Effective Moisture Diffusivity of Super Absorbent Polymer Gel and Pearlite-Mortar with Gel

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ABSTRACT

A fire wall and a fire resistant covering material are made of a mixture of cement mortar and aqua-reserve agents such as a silica gel or a humid pearlite. However, such a fire wall does not show a good fire resistant characteristics since the aqua-reserve agent such as the silica gel contains a small amount of water in it. A super absorbent polymer gel which absorbs aqueous solution of calcium chloride, absorbs or evaporates water vapor until it reaches to the equilibrium state when a humidity of a room changes. Therefore, the gel could be used as the aqua-reserve agent for the fire wall since it contains much water comparing with the silica gel. In this study, the effective diffusivity of the super absorbent polymer gel and the pearlite-mortar in which the gels are mixed, were obtained by experiments. And also the numerical simulation for the moisture diffusion in the formed gel and the pearlite-mortar in which the gels were mixed, were conducted using the obtained effective moisture diffusivity.

NOMENCLATURE

C	Moisture content (dry basis) (kg H_2O/kg dry solid)
D_{air}	Air diffusion coefficient (m^2/s)
D_{eff}	Effective moisture diffusivity of heterogeneous material (m^2/s)
Fo	Fourier number = Dt/x_0^2 (-)
h_D	Average mass transfer coefficient (m/s)
l	Reference length (m)
M	Mass (kg)
Sc	Schmidt number (-)
t	Time (s)
u	Velocity of air flow (m/s)
v	Volume (m^3)
$\overline{W}$	Dimensionless moisture content = $(C-C_e)/(C_{in}-C_e)$ (-)
w	Water vapor concentration (-)

x Space coordinate (m)
x_0 Thickness of the slab (m)
φ relative humidity
ν Coefficient of kinematic viscosity (m^2/s)

INTRODUCTION

A fire wall usually contains moisture in it. When the wall is exposed to the fire flame, water in the wall evaporates and changes into vapor. The latent heat of water in the wall plays important role of the resistance of the heat propagation in the wall. From this fact, a highly water content wall is expected to have a good fire resistant characteristics. Jin et al. (1997a) conducted the numerical analysis to confirm this fact using a simple one dimensional model proposed in their previous report (1997b).

A silica gel or a humid pearlite are widely used as aqua-reserve agents for the fire wall. However, a silica gel contains less than 30 mass% of water in it. Jin et al. (1996) reported that a super absorbent polymer gel which absorbs aqueous solution of calcium chloride, absorbs or evaporates water vapor until it reaches to an equilibrium state when a humidity of a room changes. Therefore, the super absorbent polymer gel could be used as the aqua-reserve agent for the fire wall since it contains much water comparing with the silica gel. Two ways to use the super absorbent polymer gel can be considered. One way is that the gels are formed like a plate and it is inserted in the conventional fire wall. The other way is that the gels are mixed in a conventional fire resistant material such as a pearlite-mortar. In both cases, the moisture of the wall is expected to change with the humidity of the atmosphere. The moisture migration in an unsaturated porous medium has been generally analyzed by Eckert and Faghri (1980). However, the moisture diffusivity of the gel or the mixture of the pearlite mortar and gels have not been investigated yet. Therefore, it is important to know the effective diffusivity of the super absorbent polymer gel and the fire resistant material in which the super absorbent polymer gels are mixed. This is the motivation of the present study.

In this study, the effective diffusivity of the super absorbent polymer gel and the mixture of the pearlite-mortar and the super absorbent polymer gels, were obtained by experiments. And also the numerical simulation for the moisture diffusion in the formed gel and the mixture of the pearlite-mortar and gels were conducted using the experimentally obtained effective moisture diffusivity.

EXPERIMENTS

Analytical Back Ground

The effective moisture diffusivities for the super absorbent polymer gel and the mixture of the pearlite mortar and the gels were calculated using the method of slopes (e.g. Vegenas, 1993), which is based on the solution of the Fick's equation for unsteady-state diffusion. The Fick's equation can be expressed as

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left[D_{eff}\frac{\partial C}{\partial x}\right] \tag{1}$$

under the following initial and boundary conditions:

$$\begin{array}{lll} t = 0 & 0 < x < x_0 & C = C_{in} \\ t > 0 & x = 0 & \partial C / \partial x = 0 \\ t > 0 & x = x_0 & C = C_e \end{array} \tag{2}$$

where C_{in} is the initial moisture content, and C_e is the equilibrium moisture content.

The solution of equations(1) and (2) in the case of a constant diffusivity, D_{eff}, is given by Crank(1975).

$$\overline{W} = \frac{\overline{C} - C_e}{C_{in} - C_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{(2n+1)^2\pi^2 D_{eff}t}{4x_0^{\ 2}}\right] \tag{3}$$

Where $\overline{C}$ represents the mean value of the moisture content of the wall. In the range of the Fourier number of $Fo(= D_{eff}\ t / x_0^{\ 2}) > 0.3$, the first term (n = 0) of Eq.(3) is extremely bigger than the other terms. Then, equation (3) can be rewritten as

$$\overline{W} = \frac{\overline{C} - C_e}{C_{in} - C_e} = \frac{8}{\pi^2}\exp\left[-\frac{\pi^2 Dt}{4x_0^{\ 2}}\right] \tag{4}$$

To apply the method of slopes, the experimental drying curve ($\overline{W}$ versus t) is compared to the theoretical diffusion curve ($\overline{W}$ versus $Fo = D_{eff}t / x_o^2$) for the given shape of the material. The slopes of the experimental drying curve $(d\overline{W}/dt)_{exp}$ and the theoretical curve $(d(\ln\overline{W})/dFo)_{th}$ are estimated at a given concentration of gel (C), using numerical differentiation. Then, the effective moisture diffusivity (D_{eff}) at a given moisture content C is calculated from the equation,

$$D_{eff} = [(d\overline{W}/dt)_{exp} / (d(\ln\overline{W})/dFo)_{rh}]x_o^{\ 2} \tag{5}$$

<u>Measured materials</u>

A glycol bridged polymer is selected for the super absorbent polymer because only this type of the polymer could absorb high concentration aqueous solution of calcium chloride. The selected super absorbent polymer is a powder type and it becomes a swollen gel as the polymer absorbs aqueous solution of calcium chloride. The size of the swollen gel ranges from 0.5 to 1 mm. The moisture diffusivity of the gel layer which absorbed four different concentrations of aqueous solution of calcium chloride (10, 20 30 and 40 mass%), were measured. The experiments were done with three different depth of petri-dishes. One were squeezed into petri-dishes of 5.1 mm depth, and the others were squeezed into petri-dishes of 8.85 and 14.7 mm depth. The diameters of dishes were, respectively, 58.5 ,55.5 and 52.8 mmϕ. The absorbency of the gels are tabulated in Table 1. The absorbency was measured by using a thermo-gravimeter (Seiko Densi Co., TG/DTA 300).

Table 1 Absorbency of polymer

Concentration (mass %)	10	20	30	40 mass %
Absorbency (g/g)	21.6	16.7	15.0	11.0

The moisture diffusivities of twelve different mixtures of a pearlite mortar and the gels which absorb 30 mass% of aqueous solution of calcium chloride, were also measured. Three different fresh pearlite mortars were prepared. The mixture ratio of a fresh pearlite mortar is tabulated in Table 2. And the mixture ratio of the fresh pearlite mortar and the gels are tabulated in Table 3. These mixtures whose volume ratio of the pearlite and the cement was unity, were squeezed into petri-dishes of 11.7 mm depth, and the other mixtures were squeezed into petri-dishes of 14.7 mm depth. The diameters of dishes were, respectively, 51 and 50 mmϕ. These mixtures were cured in a thermo-hygrostat (Shimazu Physical & Chemical Appliances Corp. HT30W) operated at 25 °C and relative humidity of 80 % for 21 days.

Table 2 Mixture ratio of a fresh pearlite mortar

Water/Cement weight ratio (W/C)	Pearlite/Cement volume ratio (V_{pearl}/V_{cem})
0.53	1
0.53	2
0.53	3

Table 3 Mixture ratio of gels and fresh mortar

Volume ratio of gels and fresh pearlite mortar (V_{gel}/V_{mor})
0.5
1
1.5
2

Experimental setup and methods

The effective moisture diffusivities of the gel layer and the mixture of the pearlite mortar and gels were obtained from drying experiments, which were performed in the same thermo-hygrostat. The drying data (moisture ratio C versus time t) were obtained by periodic weighing of the samples. The purpose of the drying experiments is measuring the weight of the gels and the mixtures of the pearlite-mortar and the gels to decide the effective diffusivity of these materials by using Eq. (5).

Since the effective diffusivity of the gel layer may depend on the moisture content, to confirm this fact gels were squeezed into petri-dishes of three different depth of 5.1, 8.85 and 14.7 mm. The diameters of dishes were, respectively, 55, 51 and 50 mmϕ. These dishes were put in the thermo-hygrostat, operated at temperature of 25 °C and relative humidities 50 to 80%. And the weight of these containers were measured periodically until their concentration of the aqueous solution of calcium chloride in the gel reaches to the equilibrium state. Note that the equilibrium relative humidity of the gel which absorbs the aqueous solution of calcium chloride is higher than that of aqueous solution. The correlation between the relative humidity at 25 °C and the equilibrium concentration of the aqueous solution of calcium chloride in the gel is plotted in Fig. 1. And also, the correlation between the relative humidity and the moisture content of the gel, C, are plotted by the dashed line in the figure.

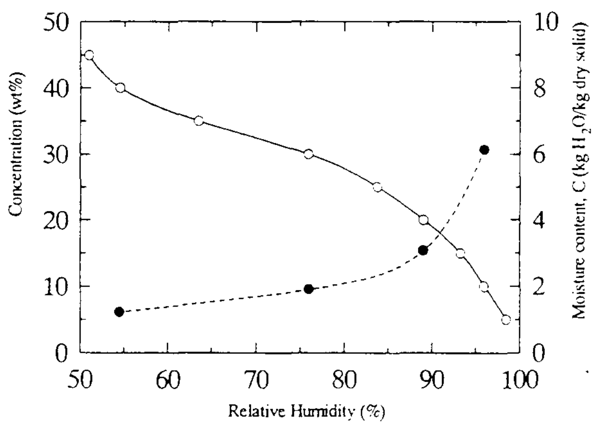

Fig. 1: Correlation between moisture content of gel and relative humidity

The mixtures of the pearlite mortar and gels which were cured in the thermo-hygrostat of 25 °C and 80 RH%, were put in the thermo-hygrostat, operated at temperature of 25 °C and relative humidity of 60%. The weight of these containers were measured periodically until their concentration of the aqueous solution of calcium chloride in the mixture reaches to the equilibrium state.
The air is circulated in the thermo-hygrostat whose velocity is about 0.72 (m/s). The mass transfer coefficient on the surface of the gel was estimated from the correlation of the mass transfer coefficient for a flat plate. The Biot number on the surface of the gel takes a value of 14,000. Then we could considered that the moisture content on the surface of the test materials equals to that of the thermo-hygrostat.

RESULTS AND DISCUSSION

Effective moisture diffusivity of gel layer

The effective moisture diffusivity of the gel layer is plotted in Fig. 2 to Fig.4, as a function of the average humidities of the initial and equilibrium humidities.

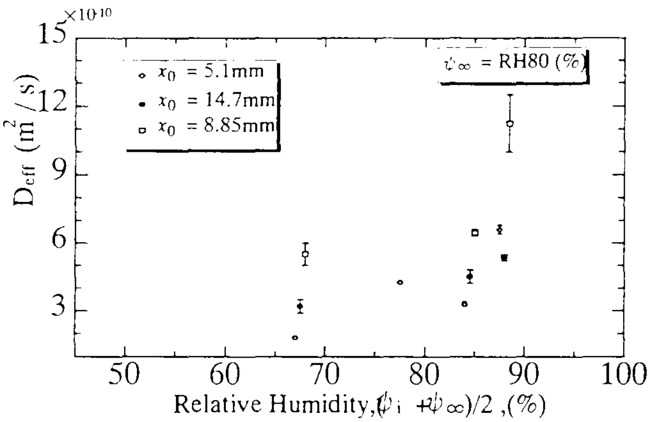

Fig.2: Effective moisture diffusivity of gel layer

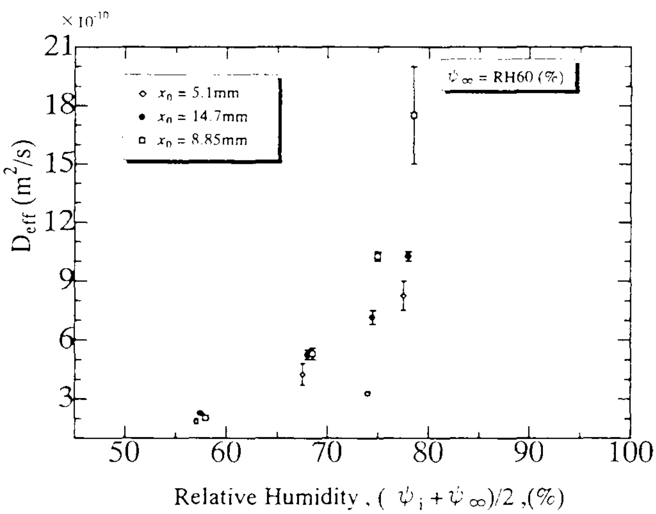

Fig.3: Effective moisture diffusivity of gel layer (RH60%)

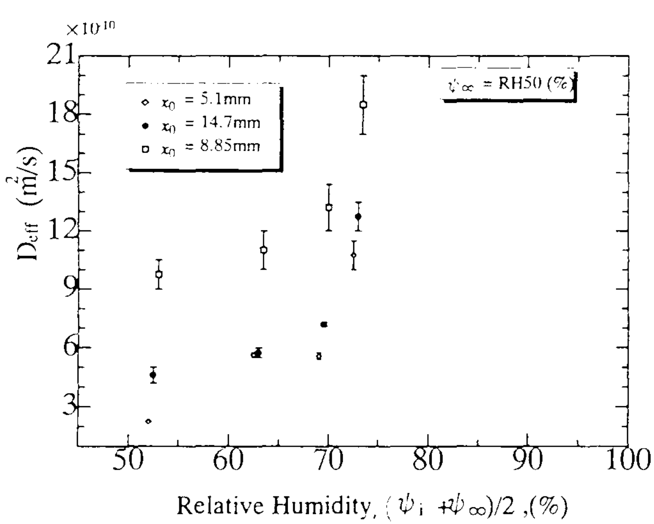

Fig.4: Effective moisture diffusivity of gel layer

Since the measured diffusivity varied, the results were presented in the form of error bars. As seen from the figure, the effective moisture diffusivity changes with the thickness of the gel layer and with the average humidity. Gels are usually complex polymer systems, in which the swelling of the polymer network and the development of stresses result in an anomalous behavior of the diffusion of moisture. And the development of air gaps between gel particles makes behavior of the diffusion of moisture complex. Therefore, more precise experimental works will be required to obtain quantitative results. The experimentally obtained effective moisture diffusivity of the gel layer varied in the range of 1.7×10^{-10} to 20.0×10^{-10} (m^2/s). Figure 2 to Fig.4 show qualitatively that the effective moisture diffusivity decreases with decreasing the moisture content of gel layer.

Effective moisture diffusivity of mixture of pearlite-mortar and gels

The effective moisture diffusivity of the mixture of the pearlite-mortar and the gels is plotted in Fig. 5, as a function of the volume mixture ratio of the gels and the pearlite mortar. The results are also presented in the form of error bars. Note that the effective moisture diffusivity of the mixture of the pearlite-mortar and the gels were obtained from the drying experiment from 80 RH% environment to 60 RH% environment. As seen from the figure, the effective moisture diffusivity of the mixture of the pearlite-mortar and the gels ranges from 2×10^{-10} to 4.5×10^{-10} (m^2/s). A weak tendency that the effective moisture diffusivity decreases with decreasing the volume ratio of the pearlite and the cement, was observed. And it is difficult to find a tendency of the volume ratio of the gels and the pearlite mortar on the effective moisture diffusivity.

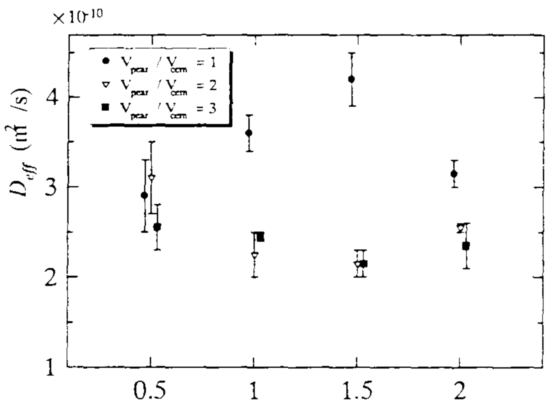

Fig.5: Effective moisture diffusivity of mixture of pearlite mortar and gels

Numerical Simulations

A schematic diagram of the problem considered here is depicted in Fig. 2. An one-dimensional fire wall of thickness x_0, which consists of the gel layer or the mixture of the pearlite mortar and the gels. The wall is set up in a room whose temperature keeps at 25 °C and only the humidity changes between 60 to 80 RH%. The relative humidity of the room, φ_∞, varies with a period of a day as

$$\varphi_\infty = 70 + 10 sin(2\pi t / 86400) \qquad (6)$$

The right surface of the wall is assumed to be an unpermeable surface and only the left surface is exposed to the air. Then, the mass transfer from the left surface of the wall is considered with the average mass transfer coefficient of h_D = 0.01127 (m/s). This value was calculated from the widely used following equation for a case of air of u = 2 (m/s), for a flat plate of l = 0.2 (m).

$$\frac{h_D l}{D_{air}} = 0.664\left(\frac{ul}{\nu}\right)^{0.5} S_C^{\ 1/3} \tag{7}$$

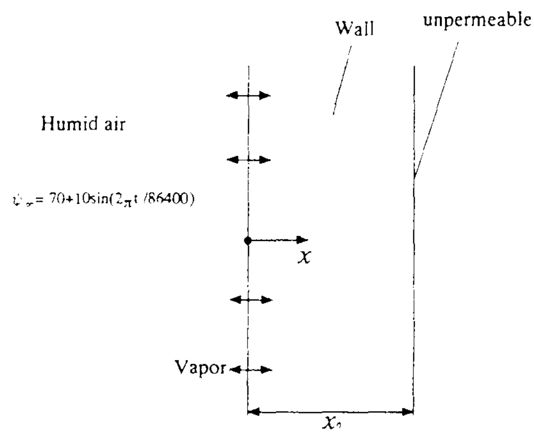

Fig.6: A shematic diagram of the problem

Formulation

The governing equation to be considered is expressed in Eq. (1). The boundary conditions are

$$\begin{array}{lll} t = 0 & 0 < x < x_0 & C = C_{in} \\ t > 0 & x = x_0 & \partial C / \partial x = 0 \\ t > 0 & x = 0 & \rho_{dry} D_{eff} \, \partial C / \partial x = h_D \rho_{air} (w_\infty - w_{x=0}) \end{array} \tag{8}$$

where C_{in} is the initial moisture content of the wall.

The problem to be solved is the parabolic problem. Then, a computer code written by Patankar (1993) for the conduction type problem was used. The methodology of the code is based on the finite volume method.

Computational range

The numerical simulations were conducted for the gel layer of 20 to 100 mm thick and also for the mixture of the pearlite mortar and gels of 20 to 100 mm thick. As seen in Fig. 3 to Fig.5, the moisture diffusivity of the gel layer depends on the average humidity. However, in the case at the average humidity of 70 RH%, the diffusivity of the gel layer takes about 5×10

^{10} (m^2/s). Then, this value was used for the simulation.

As seen in Fig. 6, the moisture diffusivity of the mixture of the pearlite mortar and gels ranges from 2×10^{-10} to 4.5×10^{-10} (m^2/s). In this case, the effective diffusivity depends on the compound ratios. However, the most of the effective diffusivity of the mixtures takes 2.5×10^{-10} (m^2/s) in the case under the average humidity of 70 RH%. Then, this value was used for the simulation for the case of the mixture of the pearlite mortar and gels.

Moisture content of gel layer

The dimensionless moisture content of the gel layer for 60 mm thick at various locations are plotted in Fig. 7 as a function of time. The computation was started from the uniform moisture content. The fluctuation of the moisture content becomes periodic after 109 days. The figure is the result for the periodically steady state. The curve parameter is the location. As expected, the moisture content near the surface follows the air humidity but the fluctuation of the moisture content decreases extremely with increasing the distance from the surface. Relatively large time lag can be seen for the moisture response. The time lag increases with increasing the distance from the surface. In the figure, the dashed line represents the average moisture content. The average moisture content of the gel layers for 20 mm to 100 mm are plotted in Fig. 8 as a function of time. The curve parameter is the thickness of the gel layer. As expected, the fluctuation of the average moisture content decreases with increasing wall thickness. In case of the wall of 60 mm thick, the fluctuation of the average moisture content is less than 4.5 %, and the average moisture content is almost constant. This tendency is accentuated with increasing the wall thickness.

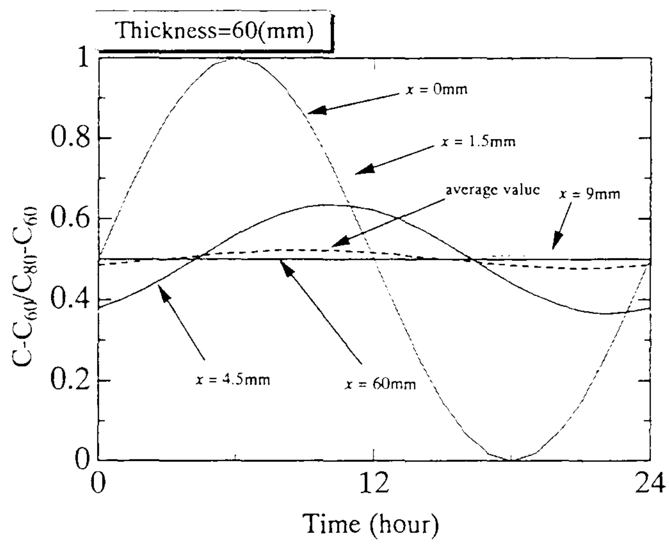

Fig.7: Dimensionless moisture content of gel layer for 60 mm thick

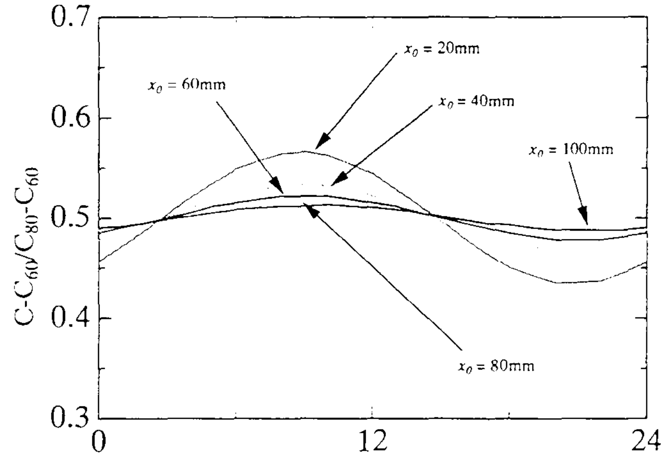

Fig.8: Fluctuation of average moisture content of gel layer

<u>Moisture content of mixture of pearlite mortar and gels</u>

The dimensionless moisture content of the mixture of the pearlite mortar and the gels for 60 mm thick at various locations are plotted in Fig. 9 as a function of time. The computation was started from the uniform moisture content. The fluctuation of the moisture content becomes periodic after 142 days. Since the effective diffusivity of the mixture is lower than that of the gel layer, it need almost twice days to reach the periodically steady state. The figure is the result for the periodically steady state.

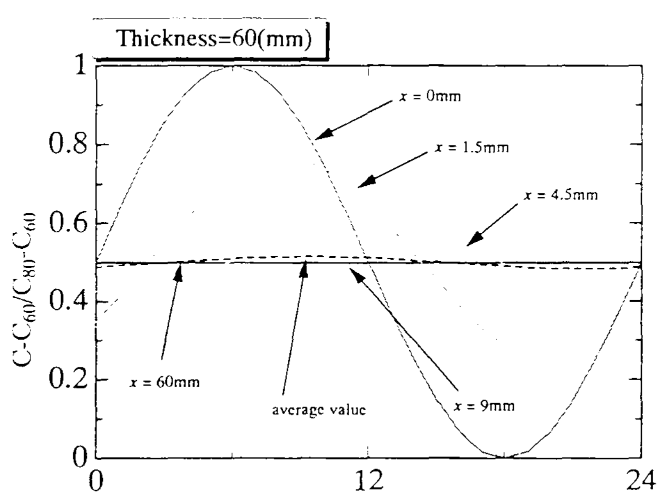

Fig.9: Dimensionless moisture content of mixture of pearlite mortar and gels for 60 mm thick

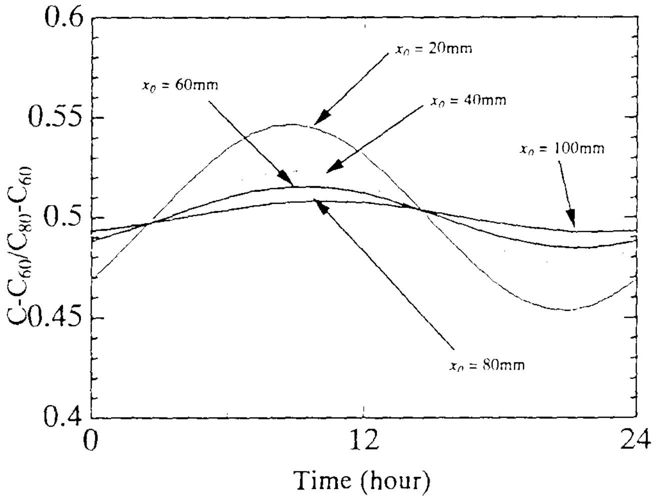

Fig.10: Fluctuation of average moisture content of mixture of pearlite mortar and gels

The curve parameter is the location. As expected, the moisture content near the surface follows the air humidity but the fluctuation of the moisture content decreases extremely with increasing the distance from the surface. Relatively large time lag can also be seen for the moisture response. The time lag increases with increasing the distance from the surface. In the figure, the dashed line represents the average moisture content. The average moisture content of the mixture of the pearlite mortar and the gels are plotted in Fig. 10 as a function of time. The curve parameter is the thickness of the mixture of the pearlite mortar and the gels. As expected, the fluctuation of the averaged moisture content decreases with increasing wall thickness. In case of the wall of 60 mm thick, the fluctuation of the average moisture content is less than 3 %, and the average moisture content is almost constant. This tendency is accentuated with increasing the wall thickness.

CONCLUSION

The effective diffusivity of the super absorbent polymer gel and the mixture of the pearlite-mortar and the gels were obtained by experiments. And also the numerical simulation for the moisture diffusion in the gel layer and the mixture of the pearlite-mortar and the gels were conducted using the obtained the effective moisture diffusivities. The main conclusions are

(1) The effective moisture diffusivity of the gel layer varied in the range of 1.7×10^{-10} to 20.0×10^{-10} (m^2/s). And the effective moisture diffusivity decreases with decreasing the moisture concentration of gel layer.

(2) The effective moisture diffusivity of the mixture of the pearlite-mortar and the gels ranges from 2×10^{-10} to 4.5×10^{-10} (m^2/s). A weak tendency that the effective moisture diffusivity decreases with decreasing the volume ratio of the pearlite and the cement, was observed.

(3) The fluctuation of the average moisture content decreases with increasing wall thickness. In case of the wall of 60 mm thick and the mixture of the pearlite mortar and the gels, the fluctuation is less than 3 %, and the average moisture content is almost constant. This tendency is accentuated with increasing the wall thickness.

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