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ORIGINAL ARTICLE

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Predicting the humidity control capacity of material based on a linear excitation–response relationship

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Abstract The *Cb* value is a useful parameter for estimating the humidity control capacity of materials. It is defined as the ratio of the range of variation of relative humidity in a steel box lined with the material of interest to that in an empty steel box, when sinusoidal temperature variation is applied. However, because it takes a long time to obtain the *Cb* values for materials at each temperature variation period, we developed an easier method based on a linear excitation–response theory to obtain the *Cb* values without measuring at each period. Japanese cedar was the material used in this study. The temperature excitation, a jump from a constant temperature to another constant temperature, was used to obtain the absolute humidity response. Under the assumption that the temperature excitation–humidity response relationship is linear, we were able to predict humidity variation to sinusoidal temperature variation at any period, and we obtained the *Cb* value for each temperature variation period. Predicted values agreed well with the experimental values. From this, it was found that the *Cb* value could be predicted without measuring the *Cb* value at each period over a long time. In addition, the peak time difference, which is closely related to the *Cb* value, could also be predicted in a similar manner.

Key words Humidity control capacity · *B* value · *Cb* value · Japanese cedar · Linear excitation–response theory

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Introduction

In a previous article,[1] we estimated the humidity control capability of materials in an airtight room using the *Cb* value. The *Cb* value is defined as the ratio of the range of variation of relative humidity in a steel box lined with material of interest to that in an empty steel box, when sinusoidal temperature variation is applied. The *Cb* value has a linear relationship with the *B* value by which we have so far estimated the humidity control capacity of materials.[2–5] It was effective to draw a *Cb* value contour map of the temperature variation period with the lined area for materials to establish an overall view of the humidity control capacity. However, it took at least 1 month to obtain *Cb* values because we had to measure each *Cb* value at each period and at each ratio of lined area *A* to the volume of steel box *V* (*A*/*V* value).

The aim of this study was to provide a method to predict the *Cb* value at each period by measuring the humidity change in a short period due to a jump in temperature from a constant temperature to another temperature, instead of measuring humidity variation at each period over a long time. In undertaking this task, the "peak time difference,"[1] which is closely related to the *Cb* value, is also predicted. The material used was Japanese cedar (sugi, *Cryptomeria japonica* D.Don.).

Materials and methods

Specimens

The material used in this study was 1-cm-thick flat-grain Japanese cedar conditioned at 25°C and 60% relative humidity for at least 1 week before testing commenced.

Measuring device

A steel box (a base of 20 × 20 cm and a height of 25 cm) lined with material was used for measurements. The box was sealed carefully to prevent air leakage before measurements. The A/V value was used to express the extent of the lined area. A/V values of 0.25, 0.5, 1.0, 1.5, 2.0, 2.5, and $3.0\,m^{-1}$ were adopted in our experiment.

Cb values

Temperature and relative humidity inside a steel box were measured over time in the climatic chamber in which temperatures varied sinusoidally around 25°C at four amplitudes of 2.5°, 5°, 7.5°, and 10°C, each of which had four wave periods of 6, 12, 24, and 48h. The *Cb* value is defined as the ratio of humidity amplitude in the steel box lined with material to that in the empty steel box. To predict the *Cb* value, we also measured the variation of relative and absolute humidity caused by a jump in temperature of 5°–20°C, centering around 25°C.

Results and discussion

As stated in our previous article,[1] we found that changing the rate of sinusoidal temperature variation over one period strongly affected the *Cb* value, although the amplitude did not. In addition to the *Cb* value, the difference between the time when peak temperature was reached and the time when peak absolute humidity was reached (peak time difference, Γ) was affected by the length of each period. The difference between the phase when peak temperature was reached and the phase when peak absolute humidity was reached (phase angle difference) was also affected by the length of each period. However, none of the variables was affected by the amplitude. The characteristics observed between sinusoidal temperature variation and the corresponding humidity seem similar to the relationship between sinusoidal strain and the corresponding stress variations in dynamic viscoelasticity, which is subjected to the linear excitation–response theory.[6] By this analogy, we could estimate the variation of humidity due to any temperature change from a simple temperature excitation–humidity response relationship.

We adopted, as an excitation, a temperature jump and observed a resulting humidity response. Figure 1 shows typical variation of both relative humidity and absolute humidity in a steel box lined with material in which $A/V = 1.0$, when the temperature jumped from 17.5°C to 32.5°C at around a time of 1400min. Corresponding to the jump in temperature, the relative humidity fell abruptly at 1400min, followed by a gradual increase toward the same level as it was initially. On the other hand, absolute humidity started to increase at 1400min and then stayed constant at around 1600min. Humidity curves similar in shape to these were observed when A/V values or the jump in temperature, centering on 25°C, were changed. In each case, the increase in both absolute humidity and relative humidity seemed proportional to the jump in temperature.

This article describes a method to obtain the relationship between sinusoidal temperature variation with any period and the corresponding humidity variation, on the basis of the relationship between the jump in temperature and the corresponding humidity change mentioned above. We focus on the absolute humidity instead of relative humidity, and denote it as $\Psi(t)$ when temperature jumps from $\theta = 0$°C to $\theta = 1$°C with a time $t = 0$. From the shape of the absolute humidity curve in Fig. 1, we assume that $\Psi(t)$ is expressed, using two parameters, a and α, as:

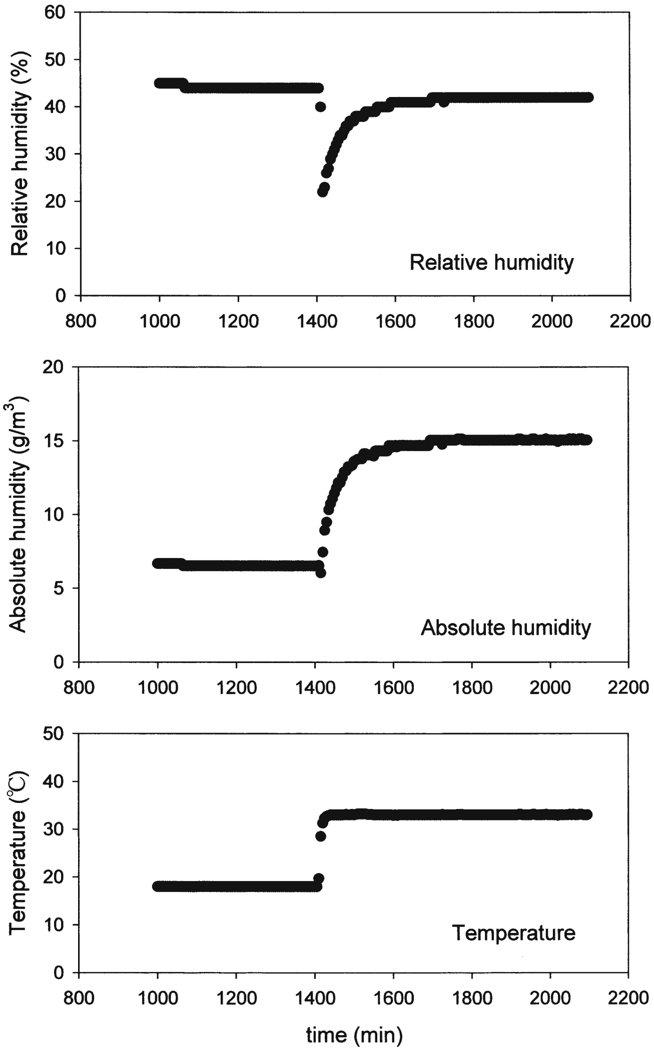

Fig. 1. Variation of relative humidity, absolute humidity, and temperature in a steel box lined with material, when the ratio of the lined area A to the volume of the steel box V is unity ($A/V = 1.0$, jump in temperature = 15°C)

$$\Psi(t) = a\left(1 - e^{-\alpha t}\right) = a - \phi(t) \tag{1}$$

where $\phi(t) = ae^{-\alpha t}$. We further assume that absolute humidity $h(t)$ at time t is proportional to temperature jump θ_0:

$$h(t) = \theta_0 \Psi(t) \tag{2}$$

where $\Psi(t)$ is a proportional coefficient at time t.

If the temperature inside the steel box is changed by $\Delta\theta_1(t_1)$, $\Delta\theta_2(t_2)$, . . . at the time of t_1, t_2, . . . , previous to time t, respectively, then absolute humidity $h(t)$ in the steel box at the time t is equivalent to the sum of absolute humidity at the same time t obtained when each of $\Delta\theta_1(t_1), \Delta\theta_2(t_2), \ldots$ is applied to the steel box independently:

$$h(t) = \sum \Psi(t - t_i)\Delta\theta_i(t_i)$$

When temperature changes continuously, this can be expressed as:

$$h(t) = \int_0^t \Psi(t-u)\frac{d\theta(u)}{du}du = \int_0^t \frac{d\phi(u)}{du}\theta(t-u)du$$

From this, when temperature changes as:

$$\theta(t) = \theta_a \cos(\omega t) \quad (3)$$

where θ_a is temperature amplitude, we obtain $h(t)$ as:

$$h(t) = k\theta_a \cos\omega(t - \Gamma) \quad (4)$$

where $k = \sqrt{A^2 + B^2}$ is the amplitude of absolute humidity variation when θ_a = 1°C, $\Gamma = \frac{1}{\omega}\tan^{-1}\frac{B}{A}$ is peak time difference as mentioned above, and

$$A = \frac{a\alpha^2}{\alpha^2 + \left(\frac{2\pi}{T}\right)^2}, \quad B = \frac{a\alpha\left(\frac{2\pi}{T}\right)}{\alpha^2 + \left(\frac{2\pi}{T}\right)^2}$$

where T is the period.

On the basis of these calculations, we can obtain absolute humidity variation around the average absolute humidity h_0 as:

$$h(t) = h_0 + k\theta_a \cos\omega(t - \Gamma)$$

when temperature $\theta(t)$ is changed around θ_1

$$\theta(t) = \theta_1 + \theta_a \cos(\omega t)$$

where $h_0 = 12.7\,\mathrm{g/m^3}$ (corresponding to 25°C and 60% relative humidity) and θ_1 = 25°C were adopted based on conditioning of specimens mentioned in the experimental section. In addition, θ_a value of 1.0 was used. Using the obtained $h(t)$, the Cb value is calculated in the following manner. At temperatures between 0° and 40°C, the relationship between saturated absolute humidity $h_s(t)$ and temperature $\theta(t)$ is

$$h_s(t) = 5.16 \times 10^{0.0255\theta(t)}$$

Thus, the relative humidity of the steel box lined with material, H_{wood}, is

$$H_{wood}(t) = \frac{h(t)}{h_s(t)} \times 100$$

On the other hand, relative humidity of the empty steel box, H_{stn}, is

$$H_{stn}(t) = \frac{h_0}{h_s(t)} \times 100$$

From this, using the change of H_{wood} in a day, ΔH_{wood}, and the change of H_{stn} in a day, ΔH_{stn}, Cb is expressed as:

$$Cb = \frac{\Delta H_{wood}}{\Delta H_{stn}}$$

To apply the above method in our study, we first had to find whether the measured value of absolute humidity variation due to the jump in temperature could be expressed by Eq. 1. We compared the measured values that were obtained by subtracting $h(t)$ values, after a jump in temperature, from the final value of $h(t)$ and $\theta_0\phi(t) = \theta_0 a e^{-\alpha t}$ with an adequate value for a and α. This result is illustrated in Fig. 2. As shown, $\theta_0\phi(t)$ corresponds with the measured values, indicating that $\phi(t)$ is suitable for expressing change in absolute humidity after a jump in temperature.

The coefficient a is the final value of $h(t)$ in a steel box per 1°C change in temperature, and should be the same, only if Eq. 2 is valid, when θ_0 is changed. Figure 3 compares a when θ_0 is changed from 5° to 20°C at different A/V values from 0.2 to 3. As expected, at each A/V value, the a value seems similar in value even when θ_0 is changed. Furthermore, the a value remained almost constant as the A/V value increased with the exception of A/V = 0.25. From this, we see that the Japanese cedar used is capable of releasing sufficient moisture to control humidity in a box, even if the

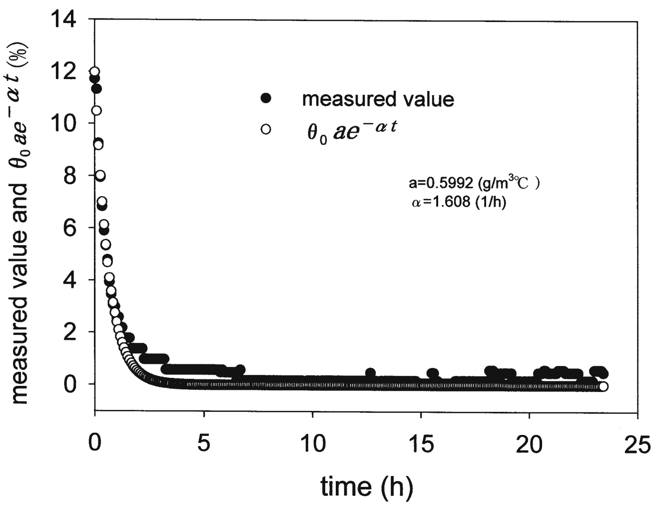

Fig. 2. Comparison of the measured values obtained by subtracting $h(t)$ values from the final value of $h(t)$ and $\theta_0\phi(t) = \theta_0 a e^{-\alpha t}$ (θ_0 = 20°C, $A/V = 2.0\,\mathrm{m^{-1}}$)

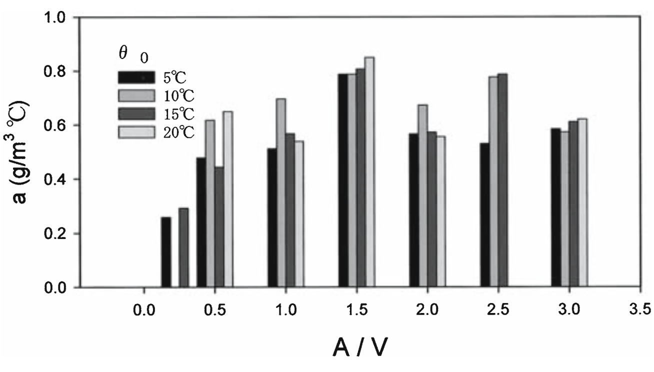

Fig. 3. Variation of a value with θ_0 and A/V (θ_0 = 5°–20°C, A/V = 0.2–3 $\mathrm{m^{-1}}$)

A/V value is as low as $0.5\,\mathrm{m}^{-1}$, and as long as sufficient time has elapsed after the jump in temperature. In our calculation below, we use an a value of $0.62\,\mathrm{g\,m^{-3}\,°C^{-1}}$ for A/V = 0.5–3.0 m^{-1}, and $0.28\,\mathrm{g\,m^{-3}\,°C^{-1}}$ for $A/V = 0.25\,\mathrm{m}^{-1}$.

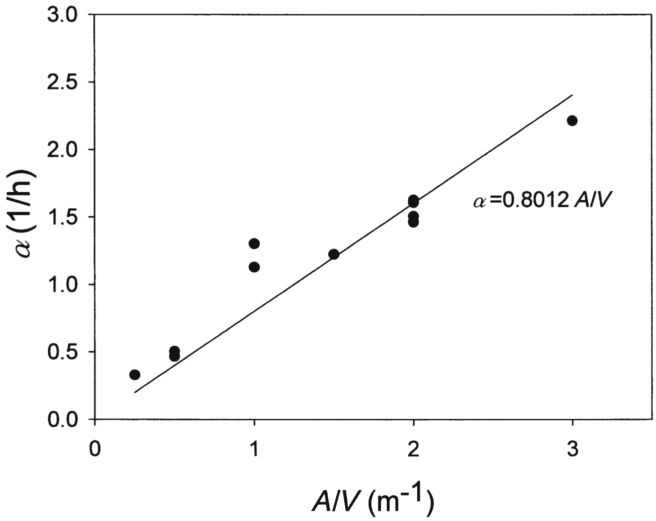

Fig. 4. Variation of α with A/V

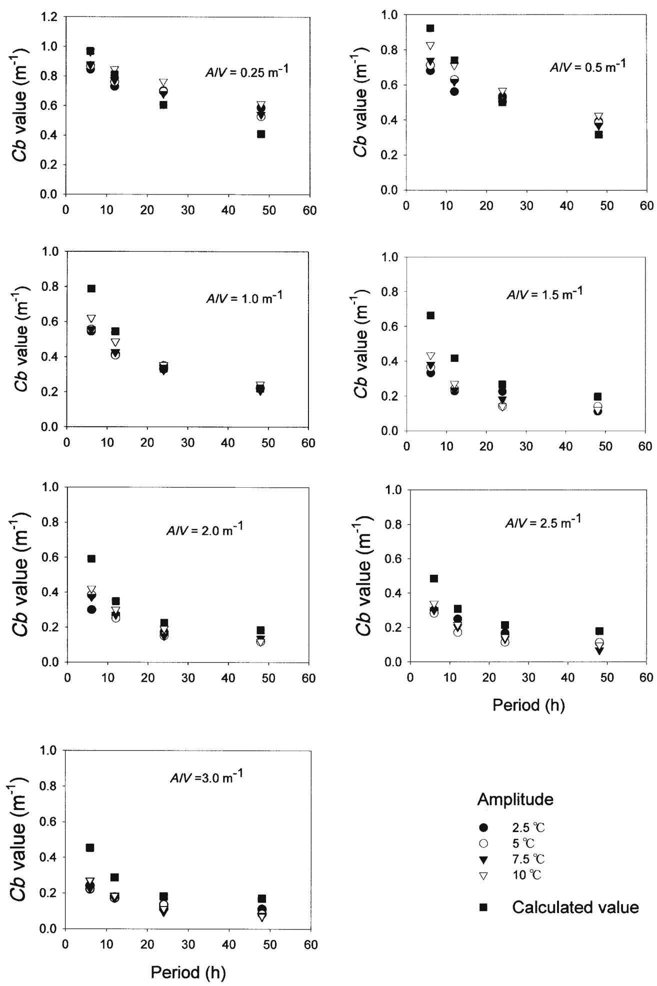

Fig. 5. Variation of measured and calculated Cb values with period for Japanese cedar for each A/V (temperature amplitude = 2.5°–10°C)

The α value is the other important factor in Eq. 1, and is a measure of how fast the maximum absolute humidity in a steel box is attained after the temperature change. Figure 4 shows the variation of α with A/V. The value of α increased linearly with A/V, indicating that cases with high A/V can reach the maximum humidity in a short time. We used the value on the line for our calculation below.

Figure 5 shows the measured values using sinusoidal temperature variation. In addition, the relationship between the calculated Cb values and each period for Japanese cedar for each A/V is plotted in Fig. 5. These calculated values when compared at a period of 6h have a trend of being higher than the measured values except when A/V = 0.25. The calculated values are somewhat lower than the measured values for periods of 24 and 48h when A/V = 0.25. Despite this, calculated Cb values appeared close to the measured values, decreasing with increasing period at each A/V. In addition to the Cb value, Γ is also a measure of humidity control capacity of materials. Figure 6 shows the relationship between calculated Γ (peak time difference) and

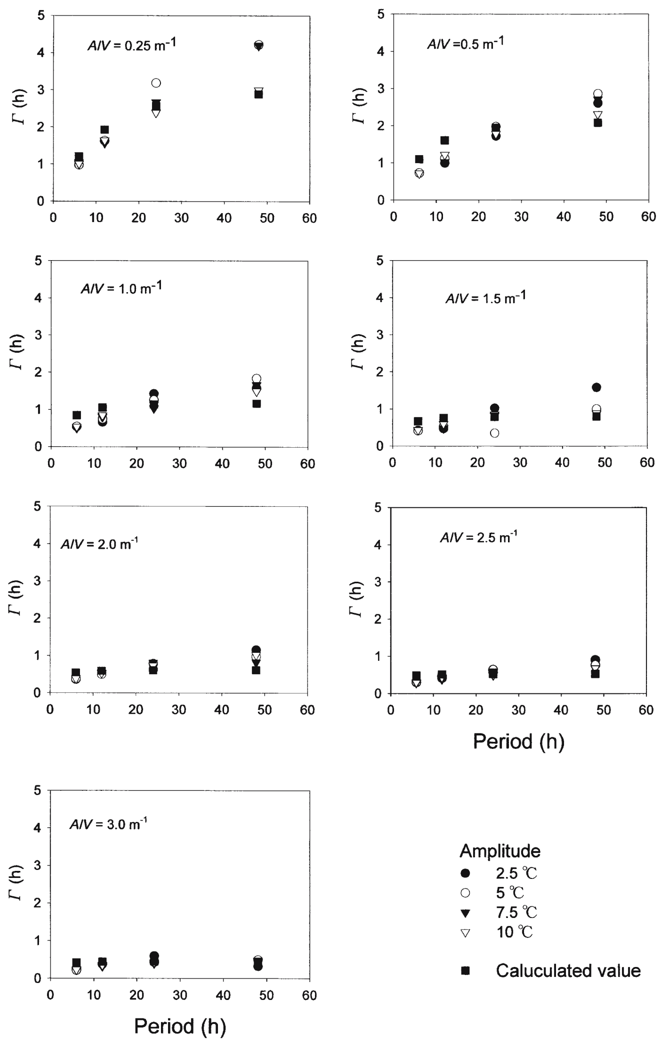

Fig. 6. Variation of measured and calculated Γ (peak time difference) with period for Japanese cedar for each A/V (temperature amplitude = 2.5°–10°C)

period for Japanese cedar for each A/V. Measured values are also plotted in Fig. 6. Once again, the calculated values are close to the measured values, increasing with increasing period at each A/V. From these results, we can conclude that both the calculated values of Cb and the peak time difference agree well with most of the measured values. To deal with the values that do not agree well with the measured values, the equation used in Fig. 2 needs to be improved so that it matches more closely with the measured values. Furthermore, the jump in temperature in a steel box has to occur within a shorter time so that any errors involved in the corresponding absolute humidity can be reduced.

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