ORIGINAL (論文)

Study on the Liquid Permeability of Softwoods*

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林 昭三**, 西本孝一**, 貴島恒夫**：針葉樹材の液体浸透性に関する研究*

Following the authors' previous report[1] dealing with liquid permeability of hardwood, a similar study concerning softwood by the same methods of experiment is reported in this paper.

Materials and Methods

For measuring the permeability, a suction method carried out under reduced pressure condition was adopted (Fig. 1) because of the conciseness and time-saving of its operation comparing with other methods under an atmospheric pressure or a certain pressure.

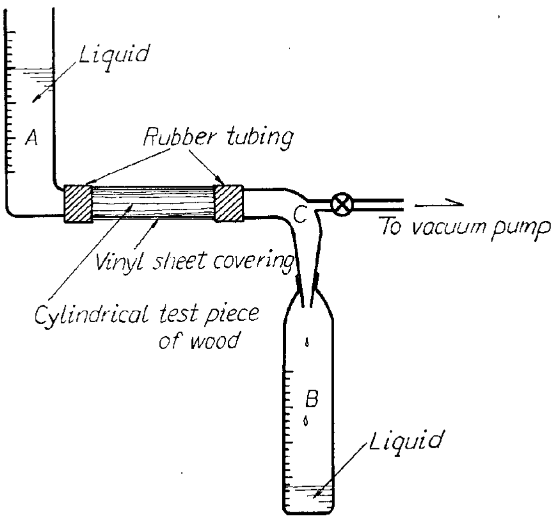

Fig. 1. Experimental apparatus.

The sample specimens of wood used were 6 species as follows:

TSUGA (*Tsuga sieboldii* CARR.) sapwood and heartwood

AKAMATSU (*Pinus densiflora* SIEB. et ZUCC.) sapwood and heartwood

RADIATA-MATSU, Monterey pine (*P. radiata* D. DON) sapwood

SUGI (*Cryptomeria japonica* D. DON) sapwood and heartwood

HINOKI (*Chamaecyparis obtusa* ENDL.) sapwood

BEIHI, Lawson cypress (*Cupressus lawsoniana* MURR.) sapwood

and their specific gravities and annual ring widths are shown in Table 1.

For the permeation tests, cylindrical test pieces, 3 cm in diameter and 15 cm in length parallel to the grain, were prepared from the normal portions of each material, of which moisture content ranged 12.8-13.2 %. They were conditioned to 15 % of

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Table 1. Specific gravities and annual ring widths of specimens

Specimens		Specific gravities	Annual ring widths (mm)
TSUGA	sapwood A	0.34	1.42
	B	0.42	0.92
	heartwood	0.49	2.46
AKAMATSU	sapwood A	0.49	0.74
	B	0.48	2.72
	heartwood	0.51	4.80
RADIATA-MATSU	sapwood	0.40	0.92
SUGI	sapwood A	0.32	2.38
	B	0.31	2.00
	heartwood	0.32	4.85
HINOKI	sapwood	0.35	0.84
BEIHI	sapwood A	0.41	1.33
	B	0.36	0.72

their moisture content by placing them in a desiccator which has been controlled at 25°C and 75% R.H.

In advance of the tests, each test piece was sealed by vinyl adhesive sheet on its lateral round side to prevent air or liquid leakage in operation. One of its open end was joined to the bottle B (Fig. 1) which has been connected to the vacuum pump by the intervening adaptor C. Then, the other end of the piece was plugged by a temporary rubber plug, and ascertaining air leakage the initial vacuum degree of the closed system of the apparatus (closed vacuum degree) was measured by a manometer equipped at the vacuum pump. The closed vacuum degree was constant after 5 min from the beginning, and the constant ranged 5 to 13 mmHg. Then taking off the plug the reduced vacuum degree (open vacuum degree) was measured to know the air permeability of the wood piece. Successively, the bottle A was connected to the piece and filled with liquids. Kind of liquids used is listed in Table 2.

Table 2. Some properties of liquids used

Liquids	Specific gravities	Specific viscosities	Surface tensions (dyne/cm)
Distilled water	1.00	1.00	72.75
Creosote oil	1.09	15.33	31.45
5% aqueous solution of PCP-Na	1.03	1.19	62.99
α-Chloronaphthalene	1.02	3.62	58.52
Swasol	0.83	0.62	58.35

To search for the longitudinal penetrability of liquid for each test piece, out-flow volume of the liquid from the bottle A and in-flow volume of it into the bottle B were measured under about 10 mmHg of vacuum condition throughout 100 min at every 5 min interval.

Proportions of resin canals in the test pieces and development degrees of their tylosoids contained were estimated by the dot-counting method in each enlarged image of cross section, 100×, of the materials after the permeation tests.

To measure average permeation length in each piece, the tested pieces were sawn radially at the middle of them along their axes, and after tracing permeated areas of their quarter sawn surfaces on the paper, the requested lengths concerned were obtained by the paper weighing method. In this connection, for this measurment applied creosote oil, 5 % aqueous solution of PCP-Na, and Swasol, and to detect the penetrated portions on the surfaces, the specific colour reaction[2] and 0.5 weight % Swasol solution of Sudan III were applied for PCP-Na solution and Swasol respectively.

Results and Discussion

For each test group of permeation, 5 specimens were prepared from every wood species. Retention of liquid in a test piece is to become constant after a certain time elapsed from the beginning of experiment, and in-flow amount of liquid from the bottle A (penetrated volume) is to become equal to the out-flow amount of the liquid

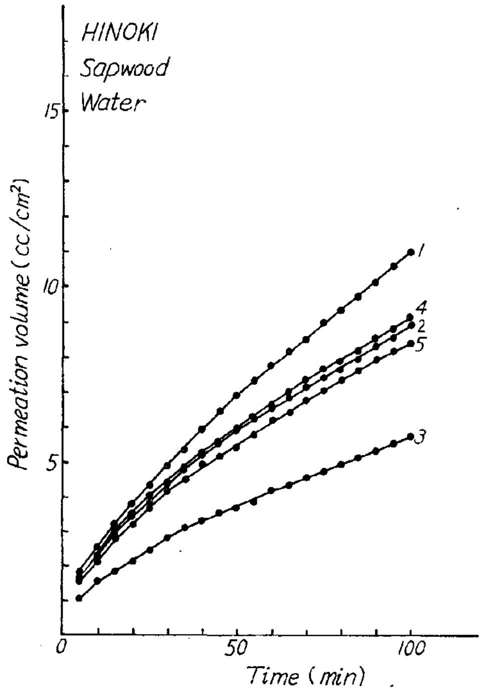

Fig. 2-1. Permeation courses.

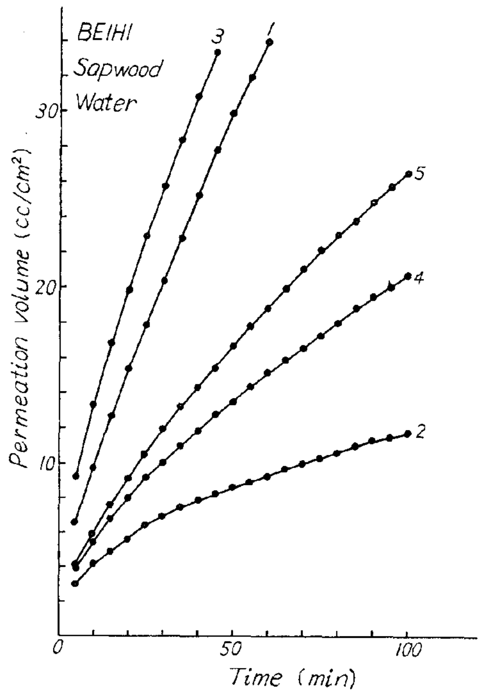

Fig. 2-2. Permeation courses.

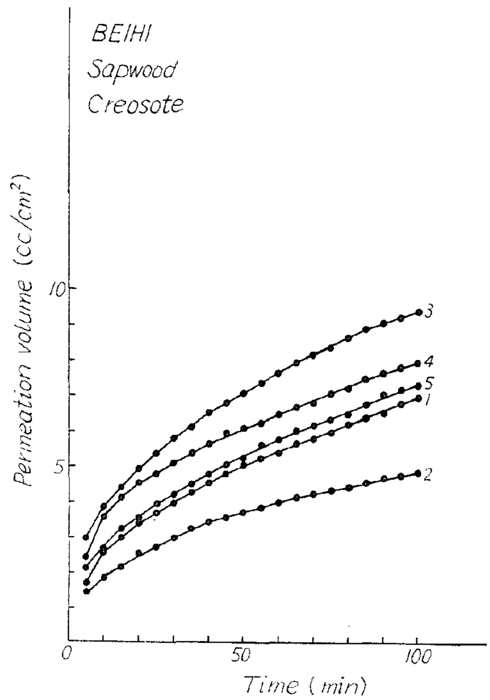

Fig. 2-3. Permeation courses.

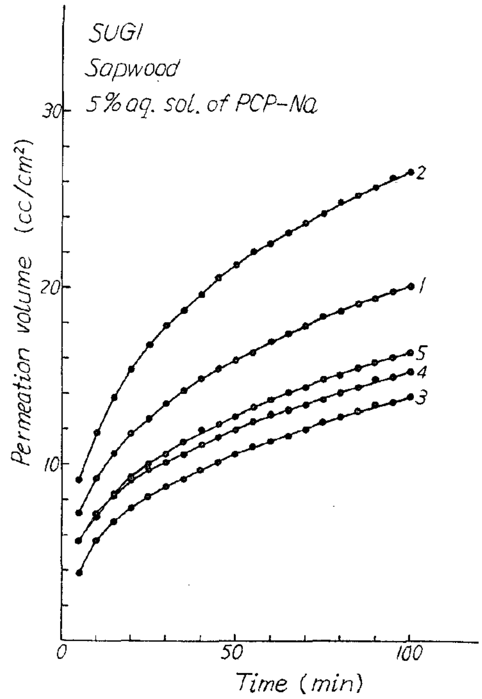

Fig. 2-4. Permeation courses.

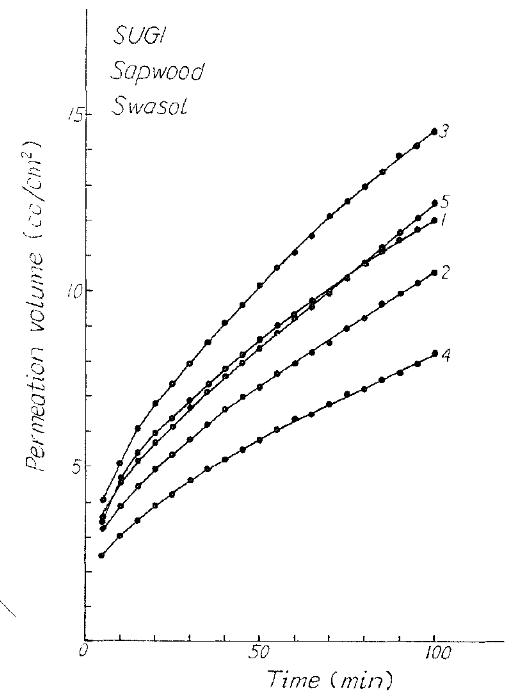

Fig. 2-5. Permeation courses.

into the bottle B (through-passed volume). But, at the beginning of experiment, liquid did not flow out to the bottle B though it flowed out from the bottle A because of its retention in the test piece. Therefore, the decreased amount of liquid from the bottle A was measured throughout 100 min at every 5 min interval, and some results of them are shown in Fig. 2. Average permeation rates calculated from the penetration amounts by cross sectional areas of the pieces are shown in Tables 3 and 4.

1. Permeabilities of wood species, separately sapwood and heartwood

TSUGA, AKAMATSU and RADIATA-MATSU have axial resin canals among the 6 wood species tested, it is obvious that these 3 species of wood having resin canals showed larger permeabilities than the others as shown in Table 3, and this also proves the evidence of the previous report[3] dealing with the influence of resin canals in woods of AKAMATSU and SUGI. Further,

Table 3. Penetration rates of distilled water and proportions of resin canals

Specimens		Penetration rate (cc/min·cm²)	Vertical resin canals (%)	Tylosoids in resin canals (%)	Effective resin canals (%)
TSUGA	sapwood A	2.27	0.14	0.0	0.14
	B	2.85	0.13	1.0	0.13
	heartwood	0.02	0.04	0.0	0.04
AKAMATSU	sapwood A	4.24	0.77	0.0	0.77
	B	2.84	0.68	8.0	0.63
	heartwood	0.00	0.32	74.0	0.08
RADIATA-MATSU	sapwoop	2.28	1.25	24.0	0.95
SUGI	sapwood A	1.44			
	B	0.49			
	heartwood	0.07			
HINOKI	sapwood	0.86			
BEIHI	sapwood A	0.35			
	B	0.49			

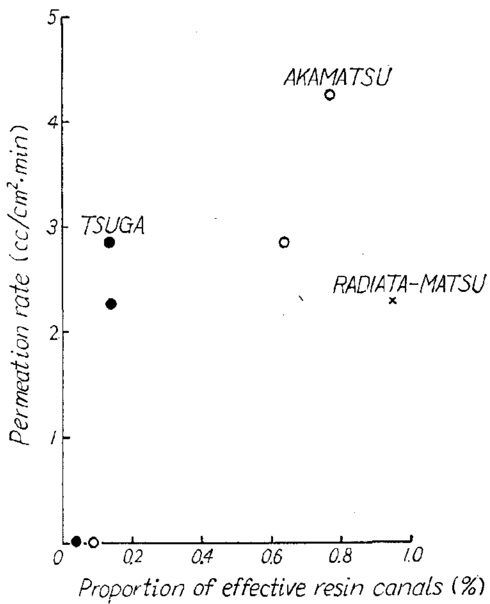

Fig. 3. Relation between permeation rates and proportions of effective resin canals.

the permeability is disturbed by the tylosoids developed in resin canals, and the proportion of effective void areas in resin canals (subtracted the tylosoid areas from them in cross section) were also calculated and shown in the same table, and the relationships between penetration rate and proportion of effective void area were shown in Fig. 3. But resin canals are of course not the only paths of liquid penetration, and this is obviously known from the fact that the woods of SUGI or HINOKI having no resin canals also shows more or less permeabilities. Resin canal proportion of TSUGA heartwood was very small because its resin canals are merely the traumatic ones (Photos 1-6).

The order of water permeabilities suggested from the results of Table 3 is as follows:

AKAMATSU sapwood > TSUGA sapwood > RADIATA-MATSU sapood > SUGI sapwood ≧ HINOKI sapwood > BEIHI sapwood > SUGI heartwood > TSUGA heartwood > AKAMATSU heartwood.

Sapwood of AKAMATSU and others having resin canals were very permeable, and, as to heartwoods, SUGI was most permeable but showed only about 10% of its sapwood permeability. In the case of TSUGA and AKAMATSU, permeabilities of their heartwood were only 1 and 0.1% respectively.

Penetrability order for the 5 kinds of liquids summarized from Table 4 is as follows:

AKAMATSU sapwood>TSUGA sapwood≧SUGI sapwood>BEIHI sapwood>SUGI heartwood>TSUGA heartwood>AKAMATSU heartwood.

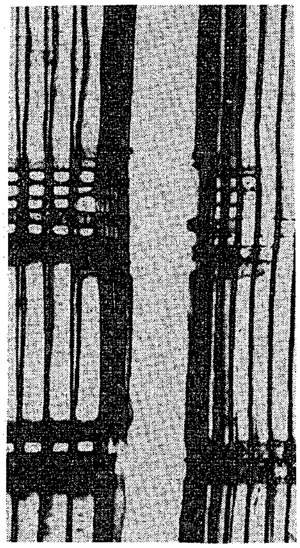

Photo. 1. An open resin canal showing good permeability. AKAMATSU sapwood, (*r*), 80×

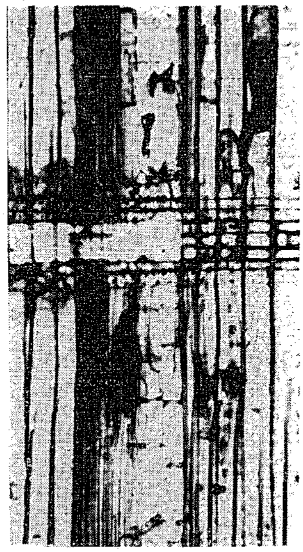

Photo. 2. A closed resin canal showing little permeability. AKAMATSU sapwood, (*r*), 80×

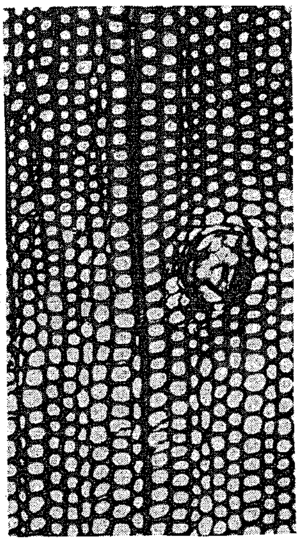

Photo. 3. A resin canal closed with tylosoids, showing little permeability. AKAMATSU heartwood, (*x*), 80×

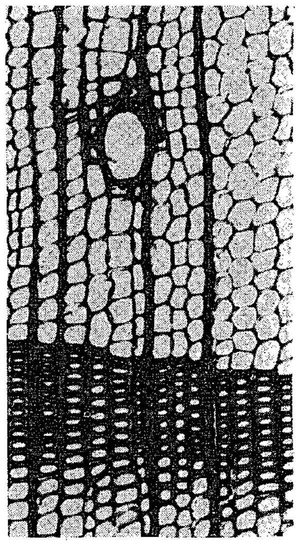

Photo. 4. An open traumatic resin canal showing good permeability. TSUGA sapwood, (*x*), 80×

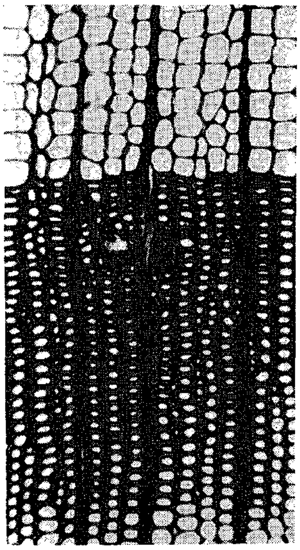

Photo. 5. A traumatic resin canal closed with tylosoids, showing little permeability. TSUGA heartwood, (x), 80×

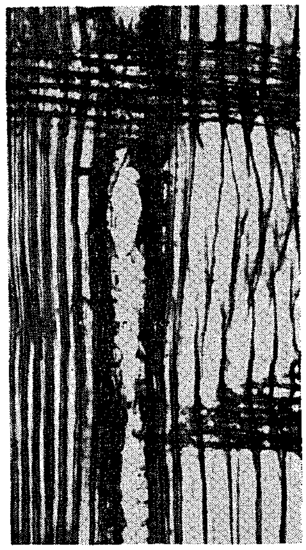

Photo. 6. A traumatic resin canal closed with tylosoids, showing little permeability. TSUGA heartwood, (r), 80×

Table 4. Penetration rates of liquids (cc/min·cm²)

Specimens		Distilled water	Creosote oil	5% aqueous solution of PCP-Na	Swasol	α-Chloro-naphthalene
TSUGA	sapwood	2.27	0.05	0.04	0.15	0.09
	heartwood	0.02	0.01	0.01	0.00	0.01
AKAMATSU	sapwood	4.24	2.81	7.12	5.98	2.56
	heartwood	0.00	0.00	0.00	0.01	0.01
SUGI	sapwood	1.44	0.12	0.18	0.12	0.18
	heartwood	0.07	0.02	0.06	0.03	0.02
BEIHI	sapwood	0.35	0.07	0.13	0.09	0.11

It is natural that the liquid permeability of sapwood was larger than that of heartwood as in the case of appling water. It is interesting that, in sapwood, permeabilities of woods having resin canals were larger than those having no resin canals, but, in heartwood, they showed an entirely reverse connection. This seems to depend largely on the difference of effective void proportions of resin canals between sapwood and heartwood.

The above order of permeability concerning wood species was determined by synthetical consideration, so that, as to the individual test piece, it may not always be held because of their existing deviation of permeability. In this experiment, each 5 test piece group was sampled at random for each specimen. It seems, therefore, that the order of permeability would be more clearly determined by the consideration to set the each group of wood species with same number of pieces having nearly equal values of open vacuum degrees, because, in the case of softwood, there is positive relationship between open vacuum degree and permeation rate as in the case of hardwood reported previously[1].

2. Permeability of different liquids adopted

Generally liquid viscosity is one of factors affecting permeability into capillaries as shown by the Poiseuille's or Darcy's law, and the permeation rate is inversely proportional to the viscosity. Therefore, from the specific viscosities of liquids which are shown in Table 2, order of permeation rate will be estimated as follows:

Swasol>Distilled water>5% aqueous solution of PCP-Na>α-Chloronaphtalene> Creosote oil.

But, according to the results obtained, the order of permeation rates was different from the above order, that is

Distilled water>5% aqueous solution of PCP-Na>Swasol>α-Chloronaphtalene> Creosote oil.

Namely, permeation rate of Swasol showing lower specific viscosity was smaller than that of water or PCP-Na solution showing higher viscosity. The reason for this disagreement may lie in the fact that Swasol (solvent chiefly composed of toluene) dissolved resinous substances in wood and transferred them through capillaries, on the other hand, permeated Swasol seems to be evaporated from the wood piece into the bottle B and adaptor C which has been kept in vacuum, then the dissolved resinous substances seem to deposit and close openings like pits or cell cavities in wood forming liquid pathways. By the way, evaporation of distilled water was about 3cc/hr in the bottle B being under about 10 mmHg, that of creosote oil was 0, but that of Swasol reached up to 30cc/hr, so the dropping or the through-passed Swasol into the bottle could not be observed.

3. Open vacuum degree and penetrability

It is recognizable that there was linear relationship between open vacuum degree and permeation rate from an example of results of water permeation in Fig. 4, and it is also held for the other liquids. From the Fig. 4, it is known that the wood species showing low vacuum degree have

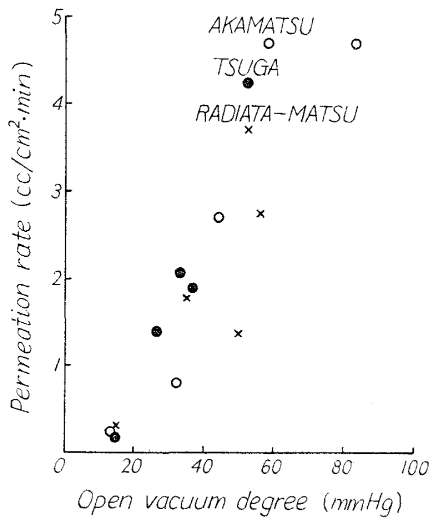

Fig. 4. Reration between water permeation rates and open vacuum degrees.

rather high permeability. Thus the open vacuum degree indicates difficulty of air permeability and will be available to suggest liquid permeability.

4. Specific gravity or annual ring width of wood and permeability of liquid

From this study, relation between specific gravity or annual ring width of wood and liquid permeability could not be obtained.

As to a porous material like wood, there are always 2 sorts of porosity estimation, i. e., so-called absolute porosity which means void volume of the material against whole volume and effective porosity which means effective void volume of the material for permeation against whole volume. If the former would be a factor influencing on permeability, the permeability could be assumed by its specific gravity to a certain extent. But the effective porosity is to be an important factor controlling permeability of wood since the specific gravity had no correlation with permeability according to the results of this experiment.

Annual ring width has also no relationship with permeation rate, but, within an annual ring, it seems that late wood has been more permeable than early wood according to the observation throughout the permeation tests or to the examination of the pieces tested as described below. In view of the general rule that there is not so much difference in the late wood widths of softwood regardless of annual ring widths, it is expected that the specimen having narrower rings should be more permeable. But no clear relation was obtained between average annual ring widths and permeabilities from the results of this study.

5. Average permeation length

Using 3 kinds of liquids among 5 kinds of the testing liquids, average permeation lengths measured from the test pieces which has been permeated under suction during 100 min were shown in Table 5. Swasol, PCP-Na solution, as well as even creosote

Table 5. Average penetration lengths (mm)

Specimens		Creosote oil	5% aqueous solution of PCP-Na	Swasol
TSUGA	sapwood	138	96	147
	heartwood	66	10	38
AKAMATSU	sapwood	141	150	146
	heartwood	28	17	32
SUGI	sapwood	150	138	150
	heartwood	117	97	138
BEIHI	sapwood	150	130	150

oil having the least permeability showed enough permeation lengths in every sapwood specimens, and SUGI heartwood also showed a considerable permeability.

Summary

Following the previous report dealing with liquid permeability of hardwood, permeabilities of 6 species of softwood adopting 5 sorts of liquid were measured by an apparatus shown in Fig. 1. Results obtained are as follows:

1. Permeation rate of sapwood was of course much larger than that of heartwood (Table 3). As to sapwood, TSUGA, AKAMATSU, and RADIATA-MATSU having axial resin canals were more permeable than SUGI, HINOKI, and BEIHI having no resin canals, but, in so far as heartwood, SUGI was more permeable than TSUGA or AKAMATSU woods. Thus the synthesized order of permeability of the examined wood species, separately sapwood and heartwood, was as follows:

AKAMATSU sapwood > RADIATA-MATSU sapwood > TSUGA sapwood $\geqq$ SUGI sapwood > HINOKI sapwood > BEIHI sapwood > SUGI heartwood > TSUGA heartwood > AKAMATSU heartwood.

2. Penetration rate of each liquid adopted is shown in Table 4. Generally penetration rate of liquid is to be inversely proportional to its viscosity, but the permeation rate from this study did not always agree with the specific viscosity as shown in Table 2. Namely the order of the penetration rates concerning liquids was as follows:

Distilled water > 5% aqueous solution of PCP-Na > Swasol > α-Chloronaphtalene > Creosote oil.

The reason why the permeation rate of Swasol was smaller in spite of its low viscosity was recognized as that it might dissolve resinous substances, deposit them at the pits or cell cavities, and close its own pathways by the evapolation of itself.

3. It is similar to hardwood that softwood specimen showing low open vacuum degree had rather high permeation rate. The higher the air penetration is, the greater the liquid penetration rate is.

4. Specific gravity and average annual ring width showed no correlation to liquid penetrability.

5. Average permeation lengths which were obtained from radially sawn surfaces of the tested pieces were, in sapwood, long enough even in the case of the pieces having small permeation rates and covered the almost whole lengths of the pieces (Table 5).

摘　　要

前報[1]にならつて針葉樹6樹種 (Table 1) の辺・心材について，水その他4種の液体 (Table 2) を用いて，減圧吸引状態 (Fig. 1) で100分間にわたつて浸透の実験を行なつた (Fig. 2)。

その結果を要約するとつぎのとおりである。

1. 辺材の浸透性は心材のそれより格段に大きい。樹脂道を有するツガ，アカマツ，ラディアータマツでは，辺材における浸透性が，樹脂道のないスギ，ヒノキ，ベイヒに較べて大きかつたが，心材では樹脂道のないスギの浸透性がツガやアカマツのそれより大きかつた（Table 3)。また樹脂道の有効面積率を求め，それと浸透速度との関係を Fig. 3 に示した。供試材の浸透性の順位を各供試液について総合的に判断するとつぎのようである。

アカマツ辺材＞ラディアータマツ辺材＞ツガ辺材≧スギ辺材＞ヒノキ辺材＞ベイヒ辺材＞スギ心材＞ツガ心材＞アカマツ心材

2. 各供試液別の浸透速度は Table 4 に示した。一般に液体が浸透する場合にはその粘度に反比例するが，実験結果では浸透速度は Table 2 に示した比粘度の順位に従わず，つぎのようになつた。

蒸溜水＞PCP-Na 5% 水溶液＞スワゾール＞α-クロロナフタリン＞クレオソート油

粘度の小さいスワゾールの浸透性が悪かつたのは，それが溶剤として木材の内容物を溶解したり，また揮発性が大きいために一度溶解した樹脂分などを蒸発のときに通路としての膜孔や細胞内腔に沈積するためと考えられる。

3. 開放減圧度の低いものほど浸透速度が大きかつたのは，広葉樹材における場合と同様で，空気の透過性の大きいものはそれだけ有効な通路が大きく，したがつて液体の浸透速度も大きくなつたと考えられる (Fig. 4)。

4. 比重，年輪幅は浸透速度とは関係がなかつた。

5. 浸透実験を終つた試片を柾目面が出るように縦断して，それから平均浸透長を求めたが，その結果，辺材においては浸透速度の小さい樹種でも試片全体にかなりよく浸透していることが判つた (Table 5)。

Literature

1) HAYASHI, S. and K. NISHIMOTO, Wood Research, No. 35, 33-43 (1965).
2) NISHIMOTO, K., G. FUSE, and Y. INOUE, Wood Research, No. 14, 37-41 (1955).
3) HAYASHI, S. and T. KISHIMA, Wood Research, No. 35, 25-32 (1965).