Tanaka *et al. Journal of Wood Science* (2026) 72:15
https://doi.org/10.1186/s10086-026-02263-y

Journal of Wood Science

ORIGINAL ARTICLE Open Access

Effects of water-hammer impacts on aspirated pits and tyloses, liquid permeation, and collapse of wood

Soichi Tanaka[1*], Masako Seki[2], Mitsuru Abe[2] and Tsunehisa Miki[2]

Abstract

This paper deals with a water-hammer impregnation method previously developed as a novel approach to improve the uniformity of liquid impregnation into wood, by targeting aspirated pits and tyloses, which are known to restrict liquid flow. Our previous study demonstrated that liquid permeation was promoted by the water-hammer impacts, although the mechanism underlying this effect remained unclear. In this study, the effects of water-hammer impacts on liquid permeation, the aspirated pits and tyloses, and the collapse of wood were investigated for several species to clarify the mechanism of this promotion of liquid permeation. Several hardwood and softwood species were tested using an improved apparatus capable of generating stable water-hammer impacts. The effect of water-hammer impacts on liquid permeation was quantitatively evaluated based on the difference in water uptake with and without the impacts, while collapse was evaluated based on external dimensions. The results showed that the water-hammer impacts promoted liquid permeation without causing significant collapse in all species. Among the species examined, sugi (*Cryptomeria japonica*) and kiri (*Paulownia tomentosa*) exhibited the most pronounced promotion. Microscopic observation suggested that aspirated pit membranes in sugi and tyloses in kiri were locally removed or ruptured, providing additional flow paths for liquid permeation. Examination of the effect of hammering conditions indicated that the region affected by the impacts extended farther into the interior in kiri than in sugi. These findings suggest that liquid permeation is promoted by partial damage to aspirated pit membranes and tyloses, which depends on the species-specific wood anatomy.

Keywords Wood impregnation, Water hammer, Aspirated pit, Tyloses, Collapse

Introduction

Impregnation treatments with various chemical agents for fire retardancy, dimensional stabilization, and preservation of wood are widely used as typical methods to improve the three major undesirable properties of wood—low fire resistance, dimensional instability, and biological deterioration. The pressure-impregnation method is widely applied as a conventional approach for improving the properties of wood. In this method, wood blocks or bars are placed in a closed vessel, evacuated to remove air from internal voids, subsequently immersed in a liquid under reduced pressure, and then subjected to atmospheric or elevated pressure, so that the pressure difference drives liquid permeation into the wood. However, this process often results in problems, such as non-uniform treatment and collapse. These problems are essentially caused by the restriction of liquid flow associated with aspirated pits and tyloses (for example, [1]), which are widely distributed in wood. Therefore, the treatment for improving the liquid flow by penetrating the aspirated pit membranes has been

*Correspondence:
Soichi Tanaka
tanaka.soichi.6w@kyoto-u.ac.jp
[1] Research Institute for Sustainable Humanosphere, Kyoto University, Uji, Kyoto 611-0011, Japan
[2] National Institute of Advanced Industrial Science and Technology(AIST), Multi-Material Research Institute, Nagoya, Aichi 463-8560, Japan

© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

studied using biological (for example, [2]), chemical (for example, [3]), or physical approaches (for example, [4–7]). While numerous studies have investigated physical approaches for enhancing the penetration of aspirated pit membranes in softwoods, comparable studies focusing on tyloses in hardwoods remain relatively scarce [8].

As one physical approach, underwater shock-wave methods [7] using detonation in a liquid have been investigated to damage aspirated pits in wood. However, such methods have not been widely adopted in practice, because the use of detonation involves serious safety risks, and repeated generation of shock waves requires impractical operation and cost.

In our previous study [9], a water-hammer impregnation method was proposed to promote liquid permeation, with the intention of acting on aspirated pit membranes in softwoods, and its potential applicability to other anatomical structures such as tyloses in hardwoods was also discussed. This approach enables repeated generation of impact pressure waves using a simple mechanical setup. In this method, a water-hammer impact, a rapid pressure change associated with liquid motion, is generated in the liquid surrounding a wood specimen, which is intended to apply impact forces to the aspirated pits and tyloses. In the previous study [9], it was shown that the water-hammer impacts, previously described as a pressure wave followed by cavitation [10], promoted liquid permeation while simultaneously suppressing collapse. This promotion was presumed to result from partial damage to aspirated pits and tyloses, forming additional liquid-flow pathways. However, the direct influence of the water-hammer impacts on these structures and the depth to which the effect propagated within the wood remained unclear. In addition, the difference in liquid-permeation promotion among wood species was not fully understood, since the previous study was limited to the softwood species Alaska cedar (*Callitropsis nootkatensis* [syn. *Chamaecyparis nootkatensis*]) and the hardwood species kiri (*Paulownia tomentosa*). This limitation was partly attributable to the water-hammer generation mechanism employed in the previous study, which constrained the generation of sufficiently strong and reproducible water-hammer impacts.

The objective of this study was to clarify the effects of the water-hammer impacts on aspirated pits and tyloses, liquid permeation, and collapse in several wood species. To achieve this objective, a new experimental apparatus capable of generating sufficiently strong and reproducible water-hammer impacts was developed. Furthermore, the mechanism of liquid-permeation promotion by the water-hammer impacts was discussed based on its effect on anatomical structure and the depth of the affected region.

Experimental

Apparatus

In the previous water-hammer generation system [9], an external impact was directly applied to the container, causing a transient elastic deformation of its wall. This deformation pushed part of the liquid out of the container. During the subsequent elastic recovery of the container, the internal pressure transiently decreased. This caused the liquid to be rapidly drawn back, thereby leading to the generation of a water-hammer impact. However, because the generation of the water-hammer impact originates from the transient elastic deformation of the container wall itself, the driving force for liquid motion was inherently limited. As a result, only a limited amount of energy could be transferred to the liquid, leading to relatively weak water-hammer impacts. In addition, repeated elastic deformation of the container wall under successive impacts frequently caused damage to the container after only several hundred cycles. These limitations severely restricted the number of water-hammer impacts that could be stably applied to wood specimens. To overcome these limitations, the apparatus was redesigned to enable sufficiently strong and reproducible water-hammer impacts.

The improved water-hammer apparatus is illustrated in Fig. 1. A photograph of the apparatus is also provided in Fig. S1. A cylindrical container filled with liquid was fixed perpendicularly to a beam, and its upper end was open to the atmosphere. When the beam was struck from below with a rubber hammer, both the container and the liquid inside acquired upward momentum. As

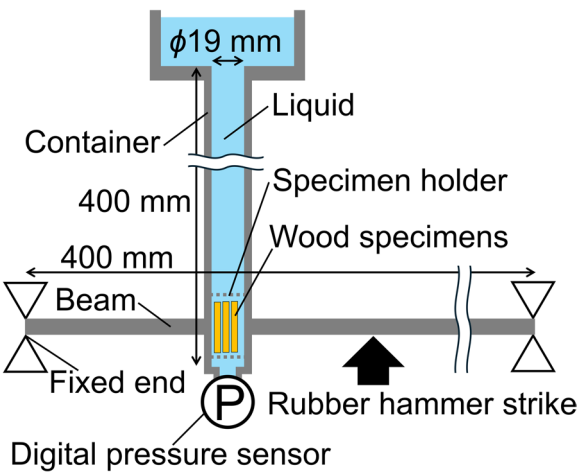


Fig. 1 Schematic illustration of the apparatus generating a water-hammer impact by striking the beam with a rubber hammer

the beam elastically rebounded, the container was pulled back to its original position earlier than the liquid, which continued its upward motion due to inertia. This delayed return of the liquid decreased the internal pressure near the bottom of the container and induced the liquid to return toward the container wall. The collision between the container wall and the returning liquid produced a water-hammer impact consisting of a transient high-pressure wave followed by a damped oscillation. A water-hammer impact can in principle also be generated by striking the beam from above, because a delayed motion of the liquid relative to the container owing to its inertia can still occur. However, striking the beam from below was adopted in this study, because it allows the water-hammer impact to be generated in a more stable and reproducible manner.

The temporal variation of the hydraulic pressure of the liquid in the container was detected using a digital pressure sensor (GP-M025, Keyence Co.), which was placed at the bottom of the container, and recorded with a data collecting system (NR-500 and NR-HA08, Keyence Co.) at room temperature. The detailed waveform and pressure characteristics are presented in the Results section. The 90% response time of the sensor and the sampling interval of the system were 5 ms and 50 μs, respectively. All measurements using this apparatus were performed at room temperature, and distilled water at room temperature was used as the liquid.

Materials

The wood samples with 3 mm (R; radial) × 10 mm (T; tangential) × 40 mm (L; longitudinal) were prepared from the heartwood blocks of sugi (*Cryptomeria japonica*), hinoki (*Chamaecyparis obtusa*), akamatsu (*Pinus densiflora*), Alaska cedar (*Callitropsis nootkatensis*), ulin (*Eusideroxylon zwageri*), and kiri (*Paulownia tomentosa*). The samples were dried at 105 °C to be in an oven-dried condition. Mass and volume of the dried sample (m_0 and v_0) were measured. The oven-dry density and the number of specimens for each treatment condition are summarized in Table 1.

Table 1 Oven-dry density and number of specimens for each treatment

Species	Treatment	Oven-dry density (g/cm^3)	Number of specimens *n*
sugi	Control	0.35[a] ± 0.03[b]	4
	Water hammer	0.36 ± 0.03	4
hinoki	Control	0.43 ± 0.02	3
	Water hammer	0.42 ± 0.01	3
kamatsu	Control	0.35 ± 0.03	4
	Water hammer	0.34 ± 0.04	4
Alaska cedar	Control	0.51 ± 0.02	4
	Water hammer	0.51 ± 0.02	4
ulin	Control	0.96 ± 0.01	4
	Water hammer	0.96 ± 0.01	4
kiri	Control	0.26 ± 0.02	4
	Water hammer	0.25 ± 0.03	4

[a] Average

[b] Standard deviation

Procedure of injection and water-hammer treatment

Eight oven-dried specimens of each species (six for hinoki) were subjected to the injection process. The specimens were vacuumed for 2 h using a diaphragm pump (ultimate pressure, 0.8–1.0 kPa). While maintaining the vacuum, they were immersed in the liquid, and the pressure was then released to atmospheric pressure to inject the liquid. The moment when the liquid was introduced into the chamber under vacuum, allowing initial liquid entry into the specimen surfaces by capillary action, was defined as the start of injection. Afterward, the specimens kept immersed in the liquid. The mass (m_i) and volume (v_i) of the specimens were measured 1 h after the start of injection. The specimens were then equally divided into two groups.

One group of specimens was placed in the water-hammer apparatus (Fig. 1) 1.1 h after the start of injection. Between 1.2 h and 2.2 h after the start of injection, the sequence of 3 min of water-hammer impacts at approximately 1 Hz and a subsequent 3 min rest was repeated ten times, resulting in a total of 1800 impacts. At 2.3 h after the start of injection, the liquid remaining on the specimen surfaces was wiped off with a paper towel, and the mass (m_w) was measured. This procedure is referred to as the water-hammer treatment.

The other group of specimens was kept immersed in the liquid without water-hammer impacts. At 2.3 h after the start of injection, the surface liquid was wiped off, and the mass, m_w, was measured. This procedure is referred to as the control treatment.

After the treatments, all specimens were kept immersed in the liquid until their swelling reached equilibrium, and the volume (v_s) was measured.

Evaluation

The initial cavity filling rates before and after the treatment (water hammer or control) were calculated based on the maximum weight percent gain of liquid take up [11] as follows:

$$\xi_i = 100\,(m_i - m_0)/\{\rho_l(v_s - m_0/\rho_c)\}[\%], \quad (1)$$

$$\xi_w = 100\,(m_w - m_0)/\{\rho_l(v_s - m_0/\rho_c)\}[\%], \quad (2)$$

where ρ_c represents oven-dry density of cell wall (=1.5 g/cm^3), and ρ_l denotes the density of the liquid, or the distilled water (=1.0 g/cm^3). The initial cavity filling rate, ξ_i, is evaluated as an indicator of the permeability unique to each wood sample. The variation in cavity filling rate, $\xi_w - \xi_i$, is evaluated as an indicator of the liquid permeation during the treatment (water hammer or control).

The maximum volumetric swelling β_m was estimated as the following equation:

$$\beta_m = 100(v_s - v_0)/v_0[\%]. \quad (3)$$

A smaller β_m for the water-hammer treatment compared with that for the control treatment indicates a higher degree of compressive deformation during the water-hammer impacts. For each specimen of each wood species (Table 1), β_m was calculated, and statistical significance between the control and water-hammer-treated specimens within each species was evaluated using Welch's t test, with differences considered significant at $p < 0.05$.

Anatomical observation

The specimens after the treatment were conditioned at 20 °C and 59% relative humidity to reach an air-dry condition. The air-dried specimens were then oven-dried at 105 °C. Each specimen was cut at the midpoint along the tangential direction to expose the radial section, and the cut surface was trimmed with a microtome. The radial sections were coated with platinum using an auto fine coater (JEC-3000FC, JEOL Ltd., Japan) and imaged using a field-emission scanning electron microscope (FE-SEM; JSM-7800F, JEOL Ltd., Japan). The accelerating voltage was set between 1.0 and 5.0 kV, depending on the specimen and imaging conditions, to obtain sufficient image contrast.

The transverse surface of kiri specimens was also imaged using a digital microscope (VHX-8000, Keyence Co., Japan).

Effect of hammering conditions

To investigate the mechanism of liquid-permeation promotion, the effect of the number of water-hammer impacts was examined. The species of sugi and kiri were selected for this examination, since the water-hammer impacts showed a greater promoting effect on liquid permeation in these species.

Eighteen oven-dried specimens each of sugi and kiri, with oven-dry densities of 0.32 ± 0.03 g/cm^3 and 0.23 ± 0.01 g/cm^3, respectively, were subjected to the injection process as described in the Sect. "Procedure of injection and water-hammer treatment". The specimens were then divided into four groups: a control (n=6) and 90-, 450-, and 1800-impact water-hammer treatments (n=4 each).

For the water-hammer treatment, one group of specimens was placed in the water-hammer apparatus (Fig. 1) 1.1 h after the start of injection. Between 1.2 h and 2.2 h after the start of injection, the sequence of 1 min 30 s of water-hammer impacts at approximately 1 Hz, followed by 1 min 30 s of rest, was repeated once, five times, and twenty times for the 90-, 450-, and 1800-impact treatments, respectively. At 2.3 h after the start of injection, the liquid remaining on the specimen surfaces was wiped off with a paper towel, and the mass (m_w) was measured.

For the control treatment, the other group of specimens was kept immersed in the liquid without water-hammer impacts. At 2.3 h after the start of injection, the surface liquid was wiped off, and the mass, m_w, was measured.

The initial cavity filling rate (ξ_i) and the variation in cavity filling rate ($\xi_w - \xi_i$) were also estimated using Eqs. (1) and (2).

Results and discussion

Transient pressure behavior under a water-hammer impact

Figure 2 shows representative pressure waveforms of the liquid around the wood specimens soon after striking the beam of the apparatus (Fig. 1). Similar waveforms were obtained for all species, characterized by a transient high-pressure peak followed by a damped oscillation, as assumed in the Sect. "Apparatus." These results confirm that water-hammer impact was successfully generated by the apparatus for all species and that the internal structure of wood had little influence on the pressure waveform in this setup. This indicates that a comparable magnitude of water-hammer impacts was applied to all specimens.

Effect of water-hammer impacts on liquid permeation

Figure 3 shows the effect of water-hammer treatment on liquid permeation. The horizontal axis represents the initial cavity filling rate (ξ_i) obtained by vacuum injection, and the vertical axis represents the variation in cavity filling rate ($\xi_w - \xi_i$) resulting from the water-hammer or control treatments. The water-hammer-treated and control specimens showed almost the same range of ξ_i values within each species, indicating that the initial permeability inherent to each specimen was comparable between the two groups. Therefore, the difference in the variation in cavity filling rate ($\xi_w - \xi_i$) between the control and water-hammer treatments in Fig. 3 is considered to

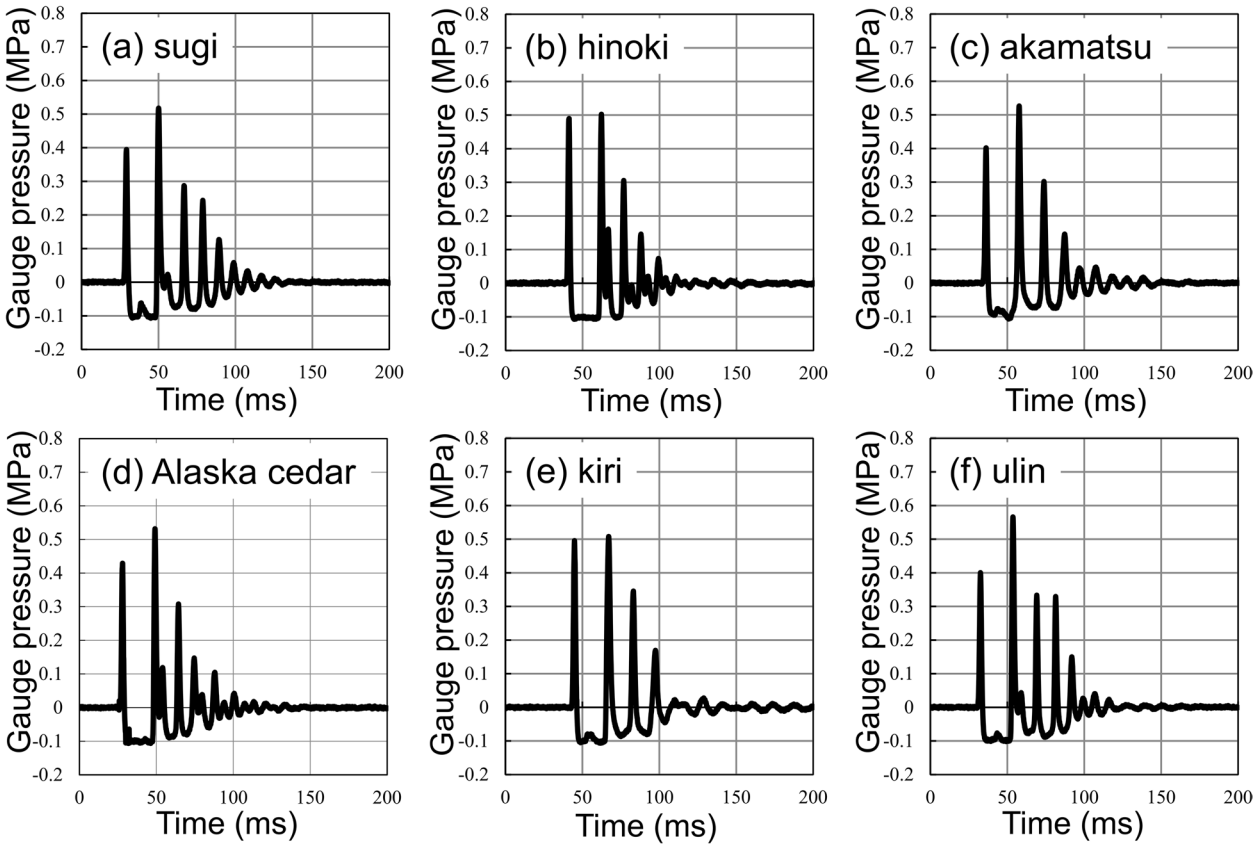


Fig. 2 Representative pressure waveforms of the water-hammer impacts for different wood species

reflect the effect of the water-hammer treatment itself rather than the inherent permeability of the specimens.

At the same initial cavity filling rate (ξ_i), the water-hammer-treated specimens showed a greater variation in cavity filling rate ($\xi_w - \xi_i$) than the control specimens for all species. This tendency was accompanied by changes in liquid permeation that were later examined in relation to aspirated pits in softwoods and tyloses in hardwoods.

The promoting effect of the water-hammer treatment on liquid permeation was small in akamatsu, Alaska cedar, and ulin, moderate in hinoki, and remarkable in sugi and kiri. This difference can be mainly attributed to variation in wood density (Table 1); species with lower density tended to exhibit a greater promoting effect in Fig. 3. This suggests that anatomical characteristics associated with low density, such as thinner cell walls or more compliant structures, might facilitate the effect of water-hammer impacts. However, akamatsu deviated from this general tendency. This exception is likely related to resin (rosin) components remaining in akamatsu; previous studies have shown that *Pinus densiflora* contains substantial amounts of resin acids, such as palustric acid [12], which may have reduced the wettability of cell wall surfaces, including aspirated pits, because these resin acids are highly hydrophobic and can diminish the interaction between the liquid and wood cell walls.

Effect of water-hammer impacts on collapse

To evaluate the collapse of wood caused by the water-hammer impacts, the maximum volumetric swelling (β_m) of the specimens with control and water-hammer treatments was measured after immersion in the liquid until their swelling reached equilibrium, as shown in Fig. 4. No significant difference in β_m was observed between the water-hammer-treated and control specimens for any species. These results indicate that, for all species, the water-hammer impacts did not cause a statistically significant degree of collapse. It is also suggested that even if slight collapse occurred, its extent was within the variation of swelling associated with moisture adsorption and within the range of experimental uncertainty.

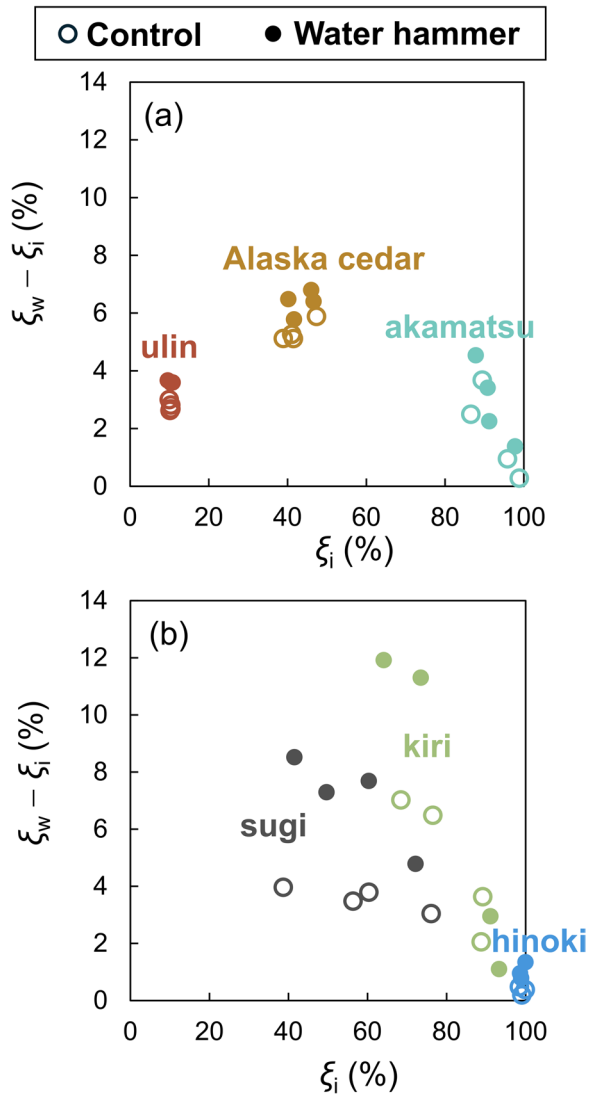


Fig. 3 Relationship between the initial cavity filling rate, ξ_i, and its variation, ξ_w–ξ_i, with control and water-hammer treatments

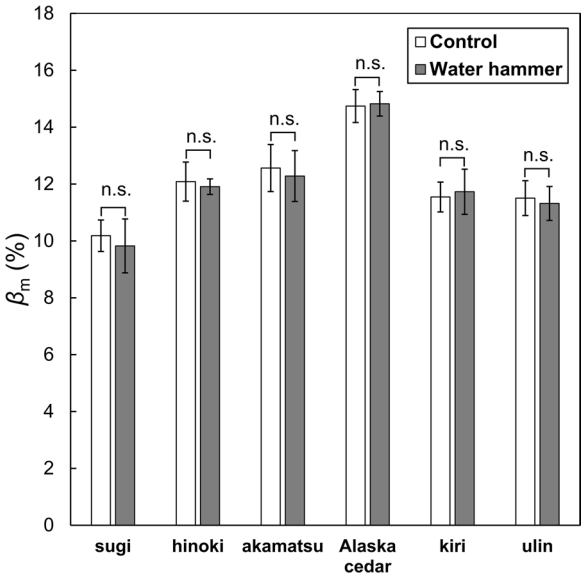


Fig. 4 Maximum volumetric swelling, β_m, with control and water-hammer treatments. Error bars indicate standard deviation. Statistical significance between control and water-hammer treatments within each species was tested using Welch's *t* test; n.s. indicates not significant ($p \geq 0.05$)

Effect of water-hammer impacts on aspirated pits and tyloses

The effect of the water-hammer impacts on aspirated pits of softwoods was examined by SEM observation. In sugi, the observations suggested local damage to the aspirated pit membrane, including local rupture or removal (Fig. 5), whereas no clear structural change was found in the other softwood species. Figure 5 shows representative micrographs of aspirated pits on the radial section located approximately 5 mm inward from the transverse surface along the L direction for sugi specimens. Among the control specimens (Fig. 5a, b), the tori remained intact, whereas in the water-hammer-treated specimens (Fig. 5c–e), the tori were locally ruptured or removed. It should be noted that the pit apertures shown in Fig. 5 were viewed from the tracheid lumen side. In this observation geometry, aspiration of the pit membrane toward the near side can be clearly identified, whereas aspiration toward the far side cannot be unambiguously distinguished from an apparent absence of the membrane. In addition, in dried wood, the direction of pit aspiration is not necessarily uniform, which further complicates interpretation based solely on lumen-side observations. Local anatomical variability, such as differences in the number of aspirated pits per unit area depending on the position within the growth ring, may also influence the observed appearance of aspirated pit membranes, including local rupture or removal. Under these considerations, the SEM observations suggest that in sugi, the aspirated pit membrane locally became permeable in the water-hammer-treated specimen.

The effect of the water-hammer impacts on tyloses of hardwoods was also examined. In the water-hammer-treated specimens, rupture of tyloses was observed even in the inner region in kiri (Fig. 6a, b, d, e), whereas only removal of tyloses near the transverse surface was observed in ulin (Fig. S2). Figures 6a, b, d, and e show representative SEM micrographs of vessels on the radial section located approximately 20 mm inward from the transverse surface along the L direction for kiri specimens. In the control specimens (Fig. 6a, b),

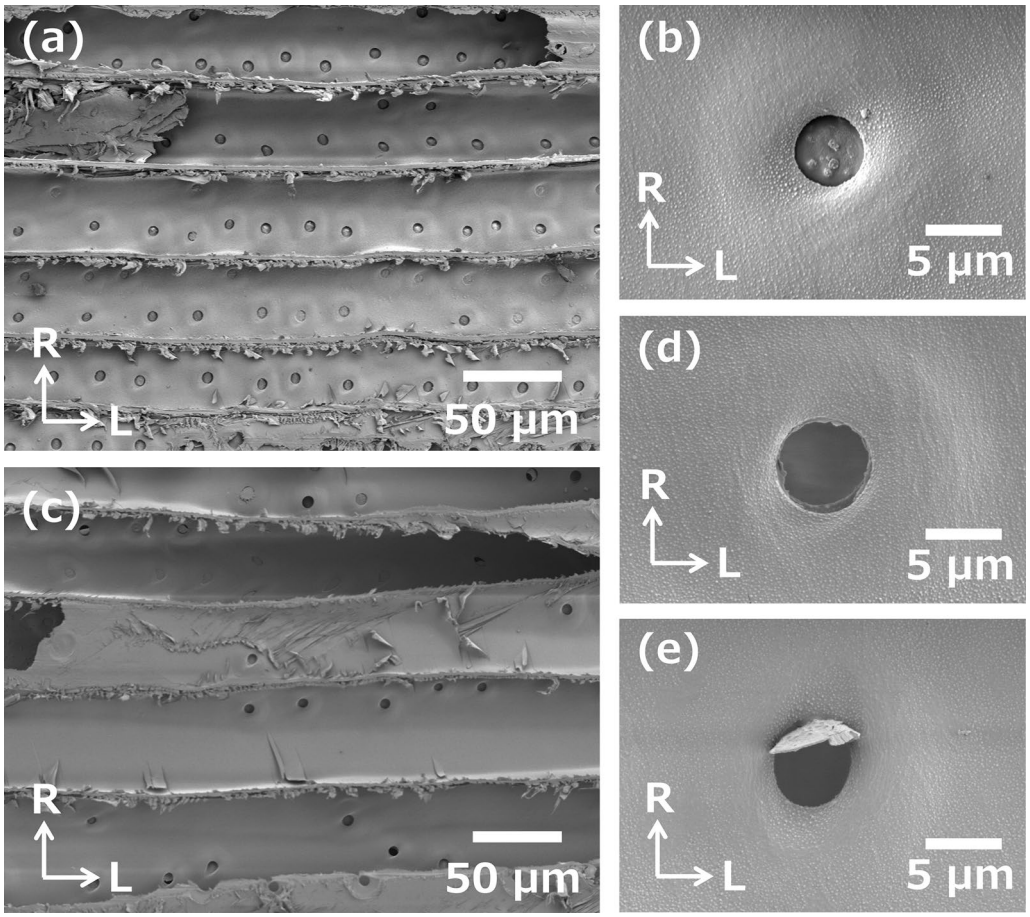


Fig. 5 SEM images of radial section of sugi with control and water-hammer treatments. **a**, **b** Control specimens showing aspirated pits. **c**–**e** Water-hammer-treated specimens showing aspirated pits whose membrane was locally ruptured or removed. SEM images were acquired at accelerating voltages of 1.0 kV (**a**, **c**–**e**) and 1.5 kV (**b**)

the tyloses remained intact, whereas in the water-hammer-treated specimens (Fig. 6d, e), the tyloses were ruptured. These observations suggest that in kiri, tyloses were ruptured by the water-hammer impacts. In addition, the optical micrographs of the transverse surface of kiri (Fig. 6c, f) showed local structural damage not only in the tyloses but also in the surrounding parenchyma cells. These observations suggest that the surrounding parenchyma cells may also be damaged by the water-hammer impacts. However, it should be noted that "collapse" in this study was evaluated based on macroscopic dimensional changes (maximum volumetric swelling, β_m). Local damage of the anatomical structures observed at the cellular level does not necessarily result in statistically detectable macroscopic collapse.

In sugi and kiri, where damage to aspirated pits and tyloses was observed (Figs. 5 and 6), the promoting effect of the water-hammer impacts on liquid permeation was also high (Fig. 3). Accordingly, the promotion of liquid permeation by the water-hammer treatment was closely associated with damage to aspirated pits and tyloses. In ulin (Fig. S2), tyloses near the transverse surface were removed by the water-hammer impacts, and liquid permeation (Fig. 3a) was likely promoted only in the region close to the transverse surface, where the tyloses were removed. In the softwood species in which rupture or removal of the aspirated pit membrane was not observed, no traces of damage to the tracheid cell walls were found. However, as shown in Fig. 3a, b, liquid permeation was promoted by the water-hammer impacts in these species. These findings suggest that some aspirated pits became permeable during the treatment, although no obvious structural change was detected by SEM.

Effect of hammering conditions

The effect of the number of water-hammer impacts on liquid permeation of sugi and kiri specimens is shown in

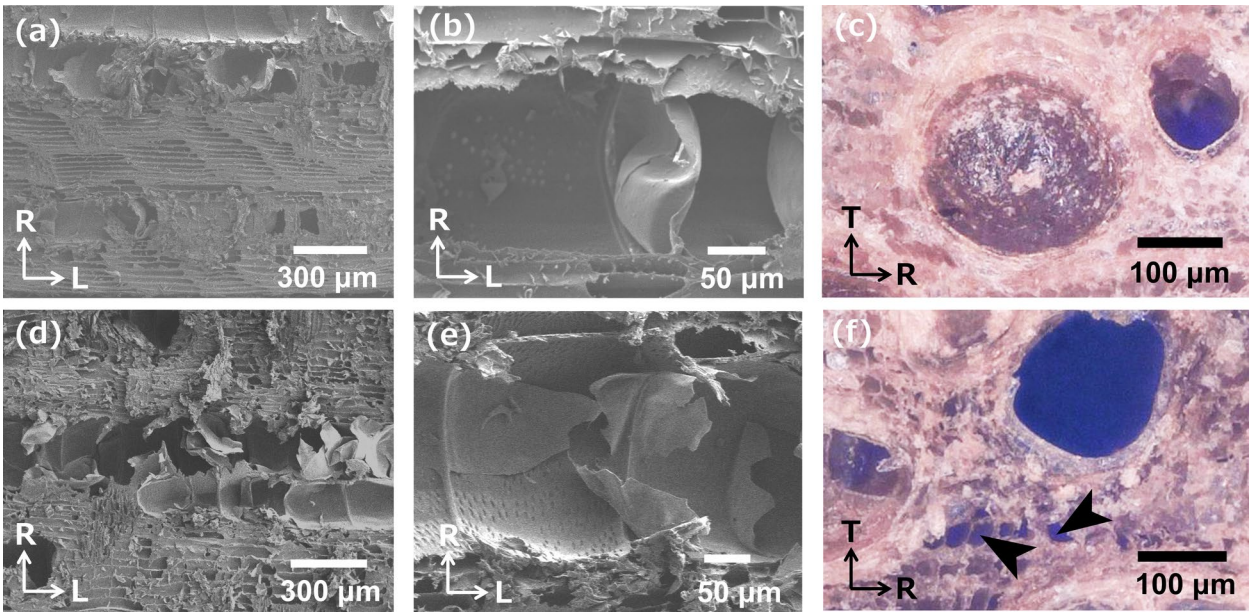


Fig. 6 SEM and optical images of radial sections and transverse surfaces, respectively, of kiri with control and water-hammer treatments. **a**–**c** Control specimens showing tyloses closing the vessel lumina and intact parenchyma cell walls. **d–f** Water-hammer-treated specimens showing ruptures of tyloses and parenchyma cell walls. Arrows indicate ruptured parenchyma cell walls. SEM images (**a**, **b**, **d**, **e**) were acquired at an accelerating voltage of 5.0 kV, while (**c**, **f**) are optical micrographs

Fig. 7a, b, respectively. In sugi (Fig. 7a), liquid permeation was markedly promoted by 90 impacts compared with the control. However, increasing the number of impacts to 450 and 1800 showed almost no further increase in liquid permeation. These results suggest that in sugi, the promoting effect of the water-hammer impacts on liquid permeation reached a saturation tendency by 90 impacts at least. In contrast, in kiri (Fig. 7b), the distribution of the plots shifted upward with an increasing number of water-hammer impacts, indicating a progressive increase in liquid permeation. Therefore, in kiri, liquid permeation tended to increase as the number of water-hammer impacts increased.

These results indicate that the region affected by the water-hammer impacts extended farther into the interior in kiri than in sugi. This indication was supported by the staining results shown in Fig. S3, which showed that the affected region in kiri extended farther from the transverse surface into wood. Furthermore, this interpretation is consistent with the SEM observations showing that penetration of aspirated pit membranes in sugi (Fig. 5c–e) occurred only near the transverse surface, whereas rupture of vessels in kiri (Fig. 6d, e) was observed at locations farther from the transverse surface.

Mechanistic interpretation

This section discusses the reason why liquid permeation extended farther into the interior in kiri than in sugi under the water-hammer treatment. This difference can be interpreted in terms of distinct structural responses of aspirated pits and tyloses to the water-hammer treatment.

In sugi, the aspirated pit membranes may be ruptured or removed by the water-hammer impacts, whereas the cell walls appear to retain their structure. In such a condition, even if the first aspirated pit membrane is removed, the subsequent water-hammer impact is attenuated by the cell walls, and only a weaker influence of the impact is expected to reach the next pit. As the impact propagation proceeds further into the interior, the number of cell walls that the impact must pass through increases, resulting in greater attenuation of the impact effects.

In contrast, in kiri, tyloses may be ruptured by the water-hammer impacts, thereby removing barriers along the liquid-permeation path. Therefore, after the first tylosis encountered along the liquid-permeation path is ruptured, the subsequent water-hammer impact is considered to act on the next tylosis along the same path with less attenuation compared with that in sugi. This situation is expected to continue in deeper regions. Moreover, as the number of water-hammer impacts increases, the probability of rupture of tyloses is

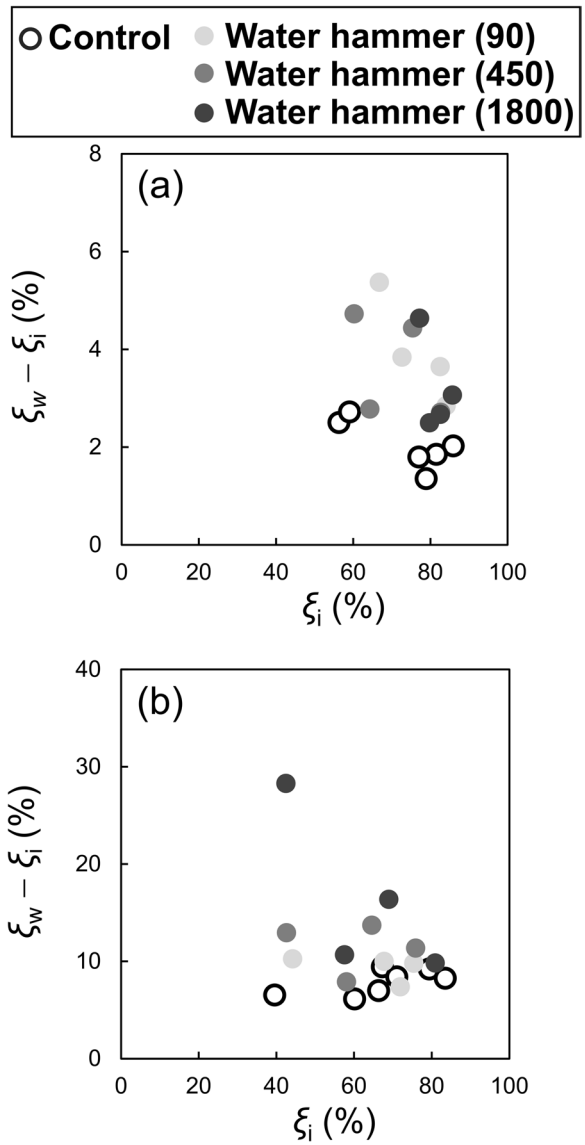


Fig. 7 Relationship between the initial cavity filling rate, ξ_i, and its variation, ξ_w–ξ_i, with control and water-hammer treatments for different numbers of impacts in (**a**) sugi and (**b**) kiri

expected to increase. A similar interpretation may also be applicable to situations in which parenchyma cells as well as tyloses are ruptured by the water-hammer impacts. Overall, in kiri, liquid permeation tends to extend farther into the interior with an increasing number of the impacts, resulting in a greater affected depth than that in sugi.

These considerations suggest that the farther extension of liquid permeation in kiri is related to the smaller attenuation of the effects of water-hammer treatment by the cell walls, compared with that in sugi. For practical application of this technique, it is important to reduce the attenuation of water-hammer impacts. It is also considered that increasing the maximum gauge pressure of the water-hammer impacts may further enhance the damage to robust aspirated pits. Possible approaches include developing an apparatus capable of generating stronger and more frequent water-hammer impacts or controlling the physical properties of cell walls to reduce attenuation.

Significance of using small wood specimens

The primary objective of this study was to clarify the effects of water-hammer impacts not only on liquid permeation but also on anatomical structures. The effects of the impacts are expected to appear locally, particularly at aspirated pits in softwoods and tyloses in hardwoods, rather than uniformly throughout a specimen. As specimen size increases, it becomes increasingly difficult to identify which structures were affected and to correlate localized anatomical changes with macroscopic liquid-permeation behavior. Accordingly, the use of small specimens facilitates anatomical observation and enables a clearer mechanistic interpretation of the effects of water-hammer impacts.

From a mechanistic viewpoint, the influence of specimen size should be interpreted in terms of the propagation behavior of water-hammer impacts. These impacts propagate primarily through liquid-filled cell lumina from the transverse surface into the interior along the L direction. In contrast, propagation perpendicular to the L direction is strongly attenuated by cell walls due to energy absorption and dissipation, which is consistent with the Sect. "Mechanistic interpretation" suggesting that cell walls in sugi may contribute to the attenuation of water-hammer impacts. Consequently, the effectiveness of water-hammer impacts is governed more by the specimen length in the L direction than by its transverse dimensions. This anisotropic propagation behavior supports the use of specimens with small cross-sectional dimensions for elucidating the underlying mechanisms.

The applicability of the present results to larger materials depends on the intended route of wood processing. For applications involving impregnation of wood chips followed by composite processing, such as wood flow forming (for example, [13]), the specimen scale used in this study is directly relevant. The specimen length in the L direction, 40 mm, was selected with reference to dimensions of commercially available wood chips. In contrast, application to lumber-scale materials would require enlargement of the apparatus and an increase in impact intensity to ensure sufficient permeation into the interior. The development of such systems remains an important subject for future study.

Conclusions

The effects and mechanism of liquid-permeation promotion in wood by the water-hammer impacts were clarified as follows:

1. The water-hammer impacts promoted liquid permeation for all wood species tested, and no significant degree of collapse was observed.
2. The degree of liquid-permeation promotion depended on the wood species.
3. Distinct anatomical changes were suggested only in the species that exhibited a high promotion effect: rupture of tyloses in kiri (*Paulownia tomentosa*) and local rupture or removal of aspirated pit membranes in sugi (*Cryptomeria japonica*).
4. The region affected by the water-hammer treatments extended farther into the interior in kiri than in sugi, because cell walls in sugi are considered to have acted as barriers to impact propagation even after removal of aspirated pit membranes, whereas fewer barriers remained in kiri after rupture of tyloses.

Abbreviations

FE-SEM	Field-emission scanning electron microscope
L	Longitudinal
R	Radial
RH	Relative humidity
SEM	Scanning electron microscopy
T	Tangential

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s10086-026-02263-y.

Supplementary Material 1.

Acknowledgements

Experiments were conducted at the Cellulosic Advanced Nanomaterials Development Organization (CAN-DO), a facility within the Research Institute for Sustainable Humanosphere (RISH), Kyoto University. We sincerely thank Mr. Akio Adachi (RISH, Kyoto University) for preparing the fine specimens, Mr. Akaeda and Mr. Matsui (Eidai Co., Ltd.) for providing a stable mechanism for rubber-hammer impacts, Mr. Yamanada and Mr. Hayashida (Hayashida Junpei Shoten Co., Ltd.) for providing the wood blocks of ulin, and Ms. Matsushima (Institute of Advanced Energy, Kyoto University) for assisting with the water-hammer experiment. We also thank Professor Emeritus Kanayama for his valuable advice. A brief summary of this work was published in the publicly available final research report for the 10th grant period of the Emachu Wood Promotion Foundation, without figures or detailed results.

Author contributions

ST: conceptualization, data curation, funding acquisition, investigation, visualization, and original draft preparation. ST and MS: methodology. ST, MS, and MA: review and editing of the manuscript. MS, MA, and TM: supervision. ST and TM: funding acquisition and project administration.

Funding

This work was partially supported by JSPS KAKENHI (Grant Numbers JP22K05764), Emachu Wood Promotion Foundation (10th grant period), and New Energy and Industrial Technology Development Organization (NEDO) [Project Number P14004].

Data availability

All data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors have read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Received: 15 November 2025 Accepted: 24 February 2026
Published online: 06 March 2026

References

1. Comstock GL, Côté WA (1968) Factors affecting permeability and pit aspiration in coniferous sapwood. Wood Sci Tschnol 2:279–291
2. Imamura Y, Harada H, Saiki H (1974) Embedding substances of pit membranes in softwood tracheids and their degradation by enzymes. Wood Sci Technol 8:243–254
3. Durmaz S, Yildiz UC, Yildiz S (2015) Alkaline enzyme treatment of spruce wood to increase permeability. BioResources 10:4403–4410
4. Iida I, Yusuf S, Watanabe U, Imamura Y (2002) Liquid penetration of precompressed wood VII: the combined treatment of precompression and extraction in hot water on the liquid penetration of wood. J Wood Sci 48:81–85
5. Amemiya S, Siriban FR (1968) Research on wood preserving treatment (II): effect of dipping with supersonic waves on the treatment of wood. Bull For & For Prod Res Inst 212:167–178
6. Nair HU, Simonsen J (1995) The pressure treatment of wood with sonic waves. Forest Prod J 45:59–64
7. Itoh S, Nagano S, Fujita M, Takano T, Honda R, Ikeda M (1998) The improvement of the permeability of wood by underwater shockwave. Metals and Mat 4:843–846
8. Siau JF (1984) Microscopic studies of flow in hardwoods. In: Transport processes in wood. Springer, Berlin, pp 61–63
9. Tanaka S, Seki M, Miki T, Umemura K, Kanayama K (2019) Influence of pulsive pressure waves on liquid penetration into wood in semi-opened container. J Wood Sci 65:54
10. The Japan Society of Mechanical Engineers (ed)(2006) Series α: 4 Fluid Engineering. In: JSME Mechanical Engineer's Handbooks, The Japan Society of Mechanical Engineers, Tokyo, pp 136–144
11. Tanaka S, Seki M, Abe M, Miki T (2025) Formulation of maximum weight percent gain of wood impregnated with resin considering cell wall swelling and resin concentration distribution: in the impregnation of six softwood species with phenol formaldehyde resin. J Wood Sci 71:3
12. Miyazaki M, Yasue M (1956) Studies on natural resins. I. On the isolation of palustric acid from oleoresin of *Pinus densiflora*. Mokuzai Gakkaishi 2:210–212
13. Sugino H, Tanaka S, Kasamatsu Y, Okubayashi S, Seki M, Miki T, Umemura K, Kanayama K (2021) Flow forming of wood irradiated with electron beam—molding load of irradiated wood and mechanical properties of the molded material. Bioresour 16:3895–3906

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.