A TECHNIQUE FOR DETERMINING THE TRANSVERSE DIMENSIONS OF THE FIBRES IN WOOD

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ABSTRACT

For softwoods, fibre width can be calculated from a count by optical microscopy of the number of cells per unit area (N) in the cross-sectional face of a small block of wood. Assuming a square cross section for the average fibre, the fibre width (b) is given by $b = (1/N)^{1/2}$. Lumen width (a) can be calculated from the fibre width thus obtained and a measurement of the bulk density of the wood (D_B) using the theoretically derived relationship $a/b = (1 - D_B/D_C)^{1/2}$. D_C is the cell-wall density, which to a good approximation is a constant from one wood to another.

For hardwoods, the count of cells per unit area is restricted to areas occupied by the libriform fibres, and the bulk density used is that of the part of the wood occupied by these fibres. This bulk density may be calculated from the bulk density of the whole wood using a measurement of the fraction of the total volume occupied by vessels and ray cells.

The results so obtained are in close agreement with those obtained by direct measurement using scanning electron microscopy and are believed to be superior to those previously obtained by the usual expedient of direct measurement by optical microscopy. This is particularly true of cell-wall thickness, (b–a)/2, the direct measurement of which has recently been shown to be subject to many sources of error.

A simple experimental procedure for measuring the dry-bulk density of small samples of wood is described and the work is illustrated by measurements of the fibre width, cell-wall thickness, and fibre coarseness of some thirty species of wood.

Additional keywords: Measurement, fiber dimensions, fiber diameter, cell-wall thickness, cell walls, lumens, bulk density, softwoods, hardwoods, microscopy.

INTRODUCTION

The mechanical and optical properties of paper made from wood fibres vary greatly with the wood species employed. A primary reason for this lies in the differences in the dimensions of the fibres, i.e., length, width, and cell-wall thickness. However, of these dimensions, the transverse dimensions, particularly cell-wall thickness, are ill-defined in the literature. The present report is an attempt to bridge this gap by suggesting a suitable method of measurement and applying it to a number of species. Wood rather than pulp has been examined, since once the dimensions of the wood fibre are known, it is possible that the dimensions of the pulp fibre may be predictable from these and the pulp yield. Thus, Stone et al. (1971) have shown that the dry cell wall of black spruce is thinned in proportion to yield after lignin removal by sodium chlorite. The fibre width, however, remains constant. In work to be published, Kerr and Goring have made similar observations when hemicellulose is removed from birchwood.

Practically all determinations of cell-wall thickness in the past have been made by direct measurement with the optical microscope and considerable doubt has been cast upon the validity of this technique. The doubt arose when several authors—for example Ifju and Kennedy (1962); Jayme and Krause (1963); and Tsoumis (1964)—coupled measurements of cell-wall cross-sectional area with measurements of fibre weight per unit length to calculate cell-wall density. Values of cell-wall density were calculated to be in the range of 0.8 to 1.2 g/cm^3, in direct conflict with the value of about 1.5 g/cm^3 found by Stayton and Hart (1965) and Stone et al.

(1966), using physicochemical techniques. It is now believed that 1.5 g/cm^3 is closer to the correct value and that the lower densities found were due to overestimates of cell-wall cross-sectional area. A calculated cell-wall density of 1.2 to 0.8 g/cm^3 rather than 1.5 g/cm^3 would result from an overestimation of cell-wall thickness by 30 to 100%, as may be shown by substitution into equations developed later in this text. Although much discussed at recent conferences, no complete treatise on the sources of error in the direct measurement of cell-wall thickness by optical microscopy has yet been published. Some possibilities are given in the paper by Kellogg and Wangaard (1969) and the discussion that follows its presentation. The cell walls of wood fibres average about two microns in thickness, which corresponds to only four wavelengths of visible radiation. Direct measurement of such an object is thus limited to a precision of no more than 10% by the theoretical resolution of a perfect light microscope. An even more important contribution to error is that the cell wall examined in cross section is far from an ideal object under the microscope. It is often much distorted by sectioning and is readily swollen in many embedding agents. In addition, the refractive index difference between air, or an unsatisfactory embedding agent, and the cell wall can cause diffraction effects that often make it difficult to determine the positions of the real edges of the cell wall.

A method of obtaining the transverse cell-wall dimensions, while avoiding many of the sources of artifacts, has been suggested by Stamm (1946, 1964). For a softwood, the method is to calculate the dimensions from a count of the number of cells per unit area in the cross section of the wood and a measurement of the bulk density of the wood. This technique was, however, applied only to a very limited extent by Stamm himself and appears to have been largely overlooked by subsequent workers. Britt (1965) made counts of the number of fibres per unit area and also made measurements of bulk density on the same samples. However, in this paper, he combined the measurements only so far as to calculate fibre coarseness (fibre weight per unit length). In a later paper, Britt (1966) suggested that a measure of cell-wall thickness might also be derived but proposed that an additional measurement of the fraction of the cross section occupied by cell walls need be determined. Smith and Miller (1964) and Smith (1965), using samples of redwood and Douglas-fir, investigated the interrelationship between bulk density and fibre dimensions using equations similar to Stamm's, and found a high degree of correlation. Here again, however, more than the minimum number of measurements were thought necessary. More recently, Ifju and Labosky (1972) deduced only tracheid cross-sectional area and fibre coarseness from the measurements of specific gravity and a count of cells per unit cross-sectional area on small blocks of loblolly pine. In all the work subsequent to that of Stamm (1946), the further step of calculating cell-wall thickness from wood density and a count of cells per unit area is not attempted. This is because the experimental determinations were made in the wet state, which does not allow one to use a fixed value for the cell-wall density as is possible if the work is done in the dry state.

This paper therefore presents a reinvestigation into the indirect method. In the light of recent findings, a number of modifications have been made to the technique. The count of cells is made on the surface of a block of wood rather than on a thin microtome section as used by some previous workers. Apart from other distortions produced by microtoming, the area of a section is different from that of the block from which it is derived. The count is made on the sample in the dry state, free from any embedding agent—this state being quite satisfactory for this purpose. The bulk density of the wood is determined in the dry state by the introduction of a simple technique suitable for small blocks. The absence of such a technique has probably been responsible for the overfrequent use of dry weight/wet volume densities in

the past. The complete absence of water from the sample throughout the determination also avoids corrections involving questionable estimations of the density of water in the presence of wood substance.

To check the validity of the results obtained by the indirect method posed a problem since there is at present no generally accepted absolute technique. However, the results were compared with those obtained by direct measurement using a scanning electron microscope. With this instrument, there is no question of cell-wall thickness being near the limits of resolution, but, as will be discussed, not all the problems of direct measurement are avoided. Nevertheless, good agreement was found and the indirect method was then used for an initial study of the variations in transverse dimensions among different species of wood.

THEORY OF THE INDIRECT METHOD

Although the basic equations relating to the indirect method have been quoted by Stamm (1946, 1964), it is felt worthwhile to present their derivation at this time, so that the basic assumptions made may be apparent.

The fibres in a piece of wood vary not only in size but in cross-sectional shape. A decision as to an average shape must therefore be made if only to have a structure upon which to base the average dimensions. 'Diameter' is often used when referring to fibre and lumen size. The use of the word 'diameter' implies that the average fibre is cylindrical; however, the fibres in wood are packed together with little space between them—a property not satisfied by a cylindrical shape. We have therefore decided to use as our model a fibre, with not a circular cross section, but a polygonal one capable of close packing. Besides being closer to reality, such a model allows one to develop relationships between the basic dimensions of the fibres and other properties such as average fibre cross-sectional area, cell-wall density and bulk density. In the following paragraphs, these relationships are derived using a square as the cross-sectional shape. However, it may be shown that the relationships are little altered if based on other commonly occurring shapes (e.g., hexagonal).

The softwoods

For the softwoods, we assume that the wood is composed entirely of fibres; that is, we assume that pits, parenchyma cells, resin ducts, and ray cells occupy a negligible fraction of the volume of the wood. We may then say that the bulk density, D_B, of the wood is equal to that of the constituent fibres which is:

$$D_B = \frac{\text{Weight of fibre per unit length}}{\text{Volume of fibre per unit length}} \quad (1)$$

or introducing 'b' as the average fibre width and 'C' as the coarseness (weight of fibre per unit length):

$$D_B = \frac{C}{b^2} \quad (2)$$

Similarly, if 'a' is the average lumen width, the density of the cell-wall material is given by:

$$D_C = \frac{C}{(b^2 - a^2)} \quad (3)$$

Combining equations (2) and (3) and eliminating C, we have:

$$\frac{a}{b} = \left[1 - \frac{D_B}{D_C}\right]^{\frac{1}{2}} \quad (4)$$

Because the cell-wall density is approximately constant from one wood to another, this equation implies that the ratio 'a/b' may be obtained simply from a knowledge of bulk density. It also follows that the Runkel Ratio may be determined without recourse to microscopy. The Runkel Ratio (double cell-wall thickness/lumen width) is given by $([1 - D_B/D_C]^{-\frac{1}{2}} - 1)$. The importance of the equation is that, if it is valid, and provided an accurate value for D_C is available, only 'a' *or* 'b' need be determined in addition to bulk density, and the other parameter may be calculated. Of course, once 'a' and 'b' are found, then cell-

wall thickness, i.e., (b–a)/2, is immediately defined.

An easy method of determining the average fibre width, which is readily applicable to the model, is to count the number of fibres in a given area in a cross-sectional face of a block of wood. Obviously, then, for fibres which are square in cross section:

$$b^2 = \frac{1}{N} \qquad (5)$$

where N is the number of fibres per unit area.

The beauty of this method is that the linear measurements made are those of the sides of the large quadrilateral area under investigation and these are readily made to a high degree of accuracy. Once this area is combined with the number of fibres in the area, a quantity over which little mistake could be made, the same degree of accuracy is transmitted to the calculated value of 'b' and subsequently to 'a' and (b–a)/2.

An additional parameter coming out of these determinations is fibre coarseness. Equations (2) and (5) combine to give:

$$C = \frac{D_B}{N} \qquad (6)$$

This equation has been used by Britt (1965) to determine the fibre coarseness of a large number of samples of softwoods.

The hardwoods

An obstacle to the direct application of the above techniques to the hardwoods is the presence of a significant fraction of "nonfibrous" elements in the wood, particularly vessels. There appears to be no reference in the literature to an attempt to overcome this factor, although only a small amount of additional work is necessary.

Average fibre width may be estimated for the softwoods with the extra precaution of confining the areas in which counts are made to those occupied by libriform fibres. In addition, in order to use the density relationship (Eq. 4) we must substitute, not the bulk density of the whole wood (D_B), but the bulk density of the parts of the wood occupied by the fibres (D'_B). Now, since most of the volume of the "nonfibrous" elements consists of vessels, which may simply be regarded as voids in the wood, it follows that

$$D'_B = \frac{D_B}{(1 - F)} \qquad (7)$$

where F is the fraction by volume of the wood that is occupied by vessels, rays, and other "nonfibrous" elements. This expression substituted into Eq. 4 gives the general relationship between fibre dimensions and measured bulk density, i.e.

$$\frac{a}{b} = \left[1 - \frac{D_B}{D_C (1 - F)}\right]^{\frac{1}{2}} \qquad (8)$$

The correction factor F may also be used for softwoods where the fraction of nonfibrous elements is high, however it may be regarded as zero without significant loss of accuracy in many softwoods.

EXPERIMENTAL

Wood samples

All samples consisted of small blocks with a cross-sectional face of 3 to 5 mm cut so as to contain either a part of an annual ring (earlywood or latewood) or an integral number of rings. A cross-sectional face was prepared for microscopy by cutting it with a razor blade, a fresh edge being used for each cut. Where cell dimensions were to be determined directly using scanning electron microscopy, debris was removed by a brief immersion of the sample in sodium chlorite, followed by a thorough washing as described by Stone et al. (1971). Where only a count of the cells per unit area was to be carried out, the chlorite treatment was not employed as debris did not interfere with the count.

All microscopic and density determinations were carried out after drying the blocks at 105 C. Care was taken to avoid moisture pickup during and between experiments.

Bulk density

The bulk density determination was carried out by mercury displacement. Because of the difficulties encountered by some previous workers (Yao 1968) in measuring the density of small samples of dry wood, the technique will be described in some detail. The apparatus is shown in Fig. 1. The dilatometer was prepared from a commercial one supplied for the Aminco mercury porosimeter. The stem was shortened to prevent too high a mercury pressure forcing mercury into the sample. The only other modification was the embedding of a small needle in center of the closure disc of the dilatometer.

The small block of wood to be examined was freed from rough surfaces and was mounted upon the needle care being taken that the block would touch neither the base nor the sides of the dilatometer once sealed. (Without the needle or these precautions, the determination would be inaccurate because of the small bubbles that would form between the block and the sides of the dilatometer when it was filled with mercury.) Once the block was suitably mounted, the disc was sealed to the body of the dilatometer with a small amount of vacuum grease, and the dilatometer was filled to capacity from a mercury-loaded syringe. The adhesive power of the grease was such that the mercury-filled dilatometer would be lifted without falling apart and could be transferred to a weighing dish. Bulk densities were calculated in the usual manner of such displacement methods:

$$D_B = \frac{W_S D_M}{W_1 - W_2 + W_S} \qquad (9)$$

where D_M = density of mercury at room temperature
W_1 = weight of dilatometer filled with mercury
W_2 = weight of dilatometer plus sample filled with mercury
W_S = weight of sample

Bulk densities measured in this way are reproducible to within 0.01 g/cm³ for blocks weighing 0.1 g. On larger blocks, the results were identical to those obtained by the more direct but more tedious method of machining a block to a rectilinear shape, measuring its dimensions with calipers and weighing it.

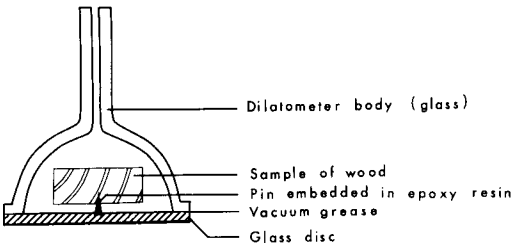

FIG. 1. Apparatus for determining the bulk density of small blocks of wood.

Cell-wall density

No determinations of cell-wall density were carried out in this study; a value of 1.50 g/cm³ was assumed throughout.

The density of the cell wall is believed to be close to that of the cell-wall substance. 1.50 g/cm³ is a rounded intermediate figure between the density of the cell wall as determined on a number of woods by toluene displacement and the density of wood substance as determined by water displacement after correction for the densification of water (Kellogg and Wangaard 1969). Although, as pointed out earlier, the errors in wall thickness are great if a value of, say, 1.0 g/cm³ is assumed, calculation from Eq. 4 shows that the error decreases rapidly as high values are assumed. The possible error in using 1.50 rather than 1.45 is less than 5% in the wall thickness.

Scanning electron microscopy

Following the bulk density determination, the block of wood was evacuated in a shadowing apparatus, and the prepared face of the block was shadowed with palladium. The block was then mounted in a scanning electron microscope at 90° to the incident beam to avoid foreshortening of the image. The instrument used was a Stereoscan Mark IIa. Micrographs were taken at from 300 × to 600 × magnification, several exposures being required to give a

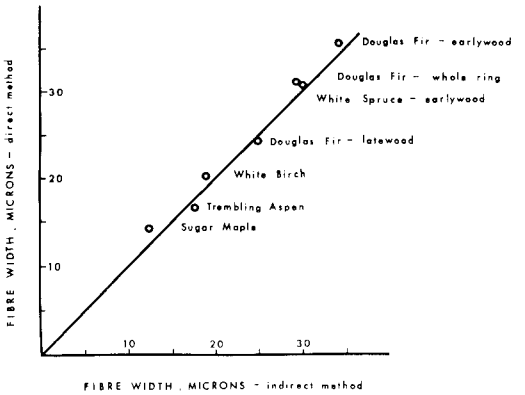

FIG. 2. Fibre widths as determined by the indirect optical method against those obtained by direct measurement using scanning electron microscopy. The line drawn is that which would have been obtained had the results of the two methods agreed exactly.

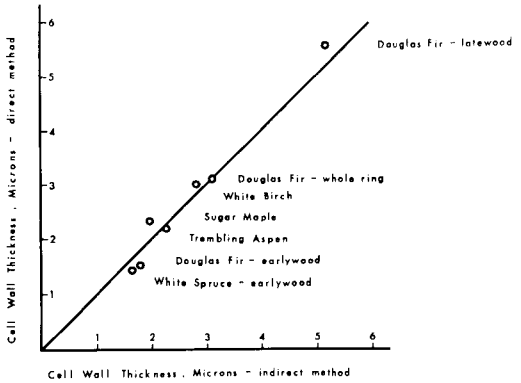

FIG. 3. Cell-wall thicknesses as determined by the indirect optical method plotted against those obtained by direct measurement using the scanning electron microscope. The line drawn is that which would have been obtained had the results of the two methods agreed exactly.

series of photographs covering the entire annual ring. The direct measurements of fibre width and cell-wall thickness were made on the micrographs using a cathetometer. Dimensions were determined in both the radial and tangential directions of all fibres in three or more randomly selected files running completely across the annual ring. The average dimensions were based on the radial and tangential measurements of at least 500 cells.

Optical microscopy

The sample was mounted on the stage of an optical microscope equipped with incident illumination and a calibrated eyepiece micrometer. An annual ring was selected, and the distance across the ring (d_r) was measured along with the number of cells in this distance (N_r). The microscope stage was then rotated through 90° and the number of cells (N_t) was counted in a measured tangential distance (d_t). These measurements were repeated in three different regions within the same ring if the sample contained only one and in different rings if the sample contained more than one. The results were then combined to give the average number of fibres per unit area, i.e.

$$N = \frac{\Sigma(N_t \times N_r)}{\Sigma(d_t \times d_r)} \qquad (10)$$

Depending on the type of sample, the number of cells, $\Sigma(N_t \times N_r)$, varied but was never less than 2000 and was often as high as a hundred times this figure.

For the softwoods, the optical microscopy was straightforward because of the regular alignment of the cells within the ring and the virtual absence of nonfibrous elements. For the hardwoods, some modification was necessary. With these, it is impossible to move very far in a straight line without encountering a vessel. Therefore, the count was stopped just before the cross-hairs reached a vessel, the sample was moved slightly at right angles to the direction of count, and the count continued, bypassing the vessels. Ray cells were traversed in the tangential count, but they were not counted as fibres and the distance occupied by them was subtracted from the total distance travelled.

Estimation of the fraction of the volume of wood occupied by nonfibrous elements (F)—principally vessels and ray cells—was made by taking a low magnification micrograph of the cross-sectional face of the wood and weighing it before and after cutting out the nonfibrous cells.

DISCUSSION

Comparison of the indirect technique with scanning electron microscopy

For this study, wood samples with rather wide annual rings were chosen so that the cross-sectional face of each block contained only one annual ring or just the earlywood or latewood part of a ring. Bulk densities were determined and the fibre dimensions were measured directly, using scanning electron microscopy. Counts of cells per unit area were then made on the same metallized blocks by optical microscopy and the transverse dimensions were calculated by the indirect method. Figures 2 and 3 show how the two types of measurements compare on fibre width and cell-wall thickness, respectively. Statistical analysis carried out at the 5% probability level showed that, in each plot, the least-squares fitted line was not significantly different from a 45° line passing through the origin. The agreement between the two methods on fibre width is good but not surprising in view of the ease of measurement of this parameter by any method. Rather more interesting is the agreement between the two methods on cell-wall thickness, which, in the light of previous difficulties with this measurement, can be considered very good.

The independence of the two sets of measurements, both with regard to instrument and method of calculation and the avoidance of many of the artifacts of previous work, suggests that between the two methods, near-correct values for the parameters measured have been obtained. Certainly, one could not say that the results were incompatible with either cell-wall density or bulk density, since these were involved in one set of calculations.

The question now arises as to which method is to be regarded as the more absolute. Although scanning electron microscopy was originally employed to check the validity of the indirect method, work with the electron microscope has caused us to wonder whether the scatter in Figs. 2 and 3 is due solely to the assumptions and approximations of the indirect method.

1. Even in scanning electron micrographs, the edge of the cell wall is often ill-defined, and an arbitrary decision must then be made as to where to draw the line between lumen and cell wall. The indirect method is free from such problems.
2. The boundaries of the cell wall are not always parallel to one another. Halfway between the cell-wall corners—the usual place to measure cell-wall thickness—may be the narrowest part of the wall or may contain a bulge. A decision must therefore be made as to where to measure the cell-wall thickness. On the other hand, the indirect method is unambiguous and necessarily averages out the whole perimeter of the cell, including cell-wall corners.
3. Even though the electron microscope is free of the limited resolution of the optical instrument, there remains the question as to whether the wall has been flared out by surfacing treatment or thinned by the chlorite-liquor. However, neither of these matters is likely to affect the number of cells per unit area.

For these reasons, we came to the conclusion that the indirect optical method is at least as accurate as direct measurement by scanning electron microscopy. Further, presumably because of the lack of ambiguity in the determination, we found the indirect method to be precise and much more so than direct measurement. Duplicate determinations had a coefficient of variation of 2% in both fibre width and wall thickness, when a duplicate determination involved measurements on the same block and a coefficient of variation of 4% when a duplicate determination involved a second block taken from a position tangentially adjacent in a disc. Because of the tedious nature of direct measurement, only a few replicates were carried out but, from these, we suspect coefficients of variation that are double those of the indirect

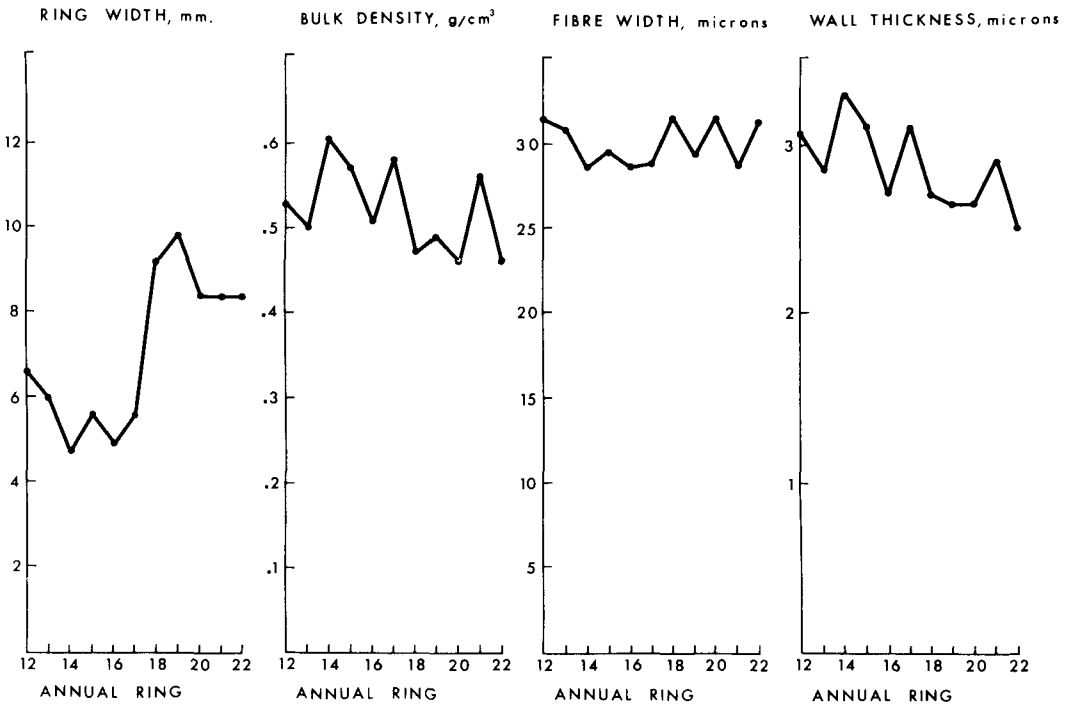

FIG. 4. Variations in properties in eleven successive annual rings of a Douglas-fir which had received fertilization in its 17th year.

method, wall thickness being determined less precisely than fibre width.

Variations in fibre dimensions with annual ring

A microscopic examination of wood is necessarily confined to a very small area and if measurements are made on such an area, it is of interest to know how representative these are of a larger sample. As an initial attempt at looking at this problem, eleven successive rings were examined in a radial strip of Douglas-fir. The sample was deliberately chosen to include rings before and after fertilization, so that we might observe the effect on dimensions of a drastic change in growing conditions. Following the determination of ring width, the strip was split into blocks each containing one annual ring and measurement of bulk density and cells per unit area made.

The results are shown in Fig. 4. As a result of fertilization, ring width had increased from about 5 mm to over 8 mm. However, fibre width was practically constant throughout the eleven years, no ring exhibiting an average fibre width more than one micron away from the 30 micron average. Cell-wall thickness did, however, fluctuate over a range from −10% to +10% of its average value for the eleven years (2.85 microns), following closely the trend of bulk density. Because fibre width was constant and cell-wall thickness was calculated from this "constant" and bulk density, one might be tempted to attribute the parallel and yet erratic trends in bulk density and cell-wall thickness to errors in determining bulk density. However, the duplicate bulk densities done in this case were within ±0.005 g/cm³, whereas the variation in density from ring to ring is considerably higher than this. We must therefore conclude that the ring-to-ring variations in bulk density and cell-wall thickness are real. These findings are in agreement with the earlier work of Britt

TABLE 1. *Dimensions of some samples of softwoods*

Species	Bulk density, g/cm^3	F,***	Fibres per mm^2	Fibre coarseness, mg/100 m	Fibre width, μm	Wall thickness, μm
Western red cedar I*	0.32	0.05	1302	26	28	1.6
Western red cedar II	0.32	0.03	1377	24	27	1.6
Eastern white cedar	0.33	0.01	2300	14	21	1.2
Yellow cedar	0.44	0.04	1448	32	26	2.2
White spruce I	0.35	0.02	1398	26	27	1.7
White spruce II (EWD)	0.31	0.02	1106	29	30	1.6
Black spruce I	0.52	0.02	1850	29	23	2.2
Black spruce II	0.56	0.02	1957	29	23	2.4
Sitka spruce	0.44	0.02	799	56	35	2.8
Balsam fir I	0.39	0.02	1293	31	28	2.1
Balsam fir II	0.38	0.05	1292	31	28	2.1
Amabilis fir	0.43	0.05	869	53	34	2.8
Jack pine I	0.46	0.05	2090	30	22	2.0
Jack pine II	0.52	0.02	1534	35	25	2.4
Jack pine III	0.58	0.04	1527	40	26	2.9
Radiata pine	0.40	0.03	1177	35	29	2.2
Patula pine	0.50	0.05	819	63	35	3.3
Red pine	0.42	0.05	987	45	32	2.5
White pine	0.44	0.04	754	61	36	3.1
Slash pine	0.66	0.05	1031	67	31	4.2
Shortleaf pine	0.55	0.08	1072	55	30	3.4
Shortleaf pine (EWD)	0.31	0.08	815	42	35	2.1
Shortleaf pine (LWD)	0.89	0.07	1455	66	26	5.2
Virginia pine I	0.48	0.04	997	50	32	2.9
Virginia pine II	0.51	0.05	1292	42	28	2.8
Loblolly pine I	0.47	0.04	1374	36	27	2.4
Loblolly pine II	0.67	0.08	1142	64	30	4.3
Loblolly pine III	0.42	0.07	821	56	35	2.9
Ponderosa pine	0.38	0.05	881	46	34	2.4
Lodgepole pine	0.43	0.04	1269	35	28	2.3
Western larch	0.40	0.05	894	47	33	2.5
Tamarack	0.53	0.02	1322	41	27	2.7
European larch	0.31	0.07	657	52	39	2.3
Western hemlock	0.44	0.02	932	48	33	2.6
Douglas-fir I	0.53	0.02	775	70	36	3.6
Douglas-fir II	0.46	0.04	1112	44	30	2.7
Douglas-fir III, Ring 15 **	0.57	0.02	1102	53	30	3.3
Ring 15 (EWD)	0.30	0.02	850	35	34	1.8
Ring 15 (LWD)	0.99	0.02	1612	62	25	5.3

* The different numerals indicate different trees of the same species, EWD and LWD refer to earlywood and latewood respectively.

** Douglas-fir III was the wood used in the study of ring-to-ring variation.

*** F ∿ fraction of volume not occupied by tracheids.

(1965), who examined successive rings in several softwoods of up to 300 years of age. His measurements of the number of fibres/mm^2 indicate that once the rings are beyond the juvenile core of the tree, fibre width changes very gradually, whereas bulk density fluctuates considerably and with little pattern.

Although fertilization *per se* was not the subject of this experiment, an analysis of the data before and after fertilization indicates that the well-known drop in average bulk density (0.55 to 0.49 g/cm^3 in our case) is caused by a slight but significant drop in cell-wall thickness (3.1 to 2.7 microns).

TABLE 2. *Dimensions of some samples of hardwoods*

Species	Bulk density, g/cm^3	F,*	Fibres per mm^2	Fibre coarseness, mg/100 m	Fibre width, μm	Wall thickness, μm
Basswood	0.42	0.32	5,145	12	14	1.6
Balsawood	0.17	0.11	1,428	13	26	0.9
Beech	0.79	0.30	10,320	11	10	2.5
Birch (white)	0.63	0.24	3,420	24	17	2.8
Cottonwood (black)	0.43	0.44	3,110	25	18	2.7
Elm	0.60	0.43	11,220	10	9	2.1
Eucalyptus (globulus)	1.02	0.18	11,480	11	9	2.7
Eucalyptus (grandis)	0.73	0.29	7,250	14	12	2.6
Eucalyptus (saligna)	0.51	0.22	12,420	5	9	1.1
Maple (sugar)	0.66	0.17	8,960	9	11	1.7
Maple (broadleaf)	0.52	0.27	6,020	12	13	1.7
Oak (red)	0.66	0.26	5,360	17	14	2.5
Trembling aspen	0.44	0.34	4,025	17	16	2.0

* F ∿ fraction of volume not occupied by libriform fibres

Variations in fibre dimensions with species

In a survey of the differences in transverse dimensions among various species, an attempt was made to "iron-out" somewhat the ring-to-ring fluctuations observed in the study on Douglas-fir. Blocks were therefore cut to contain at least three annual rings. Following the determination of bulk density, the count of fibres per unit area was averaged out from measurements on three rings.

The data are given in Tables 1 and 2. Where comparisons can be made, the measurements of fibre coarseness are of the same order as the data of Britt (1965). The measurements of average fibre width agree reasonably well with those given in the literature, and this is not surprising because the measurement presents little difficulty. However, most interesting are the data on cell-wall thickness, which, for the reasons stated in the introduction of this paper, tend to be lower than the values given in the literature. They are, for example, as low as 50% of the cell-wall thicknesses reported in Haywood's much-quoted work (1950).

Although the number of samples so far examined does not allow generalized statements to be made, a number of well-known trends is illustrated. The greatest differences in dimensions are between earlywood and latewood within an annual ring (see the data on Douglas-fir, Table 1). The differences in the transverse dimensions of fibres from different trees within a species can sometimes be greater than between trees of different species. Thus, while the two black spruces appear to be quote close, the three jack pines are widely different in cell-wall thickness. The average cell-wall thicknesses of the hardwoods appear to be of the same order as those of the softwoods examined, but their fibre widths are lower, thus accounting for the higher bulk densities of the hardwoods despite the presence of vessels.

CONCLUSIONS

On the basis of relationships between the bulk properties of wood and fibre dimensions, a method is forwarded for the determination of the transverse fibre dimensions in wood. The method avoids many of the possible sources of error associated with previous determinations of cell-wall thickness. Many fibres are readily taken into account, giving the method a good averaging ability. The technique is highly reproducible and has been used for an initial look at the variations in dimensions from ring-to-ring, tree-to-tree, and species-to-species; however, further work is

necessary to arrive at more statistically valid conclusions on these variations. The rapidity with which measurements can be made should aid this further work.

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