MOISTURE MOVEMENT IN DOUBLE LAYER BUILDING MATERIALS

Takane Terashima, Masayuki Mizuhata

Dept. of Architecture, Faculty of Eng., Mie University, Japan

To prevent the problems of internal condensation inside building walls, it is necessary to predict the moisture behavior exactly not only in the hygroscopic region of moisture content but also in the non-hygroscopic region. The purpose of this study is to understand the behavior of condensation in building materials. For a single layer wall, which consists of a single material, previous studies have been done by a variety of authors. But considering that an actual wall is multi layered and consisting of several kinds of materials, the analysis of moisture movement in a multi layer wall is necessary. In this paper, double layer wall, which consists of two kinds of materials, is considered. The change of internal moisture content in the wall under the condensation process is measured and analyzed by numerical calculation using two models. Firstly, specimens of a double layer wall are assembled. The changes of moisture content of specimens in the condensation process are measured. Next, the change of internal moisture content in that process under the experimental condition is calculated using two models. Both results are compared and the mode of internal moisture transfer calculation is discussed.

1. INTRODUCTION

It is a well-known fact that condensed water, which accumulates inside the building walls causes various problems. The phenomenon of the internal condensation process in porous material is complex, because of non-linearity of moisture transfer equation and coefficient dependency greatly on potentials. And accurate data on such coefficients is scarce. Studies dealing with quantitative analysis of the condensation and re-evaporation process of moisture movement in the porous material have been reported by Kooi [1], Matsumoto et al. [2], and many other researchers [3-8]. We have measured various physical moisture properties of calcium silicate board and cellular concrete and analyzed the moisture movement in these materials experimentally and theoretically [9-13]. These studies suggest the validity of analysis of the condensation and re-evaporation by the simultaneous heat and moisture transfer equation. Most of walls in real buildings are multi layer walls composed of two or more materials. Therefore, analysis of the moisture behavior in wall materials composed of not only single-layer walls but also multi-layer walls is needed. In this report, a double layer wall composed of two kinds of materials is regarded as a simplification model of the multi-layer wall. The double layer wall used was made of two kinds of materials, which are composed of cellular concrete and calcium silicate board, which have different moisture diffusion properties. The change of internal moisture content in the condensation process was measured and calculated numerically using two models, which have different boundary conditions at the interface between two layers. The results from measurement and calculation were compared and the models of calculation are discussed. Sensible analyses of the resistances of moisture and heat fluxes at the interface were conducted. The effects of the interface resistances were also studied.

Tab.1:Composition of Specimen

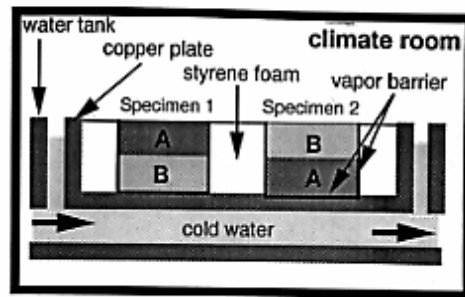| Specimen	Upper	Lower
1	Material A (15mm)	Material B (15mm)
2	Material B (15mm)	Material A (15mm)

Fig.1: Equipment of Experiment

Fig. 1 : Equipment of Experiment

2. EXPERIMENT OF CONDENSATION PROCESS

2.1 Specimen and equipment

Specimens of double layer walls dealt with here are composed of the two kinds of porous materials, one is a cellular concrete board (518 kg/m³, material "A", 15mm thick) and the other is a calcium silicate board (450 kg/m², material "B", 15mm thick). These specimens have two types whose compositions are shown in Tab. 1. The surfaces of material A and B are smooth enough, and thus stick to each other. The side and bottom surfaces of them are moisture-proof. The side surfaces are even well insulated thermally. They were set up in the experiment device shown in Fig. 1. Specimens were prepared for measuring average moisture content; for measuring internal temperature distribution; for moisture content distribution. A specimen for internal temperature distribution had 3 nodes of thermo-couples vertically. For a few days before the experiment started, all specimens were dried out and made isothermal and without moisture content distribution in vessels at 25°C. The temperature in a climate room was kept at 25°C and bottom surface temperature of the specimen was kept at 14°C. The relative humidity of the room air was kept at 75%. After the experiment started, perpendicular, downward heat flow and moisture flux are caused in the material. And thus moisture content in the specimens rises.

2.2 Outline of experiment

After the experiment started, the weight of specimens for average moisture content was measured at an interval of about a day. They were then moved back onto the copper plate. The changes of average moisture content of them were calculated from their wet weight and dry weight. Moreover, at an arbitrary time, a specimen for moisture content distribution was cut into 6 pieces after measuring its weight. And the wet weight of each piece of the specimen was measured. After that, the pieces were dried out to obtain the dry weight. The moisture distribution of the specimen was obtained from the wet and dry weight of the 6 pieces. Temperature distribution of the specimen was obtained by thermo-couple and recorder.

2.3 Results of experiment

Change of average moisture content   The solid lines in Fig. 2 ~3 show the change of average moisture content of the specimens for average moisture content. In Fig. 2, after 9 days measurement was curtailed because of leakage into the bottom area of the specimens. The marking O shows the measured value of the average moisture content from the specimen for moisture content distribution. Fig. 2 corresponds to the case of Specimen 1. The change of average moisture content from the specimens for moisture content distribution has a tendency to increase linearly and does not reach a steady state after 45 days.

Fig. 2: Change of average moisture content for Specimen 1 [A(15mm)/B(15 mm)]
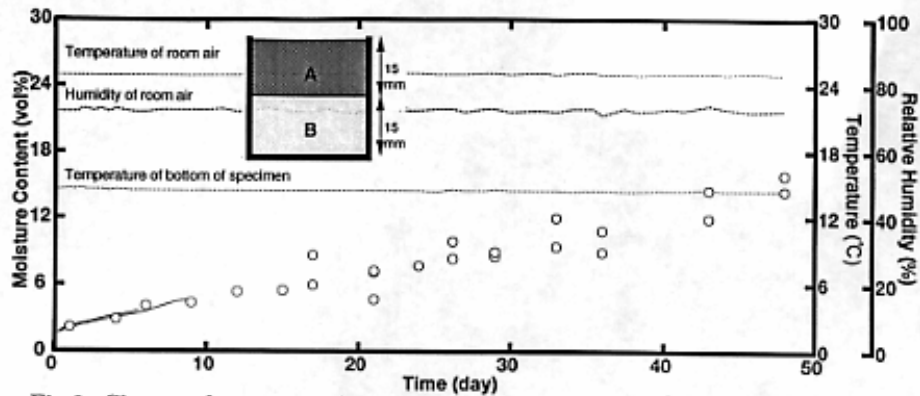
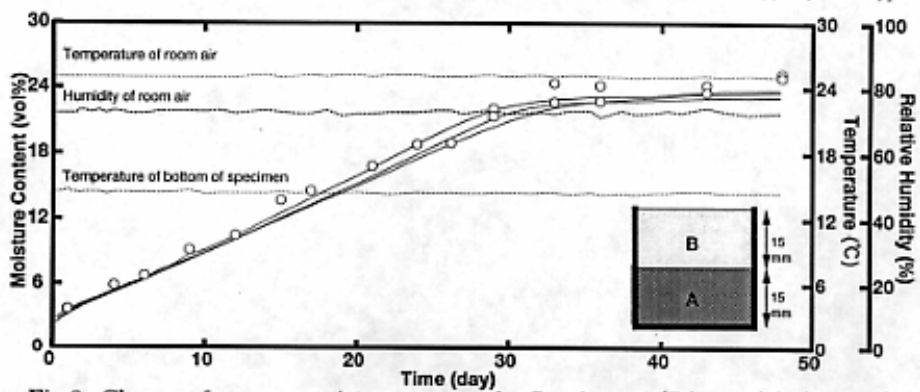Fig.2: Change of average moisture content for Specimen 1 [A(15mm)/B(15mm)]

Fig.3: Change of average moisture content for Specimen 2 [B(15mm)/A(15mm)]

Fig. 3: Change of average moisture content for Specimen 2 [B(15mm)/A(15mm)]

Fig. 3 corresponds to the case of Specimen 2. The average moisture content of the specimen increases linearly until 30 days or so, and after that reaches a steady state in 22~23 vol%. The gradient of average moisture content is larger than that in Specimen 1 and the term of moisture content rising is shorter than that in Specimen 1.

Changes in moisture content distribution Fig. 4~5 show the change of moisture content distribution. The Markings Ž~ show measured values at the each layer in the specimens.

Fig. 4 corresponds to the case of Specimen 1. The tendency of internal moisture distribution is for the moisture content near the bottom to be high. The moisture content distribution has a tendency to bipolarize after 22 days.

Fig. 5 corresponds to the case of Specimen 2. The tendency of internal moisture distribution is for the moisture content near the bottom to be high. The moisture content distribution tends to bipolarize as soon as the experiment starts.

Both specimen tends to bipolarize but the gradient of the moisture content in upper layer of Specimen 2 is larger than that in Specimen 1.
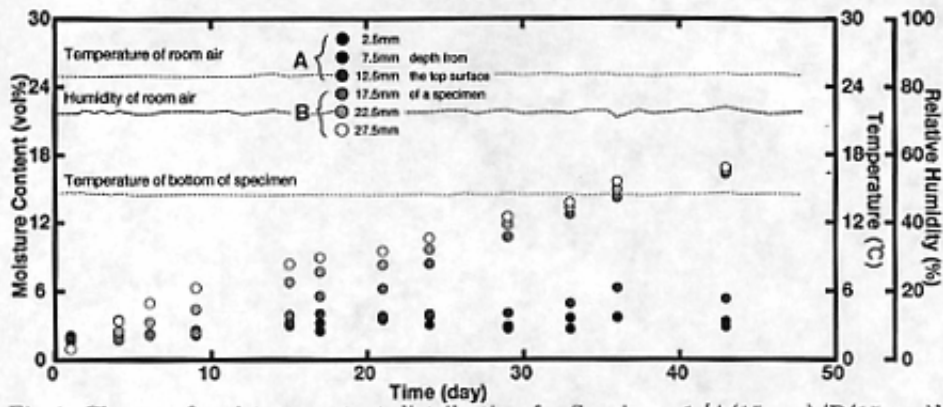
3. ANALYSIS OF CONDENSATION PROCESS

Fig.4: Change of moisture content distribution for Specimen 1 [A(15mm)/B(15mm)]
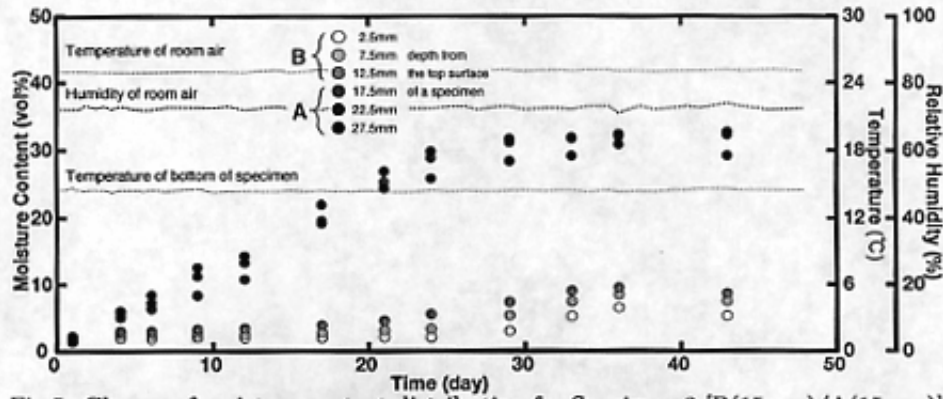

Fig.5: Change of moisture content distribution for Specimen 2 [B(15mm)/A(15mm)]

Fig. 4 : Change of moisture content distribution for Specimen 1 [A(15mm)/B(15mm)]
Fig. 5: Change of moisture content distribution for Specimen 2 [B(15mm)A(15mm)]

3.1 Theory of moisture transfer

The moisture movement in a porous material where condensation is caused, is chiefly ruled by both moisture content and temperature. In the case dealt with in this paper, the influence of gravity and the heat of adsorption can be disregarded. Therefore the transfer equation against the one-dimensional flow of heat and moisture can be described as follows [14].

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial x}\left(D_\theta \frac{\partial \theta}{\partial x}\right)+\frac{\partial}{\partial x}\left(D_T \frac{\partial T}{\partial x}\right) \qquad (1)$$

$$c\gamma \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_\theta \frac{\partial T}{\partial x}\right) \qquad (2)$$

In these equations, the influence of gravity and heat of absorption is ignored, because these are very slow phenomena. The boundary condition at the surface of the indoor side can be described as follows.

$$\alpha'(P_i - P_s) = -D_\theta \frac{\partial \theta}{\partial x} - D_T \frac{\partial T}{\partial x} \qquad (3)$$

$$\alpha(T_i - T_s) = -\lambda_\theta \frac{\partial T}{\partial x} \qquad (4)$$

At the moisture-proof surface the following is the boundary condition.

$$-D_\theta \frac{\partial \theta}{\partial x} - D_T \frac{\partial T}{\partial x} = 0 \qquad (5)$$

$$T = T_d(t) \qquad (6)$$

Two models of calculation are adopted as a boundary condition at the interface between two layers. They are shown as follows. Subscript A and B indicate the material A and B.
[Model 1] Heat and moisture flux are continuous at the interface:

$$-D_{\theta A} \frac{\partial \theta_A}{\partial x} - D_{TA} \frac{\partial TsubA}{\partial x} = -D_{\theta B} \frac{\partial \theta_B}{\partial x} - D_{TB} \frac{\partial T_B}{\partial x} \qquad (7)$$

$$-\lambda_A \frac{\partial T_A}{\partial x} = -\lambda_B \frac{\partial T_B}{\partial x} \qquad (8)$$

[Model 2] Heat and moisture flux have some resistance at the interface:

$$\frac{1}{R_{AB}}(T_A - T_B) = -\lambda \frac{\partial T}{\partial x} \qquad (9)$$

$$\frac{1}{R'_{AB}}(P_A - P_B) = -D_\theta \frac{\partial \theta}{\partial x} - D_T \frac{\partial T}{\partial x} \qquad (10)$$

3.2 Properties of material

Physical properties values of material A and B, which affect the internal moisture movement, have been already measured by authors [9-10,13] and have been verified compared with values by other works [1] [14]. Each of them is shown in Fig. 6~10 and is described as follows. Marking Ž in each figures shows the measurement value of material A and marking   the measurement value of material B and the solid line and broken line show

the approximate value to those values.

<u>Moisture diffusivity due to moisture content gradient (D_θ)</u>   The D_θ in absorption process for material A and B is shown in Fig. 6. There is a tendency for the value to fall rapidly in the region of 32 vol% or more in case of material A and in region of 16 vol% or more in material B. A suitable approximate straight line is assumed in these cases.

<u>Moisture diffusivity due to temperature gradient (D_T)</u>   Fig. 7 shows the measured ε. If ε and D_θ are already known, the moisture diffusivity due to temperature gradient D_T is obtained by $D_T = \varepsilon \cdot D_\theta$. D_T obtained from D_θ in Fig. 6 and ε in Fig. 7 is shown in Fig. 8.

<u>Thermal conductivity</u> The relation between the thermal conductivity and the moisture content of each material is measured by the non-steady method as shown in Fig. 9.

<u>Equilibrium moisture content</u>   Specimens from both materials are set for a long time in five vessels. They include saturated solutions of five kinds of salt respectively. The air temperature in them is kept at 20°C. Equilibrium moisture content can be obtained from their dry weight and wet weight after the weight change of each specimen is nearly all lost. The result is shown in Fig. 8.

3.3 Method of calculation

The implicit finite difference method of a Crank-Nicholson type is applied to equation (1)~(10). A numerical calculation of the change of internal moisture content has been performed. The time division Δt was $1/20 \sim 1/60$[h]. The divided size Δx was assumed 0.0025[m] (divided into 12 parts). The vapour pressure P_s at the indoor side surface of the specimens is calculated from surface temperature T_s and the relative humidity, which correspond to surface moisture content θ_s in the equilibrium moisture content curve of the specimens.
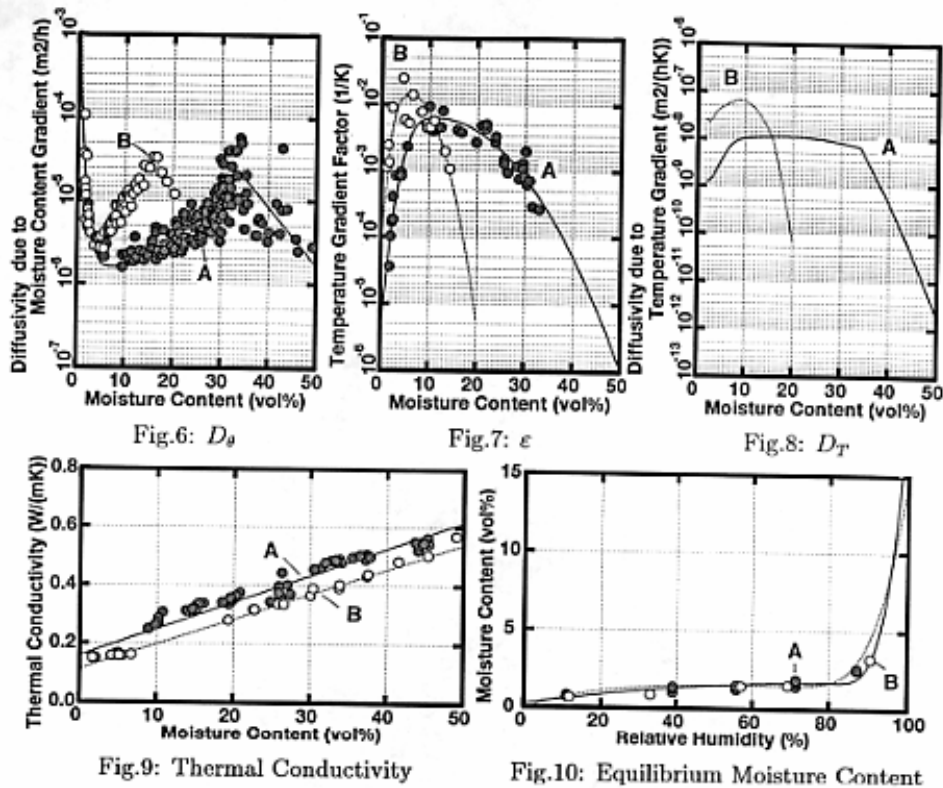
Fig.6: D_θ Fig.7: ε Fig.8: D_T

Fig.9: Thermal Conductivity   Fig.10: Equilibrium Moisture Content

Fig. 6: D_θ Fig. 7 : ε Fig. 8: D_T
Fig. 9: Thermal conductivity   Fig. 10: Equilibrium Moisture Content

The heat transfer coefficient and the vapour transfer coefficient between room air and the surface of the specimen are assumed to be α = 10.0 [W.m²K] and α' = 0.18 x 10^{-7} [m³/(m²h · Pa)] respectively. R_{AB} = (0.067[(m² · K)/W]) and R'_{AB} (=1.1 x 10^7 [(m²·h·Pa)/m³]) were estimated from the value α, α' and in particular sensible analysis was performed.

3.4 Results of calculation (compared with experimental results)

<u>Change of average moisture content</u>   The calculated values of the change of average moisture content are shown in Fig. 11~12. In the figures, the thin broken line shows the calculated value by Model 1 and the thick broken line shows the calculated value by Model 2.

In Fig. 11, the calculated value of Model 1 agree with the measured values from specimens for moisture content distribution at 0~15 days, but after 30 days the calculated value reaches a steady state at 6 vol%, while measured values increase. The calculated value of Model 2 agrees with the measured values.

In Fig. 12, the calculated value of Model 1 agree with the measured values from specimens for moisture content distribution at 0~10 days, but after 20 days the calculated value reaches a steady state at 9 vol%, while measured values increase. The calculated value of model 2 agrees with the measured values.

<u>Changes in moisture content distribution</u> The calculated values of the change of moisture content distribution are shown in Fig. 13~14. In the figures, the thin solid line ~ broken line show the calculated values by Model 1 and thick solid line ~ broken line show the values

calculated by Model 2. These lines correspond to the change of the moisture content at the center location of each piece from sliced specimen.
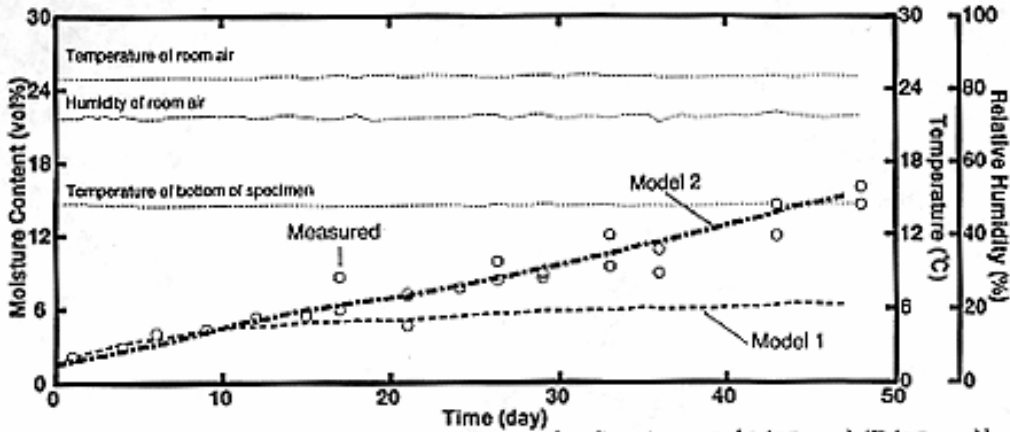

Fig.11: Change of average moisture content for Specimen 1 [A(15mm)/B(15mm)]
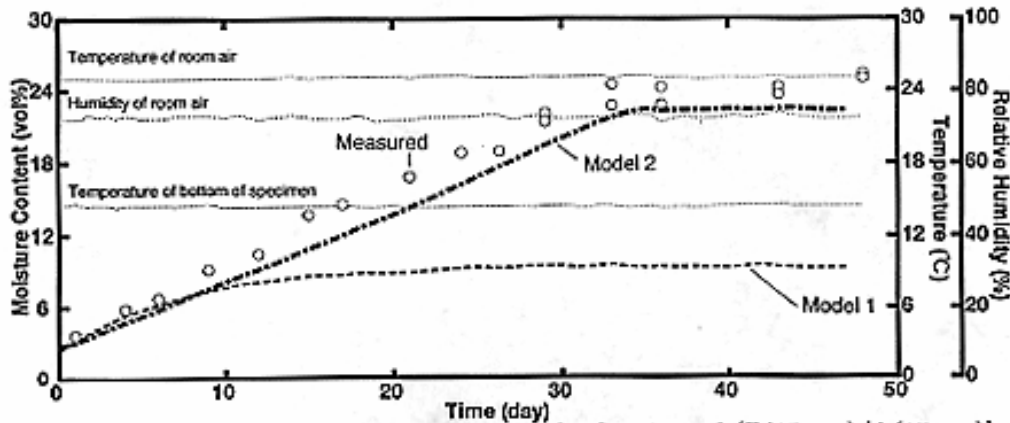

Fig.12: Change of average moisture content for Specimen 2 [B(15mm)/A(15mm)]

Fig. 11 : Change of average moisture content for Specimen 1 [A(15mm)/B(15mm)]
Fig. 12: Change of average moisture content for Specimen 2 [B(15mm)/A(15mm)]

In Fig. 13, the values calculated by Model 1 agree with the measured values at 0~20 days to some degree, but after that the calculated values do not show the tendency to bipolarize in their distribution which the measured values show. The calculated values by Model 2 agree with the measured value on the whole, except in the initial days of the condensation process.

In Fig. 14, the values calculated in Model 1 do not also show the tendency to bipolarize in their distribution, which the measured values show. The calculated values from Model 2 agree with the measured values at 0~23 days, but after that, in the lower material A, the calculated values are higher than the measured values.

3.5 Sensible Analyses on R_{AB} and R'_{AB}

The sensible analyses on the effects of R_{AB} and R'_{AB} upon the internal average moisture content change were conducted in order to investigate the properties of them by the calculation Model 2. In calculation, it is assumed that the temperature of room air is constantly 25°C, the temperature of bottom surface of specimens 14.5°C, the humidity of

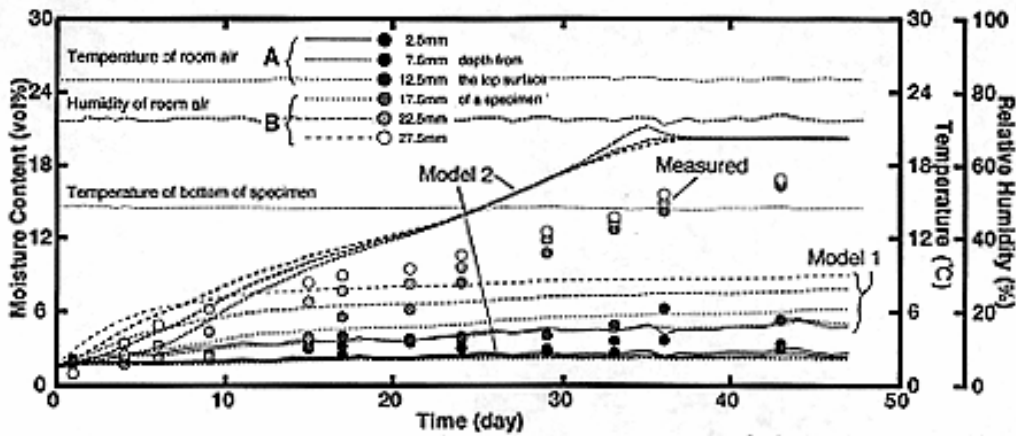room air 72%. The results are shown in Fig. 15~18.

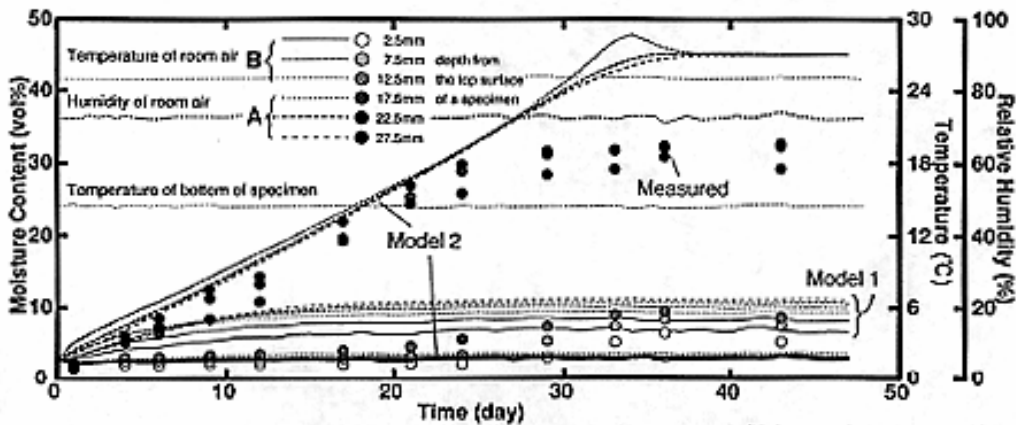Fig.13: Change of moisture content distribution for Specimen 1 [A(15mm)/B(15mm)]

Fig.14: Change of moisture content distribution for Specimen 2 [B(15mm)/A(15mm)]

Fig. 13 : Change of moisture content distribution for Specimen 1 [A(15mm)/B(15mm)]
Fig. 14 : Change of moisture content distribution for Specimen 2 [B(15mm)/A(15mm)]

In Fig. 15, in the case of Specimen 1, the calculated value of the average moisture content change by standard $R_{AB}(= 0.067[(m^2.K)/W] \equiv \overline{R_{AB}})$ is shown as a solid line, by $\overline{R_{AB}}x0.5$ as a two-dotted chain line, by $\overline{R_{AB}}x0.8$ as a chain line, by $\overline{R_{AB}}x1.3$ as broken line. The initial gradient of the moisture content change has a tendency to be small when the R_{AB} value is large, but in the case of the small R_{AB}, the moisture content change reaches a steady state at about 6 vol%, while in the other cases the average moisture content continuously increase.

In Fig. 16, in the case of Specimen 2, the calculated value of the average moisture content change by $\overline{R_{AB}}$ is shown as a solid line, by $\overline{R_{AB}}x0.5$ as a two-dotted chain line, by $\overline{R_{AB}}x0.25$ as a chain line, by $\overline{R_{AB}}x2.0$ as a broken line. The gradient of the average moisture content change tends to be large when the R_{AB} value becomes large, but the difference of gradient is small. The moisture content value at the steady state tends to be large when the R_{AB} value is small.

In Fig. 17, in the case of Specimen 1, the calculated value of the average moisture

content change by standard $R'_{AB} (= 1.1 \times 10^7 [(m^2.h.Pa)/m^2] \equiv \overline{R'_{AB}})$ is shown as a solid line, by $\overline{R'_{AB}} x 0.5$ as a chain line, by $\overline{R'_{AB}} x 0.25$ as a two-dotted chain line, by $\overline{R'_{AB}} x 2.0$ as a broken line. The gradient of the average moisture content change tends to be small when the R'_{AB} value is large except in the initial term.
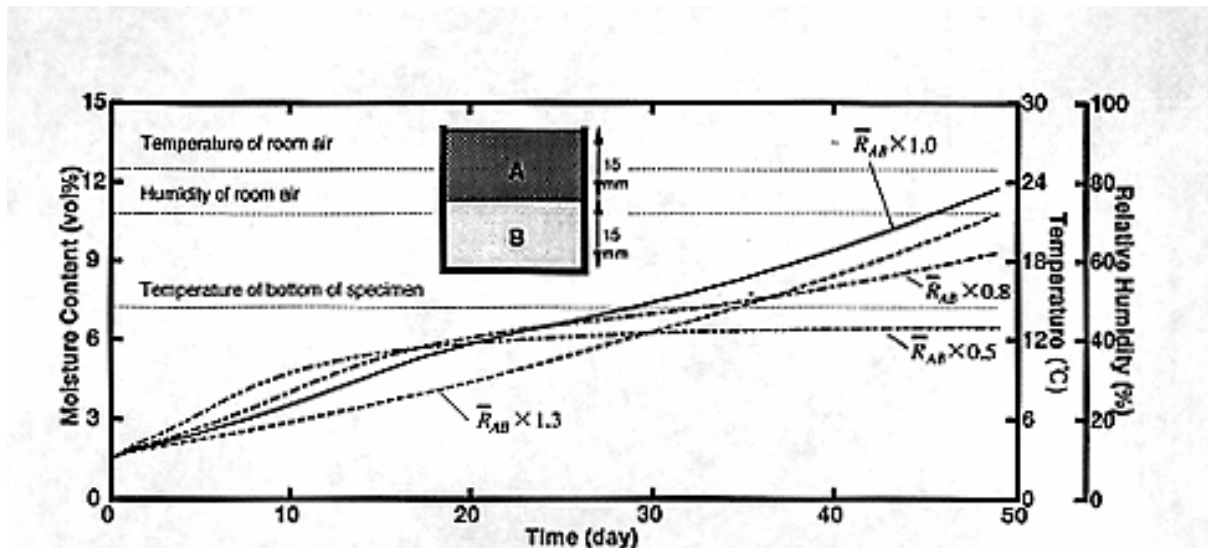

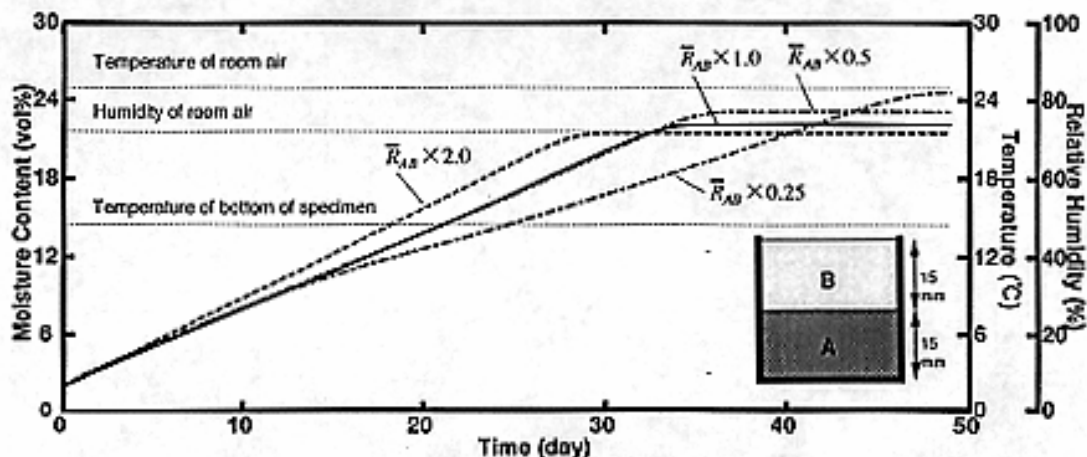Fig.15: Sensible analysis on R_{AB} for Specimen 1 [A(15mm)/B(15mm)]

Fig.16: Sensible analysis on R_{AB} for Specimen 2 [B(15mm)/A(15mm)]

Fig. 15 : Sensible analysis on R_{AB} for Specimen 1 [A(15mm)/B(15mm)]
Fig. 16: Sensible analysis on R_{AB} for Specimen 2 [B(15mm)/A(15mm)]

In Fig. 18, in the case of Specimen 2, the calculated value of the average moisture content change by $\overline{R'_{AB}}$ is shown as a solid line, by $\overline{R'_{AB}} x 0.5$ as a chain line, by $\overline{R'_{AB}} x 0.25$ as a two-dotted chain line, by $\overline{R'_{AB}} x 2.0$ as a broken line. The gradient of the average moisture content change tends to be small when the R'_{AB} value is large. The moisture content value at the steady state tends to be large when the R'_{AB} value is small.

4. CONCLUSION

The change in the internal moisture content within the double layer wall materials were measured and numerically calculated in the condensation process. Those results are compared

and discussed, and prove the following.

- The change of internal moisture content in double layer walls shows the tendency to bipolarize in the condensation process.

- The calculated values of the internal moisture behavior do not agree with the measured values when no resistance at the interface between two layers is used as a boundary condition. It should be assumed that there will be some resistance in heat and moisture movement at the interface.
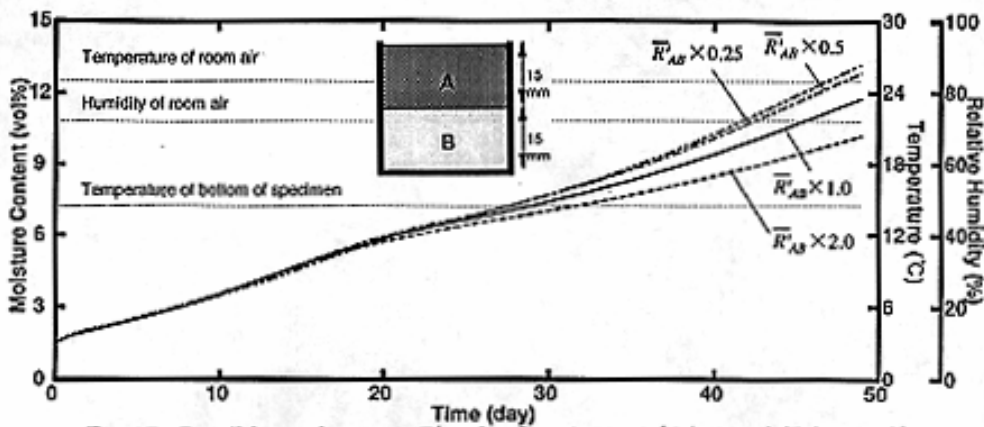

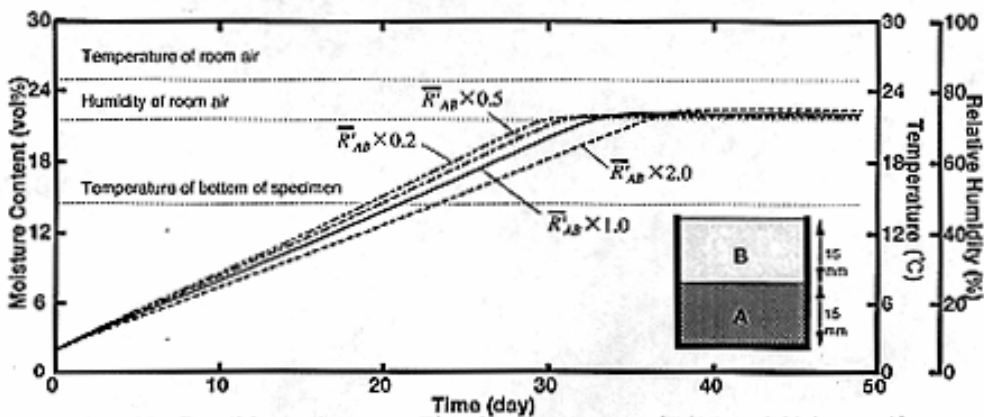Fig.17: Sensible analysis on R'_{AB} for Specimen 1 [A(15mm)/B(15mm)]

Fig.18: Sensible analysis on R'_{AB} for Specimen 2 [B(15mm)/A(15mm)]

Fig. 17: Sensible analysis on R'$_{AB}$ for Specimen 1 [A(15mm)/B(15mm)]
Fig. 18: Sensible analysis on R'$_{AB}$ for Specimen 2 [B(15mm)/A(15mm)]

- The resistance of heat and moisture flux at the interface between double layers effects on the internal moisture content.

NOMENCLATURE

θ : moisture content [vol%]

T	:	temperature	[°C]
D_θ	:	moisture diffusivity due to moisture content gradient	[m²/h]
D_T	:	moisture diffusivity due to temperature gradient	[m²/(h·K)]
c	:	specific heat of material	[W·h/(kg·K)]
γ	:	specific weight of material	[kg/m³]
λ_θ	:	thermal conductivity	[W/(m·K)]
α	:	heat transfer coefficient	[W/(m²·K)]
T_i	:	room air temperature	[°C]
T_s	:	surface temperature of specimen	[°C]
α'	:	moisture transfer coefficient	[m³/(m²·h·Pa)]
P_i	:	water vapour pressure of room air	[Pa]
P_s	:	water vapour pressure at the surface of specimen	[Pa]
T_d	:	temperature at the vapour barrier surface	[°C]
ε	:	temperature gradient factor	[1/K]
R_{AB}	:	equivalent resistance for heat flux at the interface	[(m²·K)/W]
R'_{AB}	:	equivalent resistance for moisture flux at the interface	[(m²·h·Pa)/m³]

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