Effect of Paint on Drying of Cement Paste

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Abstract

This research was aimed to investigate evaporation of water from cement pastes with and without paint. The effect of paint on evaporation of water was experimentally investigated by a drying test. The results showed that paint could substantially retard vapor diffusion from cement pastes. Different types of paint provided different degrees of retarding vapor diffusion out of the tested cement paste samples. A mathematical model for simulating drying of cement pastes with and without paint was proposed based on the results obtained from the authors' test. The diffusion of vapor was calculated following Fick's law of diffusion and mass balance equations. The time-dependent model of hydration and pozzolanic reaction was also used to calculate the amount of free water content in a specimen at any time. The effect of paint on vapor diffusion was subsequently incorporated. The model was finally verified by using the results of relative water content of both un-painted and painted specimens. The verifications showed that the proposed model provided satisfactory results in predicting evaporation of water from the cement pastes with and without paint.

Keywords: Evaporation, Paint, Vapor diffusion, Free water, Fly ash, Relative water content

1. Introduction

Movement of water in concrete highly affects many deterioration processes of concrete such as drying shrinkage, carbonation, chloride penetration, sulfate attack, and leaching. Water movement in concrete includes permeability caused by the hydraulic pressure gradient, sorptivity due to capillary suction, and vapor diffusion due to differential relative humidity [1]. When concrete is in a drying environment, the vapor diffusion mainly controls the movement of water from concrete [2, 3]. Most RC residential buildings in many countries were built with paints applied as coating material mainly for an aesthetic point of view. The paints surely have some effects on diffusion of vapor and drying rate of concrete. However, there have not been many reports on the effect of paint on the rate of drying of the painted RC buildings. Objectives of this study are therefore to evaluate effects of paints on the drying of cement pastes with and without fly ash and propose a mathematical model for simulating the drying of both bare and painted cement paste.

2. Experimental Program - Effect of Paint on Vapor Diffusion

2.1. Materials and Preparation Procedure of Specimens

An ordinary Portland cement type I and lignite fly ash from Mae Moh were used as the binders. Chemical composition and physical properties of the cement and fly ash are shown in Table 1. Mix proportions of the tested cement pastes are shown in Table 2. The water-to-binder ratio was 0.4 while the percentages of fly ash replacement were 0%, 30% and 50%. Two types of acrylic paints were used; paint HP with 35-40μm dry film thickness and paint LP with 30-35μm dry film thickness. A base paint was also applied before each painting on cement paste in order to reproduce the real practical painting process.

Table 1 Chemical compositions and physical properties of binders

Chemical composition (%)	Cement	Fly ash
Silicon dioxide (SiO_2)	20.20	36.1
Aluminum Oxide (Al_2O_3)	4.70	19.4
Iron Oxide (Fe_2O_3)	3.73	15.1
Calcium Oxide (CaO)	63.40	17.4
Magnesium Oxide (MgO)	1.37	2.97
Sulfur Trioxide (S_2O_3)	1.22	0.77
Sodium Oxide (Na_2O)	0.04	0.55
Potassium Oxide (K_2O_3)	0.28	2.17
Free lime	0.75	0.18
Gypsum content	5.60	-
Physical Properties	**Cement**	**Fly ash**
Specific gravity	3.15	2.08
Loss Ignition (%)	2.72	2.81
Blaine fineness (cm^2/g)	3430	3460

Table 2 Mix proportions of the tested cement pastes for drying test

Code	C	FA	W	wb	%FA
P0.4FA0	1379.88	0.00	551.95	0.4	0
P0.4FA30	901.68	386.44	515.25	0.4	30
P0.4FA50	616.73	616.73	493.38	0.4	50

Note: C is cement, FA is fly ash, W is water, wb is water to binder ratio, %FA is fly ash replacement percentage, respectively.

Cement paste cylinder specimens with diameter of 11.5 mm and length of 100 mm were cast by using plastic tubes as the molds. Only the top surface of each specimen was exposed to the environment. The other surfaces were coated by acrylic polymer so that the evaporation occurred only on the exposed surface. The specimens were kept in the plastic tubes and cured under moist conditions.

After 28 days under curing conditions, the specimens were separated into three groups. The first group of specimens was painted with the paint HP on the exposed surfaces. The second group of specimens was painted with the paint LP on the exposed surfaces. The exposed surfaces of specimens in the last group were not painted. Base paint was also applied before each painting on the specimen in order to reproduce the traditional painting process. After that, all specimens, including bare cement pastes and painted cement pastes, were kept at a room temperature (30 ^oC) and relative humidity (RH) of 75% for 4 days to ensure that the paints were set before exposure to subsequent drying.

2.2. Drying Test

After 4 days in the controlled conditions, the specimens were subsequently placed in a drying environment (40 ^oC and 55% RH). Moisture distribution of each specimen was measured after 7 and 28 days of drying. At the time of measurement, each specimen was split to obtain four 10 mm thick discs (see Figure 1) and the discs were then dried in an oven at 105 ^oC for 24 hours to find the weight loss. This weight loss represents the amount of evaporable water (W_e). The oven-dried discs were soaked in water for 24 hours to determine the weight gain at the saturated condition (W_{sat}). The relative water content of each disc can be computed from Equation 1.

$$C_w = 100 \times \frac{W_e}{W_{sat}} \quad (1)$$

Where, C_w is the relative water content (%). W_e is the amount of evaporable water in the air-dried concrete at the considered disc position after being subjected to drying and before being split (kg). W_{sat} is the amount of evaporable water in the water saturated disc (kg).

Figure 1 Cement paste discs for drying test

2.3. Results and Discussions

Figure 2 shows the distribution of relative water content of cement pastes with different percentages of fly ash replacement (0%, 30% and 50%) with wb=0.4 after drying for 7 days in an accelerated condition (RH=55%, t=40^{0}C), while Figure 3 presents the same distribution of relative water content of cement pastes for the case of 28 days of drying.

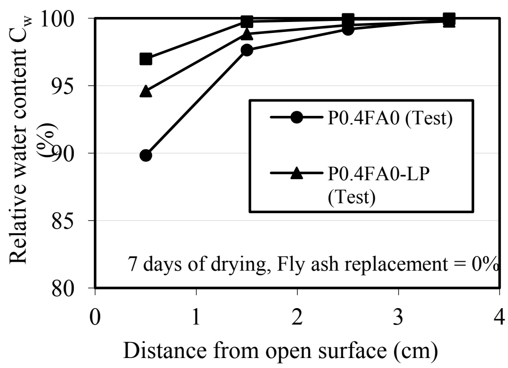
It is clear that the drying rate increases with increased percentages of fly ash replacement. This is considered the consequence of larger total porosity at an early age due to the retardation of hydration reaction and the incomplete pozzolanic reaction in the specimens with larger percentages of fly ash replacement [4].

Different types of paint retarded vapor diffusion of concrete to different extents. Paint HP demonstrated better performance than paint LP in retarding the evaporation during both after 7-day and 28-day drying.

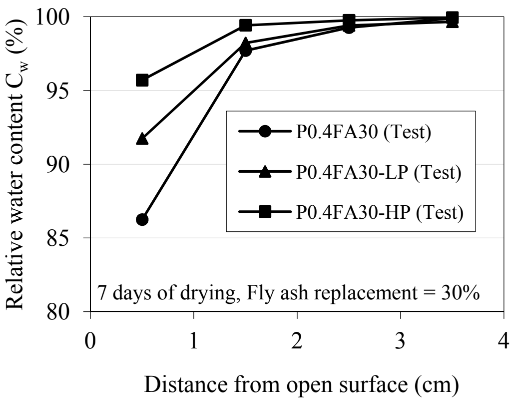
3. Mathematical Model

3.1. Overall Outline

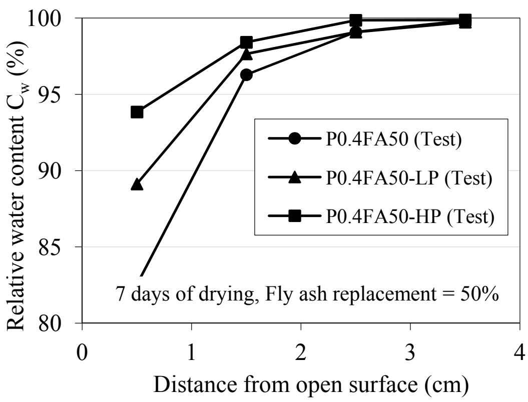
A model for simulating vapor diffusion was developed by taking into consideration mass balance and the Fick's law of diffusion of gas (vapor). Free water content of concrete is dependent on unit water content, degree of hydration reaction, and degree of pozzolanic reaction.



(a) Cement pastes without fly ash

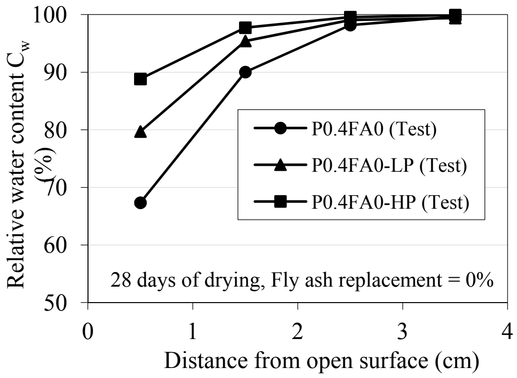


(b) Cement pastes with 30% fly ash replacement

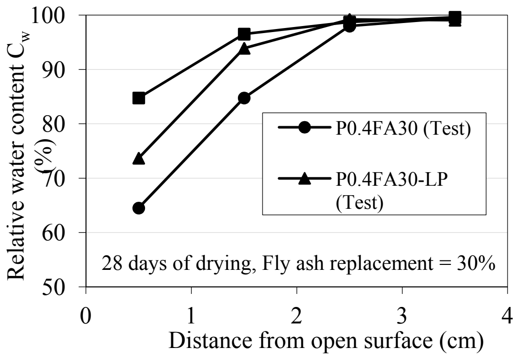


(c) Cement pastes with 50% fly ash replacement

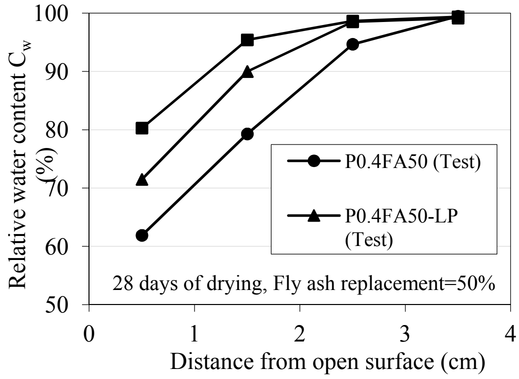
Figure 2 Relative water content in cement pastes after drying for 7 days



(a) Cement pastes without fly ash



(b) Cement pastes with 30% fly ash replacement



(c) Cement pastes with 50% fly ash replacement

Figure 3 Relative water content in cement pastes after drying for 28 days

Finally, the influence of paint on vapor diffusion was incorporated into the model by simply modifying the diffusion coefficient of the exposed surface element. Figure 4 demonstrates the flow chart for processing of the model.

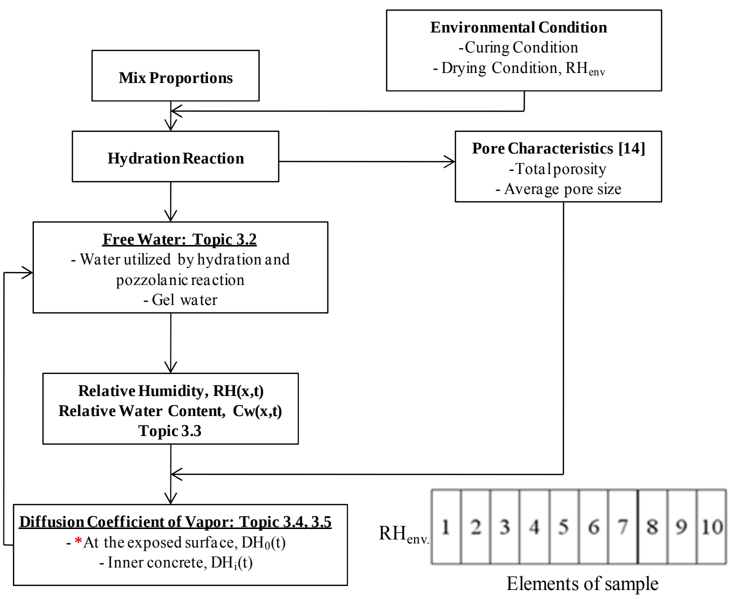


Figure 4 Flow chart of model for simulating carbonation process of painted concrete
Note: *indicates where the effect of paint is incorporated, RH_{env} is the environmental relative humidity

3.2. Water in Cement Paste or Concrete

Water in cement paste or concrete includes chemically bound water (non-evaporable water), gel water (physically bound water) and free water (capillary water) [5]. Chemically bound water is water that reacts with cement during the hydration. As an integrated part of the structure of the hydration gel solid, 1 g of cement approximately needs about 0.21 g of chemically bound water. Gel water is water absorbed on the surface or captured in the structure of the gel solid. It is approximately 0.19 g per 1 g of cement reacted if the water to cement ratio is higher than 0.4. Free water is water present in the coarse capillary pores and unbound in the cement paste. Free water is timely consumed by the hydration reaction and pozzolanic reaction as well as entrapped in the products of these reactions. From above, it is clear that the evaporation of water, in fact is the evaporation of free water in the cement paste and concrete.

Free water ($W_{free}(t)$) in cement paste and concrete can be calculated by employing the formulas proposed by Tangtermsirikul et al. [6] which are given as follows:

$$W_{free}(t) = W_t(t) - W_{hpr}(t) - W_{gel}(t) \tag{2}$$

In which,

$$W_{hpr}(t) = \theta_{hpc} \cdot W_c \cdot \frac{\alpha_{hy}(t)}{100} + \theta_{hpf} \cdot W_f \cdot \frac{\alpha_{poz}(t)}{100} \tag{3}$$

$$\theta_{hpc} = 0.21 \tag{4}$$

$$\theta_{hpf} = \frac{0.984}{3.688+\exp(2.112 \cdot r)} \tag{5}$$

And,

$$W_{gel}(t) = \varphi_{hy,wb} \cdot W_c \cdot \frac{\alpha_{hy}(t)}{100} + \varphi_{pz,r} \cdot \varphi_{pz,wb} \cdot W_f \cdot \frac{\alpha_{poz}(t)}{100} \tag{6}$$

$$\varphi_{hy,wb} = 0.0126 + \frac{0.0026}{-0.009+\exp(0.1414 \cdot wb)} \tag{7}$$

$$\varphi_{pz,r} = 11.6638 \cdot r^3 - 27.7457 \cdot r^2 + 15.953 \cdot r \tag{8}$$

$$\varphi_{pz,wb} = 0.005169 \cdot \mathrm{Exp}(wb) + 0.118379 \tag{9}$$

Where, $W_{free}(t)$, $W_{hpr}(t)$, $W_{gel}(t)$ are the weights of free water, water consumed by the hydration and the pozzolanic reactions and gel water, respectively (kg/m^3). $W_t(t)$ is the unit water content (kg/m^3 of cement paste or concrete) of cement paste or concrete. θ_{hpc} is the minimum ratio of water to cement for completing the hydration reaction ($\theta_{hpc} = 0.21$ is used in this study), θ_{hpf} is the minimum ratio of water to fly ash for achieving the maximum pozzolanic reaction. W_c, W_f are the unit weights of cement and fly ash in the mixture, respectively (kg/m^3 of cement paste or concrete). r is the replacement ratio by weight of fly ash in total binder. wb is the water to binder ratio. $\alpha_{poz}(t)$ is the degree of pozzolanic reaction of fly ash (%), $\alpha_{hy}(t)$ is the degree of hydration of cement (%). t is the age of cement paste or concrete. $\varphi_{hy,wb}$ is the effect of wb on gel water trapped in the hydration products. $\varphi_{pz,r}$ is the effect of percentage of fly ash replacement on the gel water trapped in the pozzolanic products. $\varphi_{pz,wb}$ is the effect of wb on gel water trapped in the pozzolanic products.

The comparison between the test results of Saengsoy [7] and the analytical results of the free water content of cement pastes and mortars with different water-to-binder ratios (0.25 and 0.4 for cement pastes, 0.5 and 0.6 for mortars) and different fly ash replacement percentages (0%, 30% and 50%) are shown in Figure 5, Figure 6 and Figure 7. The comparisons show that the proposed equations can be used to quantitatively predict the free water content of cement-based materials with satisfactory accuracy.

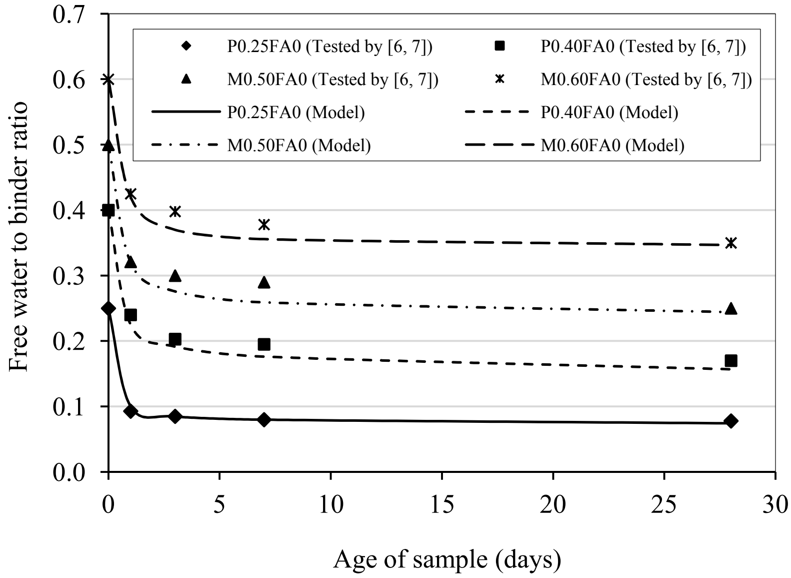


Figure 5 Test results [6, 7] and analytical results of weight ratio of free water per total binder of pastes and mortars without fly ash and wb=0.25, 0.40, 0.50, 0.60 (P: paste specimen, M: mortar specimen)

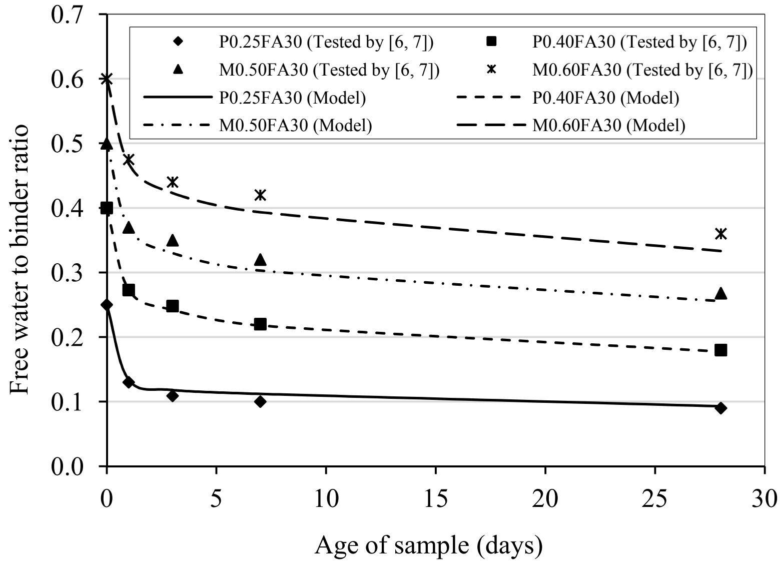


Figure 6 Test results [6, 7] and analytical results of weight ratio of free water per total binder of pastes and mortars with 30% fly ash replacement and wb=0.25, 0.40, 0.50, 0.60 (P: paste specimen, M: mortar specimen)

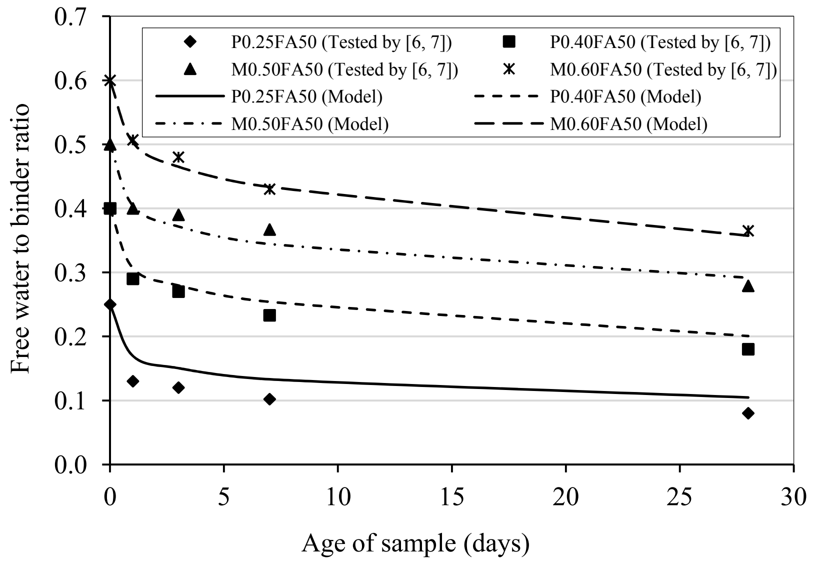


Figure 7 Test results [6, 7] and analytical results of weight ratio of free water per total binder of pastes and mortars with 50% fly ash replacement and wb=0.25, 0.40, 0.50, 0.60 (P: paste specimen, M: mortar specimen)

3.3. Relative Water Content

The rate of vapor diffusion can be described by the Fick's Law of diffusion as follows [8, 9]:

$$\mathrm{FH}(x,t) = -\mathrm{DH}(x,t)\frac{\partial \mathrm{RH}(x,t)}{\partial x} \qquad (10)$$

Where FH is the flux of water diffusing across a unit cross-sectional area of paste or concrete (kg/m^2/day), DH is the diffusion coefficient of water (kg/m/day), RH is the relative humidity in paste or concrete pores (%), x is the distance from exposed surface to the center of the considered element (mm), t is the time of exposure. It is very difficult to directly measure relative humility in the pore of specimen. This paper assumed that there is an equilibrium condition between vapor and liquid pore water throughout the vapor diffusion process [10, 11].

The relative humidity is therefore proportionally related to the relative water content (C_w) as presented in Figure 8 (Khunthongkeaw et al [9]). The value of C_w can be defined as the percentage of the evaporable water in paste or concrete at a considered time when compared with evaporable water in saturated concrete (evaporable water capacity) at that time and can be written as follows:

$$C_w(x,t) = 100 \times \frac{W_e(x,t)}{W_{sat}(x,t)} \qquad (11)$$

In which

$$W_e(x,t) = W_{sat}(x,t) - \int_0^t [\mathrm{FH}(x,t) - \mathrm{FH}(x+1,t)]A\,dt \qquad (12)$$

Where C_w is the relative water content (%), W_e is the amount of evaporable water in paste or concrete at a considered time (kg), W_{sat} is an evaporable water capacity which represents amount of evaporable water in saturated paste or concrete at that time (kg), A is the cross-sectional area of the element (m^2), $\mathrm{FH}(x,t)$ is the flux of water diffusing from element x to next element (x-1), and $\mathrm{FH}(x+1,t)$ is the flux of water diffusing from element (x+1) to element x (Figure 9). The evaporable water is free water (W_{free}) present in pores and unbound in hydrated products. It is also time-dependent because the free water is continuously consumed by the hydration and pozzolanic reactions and entrapped in the products of the reaction, and can be calculated by using Equations (2) to (9) in the previous section.

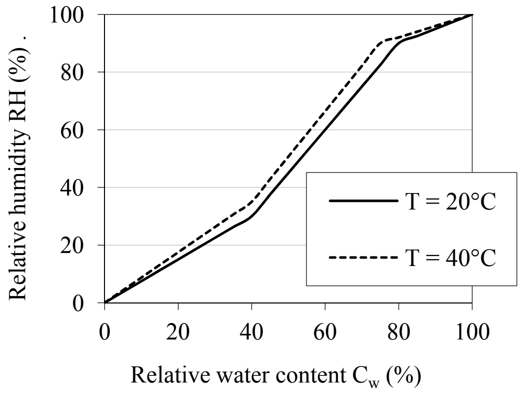


Figure 8 Relationship between relative water content and relative humidity

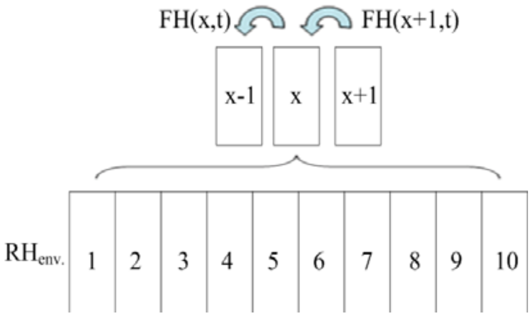


Figure 9 Diagram for demonstrating the flux of vapor diffusion in concrete

3.4. Diffusion Coefficient of Vapor

The amount of water in pores gradually decreases by the diffusion of vapor through interconnected pore system of the cement paste or concrete. The vapor diffusion coefficient mainly depends on relative water content (C_w) in the pores and the pore characteristics. The diffusion coefficients of vapor of cement paste or concrete were formulated from the results of water content distribution of the previous work [13] as follows:

$$DH_0(t) = 2.91 \times 10^{-6} d(t)^{0.3} n(t)^{(2.18-0.05wb)} \frac{\eta}{C_w^{0.35}(x,t)} \quad (13)$$

$$DH_i(t) = 2.67 \times 10^{-6} d(t)^{0.3} n(t)^{(2.18-0.05wb)} \frac{\eta}{C_w^{0.35}(x,t)} \quad (14)$$

Where DH_0 is the diffusion coefficient at the exposed surface element, DH_i is the diffusion coefficient of the inner paste or concrete (kg/m/day), wb is the water-to-binder ratio, C_w is the relative water content (%), η is the volumetric ratio of cement paste (including voids) in the concrete and η=1 for cement pastes in this study, andd is the average pore size (nm), n is the total porosity (%) and can be calculated as follows (Sumranwanich et al [14]):

$$d(t) = \exp\left[7.5(wb-0.195)^{0.085} - 2.9(wb-0.195)^{-0.19} \times \frac{\propto_{av}(t)}{100}\right] \times \left[\frac{1602}{F_c^{1.02}} + 0.57\right] \times \left[\left(\frac{C_3A}{100}\right)^{-0.06} - 0.14\right] \times \beta_{df} \quad (15)$$

$$\beta_{df} = \begin{cases} 1 & \text{if } r = 0\% \\ 1 - r(2.15 - 1.4r) \times (1.03 - 0.0033 \times \%CaO_f) & \text{if } r > 0\% \end{cases} \quad (16)$$

$$n(t) = [23.9 \times \ln(wb) + 77.4] \times \frac{27.6}{26.5 + \exp\left[(0.86 \times wb^{-1.43} + 1.2) \times \frac{\propto_{av}(t)}{100}\right]} \times \left[\frac{1602}{F_c^{1.02}} + 0.57\right] \times \left[\left(\frac{C_3A}{100}\right)^{-0.065} - 0.15\right] \times \beta_{nf} \quad (17)$$

$$\beta_{nf} = \begin{cases} 1 & \text{if } r = 0\% \\ (1 - 0.25r^{0.5}) \times (1.03 - 0.0033 \times \%CaO_f) & \text{if } r > 0\% \end{cases} \quad (18)$$

Where, d(t) is the average pore diameter (nm) and n(t) is the total porosity (% by volume) of cement-fly ash paste at the considered time, wb is the water to binder ratio, r is the ratio of fly ash replacement, F_c is the Blaine fineness of cement (cm^2/g), C_3A is the C_3A content in cement (% by weight of cement), % CaO_f is the calcium oxide content in fly ash (% by weight of fly ash), t is the age of paste (days), $\alpha_{av}(t)$ is the average degree of reaction at the considered time (%) and can be calculated as follows:

$$\propto_{av} = (1-r) \times \left[\frac{\sum_{i=1}^{4} m_i \propto_i}{\sum_{i=1}^{4} m_i}\right] + r \propto_{poz} \quad (18)$$

Where, i indicates each of main mineral compounds of cement (C_3S, C_2S, C_3A, C_4AF), m_i is the percentage by weight of each compound in cement (%), $\propto_{av}$, $\propto_{poz}$, $\propto_i$ are average degree of hydration, degree of pozzolanic reaction, and degree of hydration of each compound in cement (%), respectively, and r is the ratio of fly ash to total binder in mass.

The comparison between the test results of Khunthongkeaw [13] and the analytical results by the model are shown in Figure 10, Figure 11 and Figure 12. It is noted here that Equation (13) and Equation (14) were improved from vapor diffusion coefficients which were proposed by Khunthongkeaw et al [12]. Figure 13 presents the verification of relative water content of un-painted specimens. The verification showed that the result has very high correlation coefficient (higher than 95%). This illustrates that this model is sufficiently good for predicting the water content distribution of paste, mortar and concrete without paint.

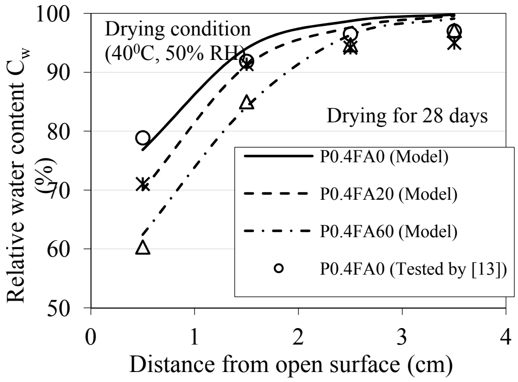
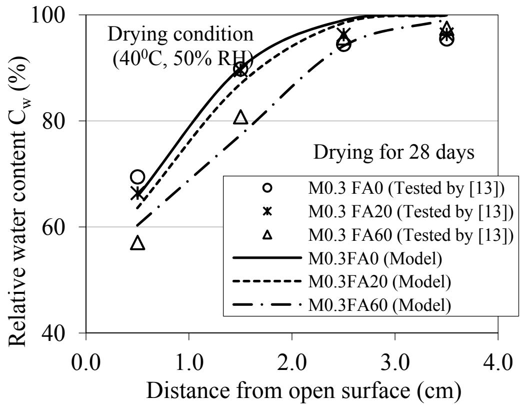
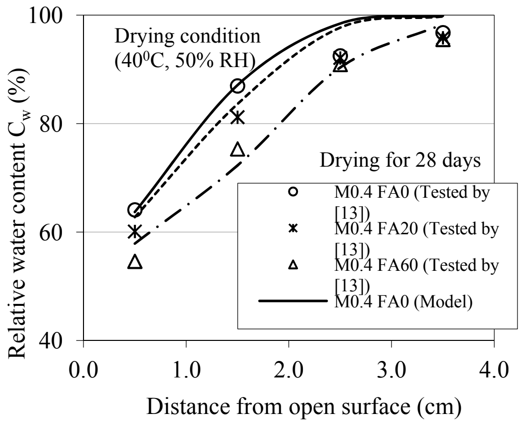


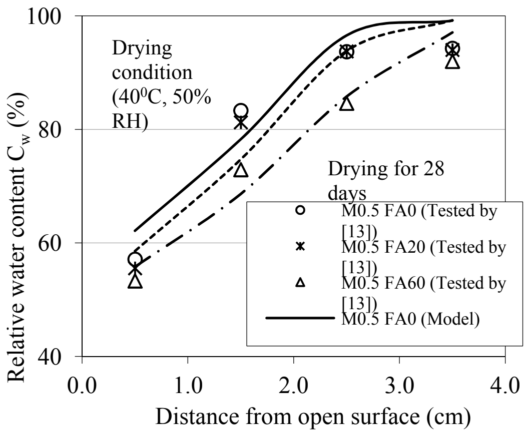
Figure 10 Test and analytical results of relative water content of cement pastes with wb=0.4 (drying for 28 days)



(a) wb=0.3



(b) wb=0.4



(c) wb=0.5

Figure 11 Test and analytical results of relative water content of mortars (drying for 28 days)

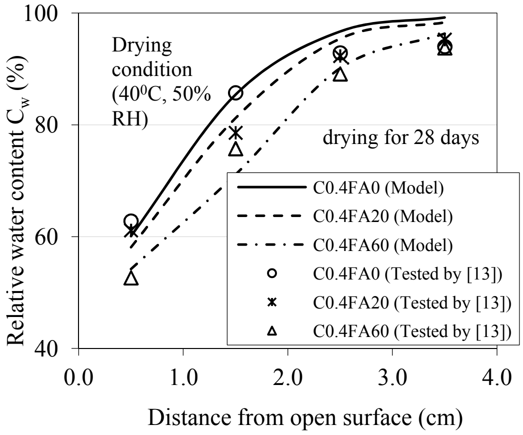


Figure 12 Test and analytical results of relative water content of no-sand concretes with wb=0.4 (drying for 28 days)

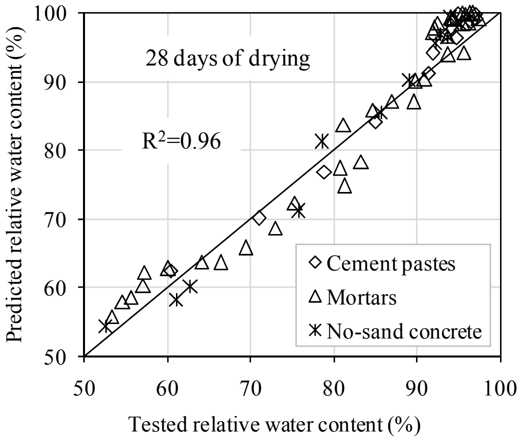


Figure 13 Verification of relative water content of un-painted specimen after drying for 28 days

3.5. Effect of Paint on Diffusion Coefficient of Vapor

Since the layer of paint is usually very thin (30-40μm), the thickness of the paint layer was assumed to be negligible. The difference of the paint HP and paint LP is included in the simulation by modifying the diffusion coefficient of vapor in surface concrete element. It is assumed that when paint is being applied on the surface of specimen, the diffusion coefficient of vapor near an exposed surface is reduced due to the effect of painting resulting in lower evaporation of water out of the specimen (Figure 14).

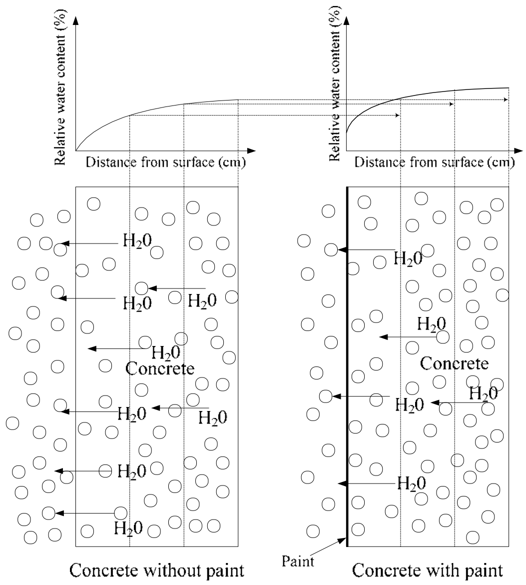


Figure 14 Illustration of the effect of paint on rate of vapor diffusion

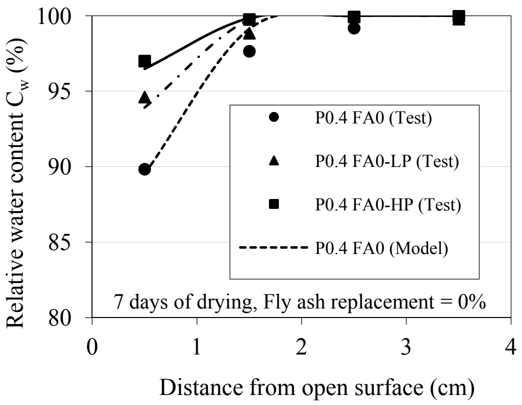
New equations of the diffusion coefficient of vapor at the surface element were formulated back from the experimental results of relative water content test as:

$$\mathrm{DH_{0-LP}(t) = 0.4845 \times DH_0(t)} \tag{19}$$

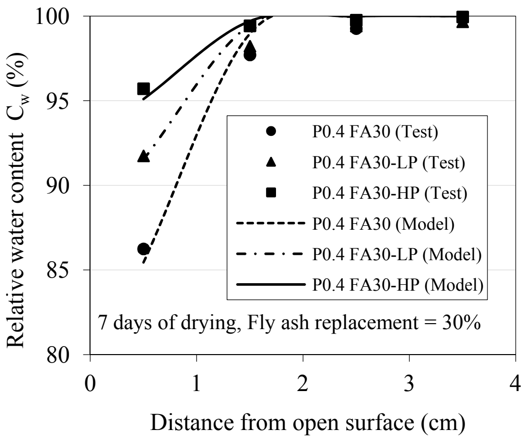
$$\mathrm{DH_{0-HP}(t) = 0.2784 \times DH_0(t)} \tag{20}$$

Where $\mathrm{DH_0(t)}$ is the diffusion coefficient of vapor at the exposed surface element of un-painted cement paste: (see Equation (13)). $\mathrm{DH_{0-LP}(t)}$, $\mathrm{DH_{0-HP}(t)}$ are the diffusion coefficients of vapor at the exposed surface element of cement paste with paint LP and paint HP, respectively.

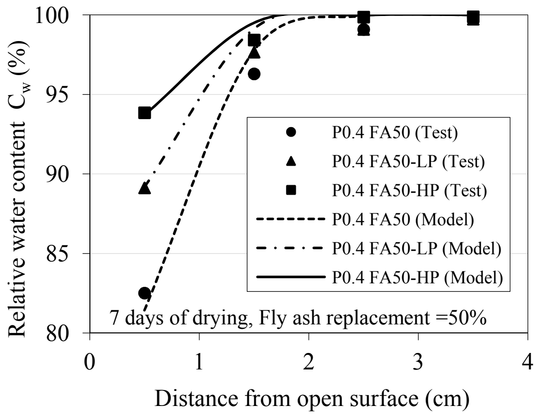
The comparisons between the experimental results and the analytical results of relative water content of pastes with and without fly ash with wb=0.4 after drying for 7 days in an accelerated condition (RH=55%, t=40^{0}C) are shown in Figure 15, while the same comparisons for the case of 28 days of drying are shown in Figure 16. Figure 17 and Figure 18 present verification of relative water contents of paste with and without paint after 7 days of drying and after 28 days of drying, respectively. The verifications show satisfactory accuracy with the correlation coefficient higher than 0.95. The comparisons and verifications indicate that the model is good for predicting the relative water content distribution of the tested pastes with different types of paint.



(a) Cement pastes without fly ash

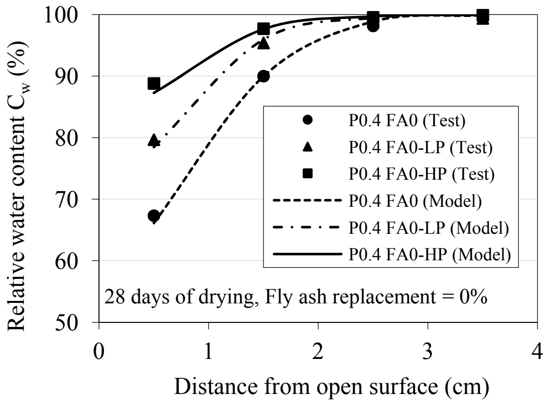


(b) Cement pastes with 30% fly ash replacement

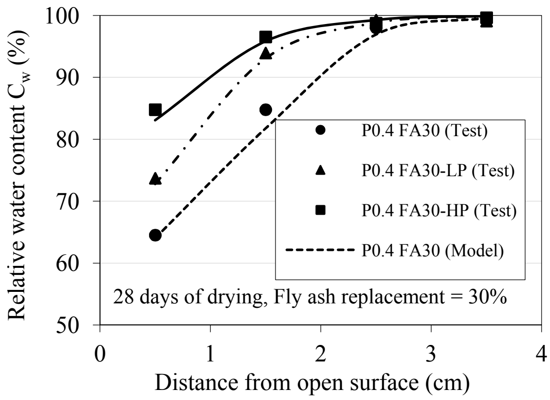


(c) Cement pastes with 50% fly ash replacement

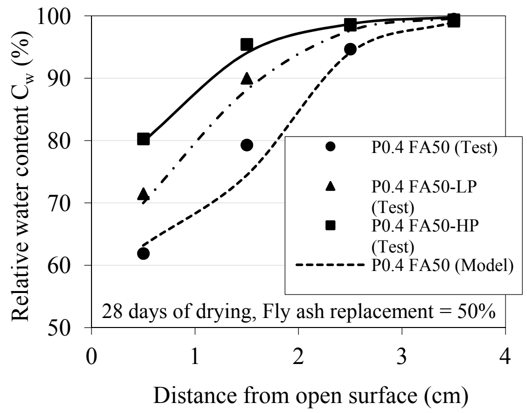
Figure 15 Relative water content in cement pastes after drying for 7 days



(a) Cement pastes without fly ash



(b) Cement pastes with 30% fly ash replacement



(c) Cement pastes with 50% fly ash replacement

Figure 16 Relative water content in cement pastes after drying for 28 days

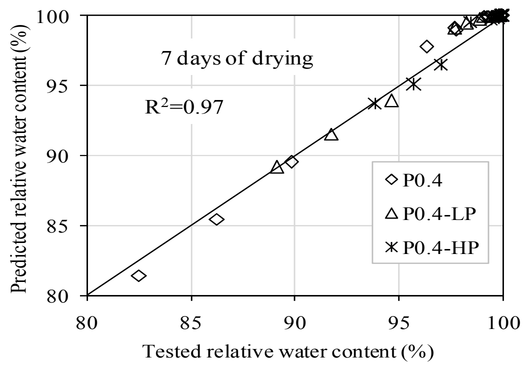


Figure 17 Verification of relative water content after 7 days of drying

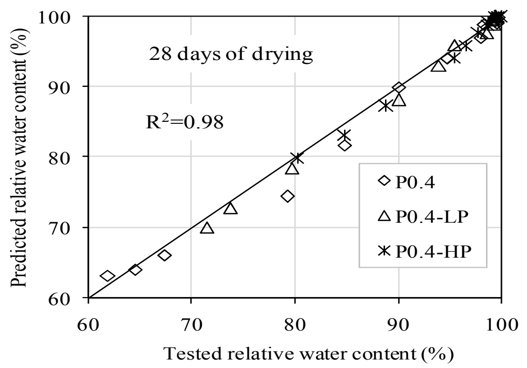


Figure 18 Verification of relative water content after 28 days of drying

4. Conclusions

Based on the results on this study, the following conclusions can be made:

- Paint could substantially retard evaporation of water from cement paste. Different types of paint, paint HP and paint LP, provided different degrees in retarding evaporation from the cement paste. Paint HP showed a better performance.
- The rate of vapor diffusion was time dependent and was governed by pore characteristics, relative water content, and concentration gradient of vapor.
- A mathematical model for predicting evaporation of water from cement paste was proposed based on the vapor diffusion, chemical reaction involving hydration, and pozzolanic reactions within the cement paste, as well as considering the effect of paint.
- The proposed model provided satisfactory prediction of free water content, water content distribution of the tested cement pastes with and without paint and therefore can be used for predicting drying of cement paste.

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