

# PITS AS NATURAL IRREGULARITIES IN SOFTWOOD FIBERS

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## ABSTRACT

Parameters for pit size, shape, orientation, and density, and their correlations with fiber dimensions in Scots pine and Norway spruce fibers were determined. Bordered pits were smaller with greater cross-sectional fiber area, and more circular the wider the fibers. Angular pit orientation became more transverse in pine fibers, and pit density increased in both species with fiber width. Normalized pit size and pit density increased towards fiber tips, especially in thin-walled pine fibers. These observations can be explained by the developing process and the functional role of tracheids in wood. The appearance of pits as stress-enhancing irregularities in fiber structure should be considered in fiber-network theories predicting paper properties, as well as in the measurement of the mechanical properties of fibers.

*Keywords:* Pit size, pit shape, pit orientation, pit density, fiber strength, *Pinus silvestris*, *Picea abies*.

## INTRODUCTION

The strength of softwood fibers is important since they are used for reinforcing paper webs. The mechanical properties of materials and objects are greatly affected by stress-enhancing irregularities, which may be natural or man-made. In softwood fibers, the most obvious natural irregularities are pits—openings transmitting water from one tracheid to another. In this paper, all kinds of microscopically observable natural openings in fiber cell walls, including associated borders, are called *pits*. Wood tracheids dissolved from wood matrix are called *fibers*.

When wood pulp fibers have been stretched under a microscope, local strain in the vicinity of a pit has been observed to be up to ten times that recorded in unpitted cell-wall areas (Groom et al. 1995). The orientation of cel-

lulose microfibrils, i.e., microfibril angle, affects the mechanical properties of a wood fiber (Page and El-Hosseiny 1983; Page et al. 1985), but dominates fiber behavior only in the case of flaw-free fibers (El-Hosseiny and Page 1975; Page et al. 1977). The appearance of man-made defects in cell walls is not necessarily independent of the appearance of natural irregularities.

Koran (1977) reported a mean diameter of 16.4  $\mu\text{m}$  for bordered pits of black spruce (*Picea mariana*) earlywood tracheids with a mean width of 36.0  $\mu\text{m}$ . In latewood fibers, the mean pit diameter was 9.0  $\mu\text{m}$  and fiber width 18.0  $\mu\text{m}$ , making the diameter of the bordered pits about 50% of fiber width.

Physiological changes, brought on by the aging of the cambium, for example, may contribute to the size of pits. Lin (1989) found the mean diameter of *Pinus radiata* bordered pits increasing 55% from growth ring 1 to growth ring 25, for both earlywood and latewood fibers. However, pit diameter normalized with

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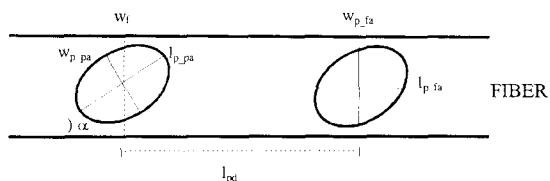


FIG. 1. Pit parameters.  $l_{p-pa}$  = pit length parallel to pit axis,  $w_{p-pa}$  = pit width perpendicular to pit axis,  $l_{p-fa}$  = pit length parallel to fiber axis,  $w_{p-fa}$  = pit width perpendicular to fiber axis,  $w_f$  = fiber width,  $\alpha$  = angle between pit axis and fiber axis,  $l_{pd}$  = distance between two pits.

fiber width did not change in earlywood fibers, but did increase 23% in latewood fibers, due to a smaller increase in fiber width among latewood fibers. The normalized mean pit diameter varied between 51 and 65%. The mean normalized pit aperture size (pit aperture width/fiber width) did not change with cambium age in earlywood fibers, but in latewood fibers it increased 30%. Average normalized pit aperture size varied between 15 and 22%.

Thomas and Scheld (1967) reported tracheid and pit diameters of *Tsuga canadensis* from growth rings 10, 20, 40, and 60. Their measurements show that the normalized pit size varied between 45 and 56%, increasing from growth ring 10 to growth ring 60 by 10% in earlywood fibers and 25% in latewood fibers. No clear trend was found in the normalized pit aperture size as a function of cambium age.

Koran (1974) reported that pit apertures were quite circular in *Picea mariana* earlywood tracheids, but elliptical in latewood fibers. Lin (1989) observed the same with *Pinus radiata*. He also reported that the ovalness of the pit aperture (the ratio between the long and short diameter) in latewood fibers was in most cases between 3 and 4.

Lin (1989) reported the mean pit density (number of pits per fiber length unit) increasing from 16 to 22 pits/mm in *Pinus radiata* earlywood fibers and from 4 to 7 in latewood fibers from growth ring 1 to 25. Pit density has also been much higher in earlywood than in latewood fibers in *Abies sachalinensis* (Takizawa and Ishida 1972) and *Larix leptolepis*

(Takizawa 1974). We can further calculate from Thomas and Scheld's (1967) measurements that from growth ring 10 to 60 of *Tsuga canadensis* the mean pit density increased from 18 to 54 pits/mm in earlywood and 8 to 18 pits/mm in latewood fibers.

Takizawa and Ishida (1972) investigated the number and distribution of pits in *Abies sachalinensis* tracheids, mainly in earlywood fibers. Only 50% of bordered pits were located within the middle  $\frac{2}{3}$  of fiber length. On the other hand, 50% of pits between axial tracheids and ray parenchyma cells were located within the middle  $\frac{1}{3}$  of the length of the tracheid. The bordered pits are thus concentrated in fiber ends, but other pits are concentrated in the middle parts of the tracheids. Takizawa (1974) later found the same phenomenon with *Larix leptolepis*.

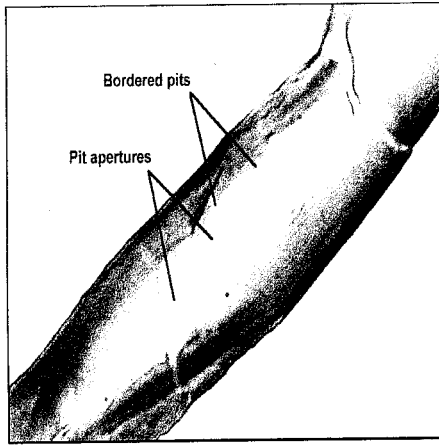
#### OBJECTIVE

This study considers pits as irregularities in softwood fibers. First, we define pit parameters. We then report observations on pit appearance, including correlations between pit parameters and fiber dimensions: fiber length, width, circumference, cell-wall thickness, and coarseness. Scots pine (*Pinus silvestris*) and Norway spruce (*Picea abies*) tracheids are considered. Experimental findings are compared with earlier results. Finally, we discuss the mechanisms of pit formation as well as the effect of pits on the mechanical behavior of wood pulp fibers on the basis of the observations.

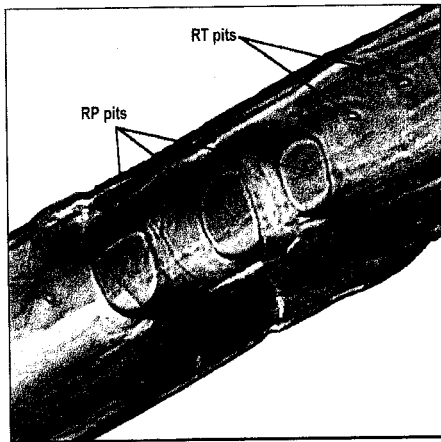
#### PIT PARAMETERS

When evaluating the influence of a pit on the strength of a fiber, the pit width perpendicular to the fiber axis  $w_{p-fa}$  should be nor-

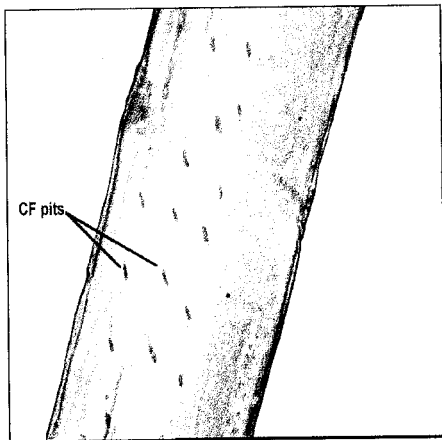
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FIG. 2. Different kinds of pits in longitudinal softwood tracheids. A: Bordered pits and their apertures in a Norway spruce tracheid, B: Pits leading from a Scots pine tracheid to a ray parenchyma cell (RP) and to a ray tracheid (RT), C: Crossfield pits in a Norway spruce tracheid.



a.



b.



c.

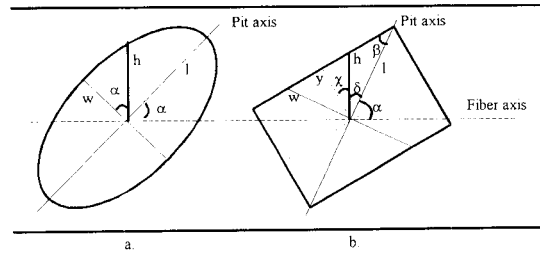


FIG. 3. Symbols used in calculating pit width perpendicular to fiber axis for (a) bordered and (b) window-like pits.

malized according to the fiber circumference  $c_f$  or fiber width  $w_f$ . Equation 1 defines a **pit size** parameter (cf. Fig. 1).

$$\text{size}_p = w_{p-fa} / w_f \quad (1)$$

where the greatest pit width  $w_{p-fa}$  perpendicular to the fiber axis is normalized by the local fiber width  $w_f$ .

Since pits are mainly circular or elliptical, a **pit shape** parameter can be defined as the longest dimension of the pit  $l_{p-pa}$ , also defining the direction of the pit axis, divided by the greatest width  $w_{p-pa}$ , being measured perpendicular to the length (Eq. [2]; see also Fig. 1).

$$\text{shape}_p = l_{p-pa} / w_{p-pa} \quad (2)$$

**Pit orientation** ( $\alpha$ ) is defined as the angle between the long axis of the pit and the local fiber axis (Eq. [3])

$$\alpha = | \alpha_f - \alpha_p | \quad (3)$$

where  $\alpha_f$  is the local orientation of the fiber and  $\alpha_p$  is the orientation of the long axis of

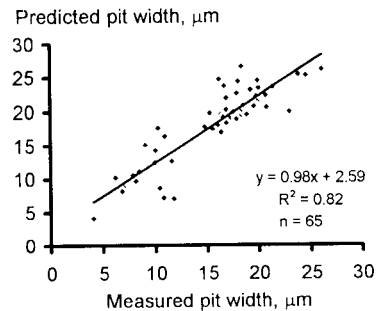


FIG. 4. Correlation between measured and predicted (Eq. [6]) width of bordered pits perpendicular to fiber axis.

TABLE 1. *The variation in pine fiber pit parameters.*

	Size				Shape				Orientation, degrees			
	Bord. pits	Aper- tures	RP pits	RT pits	Bord. pits	Aper- tures	RP pits	RT pits	Bord. pits	Aper- tures	RP pits	RT pits
Mean	0.40	0.13	0.37	0.04	1.18	1.27	1.41	2.00	55.6	51.8	49.1	32.1
Max.	0.77	0.26	0.75	0.09	1.69	2.48	2.61	3.58	89.9	89.8	85.2	83.5
Min.	0.13	0.04	0.12	0.02	1.00	1.00	1.00	1.16	0.4	0.0	9.2	0.2
Coeff. var	0.3	0.3	0.3	0.4	0.1	0.2	0.2	0.2	0.5	0.5	0.3	0.6
No. of pits	413	419	97	79	414	419	97	79	414	419	97	79

the pit. The pit orientation is defined as an absolute angle because of experimental limitations discussed below.

The size, shape, and orientation of pit apertures are defined the same way as the corresponding parameters of entire pits including borders.

**Pit density** ( $\rho_p$ ) is defined as the number of pits per fiber length unit, being calculated as the inverse of the distance between the midpoints of any two adjacent pits:

$$\rho_p = 1/l_{pd} \quad (4)$$

where  $l_{pd}$  is the distance (parallel to the fiber axis) between two pits.

The **spatial appearance** of pits is described by the distribution of the pit parameters along fiber axis.

#### EXPERIMENTAL

Small wood pieces containing wood from growth rings 13–17 were taken at the breast height of a Scots pine (*Pinus silvestris*) tree and a Norway spruce (*Picea abies*) tree. Wood samples were macerated in a mixture of glacial acetic acid and hydrogen peroxide (1:1 by volume) at 60°C for 24 hours. Fibers to be measured were randomly selected. Only un-

broken fibers were measured, which resulted in 29% of pine fibers and 14% of spruce fibers being discarded. Pit parameters as well as fiber length  $l_f$  and width  $w_f$  were measured from images created using a polarized-light microscope. Fiber circumference  $c_f$  and cross-sectional cell-wall area  $A_{cw}$  were measured from images created using a confocal laser scanning microscope. Two measurements (located at 35% of fiber length from both fiber ends) per fiber were averaged. Average cell-wall thickness  $t_{cw}$  was calculated from the fiber circumference and cross-sectional area of the cell wall as

$$t_{cw} = \frac{c_f - \sqrt{c_f^2 - 16A_{cw}}}{8} \quad (5)$$

where  $c_f$  is fiber circumference and  $A_{cw}$  is the cross-sectional area of a fiber, excluding lumen.

There are three types of pits in longitudinal softwood tracheids (Fig. 2).

- bordered pits leading from one tracheid to another
- pits leading from a tracheid to a ray parenchyma cell (RP)

TABLE 2. *The variation in spruce fiber pit parameters.*

	Size			Shape			Orientation, degrees		
	Bord. pits	Aper- tures	CF pits	Bord. pits	Aper- tures	CF pits	Bord. pits	Aper- tures	CF pits
Mean	0.41	0.12	0.04	1.18	1.34	1.95	59.31	53.25	33.13
Max.	0.71	0.24	0.09	2.04	2.50	3.09	89.98	89.61	71.57
Min.	0.18	0.06	0.01	1.00	1.00	1.16	0.37	0.20	0.19
Coeff. var	0.2	0.2	0.4	0.1	0.2	0.2	0.4	0.5	0.5
No. of pits	410	451	59	410	451	59	410	451	59

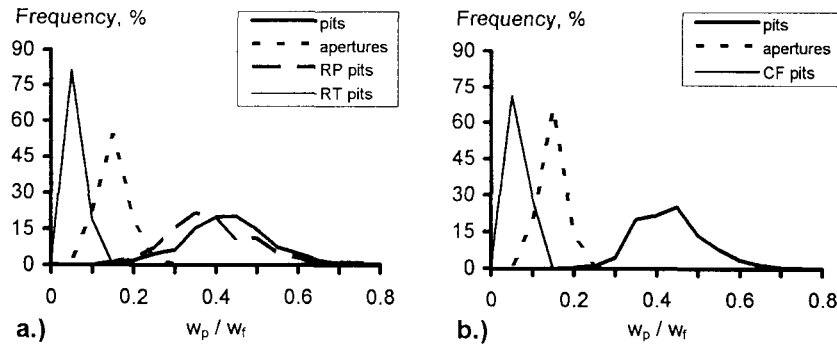


FIG. 5. Distribution of size parameter in different pit types in (a) pine and (b) spruce fibers.

- pits leading from a longitudinal tracheid to a ray tracheid (RT).

Pits leading to ray cells (parenchyma or tracheid) are often called *crossfield pits*. In Scots pine tracheids, the RP pits differ considerably from RT pits. They were all treated as different classes. However, both crossfield pit types in Norway spruce tracheids are quite small and located in the same regions. They were treated as one class, crossfield pits (CF).

To calculate the pit shape factor, the length and the width of any pit had to be measured with respect to the pit axis. The width of bordered pits perpendicular to fiber axis was calculated by Eq. (6) from these measurements. For symbols, see Fig. 3a. Here we assumed that pits were elliptical, the circle thus being one special case. Parameters for pit apertures, pine RT pits, and spruce CF pits were calculated similarly.

$$w_{p-fa} = 2h = \pm \frac{l}{\sqrt{\sin^2 \alpha + \left(\frac{l}{w}\right)^2 \cos^2 \alpha}} \quad (6)$$

RP pits of pine fibers are not elliptical but rather rectangular (see Fig. 2b). Figure 3b shows that  $y = 1 * \sin \beta$  and  $\tan \beta = w/l$ . Because  $\alpha + \delta = 90$  degrees and  $\chi + \beta + \delta = 90$  degrees, we find that  $\chi = \alpha - \beta$ . Since the values of  $l$ ,  $w$ , and  $\alpha$  are known from the measurements, we can now calculate the width (perpendicular to the fiber axis) of a window-like pit by Eq. (7).

$$w_{p-fa} = 2h = \frac{2y}{\cos \chi} \quad (7)$$

In order to determine how well the assumption of elliptical shape of bordered pits was met, direct measurements of the greatest pit width perpendicular to the fiber axis were

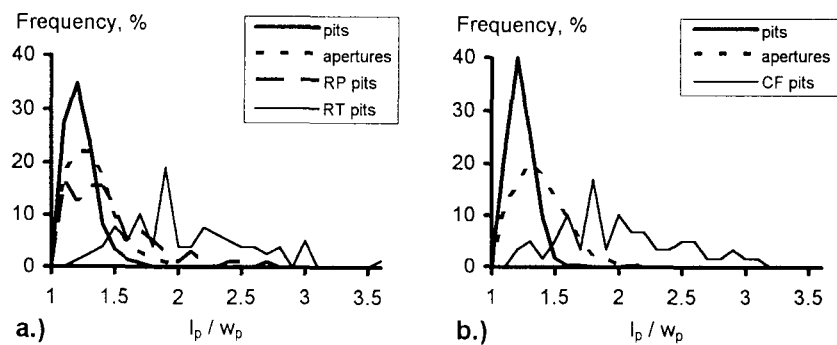


FIG. 6. Distribution of shape parameter in different pit types in (a) pine and (b) spruce fibers.

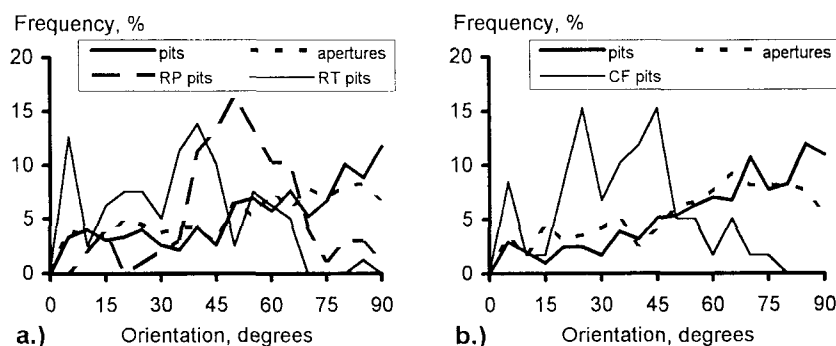


FIG. 7. Distribution of orientation in different pit types in (a) pine and (b) spruce fibers.

done for three pine fibers, with sixty-five pits altogether. The results are shown in Fig. 4. We see that the predicted dimensions, assuming elliptical shape, correlated quite well with the direct (and laborious) measurements ( $r^2 = 0.82$ ).

Pits between spruce (*Picea abies*) tracheids and ray cells form crossfield areas with many small, elliptical pits (Fig. 2c). The number and location of these crossfield pits were recorded, and every tenth was sampled for size, shape, and orientation measurements.

Pits of ten pine and seven spruce fibers were studied, the dimensions of about five hundred pits per wood species thus being measured. The pits of seven more fibers of both tree species were counted and their location within the fiber axis was measured in order to determine the correlations between fiber dimensions and pit density. All statistical comparisons were first done by variance analysis. If this indicated differences between groups, the comparison was continued by two-sample student's t-test.

## RESULTS

### *Distributions of pit parameters*

The total number of pine fiber pits whose dimensions were measured was 595, of which 70% were bordered pits. Their mean size was 40% of fiber width, while the mean size of bordered pit apertures was 13%, RP pits 37%, and RT pits 4% (Table 1). The differences in the mean size between pit types and pit apertures were statistically significant ( $P < 0.01$ ).

The number of pits observed in the first seven spruce fibers was 962, 47% being bordered pits. However, the dimensions of every tenth crossfield pit only was measured, and thus the number of CF pits measured (Table 2) is 59. The mean size of bordered pits was 41% of fiber width, bordered pit apertures were 12%, and CF pits 4% of fiber width (Table 2). The differences in the mean size parameter between pit types and pit apertures were statistically significant ( $P < 0.01$ ).

The normalized size of bordered pits and their apertures did not differ statistically be-

TABLE 3. Linear correlation coefficients of pine and spruce fiber dimensions.

	Pine					Spruce				
	Length	Width	Circumference	Thickness	Area	Length	Width	Circumference	Thickness	Area
Length	1.00					1.00				
Width	0.40	1.00				0.35	1.00			
Circumference	0.43	0.46	1.00			0.40	0.97	1.00		
Thickness	0.31	-0.25	-0.29	1.00		-0.02	-0.20	-0.24	1.00	
Area	0.65	0.15	0.36	0.76	1.00	0.25	0.66	0.63	0.58	1.00

TABLE 4. Linear correlation coefficients between mean values of bordered pit parameters and fiber dimensions.

	Pine					Spruce				
	Length	Width	Circumference	Thickness	Area	Length	Width	Circumference	Thickness	Area
Size	-0.65	0.03	-0.37	-0.66	-0.85	-0.23	-0.62	-0.45	-0.41	-0.54
Shape	0.44	-0.56	0.19	0.51	0.60	0.13	-0.84	-0.63	-0.31	-0.55
Orientation	-0.02	0.77	0.44	-0.45	-0.20	-0.74	0.21	0.37	-0.48	-0.12
Density	-0.09	0.58	0.30	-0.57	-0.37	-0.03	0.62	0.59	-0.26	0.37

tween pine and spruce fibers ( $P > 0.05$ ). The pine RT pits and spruce CF pits also had the same relative size ( $P > 0.05$ ). The size of pits and pit apertures is quite normally distributed (Fig. 5). The coefficient of variation is lowest in the case of bordered pits (Tables 1 and 2).

Bordered pits were the most circular in shape, while the window-like pits were on average over 40% longer than their width, and the length of crossfield and RT pits was twice their width (Table 1). The average shape was statistically dependent on the pit type within both tree species ( $P < 0.01$ ).

The shape parameter increased and orientation angle decreased in the sequence bordered pits—apertures—RP pits—RT pits, as well in pine and as in spruce fibers. The mean shape parameters of bordered pits in pine and spruce, as well as pine RT pits and spruce CF pits were statistically the same ( $P > 0.05$ ). The apertures of bordered pits were more circular in pine fibers. The shape distributions of pits were skewed to the right (Fig. 6).

With polarized light passing through a thin wood fiber, it is difficult to say if the pit is located in the upper or lower fiber wall. Thus we were unable to determine whether a pit is oriented to the right or to the left with respect to the fiber axis, and pit orientation was recorded as an absolute angle between 0 and 90 degrees. Almost all pit orientations were found (Fig. 7), which indicates that it is not a simple function of microfibril angle. The orientation of bordered pits differed statistically from the orientation of apertures and RP and RT pits ( $P < 0.05$ ). The orientation of RP and RT pits was quite normally distributed, the mode value being found around 45 degrees. Most bordered

pits and their apertures had large orientation angles.

#### Correlations in fiber dimensions

Pit parameters may be correlated to fiber dimensions, which in turn may be correlated with each other. These correlations may vary both between wood species and fiber populations of different origin. Linear coefficients of correlation between fiber dimensions are shown in Table 3.

There was poor correlation between fiber length and fiber width or cell-wall thickness in both wood species (Table 3). In our even-aged samples (only a few growth rings) this observation is self-explanatory, because the fiber length does not increase dramatically from earlywood to latewood in these wood species (Bisset and Dadswell 1950). Thus cross-sectional cell-wall area might not correlate with fiber length either. However, there was a correlation within pine fibers, in which the variation in cross-sectional cell-wall area was due more to variation in cell-wall thickness than fiber width or circumference (Table 3). Cell-wall thickness and cross-sectional cell-wall area increase from earlywood to latewood (Johansson 1939; Bernhart 1964), and these measures naturally were correlated (Table 3).

#### Variation of pit parameters between fibers

The pit parameters were correlated with fiber dimensions. Linear coefficients of correlation in the case of bordered pits are shown in Table 4. We find that pit size correlates negatively with cell-wall area, cell-wall thickness, and fiber length. The shape

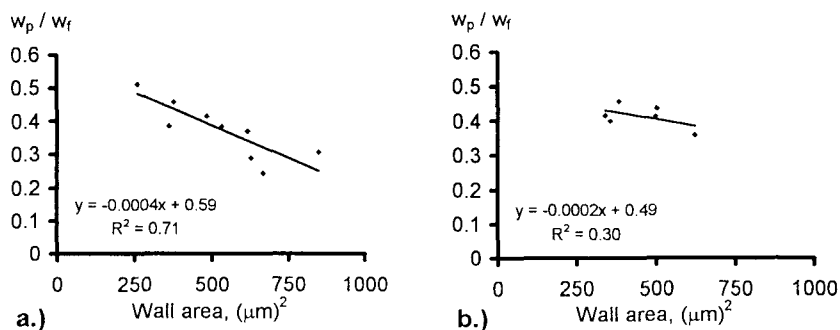


FIG. 8. Correlation between average bordered pit size and average cross-sectional area of fiber in (a) pine and (b) spruce fibers.

factor, orientation, and density correlate with fiber width. In the case of other large pits, particularly the RP pits of pine fibers, the pit parameters were not correlated with fiber dimensions. Let us explore some of these correlations further.

In Fig. 8 we see that the average size of bordered pits decreases with increasing fiber cross-sectional area. However, it is likely that the largest pit dominates fiber behavior. The size of the largest pit (of any type) within a fiber, which was 46–77% of the fiber width in pine fibers and 55–71% in spruce, did not correlate with fiber dimensions ( $r^2 < 0.30$ ).

The bordered pits tend to be more circular the wider the fiber (Fig. 9). The shape of the largest pit (of any type) within a fiber was 1.0–1.2 among the pine fibers and 1.1–1.4 among the spruce fibers. This did not correlate with fiber dimensions.

In pine fibers the average orientation of bordered pits was greater in wider fibers (Fig. 10a). This was also true in the case of the largest pit (of any type) of each fiber. The orientation of the largest pit approached the orientation of the fiber axis with increasing cell-wall thickness (Fig. 11a). In spruce fibers, the average orientation of bordered pits did not correlate with fiber width or cell-wall thickness (Figs. 10b and 11b), and neither did the orientation of the largest pit (of any type).

The size, shape, and orientation parameters of the largest pits (of any type) were not correlated to each other.

Wide fibers have more pits than narrow fibers (Fig. 12). When calculating the average pit density, all kinds of pits were included, resulting in a greater pit density in spruce fibers compared to pine because of the CF areas of many small pits.

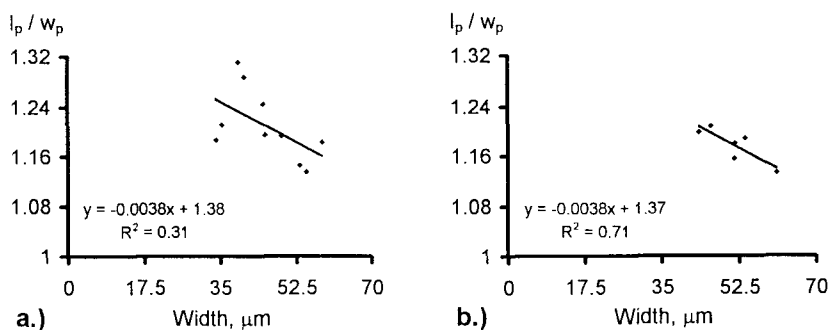


FIG. 9. Correlation between average bordered pit shape and average fiber width in (a) pine and (b) spruce fibers.



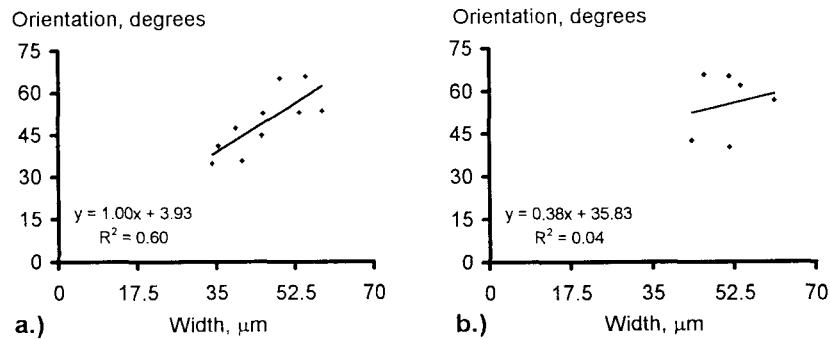


FIG. 10. Correlation between average bordered pit orientation and average fiber width in (a) pine and (b) spruce fibers.

#### Variation of pit parameters within a fiber

Wood fibers are very long in comparison to their width. Their mechanical behavior in the network structure of paper is largely determined by the local strength and ductility of fibers and bonds within a relatively short portion of the fiber. It is reasonable to assume that the mechanical behavior of a fiber is dominated by the largest pit appearing locally, the relevant length scale certainly depending on the density of the fiber network. Let us now divide any fiber into 5% fiber length portions, and study the pit parameters of the largest pit of any portion.

The relative size of the largest pits increased towards fiber ends (Fig. 13). This phenomenon is most pronounced with thin-walled pine fibers, where the average pit size at fiber ends was twice that of the middle parts.

The pit shape parameter of the largest pit

did not change systematically along the fiber axis (Fig. 14).

In thick-walled pine fibers ( $t_{cw} \geq 4.5 \mu\text{m}$ ), the orientation of the largest pit within fiber segments averaged 50 degrees, while in thin-walled fibers ( $t_{cw} < 4.5 \mu\text{m}$ ) the orientation was 65 degrees on average (Fig. 15a). No such tendency was observed with spruce fibers (Fig. 15b).

The number of pits per fiber unit length (pit density) increases towards fiber ends (Fig. 16). Only those pits exceeding 10% of fiber width are included in this figure. The pit density appears to be greatest not in the immediate vicinity of the end, but rather at about 10% of fiber length from it. Many thick-walled fibers have only a few pits near the fiber ends and many fiber portions in the center parts have no pits at all.

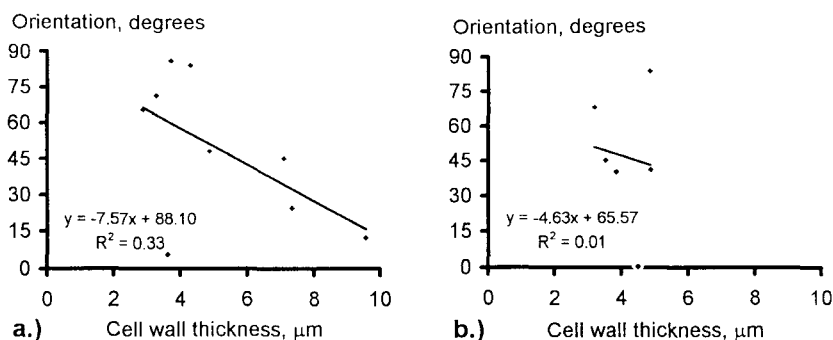


FIG. 11. Correlation between the orientation of the largest fiber pit and average cell wall thickness in (a) pine and (b) spruce fibers.

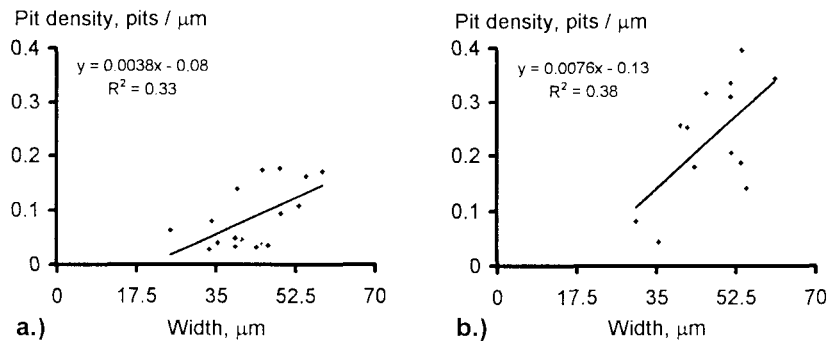


FIG. 12. Correlation between average pit density and average fiber width in (a) pine and (b) spruce fibers.

### Comparison with earlier results

Our measurements gave somewhat smaller mean normalized bordered pit size (Tables 1 and 2) than those calculated from Koran's study (1977) of black spruce of Lin's (1989) of Monterey pine. This may be partly caused by differences in sampling. Koran took his samples from both heart- and sapwood, while our samples were from growth rings 13–17. A part of the difference may be due to tree species.

Bordered pits were quite circular, as observed in earlier studies. However, pit apertures were much more circular than *Pinus radiata* apertures as reported by Lin (1989).

Pit density (the number of pits per fiber length unit, Fig. 16) was much higher than some previously reported values (cf. Thomas and Scheld 1967; Lin 1989). On the other

hand, higher average pit densities have also been reported (Takizawa and Ishida 1972). Pit density is obviously strongly related to wood species.

The number of pits per tracheid decreases from earlywood to latewood (Koran 1974; Lin 1989). Earlywood fibers are the most effective water pipes, and thus there is a greater number of pits per fiber length unit in wide and thin-walled earlywood fibers (Figs. 12 and 16).

### DISCUSSION

The main development phases of tracheids are dividing, enlarging, cell-wall thickening, and lignification (Brown 1970; Kozłowski 1971). The initial pit border is formed at the onset of enlargement (Liese 1963; Okamura et al. 1973; Barnett and Harris 1975; Barnett

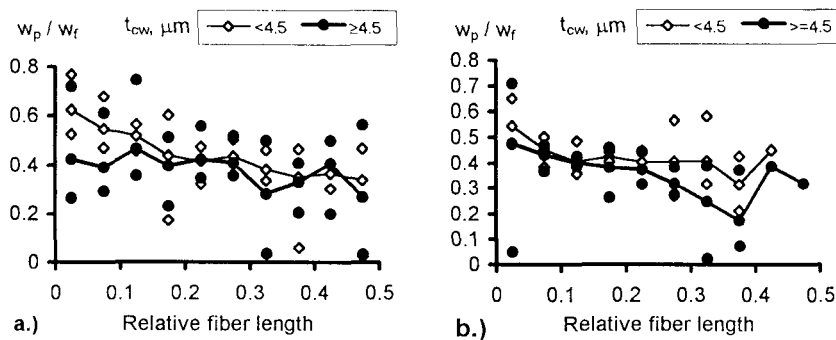


FIG. 13. Spatial appearance of the size of the largest pit in 5% length portions of (a) pine and (b) spruce fibers of different cell-wall thickness. Relative fiber length = 0 means the fiber end and 0.5 means the midpoint of a fiber. Single points without connecting line represent the maximum and the minimum values observed within any fiber length portion.

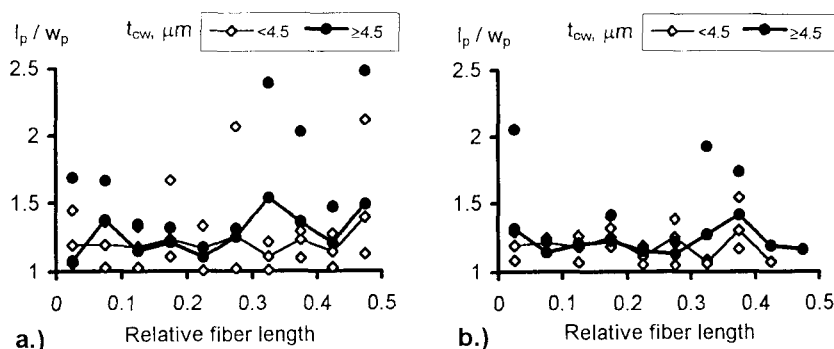


FIG. 14. Spatial appearance of the shape of the largest pit in (a) pine and (b) spruce fibers of different cell-wall thickness.

1981). The border expands while the tracheid is gaining width and length. By the beginning of cell-wall thickening, the pits have reached their final size (Wardrop and Dadswell 1957). Earlywood fibers become wider than latewood fibers (Evans 1994; Fengel and Stoll 1973), but have roughly equal length (Bisset and Dadswell 1950). This may contribute to the shape and orientation of pits so that at the end of the growing season the pits are more elliptical and oriented more parallel to the fiber axis than at the beginning of the season (Figs. 9 and 10).

The effect of window-like RP pits on the mechanical behavior of pine fibers is obviously much greater than the effect of bordered pits, even if they are somewhat smaller in dimension (Table 1 and Fig. 5), because these pits are often grouped and there are no borders that would contain load-carrying material.

Rectangular window-like pits are not often aligned cornerwise with respect to the fiber axis. Recognizing this and taking a closer look at our definition of pit orientation (Eq. 3), if window-like pits (see Fig. 3) were squared, their orientation would be around 45 degrees and the shape parameter would be 1.0. The window-like RP pits have a mode value of angular orientation distribution somewhat above 45 degrees (Fig. 7), and a shape factor somewhat above 1 (Fig. 6), which indicates that they are more often elongated perpendicular to the fiber axis than parallel to it.

Relative pit size and pit density being greatest in the vicinity of fiber tips, the strength of the fiber must be lowest there. The mechanical behavior of single fibers may be examined by elongating fibers with fiber end portions glued onto a surface. Such a method may discard the weakest parts close to fiber ends, and fiber

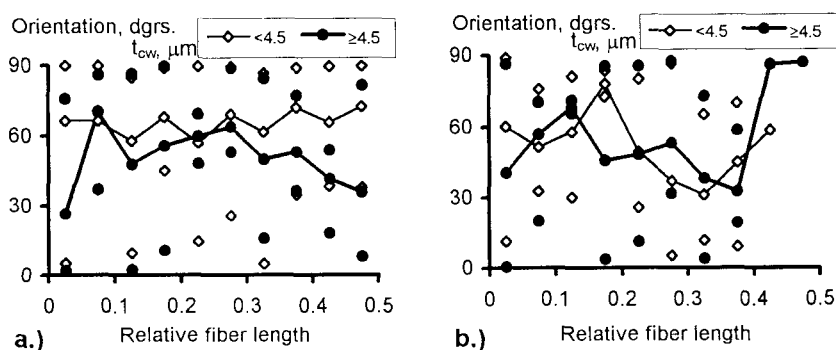


FIG. 15. Spatial appearance of the orientation of the largest pit in (a) pine and (b) spruce fibers of different cell-wall thickness.

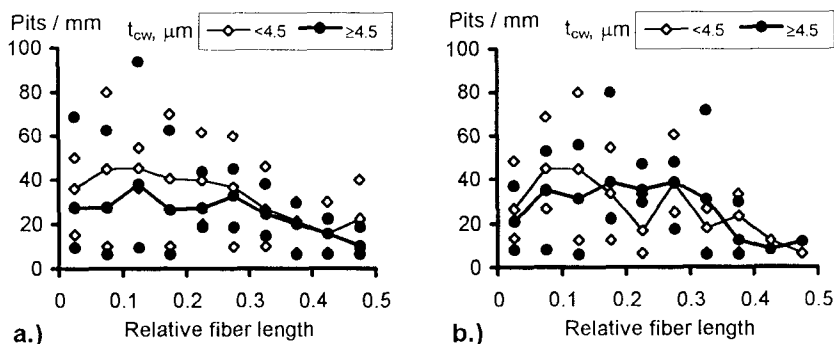


FIG. 16. Spatial appearance of number of pits per millimeter in (a) pine and (b) spruce fibers of different cell-wall thickness.

strength may be overestimated. Further, the effect of flaw-free microstructure (like microfibril angle) on fiber behavior may be overestimated and the effect of irregularities may be underestimated.

In fiber network theories, fibers are often assumed to have uniform modulus, strength, circumference, and coarseness—at least within the length of a single fiber. In addition to the pits making the effective fiber modulus and strength lowest close to fiber ends, cell-wall thickness also decreases towards fiber tips (Okumura et al. 1974). Such phenomena might make a fiber break elsewhere than in the center part, which has been indicated by some observations (Helle 1963). The nonuniformity of mechanical properties within the length of a fiber may change the implications of any analytical model of the relationship between fiber properties and paper properties (Cox 1952).

#### CONCLUSIONS

Parameters for pit size, shape, orientation, and density were determined. The size of Scots pine bordered pits varied between 13% and 77% of fiber width, the average being 40%. With Norway spruce fibers, the corresponding values were 18%, 71%, and 41%, respectively. Bordered pits were smaller with greater cross-sectional fiber area both in pine and spruce fibers, and more circular the wider the fibers. Almost all angular pit orientations

were found, which indicates that the angular orientation is not a simple function of microfibril angle. In the case of pine fibers, angular pit orientation became more transverse with increasing fiber width. Pit density varied considerably from fiber to fiber as well as within a fiber. Pit density increased in both species with fiber width. Normalized pit size and pit density increased towards fiber tips, especially in thin-walled pine fibers.

These observations can be explained by the developing process and the functional role of tracheids in wood. The appearance of pits as stress-enhancing irregularities in fiber structure should be considered in fiber-network theories predicting paper properties, as well as in the measurement of the mechanical properties of fibers.

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