MOISTURE TRANSPORT ACROSS IMPERFECT HYDRAULIC CONTACT INTERFACE – A PARAMETERIC STUDY

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ABSTRACT

Material properties, water vapor permeability, sorption/suction isotherm and moisture diffusivity, are prerequisite for application of all hygrothermal models. Based on the experimental results and well-determined material properties, a numerical model was validated. This model was then used to analyze the sensitivities of the moisture flow across imperfect hydraulic contact interface with respect to these three material properties. The results indicated that the sorption/suction isotherm had to be determined as accurate as possible since it had significant effect on moisture flow across imperfect hydraulic contact interface. In addition, the moisture diffusivity of the material moisture transported from affected the duration of the wetting process but had no noticeable effect on the moisture flow across the interface. It was also found that, during the wetting process, moisture diffusivity of the material moisture transported to and water vapor permeability of both composing materials had no critical effect on moisture accumulation in building materials with imperfect hydraulic contact interface.

KEYWORDS

Moisture transport, Imperfect hydraulic contact, Interface, Material properties, and Model.

INTRODUCTION

Moisture accumulation in the building envelope results in various problems including wasting energy, structural damage, growth of mold, and poor indoor air quality (Hogan, 2002). When moisture transports across an interface between building materials, there are two situations: 1) the interface has no effect on moisture transport, i.e., perfect hydraulic contact interface; 2) the interface resists moisture transport, i.e., imperfect hydraulic contact interface. It has been demonstrated that some typical interfaces such as bonded interface between building materials is more likely to be imperfect hydraulic contact than perfect hydraulic contact (Pel, 1995). Therefore, it is desirable to gain better understanding of moisture transport across imperfect hydraulic contact interface.

Previous studies have not investigated the impacts of the uncertainty in determination of material properties on predictions of the moisture transport in imperfect hydraulic contact building materials. However, accurately measuring material properties such as water vapor permeability, sorption/suction isotherm, and moisture diffusivity is always a challenging task due to a variety of uncertainties and practical difficulties. This paper utilizes a specially designed test and a series of simulations to analyze sensitivities of moisture flow across imperfect hydraulic contact interface with respect to material properties.

NUMERICAL MODEL

Predictions were carried out using the numerical model developed by Qiu et al (2002). This model uses the mismatching resistance to describe imperfection of the interface. Therefore, for two building materials with an imperfect hydraulic contact interface, the governing equations become:

Moisture flux in each composing material:

$$q_l = -D_w\left(\nabla w + \frac{\rho_w \vec{g}}{\partial P_c / \partial w}\right) - \delta_p \nabla P_v \tag{1}$$

Moisture flux across the interface:

$$q_{imp} = -\left(\frac{P_{c2} - P_{c1}}{R_l} + \delta_{P1}\frac{\partial P_v}{\partial x}\right) \tag{2}$$

Where D_w is the moisture diffusivity ($m^2 \cdot s^{-1}$), w is the moisture content ($kg \cdot m^{-3}$), ρ_w is the density of liquid water ($kg \cdot m^{-3}$), g is the acceleration of gravity ($m \cdot s^{-2}$), P_c is the capillary pressure (Pa), P_v is the partial water vapor pressure (Pa), δ_p is the water vapor permeability ($kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$), q_{imp} is the moisture flow across the imperfect hydraulic contact interface ($kg \cdot m^{-2} \cdot s$), P_{c1} is the capillary pressure at contact surface of the first layer (Pa), P_{c2} is the capillary pressure at contact surface of the second layer (Pa), R_l is the mismatching resistance ($m \cdot s^{-1}$), and δ_{P1} is the water vapor permeability of the first layer ($kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$). For two materials with an imperfect hydraulic contact interface in case of 1 – D free wetting process, when bottom surface of one material is in contact with liquid water and top surface of the another one is exposed to ambient air, the initial and boundary conditions become:

Initial condition of both layers:

$$At\ \ t = 0, \qquad w = w_0 \tag{3}$$

Boundary conditions of the first layer:

$$At\, x = 0, \qquad w = w_{cap} \tag{4}$$

$$At\, x = h_1, \qquad q_1 = \frac{P_{c2} - P_{c1}}{R_l} + \delta_{p1}\frac{\partial P_v}{\partial x} \tag{5}$$

Boundary conditions of the second layer:

$$At\, x = 0, \qquad q_2 = -\ q_1 \tag{6}$$

$$At\, x = h_2 \qquad q_3 = \beta \cdot (P_{va} - P_{vl}) \tag{7}$$

Where w_0 is the initial moisture content ($kg \cdot m^{-3}$), corresponding to 50%RH, w_{cap} is the capillary moisture content ($kg \cdot m^{-3}$), h_1 and h_2 are the height (m) of the first layer and the second layer, respectively. β is the mass transfer coefficient (s^{-1}) and P_{va} is the partial water vapor pressure of the ambient air (Pa). The first layer refers to the material moisture transported from, while the second layer refers to the material moisture transported to.

EXPERIMENTS AND PREDICTIONS

Two pieces of aerated concrete (AC) were cut from the same block. Both of them were 20 mm thick and 50 mm wide. However, one was 30mm long and another was 60mm. These two pieces of AC were then put together and therefore, there was a natural contact interface between two pieces of AC. Natural contact means that two materials have good physical contact without penetrating pore structure of each other. All vertical sides of this specimen were sealed with epoxy to ensure 1 – D moisture transport. During the free wetting test, the open surface of that piece of AC with length of 30mm was in contact with liquid water and open surface of another piece of AC was exposed to ambient air. The temperature of the liquid water was kept at 22.5 ± 0.1°C. The air temperature, relative humidity and velocity were 22 ± 1°C, 49.5 ± 2% and 0.1 ± 0.05m/s, respectively. Moisture content profile of the specimen during the test was measured by gamma-ray attenuation technique and shown as the various marked points in Figure 1. The vertical line on moisture content profile represents the position of the interface. As shown in Figure 1, there was a drop of moisture content across interface. Since two layers were the same materials, this phenomenon indicated that there was a jump of capillary pressure across the interface. Hence, the interface between AC was imperfect hydraulic contact.

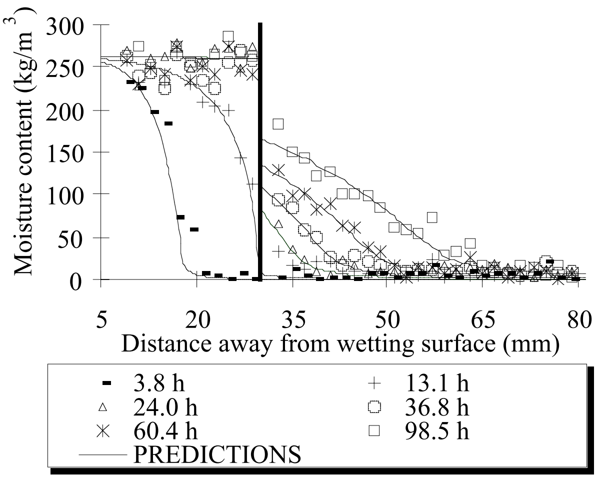

Figure 1: Comparisons of predictions of the model with experimental results.

TABLE 1
Mater properties of AC

Sorption/suction isotherm		Moisture diffusivity		Water vapor permeability	
RH (%)	*w* (kg·m^{-3})	*w* (kg·m^{-3})	D$_w$ (m^2·s^{-1})	RH (%)	δ_p kg·m^{-1}·s^{-1}·Pa^{-1}
25	3	260	1.2E-07	10	1.1E-11
50	5	254	5.1E-08	25	1.4E-11
60	7	246	2.9E-08	40	1.8E-11
70	10	243	2.6E-08	55	2.4E-11
80	21	201	9.0E-09	70	3.1E-11
95	116	172	5.9E-09	85	4.1E-11
98.5	260	86	2.3E-09	100	5.6E-11

This test was simulated with the model and the results are shown as lines in Figure 1. The material properties used, sorption/suction isotherm, water vapor permeability and moisture diffusivity, were experimentally determined and shown in TABLE 1. The mass transfer coefficient, β, was determined by Lewis law at condition of air velocity 0.1m/s, and the air permeability of air used was 2×10^{-10} $\mathrm{kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}}$ (Lackey, et al. 1995). The air partial water pressure was determined at 22°C and 49.5%RH. Based on the least error between predicted and experimental determined moisture content profiles of the second layer, the mismatching resistance was determined and shown in TABLE 2. The capillary moisture content of AC referenced to the moisture content corresponding 50%RH was 263 $\mathrm{kg/m^3}$ (Qiu, et al. 2002).

TABLE 2
Mismatching resistance of the test specimen

Time (hour)	< 24.0	2.40 – 36.8	36.8 – 60.4	60.4 – 98.5
Mismatching resistance (m/s)	2.80E+11	2.20E+11	2.10E+11	2.05E+11

As shown in Figure 1, there is a good agreement between predictions of the model and experimental results. Therefore, this model can provide reliable prediction on moisture transport in building materials with imperfect hydraulic contact interfaces, and the parameters used were well determined.

PARAMETERIC ANALYSIS

Since moisture accumulation in the second layer is an indicator of the moisture flow across the interface, according to the prediction shown in Figure 1, the average moisture content of the second layer during the test is plotted and called as "Acc-M". Therefore, it is accurate prediction and can be a benchmark for other predictions. Then, the predictions were carried out varying each of three accurate material properties listed in TABLE 1: water vapor permeability, sorption/suction isotherm and moisture diffusivity. The predictions performed are listed in the TABLE 3 and the results are shown in Figures 2–4.

TABLE 3
Predictions performed for parametric analysis

Code	Variation of material properties listed in TABLE 1
Acc-M	Material properties used are accurate and the predictions agree with experimental results well
0.7Diff1	The moisture diffusivity of the first layer was decreased by 30% of the accurate one
1.3Diff1	The moisture diffusivity of the first layer was increased by 30% of the accurate one
0.7Diff2	The moisture diffusivity of the second layer was decreased by 30% of the accurate one
1.3Diff2	The moisture diffusivity of the second layer was increased by 30% of the accurate one
0.7Sorp1	The sorption/suction isotherm of the first layer was decreased by 30% of the accurate one
1.3Sorp1	The sorption/suction isotherm of the first layer was increased by 30% of the accurate one
0.7Sorp2	The sorption/suction isotherm of the second layer was decreased by 30% of the accurate one
1.3Sorp2	The sorption/suction isotherm of the second layer was increased by 30% of the accurate one
0.7Vap1	The water vapor permeability of the first layer was decreased by 30% of the accurate one
1.3Vap1	The water vapor permeability of the first layer was increased by 30% of the accurate one

0.7Vap2	The water vapor permeability of the second layer was decreased by 30% of the accurate one
1.3Vap2	The water vapor permeability of the second layer was increased by 30% of the accurate one

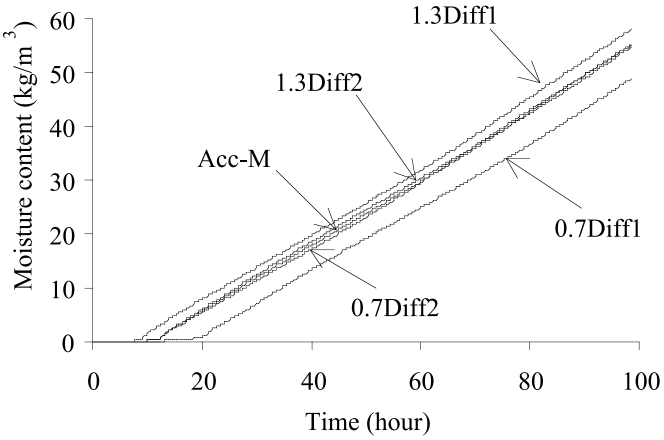

Figure 2: Impacts of moisture diffusivity on moisture flow across the interface.

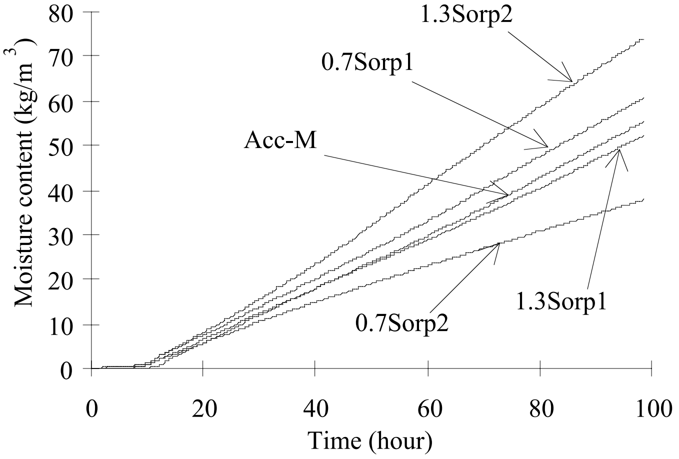

Figure 3: Impacts of sorption/suction isotherm on moisture flow across the interface.

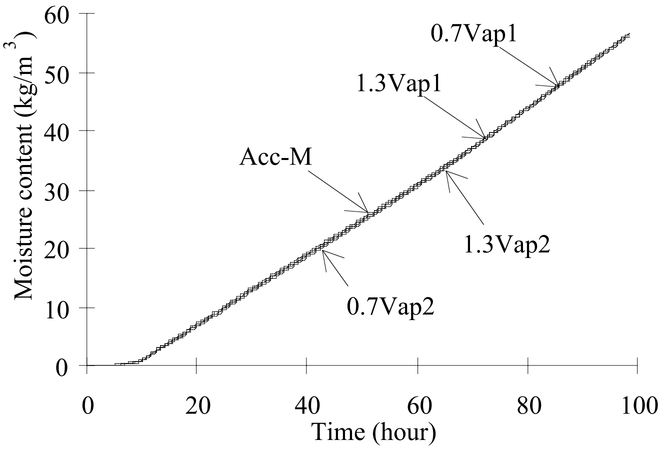

Figure 4: Impacts of water vapor permeability on moisture flow across the interface.

As shown in Figure 2, the 30% error in moisture diffusivity of the second layer alone has no noticeable impact on predictions. Figure 2 also shows that the moisture content curves due to the 30% error in moisture diffusivity of the first layer are parallel to the accurate curve. This phenomenon indicates that the uncertainty in estimation, especially underestimation, of moisture diffusivity of the first layer affects prediction of the wetting process duration but has no noticeable impact on prediction of moisture flux density across the interface.

Figure 3 shows that the 30% error in sorption/suction isotherm of the second layer alone has significant impact on predictions. Furthermore, even though the 30% error in sorption/suction isotherm of the first layer has less impact on the predictions, the shape of the predicted moisture content curve of the second layer is also changed. This is because that, all model calculations assume local equilibrium at all time. Therefore, the uncertainty in determination of sorption/suction isotherm of the composing materials results in significant error in predicting moisture transport across imperfect hydraulic contact interface, especially when sorption/suction isotherm of the second layer is not well determined.

Figure 4 shows that either 30% error in water vapor permeability of the first layer or the second layer has no significant effect on predictions. This indicates that uncertainty in the estimation of the water vapor permeability of the composing materials has no critical effect on prediction of moisture transport in building material with imperfect hydraulic contact interface during wetting process.

CONCLUSIONS

The experimental results showed that the natural contact interface between two pieces of AC was imperfect hydraulic contact. In addition, a parametric study was carried out to study the impacts of three material properties of the composing materials, water vapor permeability, sorption/suction isotherm and moisture diffusivity, on moisture transport across imperfect hydraulic contact interface. This parametric study was accomplished by comparing experimental results with predictions of a numerical model. It was found that sorption/suction isotherm of the composing materials had significant effect on the moisture flow across imperfect hydraulic contact interface and thereby, sorption/suction isotherm of the materials is better to be determined as accurate as possible. Moreover, the moisture diffusivity of the composing materials had no noticeable effect on the moisture flow across imperfect hydraulic contact interface, but the moisture diffusivity of the material moisture transported from affected the wetting process duration. In addition, it was also found that, during the wetting process, water permeability of composing materials had no critical effect on moisture flow across imperfect hydraulic contact interface.

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