

# DISTRIBUTIONS AND CORRELATIONS OF SOFTWOOD FIBER PROPERTIES WITHIN AGE-CLASSIFIED PULPS

*Jari Sirviö*

Graduate Student

and

*Petri Kärenlampi*

Associate Professor

Department of Forest Resource Management

Box 24

FIN-00014 University of Helsinki

Helsinki, Finland

(Received July 1996)

## ABSTRACT

The properties of softwood tracheids vary within a tree. This within-tree variation is a major source of variation between trees and stands. The effect of cambium age on the length, coarseness, and strength of *Pinus silvestris* and *Picea abies* tracheids is discussed. Distributions and correlations of *Pinus silvestris* tracheids within two age classes are introduced. Between pulps of different cambium age group, fiber length and coarseness are correlated; but within an age group, no correlation exists between fiber length and cross-sectional fiber dimensions. Between age groups, the major source of coarseness variation is cell-wall thickness; but within age groups, fiber perimeter also contributes to coarseness.

**Keywords:** Fiber length, fiber perimeter, cell-wall thickness, coarseness, growth mechanisms.

## INTRODUCTION

The properties of softwood tracheids change from the pith of the tree towards the bark. The dimensions of tracheids, especially length, increase (Dinwoodie 1961) and cell walls become thicker (Nylinder 1953). The microfibril angle decreases significantly at the early stages of cambium aging, later showing only minor change (Zobel and van Buijtenen 1989). With perimeter and cell-wall thickness, the coarseness of tracheids, defined as weight per unit length, increases (Kibblewhite and Bawden 1992) as does the basic density of xylem (Zobel and van Buijtenen 1989). Even if most trends are quite common to conifers, there are also differences between tree species (Zobel and van Buijtenen 1989).

The tracheids are produced by the lateral meristem of the tree, the cambium, and as these tracheids become lignified during the

same growing season as they are generated, the dimensions of tracheids are consequently determined by cambial activity. As any living organism undergoes aging, the change of tracheid properties from pith to bark can be interpreted as a consequence of the maturation of the cambium.

Another argument, however, relates to the fact that the cambium is produced by the apical meristem of the tree. Thus the activity of the cambium is possibly affected by the maturity of the apical meristem (Olesen 1978). This phenomenon results as the properties of tracheids change as a function of height within the bole even if cambium age is constant (Atmer and Thörnqvist 1982). However, the change of tracheid properties as a function of height is not typically logarithmic, which favors another kind of explanation for the variation with height. Growth regulators are most-

ly produced in the foliage and then transported to the lower parts of the bole (Larson 1969; Little and Savidge 1987), so the supply of these regulators may be at their highest at the region of the crown limit (Larson 1969).

The activity of the cambium varies not only in the scale of tree age, i.e., from the pith towards the bark and from the root towards the top, but a considerable variation in tracheid properties is found within any growing season. The length of the tracheids does not change dramatically, at least not for *Pinus silvestris* or *Picea abies* (Omeis 1895; Mork 1928; Bisset and Dadswell 1950), but the tracheid perimeter (with the radial diameter) decreases and the cell walls become thicker. The microfibril angle hardly changes within a growth ring within these wood species (Paakkari and Serimaa 1984). Since the cell-wall thickness increases, the basic density of xylem also increases (Zobel and van Buijtenen 1989). Fiber coarseness increases as well, but this change is not very pronounced since the reduction in the fiber perimeter partly balances the increment of cell-wall thickness (Johansson 1939; Meylan 1972; Evans 1994; Evans et al. 1995a).

The physiological intensity of the tree may affect any of the above-mentioned mechanisms of tracheid formation. It is typical that in spruce species there is a strong relationship between growth rate and wood properties (Manwiller 1972; Siddiqui et al. 1972; Erickson and Harrison 1974; Blouin et al. 1994; Kärenlampi and Suur-Hamari 1995); but with pine species, only moderate effects of growth rate on xylem properties are found (Dorn 1969; Saranpää 1985; Zobel and van Buijtenen 1989; Kärenlampi and Suur-Hamari 1995). However, findings vary somewhat with tree species and are confounded by age from pith, and they may depend on the factors controlling the growth rate. Further, all the mechanisms affecting the properties of tracheids have so far been discussed within a genotype: changes in genotype contribute to tracheid properties not only between but also within a species (Ericson et al. 1973; Blouin et al. 1994).

Most studies discussing the variation of tracheid properties have focused on the variation of representative "average" values within any scale of variation under discussion. In reality, the properties of tracheids are distributed, and these distributions change with cambium age, height within the tree, growth rate, and also within a growing season. The distributions of fiber properties are not insignificant. Some fiber length distributions have been reported (Ollinmaa 1959; Jackson 1988) as well as distributions of other fiber properties (Ollinmaa 1959; Evans 1994; Evans et al. 1995a, b). Fiber length is quite normally distributed if the fibers are not cut during pulping (Ollinmaa 1959; Jackson 1988). Fiber coarseness is either normally distributed or skewed to the right (Evans 1994; Evans et al. 1995b). Also the distributions of density and cell-wall thickness are skewed to the right (Evans 1994; Evans et al. 1995a, b), while the perimeter distribution is skewed to the left (Evans 1994). In those investigations shapes of fiber property distributions were measured mainly from small pieces of wood, thus restricting the variation caused by seasonal changes in cambial activity.

In paper products, for example, long fibers are largely responsible for mechanical properties, and small particles mostly stand for the optical properties. Furthermore, the heterogeneity of the fibers as such may well contribute to the properties of products made from the fibers (Alava and Ritala 1990; Kärenlampi 1995a, b). Another issue that has not received much attention is the fact that the properties of tracheids are not statistically independent of each other. The behavior of a fiber product, for example, clearly changes with the correlation of cell-wall thickness and fiber length. Thus, it is important to know whether the properties of tracheids are correlated within any scale of variation.

Between growth rings, fiber length correlated negatively with microfibril angle and positively with wood density in *Pinus taeda* (Bendtsen and Senft 1986). Between pulps fiber length has been observed to correlate pos-

itively with cell-wall thickness and coarseness in *Pinus silvestris* and *Picea abies* (Kärenlampi and Suur-Hamari 1995). When comparing average values *between* growth rings or pulps in *Pinus radiata*, cell-wall thickness correlates positively with coarseness, but when comparing these properties *within* one growth ring or pulp, cell-wall thickness and coarseness are not well correlated (Evans et al. 1995b). Although the cell-wall percentage in crosscut section of wood was highly correlated with specific gravity in Douglas fir (Ifju and Kennedy 1962), coarseness and density did not correlate within or between pulps in radiata pine (Evans 1994; Evans et al. 1995b). Because coarseness is important to paper quality, density is an insufficient indicator of pulpwood quality (Evans 1994). Perimeter and cell-wall thickness are not correlated within growth rings because of their independent development during the growth season (Evans et al. 1995b).

#### OBJECTIVE

In this paper, we intend to study the distributions and correlations of tracheid properties. First, we review recent results concerning the variation of mean values of tracheid properties between laboratory kraft pulps of *Pinus silvestris* and *Picea abies* as a function of cambium age. Then, we present a more detailed study of two fiber populations classified according to cambium age. We analyze how the distributions of fiber properties of *Pinus silvestris* are affected by cambium age. Finally, we introduce correlations of fiber properties within populations classified according to cambium age, where most of the variation is due to cambial activity within a growing season.

#### EXPERIMENTAL

The experimental pulps analyzed in this study were produced from chips originating from pine logs cut from 1 to 4 meters above the ground. The *first thinning sample* included stems of young, 28-year-old trees. The *slab-*

*wood sample* was produced by sawing the logs of old trees longitudinally so that only the outer parts of the logs were used in chipping (annual rings from 45 to 100). The chips were kraft pulped in a laboratory mill.

The fibers of small samples were lightly stained by acridine orange fluorochrome dye. Handsheets of 2 g/m<sup>2</sup> were formed from fibers. Microscope object slides were mounted into the wet press together with the sheets that resulted as the fibers entangled with the slides. A drop of mounting medium (DPX Mountant for histology; refractive index of 1.5) on the fibers and a cover slip completed the slide for subsequent viewing. All the measurements were made in the wet stage (between the measurements, the slides were wrapped with moist paper and stored in a refrigerator, thus preventing drying).

The fibers and the points of measurement were randomly selected from the slides by line sampling with the help of an image analysis system (IAS) attached to a light microscope. IAS consisted of a CCD-camera (Cohu MS12E), a frame grabber (Matrox IP8) attached to a microcomputer, and analysis software (Image Pro Plus 1.3). The real length of the sampled individual fibers was measured using the IAS. The cross-sectional dimensions (perimeter and cell-wall area) of the fibers were measured by IAS from pictures produced by a CLSM (confocal laser scanning microscope, manufactured by Leica; for more details, see Moss et al. 1993). By CLSM it is possible to generate fiber cross-sectional images through optical sectioning (see e.g., Jang et al. 1991, 1992; Robertson et al. 1992; Moss et al. 1993). The average cell-wall thickness was calculated on the basis of fiber perimeter and cross-sectional area (Eq. 1).

$$T = \frac{P - \sqrt{P^2 - 16 \times A}}{8}, \quad (1)$$

where T = average cell-wall thickness,  $\mu\text{m}$ ; P = fiber perimeter,  $\mu\text{m}$ ; and A = cross-sectional area without lumen,  $\mu\text{m}^2$ .

The cross section of a fiber is assumed to

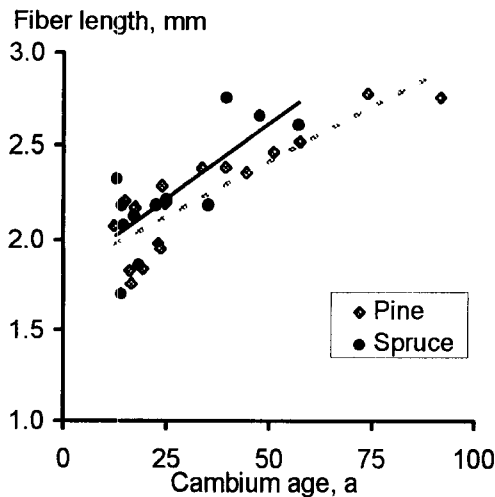


FIG. 1. Fiber length of Scots pine and Norway spruce as a function of cambium age. (Kärenlampi and Suur-Hamari 1995).

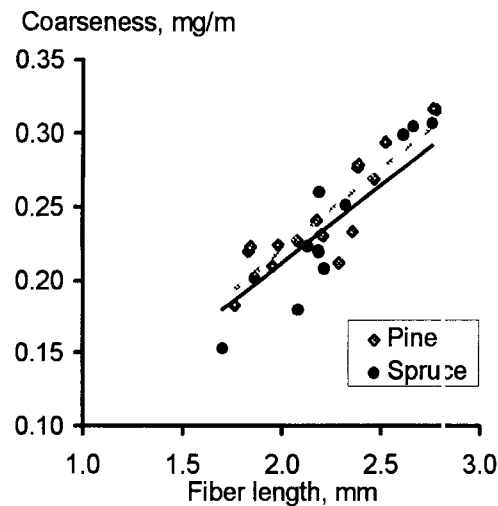


FIG. 2. The relationship of fiber coarseness and fiber length. (Kärenlampi and Suur-Hamari 1995).

be rectangular in Eq. (1.) Thus, the result is not dependent on the degree of collapse. If the lumen is totally collapsed and the cross section happens to be nearly circular, Eq. (1) is not valid, and Eq. (2) should be used.

$$T = \frac{P - \sqrt{P^2 - 4 \times \pi \times A}}{2 \times \pi} \quad (2)$$

The representativeness of the sampling system was verified by comparing the fiber length results with the results of the Kajaani FS-200 fiber length analyzer.

#### VARIATION OF TRACHEID PROPERTIES WITH CAMBIUM AGE

Recent observations (Kärenlampi and Suur-Hamari 1995) suggest that the length-weighted mean of fiber length of laboratory kraft pulps increases strongly with cambium age (Fig. 1). However, in the case of spruce (*Picea abies*), the fiber properties depended also on growth rate, whereas the properties of pine (*Pinus sylvestris*) were almost independent of it (Kärenlampi and Suur-Hamari 1995). This agrees with earlier findings (Stairs et al. 1966; Dorn 1969; Manwiller 1972; Siddiqui et al. 1972; Zobel and van Buijtenen 1989).

The mean values of fiber length and coarseness are almost linearly proportional between pulps classified according to cambium age (Fig. 2) (Kärenlampi and Suur-Hamari 1995). No significant variation was found in the zero-span tensile index of well-bonded handsheets (Fig. 3) (Kärenlampi and Suur-Hamari 1995).

The distributions of fiber properties within two pine pulps have been examined in detail. These two particular pulps (originating from

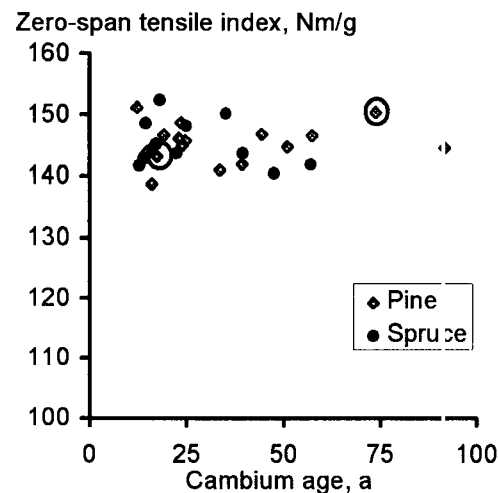


FIG. 3. Fiber strength index as a function of cambium age. (Kärenlampi and Suur-Hamari 1995).

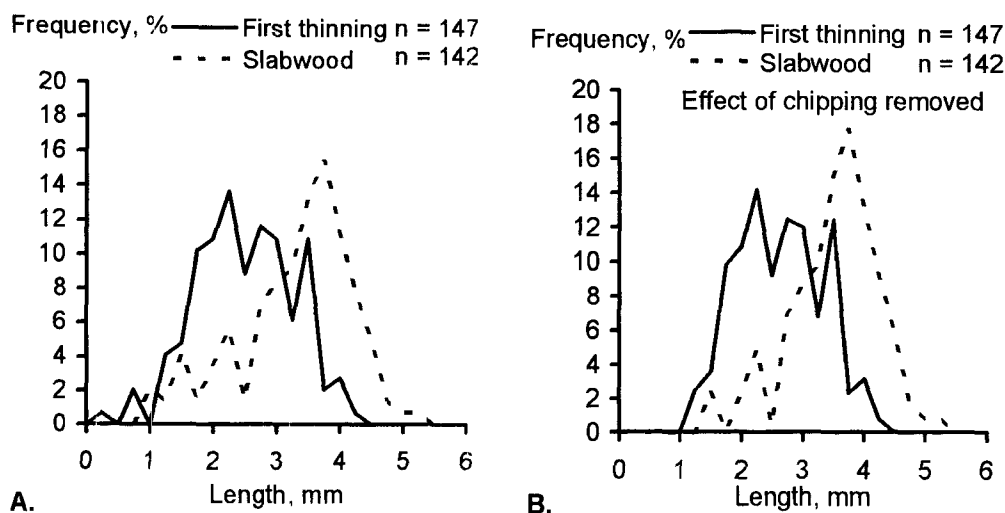


FIG. 4. Distributions of fiber length in two pine pulps of different cambium age. A: observed distribution, B: length distribution before chipping (approximated by Eq. (3)).

the material used in the study of Kärenlampi and Suur-Hamari 1995), a first thinning pulp and a slabwood pulp, have been circled in Fig. 3. On the basis of 150 randomly selected, never-dried fibers of each population, we find from Fig. 4a that the length of fibers is somewhat more widely distributed in the first thinning pulp. Wider distribution is understood here as greater coefficient of variation. In first thinning fibers, the coefficient of variation was 22% larger than in slabwood fibers (0.33 and 0.27, respectively). However, these fiber length distributions have been affected by the chipping procedure: the longer the fiber, the greater the probability of fiber failure in chipping. In Fig. 4b the original frequency of fibers in any length class has been approached by diminishing the fiber portions originating from longer fibers and dividing the result by fiber survival probability according to Eq. (3).

$$f_T(n) = \frac{f_O(n) - \sum_{j=n+1}^m \frac{f_O(j) \times \frac{l_j}{l_c}}{j-1}}{1 - \frac{l_n}{l_c}}, \quad (3)$$

where  $f_O(n)$  = original total length of fibers in length class  $n$ , mm;  $f_T(n)$  = measured total

length of fibers in length class  $n$ , mm;  $l_n$  = average fiber length in length class  $n$ , mm; and  $l_c$  = chip length, mm.

We find from Fig. 4b that the distribution of the length of slabwood tracheids is considerably narrower than the distribution of first thinning tracheids. Coefficient of variation is even 33% larger in first thinning fibers than in slabwood fibers (0.28 and 0.21, respectively). An obvious reason for the wider distribution within the first thinning pulp is the effect of cambium age on the dimensions of tracheids, being greatest at low age (Boutelje 1968; Le-wark 1986; Kucera 1994).

The distribution of fiber perimeter (Fig. 5a), determined from CLSM-images, is surprisingly similar between the two pulps (cf. Evans et al. 1995b). This indicates that the change of coarseness with cambium age, seen in Fig. 2, must mainly be due to change in the thickness of the cell wall. This is also seen in Fig. 5b: the cell-wall cross-sectional area, measured from CLSM-images, shows a considerable difference between the two pulps. Further, the variation in cell-wall cross-sectional area is much greater in the slabwood pulp. Tracheids with small cell-wall area also appear in the slabwood pulp, but large tracheid areas are not found in the first thinning pulp.

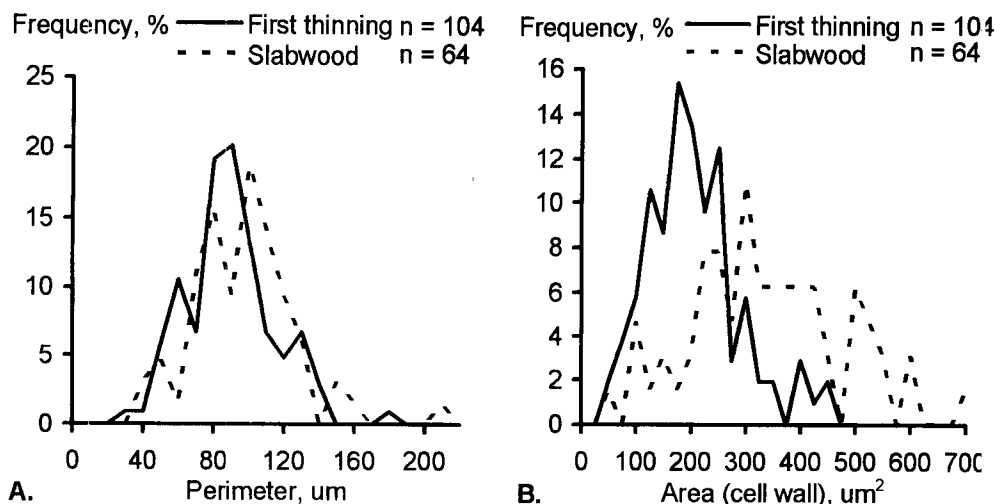


FIG. 5. Distributions of fiber perimeter (A) and cell-wall area in cross section of fiber (B) in two pine pulps of different cambium age.

The findings for the cell-wall area are virtually identical for the average cell-wall thickness within fiber cross sections (see Fig. 6a).

The shape of the fiber cross section was determined as the ratio of the longer and shorter axis of an ellipse fitted to any cross section image. The distribution of the shape of fiber cross section was very different between these two pulps, indicating that the cross sections of slabwood fibers are much more isodiametric,

while first thinning fibers with narrower cell walls tend to flatten in given pressure actions (Fig. 6b).

#### CORRELATIONS OF FIBER PROPERTIES WITHIN CLASSIFIED PULPS

Let us now examine how the properties of tracheids are correlated *within* the two above introduced pulps, both representing a relatively narrow range of cambium age.

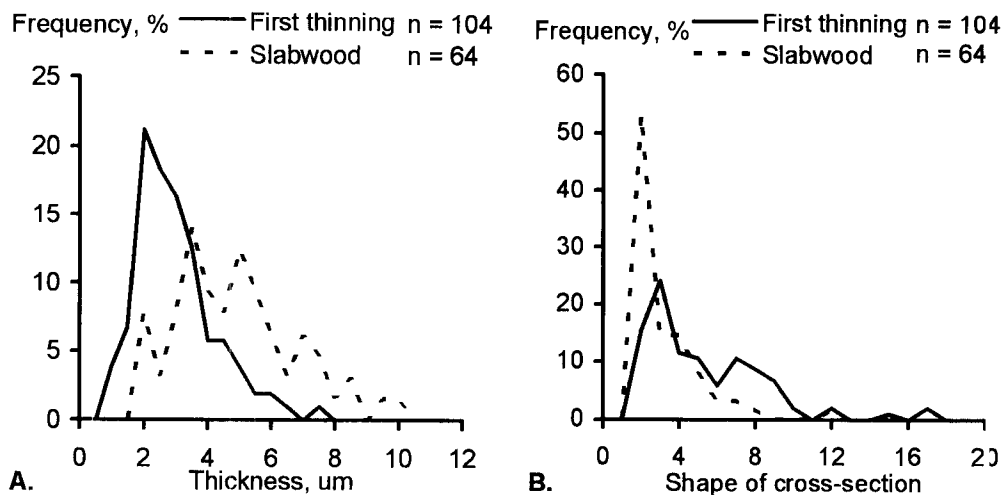


FIG. 6. Distributions of cell-wall thickness (A) and shape of cross section of fiber (B) in two pine pulps of different cambium age.

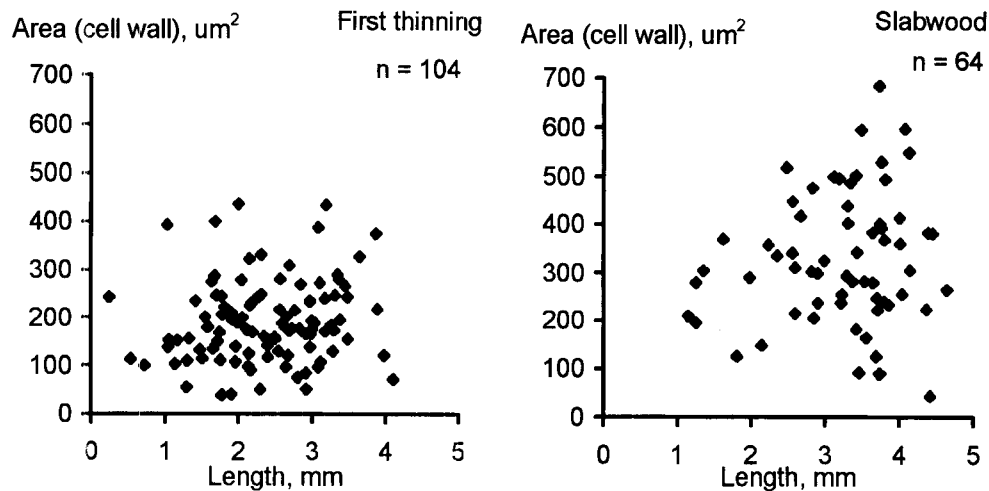


FIG. 7. Correlations of fiber length and area of cell wall in cross section of fiber (coarseness) in two pine pulps classified according to cambium age.

The length of pulp fibers does not correlate with any other property measured from the fibers of the pulps; the relationship of fiber length and cross-sectional cell-wall area is shown in Figs. 7a and 7b. This finding supports the hypothesis according to which fiber length does not appreciably change during one growing season in *P. silvestris* (Bisset and Dadswell 1950, see also Liese and Dadswell 1959); it is obvious that the cross-sectional

area of cell wall increases from earlywood to latewood (Johansson 1939; Evans et al. 1997a, b), and if latewood fibers were considerably longer, a correlation should be found between the length and the cross-sectional area.

The fiber perimeter and the cross-sectional cell-wall area are correlated within both experimental pulps (Figs. 8a and 8b). This is somewhat surprising since according to Fig. 5a, the fiber perimeter does not differ appreciably

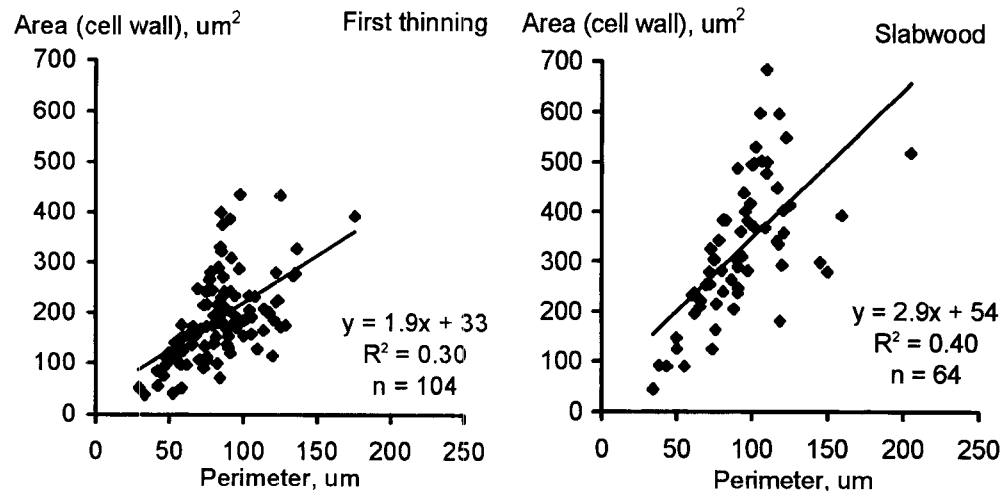


FIG. 8. Correlations of fiber perimeter and area of cell wall in cross section of fiber (coarseness) in two pine pulps classified according to cambium age.

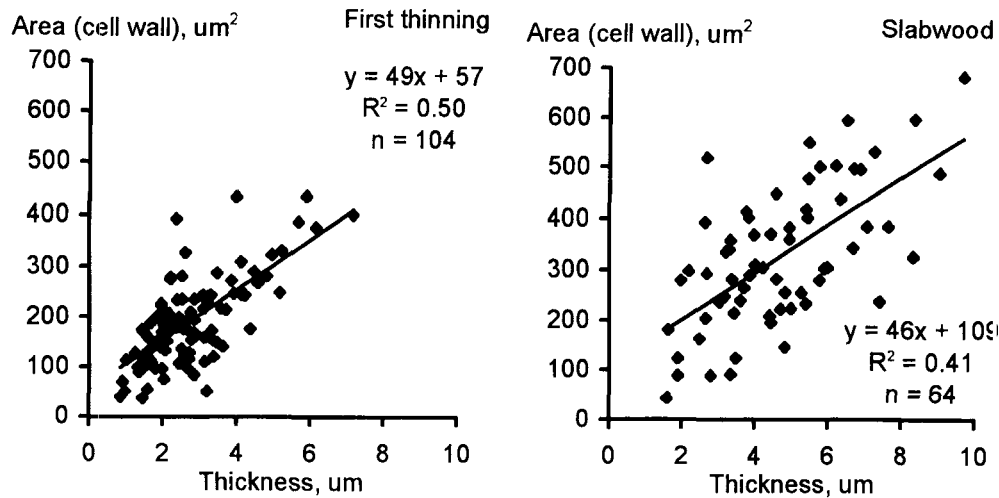


FIG. 9. Correlations of cell-wall thickness and area of cell wall in cross section of fiber (coarseness) in two pine pulps classified according to cambium age.

ciably *between* the two experimental pulps (cf. Kibblewhite and Bawden 1992; Kärenlampi and Suur-Hamari 1995). Anyway, now we find that *within* classified pulps, these two quantities are correlated.

There is naturally a causal relationship between fiber perimeter and cross-sectional area: the area can be interpreted as a function of the perimeter and cell-wall thickness. The apparent weak connection between the perimeter

and the cross-sectional area may just be due to minor differences in the mean values of perimeter *between* pulps (Kibblewhite and Bawden 1992; Fig. 5a). *Within* the present experimental pulps, there is a considerable variation in perimeter (Figs. 5a, 8a and 8b), which results also in correlation between the perimeter and the cross-sectional area.

The other primary component contributing to the cross-sectional area of fibers, the thick-

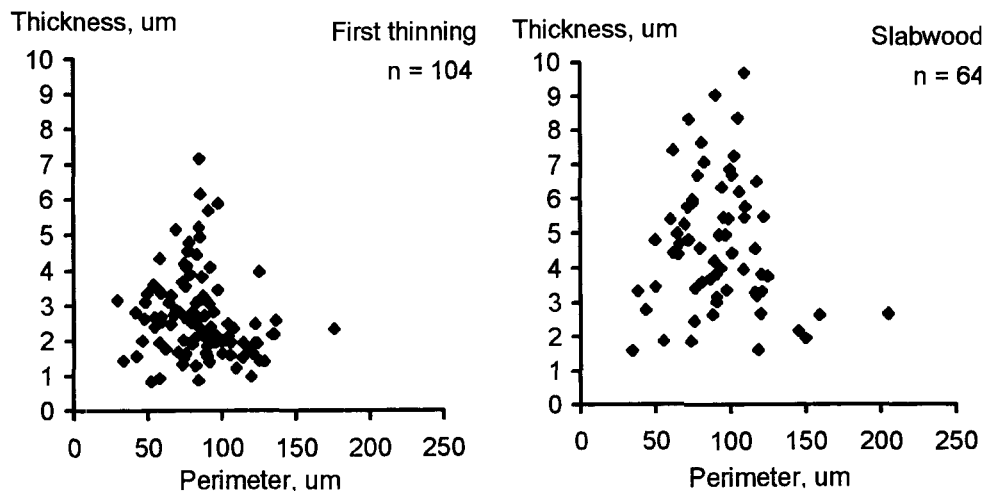


FIG. 10. Correlations of cell-wall thickness and fiber perimeter in two pine pulps classified according to cambium age.



ness of the cell wall, shows considerable variation within both experimental pulps (Fig. 6a), and also a correlation with the cross-sectional area (Figs. 9a and 9b). Thus, *within* pulps classified according to cambium age, both the perimeter and the thickness contribute to the fiber coarseness.

Since experimental pulps represented a relatively small range of cambium age, one might think that most of the within-pulp variation arises from the change of cambial activity within a growing season, where fiber perimeter decreases and the cell-wall thickness increases (Johansson 1939; Saranpää 1985; Evans et al. 1995b), and thus a negative correlation might be expected. However, outer tracheid dimensions develop more rapidly after cell division, whereas the thickness of the cell wall develops mainly after enlargement and over a longer period of time (Larson 1969; Murmanis and Sachs 1969; Skene 1969; Brown 1970; Kozłowski 1971). Thus the tracheid perimeter and cell-wall thickness are results of two different growth processes, and in this case they are hardly correlated (Figs. 10a and 10b). Previous observations indicate only a slight correlation between cell-wall thickness and perimeter of *P. radiata* (Evans et al. 1995a, b).

#### CONCLUSIONS

We conclude that different methods of classification and fractionation of fiber raw materials result in very different distributions and correlations of fiber properties.

Fiber length, cell-wall thickness, and coarseness are strongly correlated between pulps of *Pinus silvestris* and *Picea abies*, the pulps being classified according to cambium age. No significant variation in fiber strength has been observed (Kärenlampi and Suur-Hamari 1995).

*Within* pulps of *Pinus silvestris*, classified according to cambium age, cell-wall thickness and coarseness were not correlated with fiber length. Coarseness was related both to fiber perimeter and cell-wall thickness, while be-

tween pulps only the latter was significant. There was no negative relationship between fiber perimeter and cell-wall thickness because of their independent development processes (Larson 1969; Murmanis and Sachs 1969; Skene 1969; Brown 1970; Kozłowski 1971).

In this study, the consequences of only two mechanisms of wood variation were investigated: the effect of cambium age and the variation within a growing season. More effort is needed to clarify the effects of the maturation of the apical meristem, the supply of growth regulators, and the possible effects of growth rate. Such work is in progress.

#### ACKNOWLEDGMENTS

The authors are obliged to Mr. H. Nätt for performing fiber measurements, Dr. P. Moss for advice with confocal microscopy, and the Technology Development Centre of Finland for partial financing. Drs. J. E. Phelps and R. W. Kennedy constructively criticized the manuscript.

#### REFERENCES

- ALAVA, M. J., AND R. K. RITALA. 1990. Fracture of fibrous networks with varying fibre length. *Physica Scripta* T33:155-158.
- ATMER, B., AND T. THÖRNQVIST. 1982. Fiberegenskaper i gran (*Picea abies* Karst.) och tall (*Pinus silvestris* L.). The properties of tracheids in spruce (*Picea abies* Karst.) and pine (*Pinus silvestris* L.). Sveriges lantbruksuniversitet, institutionen för virkeslära, Rapport 134. (The Swedish University of Agricultural Sciences, Dept. of Forest Products, Research Note 134.) 120 pp.
- BENDTSEN, B. A., AND J. SENFT. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. *Wood Fiber Sci.* 18(1):23-28.
- BISSET, I. J. W., AND H. E. DADSWELL. 1950. The variation in cell length within one growth ring of certain angiosperms and gymnosperms. *Aust. For.* 14(1):17-29.
- BLOUIN, D., J. BEAULIEU, G. DAoust, AND J. POLIQUIN. 1994. Wood quality of Norway spruce grown in plantations in Quebec. *Wood Fiber Sci.* 26(3):342-353.
- BOUTELJE, J. 1968. Juvenile wood, with particular reference to northern spruce. *Sven. Papperstidn.* 71(17):561-585.
- BROWN, C. L. 1970. Physiology of wood formation of conifers. *Wood Sci.* 3(1):8-22.

- DINWOODIE, J. M.: 1961. Tracheid and fibre length in timber. A review of literature. *Forestry* 34(2):125–144.
- DORN, D.: 1969. Relationship of specific gravity and tracheid length to growth rate and provenance in Scotch pine. Pages 1–6 in *Proc. 16th Northeastern Forest Tree Improvement Conference*, Quebec, Canada.
- ERICSON, B., T. JOHNSON, AND A. PERSSON.: 1973. Ved och sulfatmassa från tall: orörda bestånd. Wood and sulphate pulp of Scots pine from virgin stands. Skogshögskolan, Not. för skogsproduktion, Rapporter och uppsatser nr. 25. 143 pp.
- ERICKSON, H. D., AND A. TH. HARRISON.: 1974. Douglas fir wood quality studies. Part 1: Effects of age and stimulated growth on wood density and anatomy. *Wood Sci. Technol.* 8(3) 207–226.
- EVANS, R.: 1994. Rapid measurement of the transverse dimensions of tracheids in radial wood sections from *Pinus radiata*. *Holzforchung* 48(2):168–172.
- , G. DOWNES, D. MENZ, AND A. STRINGER.: 1995a. Rapid measurement of variation in tracheid transverse dimensions in a radiata pine tree. *Appita* 48(2):134–138.
- , G. GARTSIDE, AND G. DOWNES.: 1995b. Present and prospective uses of Silviscan for wood microstructure analysis. Pages 91–96 in *Appita 1995 Annual Conference*.
- IFJU, G., AND R. W. KENNEDY.: 1962. Some variables affecting microtensile strength of Douglas fir. *Forest Prod. J.* 12(5):213–217.
- JACKSON, F.: 1988. Fibre length measurement and its application to paper machine operation. *Appita* 41(3):212–216.
- JANG, H. F., A. G. ROBERTSON, AND R. S. SETH.: 1991. Optical sectioning of pulp fibres with confocal scanning laser microscopy. Pages 277–279 in *1991 International Paper Physics Conference*, Kona, Hawaii.
- , and ———.: 1992. Transverse dimensions of pulp fibers by confocal laser scanning microscopy and image analysis. *J. Mater. Sci.* 27:6391–6400.
- JOHANSSON, D.: 1939. Något om vår- och höstved hos tall och gran och dess inverkan på sulfat- och sulfatmassans egenskaper. Summary: On the spring and summer wood of pine and spruce and their influence on the properties of sulphite and sulphate pulp. *Suomen paperi- ja puutavaralehti* (The Finnish Paper and Timber Journal) 1939(7a, special number):54–72.
- KÄRENLAMP, P.: 1995a. Tensile strength of paper. A simulation study. *J. Pulp Paper Sci.* 21(6):J209–214.
- .: 1995b. Tensile strength of a mixture of two pulps. *J. Pulp Paper Sci.* 21(12):J432–436.
- , AND H. SUUR-HAMARI.: 1995. Classified wood raw materials for diversified softwood kraft pulps. Pages 683–690 in *TAPPI 1995 Pulping Conference*, Oct. 1995. Chicago, IL.
- Kibblewhite, R. P., and A. D. Bawden.: 1992. Kraft fibre qualities of *Pinus radiata* toplogs, thinnings, and slabwood, and a “genetic misfit”. *N. Z. For. Sci.* 22(1):96–110.
- KOZLOWSKI, T. T.: 1971. Growth and development of trees. Vol II. Cambial growth, root growth and reproductive growth. Academic Press, New York, NY. 514 pp.
- KUCERA, B.: 1994. A hypothesis relating current annual height increment to juvenile wood formation in Norway spruce. *Wood Fiber Sci.* 26(1):152–167.
- LARSON, P. R.: 1969. Wood formation and the concept of wood quality. Yale University, School of Forestry. *Bulletin* 74:1–54.
- LEWARK, S.: 1986. Anatomical and physical differences between juvenile and adult wood. Pages 272–281 in *Proc. 18th IUFRO World Congress*, Sept. 7–21, 1986, Yugoslavia. Div. 5.
- LIESE, W., AND H. E. DADSWELL.: 1959. Über den Einfluss der Himmelsrichtung auf die Länge von Holzfasern und Tracheiden. On the influence of cardinal points in the lengths of wood fibers and tracheids. *Holz Roh- Werkst.* 17(11):421–427.
- LITTLE, C. H. A., AND R. A. SAVIDGE.: 1987. The role of plant growth regulators in forest tree cambial growth. Pages 137–169 in S. V. Kossuth and S. D. Ross, eds. *Hormonal control of tree growth*. Martinus Nijhoff Publishers, Dordrecht, Netherlands.
- MANWILLER, F. G.: 1972. Volumes, wood properties, and fiber dimensions of fast- and slow-grown spruce pine. Pages L1–9 in *Proc. Symposium on the Effect of Growth Acceleration on the Properties of Wood*. USDA Forest Products Laboratory, Nov. 1971.
- MEYLAN, B. A.: 1972. The influence of microfibril angle on the longitudinal shrinkage–moisture content relationship. *Wood Sci. Technol.* 6(4):293–301.
- MORK, E.: 1928. Granvirkets kvalitet særlig med røkte paa slip- og selluloseved. *Papir-Journalen* 16(4):40–44, (5):54–58, (6):65–69, (7):79–83, (8):88–91, (9):101–105, (10):111–114. In Norwegian.
- MOSS, P. A., E. RETULAINEN, H. PAULAPURO, AND P. AALTONEN.: 1993. Taking a new look at pulp and paper: Applications of confocal laser scanning microscopy (CLSM) to pulp and paper research. *Paperi ja Puu* 75(1–2):74–79.
- MURMANIS, L., AND I. B. SACHS.: 1969. Seasonal development of secondary xylem in *Pinus strobus* L. *Wood Sci. Technol.* 3(3):177–193.
- NYLINDER, P.: 1953. Volymviktsvariationer hos planterad gran. Variations in density of planted spruce. *Meddelanden från statens skogsforskningsinstitut*, Stockholm. 43(3):1–44.
- OLESEN, P. O.: 1978. On cyclophysis and topophysis. *Silvae Genetica* 27(5):173–178.
- OLLINMAA, P. J.: 1959. Reaktiipuututkimuksia. Summary: Study on reaction wood. *Acta For. Fenn.* 72.1. 54 pp.
- OMEIS, E.: 1895. Untersuchungen des Wachstumsanges und der Holzbeschaffenheit eines 110jährigen Kiefern-

- bestandes. Forstlich-Naturwissenschaftliche Zeitschrift 4(4):137-170.
- PAKKARI, T., AND R. SERIMAA. 1984. A study of the structure of wood cells by X-ray diffraction. Wood Sci. Technol. 18(2):79-85.
- ROBERTSON, A. G., H. F. JANG, AND R. S. SETH. 1992. Three-dimensional visualization of confocal images of wood pulp fibers. J. Mater. Sci. Letters. 11:1416-1418.
- SARANPÄÄ, P. 1985. Kontortamännyn runkopuun trakeidien pituuden, halkaisijan ja soluseinämän paksuuden vaihtelu. Summary: Length, diameter and thickness of tracheids in mature lodgepole pine bolewood. Silva Fennica 19(1):21-32.
- SIDDIQUI, K. M., W. T. GLADSTONE, AND R. MARTON. 1972. Influence of fertilization on wood and pulp properties of Douglas fir. Pages C1-16 in Proc. Symposium on the Effect of Growth Acceleration Effect on the Properties of Wood. USDA Forest Products Laboratory, Nov. 1971.
- SKENE, D. S. 1969. The period of time taken by cambial derivatives to grow and differentiate into tracheids in *Pinus radiata* D. Don. Ann. Bot. 33:253-262.
- STAIRS, G. R., R. MARTON, A. F. BROWN, M. RIZZIO, AND A. PETRIK. 1966. Anatomical and pulping properties of fast- and slow-grown Norway spruce. Tappi 49(7): 296-300.
- ZOBEL, B. J. AND J. P. VAN BUIJTENEN. 1989. Wood variation. Its causes and control. Springer-Verlag, Berlin and Heidelberg, Germany. 363 pp.