Relationship between Wood Anatomical Properties and Specific Permeability of Sugi (Cryptomeria japonica) Sapwood and Intermediate Wood

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Relationship between Wood Anatomical Properties and Specific Permeability of Sugi (*Cryptomeria japonica*) Sapwood and Intermediate Wood.*

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Abstract

The objective of this study was to clarify anatomical factors which determine specific permeability of sapwood and intermediate wood in air-dried sugi (*Cryptomeria japonica*) wood. Superficial air permeability of sugi sapwood and intermediate wood was measured and then specific permeability was determined. Using these specimens for permeability tests, the proportion of latewood and earlywood, the percentage of aspirated and incompletely aspirated pits, the number of bordered pits per tracheid, the number of tracheids per unit area and tracheid length were obtained.

Specific permeability decreased with increasing levels in the stem except for the lowest level and also related to distance from pith, suggesting that cambial age is related to specific permeability. A clear relationship between percentage of latewood and specific permeability was not found, suggesting that effective pathways in earlywood determines permeability. Specific permeability of intermediate wood and sapwood were significantly related to the number of effective open pits in earlywood, *Nef*, which was determined by anatomical properties such as aspirated and incompletely aspirated pits, the number of pits and tracheids, and proportion of latewood, suggesting that specific permeability of sugi sapwood and intermediate wood is a physical value determined by the intrinsic properties of earlywood in addition to the condition of bordered pits.

Key words：*Cryptomeria japonica*; sapwood, intermediate wood; earlywood; pit aspiration; incompletely aspiration; effective open pits; specific permeability.

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* 松村順司・樫原嘉代子・堤壽一・小田一幸：スギ辺材および移行材の比透過率に関与する木材組織構造

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1. Introduction

Wood anatomical structure is related to physical properties of wood. For example, the states of bordered pit pairs affect the permeability of softwoods. The permeability is shown by the magnitude of bulk flow of fluids through wood. Côté (1963) described three changes in pit pairs, the first condition being pit aspiration and the second condition pit occlusion with extractives. In the latter case the permeability of wood can be increased by extraction with hot water and alcohol (Siau 1971). The third condition is encrustation with materials: this materials are insoluble in both hot water and alcohol (Siau 1971).

The permeability of natural-dried sugi (*Cryptomeria japonica*) wood differs among heartwood, intermediate wood and sapwood. This is caused by bordered pit aspiration which occurs during heartwood formation. In both intermediate wood and sapwood, pit aspiration occurs during the drying process after felling (Philips 1933) also affects permeability, as a result, permeability of freeze-dried and solvent exchange-dried woods is higher in comparison with that of natural-dried wood (Siau 1984 ; Matsumura *et al.* 1995a, 1995b). On the other hand, it is difficult to explain permeability using the aspiration theory only. Some workers have studied the percentage of aspirated pits using various species. For example Booker (1990) reported that more than two thirds of the pits were aspirated in radiata pine heartwood. According to Matsumura *et al.* (1994), the percentage of aspirated pits in heartwood of air-dried sugi is 65-80%, and that of Japanese larch is 70-90%. Heartwood permeability indicated a wide range in comparison with the range of the percentage of aspirated pits. This is caused by occlusion with extractives and encrustation with heartwood materials, which occurs in both aspirated and non-aspirated pits.

Sapwood permeability, in comparison with heartwood, may be determined by the wood structure itself. Meyer (1971) studied the relationship between earlywood permeability and pit aspiration using sapwood of Douglas-fir, and concluded that, when fewer than 80% of the pits are aspirated, the probability of occurrence of a continuous flow path between the entrance and exit faces of permeability specimens increased rapidly. On the other hand, he also pointed out that the effect of pit aspiration on permeability should be considered in relation to other important anatomical characteristics contributing to green sapwood permeability. The objective of this study is to clarify the relationship between wood anatomical characterisitcs and the permeability of sugi sapwood and intermediate wood at different heights of a tree stem.

2. Materials and Methods

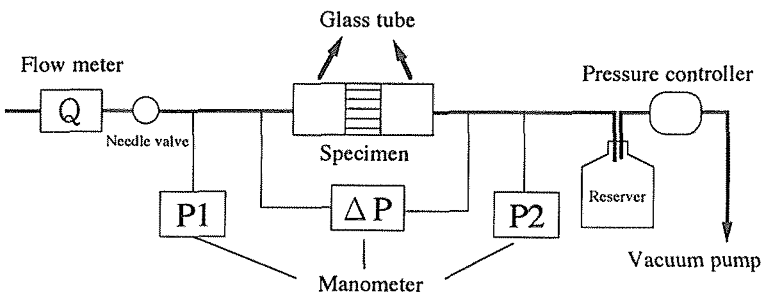
2.1. Materials

A sugi (*Cryptomeria japonica*) tree from the Kyushu University Forests in Fukuoka was felled. Eight disks from 1.5m to 12.0m in height above ground level were used for permeability measurement, and five disks from 1.5, 3.0, 4.5, 6.0 and 9.0m were observed anatomically.

2.2. Specific Permeability

Columnar specimens (15mm in diameter and 8mm long) were taken from intermediate wood, inner sapwood and outer sapwood along a radial direction from the green disks and used for permeability tests. Transverse end surfaces of the specimens were planed smooth using a microtome. These specimens were air-dried in a laboratory and left in a room at 20℃ Temperature controlled and relative humidity of 65% till the permeability experiment was carried out. The air permeability apparatus is schematically shown in Fig. 1. Both ends of specimens were adhered to two glass tubes (inner diameter 8mm) with epoxy resin, and the lateral surfaces of the specimens and the glass tubes were sealed with liquefied silicone to prevent leaks. The pressure of one side of the specimens was controlled by a vacuum rotary pump and a pressure controller. Air flow through the specimens was controlled by a needle valve. Air permeabilities were measured at 20℃ and at a relative humidity of 65%.

Superficial air permeabilities (*kg* [cm^3/(cm•atm•s)] - based on Darcy's law for gases), were obtained from the following equation (1):



$$kg = \frac{Q \cdot L \cdot P}{S \cdot \Delta P \cdot Px}$$

kg=superficial gas permeability, cm^3(gas)/(cm·atm·s) *Q*=volumetric flow rate, cm^3/s
L=length of specimen in the flow direction, cm *ΔP*=pressure differential, atm
S=cross-sectional area of specimen perpendicular to flow direction, cm^2
P=pressure at which the flow rate *Q* is measured, atm
Px=the arithmetic average pressure in the specimen, $(P1+P2)/2$, atm

Fig. 1 Schematic diagram of gas permeability measurement.

$$kg = \frac{Q \cdot L \cdot P}{S \cdot \Delta P \cdot Px} \quad \cdot\cdot\cdot\cdot\cdot \quad (1)$$

where Q = flow rate (cm^3/s), L = specimen length (cm), P = pressure at which the flow rate Q is measured (atm), S = cross-sectional area of specimen (cm^2), ΔP = pressure differential (atm), Px = the arithmetic average pressure in the specimen (atm).

Superficial air permeability unit was converted into darcy using the following equation:

1 darcy = 55.3 cm^3 (air) / (cm•atm•s) at 20℃

where the converted value Kg (darcy) is equal to the product of kg and the viscosity of the fluid. In this study, air permeabilitie was measured at various mean pressures (5 or 6 stages), and specific permeability K was calculated using the following Klinkenberg equation (Klinkenberg, 1941).

$$Kg = K\,(1 + b/Px)$$

where b = slip flow factor. This K value is not affected by the measuring fluids and is only a function of the porous structure of the medium (Siau, 1984).

2.3. Observation on wood structure

The proportion of latewood in the cross-sectional area of the permeability specimens was measured, because resistance to aspirated pit membranes is known to be different between earlywood and latewood.

Specimen of earlywood and specimen including latewood (2mm square × 8mm long), were obtained from the permeability specimens and macerated with Shultz solution. The macerated tracheids were mounted on a microscope slide, and the lengths of fifty randomly selected tracheids were measured. The number of bordered pits per tracheid of thirty randomly selected was also determined.

Specimens (2mm square × 8mm long) cut from the permeability specimens, were resaturated in water and epoxy resin embedded via acetone and propylene oxide. The resin was polymerized at 60℃. Cross sections (1-2μm thick) cut with a glass knife in an ultramicrotome were stained with safranin, and used to count aspirated pits under a light microscope. The percentage of incompletely aspirated pits was also determined. (Incompletely aspirated pits meant that pit membranes were deflected to one side). The number of earlywood and latewood tracheids was also counted, and the number per unit area of each specimen was determined.

Radial sections (4mm square) were cut from the permeability specimens to observe the structure of pit membrane using Scanning Electron Microscopy.

3. Results and Discussion

Specific permeability, K, of intermediate wood and sapwood in relation to height above the ground is shown in Fig. 2. In longitudinal direction, permeability decreased with increasing height levels in the stem except at the lowest level. The relationship between specific permeability and distance from the pith in all specimens is shown in Fig. 3. There are previous reports on eastern hemlock (Comstock 1965) and on red

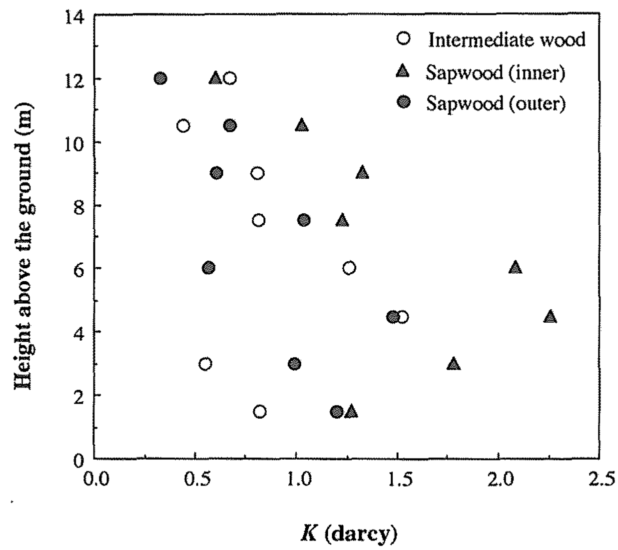


Fig. 2 Relationships between specific permeability K of sapwood and intermediate wood in sugi and tree height above the ground.

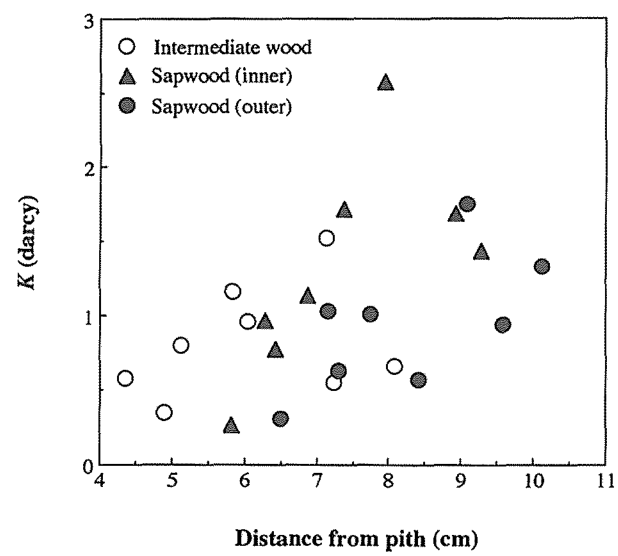


Fig. 3 Relationships between distance from pith and specific permeability K of sapwood and intermediate wood in sugi.

spruce (Perng 1983), in which permeability increases with distance from the pith. These results show that cambial age is related to specific permeability, that is, specific permeabilities in samples from higher levels where the wood were juvenile, were lower, and those from middle or lower levels where the wood was mature, were higher except at the lowest level.

When specific permeability of intermediate wood and sapwood at the same level were compared, intermediate wood was lower than for sapwoods, and inner sapwood permeability was higher than for outer sapwood at each different level. In this study, wood structure of samples with these permeability values was compared. Percentages of aspirated pits of natural-dried sapwood and intermediate wood from a disk at 1.5m height in a sugi tree are listed in Table 1. The intrinsic wood properties and the specific permeability are listed in Table 2. Percentage of aspirated pits in intermediate wood was 24% in earlywood and 19% in latewood, while percentage in sapwood was 9% in earlywood and 8% in latewood. These results show that differences between the permeabilities of intermediate wood and sapwood are mainly caused by the states of bordered pit aspiration. On the other hand, as shown in Fig. 2, though permeabilities of outer sapwood were smaller than those of inner sapwood, the percentages of aspirated pits in outer sapwood were not necessarily smaller than in inner sapwood. This means that the difference of permeability in sapwood should be considered both as a consequence of bordered pits and of other anatomical factors, for example percentage of latewood in cross-section of specimen, the number of bordered pits per tracheid, or

Table 1 The conditions of bordered pits in earlywood and latewood at 1.5m height above the ground.

	Earlywood			Latewood		
	Open (%)	Incomplete aspiration (%)	Aspiration (%)	Open (%)	Incomplete aspiration (%)	Aspiration (%)
Intermediate wood	56.7	18.9	24.4	69.2	11.5	19.2
Sapwood (inner)	72.4	19.5	8.0	80.0	11.4	8.6
Sapwood (outer)	77.3	13.1	9.6	82.3	9.7	8.0

Incomplete aspiration : Pit membranes are deflected to one side.

Table 2 Permeability and wood structure at 1.5m height above the ground.

	K (darcy)	lw (%)	Earlywood			Latewood		
			Nt	Np	Tl	Nt	Np	Tl
Intermediate wood	0.6581	26.54	1386	51	2.17	3286	15	2.06
Sapwood (inner)	1.4291	18.40	1160	55	2.36	3846	15	2.23
Sapwood (outer)	1.3288	18.85	946	64	2.85	3180	18	2.56

lw : proportion of latewood in cross-sectional area Nt : tracheid numbers per unit area (/mm^2)
Np : bordered pit numbers per tracheid Tl : tracheid length (mm)

the number of tracheid per unit area.

It is known that resistance to aspiration of latewood pits in comparison with earlywood pits is greater because of the greater rigidity of pit membranes due to thicker cell wall and the small diameter of latewood pits (Bolton and Petty 1978). Table 1 shows that the percentage of open pits in latewood was higher than in earlywood. Moreover, the percentage of incompletely aspirated pits, which may have become deflected during the drying process, was larger in earlywood. These results indicate that the difference between the percentage of open pits in earlywood and latewood was the difference in incompletely aspirated pits deflected during drying. However, the relationship between the percentage of latewood in the cross-section of a test specimen and permeability, as shown in Fig. 4, was not statistically significant. Other anatomical factors of the test specimens are listed in Table 2. Although percentages of aspirated or incompletely aspirated pits in latewood in comparison with earlywood are low (Table 2), the diameters of tracheids in latewood are approximately one third of those in earlywood, and the number of bordered pits per tracheid is 13 to 18 in latewood in contrast to 50 to 80 in earlywood. Therefore it is inferred that the proportion of effective pathways in latewood is low in comparison to total possible effective pathways. That is, it is possible that permeability of sapwood and interemediate wood is almost entirely determined by earlywood. In order to confirm this, the following trial calculation was carried out as shown in equation (2), where incompletely aspirated pits were considered as a half of open pits because the pit membranes were deflected

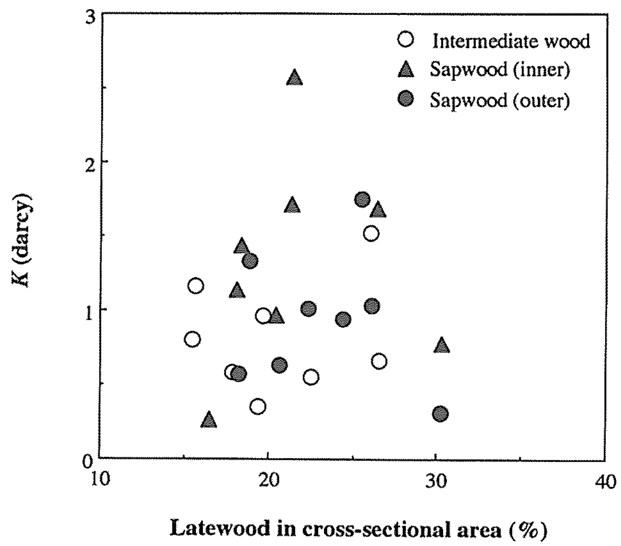


Fig. 4 Relationship between the percentage of latewood in cross-sectional area in a specimen and specific permeability K of sapwood and intermediate wood in sugi.

to one side of the pit border on the cross sections.

The number of effective open pits in a specimen, *Nef*, was estimated using the actually measured values of the anatomical properties. *Nef* means the number of effective pits of earlywood in a columnar specimen for permeability.

$$Nef = S \cdot (1 - lw) \cdot Nt \cdot Np \cdot (Op + \frac{1}{2} Ic) \quad \cdots\cdots \quad (2)$$

where S is the cross-sectional area of the test specimens, lw is the proportion of latewood in a cross-sectional area, Nt is the number of earlywood tracheids per unit area, Np is the number of bordered pits per earlywood tracheid, Op is the proportion of open pits in earlywood, and Ic is the percentage of incompletely aspirated pits in earlywood.

The result of this calculation, intrinsic wood properties of earlywood, and specific permeability in intermediate wood and sapwood from 1.5, 3.0, 4.5, 6.0, 9.0m height are listed in Table 3. The relationship between the percentage of aspirated pits, effective open pits and specific permeability at each height in the tree are shown in Fig. 5. The results indicated that permeability of sapwood and intermediate wood increased with increases in the number of effective open pits, *Nef*, regardless of the height on the tree. Moreover, the relationship between the specific permeability and the number of effective open pits was better than the relationship between specific permeability and

Table 3 Permeability and wood structure of earlywood in sugi intermediate wood and sapwood.

Tree height above the ground		Ring No.	*D* (cm)	*K* (darcy)	*lw* (%)	*Nt* ($/mm^2$)	*Np*	*Op* (%)	*Ic* (%)	*Nef*	*Tl* (mm)
1.5m	I.W.	16	8.08	0.6581	26.54	1386	51	56.7	18.9	1725600	2.169
	S.W.(inner)	20	9.28	1.4291	18.40	1160	55	72.4	19.5	2148583	2.357
	S.W.(outer)	23	10.13	1.3288	18.85	946	64	78.0	13.1	2087053	2.847
3.0m	I.W.	13	7.23	0.5507	22.52	1174	65	41.2	28.2	1642568	2.382
	S.W.(inner)	19	8.93	1.6778	26.49	1240	65	84.4	13.0	2705906	2.533
	S.W.(outer)	22	9.58	0.9419	24.42	1020	60	86.8	10.3	2136864	2.223
4.5m	I.W.	13	7.13	1.5207	25.99	1146	62	48.9	32.6	1722542	2.549
	S.W.(inner)	16	7.95	2.5699	21.46	1114	67	83.6	14.1	2669872	2.362
	S.W.(outer)	21	9.08	1.7532	25.48	1046	61	69.1	26.0	1961355	2.546
6.0m	I.W.	10	6.05	9.9591	19.68	1220	68	52.4	27.6	2215919	2.555
	S.W.(inner)	14	7.38	1.7118	21.34	1346	71	69.9	17.3	2968967	2.472
	S.W.(outer)	18	8.40	1.5663	18.22	1234	76	64.6	16.8	2813374	2.417
9.0m	I.W.	8	5.13	0.8035	15.43	1146	63	57.3	25.8	2392743	2.331
	S.W.(inner)	12	6.45	1.3286	30.29	1206	80	76.0	17.3	2860160	2.605
	S.W.(outer)	15	7.30	0.6285	20.62	994	77	89.3	6.3	2235688	2.481

D : distance from pith to the center ring of cross-sectional area of permeability specimens
Op : the percentage of open pits
Nef : the number of effective open pits
Ic : the percentage of incomplete pits
lw, Nt, Np, Tl : See the remark of Table 2

$$Nef = S \cdot (1 - lw) \cdot Nt \cdot Np \cdot (Op + \frac{1}{2} Ic)$$

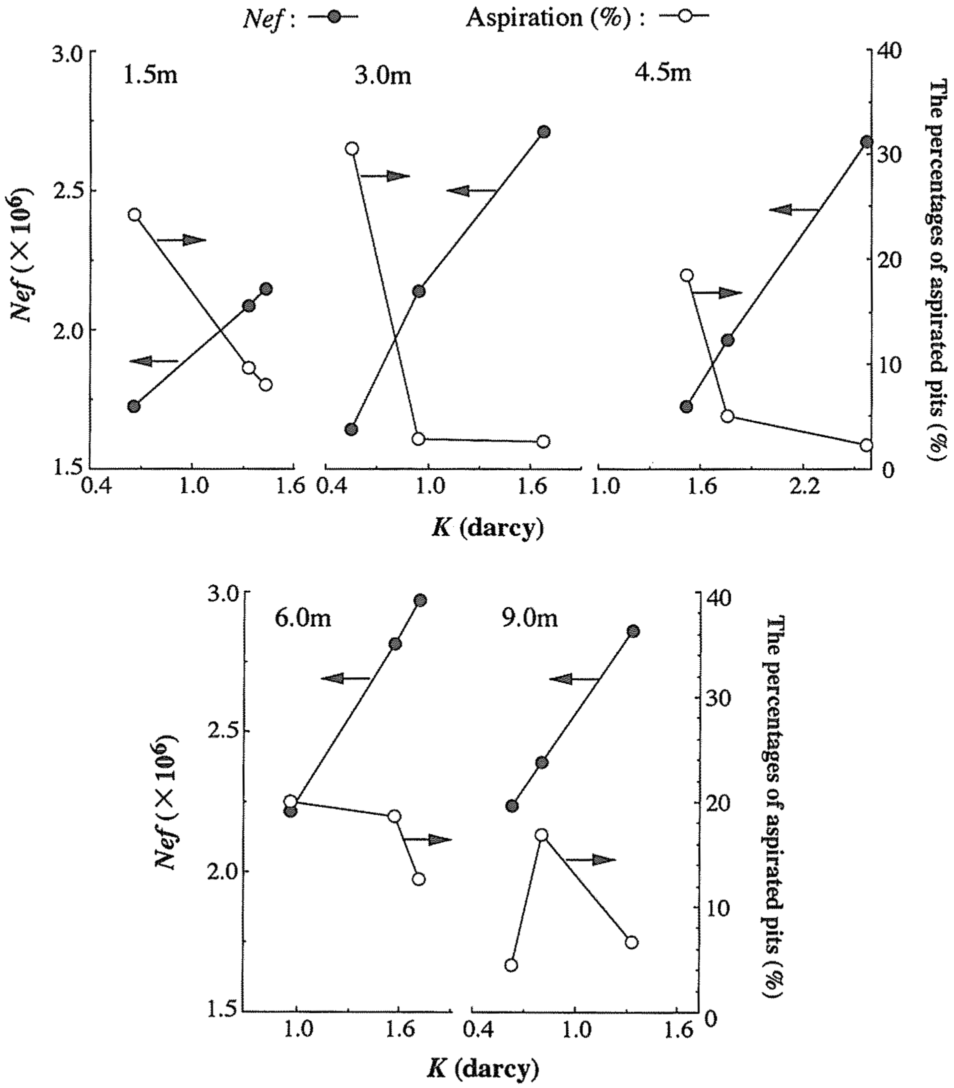


Fig. 5 Relationships between specific permeability *K*, and number of effective open pits (*Nef*) or the percentage of aspirated pits in sapwood and intermediate wood of sugi

the percentage of aspirated pits. In other words, it was shown that permeability of sapwood and intermediate wood is a physical value which is determined by intrinsic wood properties of earlywood in addition to the condition of bordered pits in earlywood.

4. Conclusion

The relationship between anatomical properties and specific permeability of sugi (*Cryptomeria japonica*) sapwood and intermediate wood was investigated. The results obtained are as follows.

(1) Specific permeability decreased with increasing levels in the stem except at the lowest level and was also related to distance from pith, suggesting that cambial age is related to specific permeability. (2) A clear relationship between percentage of latewood and specific permeability was not found, suggesting that effective pathways in earlywood determine permeability. (3) Specific permeability of intermediate wood and sapwood was significantly related with the number of effective open pits in earlywood, *Nef*, which was determined by anatomical properties such as aspirated and incompletely aspirated pits, number of pits and tracheids, proportion of latewood, suggesting that specific permeability of sugi sapwood and intermediate wood is a physical value determined by intrinsic properties of earlywood in addition to the condition of bordered pits.

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スギ辺材および移行材の比透過率に関与する木材組織構造

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要 約

スギ辺材と移行材の比透過率を決定する木材組織構造因子を明らかにする目的で，地上高別に移行材，辺材内側と外側の比透過率を算出した。そのあと，その試験片の組織構造を計測し，比透過率との関係を見た．比透過率は樹幹上部に向かって減少，髄からの距離が大きくなるに伴って上昇する傾向を示した。このことは比透過率への形成層齢の関与を示唆した．晩材割合と比透過率との間に有意な相関関係が認められなかったことから，比透過率には早材が大きな役割を担うことが明らかになった．比透過率を決定する組織構造因子として，早材の有縁壁孔閉塞率，不完全閉塞率，仮道管当たりの有縁壁孔数，単位面積当たりの仮道管数および晩材割合を考慮して算出した有効開放壁孔数 *Nef* が提案された．すなわち，有効開放壁孔数と比透過率との間に直線関係が認められ，スギ辺材と移行材の比透過率が，有縁壁孔の状態に加えて他の早材組織構造によって決定されることを明らかにした．

キーワード：スギ，辺材，移行材，早材，有縁壁孔閉塞，不完全閉塞，有効開放壁孔数，比透過率