論　文

# Dehydration to longitudinal direction of wood under centrifugal fields

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## Abstract

The centrifugal method was developed as a new method which evaluates the permeability of never-dried wood under the unsteady state. This method was designed to estimate the water permeability from the behavior of dehydration under various centrifugal fields and the water saturation ratio after centrifugal treatment. This centrifugal method is based on the concept that water movement occurs by the balance of centrifugal force and water potential by meniscus (capillary pressure). According to this concept, the water permeability is evaluated from the amount of dehydrated free water under the given centrifugal conditions. The relationship between the water saturation ratio (*SR*) after the centrifugal treatment and the measure of water potential ($\Psi$) in the specimen was expressed by a simple linear regression for all conditions. The results showed that Sugi had a larger variation of the water permeability than Douglas fir and was estimated to have a good water permeability than Douglas fir from the comparison of the slope of the regression line.

**key words** : permeability, free water, centrifugal method, water potential, dehydration

## Introduction

There have been many studies to estimate the permeability from not only practical aspects but also anatomical aspects. To study the wood permeability, we must consider the moisture condition of wood, whether it is wet or dry, and the movement of fluid in wood is in a steady or unsteady state.

There are a few studies evaluating the liquid flow through wood in never-dried conditions (Comstock 1965, Ohgoshi et al. 1978). They measured the steady flow under the constant pressure differential. The measurement under the steady state is useful to elucidate the factors which

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affect the permeability. However, the data from this method sometimes may not coincide with the unsteady flow accompanied by a change of water volume in wood. Therefore it may be important to understand a unsteady flow in case of considering about a practical wood processing such as drying.

We have tried to develop a new approach here, called the centrifugal method, to evaluate the permeability of never-dried wood under the unsteady state. The centrifugal method was originally developed by Hassler and Brunner (1945) for the determination of the capillary pressure in small consolidated core samples. Choong and Tesoro (1989) measured ultimate moisture content at varied centrifugal forces using short specimens in longitudinal direction and reported that the relationship between capillary pressure and moisture content was dependent on the permeability characteristics of each wood species. Park et al. (1999) estimated the size distribution of free water paths in the never-dried heartwood of softwoods using the centrifugal method.

In this study, we tried to express the water permeability using simple coefficient from the behavior of dehydration under various centrifugal fields and the water saturation ratio after centrifugal treatment.

## Basic concept

The centrifugal method is based on the concept that water movement occurs by the balance of centrifugal force and water potential by meniscus (capillary pressure). Free water will stop where the pressure differential is zero. In the centrifugal field, only two factors affect water movement in wood, that is, centrifugal force and water potential by meniscus.

Centrifugal force ($\Psi_f$), which is independent of wood structure and is determined only by experimental conditions, is calculated from Eq.(1).

$$\Psi_f = \frac{\rho_w}{2} l_m (2r_0 - l_m)\omega^2 \qquad (1)$$

where $\Psi_f$ is the pressure differential by the centrifugal force (Pa), $r_0$ is the distance from the rotational center to the dehydrated surface (m), $l_m$ is the arbitrary distance inward from the dehydrated surface (m) and $\omega$ is the angular velocity ($s^{-1}$, $2\pi n$, n : revolution per second).

Capillary pressure ($\Psi_c$), which is the pressure decreased by the curved surface of an air-water meniscus in wood, is calculated from Eq.(2).

$$\Psi_c = -\frac{2\gamma \cos\theta}{r} \qquad (2)$$

where $\Psi_c$ is the capillary pressure (Pa), $\gamma$ is the surface tension of water (N/m), $\theta$ is the contact angle, and $r$ is the radius of capillary (m). Here, the minus means that the pressure in the water is lower than the pressure at the reference point. The reference point is the dehydrated surface in this case. The absolute value of $\Psi_c$ shows the pressure differential between the water and ambient pressure.

If the water in the wood specimen is continuous, $\Psi_f$ becomes larger toward the rotational center. When $\Psi_f$ becomes larger than $\Psi_c$, free water moves from the original site to dehydrated surface. When $\Psi_f$ becomes equal to $\Psi_c$ in wood, the movement of free water stops. As the water saturation ratio after dehydration shows the degree of water movement, it can be considered to indicate the permeability of wood.

## Materials and Methods

Two green logs each of Sugi (*Cryptomeria japonica*) and Douglas fir (*Pseudotsuga menziesii*) were used in this study. Logs were cut into about 20cm long disks in order to take four end matched specimens of 5cm. Disks were split into several sticks with about $2\times 2cm^2$ cross section and 20cm long. These sticks were taken from sapwood and heartwood. Then each stick was cut into two short sticks with 10cm long. All the short sticks were saturated by an immersion in distilled water under alternating vacuum and atmospheric pressure. After the short sticks sank in the water, they were left to the immersion in distilled water more than a week to ensure complete saturation. After water saturation treatment was completed, the short stick was divided into two 5cm long specimens.

The distance from the rotational center to the dehydrated surface was 9.7cm. The rotational speed was selected at 5 level of 2200, 3000, 3300, 4800 and 6900rpm. End matched specimen were allocated to 5 levels of different rotational speed. The ambient temperature of the centrifugal treatment was maintained at 10℃.

Four samples were simultaneously treated for each run. Free water was dehydrated in the longitudinal direction. The time treated under the centrifugal fields was determined to the time until the weight of each sample become constant. The dehydration ratio of Sugi became nearly constant after 3 hours, but Douglas fir did not show a constant value even after 5 hours. However, the treatment was finished by 5 hours.

After the treatment, the samples were divided into 6 longitudinal section (four sections of 1cm thick and both end section of 0.5cm) at the lines drawn before. Each section was weighed immediately and was then re-saturated to obtain the maximum moisture content, $m_{max}$. After saturation, it was oven dried at 103±2℃.

## Water saturation ratio, *SR*

The water saturation ratio of each section was obtained as follows ;

$$SR_i = \frac{\text{Liquid Volum}}{\text{Void Volum}} = \frac{m_i - FSP}{m_{imax} - FSP} = \frac{\dfrac{W_i - W_{io}}{W_{io}} \times 100 - 28}{\dfrac{W_{imax} - W_{io}}{W_{io}} \times 100 - 28} \qquad (3)$$

where $W_{imax}$, $W_i$ and $W_{io}$ are the weight of a small section at water saturation, after centrifugal treatment and at oven dried. The value of 28% means the fiber saturation point(FSP).

As the specimen was cut into 6 small sections to obtain the distribution of water saturation ratio, the process of dehydration for each specimen could be not obtained directly. The oven dried weight, $W_o$, of the original specimen was estimated at first by the following equation ;

$$W_o = \frac{W_{cf}}{1 + \frac{MC_{ave}}{100}} \tag{4}$$

Where, $MC_{ave}$ was calculated as the following equation ;

$$MC_{ave} = \frac{\sum W_i - \sum W_{io}}{\sum W_{io}} \times 100 \tag{5}$$

$W_{cf}$ is the weight of the specimen before cutting it into 6 small sections. The water saturation ratio at each stage was calculated using this $W_o$.

## Results and Discussion

Figure 1 shows the process curves of *SR* for heartwood of Sugi and Douglas fir. Sugi was dehydrated more than Douglas fir for all rotational speeds. The difference in the amount of dehydration under the centrifugal field indicates the difference of water permeability in an unsteady state. The decrease of the *SR* of Sugi almost stopped after 3 hours for all conditions of rotational speed, but that of Douglas fir did not stop even after 5 hours.

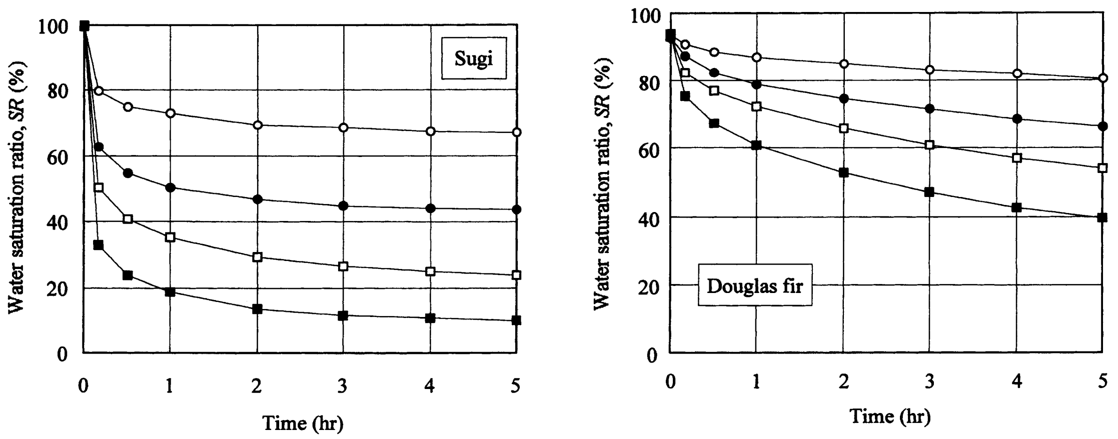


**Figure 1. The progress of dehydration for Sugi and Douglas fir heartwood under various rotational speed. Open circles : 2200rpm, Filled circles : 3300rpm, Open squares : 4800rpm, Filled squares : 6900rpm.**

Figure 2 shows the relationship between the *SR* reached after 5 hours and the rotational speed. The *SR* decreased with the increment of the rotational speed. The decrease rate of the *SR* with the rotational speed depended on the species and the rate for Sugi was greater than that for Douglas fir.

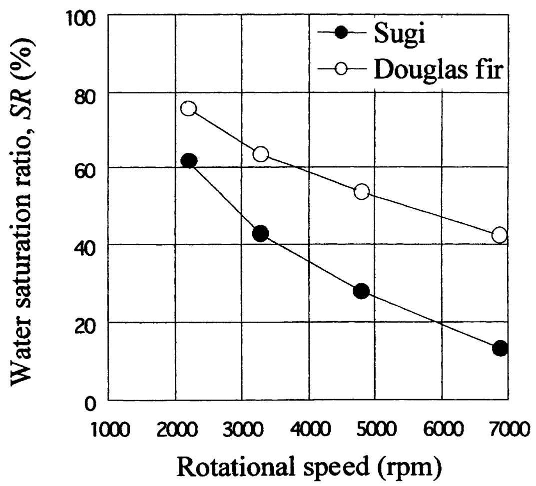


**Figure 2. Relationship between the water saturation, *SR*, after 5 hours, and the rotational speed for Sugi and Douglas fir heartwood.**

Figure 3 shows the difference of the dehydration progress for sapwood and heartwood of Sugi. The dehydration of heartwood was easier than that of sapwood under centrifugal fields of 2200 and 3300rpm. Whereas the opposite results were obtained for 4800 and 6900rpm. That is, free water in sapwood was dehydrated more easily than that in heartwood. Moreover, it was clear that the *SR* in sapwood became constant more quickly than that in heartwood.

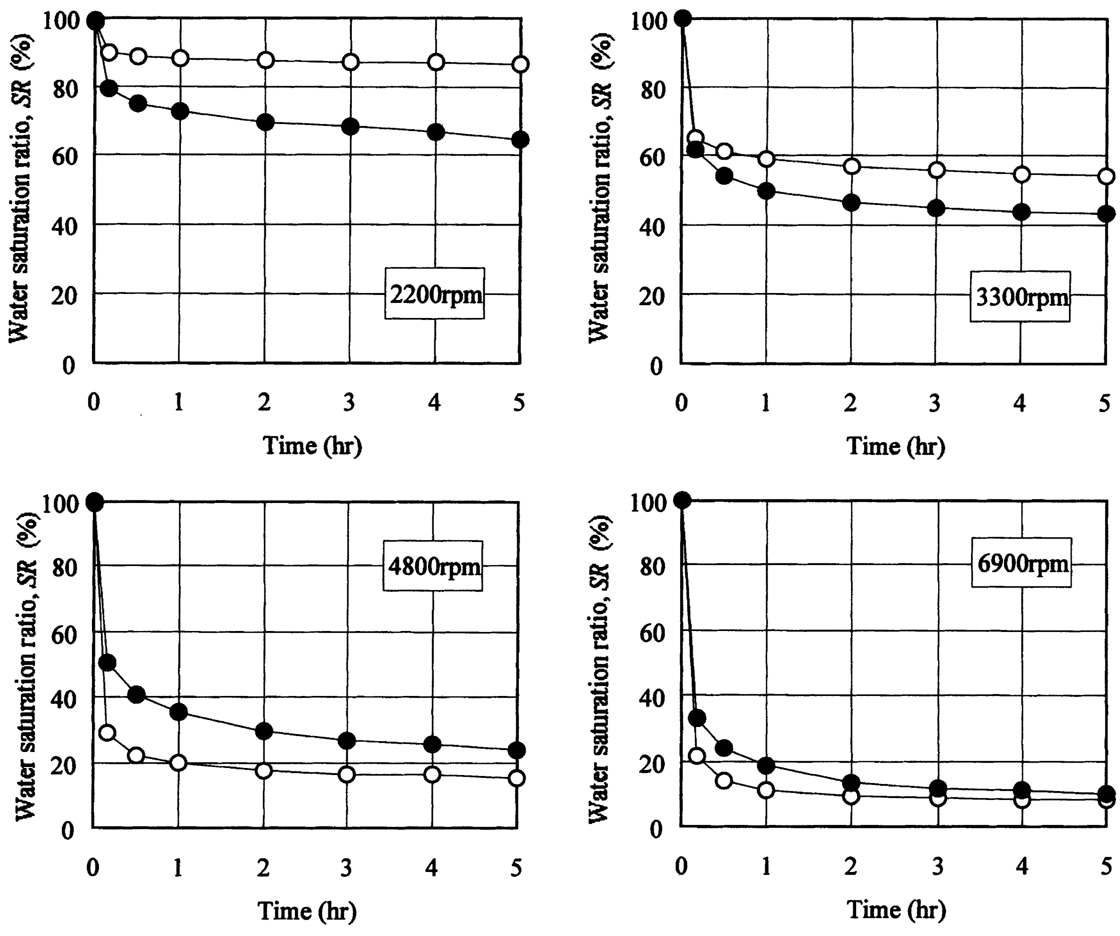


**Figure 3. The progress of dehydration for sapwood and heartwood of Sugi under various rotational speeds. Open circles : sapwood, Filled circles : heartwood.**

Figure 4 shows the behavior of dehydration for sapwood and heartwood of Douglas fir. Douglas fir showed quite different patterns compared with Sugi. Sapwood was more permeable than heartwood for all of the centrifugal fields. The decrease rate did not become zero in 5 hours for either sapwood and heartwood.

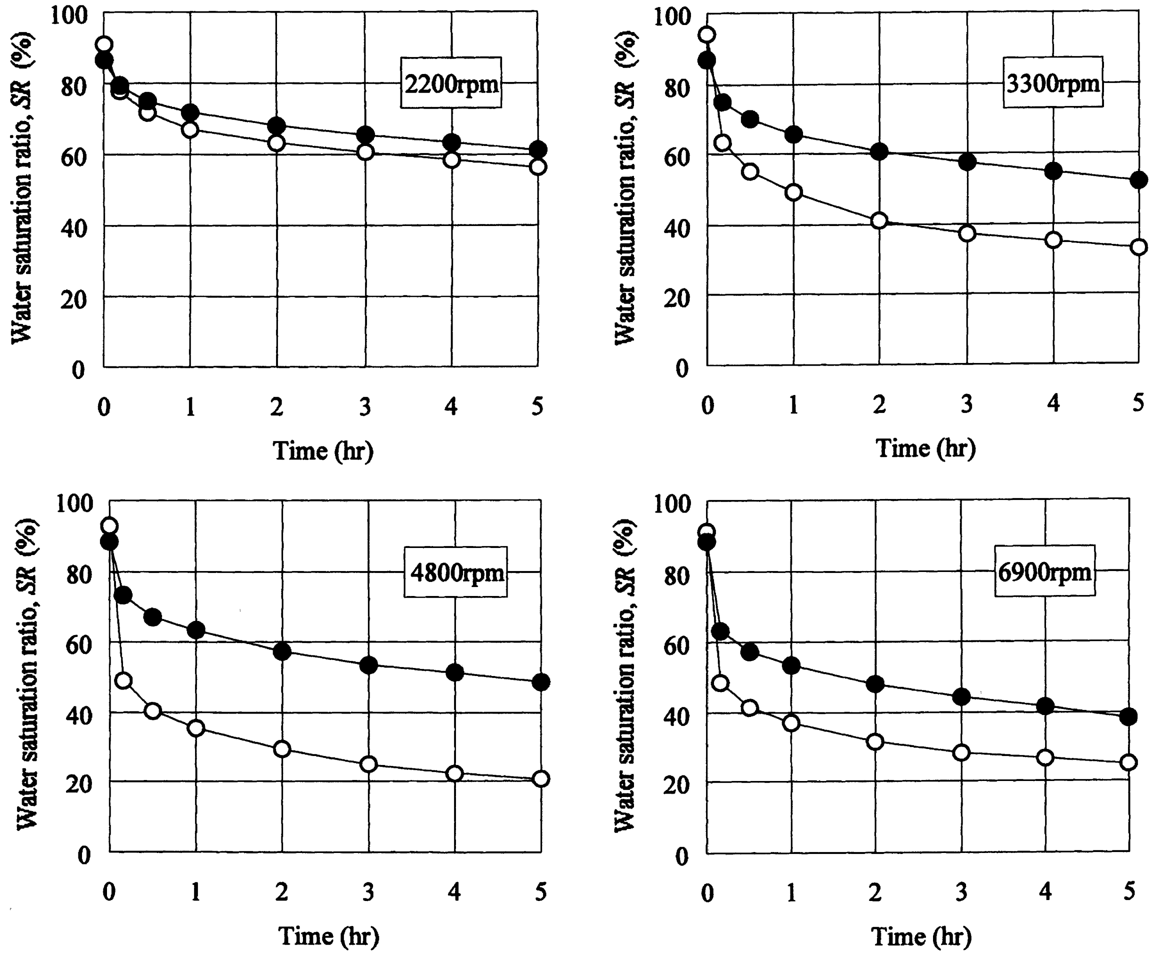


**Figure 4. The progress of dehydration for sapwood and heartwood of Douglas fir under various rotational speeds. Open circles : sapwood, Filled circles : heartwood.**

Sapwood is known to be much more permeable than heartwood (Wardrop and Davies 1961, Krahmer and Côté 1963, Hayashi et al. 1966). However, the water permeability in Sugi sapwood in the unsteady flow such as dehydration under centrifugal field was estimated to be lower than that in heartwood when the rotational speed was 2200 and 3300rpm.

The torus are aspirated to the pit aperture by the capillary tension produced during drying or heartwood formation. It is well-known that the pit aspiration causes the decrease of permeability (Phillips 1933 ; Hart and Thomas 1967 ; Comstock and Côté 1968). Therefore, there is a possibility that the pit membranes in sapwood are moved from a original position in the pit chamber to the pit border by applied centrifugal force and the pit aperture is covered by torus. This is the reason why the sapwood in sugi showed the lower permeability than heartwood.

On the contrary, at the elevated rotational speed of 4800 and 6900rpm, the water permeability in sapwood was more permeable than that in heartwood. In regard to this phenomenon, we would like to propose a new idea by which the pit membrane is ruptured by the produced water potential at the meniscus with a small radius.

When the applied centrifugal force is equal to capillary tension (water potential) produced at the meniscus in wood, the movement of free water stops and *SR* will theoretically maintain a constant value. However neither sapwood or heartwood of Douglas fir showed constant values and continued slight dehydration up to 5 hours under all centrifugal fields. Also, the SR of Douglas fir did not become 100% in both sapwood and heartwood at the water saturation treatment. The reason why these phenomenon happen is not clear at present.

Figure 5 shows the variation of water permeability within trees for heartwood of Sugi and Douglas fir. These data were obtained under the rotational speed of 3000rpm and each value was an average of 8 specimens. Although variation within trees existed in both species, Douglas fir showed less variation than Sugi in both tangential and radial directions. This indicates that Sugi has a large variation of liquid permeability in the wood.

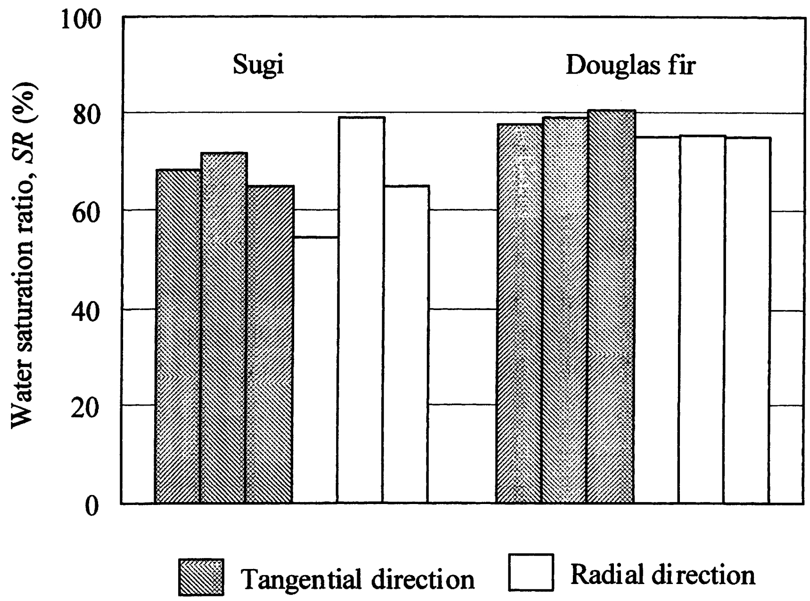


**Figure 5. The *SR* within logs of Sugi and Douglas fir under a constant centrifugal field. Rotational speed : 3000rpm, Rotational radius : 9.7cm. Each value is an average of 8 specimens.**

Figure 6 shows the *SR* of each section after 5 hours. The *SR* of both end-sections No.1 and 6 were not measured, because they contained many incomplete tracheids. Sections near the rotational center always had a lower *SR* than those near the dehydration surface. This means that the closer a position gets to the rotational center, the lower the *SR* becomes. This tendency coincides with the centrifugal force as known in Eq. (1). However, the shapes of the curves are different.

If water movement stops, the centrifugal force equals the water potential produced at a meniscus. As the specimen used was long comparatively, the range of the water potential in a

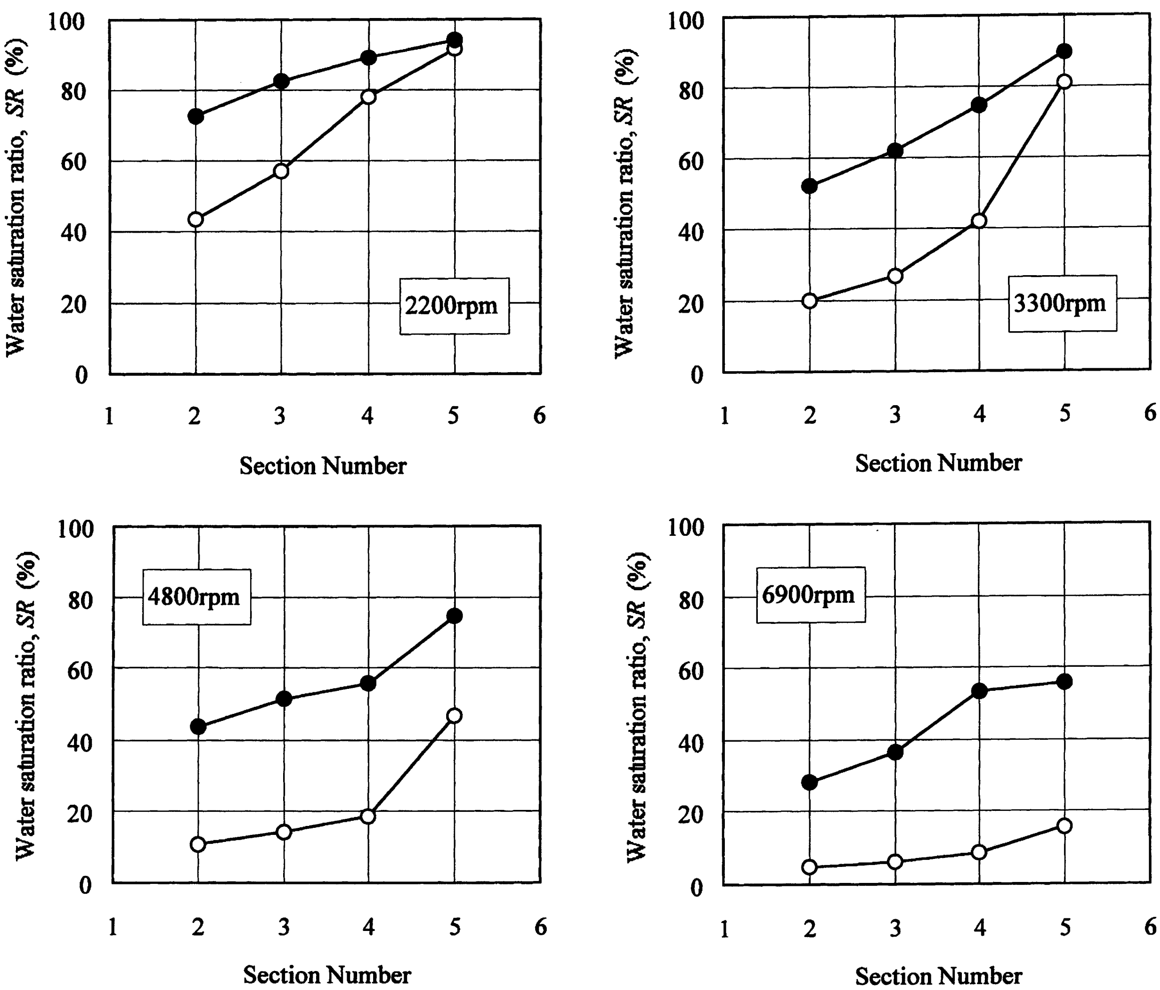


**Figure 6.** The distribution of the water saturation ratio, SR, in each specimen after various centrifugal treatment. The small number of X-axis represents the section near the center of rotation. Open circles : Sugi, Filled circles : Douglas fir.

specimen can be overlapped using another specimen treated by a different rotational speed.

Figure 7 shows the relationship between the water saturation ratio and the water potential of each section for two species. The master curve between the water saturation ratio ($SR$) in a small section after centrifugal treatment and the measure of water potential ($\Psi$) in a specimen was expressed by the following equation ;

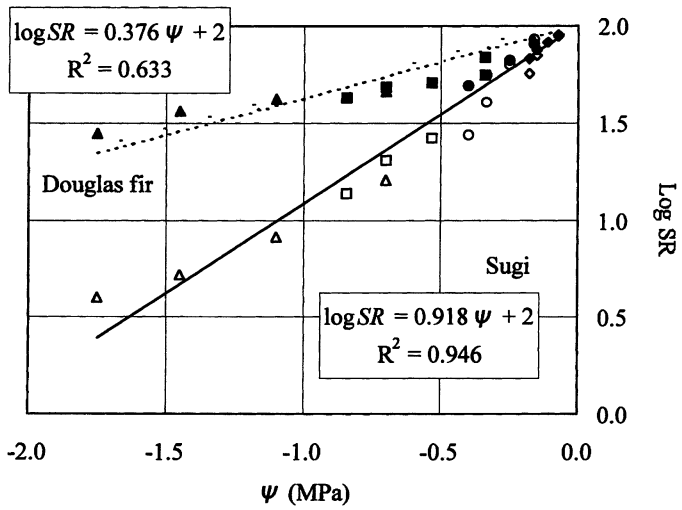


**Figure 7.** Relationship between water potential ($\Psi$) and the logarithm of water saturation ratio (log $SR$) for Sugi and Douglas fir. Diamonds : 2200rpm, Circles : 3300rpm, Squares : 4800rpm, Triangles : 6900rpm.

$$\text{Log}_{10} SR = \alpha \Psi + 2 \quad (6)$$

where the range of $\Psi$ was from 0 to -2 in this study. $\Psi$ was calculated at the center of each section. If $\Psi$ equals zero, $\text{Log}_{10}\ SR$ is 2, that is, $SR$ equals 100. Coefficient " $\alpha$ " is the slope of the master curve and it seems to show the degree of liquid permeability under an unsteady state. It was clear that the liquid permeability of Sugi was larger than that of Douglas fir from the comparison of " $\alpha$ ".

## Conclusion

In this study, we tried a new approach to evaluate the water permeability of never-dried wood from the behavior of dehydration under the applied centrifugal fields. Following results were obtained ;

(1) Water permeability of Sugi was larger than that of Douglas fir.

(2) From the comparison of dehydration behavior of free water between sapwood and heartwood of sugi, pit aspiration and pit aperture were predicted by the water potential caused under the centrifugal fields.

(3) There were a variety in water permeability even within the same wood. The degree was larger in Sugi than in Douglous fir.

(4) The master curves were obtained for the relationship between the water saturation ratio ($SR$) after the centrifugal treatment and the measure of water potential ($\Psi$) calculated by the treated condition. The regression curve was expressed by the following simple equation ; $\text{Log}_{10}\ SR = \alpha\Psi + 2$. Here, " $\alpha$ " is expected as an indicator of the water permeability.

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