

Toshiro Morooka · Yoko Homma · Misato Norimoto

Criterion for estimating humidity control capacity of materials in a room

Received: June 16, 2006 / Accepted: August 30, 2006 / Published online: February 9, 2007

Abstract As a measure of estimating humidity control capacity of materials in an airtight room under sinusoidal temperature variation, we used the Cb value, which is the ratio of the range of variation in relative humidity in a steel box lined with the material of interest to the range in an empty steel box. In order to clarify the factors that affect the Cb value, we focused on both the temperature variation rate and the area that is lined in the box. It was found that changing the rate of temperature variation over one period strongly affected the Cb value, although the amplitude of temperature variation did not. We further noticed that the difference between the time when peak temperature was reached and the time when peak absolute humidity was reached (peak time difference), was found to be useful for estimating the humidity control capacity of materials. Knowing the difference between the phase when peak temperature was reached and the phase when peak absolute humidity was reached (phase angle difference) was also useful. Because the Cb value was affected by both the variation period and the lined area in the box, we can draw a contour diagram of the period and the lined area for materials to give an overview of the humidity control capacity of a material. The materials of primary interest in this study were Japanese cedar and porous ceramics.

Key words Humidity control capacity · B value · Cb value · Japanese cedar · Porous ceramics

Introduction

A house should be built in such a way that humidity can be controlled by the house itself and with as little artificial air conditioning as possible. For this purpose, materials that can control humidity have been used in applications such as interior wall materials, wall material for making closets, and materials under floors. However, before using these materials we need to have a clear understanding of their capability to control humidity so that we can use them properly. To estimate the variation of relative humidity due to materials in an airtight room, we have so far used the B value reported by Maki et al.,¹ which is the slope of the line formed by the plot of logarithmic relative humidity against the temperature inside a steel box lined with the material of interest. The B value is especially useful when temperature changes irregularly with time, because as long as the B value is used the relationship between the temperature and relative humidity is expressed in a simplistic fashion without any detailed information. To obtain a B value, different modes of temperature variation have been used: Norimoto et al.² used step variation and less controlled variation, Ohgama et al.³ employed a typical variation over a day, and Kurimoto et al.⁴ adopted saw-tooth variation. From a mathematical point of view, however, it seems most convenient to use sinusoidal variation, because such variation can be easily handled by theoretical means whenever necessary. Sinusoidal temperature variation is also adopted as a JIS standard⁵ to examine adsorption/desorption efficiency of material in a box. However, when sinusoidal temperature variation is employed, the resulting logarithmic relative humidity–temperature plots do not form a line but rather a Lissajous figure with a frequency ratio of unity. Therefore, no matter how broad the figure is, the slope of the regression line from this figure is used as the B value when sinusoidal temperature variation is used. This indicates that the B value is not necessarily the best index for expressing humidity control capacity.

In addition, the B value depends on the temperature variation rate. Even if an index for humidity control effect

T. Morooka (✉)
Research Institute for Sustainable Humanosphere, Kyoto University,
Uji, Kyoto 611-0011, Japan
Tel. +81-774-38-3654; Fax +81-774-38-3600
e-mail: tmorooka@rish.kyoto-u.ac.jp

Y. Homma
Koshii & Co., Ltd., Osaka 550-0025, Japan

M. Norimoto
Faculty of Engineering, Doshisha University, Kyoto 610-0394, Japan

(other than B value) is used, it still depends on the temperature variation rate, because this effect is a nonequilibrium phenomenon based on adsorption/desorption of materials. Although previous works²⁻⁴ have touched on the effect of temperature variation rate on B value, they lack uniformity because different works used different definitions of variation rate as mentioned above.

In this study, to measure the humidity control capacity of materials, sinusoidal temperature variation was used. We focused on clarifying the kind of variation rate required to vary the humidity control capacity of materials. We also examined how the amount of materials affects the humidity control. We hereby propose a new index (Cb) to estimate humidity control capacity by directly comparing relative humidity change in the box lined with materials and that without materials. The materials mainly used are Japanese cedar (*sugi*, *Cryptomeria japonica* D. Don.) wood and commercially available porous ceramics.

Materials and methods

Specimens

Materials used were 1-cm-thick Japanese cedar flat-grain wood, and 0.5-cm-thick commercially available porous ceramic wall materials. Some testing was also performed with 1-cm thick commercially available gypsum board and 1-cm thick gypsum board incorporating diatomite. These materials were conditioned at 25°C and 60% relative humidity for at least a week before testing commenced.

Measuring device

Relative humidity was measured in a steel box (a base of 20 × 20 cm and a height of 25 cm) lined with material. The box was sealed carefully to prevent air leakage before measurement. The extent of the lined area was expressed as the ratio of lined area (A) to the volume of steel box (V). 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.

B and Cb values

Temperature and relative humidity inside the box were measured over different periods of time in the climatic chamber with temperatures initially set at 25°C and with relative humidity kept at 60% during measurements. The temperatures of the climatic chamber 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 48 h. The B value is defined as the slope of the regression line obtained when logarithmic relative humidity H inside the steel box is plotted against the temperature. On the other hand, 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.

Results and discussion

Figure 1 shows the resulting variation of B and Cb values with A/V for Japanese cedar and porous ceramics measured at a temperature variation period of 24 h with the amplitude of 5°C. The data for gypsum board and gypsum board incorporating diatomite are also plotted for A/V values of 0.5 and 1.0 m⁻¹. The B value for both Japanese cedar and porous ceramics increased markedly with increasing A/V up to $A/V = 1.5$ m⁻¹, and then leveled off at $A/V = 1.5$ m⁻¹ (Fig. 1a). When we compared four samples at around $A/V = 0.5$ or 1.0 m⁻¹, gypsum board incorporating diatomite was found to be the highest, followed by Japanese cedar, and then porous material and gypsum board. On the other hand, changes in Cb value with A/V were inversely related to the changes in B value (Fig. 1b), decreasing rapidly up to 1.5 m⁻¹, followed by slight decrease for porous ceramics and leveling off for Japanese cedar. These results suggest a linear relationship between B and Cb values of the materials examined.

From the definition of the B value, relative humidity H and temperature T are related by a regression line:

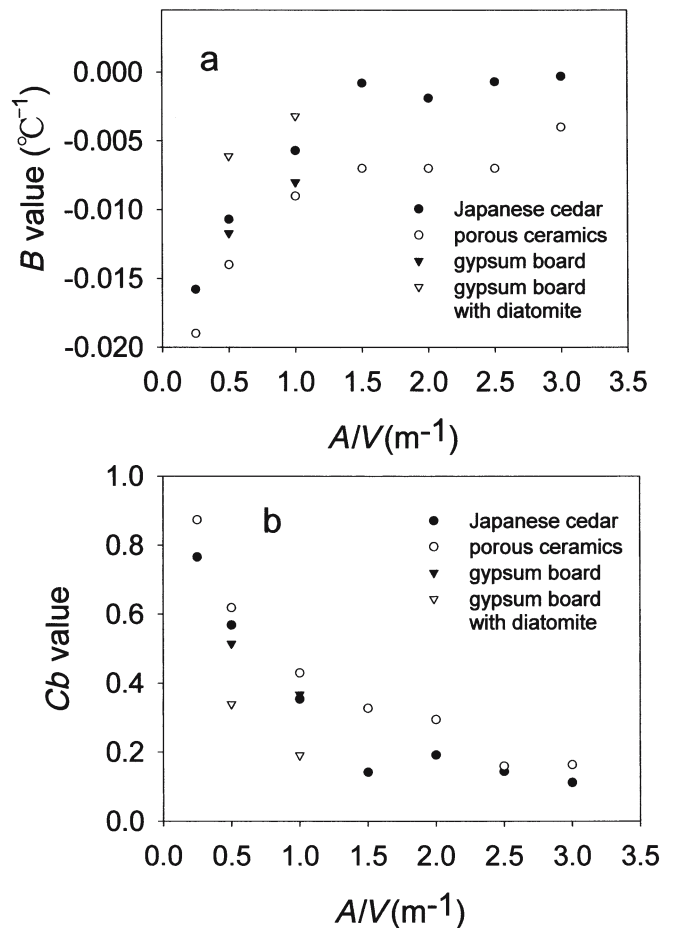


Fig. 1a, b. Variation of **a** B value and **b** Cb value with A/V (ratio of lined area A to the volume of steel box V) for materials measured at a period of 24 h with temperature amplitude of 5°C

$$\log H = \text{constant} + B \cdot T$$

Then the increment ΔH corresponding to increment ΔT can be written as:

$$\Delta H = H \cdot B \cdot \Delta T$$

Thus, the increment of relative humidity at temperature $T = T_0$ when lined with material, ΔH_w , is:

$$\Delta H_w = H(T_0) \cdot B \cdot \Delta T$$

while the increment without material inside, ΔH_{stin} , that is only the steel box, is:

$$\Delta H_{\text{stin}} = H(T_0) \cdot -0.0255 \cdot \Delta T$$

where the B value for the steel box only is $-0.0255^\circ\text{C}^{-1}$.

Because these equations are also valid when temperature varied sinusoidally, both ΔH_w and ΔH_{stin} can be regarded as the amplitude of relative humidity variation corresponding to the temperature amplitude applied.

The Cb value is written as:

$$Cb = \Delta H_w / \Delta H_{\text{stin}} = B / (-0.0255)$$

The Cb value is always positive, although the B value is not necessarily negative. We obtain the relationship between the B and Cb values as follows:

$$|B| = 0.0255 Cb$$

In Fig. 2, all of the data for B and Cb for Japanese cedar employed in our experiment are plotted, and the line from the equation just above is also illustrated. We see that the measured values nearly match up with the calculated line. This enables us to easily estimate humidity control capacity of the Cb value in relation to the B value for which much data have been collected to date. For instance, the Cb value of 0.2 corresponds to a B value of -0.004 , indicating high humidity control capacity. A result similar to that shown in Fig. 2 was also obtained for porous ceramics. From this point, we will use the Cb value as the index of humidity control capacity of materials instead of the B value.

Because the Cb value depends on the rate of temperature variation, as does the B value, it should be measured

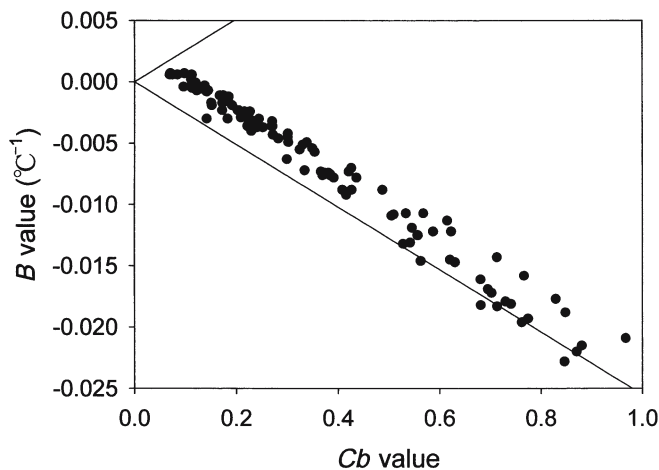


Fig. 2. Relationship between B and Cb values. Solid line shows $|B| = 0.0255 Cb$

for a wide variety of temperature increase rates. However, when temperature varies sinusoidally, the Cb value can be changed in two different ways: one is by changing the temperature amplitude with a constant wave period, and the other is by changing the wave period with a constant amplitude.

To clarify the effect on Cb value of the amplitude and period of sinusoidal temperature variation, Fig. 3 shows the change of Cb value for porous ceramics with temperature variation period at different temperature amplitudes from 2.5° to 10°C for different values of A/V . For the cases shown in Fig. 3, the Cb values at the same period were almost the same irrespective of amplitude other than the data for a period of 48h shown in Fig. 3c. In general, the Cb value appeared to decrease slightly as the period increased. This tendency observed for porous ceramics is clearer for Japanese cedar. Figure 4 shows the variation in Cb value with each period for Japanese cedar as shown in Fig. 3 for porous ceramics. For Japanese cedar, the decrease in the Cb value with increase in the variation period was more marked than for porous ceramics. However, the Cb values were almost

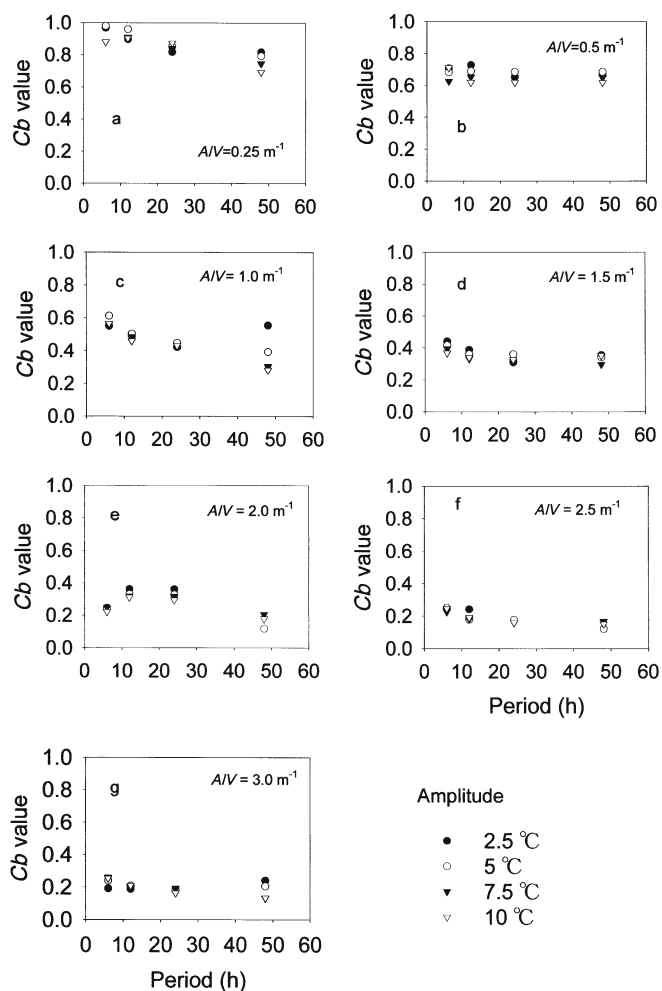


Fig. 3a–g. Variation of Cb value for porous ceramics with period at different amplitudes. A/V ratios are **a** 0.25m^{-1} , **b** 0.5m^{-1} , **c** 1.0m^{-1} , **d** 1.5m^{-1} , **e** 2.0m^{-1} , **f** 2.5m^{-1} , **g** 3.0m^{-1}

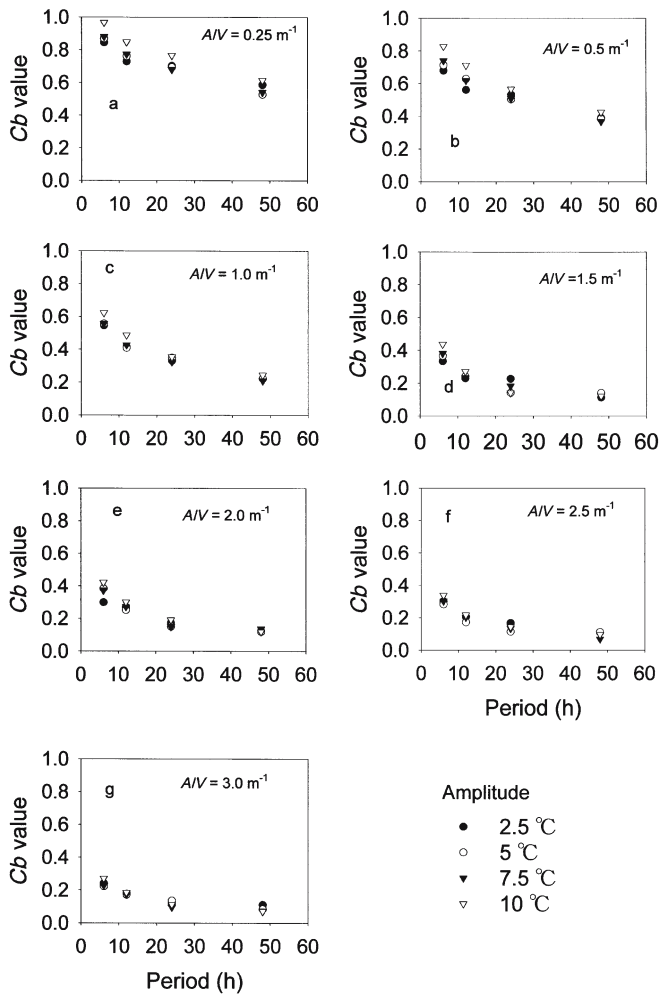


Fig. 4a–g. Variation of the C_b value for Japanese cedar with period at different amplitudes. A/V ratios are **a** 0.25 m^{-1} , **b** 0.5 m^{-1} , **c** 1.0 m^{-1} , **d** 1.5 m^{-1} , **e** 2.0 m^{-1} , **f** 2.5 m^{-1} , **g** 3.0 m^{-1}

the same regardless of change in amplitude. From these findings, we may conclude that the C_b value varies with each period while there is little difference for changes in amplitude. The more marked decline in the C_b value for Japanese cedar in comparison with that for porous ceramics might be due to the difference in the adsorption mechanism. For Japanese cedar, adsorption of water molecules occurs at specific adsorption sites, for example, by hydrogen bonding at hydroxyl groups, while for porous ceramics it occurs at small pores due to dispersion force. We further observed that increasing the A/V value reduced the C_b value for any variation period.

When sinusoidal temperature variation is used, as mentioned above, we noted that there is a difference between the time when the peak temperature is reached and the time when the peak relative humidity or peak absolute humidity is reached. This time difference is thought to be another indicator for the index of judging humidity control capacity of materials. In this article, we refer to the time difference between peaks in temperature and absolute humidity as the “peak time difference.” Figure 5 shows the variation of

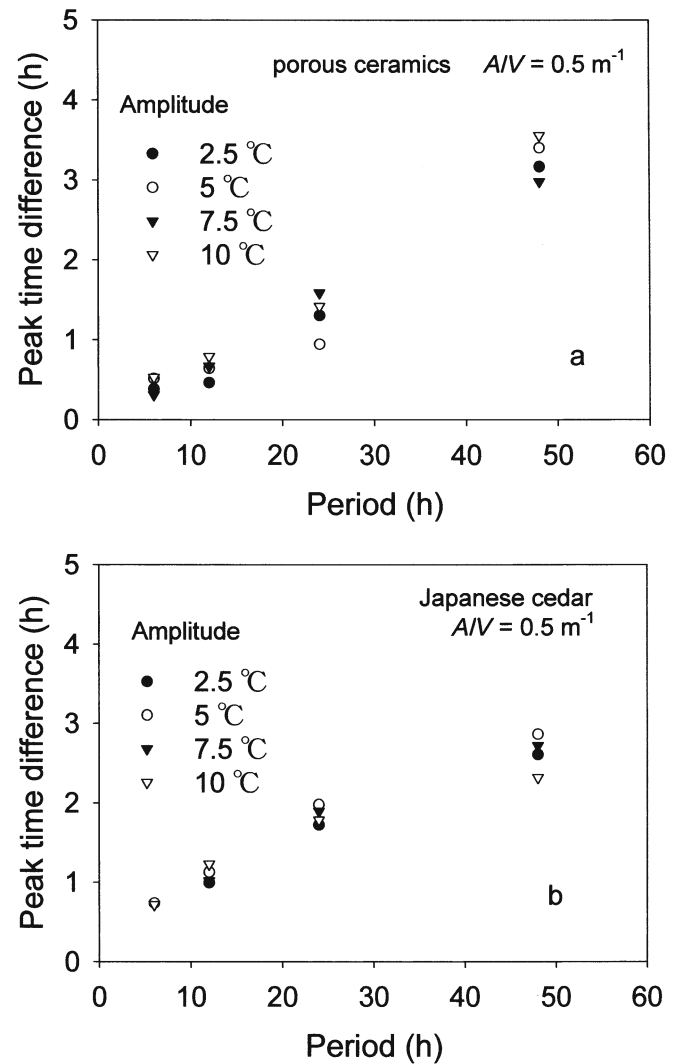


Fig. 5a, b. Variation of peak time differences with period for $A/V = 0.5 \text{ m}^{-1}$ at different amplitudes for **a** porous ceramics and **b** Japanese cedar

peak time differences for each period (with $A/V = 0.5 \text{ m}^{-1}$) at different temperature amplitudes for porous ceramics and Japanese cedar. For either material, it is clear that the peak time difference increases with increasing variation period, although again there appears to be little difference in the effect of change of amplitude. Here, peak time difference could include the effect brought about by the length of each period. For example, suppose that the temperature variation period is 10 min. Then, peak time difference is automatically restricted to some time within 10 min. In order to deal with such influence of variation period on the peak time difference, which is irrespective of the temperature variation rate, we used “phase angle difference.” This is the value of each peak time difference divided by its period. The relationship between the phase angle difference and period for porous ceramics and Japanese cedar for $A/V = 1.0 \text{ m}^{-1}$ at different temperature amplitudes are shown in Fig. 6. Contrary to the peak time difference, the phase angle difference decreases with each period for both samples,

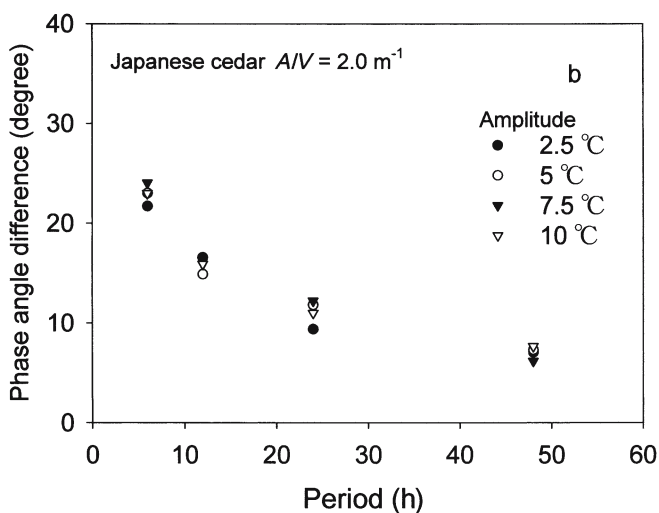
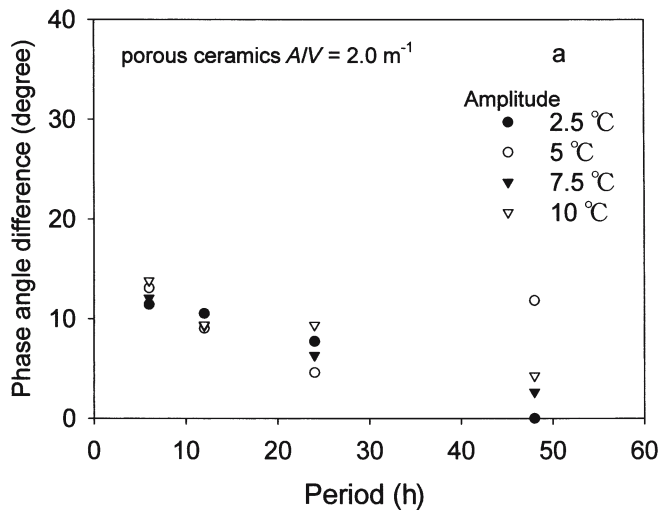


Fig. 6a, b. Variation of phase angle differences with period for $A/V = 2.0\text{m}^{-1}$ at different amplitudes for **a** porous ceramics and **b** Japanese cedar

which appears similar to the relationship between Cb value and variation period. Again they are not affected by variations in amplitude except for porous ceramics with $A/V = 2.0\text{m}^{-1}$ (Fig. 6a) and with $A/V = 1.5\text{m}^{-1}$ at a period of 48h and an amplitude of 5°C . From these results, we may conclude that both the Cb value and phase angle difference are independent of the variation of temperature amplitude, but are strongly affected when the period is changed. In addition, it is of interest to know how the Cb value relates to peak time difference or phase angle difference. For Japanese cedar at different periods and amplitude variations, the relations are shown in Fig. 7. In Fig. 7, each dataset (symbol) represents a different variation period, but each dataset does include variations in amplitude. The plots of Cb value against peak time difference (Fig. 7a) have a linear relationship for each period. The gradient is the steepest at 6h, and the slope levels off as the period increases. It should be noted that when we eliminated the influence of period as mentioned above, (i.e., phase angle difference), all the plots appeared on a single curve (Fig. 7b). Plots for porous

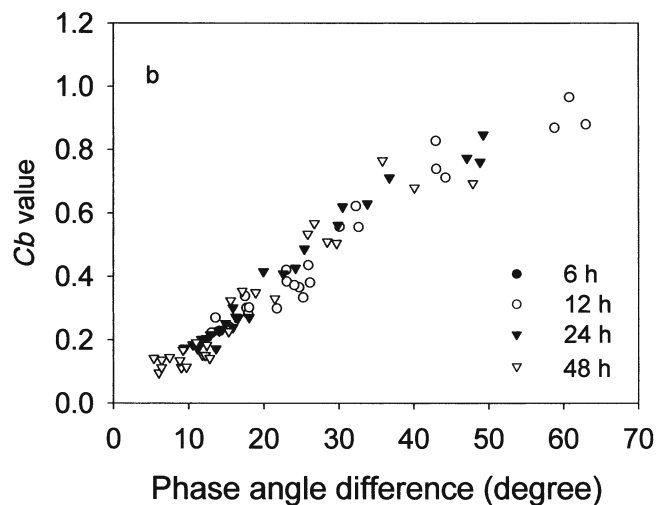
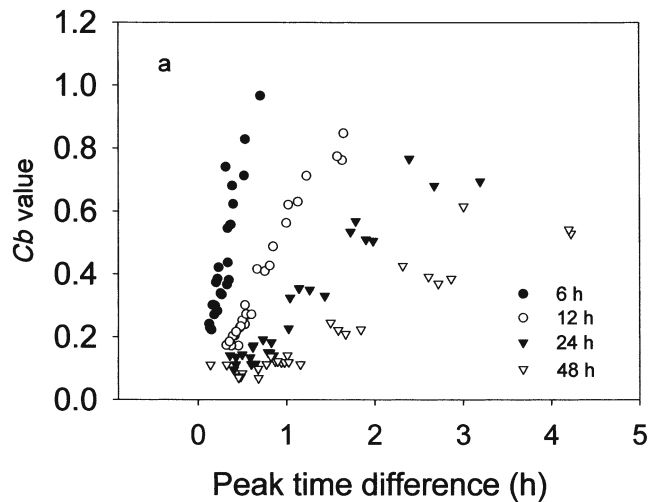


Fig. 7a, b. Relationship between **a** Cb value and peak time difference and **b** between Cb value and phase angle difference for Japanese cedar

ceramics appeared on a single curve similar to Japanese cedar. These facts suggest that the relationship between phase angle difference and Cb value is independent of the material type.

In addition to period, Cb value for both Japanese cedar and porous ceramics changed greatly by varying A/V values as seen in Figs. 3 and 4. Figure 8 shows the relationship between Cb value and A/V for periods of 6h and 48h at amplitudes of $2.5^\circ\text{--}10^\circ\text{C}$ for both porous ceramics and Japanese cedar. In Fig. 8, the Cb value for the two sample types decreased markedly with A/V value, although they were similar when the amplitude was changed at the same A/V except for $A/V = 1.0\text{m}^{-1}$ at a period of 48h. At a period of 6h (Fig. 8a), in most of the cases, porous ceramics are shown to have slightly smaller Cb values than Japanese cedar when compared at the same A/V value. However, this trend is not true for other periods. At a period of 12h, this trend is reversed. Japanese cedar showed smaller Cb values than porous ceramics. This trend continued as the period increased, and finally at a period of 48h, Japanese cedar had noticeably

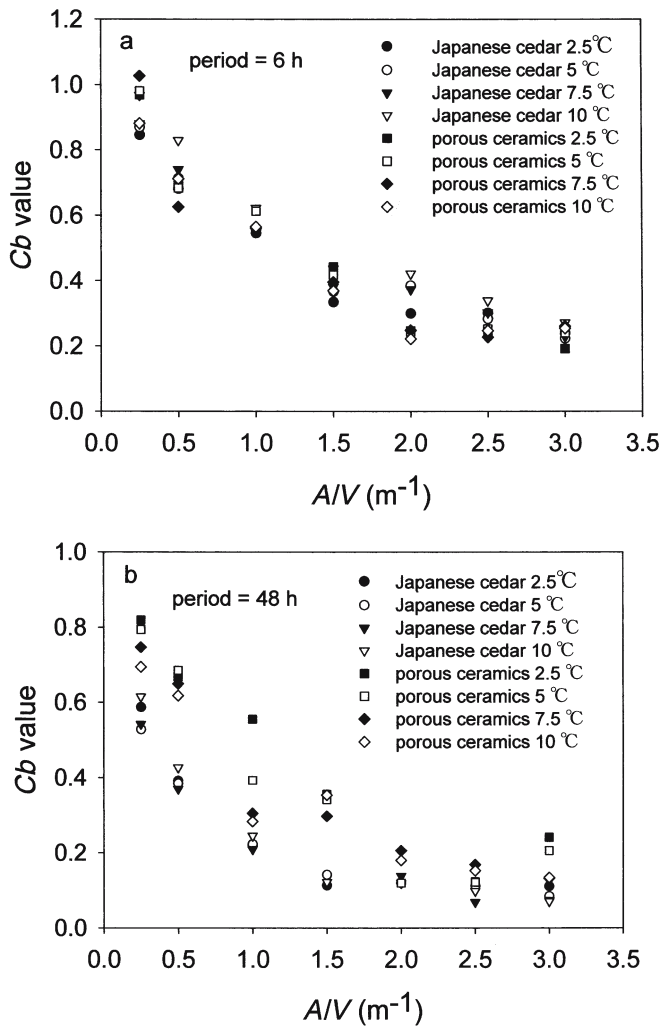


Fig. 8a, b. Relationship between C_b value and A/V for **a** variation period of 6h and **b** variation period of 48h, for temperature variation amplitudes of 2.5°–10°C for Japanese cedar and porous ceramics

smaller C_b values than those of porous ceramics. From this, we see that C_b value should be examined not only at a single period or a single A/V value, but for a wide range of periods and A/V values.

One of the quickest ways of observing both effects at the same time is through C_b value contour diagrams of each period and A/V in the range examined. These diagrams are shown in Fig. 9 for Japanese cedar and porous ceramics. In this case, a temperature amplitude of 7.5°C was adopted. The overall impressions of the two contour plots differ greatly. Noting patterns of contour lines, we see that those for porous ceramics run almost parallel to the horizontal axis. On the other hand, those for Japanese cedar run from the top left to the bottom right, indicating that the map is symmetrical about the line passing through the origin, inclining at 45 degrees. From these plots, we further noticed that $C_b = 0.2$, which indicated high humidity control capacity as mentioned above, was attained at the period of 25h and A/V of 1.5 m^{-1} for Japanese cedar. However, the same C_b value was not attained until 30h and with an A/V of

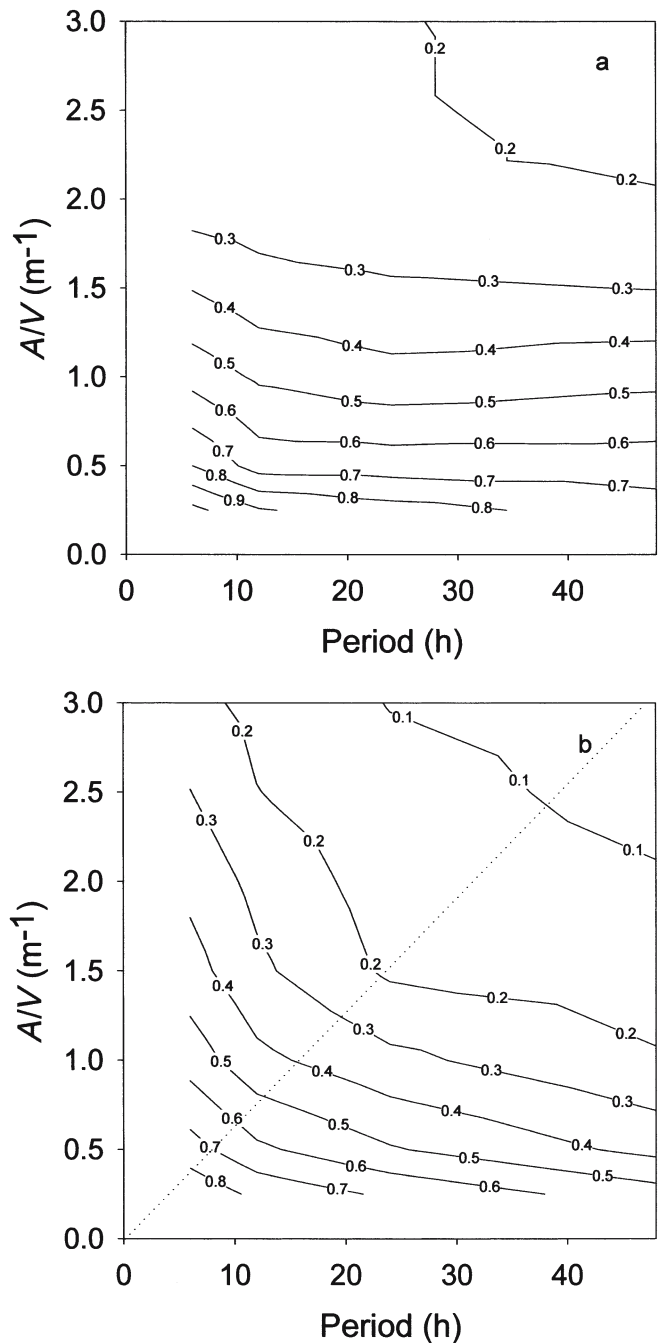


Fig. 9a, b. C_b value contour diagrams of each period and A/V in the range examined for **a** porous ceramics and **b** Japanese cedar

2.5 m^{-1} for porous ceramics. From these results, we can conclude that the humidity control capacity of Japanese cedar is higher than that of porous ceramics in the range examined.

In this way, in order to understand the humidity control capacity of a material as a whole, it is effective to draw each C_b value contour map of each period and A/V covering their wide ranges. However, it takes a long time to draw these maps. For example, if we want to gather C_b value data at 6, 12, 24, and 48h at a single A/V , we have to measure them at least twice for each period, which takes up to 8 days

for the measurement. We then have to repeat these measurements for each A/V , which results in measuring times in the order of months to obtain one map. In order to cut down the measuring time, a high speed measuring method should be exploited.

References

1. Maki F, Norimoto M, Aoki T, Yamada T (1981) Estimation of humidity control effect for interior-wall materials. *Mokuzai Kogyo* 36:476–480
2. Norimoto M, Ohgama T, Yamada T (1990) Humidity conditions caused by wood. *Mokuzai Gakkaishi* 36:341–346
3. Ohgama T, Ishikawa H, Norimoto M, Kamba N (2001) Humidity control effects of woods and artificial woods made of ceramics. *Mokuzai Gakkaishi* 47:97–102
4. Kurimoto Y, Kano K, Norimoto M, Sawabe O (2002) Performance of carbonized sugi wood and bark for humidity control. *Mater Sci Res Int* 8:38–42
5. Japanese Standards Association (2002) Japanese Industrial Standard (JIS) A 1470-2. Test method of adsorption/desorption efficiency for building materials to regulate an indoor humidity. Japanese Standards Association, Tokyo