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Liquid penetration in different cells of two hardwood species

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Abstract Two experimental techniques were used to test the water permeability of two Korean hardwood species: diffuse porous *Populus tomentiglandulosa* T. Lee (eunsasi poplar) and ring porous white oak, *Quercus serrata* Thunb (konara oak). The first technique measured the void volume filled at different moisture content (MC) levels. Samples were treated with water via a schedule of full-cell impregnation. A significant relation between MC and permeability (the fractional void volume) was found. A reduction in liquid permeability was observed at MC above the fiber saturation point (FSP), whereas the opposite result was observed at MC below FSP due to the effect of the voids available in the wood. However, the differences of increased permeability from MC level 20% to 0% were found satistically the same in either wood species. The second technique measured the speed of liquid penetration in vessels, fibers, and rays with no application of external pressure. In this method, liquid flow was captured via video and the penetration speed was measured. Vessels, fibers, and rays in poplar were found to be more permeable than those in oak. Different anatomical factors such as cell diameter, cell length, pit number, pit aperture area, and thickness of the pit membrane seemed to be responsible for the variation of liquid flow rate in different cells of the two hardwood species.

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Introduction

Knowledge of water permeability in different wood cells is very important in wood treatment. The principal vehicle for bulk flow of liquid in hardwoods is vessels, unless they are occluded by tyloses.[1,2] Vessel elements are connected from end to end through a perforation plate to form vessels. Vessel lengths range from a few centimeters up to a few meters.[3] However, when the vessels are filled with tyloses, fibers were shown to be the main conductive channel.[4] Vasicentric tracheids have also been reported to be a conductive channel between the intervessel fluid transports.[5] Not only anatomical features but also the amount of moisture in wood has an influence on the liquid permeability,[6] but there is little information regarding the optimum level of moisture for individual species. Determination of the optimum moisture level also depends on the treatment method, e.g., if wood is treated by diffusion or a sap-displacement method, a high wood moisture content (MC) is desirable.[7] However, when wood is treated by other bulk flow methods, the moisture level should be reduced to the fiber saturation point (FSP) or below the FSP. When the wood capillary structure is occupied by free water, the available volume for liquid to permeate is reduced. The capillary structure in wood consists of cavities interconnected with narrow channels which vary in size and shape from species to species and between trees of the same species in different locations. In the presence of high structural complexity and differences in the type, geometry, and distribution of capillaries, fluid permeability in wood varies considerably among different families, genera, and species.[8] Factors affecting permeability include anatomical structure,[4] liquid properties,[9,10] effective capillary radius of wood cells,[11,12] and treatment method;[13,14] these factors combine to determine the liquid flow rate and speed.

The variations in liquid permeability and flow path are documented in considerable detail,[6,15,16] and the variation of

permeability in different directions is well understood.[17–20] The theoretical background and description of liquid penetration measured by the capillary method are also available.[11,13,14] However, there is no specific method that can describe clearly liquid conduction by different wood cells and estimate their liquid flow rates. In contrast, no attempt has been made so far to measure the liquid water penetration speed in major conducting cells individually to compare and explain permeability levels. Therefore, the aim of this study was to describe a suitable dynamic technique to measure the penetration speed of liquid water in different cells of two hardwood species by the capillary uptake method. The variation of liquid permeability has been explained based on different anatomical features. This investigation will help us better to understand the various factors controlling fluid flow in wood.

Materials and methods

This study was carried out in 15-year-old *Populus tomentiglandulosa* T. Lee (eunsasi poplar) and 20-year-old *Quercus serrata* Thunb (konara oak). Wood discs were collected from nonleaning and defect-free trees at breast height obtained from Jiamri, Sabukmeyon, Chuncheon, Gangwon-do, Republic of Korea (37°58′N, 127°35′E, 290 m above sea level). After preparing discs 15 cm long with the bark intact, they were immediately stored in air-tight bags to prevent them from losing moisture and brought to the laboratory.

Microstructural measurement

Cross, radial, and tangential micro-sections of 15–20 μm thick were obtained by using a sliding microtome. These were double-stained with safranine (Junsei Chemical Co., Ltd., Japan) and light green (Alfa Aesar, Germany) solution, dehydrated in alcohol, and mounted in Canada Balsam on glass slides. The vessel and the fiber length of two wood species macerated from sample strips ($1 \times 1 \times 10$ mm^3) using Schultz's solution were measured with image processing software (Image and Microscope Technology, *i*-solution 2.5) equipped with an *i*-Camscope (SV32). Each microstructural feature was measured from pith to bark. Radial, tangential, and cross-sectional blocks were finished with a microtome and the clean-cut surface (3×3 mm^2) was 1 mm thick. After vacuum drying, blocks were adhered onto aluminum stubs with double-sided tape and coated with platinum (Pt) by using an ion sputter apparatus (Hitachi E-1010). The samples were then examined at different resolutions and magnifications using a Hitachi S-4300 field emission scanning electron microscope (FE-SEM) at an accelerating voltage of 5 kV. Different magnifications were taken in order to measure the microstructural features of different cells. Tangential diameters of vessels, fibers, rays, intervessel pit apertures, fiber pit apertures, and end-wall (tangential wall) pit apertures in rays were recorded. All features were measured between 47 and 946 times.

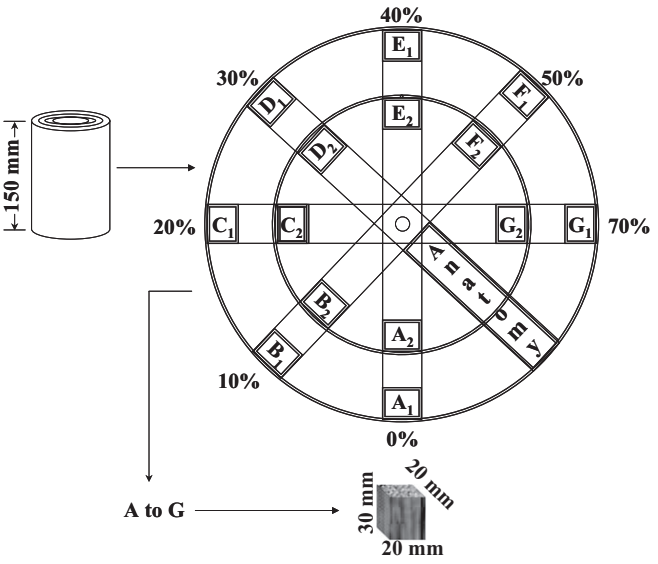

Fig. 1. Schematic showing sample collection and preparation (dimensions not to scale). *A–G*: sample blocks at moisture contents (MCs) between 0% and 70%

Permeability measurement (as the percentage of void volume filled)

Short discs (150 mm) were converted to working samples as shown in Fig. 1. Fourteen stakes [which were selected from outer sapwood (SW) and heartwood (HW)] were cut in cross sections of 20×20 mm^2. Thereafter each stake was cut into four sample blocks 30 mm long in the grain direction. Sample blocks were kiln dried within the range of desired moisture levels. After kiln drying, samples were then treated with distilled water. The treating schedule was a full-cell process of 15-min vacuums at –82.7 kPa followed by a pressure impregnation of 1471 kPa for 60 min. After the treatment process, the maximum possible water uptake was calculated to give the percentage of void volume filled in the individual block because it takes account of the variation in densities of the different samples. Based on the assumption that within the given volume of the sample with known basic density and constant cell wall density (1530 kg/m^3), there will be a void volume basically composed of cell lumina, intercellular spaces, and penetrable cell wall voids, which can be filled by liquids. Thus the uptake can be expressed as the percentage of this value. Further details of this can be found in Siau[21] and Dinwoodie.[22]

Nine samples $20 \times 20 \times 30$ mm^3 were collected from both sapwood and heartwood to determine the density. Wood density was measured by weighing each wood sample when fully immersed in a beaker of water and then the oven-dry mass was measured after oven drying at $103° \pm 2°$C for 48 h until there was no change in the mass of samples. Sample dimensions were measured in all principal directions with a micrometer to the nearest 0.01 mm. The specific gravity of the samples was calculated based on the oven-dry mass and green volume as discussed in KS.[23] The water permeability

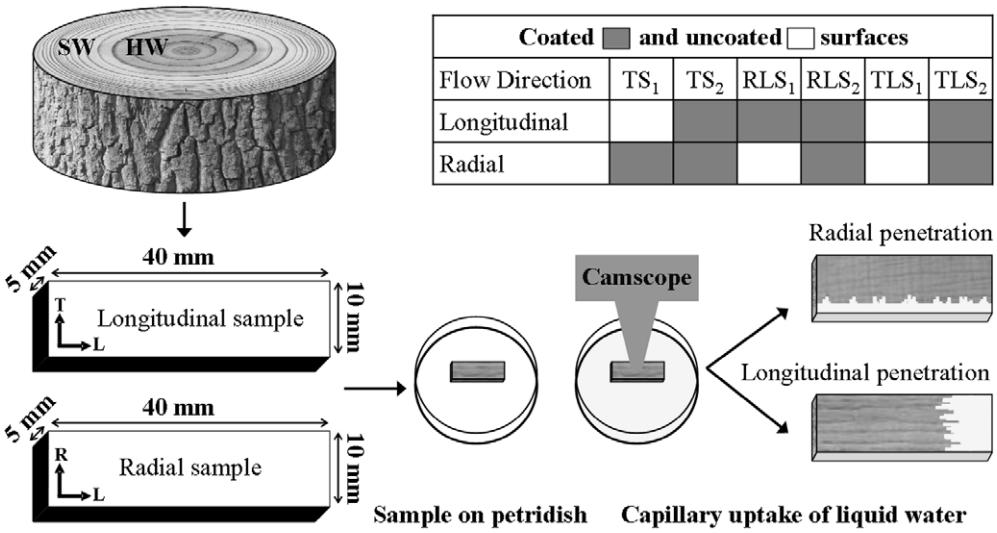

Fig. 2. Preparation of the experimental samples for the measurement of liquid penetration speed. *SW*, sapwood; *HW*, heartwood; *TS*, transverse section; *RLS*, radial–longitudinal section; *TLS*, tangential–longitudinal section

as percent void volume filled was calculated using the following equation:[24]

$$\mathrm{VVF}\% = \frac{\left(\frac{M_t - M_d}{V}\right) \times 100}{P} \quad (1)$$

where VVF is the void volume filled, M_t is the mass of a treated block (g); M_d is the mass of an untreated block at the respective moisture level (g), V is the block volume at the respective moisture level (cm^3), and P is the porosity. Samples of two different species vary in wood density. This is an important factor that influences the theoretical maximum amount of liquid that can be absorbed in a given block volume, and this is taken account of here in the way liquid uptakes are expressed. Therefore, the gross pore space or porosity of each sample was assessed. This takes into account the nominal density as follows: porosity = [{1 − (density/1.53)} × 100].

Measurement of liquid penetration speed

The FSP is a very important property and it is assumed that the FSP is the MC below which the physical and mechanical properties of wood begin to change.[10] At the FSP, i.e., at around 30% MC, cell walls are saturated with bound water and no free water is present in the cell cavities. At this MC, the error regarding the measurement of liquid penetration speed can be minimized because it is attributed to liquid absorption by cell walls. Considering the above-mentioned point, sample MCs were adjusted to 30%. For the impregnation of distilled water, the procedure was followed as described elsewhere.[25] In brief, 40 mm (longitudinal) × 10 mm (radial) × 5 mm (tangential) for radial and 40 mm (longitudinal) × 10 mm (tangential) × 5 mm (radial) for longitudinal samples were prepared from sapwood. Samples were sealed with silicon resin except for one tangential and cross-end surfaces for longitudinal penetration and one radial and tangential surface for radial penetration. Longitudinal penetration was observed on the tangential surface as there is no contact of ray parenchyma with tangential walls of vessels and fibers, which can interrupt the measurement of liquid penetration. Water was allowed to penetrate the surface of the sample from the corresponding nonsealed end and the water penetration was video captured by *i*-Camscope (Fig. 2). The penetration speed was measured by fractioning the video file into JPEG format using *i*-solution software. The penetration depth was measured and the speed was expressed in micrometers per second.

Oak vessels in heartwood are plugged with tyloses; it is impossible to measure the capillary rise of liquid in such vessels. To simplify the experiment, only sapwood cells were considered to compare the liquid penetration speed in vessels, fibers, and ray parenchyma of poplar and oak. As poplar is a diffuse porous wood with a very low latewood proportion, it was difficult to obtain a true latewood sample and hence the liquid flow speed was measured only in the earlywood portion. All samples were measured in triplicate.

Statistical analysis

Water permeability was analyzed by using a one-way analysis of variance (ANOVA). When significant differences occurred ($P \leq 0.05$), the ANOVA procedure was performed followed by a Duncan significant difference post hoc test to separate the moisture effect on liquid permeability in poplar and oak (SPSS, Version 12.0.1, 2003).

Results and discussion

Anatomical characteristics

Table 1 represents the anatomical features of the two species. Differences in anatomical features such as ray cell

Table 1. Different anatomical features (means ± SD) measured for poplar and oak

Species	Location in growth ring	Vessel frequency, number/mm^2	Vessel diameter (μm)	Vessel length (μm)	Fiber diameter (μm)	Fiber length (μm)	Area of intervessel pit aperture (μm^2)	Area of fiber pit aperture (μm^2)	Lumen area of ray (μm^2)	End-wall pit number in ray	Area of end-wall pit aperture in ray (μm^2)
Poplar	Earlywood	130.06 ± 30.29	68.81 ± 16.39	512.95 ± 127.81	13.40 ± 2.97	906.63 ± 218.29	5.77 ± 2.25	0.82 ± 0.35	61.56 ± 14.99	11.06 ± 3.17	0.54 ± 0.43
	Latewood	172.97 ± 34.54	46.70 ± 11.65	544.23 ± 132.55	11.48 ± 3.53	1107.21 ± 264.22	5.77 ± 2.02	0.73 ± 0.31	58.10 ± 15.08	12.60 ± 3.76	0.61 ± 1.02
	Average	**151.52**	**57.75**	**528.59**	**12.44**	**1006.92**	**5.77**	**0.78**	**59.83**	**11.83**	**0.58**
Oak	Earlywood	4.84 ± 1.86	170.87 ± 60.93	343.52 ± 75.80	5.79 ± 1.76	1069.36 ± 192.32	5.67 ± 2.16	1.35 ± 0.57	107.43 ± 38.52	11.03 ± 3.22	0.90 ± 0.72
	Latewood	17.38 ± 16.83	30.39 ± 9.03	448.87 ± 78.22	4.30 ± 1.13	1147.40 ± 395.22	1.95 ± 0.88	1.08 ± 0.51	100.58 ± 36.41	13.65 ± 3.82	0.68 ± 1.53
	Average	**11.11**	**100.63**	**396.19**	**5.04**	**1108.38**	**3.81**	**1.22**	**104.01**	**12.34**	**0.79**

lumen diameter, end-wall pit number and diameter, ray cell length, vessel number, vessel diameter, fiber length, and fiber diameter affect the longitudinal or radial liquid flow.[25,26] As expected, latewood had higher vessel frequencies and lower openings of different cells (Table 1). Latewood also had longer vessels and fibers. When the luminal areas of ray parenchyma, the area of fiber pits, and the end-wall pit aperture in ray parenchyma were examined, oak had wider openings than those in poplar. The average area of intervessel pit apertures and fiber diameters were found to be larger in polar than those in oak. The number of end-wall pits in ray parenchyma was almost the same for both species, while longer vessels and shorter fibers were observed in poplar than those in oak. FE-SEM micrographs of poplar and oak in Figs. 3 and 4 show the pits in different cells that are assumed to be responsible for liquid permeability. The pit membranes of oak were found to be heavily encrusted (Fig. 4A). The radial permeability of this species is expected to be low compared to that of poplar because of the encrustation of pit membranes in ray parenchyma. The longitudinal permeability is mainly facilitated by vessels, and those vessels are connected with intervessel pits on the tangential wall, which also facilitate the radial flow of sap. The presence of minute pores in pit membranes, which are submicroscopic paths of liquid, can affect the permeability. The porosity of pit membranes differed between the two species examined. In poplar, microfibrils were loosely packed compared with those in oak (Figs. 3F and 4E).

Void volume filled

There was a great difference in permeability between the two species studied. Poplar had higher permeability than oak because of having higher frequencies of conductive vessels (151.52/mm^2). A higher frequency of vessels can significantly increase the permeability.[27]

The permeability of water in the two hardwood species varied in different moisture regimes, especially below and above the FSP (Tables 2 and 3). The FSP is the MC above which no changes in mechanical and physical properties are seen and the cell walls are saturated with bound water.[10] It has been reported that near the FSP, the conditions are ideal for liquid flow and for diffusion in wood;[28] however, this effect was not evident in this study. The reason might have been the liquid water entrapped in ray parenchyma, which reduced the permeability at this MC level.[29,30] Excessive moisture could act as a physical barrier for mass flow of liquid in different wood cells. Tables 2 and 3 indicate that below the FSP, the permeability still increases to a great extent. However, the differences of liquid permeability increased from 20% to 0% MC levels were found statistically similar. In this contrast, drying below 10% MC would not be economical for any commercial purpose, but reducing the moisture level to a range of 10%–20% is practicably achievable.

As expected, liquid permeability varies widely for different MC levels. The overall permeability in poplar was roughly 20% higher than that in oak. This fact could be

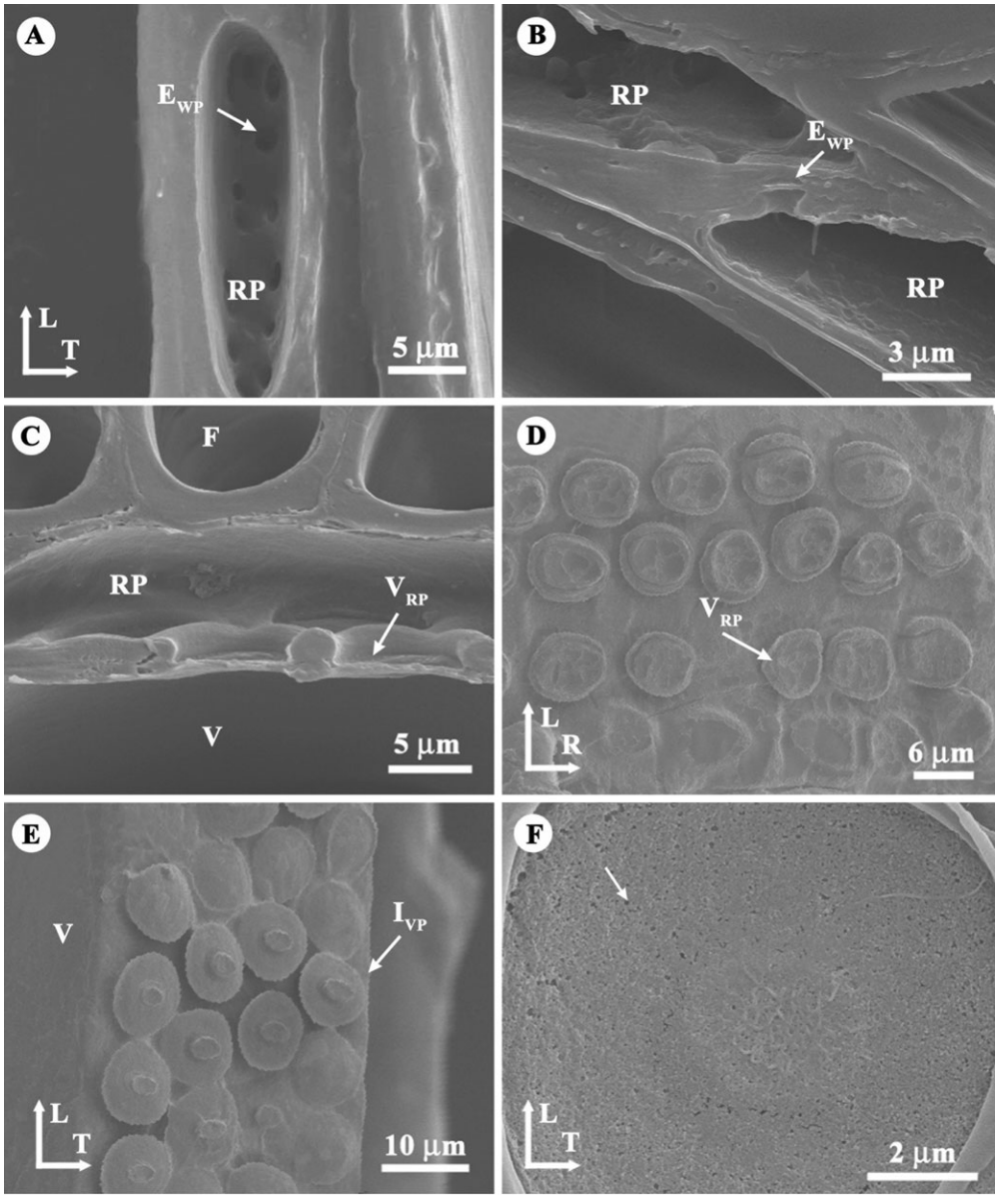

Fig. 3A–F. Scanning electron micrographs of poplar. **A, B** Pits in ray parenchyma (*RP*). E_{WP}, end-wall pit. **C, D** Vessel-ray pit (V_{RP}); *F*, fiber; *V*, vessel. **E** Intervessel pit (I_{VP}). **F** Intervessel pit membrane. *Arrow in **F***, porous intervessel pit membrane

attributed to the lower specific gravity of poplar (0.35) compared with oak (0.62). Studies have shown that the density of wood is negatively correlated with liquid permeability,[31–33] which is in full agreement with this finding. However, some studies have reported that the permeability is independent of wood density.[1,34] A high percentage of latewood, corresponding to lower porosity, significantly reduced the permeability of oak. Moreover, the variation of permeability between the two species did not solely depend on the wood density but is also related to different anatomical features.[4,25] It is well known that heartwood permeability is generally low due to the presence of tyloses, gums, and chalky extractives.[10] Large vessels in the heartwood of oak were plugged with tyloses, which contributed to the large differences in permeability between sapwood and heartwood. This difference was found to be low for poplar as it does not have any vessels occluded by tyloses. According to the overall results of this part of the investigation, it was clearly observed that there is a negative relationship between MC and permeability (R^2 = 0. 8821 for poplar and 0.9694 for oak), i.e., permeability increased as MC levels decreased; therefore, the relation could be expressed by linear regression lines (Fig. 5). Similar trends were reported by Hassler et al.,[6] Usta,[35] and Islam et al.,[33] who concluded that lower MC levels resulted in improving treatability. For instance, Skaar[36] stated that the existing amount of moisture in wood affects the amount of space (void volume) available for fluid uptake by reducing the porosity. Permeability could be increased by drying. In this respect, we have seen that our results fit the previous findings.

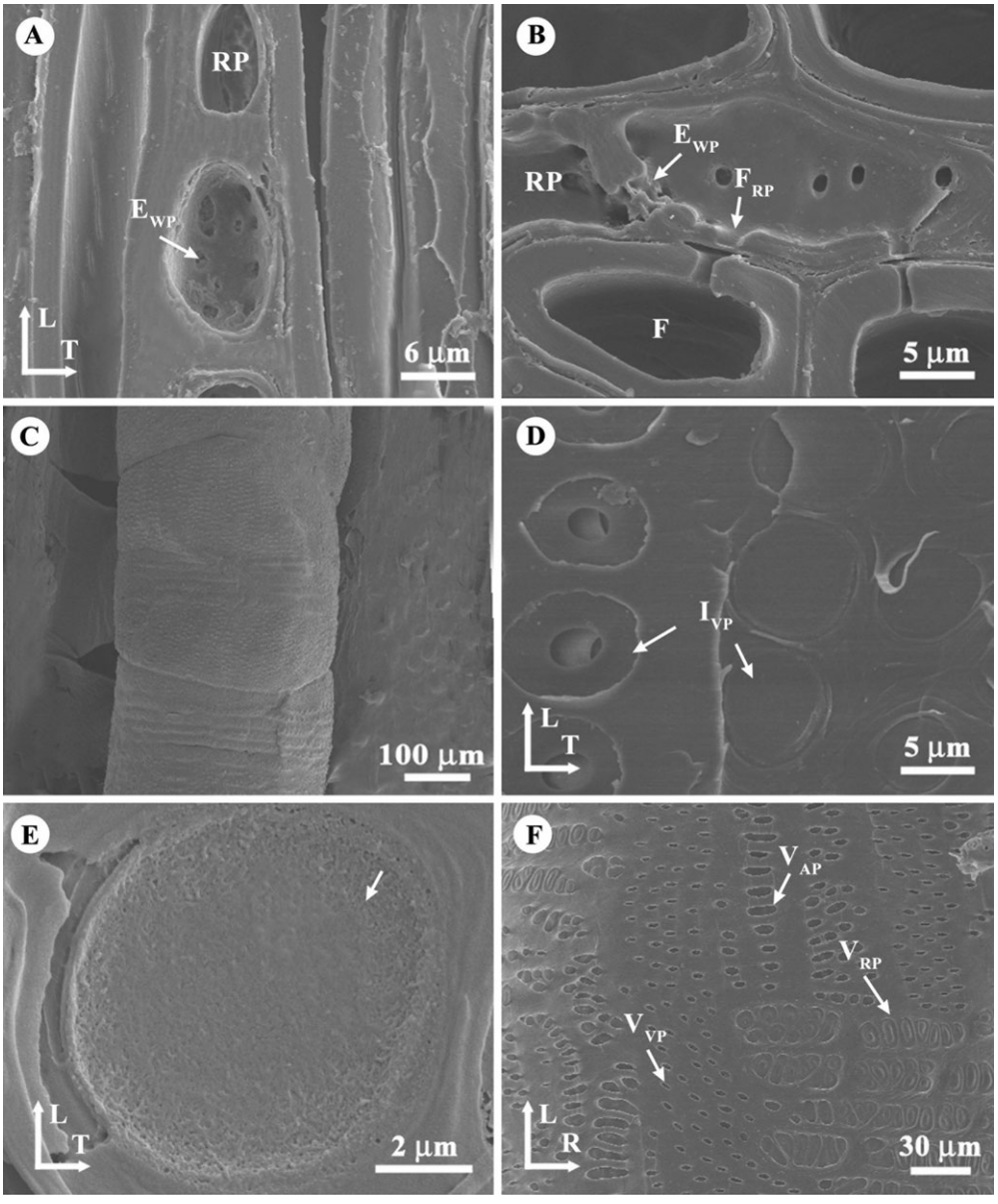

Fig. 4A–F. Scanning electron micrographs of oak. **A, B** Pits in ray parenchyma (*RP*). E_{WP}, end-wall pit; F_{RP}, fiber-ray parenchyma pit. **C** Vessel. **D, E** Intervessel pit (I_{VP}). *Arrow in E* indicates compact microfibril in intervessel pit membrane. **F** Different pits in vessels. V_{AP}, vessel-axial parenchyma pit; V_{VP}, vessel-vasicentric tracheid pit; V_{RP}, vessel-ray pit

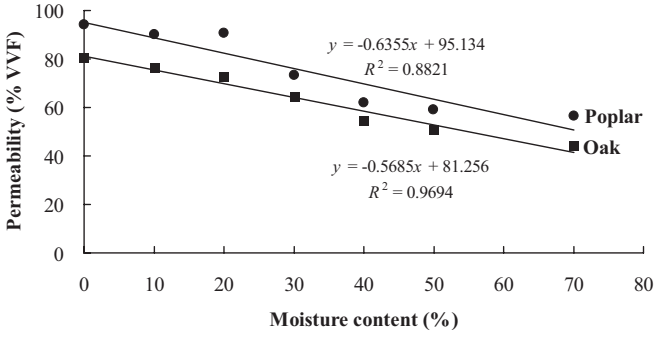

Fig. 5. Relationship between liquid permeability and wood MC. Each point reflects the mean of eight replications. *VVF*, void volume filled

Penetration speed

Liquid flow through the capillary structure of wood may be comparable to the flow through glass capillaries in series. The flow rate in a capillary is the integral of the flow speed over the cross section. For a circular conduit, the flow rate D can be expressed by Poiseuille's equation:

$$D = \frac{n\pi r^4 \Delta P}{8\eta L} \equiv \frac{q r^2 \Delta P}{8\eta L} \quad (2)$$

where n is the number of capillaries in parallel, D is the volume of flow in cm^3/s, r is the capillary radius and L is their length, q is the cross-sectional area of the channel, ΔP is the pressure difference in dyn/cm^2, and η is the liquid viscosity in poise. According to Eq. 2, for two capillaries

Table 2. The wood density, porosity (void volume), and percentage of void volume filled with water for various values of moisture content (from green to kiln dried) in poplar

	Experimental MC levels													
	0% MC		10% MC		20% MC		30% MC		40% MC		50% MC		70% MC	
	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW
D_{MC} (kg/m^3)	348.11	361.40	382.93	397.54	440.38	454.58	452.55	469.82	487.36	505.96	522.17	542.10	591.79	614.37
Porosity (%)	77.25	76.38	74.97	74.02	71.22	70.29	70.42	69.29	68.15	66.93	65.87	64.57	61.32	59.84
VVF (%)	95.13a	93.25a	91.44a	88.79a	90.65a	90.52a	74.74b	71.83b	63.61c	60.72cd	60.92cd	57.33cd	58.88cd	54.44d

Values are means of four replicate experiments for each MC level
Porosity (%) is the fractional void volume of wood
MC, moisture content; SW, sapwood; HW, heartwood; D_{MC}, wood density at respective MC; VVF, percentage of void volume filled with water
Means with common letters in a given row are not significantly different at the $P < 0.05$ level (Duncan multiple range test)

Table 3. The wood density, porosity (void volume), and percentage of void volume filled with water for various values of moisture content (from green to kiln dried) in oak

	Experimental MC levels													
	0% MC		10% MC		20% MC		30% MC		40% MC		50% MC		70% MC	
	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW
D_{MC} (kg/m^3)	590.48	644.64	649.53	709.11	753.78	802.48	767.63	838.04	826.68	902.50	885.72	966.97	1003.82	1095.90
Porosity (%)	64.41	57.87	57.55	53.65	50.73	47.55	49.83	45.23	45.97	41.01	42.11	36.80	34.39	28.37
VVF (%)	82.16a	78.92a	77.57ab	75.53ab	74.85ab	70.54bc	66.00cd	62.80de	56.82ef	52.6fg	52.43fg	49.00gh	46.15gh	42.11h

Values are means of four replicate experiments for each MC level
Porosity (%) is the fractional void volume of wood
MC, moisture content; SW, sapwood; HW, heartwood; D_{MC}, wood density at respective MC; VVF, percentage of void volume filled with water
Means with common letters in a given row are not significantly different at the $P < 0.05$ level (Duncan multiple range test)

Table 4. Analysis of variance for longitudinal penetration speed in earlywood of poplar and oak measured at different treatment times

		Penetration speed (μm/s)							
		15 s		30 s		45 s		60 s	
Source	df	MS	F-value	MS	F-value	MS	F-value	MS	F-value
S	1	13.569	2.552^{NS}	13.123	5.540*	9.698	6.584*	7.300	7.061*
C	1	437.192	82.240**	242.935	102.555**	153.405	104.148**	107.349	103.841**
S × C	1	98.542	18.537**	49.330	20.825**	30.134	20.458**	20.650	19.975**
Error	16	5.316		2.369		1.473		1.034	
Total	20								

Source represents the source of variation
df, degrees of freedom; MS, mean of the squares; S, species; C, cell type; NS, not significant
* $P < 0.05$; ** $P < 0.001$

with the same length, one with a radius ten times that of the other, the flow through the larger capillary would be 10000 times that of the smaller capillary under the same driving force. But if they were connected in series, then the volume of liquid flow would be the same. When we compare individual wood cells as a single capillary conduit, the liquid flow will follow the capillary equation:

$$h = \frac{2\gamma\cos\theta}{\rho g r} \tag{3}$$

where h is the capillary rise of liquid in a capillary of radius r, ρ is the density and γ is the surface tension of the liquid, θ is the contact angle between the liquid and the capillary surface, and g is the acceleration of gravity. Based on this model, it is assumed that liquid will penetrate more into narrow capillaries than into wider capillaries. Thus, the flow speed in the wood capillary structure is directly related to the capillary radius. However, it is very difficult to use this approach in wood composed of parallel porous capillaries with different radii. In addition, as penetration proceeds, the air in the capillaries is compressed by the advancing liquid, which gradually reduces the ΔP. The entrapped air needs to pass through any encountered constrictions (pits) for further liquid penetration to occur. Therefore, pits play an important role in liquid conduction.

Longitudinal flow

The permeability between longitudinal and transverse samples varied greatly between species and cells, especially in the longitudinal direction; therefore, a separate ANOVA was carried out for this direction. The results of analysis of variance (according to species, S; cell type, C; and species and cell type interaction, S × C) are shown for earlywood in Table 4. ANOVA analysis for latewood was not performed because the penetration speed of poplar was not measured in this location (sample preparation was not possible due to the narrow latewood area). Liquid penetration speeds measured at different times, i.e., 15, 30, 45, and 60 s, between species were significantly different, except for the starting point at 15 s, but that difference was highly significant among cell types (C) and species × cell interaction (S × C). Descriptive statistics of the experimental results for oak are given in Table 4.

According to Eq. 3, it is clear that the capillary rise of liquid will be high in cells with narrow cell lumina. Thus, we found a significant flow rate difference between large and small vessels. As the liquid negotiates the wood capillary structure, the liquid flow rate does not only relate to capillary radius, but also to the inner surface properties of the conduits.[12] Different pits are present in the vessels, i.e., intervessel pits, vessel ray pits, vessel fiber pits, and vessel axial parenchyma pits (Fig. 4F). These kinds of pits are expected to interrupt the spontaneous liquid flow in the conduits. The small vessels in oak conducted liquid about twice as fast as the large vessels. Furthermore, the liquid flow speed in poplar vessels was found to be 30% higher than that in the large vessels of oak. Concerning liquid penetration in fibers, the highest penetration speed was observed in the latewood fibers of oak due to their narrow cell lumina. The average flow speed of earlywood fibers of oak was 20% higher than that of poplar, but no significant difference was observed. Even though fiber lumina were found to be narrower than vessel lumina, end-to-end connection of vessel elements with simple perforation plates facilitates efficient flow of liquid in vessels compared to that in fibers.

A constant flow rate with respect to time was not observed in vessels, fibers, or even in ray parenchyma; rather, there was a decreasing trend (Fig. 6). It is, however, worth noting that an initial rapid fall-off in liquid permeability did occur. In all cases, there was a significant reduction of flow speed over time, i.e., there was a negative relationship with penetration speed and time. It is generally accepted that the decrease in liquid permeability of wood over time can be largely attributed to the generation of gas embolisms in the flow paths.[25] Such embolisms develop in the presence of gas nuclei or where the pressure gradient in wood is large enough to cause gas in the liquid to come out of solution. In this regard, many authors have been able to obtain constant flow rate with respect to time by subjecting their test liquids to microfiltration, boiling or distillation, shock-cavitation, and storage under vacuum conditions.[37] Liquid flow was found to be different in fibers and vessels (Fig. 6). The mean penetration speed was reduced up to 53% in poplar fiber compared to that in vessels, whilst it was reduced by 26% for earlywood and 56% for latewood fiber in oak compared to flow in small and large vessels, respectively. Because of the high permeability of small vessels, large

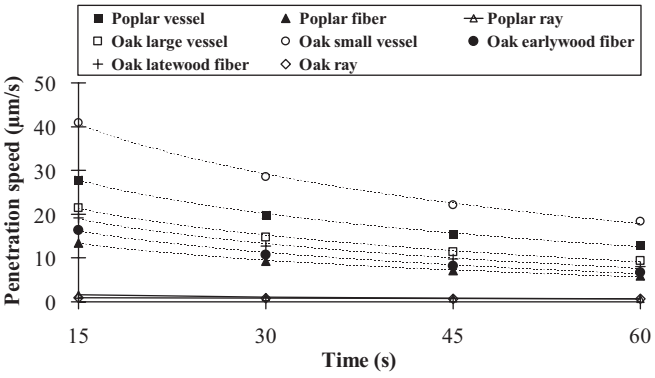

Fig. 6. Liquid penetration speed in different cells of poplar and oak measured at different treatment times

deviations were observed between latewood vessels and fibers in oak.

Lateral flow

The variability of hardwood structure causes wide differences in water permeability not only between species but also within the investigated sections. The largest difference in permeability occurred between the longitudinal and transverse directions. Indeed, longitudinal flow is obviously much greater than transverse flow, mainly because of the high conductivity of vessels.[34] The average longitudinal flow rate by vessels and fibers was 13 times higher in poplar and 16 times higher in oak than the respective radial penetration by ray parenchyma. The radial flow rate was observed in the earlywood portion only and was compared between the two species; in latewood, the radial flow rate was not measured. The very thin latewood area in poplar made it difficult to obtain a true latewood sample. Also, it was assumed that there would not be pronounced radial flow differences between earlywood and latewood as they have almost the same anatomical measurements for ray parenchyma (Table 1). We expected a significant difference of radial flow rate between the two species because of the anatomical variations of ray parenchyma; however, the flow rate differences between poplar and oak were found to be very low. Even though significant differences were not observed, the radial flow rate was found to be higher in poplar (Fig. 6) due to its narrow ray cell luminal area. Furthermore, the numerous lateral wall and end-wall pits of ray parenchyma were assumed to interrupt the liquid flow rate. As counted, the average number of lateral wall (radial wall) pits was two in poplar and six in oak. In addition, continuous liquid flow is interrupted by perforated end-walls. The end-wall pit number and diameter and the thickness of the pit membrane are thought to determine the extent of liquid flow in the radial direction. Even though the end-wall pit number was found to be the same for both species, the different membrane thicknesses (220.11 nm in poplar and 312.48 nm in oak) would be a reason for the flow variations. The structure of the ray tissue and other anatomical features may be the most important factors determining permeability in this direction. Among vessels, fibers, and ray parenchyma, the cell lumina of ray parenchyma were found to be the narrowest, and hence the capillary rise would be the highest according to the capillary equation (Eq. 3). In practice, however, the liquid penetration in ray cells was found to be the lowest because ray cells are short and are connected with end-walls. In addition, studies have shown that pit membranes between parenchyma are thicker than intervessel pit membrane or fiber–fiber pit membranes, and consequently are less efficient as liquid pathways.[38] Despite the absence of margo unlike in softwood, the hardwood pit membrane is permeable.[10,39] In this experiment, it was found that the ray parenchyma end-wall pit membrane thickness was 220.11 nm in poplar and 312.48 nm in oak, whereas the thicknesses of the intervessel pit membrane was found to be 111.47 nm in poplar and 163.79 nm in oak. Variations in cell alignment and cell structure are thought to be responsible for the large differences between the longitudinal and radial flow rates.

All the experimental findings of this study are in reasonable agreement with the previous reports of Comstock,[18] Banks,[12] Hassler et al.,[6] Ahmed and Chun,[25] and Islam et al.[33] The wood of the two species was found to have different treatability properties in different flow pathways due to the orientation and direction of the wood cells. As wood reflects the structure of living trees regarding longitudinal fluid transport from roots to leaves, with less need for lateral transport via the ray cells, the permeability and penetration speed of the two hardwood species mirrored this, and hence, the longitudinal flow speed from end grain through the wood was found to be higher than the lateral penetration.

Conclusions

Different anatomical features affected longitudinal and lateral liquid permeability. Herein, the microstructures that control the liquid penetration were described and compared. Variations in the extent of cell structures and shapes related to capillary pressure were thought to be the major reasons for the differences in liquid permeability between the two hardwood species. The experimental conclusion can be summarized as follows:

1. The variation of water permeability between the two hardwood species was found to be large. Generally, the heartwood permeability was lower than the sapwood permeability. The MC of wood significantly affected the liquid permeability.
2. Experimental observations indicated that the liquid permeability (as indicated by the percentage of void volume filled) increased to a greater extent below the FSP. As the MC level increases, the liquid uptake gradually decreases.
3. Drying to a very low MC did not show any significant differences in permeability, especially below 20% MC.
4. Different liquid uptake behaviors existed between high-density and low-density wood. High-density oak wood

had a roughly 20% lower permeability (VVF%) than the low-density wood poplar did.
5. The surface properties of cell lumen, particularly pits and their membrane thickness, affected the speed of liquid penetration.
6. It was observed that ray parenchyma with a narrow lumen diameter, end-walls with a wide pit aperture, and a thin pit membrane facilitated the liquid flow in radial direction.
7. Longitudinal flow speed of liquid was observed higher in narrow vessels and fibers than in wider ones.

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