THE EFFECT OF PCM INTERIOR FINISHING MATERIAL WITH MOISTURE SORPTION AND DESORPTION CHARACTERISTICS ON HYGROTHERMAL CONTROLL OF ROOMS

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ABSTRACT

In this paper, the hygrothermal controll material, the interior finishing material with moisture sorption and desorption characteristics containing PCM (Phase Change Material utilizing latent heat), is developed to provide the function of constant temperature and humidity in buildings. The model experiments and the numerical simulation have examined the influence of the hygrothermal controll materials on the indoor environment. The simulation software "THERB" which has complete HAM features (heat and moisture transfer and airflow) including principles of moisture transfer within walls is used and its accuracy is also verified through the comparison of the calculations and the experiments.

INTRODUCTION

Japanese houses of recent years tend to be insulated and built airtight to improve the indoor thermal environment and to decrease the heating and cooling load, and, putting more emphasis on handiness in construction and certainty of precision, the building method and materials have both changed from the traditional house "wet type" with clay walls to the "dry type" house in which industrial building materials such as ceramic siding and plasterboard are used.

Due to the enforcement of the "Energy Conservation Standard for Housing" and the "Housing Performance Indication Law" in Japan, insulation and air-tightness have been all the more emphasized, and concomitantly, the qualitative descriptive explanation in the past about the housing thermal performance has shifted to a numerical quantitative evaluation. As a result, insulation and air-tightness have drastically advanced, and yet, the performance is indicated by "specification standard" or "thermal loss coefficient" without reflecting free cooling, solar heat gain, thermal storage in buildings, and internal heat and moisture generation from the dynamic phenomena arising from human living.

In addition, the factors significantly interconnected to the comfort such as indoor humidity variation with moisture sorption and desorption of walls and thermal radiation have also been disregarded. In other words, the characteristics such as variation in temperature and moisture properties, specific to the individual construction method and building materials used for wet and dry types respectively have not been taken into account. This has slashed demand for the wet construction method and, on the contrary, has exponentially driven up contrariwise the demand for the dry method.

It has been generally evaluated that the wet construction method is very limited in energy conservation due to inferior insulation and air-tightness although it is excellent in heat storage and moisture sorption and desorption of walls (constant or equilibrium temperature and humidity) compared to the dry method. In this paper, the hygrothermal controll material, the interior finishing material with moisture sorption and desorption characteristics containing PCM (Phase Change Material utilizing latent heat), is developed to provide the function of constant temperature and humidity to the dry construction method. Then the model experiments and the numerial simulation have examined the influence of the hygrothermal controll materials on the indoor environment.

PCM INTERIOR FINISHING MATERIAL WITH MOISTURE SORPTION AND DESORPTION CHARACTERISTICS

A phase change material (PCM) is composed of from paraffin and can storage heat by utilizing its latent heat. PCM absorbs melting heat from indoor air when it increases to the melting point in temperature. And in reverse action, PCM diffuses, to the contrary, solidification heat to indoor air when it decreases to the freezing point in temperature. In the range of phase-change between solid and liquid, the apparent specific heat of PCM becomes extremely large and the PCM temperature is kept constant as a result of the melting heat and solidification heat. Indoor air is also maintained at a definite temperature because of the endothermic and exothermic response of PCM (Zalba et al., 2003, Khudhair et al., 2004, Tyagi et al., 2007).

The moisture sorption and desorption material has a function of humidity conditioning of indoor air. It adsorbs moisture when the ambient humidity increases and it also releases, to the contrary, moisture when the ambient humidity decreases. The pores of the material, which is particularly porous structure, characterizes the range of humidity conditioning, the moisture sorption and desorption rate and its amount.

We have developed the interior finishing material with moisture sorption and desorption characteristics containing PCM, hereinafter called the humidity conditioning material containing PCM (the HCMP), by using a base material composed of mineral fiber and volcanic glass. Microcapsules of PCM are contained 10% into the base material per unit volume.

MODEL EXPERIMENTS

Figure 1 illustrates the model experiments. The model rooms in the shape of regular hexahedrons (inside dimension: 30cm wide, 30cm high and 30cm long) are constructed by using three interior finishing materials of the plasterboard, the humidity conditioning material (HCM) and the humidity conditioning material containing PCM (HCMP). The outside of the model rooms are insulated by polyurethane (25mm). Aluminium foil and polyethylene sheets are installed on all-external sides of the interior finishing materials and polyurethane, respectively, as the moisture-proof materials. The venting holes are bored at the diagonal high and low positions and the room air is mechanically ventilated with air change rate of 0.5 times per hour. The model rooms are placed in the environmental test laboratory.

Tables 1 to 3 describe the experimental conditions and material properties. The moisture capacity indicated in the table 2 is defined as the gradient of the moisture content ϕ for the unsaturated water potential μ ($\partial\phi/\partial\mu$) as described in Eq.(2). Figures 2 to 3 shows the sorption curves (the equilibrium moisture content) of the plasterboard and the humidity conditioning material. Temperature and relative humidity in the environmental test laboratory, which are assumed to be the outdoor air, are varied between 16 degrees C, 90% to 24 degrees C, 55% in a cycle of six hours (Absolute humidity is kept at constant). The model rooms have been cured in the conditions of 16 degrees C, 90% for three days prior to the start of the experiment.

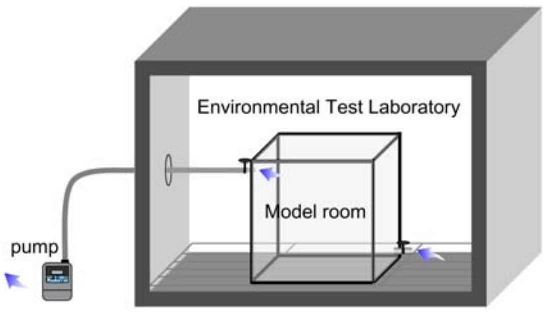

Figure 1 The model experiments

Table 1 Experimental Conditions

Environmental test laboratory *				**Model room**		
Temperature	16°C	24°C	16°C	Temperature	Relative humidity	Air change rate
Relative humidity	90%	55%	90%	Non-conditioning		0.5 times/hour

* Repeating

Table 2 Properties of the Base Materials

		Plasterboard	**HCM** *	**HCMP** **
Thickness	[mm]	12		
Thermal conductivity	[W/(m·K)]	0.220	0.096	
Specific heat	[J/(kg·K)]	650	978	
Specific density	[kg/m^3]	700	820	
Moisture conductivity	[kg/(m·s·Pa)]	1.880e-11	1.360e-11	
Moisture Capacity***	[kg/(m^3·kJ/kg)]	1.832e-02	7.364e-01	
PCM		non-containing		containing 10% per unit volume

* HCM : Humidity conditioning material
** HCMP : Humidity conditioning material containing PCM
*** Moisture Capacity for the range 40% to 80% relative humidity

Table 3 Properties of PCM

Phase change temperature	[°C]	18 - 22
Specific heat (Liquid and Solid phase)	[kJ/(kg·K)]	2.0
(Phase change heat)	[kJ/(kg·K)]	125.0
Specific density (Liquid and Solid phase)	[kg/m^3]	300.0

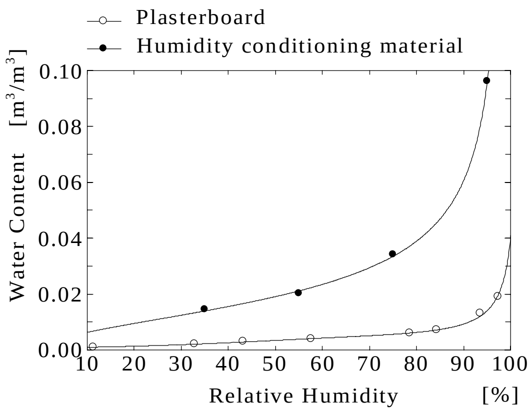

Figure 2 Equilibrium moisture content for relative humidity

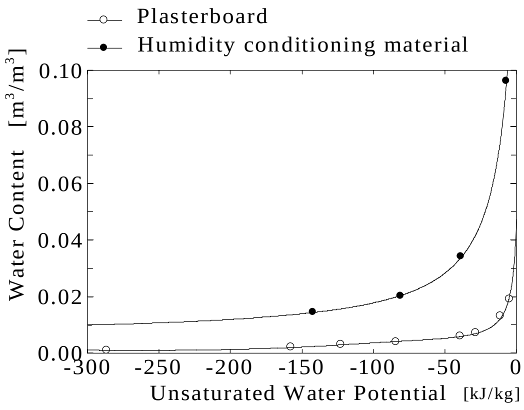

Figure 3 Equilibrium moisture content for the unsaturated water potential

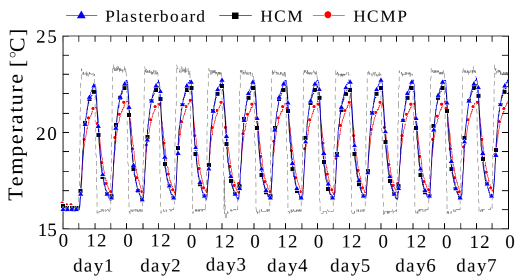

Figure 4 Air temperature in the model room

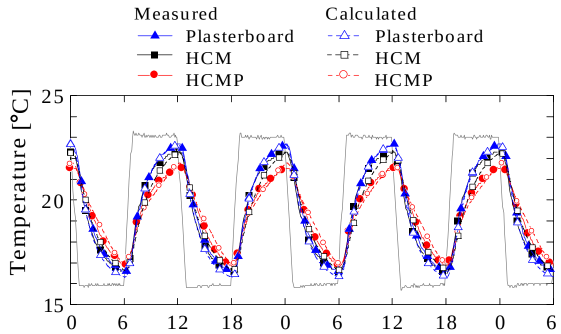

Figure 6 Measured and calculated air temperature (54 hours after 3 days)

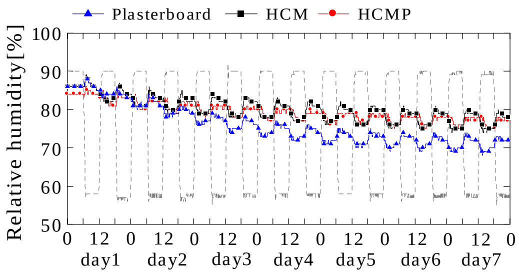

Figure 5 Relative humidity in the model room

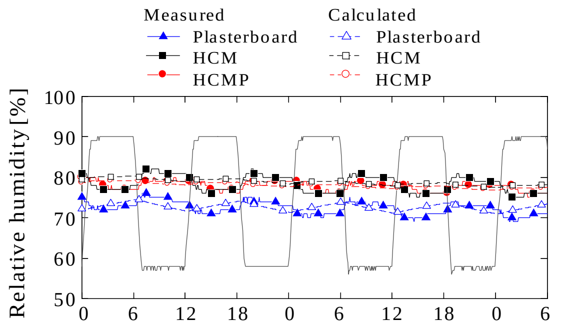

Figure 7 Measured and calculated relative humidity (54 hours after 3 days)

Figures 4 to 7 show the fluctuation of temperature and relative humidity of the model room air for the first seven days and for 54 hours after three days of starting the experiment. Figures 6 and 7 show the calculated results and the measured results. Comparing the temperature of each model room with different finishing materials, there is really not much difference between the plasterboard and the humidity conditioning material. The temperature of the model room using the humidity conditioning material containing PCM fluctuates sluggishly and then the maximum temperature becomes lower and the minimum temperature becomes higher than the other model rooms. PCM is functioning as a heat storage material because of the endothermic and exothermic response caused by phase-change. Comparing the relative humidity of each model room, the plasterboard finishing decreases less than the others using the humidity conditioning material. Particularly, the difference between the plasterboard and the others gradually increases after three days of starting the experiment.

NUMERICAL SIMULATION

Numerical model of heat and moisture transfer

Water Potential which is derived by applying the chemical potential of thermodynamics to moisture diffusion is used as the driving force of moisture transfer. The numerical model called P-model using water potential (Ozaki et al., 2001) makes it possible to combine moisture transfer with heat transfer perfectly, and take into account internal energy and external forces such as gravity. The balance equations of heat and moisture transfer in material are obtained as follows.

- Heat balance

$$\frac{\partial C\rho T}{\partial t} + c_{lw} j_{lw} \nabla T = \nabla \lambda \nabla T + r_v \nabla \lambda_g' \nabla \left(\mu_w + \mu_f\right) \quad (1)$$

- Moisture balance

$$\rho_{lw} \frac{\partial \phi}{\partial \mu} \frac{\partial \mu}{\partial t} = \nabla \lambda_g' \nabla \left(\mu_w + \mu_f\right) + \nabla \lambda_l' \nabla \left(\mu + \mu_f\right) \quad (2)$$

where C and ρ are specific heat and specific density of material containing water. c_{lw}, ρ_{lw} and j_{lw} are specific heat, specific density and flux of liquid phase water. λ is thermal conductivity. λ_g' and λ_l' are gaseous and liquid phase water conductivity for μ_w and μ gradients. r_v is heat of sorption (= latent heat of evaporation).

μ_w is the water potential and defined from the basic thermodynamic principles as Eqs.(3) to (5). The water potential is composed by the saturated water potential μ_w^o and the unsaturated water potential μ. μ_w^o expresses the thermodynamic energy of saturated vapour and μ expresses the difference of thermodynamic energy between the saturated vapour and the unsaturated vapour of moisten air.

$$\mu_w(p,T) = \mu_w^o(T) + \mu(p) \quad (3)$$

$$\mu_w^o(T) = 6.44243 \times 10^5 + c_{p,w_{kg}} (T - 273.15)$$
$$- Tc_{p,w_{kg}} \ln \frac{T}{273.15} + R_{w_{kg}} T \ln \frac{p_s}{1.01325 \times 10^5} \quad (4)$$

$$\mu(p) = R_{w_{kg}} T \ln \frac{p_w}{p_s} \quad (5)$$

where p_w is the vapor pressure of the humid air, and p_s is the saturated vapor pressure at temperature T. $c_{p,w_{kg}}$ is the specific heat which is expressed in units of [J/(kg K)] and $R_{w_{kg}}$ = 461.50 [J/(kg K)] which is calculated by dividing the gas constant R = 8.31441 [J/(mol K)] by the molecular weight of water 18.016x10-3 [kg/mol].

μ_f is the force water potential caused by internal energy and external forces. For instance, the force water potential which includes the influences of gravity and internal pressure is calculated by Eq.(6).

$$\mu_f = gz + p\overline{V}_w \quad (6)$$

where g is gravitational constant, z is height from reference position, $\overline{V}_w$ is the volume per unit weight of water and $p\overline{V}_w$ is equal to $R_{w_{kg}} T$.

The boundary conditions of the heat and moisture balance equations are expressed as follows.

- Boundary conditions

$$-\lambda \frac{\partial T}{\partial n_v} - r_v \cdot \lambda_g' \frac{\partial \mu_w}{\partial n_v} \quad (7)$$

$$-\lambda_g' \frac{\partial \mu_w}{\partial n_v} = \alpha_\mu' \left(\mu_{w,a} - \mu_{w,s}\right) \quad (8)$$

where n_v is normal line vector directed inward on a boundary surface, q_s is quantity of radiant heat. T_a, T_s, $\mu_{w,a}$ and $\mu_{w,s}$ are the temperature and water potential of the air and surface, respectively. α_c is the convective heat transfer coefficient and α_μ' is the convective moisture transfer coefficient for the water potential gradient. α_μ' can be calculated from the general convective moisture transfer coefficient α_p' for the vapour pressure gradient on the basis of Eq.(3).

$$\alpha_\mu' = \alpha_p' \left(\frac{\partial p_w}{\partial \mu_w}\right) = \alpha_p' \frac{p_s}{R_{w_{kg}} T} e^{\mu / R_{w_{kg}} T} \quad (9)$$

Simulation software

A Heat, Air and Moisture (HAM) simulation software called THERB for HAM has been developed for the purpose of estimating the hygrothermal environment within buildings (Ozaki et al., 2005). THERB is a dynamic simulation software which can estimate temperature, humidity, sensible temperature and heating/cooling load for multiple zone buildings and wall assemblies. This software has complete HAM features including principles of moisture transfer within walls. The heat and moisture transfer models such as conduction, convection, radiation and ventilation (or air leakage) are based upon the detailed phenomena describing actual building physics (Ozaki et al., 2006), and can be applied to all forms of building design, structure or occupant schedules, etc. All the phenomena are calculated without simplification of the heat and moisture transfer principles of any building component or element. The moisture transfer model called P-model using the water potential, which is defined as thermodynamic energy, is a progressive feature of THERB, which incorporates moisture transfer including moisture sorption and desorption of walls. Thus THERB can predict the hygrothermal environment of the whole building taking into consideration the complex relationship between heat and moisture transfer and air flow in detail.

Comparing the calculated and measured results in Figures 6 and 7 (The liquid phase water conduction is ignored here because the calculated range is mostly less than 80% relative humidity.), the calculated results of temperature and humidity are in excellent agreement with the measured results. The simulation software THERB shows an extreme precision.

Calculation conditions

Figures 8 and 9 illustrate the building model assumed to be a detached house for numerical simulation. This house is highly insulated and its thermal performance is following the "Energy Conservation Standard for Housing" in Japan (IBEC, 2007). Table 4 describes the calculation conditions. Table 5 indicates the hygrothermal properties of the interior finishing materials (plasterboard and two kinds of humidity conditioning materials). A total of six materials based on the different kind of three base materials and the absence or presence of PCM are applied as the interior finishing. The standard weather data in Osaka is used. The calculated results for a room on the first floor are just explained in the following.

Performance of the humidity conditioning materials containing PCM

Figures 10 and 11 show the calculated temperature and relative humidity of rooms applying the plasterboard and the B-humidity conditioning material containing PCM (hereinafter called B-HCMP) on November 7th and 8th. The fluctuation of indoor air temperature and humidity of the B-HCMP is sluggish and its daily range is less than the plasterboard. The lowest temperature of the B-HCMP is 19.5 degrees C, while the indoor temperature of the plasterboard decreases to 17.2 degrees C. The indoor humidity of the B-HCMP fluctuates slowly in a range from 38% to 45%, while that of the plasterboard fluctuates rapidly in the range from 29% to 52%. Figures 12 and 13 show the frequency of distribution and cumulative ratio of appearance time of the indoor temperature and humidity during the period of October to November. There is not much difference between the plasterboard and the B-HCMP in the range below 14 degrees C and above 30 degrees C. Meanwhile, the percentage in the range from 16 to 18 degrees C and from 22 to 28 degrees C is higher in the plasterboard and the B-HCMP, respectively. The indoor temperature around 22 degrees C appears with

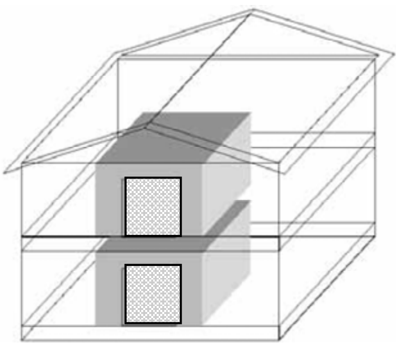

Figure 8 Building model

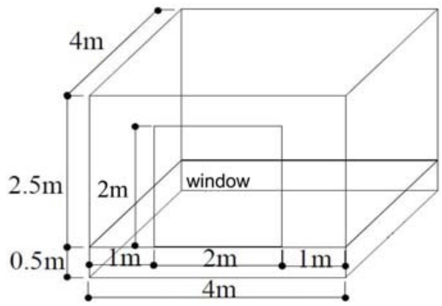

Figure 9 Target room of calculation (1F)

Table 4 Calculation Conditions

Floor area	**Volume**	**Air change rate**
16 m^3	40 m^3	0.5 times/hour
Weather data	Standard weather data in Osaka	
Indoor condition	Jun. to Jul. (Non-conditioning) Oct. to Nov. (Non-conditioning) Dec. to Mar. (Intermittent heating 7:00 to 23:00)	

Table 5 Properties of Components

		Plaster board*	**A - HCM***	**B - HCM***
Thickness	[mm]	9		
Thermal conductivity	[W/(m･K)]	0.220		0.096
Specific heat	[J/(kg･K)]	650		978
Specific density	[kg/m^3]	700		820
Moisture conductivity	[kg/(m･s･Pa)]	1.880e-11	1.360e-11	
Moisture capacity	[kg/(m^3･J/kg)]	1.832e-02	7.364e-01	

* A total of six materials, which are based on the different kind of three base materials and the absence or presence of PCM, are applied.

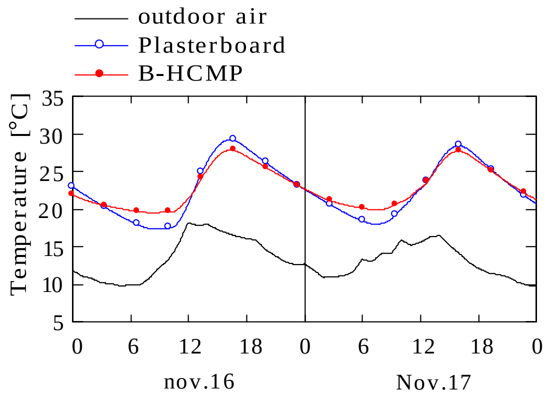

Figure 10 Room air temperature in the fall

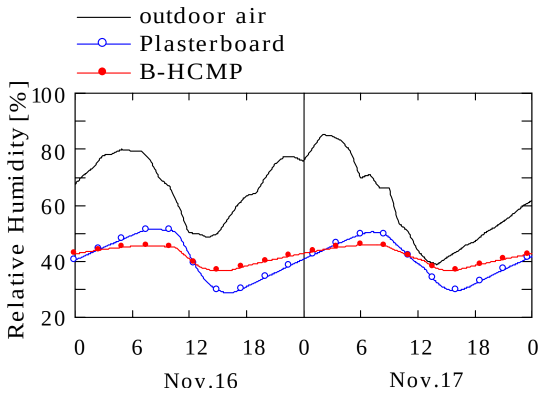

Figure 11 Calculated Relative humidity in the fall

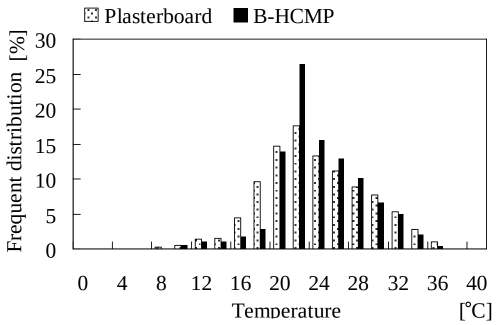

Figure 12 Frequent distribution of room of temperature in the fall

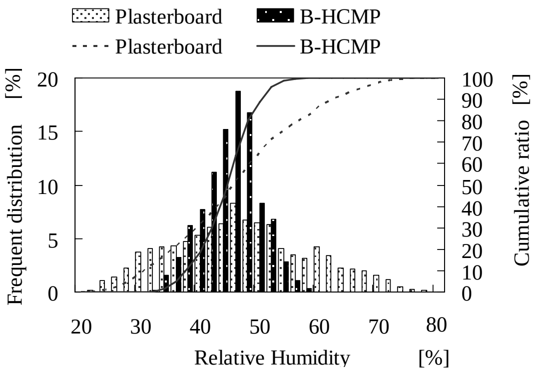

Figure 13 Frequent distribution of room relative humidity in the fall

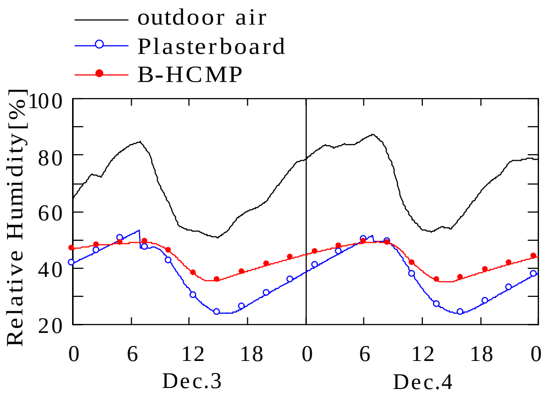

Figure 14 Calculated relative humidity in Winter

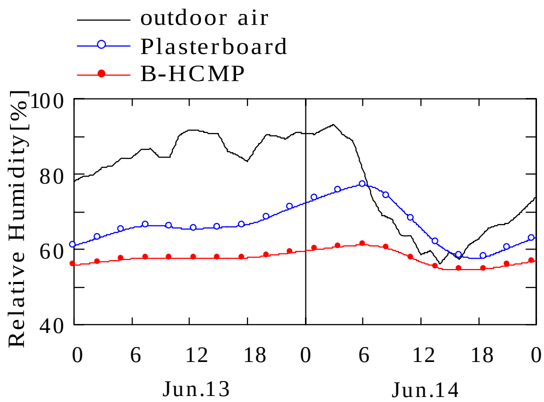

Figure 16 Calculated relative humidity in Summer

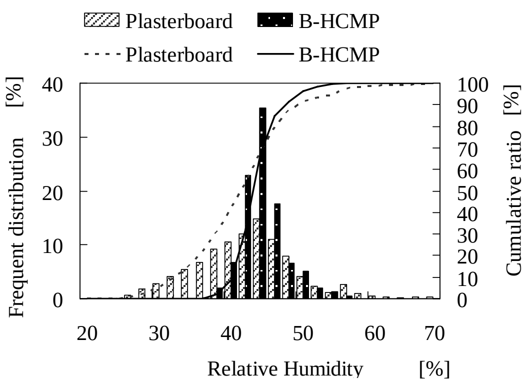

Figure 15 Frequent and Cumulative distribution of relative humidity in Winter

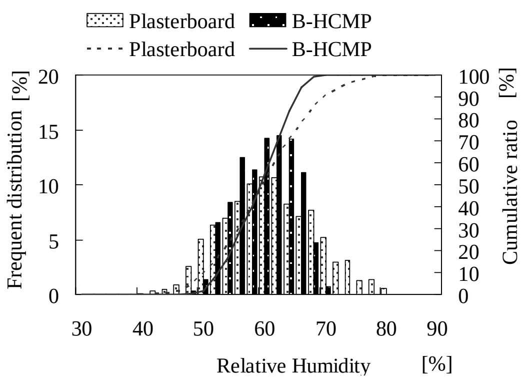

Figure 17 Frequent and Cumulative distribution of relative humidity in Summer

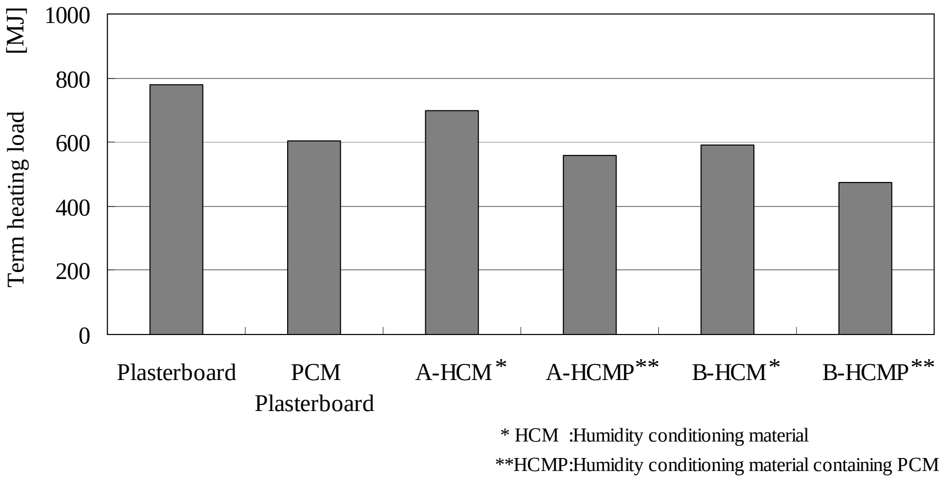

Figure 18 Term heating load (from December to March)

significant frequency in the B-HCMP because of the heat storage in PCM. The indoor humidity of the B-HCMP is mostly concentrated in the middle range from 34% to 58%, while that of the plasterboard is widely distributed in the range from 20% to 78%. The B-HCMP has an excellent performance of hygrothermal conditioning of a room because of the multiplier action of the heat storage in PCM and the moisture sorption and desorption of the humidity conditioning material.

Figure 14 shows the calculated relative humidity of rooms applying the plasterboard and the B-HCMP on December 3rd and 4th. The indoor humidity of the plasterboard decreases to 24% during heating time. The room applying the plasterboard is over dried by heating. The indoor humidity of the B-HCMP is higher than 35%. Figure 15 shows the frequency of distribution and cumulative ratio of appearance time of the indoor humidity on heating time during the period of December to March. The plasterboard has a high proportion in the range below 40%, while the B-HCMP is kept above 40%. The B-HCMP can prevent humidity decrease during heating time.

Figure 16 shows the calculated relative humidity of rooms applying the plasterboard and the B-HCMP on June 13th and 14th. The indoor humidity of the plasterboard becomes higher than that of the B-HCMP throughout the day. Figure 17 shows the frequency of distribution and cumulative ratio of appearance time of the indoor humidity during the period of June to July (during the rainy season). The plasterboard has a high proportion in the range above 70%, while the B-HCMP is kept below 70%. The B-HCMP can prevent humidity increase in the rainy season.

Term heating loads

Figure 18 shows the term heating loads of rooms applying different kinds of interior finishing materials, which are differ in the base material and the absence or presence of PCM. By containing PCM, the term heating loads are decreased about 23%, 20%, 19% in order of the plasterboard, A-HCM and B-HCM. The effect of heat storage by PCM becomes larger in the base material of higher thermal conductivity. The term heating load of the B-HCMP is reduced by approximately 40% as compare to the plasterboard because of the joint results of the heat storage in PCM and the improvement of thermal insulation performance.

CONCLUSION

In this paper, the effects of the hygrothermal controll materials, which have been developed to provide the function of constant temperature and humidity in buildings, were examined by the experiments and numerical simulation. The major results obtained are listed below.

1) The interior finishing material with moisture sorption and desorption characteristics containing PCM (HCMP) is developed by incorporating PCM into the base material composed of mineral fiber and volcanic glass.
2) The HCMP has an excellent performance of hygrothermal conditioning of room. The indoor temperature and humidity mostly concentrates in the middle range from 22 to 28 degrees C and 34% to 58% in fall because of the multiplier action of the heat storage in PCM and the moisture sorption and desorption of the humidity conditioning material.
3) The room using the plasterboard is over dried to a range below 40% by heating, while the HCMP can prevent humidity decrease and maintain the indoor humidity above 40% during heating time.
4) The HCMP can prevent humidity increase in the rainy season. The plasterboard has a high proportion in the range above 70%, while the HCMP is kept below 70%.

5) The HCMP can dramatically reduce the term heating load because of the joint results of the heat storage in PCM and the improvement of thermal insulation performance of the base material.
6) A Heat, Air and Moisture simulation software called THERB for HAM, which has complete HAM features including principles of moisture transfer within walls, shows the extreme precision through the comparison of measurement and calculation.

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