes. Les fibres à paroi épaisse influencent défavorablement les résistances à l'éclatement, à la traction et au pliage, mais elles augmentent celle au déchirement, surtout si elles sont longues. La densité du bois, en rapport direct avec l'épaisseur de la paroi est donc très utile pour prévoir la valeur papetière du bois provenant d'un arbre quelconque ou d'une espèce (ou du bois des plusieurs espèces du même genre). Plus la densité est basse dans chacun de ces cas, meilleures sont les caractéristiques papetières. Dans le cas des feuillus, les vaisseaux apportent peu en ce qui concerne la résistance et en plus provoquent des perturbations à l'impression. Il y a peu de preuve que le diamètre de la fibre ou le rapport longueur/diamètre ait, en soi, une influence significative. La structure de la paroi des fibres individuelles peut influencer les caractéristiques papetières. Ceci ressort clairement dans le cas des bois de réaction, dont la structure diffère beaucoup de celle des bois normaux.

Einfluss der Morphologie von Holzzellstoffasern auf die Papiereigenschaften

Nach einer Diskussion über die gegenwärtige Kenntnis des Einflusses, den die Fasermorphologie des ursprünglichen Holzes auf die Stoffestigkeit und die Blattbildung hat, wurde die Faserlänge in ihrer besonderen Bedeutung für die Durchreissfestigkeit behandelt. Für diejenigen Eigenschaften, die von den Zwischenfaserbindungen abhängen, ist sie weniger wichtig. Die Zellwanddicke wirkt sich auf die meisten Papiereigenschaften aus. Dicke Zellwände führen zu einem auftragenden Blatt mit rauher Oberfläche, dünnwandige Fasern zu einem dichten, gleichmässigen Blatt. Dickwandige Fasern beeinflussen Berstdruck, Reisslänge und besonders die Falzzahl

negativ, erhöhen aber die Durchreissfestigkeit und zwar in besonderem Masse, wenn die Fasern gleichzeitig lang sind. Daher ist die ursprüngliche Holzdichte, die von der Zellwanddicke abhängt, zur Beurteilung der Blattbildungseigenschaften des Holzes das von einem gewisssen Baum, einer gewissen Art oder den vielen Arten (Spezies) einer ganzen Gattung genommen worden ist, sehr nützlich. Je niedriger die ursprüngliche Dichte, umso bessere Blattbildungseigenschaften sind zu erwarten. Bei Laubholz tragen die Gefässzellen nur wenig zur Festigkeit bei und verursachen Schwierigkeiten beim Bedrucken. Es gibt wenig Hinweise dafür, dass der Zellendurchmesser oder das Verhältnis von Zellenlänge: Durchmesser einen signifikanten Einfluss haben. Der Aufbau der Zellwand innerhalb der einzelnen Faser kann die Papiereigenschaften beeinflussen, was ganz deutlich bei Reaktionsholzfasern aufgezeigt wurde, die sich klar von normalen Holzfasern unterscheiden.

Introduction

THIS paper considers the influence on papermaking properties of (*a*) the size and shape of the wood fibre* and (*b*) its general organisation. The discussion will be limited to chemical woodpulps, but no consideration will be given to the way in which paper properties may be influenced by their chemical characteristics or by the addition of non-fibrous constituents to the pulp. Other wood elements such as vessels, ray and vertical parenchyma influence certain paper properties, even though they do not form a substantial part of the pulp furnish. Present knowledge of their effects will be reviewed.

Although it has been recognised for many years that some wood fibres are better than others for papermaking, the amount of information in the literature on the influence of fibre characteristics on paper properties is rather limited. Some writers have treated the subject in a purely qualitative manner. In other cases, there are quantitative details relating to fibre properties, but the way in which these are correlated with paper characteristics is supported only by general observations, not by experimental data. Similar generalisations are made also about the manner in which experimentally determined variations in paper properties may be influenced by the fibre characteristics.

Therefore, in the present discussion, only those results that are based on experimental data relevant to both the characteristics of the fibres and to the papermaking properties of the same fibres, have been considered.

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* The term *fibre* is used to include both the tracheid of the softwoods and the fibre of the hardwoods.

Fibre characteristics influencing paper properties

BEADLE(1) and Cross and Bevan(2) in their respective books on papermaking have referred, in a qualitative sense, to the importance of different fibre characteristics in promoting certain properties of the paper made from these fibres. It was not until the 1930s, however, that any real advance was made in relating fibre characteristics to paper properties. By this stage, the development of reliable paper testing procedures had greatly facilitated such investigations.

Woodpulp fibres may be thought of as long thin hollow cylinders, somewhat tapered at both ends. As such, they will vary in total length, in diameter, in the ratio of length/diameter and in the thickness of the cell wall. In addition, some hardwood fibres in particular depart from this usual cylindrical shape and have a rather bulky mid-section with thin tapering ends. Variations in the fine structure of the cell wall of different types of fibres also have a bearing on papermaking properties.(3)

It is our intention to consider the various aspects of fibre morphology and the influence of each one of these on paper strength properties.

Fibre length

It has been considered for many years that a pulp containing long fibres will give a high quality paper. This concept probably arose from the fact that the fibres originally used for papermaking (mainly cotton or linen fibres derived from rags) were quite long and it was thought desirable that the wood fibres substituted for them should resemble them as closely as possible. Nearly 40 years ago, however, Benjamin(4) demonstrated that some of the Australian eucalypts gave satisfactory grades of pulp despite their short fibre length (about 1 mm).

Doughty(5) prepared sulphite pulps from spruce and black gum to give pulps differing widely in fibre length. Although he concluded that fibre length had a considerable effect on the tensile strength of a sheet of paper he realised that differences other than fibre length could have influenced the result. (It would appear, in the light of present knowledge, that his results could be better interpreted in relation to the influence of cell wall thickness.) He observed also that paper made from long-fibred pulps had a higher tearing resistance than that made from shorter fibres.

Brainerd(6) reported various test results obtained with pulp fractions. The longest fibres—those retained on a 14 mesh screen—gave the strongest paper, particularly in tearing resistance.

One of the most important contributions to this study was made by Clark,(7) who has described a procedure for the measurement of the 'average fibre length by weight'. He emphasised the importance of understanding what was meant by *fibre length* and discussed how fines could influence the measurement of the 'average' fibre length.

Fractionation procedures have been used quite extensively in studying the influence of fibre characteristics on paper properties, but the results have given only general information on the interrelationships. It was realised at an early date(8) that, although pulp classifiers gave some separation of fibres into different length fractions, the fractions differed among themselves in other properties, the finest containing other wood elements in addition to the fibre debris. This fraction has also been shown to differ chemically from the other fractions.(7)

A technique to give fibres of different lengths, while avoiding most of the other variables inherent in fibre fractionation procedures, was used by Brown(9) and subsequently by other workers. Brown cut paper into narrow strips with a sharp knife, repulped the pieces and formed handsheets. Such a procedure ensured that the main difference between the original paper and that made from the repulped paper strips would be in fibre length. All paper strength properties, particularly tearing resistance, were impaired by this reduction in fibre length, but properties such as bulk were not affected.

Clark(7) cut viscose fibres into a series of predetermined lengths using a sharp guillotine and formed handsheets from the various fibre length fractions, using a mucilage to assist fibre bonding. Similar techniques have also been applied more recently using staple fibre,(10) cotton(11) and nylon.(12) By this approach and by the careful fractioning of pulps, Clark(7) established the following empirical relationships between paper strength and fibre length—

$$\begin{aligned}\text{Burst factor} &= k_1L\\ \text{Breaking length} &= k_2L^{0\cdot5}\\ \text{Rigidity factor} &= k_3L^{0\cdot5}\\ \text{Tear factor} &= k_4L^{1\cdot5}\end{aligned}$$

where L=weighted average fibre length.

In recent investigations, particularly those carried out in our laboratories, the aim has been to ascertain the correlation, if any, between the fibre length of the wood as it occurs in the tree and the strength properties of the pulp made from such wood. To this end, experiments have been designed so that only one feature, in this case the fibre length, is varied while all others remain constant.

In the first instance, Watson *et al.*(13, 14) used the fact that the average fibre length increases through successive growth rings from the pith outwards at any one level in any selected tree. It was found possible to select cross-sections of samples of *Pinus radiata* and *Pinus taeda*, from which the wood of each growth ring could be separated in sufficient quantity to be pulped. The papermaking properties of these various pulps were then determined. The variation in average cell length was reflected in the various strength properties. The variation in fibre properties, other than cell length, however, made it difficult to assess the effect that fibre length had on paper strength. A further investigation was planned in which fibres were cut to predetermined lengths to ascertain the influence of fibre length on paper properties.(15, 16)

Wood from the outer growth zones of a mature tree of *Araucaria klinkii* with an average fibre length of approximately 8 mm was chipped and then delignified by treatment with acidified sodium chlorite solution. The delignified chips would not separate into individual fibres unless treated with dilute sodium hydroxide solution. It was therefore possible to cut them to predetermined lengths (1, 2, 3, 4, 5, 6 and 7 mm) using a hand guillotine and treat them with alkali to liberate the individual fibres, on which average lengths were determined. Photomicrographs of these cut fibres are shown in Fig. 1.

Each batch of pulp was made into handsheets using either unbeaten material or material beaten for 30 min in a high-speed laboratory stirrer. Tear factor and breaking length were measured on these handsheets: the results are shown in Fig. 2. The actual fibre lengths were in general agreement with the chip length up to about 4 mm, beyond which the shorter fibre ends caused a progressive departure from the predetermined length.

For handsheets made from the unbeaten pulps, tearing resistance showed a direct linear correlation with fibre length; the other properties measured were not affected. For the beaten pulps, tearing resistance still showed a linear relationship with fibre length; breaking length and folding endurance also increased with fibre length, but appeared to reach a constant value at a fibre length of 4–5 mm.

It is generally recognised that fibre bonding is important for the development of breaking length; it is obvious that fibre bonding is poorly developed in the handsheets made from the unbeaten pulps (Fig. 2) and that the main, possibly the only factor responsible for the tearing resistance is the fibre length. Even when the fibre bonding has been developed by beating, it is clear that the tearing resistance is still controlled mainly by the length.

Similar general results were obtained with handsheets prepared from sulphate pulps made from the same bulk sample of *A. klinkii*, but with chips sawn to predetermined lengths in the longitudinal direction.(16)

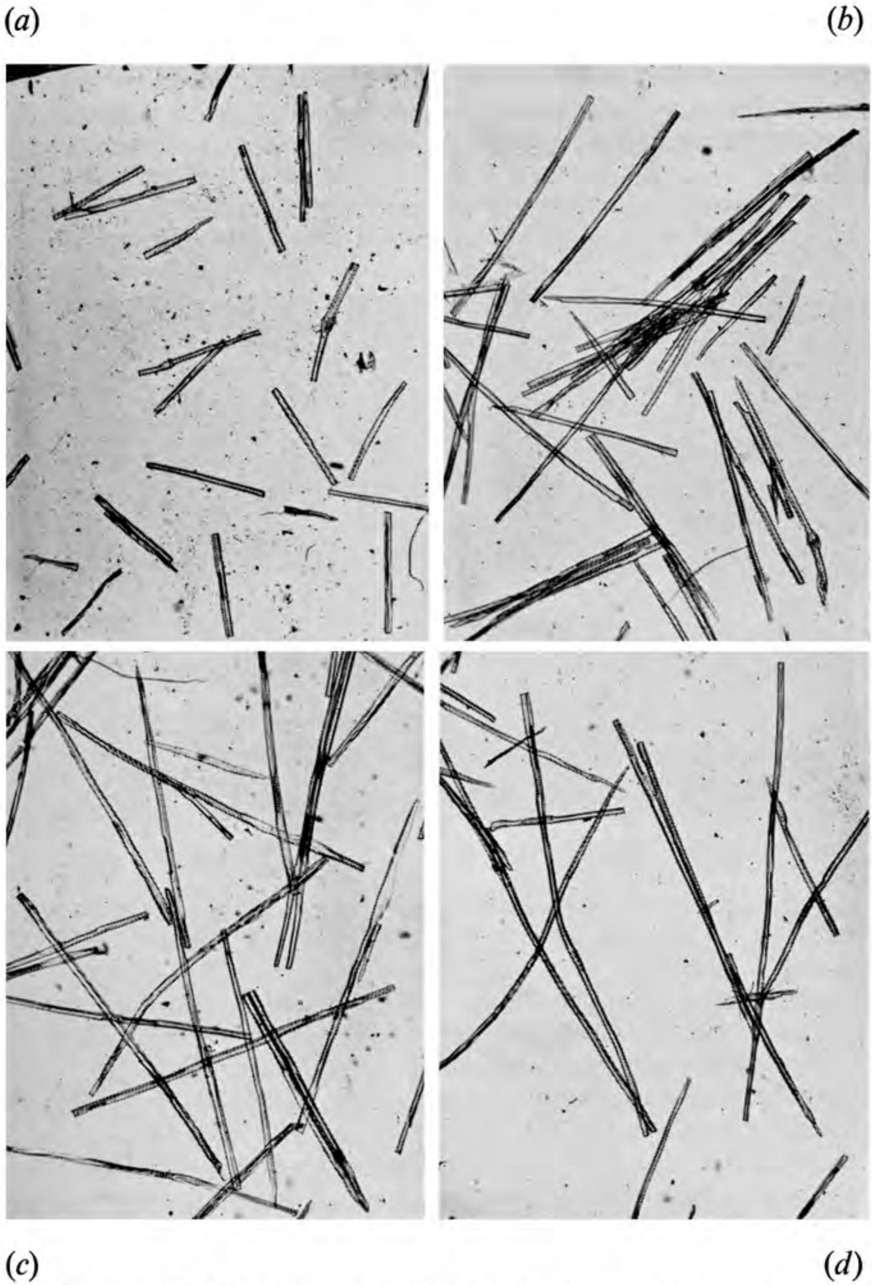
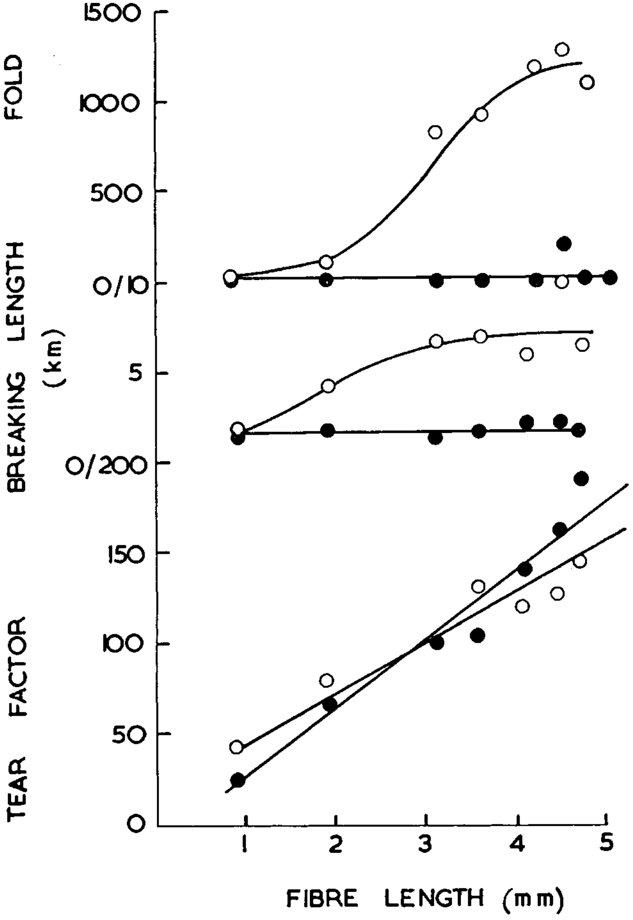


Fig. 1*—Araucaria klinkii* fibres cut approximately to (*a*) 1 mm, (*b*) 2 mm, (*c*) 3 mm and (*d*) 4 mm in length (from Higgins and Goldsmith(17))

Fibres differing widely in fibre length may also be obtained by collecting juvenile wood from near the pith and mature wood from the zone adjacent to the bark. Such a procedure gives fibres differing in properties other than fibre length, but it does permit samples large enough for fairly detailed studies. Pulps made from the inner and outer growth rings of different species,



● Unbeaten pulps
○ Beaten pulps made from cut fibres prepared from *Araucaria klinkii* holocellulose (30 min in laboratory high-speed stirrer)

Fig. 2—Influence of fibre length on strength properties

both hardwoods and softwoods,(6) have supported the view that fibre length has an important influence on tearing resistance, but that it is not a major factor in other paper properties.

Fibre length can also influence the general structure and surface properties of a paper sheet. It is well known that hardwood pulps differ in their papermaking properties from pulps derived from softwoods, but it is not possible to ascribe their different papermaking properties solely to differences in fibre length. However, investigations by Watson *et al.*(13) using sulphate pulps prepared from *Pinus radiata* with fibres of 1·7 mm and 3·0 mm in length, but similar in other morphological and chemical properties, clearly demonstrated the influence of fibre length on sheet structure. Micrographs of very thin handsheets made from unbeaten pulps from each set of fibres are shown in Fig. 3. It is clear that the longer fibres give a sheet with a much more open structure. This was supported by the higher bulk and much lower air resistance values for the handsheets made from the pulp with a fibre length of 3·0 mm.


(*a*) (*b*)

Fig. 3—Influence of fibre length on sheet formation—thin paper sheets made from *Pinus radiata* sulphate pulps from (*a*) fibres 1·7 mm long and (*b*) fibres 3·0 mm long

Moreover, long-fibred pulps have a greater tendency towards clotting than have short-fibred pulps. This characteristic is reflected in the papers made from the two types of pulp, long fibres giving a more uneven structure; in extreme cases, large clots being evident in the paper structure. It has been demonstrated,(18) however, that fibre properties have less influence in general on paper formation than factors such as the presence of electrolytes, stock concentration, beating and fibrillation.

Present position—The information now available enables a good assessment to be made of the importance of fibre length in relation to the properties of paper prepared from the one species. It is the dominant factor controlling the tearing resistance of paper, long fibres producing paper with the highest tearing resistance. Other paper properties can be improved by processing (beating and addition of mucilages), but all such treatments have an adverse effect on tearing resistance once sufficient fibre bonding has been achieved to give maximum tear. Increase in fibre length causes only a small improvement in properties such as bursting strength, tensile strength and folding endurance. Except for tear, it appears that there is little gain in having a fibre length in excess of 4–5 mm. Both bulk and porosity increase to some extent with increasing fibre length, the sheet having a more open and coarser structure.

Fibre length/diameter ratio

Although the idea that the fibre length/diameter ratio has an important influence on paper properties is widely held, there is little evidence to support it. Hägglund,(19) when examining the general relationships between fibre properties and paper strength, commented that other factors were of much greater importance than this ratio. It is probable that the similarity observed between the length/diameter ratio for pulps derived from both softwoods and hardwoods is responsible for the wide acceptance of its importance as a guide to pulp quality. This provided a ready explanation why good quality pulps could be made from the hardwoods that had previously been considered as quite unsuitable for papermaking.

In an endeavour to get some experimental data on the influence of length/diameter ratio on paper properties, sulphate pulps were prepared from a number of hardwoods and subsequently bleached, using sodium chlorite. Fibre lengths and diameters were measured for the various pulps. The properties of handsheets made from some of these in the unbeaten state are shown in Table 1.

These pulps were selected as having (*a*) similar fibre diameters, with fibre length and consequently the length/diameter ratio, gradually increasing;

TABLE 1—INFLUENCE OF THE L/D RATIO⁽¹⁾ ON PROPERTIES OF HANDSHEETS MADE FROM UNBEATEN, BLEACHED HARDWOOD SULPHATE PULPS

(*a*) *Fibre diameter maintained constant* (*b*) *L/D ratio maintained constant*

No.	*Species*	*Fibre length, mm*	*Fibre diameter, μ*	*L/D*	*Bulk*	*Burst factor*	*Stretch, %*	*Breaking length, km*	*Tear factor*	*Air resistance, sec*	*Fold (Köhler-Molin)*	*Freeness,* CSF
(*a*)	*Eucalyptus regnans*	1·05	22	48	1·69	43	2·3	7·0	120	15	42	421
	Eucalyptus fastigata	1·14	23	50	1·98	34	2·8	6·1	109	4	24	430
	Acmena smithii	1·32	22	60	2·04	22	1·8	4·4	77	4	10	401
	Acmena hemiphloia	1·47	24	61	1·81	26	2·1	4·8	92	35	17	235
	Syzgium francisii	1·62	24	68	2·11	25	2·1	4·4	110	4	11	563
	Syzgium francisii	1·69	23	74	2·22	22	2·1	4·5	130	3	11	557
(*b*)	*Eugenia leuhmannii*	1·94	29	67	2·19	23	1·6	4·4	138	1	13	636
	Syzgium francisii	1·62	24	68	2·11	25	2·1	4·4	110	3	17	235
	Syzgium samarangensi	1·99	29	68	2·23	14	1·8	2·9	94	1	4	662

⁽¹⁾ L = length of fibre; D = diameter of fibre (*b*) a similar length/diameter ratio, but with differing values for fibre length and fibre diameter. The third alternative of keeping the fibre length constant and varying the ratio by selecting fibres of different diameter proved to be impracticable, because fibres with similar diameters showed little variation in length.

Examination of the test results in Table 1 does not show any systematic relationship between the length/diameter ratio and the various paper properties. Even if this ratio has some effect on paper properties, its influence is small compared with the effect of fibre length and cell wall thickness (see next section).

Cell wall thickness

The importance of the thickness of the fibre wall on the properties of the paper had been recognised for a number of years, but few attempts have been made to obtain a numerical correlation between wall thickness and any particular strength property. This is not surprising, because, although the measurements of fibre length and fibre diameter present some technical problems and are rather tedious and time-consuming, they are much simpler operations than those involved in determining cell wall thickness. Because of the variation from tree to tree, within a tree, even within one growth ring, quite a number of measurements are involved in providing adequate information.

Timbers from temperate regions have clearly defined growth rings (Fig. 4). The early wood (springwood) portions of the growth ring have fibres with comparatively thin cell walls and the late wood (summerwood) portions of the same growth ring have fibres with much thicker cell walls, this being the only major difference between these two types of fibre. The different papermaking properties of early wood and late wood were early recognised by Cross and Bevan.(2) Later, Nilssen(20) separated early wood zones from late wood zones in selected pines and pulped these independently. Papers made from pulps derived from the late wood had higher tearing resistance, but lower bursting and tensile strengths, than those made from pulps from the early wood. During the 1930–40 decade, workers at the United States Forest Products Laboratory investigated the effect of percentage late wood, using specimens of the Southern pines of the United States, in which varying amounts of late wood were present.(21–24) By selecting extreme cases, it was possible to prepare pulps from samples in which the percentage of late wood varied 25–65 per cent. Those pulps obtained from the wood in which a high percentage of early wood occurred gave dense well-bonded sheets; those from late wood, open and bulky sheets with high tearing resistance. The general appearance of paper made from thick-walled and thin-walled fibres is clearly shown in the photomicrographs of very thin sheets made from 100 per cent late wood and 100 per cent early wood of sulphate pulps from *Pinus taeda* (Fig. 5). Similar results were obtained with Douglas fir specimens, containing varying amounts of late wood.(25) It was suggested(23) that the thin-walled cells collapsed when being formed to give a dense, closely bonded sheet of paper.

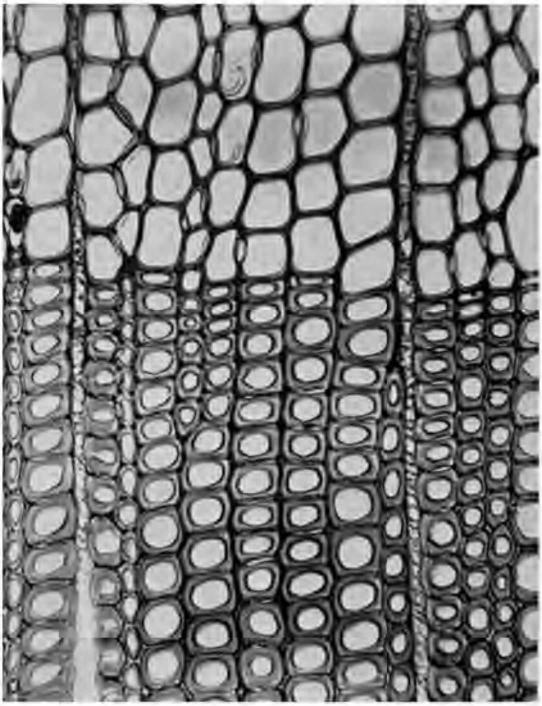


Fig. 4—Cross-section of *Pinus taeda* showing bands of late wood and early wood

The influence of cell wall thickness on the structure of the paper sheet is evident also in the cross-sections of handsheets shown in Fig. 6. The handsheets were made from bleached sulphate pulps prepared from *Pinus taeda*;(14) one pulp was prepared from wood containing thin-walled fibres, the other from thick-walled fibres. The fibre dimensions of these pulps and their paper properties are given in Table 2 (pulps No. 1 and 4). The only important difference between these two sets of fibres was in cell wall thickness. Examination of Fig. 6 shows the much closer structure of the paper made from the thin-walled fibres. The high air resistance and low bulk values obtained for the papers made from the thin-walled fibres support these observations. It will be observed that fibre cross-sections can be seen in paper made from both the thin-walled and the thick-walled fibres. Both thin-walled and thick-walled fibres can be observed in the uncollapsed state. This aspect is discussed later in this paper.

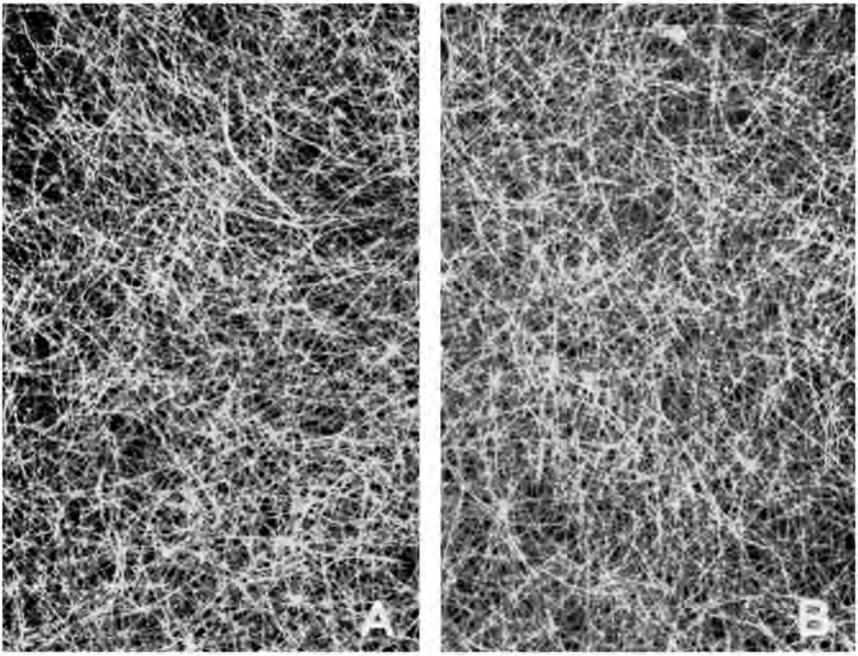


Fig. 5—Influence of cell wall thickness on sheet formation—thin sheets made from *Pinus taeda* sulphate pulps from (*A*) late wood, (*B*) early wood

Kress and Ratcliff(26) concluded that the differences in papermaking properties between pulps from various softwood species could be attributed mainly to the differences in amounts of late wood present in the original wood. A high percentage of late wood always resulted in the formation of bulky sheets with high tearing resistance.

More recent workers(14, 27) have followed the techniques of Nilssen and separated the late wood from the early wood, pulping each separately. They obtained results similar to those of Nilssen and these again indicated that the pulps from the late wood did not respond readily to beating. Tearing resistance was high in papers prepared from late wood pulps, but all properties associated with fibre bonding were rather low. On the other hand, the pulps made from the early wood developed strength readily on beating and gave dense, well-formed sheets with high bursting and tensile strength, but relatively low tearing resistance.

Mulsteph(28) classified wood cells into four groups based on measurements of wall area in the total cross-section of the fibre. He found that papers with good strength properties were usually obtained from pulps from fibres with comparatively thin cell walls. Runkel,(29) in investigating a wide range of species, mainly hardwoods, found that the papermaking properties of the pulps prepared from these species could, in general, be assessed in relation to the cell wall thickness and the lumen diameter. He observed that the fibres isolated from these woods were unsuitable for papermaking if the ratio $2w/l$ (where w is the cell wall thickness and l is the lumen diameter) was greater than 1. On the other hand, if $2w/l$ was approximately 1, the fibres were satisfactory for papermaking and were particularly suitable when the ratio $2w/l$ was less than 1. From his work, it was clear that cell wall thickness played a dominant role. The general validity of his ratio has been confirmed by many other investigators.

Fig. 6—Section through handsheets made from (*a*) late wood fibres and (*b*) early wood fibres from *Pinus taeda*

As cell diameter, wall thickness and fibre length are all interrelated, it is difficult to isolate the influence of cell wall thickness while keeping all other properties constant. However, selection of some of the results reported by

TABLE 2—INFLUENCE OF CELL WALL THICKNESS ON HANDSHEETS MADE FROM UNBLEACHED AND BLEACHED SULPHATE PULPS FROM PINUS TAEDA(14)

Samples selected to maintain fibre length and fibre diameter as constant as possible

Pulp	*Sample no.*	*Beating rev.*	*Fibre dimensions*			2w/l*	*Bulk*	*Burst factor*	*Breaking length, km*	*Tear factor*	*Air resistance, sec*	*Fold (Köhler-Molin)*	*Freeness,* CSF
			Length, mm	*Diameter, μ*	*Cell wall thickness, μ*								
Unbleached	1	0	2·99	36	3·6	0·26	1·85	59	5·4	258	4·4	4 810	712
	2	0	2·81	37	3·8	0·26	1·72	49	4·3	234	3·2	2 655	704
	3	0	2·61	33	4·0	0·32	1·81	57	5·0	232	4·6	3 316	702
	4	0	2·99	36	6·1	0·53	2·57	22	2·6	243	0·5	39	766
	0	0	2·80	33	6·3	0·60	2·46	24	2·8	229	0·5	59	762
Bleached	1	0 9 000	2·99	36	3·6	0·26	1·50 1·37	75 97	6·7 9·8	242 130	29·9 17·8	4 771 4 572	665 594
	2	0 9 000	2·81	37	3·8	0·26	1·54 —	70 —	5·9 —	254 —	19·2 —	4 139 —	— —
	3	0 9 000	2·61	33	4·0	0·32	1·49 1·34	72 95	6·4 9·3	224 141	25·0 39·9	2 993 3 687	646 588
	4	0 9 000	2·99	36	6·1	0·53	1·86 1·56	40 61	3·3 6·4	297 231	0·5 0·5	148 1 013	736 650
	5	0 9 000	2·80	33	6·3	0·60	1·83 1·52	37 59	3·4 6·4	280 219	0·5 1·5	106 1 143	739 642

* w = cell wall thickness, l = lumen diameter

Watson and Hodder,(14) using pulps made from the early wood and late wood of different growth rings of *Pinus taeda*, in which all characteristics other than cell wall thickness are relatively constant, demonstrate clearly the influence of this feature on the paper strength. The results obtained with two groups of fibres, using both unbleached and bleached sulphate pulps, are given in Table 2. It is clear that any appreciable increase in cell wall thickness causes a marked reduction in bursting strength, breaking length, folding endurance and air resistance; on the other hand, tearing resistance shows a slight increase.

All comparisons between thick-walled and thin-walled fibres have been made at a common sheet weight. Under these conditions, there will be a smaller number of fibres in the paper made from the thick-walled fibres, hence fewer interfibre bonds are possible.

If it is assumed that the fibres are long hollow cylinders and that the specific gravity of cellulose is 1·60, the number of fibres in a given weight of paper can be calculated if the fibre length, diameter and wall thickness are known. Using this as a basis, strength data for papers made from various pulps can be calculated on the basis of an equal number of fibres per unit area. Some of the actual strength data given in Table 2 have been recalculated on a basis of 22×10^7 fibres per m^2; this number of fibres per m^2 was actually calculated for sample No. 2. The results of such a recalculation are set out in Table 3. All the other samples contained a greater number of fibre per m^2, therefore the strength data for them have been reduced proportionately.

From Table 3, it is clear that burst factor and breaking length, two properties which depend largely on fibre bonding for their development, show only small differences whether thick-walled or thin-walled fibres are used in the preparation of the paper. With beating, any small difference between the two types of fibre almost disappears. The main reason that papers made from thick-walled fibres are inferior in bursting and tensile strength is that paper is made on a weight basis; the poorer strength is largely a reflection of the smaller number of fibres in the paper. When the tear factor is expressed on the basis of a common number of fibres, it is clear that it is greatly enhanced by the thicker cell wall. This applies even when fibre bonding has been improved by beating.

The only important difference between the fibres in pulp samples No. 1–5 (Tables 2 and 3) is in cell wall thickness and it is evident that this factor is the major one governing tearing resistance. If the tear factor values given in Table 3 are examined, it will be observed that within the thick-walled and thin-walled groups of fibres the tearing resistance is greatest for the longest fibres. This would be expected from the earlier discussion above.

TABLE 3—STRENGTH DATA FROM TABLE 2 CALCULATED ON THE BASIS OF 22 × 10^7 FIBRES/m^2

Pulp	*Sample no.*	*Beating, rev.*	*Sheet thickness, μ*	*Burst factor*	*Breaking length, km*	*Tear factor*
Unbleached	1	0	111	37	3·4	162
	2	0	103	31	2·8	150
	3	0	109	32	2·8	132
	4	0	154	22	2·6	243
	5	0	157	21	2·5	210
Bleached	1	0	90	46	4·2	150
		9 000	82	60	6·1	81
	2	0	92	45	3·8	143
		9 000	—	—	—	—
	3	0	89	41	3·6	128
		9 000	80	54	5·3	65
	4	0	112	40	3·3	297
		9 000	94	61	6·4	231
	5	0	111	33	3·0	246
		9 000	91	52	5·6	193

Assuming a linear relationship between fibre length and tearing resistance, the results in Table 3 have been calculated for a common fibre length and plotted against the cross-sectional area of the fibres (Fig. 7). Despite the difficulty inherent in measuring the cross-sections of the fibres, it is clear that there is a strong linear relationship between tearing resistance and cross-sectional area.

The tearing resistance values reported in Table 3 and shown in Fig. 7 also provide strong evidence that the thickness of the cell wall does not, in itself, have any great influence on bonding properties. If the thick-walled fibres were poorly bonded they would be pulled readily from the paper web during tearing and give low test values. The high tearing resistance obtained with the thick-walled fibres indicates that bonding is sufficiently well developed to cause the fibres to be broken during the actual test itself.

Present position—Cell wall thickness is a most important factor in relation to paper formation and paper strength. Fibres with thick cell walls give bulky sheets with an open porous structure, whereas thin-walled fibres form well-bonded, dense sheets. With long-fibred pulps, an increase in cell wall thickness is usually accompanied by an increase in tearing strength; this relationship does not hold in general for paper made from short-fibred pulps.

Papers made from fibres with thick cell walls are low in bursting and tensile strengths. This is due partly to the better bonding properties of the thin-walled fibres, but mainly because in practice paper is made to a given weight per unit area. Thus, when all fibre characteristics other than the thickness of the fibre wall are constant, papers made from the thicker-walled fibres contain fewer fibres for the same weight of paper than papers made from thin-walled fibres. The reduced opportunity of fibre-to-fibre bonding is then reflected in lower bursting and tensile strengths. It may, however, be misleading to attempt to interpret paper properties only in terms of cell wall thickness.

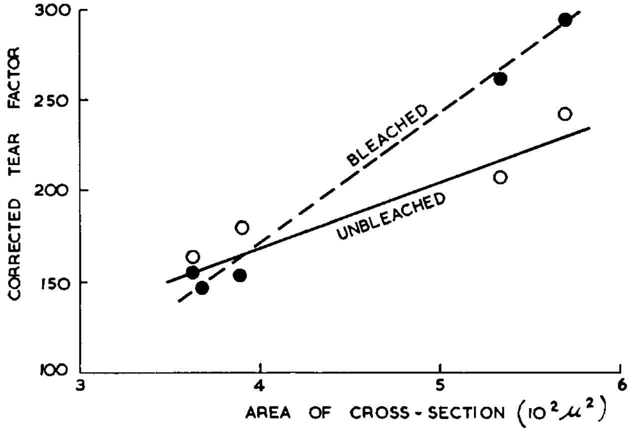


Fig. *7*—Relationship between cross-sectional area of fibres and tear factor

Cell wall organisation

The secondary wall in a wood fibre is made up usually of three distinct layers—the outer (S1), the middle (S2) and the inner (S3).(3, 30) The microfibrillar orientation varies in each of these layers. Recent work(31) has indicated that in the outer layer S1 there are two directions of the microfibrils, each at approximately 90° to the other. In the middle layer S2, the microfibrils are more closely packed together and generally arranged in one direction at only a small angle to the longitudinal cell axis. In those fibres in which the inner layer S3 is present, there is again predominantly one direction of microfibrillar orientation; this is at a large angle to the cell axis.

Not all fibres have the same organisation; in some cases, particularly in the case of fibres derived from reaction wood, different cell wall layering is present. For example, the compression wood tracheids (or fibres) do not have the layer S3 and, in the layer S2, the microfibrils are always arranged at a large angle to the longitudinal cell axis. In fibres derived from tension wood, there may be a variety of structures present. These have been referred to previously,(3) but it can be mentioned here that there is always an inner layer G in which the cellulose is highly oriented and the microfibrils are closely packed together in a direction nearly parallel to the cell axis. Although layer G is always present in the tension wood fibres, it may replace both the layers S2 and S3 or only layer S2 or may be present in addition to both these layers. In normal and softwood fibres, the microfibrillar orientation in each layer of the cell wall varies with changes in cell length. For example, in any one species, the shorter fibres show a larger angle of microfibrillar orientation to the longitudinal cell axis than do the longer fibres.

Little attention has been paid to this particular fibre property from the papermaking viewpoint. It is known, however, that the breaking load in tension of individual fibres is influenced by the angle of microfibrillar orientation in the layer S2;(32) the smaller the angle of orientation in this layer, the greater the tensile strength of the fibres. In a sheet of paper, however, it is problematical just how the tensile strength of the individual fibres affects the tensile strength of the sheet.

It is difficult to segregate effects due to changes in cell wall organisation with respect to changes in paper strength properties from the effects of cell length and cell wall thickness. From investigations using *Pinus taeda*,(14) it was not possible to correlate angle of microfibrillar orientation with any particular paper property, although in the pulps used both the cell length and the angle of microfibrillar orientation in each of the three layers of the secondary wall were changing.

One way of interpreting the effects of cell wall organisation is from results obtained from the examination of the strength properties of paper made from pulp derived from reaction wood fibres, both compression wood and tension wood, although here of course there are chemical as well as structural differences. In addition to their different cell wall organisation, compression wood fibres are shorter than comparable normal fibres and have much thicker cell walls. The poorer strength properties of papers made from these fibres could be due to differences in cell length and cell wall thickness compared with normal wood fibres or to the differences in cell wall organisation. The cell wall thickness does not differ greatly from that of normal wood fibres taken from late wood, but the compression wood fibres appear to have a more compact structure, they show less response to beating and give poorly bonded sheets. There may be a chemical explanation for this in that compression wood is known to have more cell wall lignin than has normal wood. It might be expected that the thicker cell walls of compression wood pulp would give paper with a higher tearing strength than paper made from normal wood fibres, but the converse actually applies.(3) Thus, there might be some correlation between this particular strength property and the cell wall organisation.

The tension wood fibres do not show any great variation in general dimensions from normal wood fibres of the same piece of wood, but they have a much thicker cell wall owing to the presence of the G layer.(3) As might be expected, the tension wood fibres yield bulky sheets with an open structure and these are much poorer in tensile and bursting strengths than are sheets made from normal wood pulp of the same species. The results conform with those reported earlier on the effect of cell wall thickness on paper properties. These fibres, too, do not respond to beating, but there is considerable evidence that this is a reflection of chemical composition.(3)

Wood elements other than fibres

The discussion so far has related only to the tracheids of softwoods and the fibres of hardwoods. Both of these have been considered under the general term of *fibres*, but there are other wood elements present in the pulp that may influence various paper properties. These are not of any practical importance in the case of the softwood pulps, because over 90 per cent of the wood volume in softwoods consists of fibrous tissue. In hardwoods, vessel elements and cells from both ray and vertical parenchyma occupy quite a percentage of the wood volume. The percentage of fibres in the wood volume will vary according to the structure of the hardwood species.(33)

In certain hardwoods—for example, eucalypts of the lightweight ash type, aspen and other species, in which the rays are not large and the amount of parenchyma is small in comparison with the other tissue—the volume of fibres may be as high as 80 per cent. In the various hardwoods, the individual elements of the vessels are, in general, shorter in length than the fibres of the same wood, but considerably greater in diameter. This diameter may vary from 300 μ in certain cases down to as low as 35–50 μ in other cases. Such vessel elements have much thinner walls than have the fibres and are readily damaged during pulping and beating. During sheet formation, some of the damaged pieces of the vessel elements, together with the parenchyma cells, will be lost. It has been stressed(32, 33) that considerable attention should be paid to this question of anatomy of hardwoods used for pulping; when the percentage of fibres by volume is low, the yields of pulp will be much less than might be expected from wood of the particular density.

There is little actual information available on the influence of the vessel elements or parenchyma on pulp strength properties. It would be expected from their general properties that they would only add to the fine fraction of the pulp, thus give a somewhat more compact sheet of paper. They would not necessarily make any contribution to the strength development, though they might make some contribution to the fibre bonding. Some support for this view is obtained from examination of the properties of paper made from the finest fraction of screened pulps.(8)

The vessel elements do, however, have an important effect on the surface properties of the paper. Because of their general shape, they do not bond readily with the fibres and when present on the surface of a paper tend to pick during printing.(34) This situation may be improved by the addition of suitable binders or by further beating of the pulp to break up the vessel elements and so improve the general structure of the paper.

General discussion

It is evident that some fibre characteristics exert a much greater influence on pulp strength properties than do others. In this respect, fibre length and cell wall thickness are the most important. Because of the interrelationship among fibre length, fibre diameter, cell wall thickness, cell wall organisation and chemical composition, however, it is difficult in practice to segregate the influence of any particular characteristic. When length is the only variable, its effect can, we believe, be clearly established, but the effect of cell wall thickness is not so easy to determine and it will vary from species to species.

Therefore, in some recent investigations, we have endeavoured to obtain more data on the influence of cell wall thickness on paper properties. Early wood and late wood of selected growth rings of plantation-grown species have been pulped separately and the pulps blended together in varying proportions. These blends were used to make handsheets of 60 g/m^2, which were used for the usual testing of paper properties.(35) The results obtained for various blends beaten for 9 000 rev in the Lampén mill, in the case of *Pinus radiata*, *Pinus pinaster* and *Pinus taeda*, are shown in Fig. 8. The burst factor, which is typical for all paper properties associated mainly with fibre bonding for strength development, shows the same general trend in all cases, the best results being obtained when only the thin-walled fibres from the early wood were present in the furnish. On the other hand, the tear factor shows a much more varied behaviour. In the case of pulps from the *Pinus taeda* (and to a lesser extent with *Pinus pinaster*), there was a rapid drop in tearing resistance of handsheets as the percentage of thick-walled fibres in the furnish decreased. With *Pinus radiata*, there was a much less pronounced drop in tearing resistance.

These particular experiments were designed to investigate the effect of the thick-walled fibres of the late wood of pines on paper properties. In the case of hardwoods, it is difficult to isolate the late wood and early wood bands, because of their much narrower growth rings. To obtain thick-walled and thin-walled hardwood fibres, it was necessary to use two species of the one genus and here we selected *Eucalyptus regnans* and *Eucalyptus hemiphloia*. The wood of the former species is comparatively low in density with thin-walled fibres, while the wood of the latter species is high in density with thick-walled fibres. The selection was made so that the average fibre lengths number

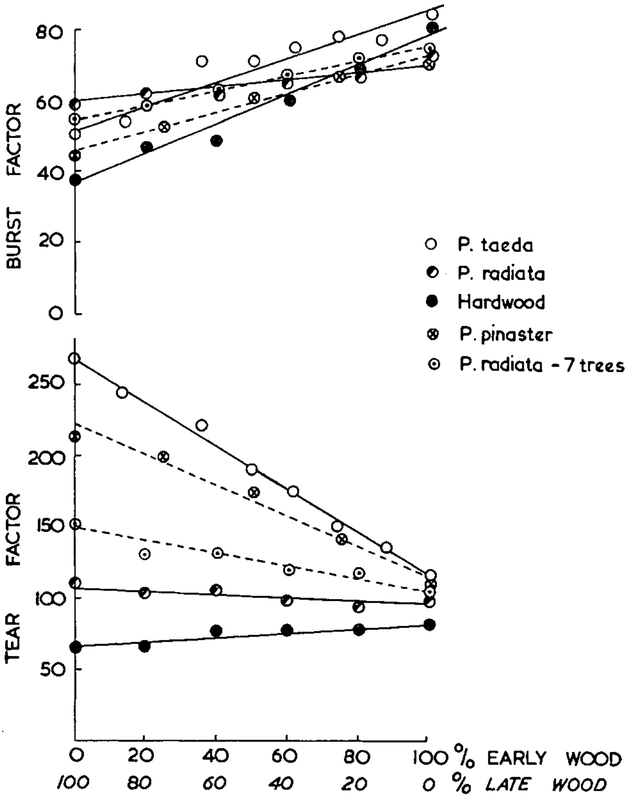


Fig. 8—Influence of late/early wood mixture on the bursting strength and tearing resistance of pulps beaten for 9 000 rev in the Lampén mill

of both samples (measured on whole fibres) was much the same. In this case, the blending of the thicker-walled fibres with the thinner-walled fibres did not assist the tear factor. From the point of view of bursting strength, the thin-walled fibres gave the best pulp. With the hardwood pulps, apparently their shorter fibre length does not permit the thicker-walled fibres to make a greater contribution to tearing resistance.

This work is only beginning, but it is apparent that for each species there is an optimum for the late wood/early wood ratio for any particular paper property; for *Pinus taeda* and *Pinus pinaster*, it would appear that a percentage of late wood between 20 and 40 would give the best general strength properties. In the case of *Pinus radiata*, it would seem that the smallest amount of late wood present would be consistent with good strength properties, but that an increase in the amount of late wood would not reduce the strength unduly. In the case of the hardwoods of the genus *Eucalyptus* type, the 100 per cent early wood type of pulp gives by far the best general properties.

It is most important to remember these facts, because of the attention now being paid to increasing the density of pulpwood species, particularly softwoods, in plantation-grown material. An increase in basic density means that a greater weight of wood can be charged into a digester giving a greater yield of pulp per charge. As the increase in density is usually associated with an increase in the percentage of late wood in most of the softwood species, it is evident that any change in density must be accompanied by some change in the papermaking properties of the pulp.

Basic density, which can be measured readily, can provide a useful indication of cell wall thickness, a high basic density being indicative of a thick cell wall. This relationship is quite definite within any one species, also within the many species of one genus such as *Eucalyptus*. Thus, the necessity of making rather difficult and time-consuming measurements of cell wall thickness can be avoided and the basic density values used as the required guide. The value of such a procedure is clearly shown in the comparison of the papermaking properties of two eucalypt species, namely, *Eucalyptus regnans* and *Eucalyptus marginata*.(15) In this particular comparison, it should be noted that the fibre length and fibre diameter of the two species were virtually identical, but the basic density for the *Eucalyptus regnans* specimen was approximately 30 lb/ft^3, while that of the *Eucalyptus marginata* specimen was 40·5 lb/ft^3. Table 4 shows the differences in pulp strength properties and these can be attributed, in view of the differences in basic density values, to the thicker cell walls of the pulp from the *Eucalyptus marginata*.

Cell wall thickness was not determined in these particular investigations,

TABLE 4—INFLUENCE OF BASIC DENSITY OF THE WOOD ON PAPER MADE FROM SULPHATE PULPS FROM E. REGNANS AND E. MARGINATA

(Fibre length and fibre diameter similar for both pulps)

	Basic density, lb/ft³	*Beating, rev.*	*Bulk*	*Burst factor*	*Breaking length, km*	*Tear factor*	*Air resistance, sec*	*Fold (Köhler-Molin)*	*Freeness,* CSF
Eucalyptus regnans	30	0	1·79	36	6·6	109	5·2	30	464
		1 125	1·62	49	8·6	135	5·4	81	478
		4 500	1·50	68	10·0	133	11·0	401	458
		9 000	1·42	78	10·8	123	43·1	1 734	363
		18 000	1·37	86	11·4	119	318·5	1 932	211
Eucalyptus marginata	40·5	0	2·04	19	4·4	70	1·2	8	453
		1 125	1·87	32	6·2	97	2·0	29	432
		4 500	1·71	46	7·9	117	6·9	145	291
		9 000	1·65	58	8·9	126	42·3	394	162
		18 000	1·57	66	9·6	129	185·9	1 603	72

but, using the basic density of the wood as an indication of cell wall thickness, the relative number of fibres present in a given weight of paper derived from pulps of each of the two species can be calculated. In the case of the *Eucalyptus regnans*, there will be approximately 135 fibres for every 100 fibres from *Eucalyptus marginata*. If the strength data given in Table 4 are calculated on this basis, the results shown in Table 5 are obtained. As with the earlier results obtained with *Pinus taeda* (Tables 2 and 3), it is clear that those paper strength properties depending on fibre bonding give similar values when expressed on an equal number of fibres basis, whereas the differences between tear factor values become more marked.

TABLE 5—DATA FOR BURST FACTOR, BREAKING LENGTH AND TEAR FACTOR FROM TABLE 4 CALCULATED TO A COMMON NUMBER OF FIBRES PER UNIT AREA FOR HANDSHEETS MADE FROM E. REGNANS AND E. MARGINATA

	Beating, rev.	*Burst factor*	*Breaking length, km*	*Tear factor*
Eucalyptus regnans	0	27	4·9	81
	1 125	36	6·4	100
	4 500	50	7·4	99
	9 000	58	8·0	91
	18 000	64	8·5	88
Eucalyptus marginata	0	19	4·4	70
	1 125	32	6·2	97
	4 500	46	7·9	117
	9 000	58	8·9	126
	18 000	66	9·6	129

Conclusions

PRESENT knowledge of the influence of fibre characteristics on paper properties may be summarised as follows—

1. The length of the fibre in the original wood from which the pulp is derived is of particular importance for tearing resistance. It is of less importance for properties such as bursting strength and tensile strength, which can be developed by beating and which depend more on fibre bonding than on fibre length for their strength properties. Longer fibres tend to give a more open and less uniform sheet structure. It would seem that there may not be, under present conditions, any great advantage in having fibres in excess of 4–5 mm in length, except for tearing resistance.

2. The thickness of the cell wall has an important bearing on most paper properties. Thick-walled fibres give bulky, open sheets with rather rough surfaces; on the other hand, thin-walled fibres give dense, well-formed sheets. Pulp strength properties such as burst, tensile, particularly folding endurance, are adversely affected by an increase in the cell wall thickness. The thick-walled fibres give some improvement in tearing resistance, however, particularly with long-fibred pulps as obtained from the softwoods. The thick-walled fibres do not collapse readily when made into a paper sheet and therefore present less opportunity for fibre bonding, although the poorer bonding strength properties of paper made from thick-walled fibres are due mainly to the smaller number of fibres in a given weight of paper compared with paper made from thin-walled fibres. When results are calculated on the basis of an equal number of fibres per unit area, there is no great difference in bursting and tensile strength between the papers made from either thick-walled or thin-walled fibres. Tearing resistance on this basis, however, is much higher for paper made with thick-walled fibres.
3. There is little evidence that cell diameter in itself has much influence on paper properties; similarly, there is little evidence that the cell length/diameter ratio has any significant influence on paper strength, except in so far as cell length is the dominating factor.
4. Cell wall organisation has an influence on paper properties only in the case of reaction wood fibres; in these, the cell wall organisation is markedly different from that of normal wood fibres. Pulp yields are reduced, if a large percentage of parenchyma cells, which are short and extremely thin-walled, are present in the wood. Vessel elements also reduce the yield and adversely influence the printing characteristics of the paper.

It should be understood, of course, that, generally speaking, there is a complex relationship between properties of a sheet of paper and the general morphological and chemical characteristics of its constituent fibres, but it is, in our opinion, possible to assess the value of any particular wood species as a source of pulpwood from an examination of the fibre characteristics.

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Transcription of Discussion

DISCUSSION

MR. J. D. PEEL: I was surprised that no reference was made in the paper to the extensive work of Dr. Peteri done when he was at the Régie Industrielle de la Cellulose Coloniale (R.I.C.C.) in France.

The technique reported in Dadswell and Watson's paper was, briefly, to keep two of the fibre dimensions constant and to vary the third. It is not stated whether the wall thickness was constant in Table 1, on the evidence in which you conclude the fibre *L/D* (length/diameter) ratio is not important.

MR. A. J. WATSON (*written contribution*): Cell wall thickness was not kept at a constant value; this would be most difficult to accomplish. As stated in the text, it is considered that cell wall thickness has a much greater influence on strength properties than does the *L/D* ratio.

DR. R. PETERI: Work done on 70 species of tropical woods in the laboratories of the French R.I.C.C. between 1948 and 1955 and continued by Petrof at the Technical Tropical Forestry Centre, leads to a conclusion quite different from that of Dadswell and Watson.

Our studies were conducted on the basis of generally six, often more, sulphate cooks on each species of wood. Then we established graphs for several paper properties as functions of beating. We chose for each species the data corresponding to optimum cooking conditions.

We found that fibre length, which varied 0·6–3·2 mm, had no significant influence on paper properties, not even on tearing strength. (An African species, *Dacriodes klaineana*, with a mean fibre length of 0·95 mm, gives one of the best pulps for tear!) Wall thickness also gave no satisfactory correlation.

We got much better results by using two ratios—the relative length, sometimes called *felting power* (that is, the *L/D* ratio) and the flexibility coefficient (that is, the lumen width to fibre width* ratio, somewhat similar to Runkel's 2W/1).

The relative length seemed to be the most important factor for tearing strength, the flexibility coefficient for tensile strength and, somewhat less so, for bursting strength.

We do not believe that these two ratios are the only factors determining paper properties, but we do think that by their use it is possible to approximate

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* Measurements were made on separated fibres, not on cross-sections

sufficiently to the papermaking properties one can expect from a given species of wood under the most favourable sulphate cooking conditions.

Dadswell and Watson's data to prove the insignificant effect of the *L/D* ratio did not convince me. It is possible to prove by the same table (Table 1) that the fibre length has no significant influence on tearing strength—proved just a few paragraphs before the table. It is shown, too, that the shorter the fibre, the better the tensile and the burst strengths, but Fig. 2 proves the contrary!

It seems to me dangerous to draw any conclusion or to reject any theory with three or even six readings.

MR. H. G. HIGGINS: I am sorry if the work of our French colleagues has apparently been overlooked in this study. The authors made it quite clear to me, however, that this was not intended as a comprehensive review of the literature. The evidence obtained by comparison of species can be misleading and it was for this reason that experiments were devised in which only one variable would be changing at a time. The work on different species can be regarded as supplementary to experiments of a more controlled nature. Of course, when we introduce slightly artificial systems such as the holocellulose fibres we have described, there is some deviation from reality. We know, for instance, that the stiffness of the holocellulose segments must influence the paper properties.

MR. P. G. SUSSMAN: How is the fibre lumen diameter measured?—before or after cooking and/or refining?

MR. HIGGINS: The cross-section dimensions referred to in this paper apply to the state of the fibre in the wood, not in the paper specimen. In some cases, the fibres are subsequently collapsed, so that the lumen is elliptical or even closed.

DR. E. BACK: One paper property, rigidity, is dependent not so much on density, but on thickness *per se*. Accordingly, rigidity increases when, in papers of the same basis weight, the fibre diameter increases. In your work, this fact nicely occurs in the inverse relationship between folding endurance and bulk. Increased thickness also imparts form stability—that is, curl resistance. Is not tearing resistance also primarily affected by paper thickness?

MR. HIGGINS: Watson has carried out tear experiments with different numbers of sheets and he found that the tearing strength is not proportional to the number of sheets.

MR. WATSON (*written contribution*): We have not had any experience in our laboratory with measuring the rigidity of paper. We have found that both folding endurance and tearing resistance increase for a given pulp with an increase in paper thickness.

MR. C. R. G. MAYNARD: Leopold and McIntosh[1] have shown that summerwood fibres have a higher breaking stress than have springwood fibres. Has this difference in strength of fibre been considered in experiments that have compared paper properties of the different sized summerwood and springwood fibres?

MR. HIGGINS: It seems to me that fibre strength may not be quite as significant as is often thought. Obviously, when fibres are highly degraded, there is a weakening of the paper made from them; but, for most pulps, the relationship between tenacity of the fibres and interfibre bonding is such that the fibre strength may not be the critical factor in paper strength. It is only when the fibre strength is reduced below the strength of the new bonds formed between the fibres that it becomes really significant. Quite a lot of work is being carried out in several laboratories on the relationship between fibre strength and paper strength; in the next few years, some further definite information on this question may be forthcoming to supplement the data available from Van den Akker's work on zero span tensile strength.

Written contributions

MR. F. M. CROOK: Referring to Table 3 and Fig. 5, you have stated that 'if the thick-walled fibres were poorly bonded, they would be pulled readily from the paper web during tearing and give low test values. The high tearing resistance obtained with the thick-walled fibres indicates that bonding is sufficiently well developed to cause the fibres to be broken during the actual test itself.'

If Van den Akker's tear theory[2] is tenable (and much evidence so far supports it), this cannot be entirely correct. Maximum tearing strength should be obtained before the fibre is so well bonded that it breaks during tear testing—the total work involved in pulling an entire fibre from the web is much greater than the work expended in breaking the fibre itself. Assuming that by thick-walled, a fibre with a large solid cross-sectional area is meant, then, for a given fibre length, maximum tearing strength will occur at a high degree of bonding, because the fibre's high tensile strength will allow it to be drawn out of the web without breaking. This is in accord with your

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[1] *Tappi*, 1961, **44** (4), 235–240

[2] *Paper Trade J.*, 1944, **118** (5), 13–16, 18–19

results, but would put the degree of beating for maximum tear a little below where your statement implies it would be.

It is agreed with Dadswell and Watson that cell wall thickness as such has little effect, except to reduce the number of fibres per unit weight as it increases. Of far more importance is the solid fraction of the cross-sectional area, which we have expressed in terms of L/D ratio (ratio of lumen diameter to cell diameter) and is an expression of both strength and rigidity. The upcurve in the tear/length relationship in Fig. 2 may be, as well as an expression of the effect on predetermined length of cut fibre ends, an expression of the use of longer and longer fibres of the same L/D ratio—the fibres becoming less and less rigid over their length, less strong in proportion to the total strength of all the bonds along their lengths, so that at a given degree of bonding, the fibres break during test and give lower tearing strength.

With increasing rigidity reducing bonded area and increasing weight reducing fibre numbers, there is a practical optimum length for tearing strength for each L/D ratio. As I have said, optimum conditions for tear are reached when the fibre has a sufficiently high L/D ratio just to survive breaking during test when bonded over the majority of its length. It occurs long before maximum burst is reached; moreover, beating to maximum tear becomes longer and longer, the lower the L/D ratio, until unusable freenesses are reached to satisfy this condition. This means that, *at a freeness*, tearing strength depends on both fibre length and L/D ratio and passes through a maximum for both, even after correcting for number of fibres per unit weight. At practical freenesses, for very low L/D, maximum tear is never reached; for very high L/D, tear has already begun to fall. We have evaluated tear in terms of both fibre length and L/D ratio.

Speaking of evaluation of properties in terms of L/D ratio (or Mühlsteph coefficient), the relationship between L/D ratio and bursting strength is well known and well established, burst increasing with increasing L/D ratio (that is, decreasing with increasing density of the fibres); but burst, as Dadswell and Watson have said, remains constant against L/D ratio, when the values are corrected for numbers of fibres.

PROF. G. JAYME: I agree in all points with the conclusions drawn by Dadswell and Watson on the morphological factors influencing paper properties. Our work on 'biological' pulps has shown, however, that there are still other factors to be taken into consideration. Our experience of these were summarised in a paper dealing with the influence of various fibre properties on paper strength as determined by the German standard method.[3]

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[3] *Das Papier*, 1961, **15** (8), 372 (summary only)

The summary consists of three strength tables, in which only factors of prime influence have been taken into consideration; those dependent on other factors have been omitted—for example, with a high water retention value, the fibre will be more plastic: therefore, plasticity is a dependent factor and has not been considered again.

The various trends of influences have been indicated as follows—

0	no influence or no distinct influence
+	marked positive influence
+ +	decisive positive influence
–	marked negative influence
– –	decisive negative influence
optimum	if maximum of a certain property occurs at an optimum value of influencing factor.

Table 1 deals with *morphological* factors, Table 2 with both *chemical* and *physico-chemical factors* and Table 3 with *physical* and *topostructural factors.* Some of these influences have been known for a long time and are recognised by most research workers in this field.

TABLE 1—STRENGTH TABLE FOR MORPHOLOGICAL FACTORS

Trend		*Tensile and bursting strengths*	*Tearing strength*	*Folding strength*	*Sheet density**
Fibre length	rising	0 to +	+ +	0 to +	0 to –
Cell wall thickness late wood fraction (tube structure)	rising	–	0 to +	– –	– –
Cell wall thickness early wood fraction (ribbon structure)	falling	+	0 to –	+ +	+ +
Ratio fibre length to fibre width	rising			+	
Curling of fibres	rising	– –	+	+ (?)	–

* Porosity, absorbency, air permeability, 'bulk' have a contrary trend

I might point out the influence of two newer factors. First of all, the very considerable effects of water retention value (boiled macaroni theory) has to be stressed. Highly swollen pulp fibres will be more plastic and will therefore make better fibre-to-fibre contacts. If data of strength properties developed during beating are plotted against WRV for a given pulp, straight

TABLE 2—STRENGTH TABLE FOR CHEMICAL AND PHYSICO-CHEMICAL FACTORS

Trend	*Tensile and bursting strengths*	*Tearing strength*	*Folding strength*	*Sheet density**
Average degree of polymerisation (D.P.) rising	0 to +	0 to +	0 to +	0
D.P. very low	–	–	–	–
Hemicellulose content rising	optimum	optimum	optimum	+
Lignin content Stiffness rising**	–	–	– –	–
Water retention value rising**	+	optimum to +	+ +	+
Topochemical influences distribution of components within the cell wall	For example, difference between sulphite and sulphate pulps is partly due to topochemical influences			

* Porosity, absorbency, air permeability, 'bulk' have a contrary trend
** Plasticity, bendability have a contrary trend

TABLE 3—STRENGTH TABLE FOR PHYSICAL AND TOPOSTRUCTURAL FACTORS

Trend	*Tensile and bursting strengths*	*Tearing strength*	*Folding strength*	*Sheet density**
Fibre's intrinsic strength rising	+	+	?	?
Packing density of microfibrils rising	–	optimum	– –	– ?
Surface roughness rising	–	optimum to –	–	–
External fibrillation rising		Little influence		
Internal fibrillation rising	+	optimum to +	+ +	+
Surface consisting of primary wall, S1 or S2	?	?	?	?
Fines, large fibre fragments rising	–	–	–	–
Fines, fibrils and microfibril lamellae rising**	+ +	optimum to – –	– to +	+

* Porosity, absorbency, air permeability, 'bulk' have a contrary trend
** Probably different influences derived from P, S1 or S2

lines are obtained for tensile and bursting strengths, sometimes for folding strength as well.

A quite new factor is the recognition of 'initial packing density' of fibres. The biological pulps prepared first by Jayme, Kohler and Haas[4] show the unique property that the extremely high fold figures exhibited by *unbeaten* biological pulps (for example, up to 50 000 double folds) are reduced drastically during the first few minutes of beating (for example, down to 6 000) and only then start again to rise slowly. Jayme and Hahn (*publications in preparation*) have shown that this effect is due to a new phenomenon, termed by them 'denaturation of the cell wall' and characterised by a 'bundling up' of microfibrils within the walls, which before that were in a state of maximum lateral dispersion (biological pulp). This concept was arrived at by measuring WRV changes during beating and by electron micrograph investigation of the surface changes of fibres during beating.

I hope that these tables will point the complexity of the whole problem and that the data given will form the foundatiion for a better understanding for the influences to be considered.

MR. E. J. HOWARD: There has been little or no reference during this symposium to the importance of hardwood pulps in the formation and structure of paper. This was particularly stressed by Steenberg at the hardwood symposium at Montreal a couple of years ago. Today, hardwood pulps are universally used to improve formation and other vital properties. I suggest the next symposium devote some time to these pulps.

DR. H. E. DADSWELL: Mr. Watson and I are particularly grateful to Mr. Higgins for presenting our paper and for answering questions that arose in the discussion. We are also grateful to the editor for giving us the opportunity of commenting on the discussion. It is regretted that reference to the work of our French colleagues was omitted from the paper itself. They have investigated very thoroughly the effect of various factors on the pulp properties of numerous tropical species. It is, unfortunately, not possible to comment in detail on their results, because we do not have available the actual data on which their conclusions, relative to the effect of fibre dimensions on tearing strength, have been drawn. It does appear to me, however, as if the use of different species has introduced other factors relating to the morphology of the wood. Thus, from examination of the anatomy of the wood, I would expect *Dacriodes klaineana* to give an excellent pulp. This timber consists

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[4] Jayme, G., Kohler, L. and Haas, W. L., *Das Papier*, 1956, **10** (21/22), 495–504; (23/24), 540–545

of many thin-walled fibres, few vessels, comparatively narrow rays and little, if any, vertical parenchyma. On the other hand, I would not expect timbers of the genus *Uapaca* to give pulps with good strength properties, because these have thick-walled fibres, numerous vessel elements and quite a large volume of ray and vertical parenchyma that, on pulping, would, I believe, seriously affect strength properties.

It was in order to eliminate structural variables, as far as possible, that the experiments described in our paper were carried out. When this was done by cutting up the fibres of the one piece of wood or by comparing the strength properties of pulps taken from inner and outer growth rings of the same species, it was found that there was a direct correlation between tearing strength and length of fibre within the one species. This conclusion can possibly be extended to cover the different species of the one genus (such as *Eucalyptus*), but other morphological factors immediately start to exert their influence.

It is very difficult to study the effect of the L/D ratio while keeping all other variables constant. In the paper itself, it was impossible to present in detail all the results of our work in this direction, but we did attempt the difficult task of determining the effect of the L/D ratio, using numerous species of the one genus *Eucalyptus* and at times species of related genera within the family Myrtaceae. By careful selection of the actual wood specimens in which the fibre dimensions had been determined, it was possible to make some comparisons of strength properties of the pulps derived from these specimens. Admittedly, all the work was carried out on very small specimens, but it seemed quite clear from the results that the L/D ratio had no really significant effect. We agree with Peteri about the low degree of correlation between fibre length and tensile and bursting strengths.

In answer to Maynard's question, I would say that both the cell wall thickness and the cell wall organisation would be associated with the higher breaking stress of late wood fibres in relation to that of early wood fibres.

Table 1 of the written contribution by Jayme has clearly summarised the position and it is most gratifying to note that both he and Crook are in general accord with the conclusions we have drawn. Many of the points raised by Jayme in his Table 3 have been considered by Higgins and De Yong in their paper.

The discussion has, I consider, indicated the complexity of the problem of determining exactly what effects fibre dimensions have on the paper that is produced. We have attempted to clarify some aspects of the problem, because of the interest at the present time in the development of plantation-grown softwoods, in which it is desired to have the best wood and fibre properties for the production of various grades of paper.