Quantitative Study on the Moisture Properties of Japanese Cedar-Estimation of Moisture Permeability Using the Cup Method

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Abstract: Wood is a common porous material used in building interiors. It is therefore expected to adjust water vapor levels in indoor spaces. To examine humidity adjustment by wood, it is necessary to measure its moisture permeability, and to quantify humidity adjustment by wood, the accurate measurement of moisture properties is critical. This paper focuses on the measurement of the moisture permeability (λ') of wood (Cryptomeria japonica). First, the measurement theory of the cup method and the error estimation method are described. Then, the moisture-permeability measurement results for the wood are presented. In the cup method, removal of the permeation resistance of the cup (R'_{cup}) was important to estimate the λ' of the materials. In particular, in the material with low moisture-permeation resistance (e.g. wood shaving), the effect of adding the R'_{cup} was significant. The relationship between average relative humidity(H) and the moisture permeability was experimented. The results of the linear approximation are: Moisture permeability of board: $\lambda'_{board} = 10^{-6} \cdot e^{0.0398H}$ [kg/(m·s·Pa)], Moisture permeability of the wood shavings: $\lambda'_{wood\ shavings} = 9.88 \cdot 10^{-6}H + 1.20 \cdot 10^{-4}$ [kg/(m·s·Pa)]. The moisture permeability of wood shavings of cedar was about 10 times that of the cedar board. It is therefore confirmed that moisture permeability can be increased by changing the shape of a wooden material.

Keywords: Permeability, Cup Method, Cryptomeria Japonica, Board, Wood Shaving

1. Introduction

Wood is a common porous material used in building interiors. It is therefore expected to adjust water vapor levels in indoor spaces [1-3]. However, since the moisture permeability of the board is small, only the surface contributes to the humidity adjustment with respect to the daily fluctuation of the water vapor in the room. It is expected that if the wood is processed into wood shaving, the moisture permeability will be high and the humidity adjustment ability of the wall will be improved. Fukuta [4, 5] developed a method for manufacturing mats from a mixture of wood shavings and kenaf fibers and reported their mechanical, sound absorption, and fireproofing properties. Nakaya [6] measured thermal properties of planar waste mats, and found thermal conductivity and specific heat. However, the moisture property of the wood shaving mat is not measured. To examine humidity adjustment by wood, it is

necessary to measure its moisture permeability and capacity, and to quantify humidity adjustment by wood, the accurate measurement of moisture properties is critical.

Moisture permeability affects the amount of water vapor movement. The moisture flux is obtained by multiplying the moisture permeability rate and the water-vapor pressure gradient. To estimate the moisture permeability rate, the cup method has been widely adopted [7-14]. The amount of moving water vapor cannot be directly measured. Therefore, the amount of transferred water vapor adsorbed by a saturated salt solution, a desiccant, water, or similar is measured. The moisture permeability is thus indirectly estimated by measuring the weight of the adsorbent. However, measurement of the moisture permeability rate by the cup method has been reported to have large measurement errors [15]. Vololonirina [14] was examined on the cup method by the theory of water vapor movement. The estimation of the moisture permeability by the cup method

showed that the inside and outside boundaries of the cup influenced the moisture permeable resistance of the material. Richter [16] examined the vapor tightness and materials of a moisture - permeable cup. As a result, it showed that it influences the estimated value of the moisture permeability. Osawa [15] reported that the measured value determined by the cup method is the moisture-permeation resistance, which is the sum of the moisture-permeation resistance of the specimen and the moisture-permeation resistance of the moisture-permeable cup itself. The moisture-permeation resistance of the cup is influenced by multiple factors such as the change in the concentration of the salt solution in addition to the moisture-transmission resistance of the surface of the specimen. Fiber materials, such as wood shavings, have low moisture permeability resistances. Therefore, estimation of the moisture-permeation resistance of the cup in cup-method measurements is important for improving the measurement accuracy of the moisture permeability.

This report details a study of the measurement of the moisture permeability of cedar wood. First, the measurement theory of the cup method and the error estimation method are described. Then, the moisture-permeability measurement results for the wood are presented, and finally, a short summary of the study is given.

2. Method

2.1. Definition of Moisture Permeability

Moisture permeability is a physical property that describes moisture transfer in a porous material [17]. The amount of moving water vapor is proportional to area A, time Δt, and moisture flux q' as follows:

$$\Delta W = A \cdot \Delta t \cdot q' = A \cdot \Delta t \cdot \lambda' \frac{\Delta f}{\Delta x}, \quad (1)$$

$$\lambda' = \frac{\Delta W}{\left(A \cdot \Delta t \cdot \frac{\Delta f}{\Delta x}\right)}. \quad (2)$$

Moisture permeability λ' is an index representing the amount of moisture moving per unit area, unit time, and unit water-vapor pressure gradient. By rearranging these two expressions, the units of moisture permeability can be obtained:

$$\frac{kg}{m^2 \cdot s \cdot \frac{Pa}{m}} = \frac{kg}{m \cdot s \cdot Pa}. \quad (3)$$

The unit of the moisture permeability is therefore $kg/(m \cdot s \cdot Pa)$ [9].

2.2. Estimating Moisture Permeability

2.2.1. Cup Method

In the cup method, a water vapor pressure gradient is applied to the specimen allow the absorption of water vapor by a saturated salt solution inside the cup. If the moisture flux is in a steady state, the moisture flux from outside the cup is equal to the moisture flux through the specimen. Because the increased amount in the cup is equal to the amount of water

vapor that has moved, the entire moisture-permeation resistance of the cup can be estimated.

However, the moisture-permeation resistance estimated by the cup method includes the moisture-permeation resistance of the cup in addition to that of the material. By estimating the moisture-permeation resistance of the cup and subtracting it from the value of the moisture-permeation resistance measured by the cup method, the moisture-permeation resistance of the material can be estimated. The experimental apparatus is shown in Figure 1. In the experiment, desiccators were placed in a thermostatic chamber and the temperature was controlled at 23°C. The experimental apparatus, consisting of a moisture-permeable cup, a saturated salt solution for moisture release, and a stirring fan, was placed inside a desiccator. Figure 2 shows a moisture-permeable cup.
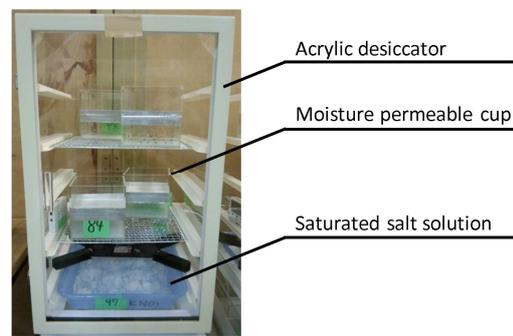

Figure 1. *Experimental device.*

Figure 2. *Specimens.*

The moisture-permeable cup was shaped into a box from

an acrylic plate (thickness 3 mm). The specimens is cedar (Cryptomeria japonica); two samples were prepared and experimented, both a board and shavings of the wood. Because the core-sheath fiber material is known to absorb less water, it was neglected from the examination. The average density of the air-dried board was 0.368 g/cm^3; and its size is 100 mm × 100 mm × 10 mm. The side of the board was humidified with aluminum tape. The average density of the air-dried shavings was 0.053 g/cm^3. The shavings were made to fill a moisture-permeable cup. The size of the specimen for the shavings was adjusted to 100 mm × 100 mm × 25 mm.

In order to investigate the influence of the humidity range, an arbitrary water-vapor pressure difference was used for the experiment, given by the saturated salt solution method rather than the dry (JIS) or wet (ISO) methods. The use of these latter two methods can avoid the problem of measurement error due to a saturated salt solution as described later; however, it is doubtful whether experiments with extremely high water-vapor pressure differences on both sides of the specimen can reproduce actual humidity environments. The moisture permeability differs depending on the humidity range to which the specimen is exposed. It is important to make measurements at each humidity when considering water-vapor regulation in the mid-humidity range and suppression of dew condensation in the high-humidity range.

Six salts were adopted [17]: LiCl (11%), MgCl$_2$ (33%), Mg(NO$_3$)$_2$ (53%), NaCl (75%), KCl (82%), and K$_2$SO$_4$ (97%). The salt was selected such that the moisture flux direction moved from the desiccator to the moisture-permeable cup. The outside of the moisture-permeable cup was set at a high humidity and the inside of the moisture-permeable cup was set at a low humidity, and water vapor was absorbed by a saturated salt solution inside the moisture-permeable cup.

2.2.2. Moisture-Transfer Resistance

Water-vapor transfer via the cup method is shown in Figure 3. The moving potential is the water-vapor pressure. Water vapor passes through the specimen from outside the moisture-permeable cup. Then, it is absorbed by the saturated salt solution inside the moisture-permeable cup.

The movement of water vapor in steady state conditions is shown by equations (4)–(9):

$$q'_1 = \alpha'_1(f_0 - f_1) \rightleftharpoons R'_1 \cdot q'_1 = f_0 - f_1 \qquad (4)$$

$$q'_s = \frac{\lambda'_s}{x_s}(f_1 - f_2) \rightleftharpoons R'_s \cdot q'_s = f_1 - f_2 \qquad (5)$$

$$q'_2 = \alpha'_2(f_2 - f_3) \rightleftharpoons R'_2 \cdot q'_2 = f_2 - f_3 \qquad (6)$$

$$q'_3 = \frac{\lambda'_a}{x_a}(f_3 - f_4) \rightleftharpoons R'_3 \cdot q'_3 = f_3 - f_4 \qquad (7)$$

$$q'_4 = \alpha'_3(f_4 - f_5) \rightleftharpoons R'_4 \cdot q'_4 = f_4 - f_5 \qquad (8)$$

$$q'_5 = \frac{\lambda'_l}{x_l}(f_5 - f_6) \rightleftharpoons R'_5 \cdot q'_5 = f_5 - f_6 \qquad (9)$$
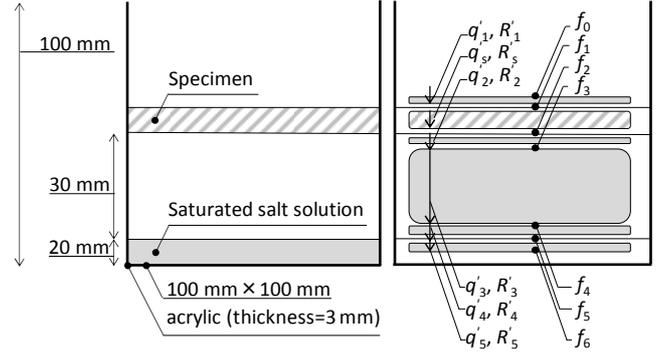
Figure 3. *Water vapor movement in each part of the cup.*

q'_1 is the moisture flux at the outer-surface boundary of the breathable cup, and R'_1 is the outer-surface moisture-transfer resistance. q'_s is the moisture flux diffusing inside the specimen, and R'_s is the moisture-permeation resistance of the specimen. q'_2 is the moisture flux at the surface boundary of the specimen inside the moisture-permeable cup, and R'_2 is the surface-moisture transmission resistance of the specimen inside the moisture-permeable cup. q'_3 is the moisture flux in the inner space of the moisture-permeable cup, and R'_3 is the moisture-permeation resistance of the air in the inner space. q'_4 is the moisture flux at the surface boundary of the saturated salt solution inside the moisture-permeable cup, and R'_4 is the surface-moisture transmission resistance of the saturated salt solution inside the moisture-permeable cup. q'_5 is the moisture flux from the surface of the saturated salt solution of the moisture-permeable cup to the center of the saturated salt solution, and R'_5 is the moisture-permeation resistance including various factors on the surface of the saturated salt solution.

At steady state, each moisture flux in equations (4)–(9) is identical, i.e. $q'_1 = q'_s = q'_2 = q'_3 = q'_4 = q'_5 = q'$. Because the moisture flux q' of equations (4)–(9) are identical, f_1 to f_4 may be eliminated and equation (10) is obtained:

$$(R'_1 + R'_s + R'_2 + R'_3 + R'_4 + R'_5)q' = (f_0 - f_6) \qquad (10)$$

The steady-state moisture flux may then be obtained by transforming equation (1) into equation (11):

$$\Delta W = A \cdot \Delta t \cdot q' \rightleftharpoons q' = \frac{1}{A} \cdot \frac{\Delta W}{\Delta t} \qquad (11)$$

The moisture flux q' is obtained by dividing the change in weight in the cup by the time duration of the change, and the surface area of the specimen. The sum of the moisture-permeation resistances of the cup and of the specimen was taken to be the total moisture-permeation resistance R'_{all}.

$$R'_{all} \cdot q' = (f_0 - f_5)$$

$$R'_{all} = \frac{1}{\left(\frac{\Delta W}{\Delta t}\right)} \cdot A \cdot (f_0 - f_5) \qquad (12)$$

In addition to the moisture-permeation resistance of the specimen R'_s, the total moisture permeation resistance

includes the moisture-permeation resistance of the cup R'_{cup}.

$$R'_{cup} = R'_1 + R'_2 + R'_3 + R'_4 + R'_5$$

$$R'_{all} = R'_{cup} + R'_s \rightleftharpoons R'_s = R'_{all} - R'_{cup} \qquad (13)$$

That is, when estimating the moisture-permeation resistance of a sample from the weight change of the moisture-permeable cup, the moisture-permeation resistance of the device is included. Therefore, the apparent moisture-permeation resistance of the specimen is larger than the actual value, and the moisture permeability is erroneously estimated with a small value.

In JIS, it is recommended to increase the wind speed on the outside air [7] of the moisture-permeable cup, and the intention is to reduce $R'_1 (= 1/\alpha'_1)$ by increasing α'_1. However, it is impossible to alleviate the moisture-permeation resistance $(R'_2 + R'_3 + R'_4 + R'_5)$ inside the breathable cup. In particular, the moisture-permeation resistance R'_5 related to the saturated salt solution changes the solution concentration on the surface of the saturated salt solution due to absorption of water vapor. The saturated water-vapor pressure on the surface of the saturated salt solution approaches the water-vapor pressure of water. Therefore, the saturated salt solution interface (f_5) inside the

moisture-permeable cup and the internal water-vapor pressure (f_4) of the moisture-permeable cup are higher than the saturated water-vapor pressure of the salt.

Osawa [9] proposed a method for removing the moisture-permeation resistance of the cup. A conceptual illustration of the removal method is shown (Figure 4). A material with low moisture-permeation resistance such as paper is attached to a moisture-permeable cup. For each moisture-permeable cup in which one sheet of Kent paper and two sheets are inserted, the change in the weight of the cup is measured. The water-vapor balance expression for each cup in the steady state is shown as equations (14) and (15):

$$\left(R'_{cup} + R'_{1\_paper}\right) = \frac{A}{\left(\frac{\Delta W_{1\_paper}}{\Delta t}\right)}(f_0 - f_5) \qquad (14)$$

$$\left(R'_{cup} + 2R'_{2\_paper}\right) = \frac{A}{\left(\frac{\Delta W_{2\_paper,(t)}}{\Delta t}\right)}(f_0 - f_5) \qquad (15)$$

where $\frac{\Delta W_{x\_paper,(t)}}{\Delta t}$ is the change in weight when x sheets of paper are inserted into the cup.
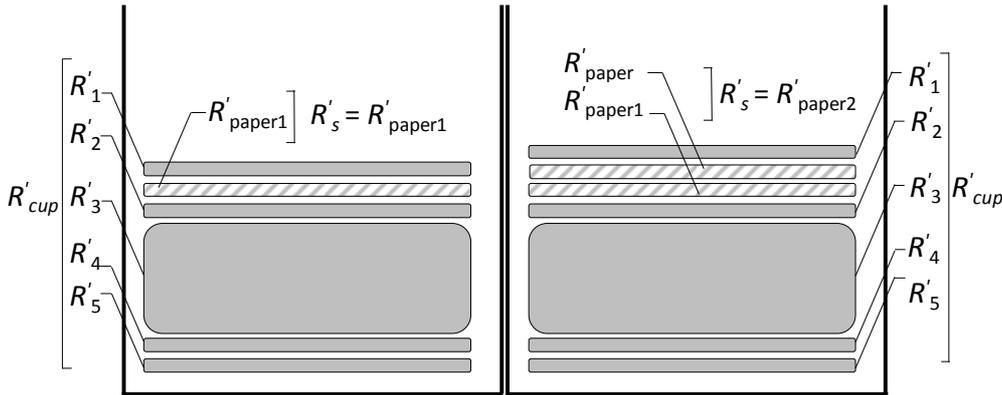

Figure 4. Method for removing the moisture-permeation resistance of the cup.

ΔW can be measured by changing the area and weight time, f_0 is the water-vapor pressure of the saturated salt solution outside the moisture-permeable cup, and f_5 is the water-vapor pressure of the saturated salt solution inside the moisture-permeable cup. By subtracting equation (14) from equation (15), the moisture-permeation resistance of the moisture-permeable cup R'_{cup} can be estimated as

$$R'_{cup} = \left[\frac{2}{\left(\frac{\Delta W_{1paper}}{\Delta t}\right)} - \frac{1}{\left(\frac{\Delta W_{2paper}}{\Delta t}\right)}\right] A(f_0 - f_5) \qquad (16)$$

In this study, the regression method was used to improve the estimation accuracy of R'_{cup} by increasing the number of specimens of the cup. In the regression method, 1 to x sheets of paper are installed in a moisture-permeable cup, and each R'_{x_paper} is obtained. Linear regression is then performed on the number of paper sheets and the moisture-permeation resistance, and the value corresponding

to zero sheets is obtained as the estimation of R'_{cup}.

2.2.3. Moisture Permeation

The moisture-permeation resistance (R'_s) of the specimens is estimated from equation (17) by subtracting R'_{cup} (equation (16)) from R'_{all} (equation (12)).

$$R'_s = R'_{all} - R'_{cup} = \frac{1}{\left(\frac{\Delta W_{all}}{\Delta t}\right)}A(f_0 - f_5) - R'_{cup}$$

$$R'_s = \left[\frac{1}{\left(\frac{\Delta W_{all}}{\Delta t}\right)} - \frac{2}{\left(\frac{\Delta W_{1paper}}{\Delta t}\right)} - \frac{1}{\left(\frac{\Delta W_{2paper}}{\Delta t}\right)}\right] \cdot A \cdot (f_0 - f_5) \qquad (17)$$

λ' is then obtained by dividing the thickness of the specimen (Δ) by R'_s:

$$\lambda' = \frac{\Delta x}{R'_s} \qquad (18)$$

3. Results

3.1. Moisture-Permeation Resistance of the Cup

R'_{cup} was estimated for the moisture-permeable cup in this experiment. For each relative humidity, four types of moisture-permeable cups were prepared, using from 1 to 4 sheets of paper in the cup. Figure 5 shows an example of the result (average relative humidity 64%). The number of paper sheets and the moisture-permeation resistance were linearly proportional to each other. R'_{cup} for each average relative humidity is shown (Figure 6); these values range from 66.2 to 104.0 (m^2·s·Pa)/kg.
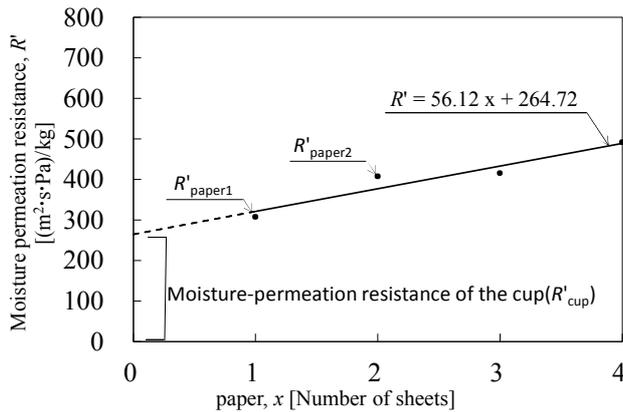
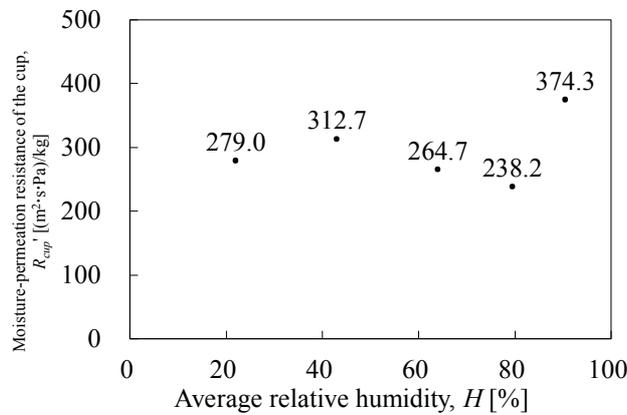*Figure 5. Relationship between paper and moisture permeation resistance.*

Figure 6. Relationship between paper and moisture permeation resistance of the cup.

3.2. Moisture Permeation Resistance of the Specimens

R'_{all} was calculated from the sample area and the weight change of the moisture-permeable cup. The total moisture permeation resistance was decomposed into R'_{cup} and R'_s. Figure 7 shows the moisture-permeation resistance of the board; R'_s of the board decreased as the average relative humidity increased. The moisture-permeation resistance was 2862 (m^2·s·Pa)/kg at an average relative humidity of 22%, and 185185 (m^2·s·Pa)/kg at 91%. The moisture-permeation resistance in the high-humidity region decreased to about 1/10 of that in the low-humidity region. If R'_{cup} is not removed from the total moisture-permeation resistance, since

R'_s is added to R'_{cup} in the measurement, an erroneously large estimation is made. When R'_s of the board was set to 100%, the moisture-permeation resistance was estimated to be 103% in the low-humidity range (22%) when R'_{cup} was not removed from the total moisture-permeation resistance value. This value increased to 111% in the mid-humidity region (64%) and 156% in the high-humidity region (91%); for the board, because R'_s decreases at high humidity, the relative effect of adding R'_{cup} is increased.
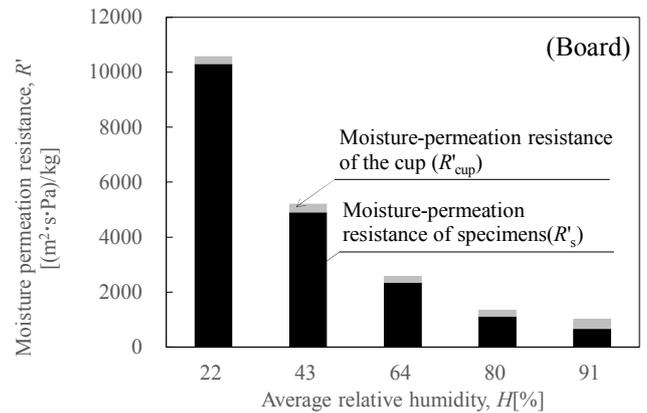
Figure 7. Relationship between average relative humidity and moisture permeation resistance in board.
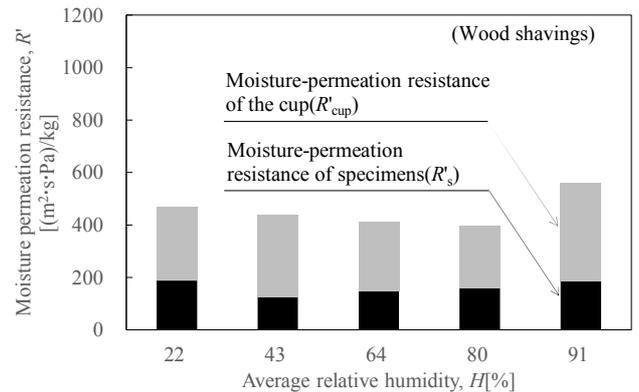
Figure 8. Relationship between paper and moisture permeation resistance in wood shavings.

Figure 8 shows the moisture permeation resistance of the wood shavings. The average relative humidity and the moisture-permeation resistance were uncorrelated, and the moisture permeation resistance ranged from 35 to 52 (m^2·s·Pa)/kg. When R'_s of the wood shaving was set to 100%, the moisture-permeation resistance was estimated to be 248% in the low-humidity range (22%) unless R'_{cup} was removed; the moisture permeation resistance was 280% in the mid-humidity region (64%) and 300% in the high-humidity region (91%). Fiber-based materials such as scraps have low moisture-permeation resistance, and hence, the measured values of this quantity for the shavings were strongly influenced by R'_{cup} such that the estimate is significantly higher than the real value of R'_s for the specimen. Therefore, removal of R'_{cup} in high-humidity

conditions or for the measurements of fibrous materials is an important experimental procedure for reducing errors.

3.3. Moisture Permeability

The moisture permeability was calculated by diding the thickness of the specimen by the moisture-permeation resistance. To examine the influence of R'_{cup}, the moisture permeability estimated without removing R'_{cup} from R'_{all}, as well as the moisture permeability after removal of R'_{cup}, were both calculated. Figure 9 shows the board, and Figure 10 shows the moisture permeability per average relative humidity of the shavings.

The average relative humidity and the moisture permeability in the board can be approximated by a negative exponential function.

Moisture permeability of board (moisture-permeation resistance of the cup removed)

$$\lambda'_{board} = 10^{-6} e^{0.0398H} (R^2 = 0.99)$$

Total moisture permeability of board (moisture permeation resistance of the cup not removed)

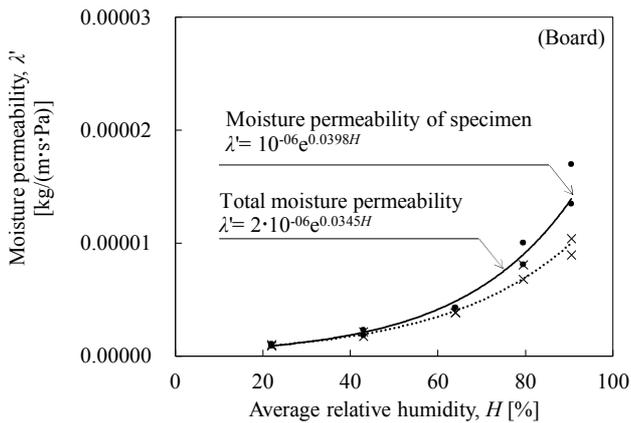$$\lambda'_{(cup+board)} = 2 \cdot 10^{-6} e^{0.0345H} (R^2 = 0.99)$$

Figure 9. *Relationship between average relative humidity and moisture permeability in board.*
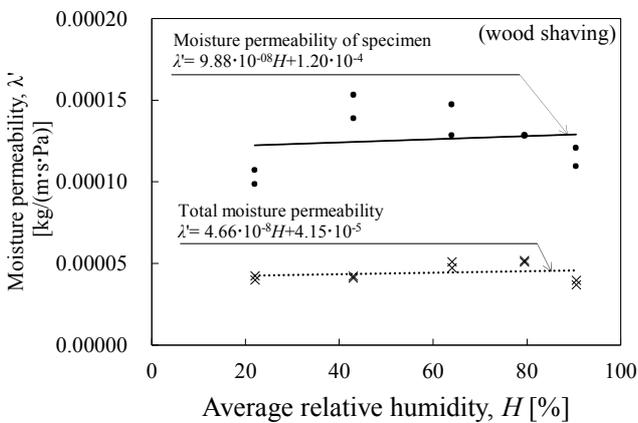

Figure 10. *Relationship between paper and moisture permeability in wood shavings.*

When the moisture-permeation resistance of the

moisture-permeable cup is removed, an erroneously low value for the moisture permeability rate was predicted, especially in the mid- and high-humidity ranges.

The relationship between the average relative humidity and the moisture permeability was uncorrelated for the wood shaving; the results of the linear approximation in these samples are:

Moisture permeability of the wood shavings (moisture-permeation resistance of the cup removed)

$$\lambda'_{wood\ shaving} = 9.88 \cdot 10^{-8} H + 1.20 \cdot 10^{-4} (R^2 = 0.02)$$

Total moisture permeability of the wood shavings (moisture permeation resistance of the cup not removed)

$$\lambda'_{(cup+wood\ shaving)} = 4.66 \cdot 10^{-8} H + 4.15 \cdot 10^{-5} (R^2 = 0.05)$$

When the moisture-permeation resistance of the moisture-permeable cup was not removed, the resulting moisture permeability rate of the material in the entire average relative humidity range was less than half of the actual value. The moisture permeability performance is erroneously estimated at less than the real performance of the specimen. For fibrous materials with low moisture-permeation resistances, this work to remove the moisture-permeation resistance of the moisture-permeable cup is important. The moisture permeability of wood shavings of cedar was about 10 times that of the cedar board. It is therefore confirmed that moisture permeability can be increased by changing the shape of a wooden material.

4. Conclusion

Moisture permeability was examined for wood (Cryptomeria japonica). The experiment method was the cup method, and the influences of material shape and humidity range were examined. From the water-vapor movement theory of the cup method, the effect of the moisture-permeation resistance of the moisture-permeable cup and a procedure for its removal were summarized. The following findings were obtained.

The moisture-permeation resistance of the moisture-permeable cup was added to that of the material in the experimental measurement of the total moisture-permeation resistance. This caused the estimation of erroneously high moisture-permeation resistances for the specimen. In particular, in a material with low moisture-permeation resistance, the effect of adding the moisture-permeation resistance of the cup was significant. Estimating the moisture-permeation resistance of the moisture-permeable cup for cup-method measurements is very important to avoid error in the estimation of the moisture-permeation resistance of specimens. The moisture-permeation resistance of the material was affected by material shape and humidity range. The moisture-permeation resistance of the board was influenced by relative humidity; it was large at low humidity and small at high humidity. By contrast, the moisture-permeation resistance of the wood

shavings was very little affected by relative humidity. An expression relating the moisture permeability and average humidity was obtained for each of the shapes of the cedar specimen.

$$\text{Board: } \lambda'_{\text{board}} = 10^{-6}e^{0.0398H}$$

Wood shavings: $\lambda'_{\text{wood shaving}} = 9.88 \cdot 10^{-8}H +$

Symbol

W	:	Weight	[g]
A	:	Area	[m^2]
q'	:	Moisture flux	[kg/(m^2·s)]
t	:	Time	[s]
f	:	Water vapor pressure	[Pa]
H	:	Relative humidity	[%]
x_s	:	Thickness of the specimen	[m]
x_l	:	Thickness of the surface adsorption layer in the saturated salt solution	[m]
x_a	:	Thickness of the air layer	[m]
R'_{all}	:	Total moisture permeation resistance	[(m^2·s·Pa)/kg]
R'_{cup}	:	Moisture-permeation resistance of the cup	[(m^2·s·Pa)/kg]
R'_s	:	Moisture-permeation resistance of the specimen	[(m^2·s·Pa)/kg]
R'_{paper}	:	Moisture-permeation resistance of the paper	[(m^2·s·Pa)/kg]
λ'_s	:	Moisture permeability of the specimen	[kg/(m·s·Pa)]
λ'_l	:	Moisture permeability near solution surface	[kg/(m·s·Pa)]
λ'_a	:	Moisture permeability of the air layer	[kg/(m·s·Pa)]

$1.20 \cdot 10^{-4}$ (H: Relative humidity [%])

Water vapor diffusion inside wood is determined by the relationship between moisture permeability and moisture capacity. In the next study, equilibrium moisture content will be measured and moisture capacity calculated, and the depth of penetration of indoor water-vapor fluctuations will then be examined.

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