MODELING MOISTURE ACCUMULATION IN MULTI-LAYERED BUILDING MATERIALS

Xiaochuan Qiu[1], Fariborz Haghighat[1] and Kumar Kumaran[2]

[1]Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec
[2]Institute for Research Construction, National Research Council Canada, Ottawa, Ontario

raymond_qiu@hotmail.com, haghi@cbs-engr.concordia.ca, Kumar.Kumaran@nrc.ca

ABSTRACT

A numerical model was developed to predict moisture transport in building materials with imperfect hydraulic contact interfaces. This model considers the increased length of the moisture path due to mismatching as the source of imperfection of the interface. All parameters could be experimentally determined, or found in literature. In addition, a series of experiments were performed, and the results showed that the assumption of imperfect hydraulic contact is more appropriate and accurate than the assumption of perfect hydraulic contact for both bonded and natural contact interfaces. Based on the tests performed, the predictions of the model were compared with experimental results. The results indicated that there was good agreement between predictions of the model and experimental results. Moreover, it is found that imperfection of the interface varies with moisture content of the composing materials during wetting process.

INTRODUCTION

Moisture has been identified as a major factor affecting durability of building materials. In addition, moisture accumulation in building envelopes can promote growth of mold and fungi, both of which have adverse impacts on human health. The physics of moisture transport in a single porous material have been extensively studied. However, the characteristics of moisture accumulation in multi-layered building materials are still not clear and thereby, simplified assumption, perfect hydraulic contact between building materials, is widely used in hygrothermal models (e.g., Wilson *et al.* 1995, Karagiozis *et al.* 2001, and Nofal *et al.* 2001). Hydraulic contact refers to the impacts of a contact between two materials on moisture transport. The assumption of perfect hydraulic contact means that an interface between two materials has no effect on moisture transport. However, some typical interfaces such as bonded and natural contact interfaces may resist moisture transport, i.e., imperfect hydraulic contact. Bonded interface refers to the interface between two bonded materials. When two materials have good physical contact without penetrating pore structure of each other, the interface between these two materials is called as natural contact interface.

Pel (1995) compared the capillary moisture content reached by bonded materials to that reached by each single composing material during free wetting process, and concluded that the bonded interface between fired-clay brick and mortar is imperfect for moisture transport. Pel's study revealed that, even for bonded interfaces, the assumption of perfect hydraulic contact might not be applied properly. De Freitas *et al.* (1996) investigated moisture accumulation in the natural contact building materials made by autoclaved aerated concrete and clay brick during free wetting process. They concluded that the natural contact interface is imperfect for moisture transfer, and hypothesized that the moisture flux across natural contact interface is limited by a maximum flow rate.

Previous studies, however, have not developed a model for predicting moisture transport in building materials with imperfect hydraulic contact interfaces. Furthermore, the characteristics of an imperfect hydraulic contact interface have not been established. The present study describes the development of a numerical model that predicts moisture transport in building materials with imperfect hydraulic contact interfaces. Furthermore, the characteristics of the resistance created by imperfect hydraulic contact are also investigated.

DEVELOPMENT OF A NUMERICAL MODEL

The following assumptions were made in the

development of the numerical model.

(1) Building materials are macroscopically rigid, isotropic and homogeneous;
(2) Water vapor transport by diffusion;
(3) Air is at atmospheric pressure throughout the porous medium;
(4) The liquid water is pure and incompressible.
(5) The contact between building materials is imperfect hydraulic contact.

Moisture transport in a single building material
Since water vapor pressure is significantly lower than the atmospheric pressure under normal conditions building constructions exposed to (Lackey *et al.* 1997), the water vapor can be treated as ideal gas. Therefore, water vapor transport can be expressed as well-known equation:

$$q_v = -\delta_v \nabla P_v \qquad (1)$$

Where q_v is the rate of water vapor flow (kg·m^{-2}·s^{-1}), δ_v is the water vapor permeability (kg·m^{-1}·s^{-1}·Pa^{-1}), and P_v is the partial water vapor pressure (Pa). Liquid water flow in building materials is mainly forced by the gradient of capillary pressure (Bear *et al.* 1990), and the effect of gravity force on liquid water transport is also taken into account. Hence, the liquid water transport can be expressed into:

$$q_l = -K(\nabla P_c + \rho_w \vec{g}) = -D_w \left(\nabla w + \frac{\rho_w \vec{g}}{\partial P_c / \partial w} \right) \quad (2)$$

Where q_l is the rate of liquid water flow (kg·m^{-2}·s^{-1}), K is the water conductivity (kg·m^{-1}·s^{-1}·Pa^{-1}), P_c is the capillary pressure (Pa), ρ_w is the density of liquid water (kg·m^{-3}), g is the acceleration of gravity (m·s^{-2}), D_w is the moisture diffusivity (m^2·s^{-1}), and w is the moisture content (kg·m^{-3}). Therefore, according to mass balance equation, moisture flux in a single material can be derived:

$$\frac{\partial w}{\partial t} = div \left(D_w \nabla w + \frac{D_w}{\partial P_c / \partial w} \rho_w \vec{g} \right) + div(\delta_v \nabla P_v) \quad (3)$$

Where, t is the time (s).

Moisture transport across imperfect hydraulic contact interface
Compared to moisture accumulation in a single material, moisture accumulation in the multi-layered building materials is much more complex because of interface phenomena. However, when two materials come into contact, the interface is either perfect or imperfect hydraulic contact. In case of perfect hydraulic contact, because the interface has no effect on moisture transport, driving forces of moisture transport at two contact surfaces are the same. Hence, there is no complication when two materials have perfect hydraulic contact. Imperfect hydraulic contact interface, however, resists moisture transport from one layer to another. Therefore, the driving forces of moisture transport at two contact surfaces are not the same anymore and moisture flow across interface will also depend on interface itself.

Understanding physics of moisture transport in a single material provides a clue for determining moisture transport across imperfect hydraulic contact interface. For 1 – D horizontal moisture transport in a single material, i.e., no gravitational effect, equation (2) can be rewritten as following:

$$q_l = -K \frac{dP_c}{dx} = \frac{dP_c}{dx/K} = -\frac{\Delta P_c}{\frac{1}{K} \cdot \Delta x} = -\frac{\Delta P_c}{R'} \quad (4)$$

Therefore, the rate of moisture flow in a porous material is forced by unbalanced capillary pressure and resisted by 'material resistance', *R'*, which is related to moisture conductivity and the distance corresponding to unbalanced capillary pressure. When a porous material is in contact with free liquid water directly, every pore on wetting surface is covered with liquid water. Therefore, every pore on the contact surface absorbs moisture independently. When two materials come into contact, however, some pores on the contact surfaces are not available for the moisture transport because of mismatching pore structures of two layers. Consequently, these pores on contact surface of the second layer have to absorb liquid water from those pores connected with the first layer. The first layer refers to the material moisture transported from, while the second layer refers to the material moisture transported to. Therefore, actual length of moisture path at the interface increases. The resistance resulting from this increased length of the moisture path at the interface, in the present study, is defined as 'mismatching resistance'. Therefore, moisture flux across imperfect hydraulic contact interface is forced by unbalanced capillary pressure at two contact surfaces, and is resisted by mismatching resistance. In addition, it is assumed that the interface is perfect for water vapor transport when the composing materials are in good physical contact. Hence, moisture flux

across the imperfect hydraulic contact interface becomes:

$$q_{imp} = -\left(\frac{P_{c2} - P_{c1}}{R_l} + \delta_{P1}\frac{\partial P_v}{\partial x}\right) \qquad (5)$$

Where q_{imp} is the rate of moisture flow across the imperfect hydraulic contact interface (kg·m^{-2}·s^{-1}), 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·s^{-1}), and δ_{P1} is the water vapor permeability of the first layer (kg·m^{-1}·s^{-1}·Pa^{-1}).

Initial and boundary conditions during free wetting process
Some initial conditions and boundary conditions are needed to close moisture transport equations. This model considers the moisture flow across the interface as one of the boundary conditions of the composing materials.

(a) *Initial conditions*
For a single homogenous material with an initial moisture content w_0, the initial condition is:

$$At\ t = 0, \quad w = w_0 \qquad (6)$$

For the multi-layered building materials with the imperfect hydraulic contact interfaces, the initial conditions become:

$$At\ t = 0, \quad w_i = w_0 \quad (i=1,2,...n) \qquad (7)$$

Where i represents the ith layer referenced to the wetting surface.

(b) *Boundary conditions*
During 1 – D free wetting tests, when the bottom surface of the material is in contact with liquid water and the top surface is exposed to the air, boundary conditions of a single material can be expressed as:

$$At\ x = 0, \quad w = w_{cap} \qquad (8)$$

$$At\ x = h, \quad q = \beta \cdot (P_{va} - P_{vl}) \qquad (9)$$

Where w_{cap} is the capillary moisture content (kg·m^{-3}), h is the length of the material (m), β is mass transfer coefficient (m·s^{-1}), P_{va} is the partial water vapor pressure of ambient air (Pa), and P_{vl} is the partial water

vapor pressure of material surface exposed to the ambient air (Pa).

For the multi-layered building materials with the imperfect hydraulic contact interfaces, the boundary conditions become:
For the first layer:

$$At\ x = 0, \quad w = w_{cap} \qquad (10)$$

$$At\ x = h_1, \quad q_1 = \frac{P_{c2} - P_{c1}}{R_1} + \delta_1\frac{\partial P_{v1}}{\partial x} \qquad (11)$$

For the ith layer:

$$At\ x = h_{i-1}, \quad q_{i-1} = -\left(\frac{P_{ci} - P_{ci-1}}{R_i} + \delta_{i-1}\frac{\partial P_{vi-1}}{\partial x}\right) \qquad (12)$$

$$At\ x = h_i, \quad q_1 = \frac{P_{ci+1} - P_{ci}}{R_{i+1}} + \delta_i\frac{\partial P_{vi}}{\partial x} \qquad (13)$$

For the last layer:

$$At\ x = h_{l-1}, q_{l-1} = -\left(\frac{P_{cl} - P_{cl-1}}{R_l} + \delta_{l-1}\frac{\partial P_{vl-1}}{\partial x}\right) \qquad (14)$$

$$At\ x = h_l \quad q_l = \beta \cdot (P_{va} - P_{vl}) \qquad (15)$$

Parameters determination
Material properties, water vapor permeability, moisture diffusivity coefficient and sorption curve, can be experimentally determined or found in literature (e.g., Kumaran 1996). Partial vapor pressure of the air can be determined with air temperature and relative humidity. The water vapor permeability of the air is 2×10^{-10} kg·m^{-1}·s^{-1}·Pa^{-1} (Lackey *et al.* 1995). The mass transfer coefficient can be calculated using Lewis relation:

$$\beta = \frac{\alpha}{R_v T \rho_a c_p} \qquad (16)$$

Where α is the convection heat transfer coefficient (W·m^{-2}·K^{-1}), R_v is the gas constant for water vapor (461.5J·K^{-1}·kg^{-1}), T is the temperature (K), ρ_a is the

density of the air (kg·m^{-3}), and c_p is the specific heat capacity of the air (J·kg^{-1}·K^{-1}).

The convection heat transfer coefficient can be estimated from surrounding air velocity with an empirical formula (Pedersen 1990).

$$\text{At } \ v_a \leq 5\,\text{m/s}, \ \ \alpha = 5.82 + 3.96 \cdot v_a \qquad (17)$$

$$\text{At } \ v_a > 5\,\text{m/s}, \ \ \alpha = 7.68 \cdot v_a^{0.75} \qquad (18)$$

Where v_a is the velocity of the ambient air (m·s^{-1}).

Based on the above equations, a numerical model MTIMB (*M*oisture *T*ransport *I*n *M*ulti-layered *B*uilding materials) was developed using the finite control volume numerical method.

EXPERIMENTS

This model is validated with experimental results from the specially designed tests. The test materials were **P**ortland **C**ement – **L**ime **M**ortar **S** type (PCLMS) and **A**erated **C**oncrete (AC). The test specimens are listed in Table 1.

Table 1. Specimens used in the free wetting tests.

Specimen	First layer (Height)	Contact	Second layer (Height)
A	AC (90mm)		
B	AC (30mm)	Natural	AC (60mm)
C	AC (15mm)	Bonded	PCLMS (15mm)

All specimens listed in Table 1 have the same width (50mm) and thickness (20mm). The vertical sides of all specimens were sealed with epoxy to ensure 1-D moisture transport. In addition, the specimens used in the free wetting tests were dried in a 50%RH humidity chamber before the tests. The moisture content profiles of the specimens during the tests were measured using gamma-ray attenuation technique. During the tests, the temperature of the liquid water was kept at 22.5±0.1$^{\text{o}}$C. In addition, the ambient air temperature, relative humidity and velocity were 22±1$^{\text{o}}$C, 49.5±2% and 0.1±0.05m/s, respectively. The material properties of AC and PCLMS were experimentally determined. The water vapor permeability of AC and PCLMS were determined using dry cup and wet cup methods and shown in Figure 1. The moisture retention curves of AC

and PCLMS were measured using the pressure plate and relative humidity chambers. The results are shown in Figure 2. In addition, the moisture diffusivity coefficients of AC and PCLMS were determined using gamma-ray attenuation technique (Kumaran *et al.* 1985) and shown in Figure 3.
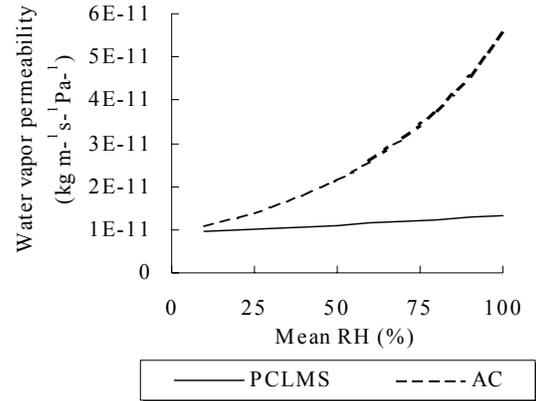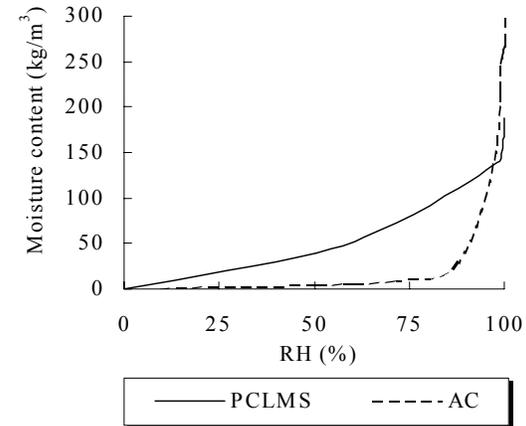

Figure 1. Water vapor permeability of AC and PCLMS.

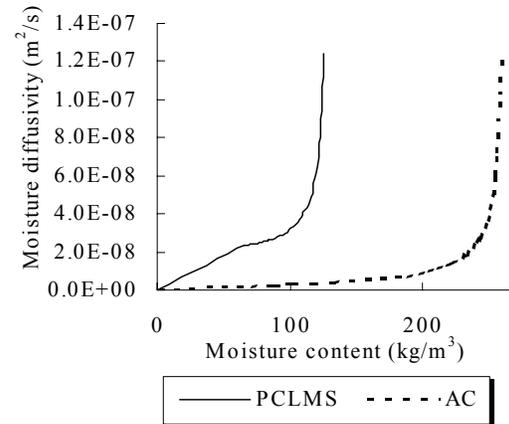
Figure 2. Moisture retention curves of AC and PCLMS.

Figure 3. Moisture diffusivity coefficients of AC and PCLMS.

EXPERIMENT RESULTS AND ANALYSIS

The moisture content profiles of test specimens during the free wetting tests are shown in 4 – 6. The vertical lines on moisture content profiles represent the positions of the interfaces. The moisture content profiles in this paper describe moisture content (kg/m^3) with position (mm) relative to the wetting surface and time (hour) referenced to the time the specimens came into contact with liquid water. The marked points are values actually measured during the tests.

Figure 4 shows that moisture content was continuous at any cross section in a single piece of AC during free wetting process. However, there was a drop of moisture content across the natural contact interface between two pieces of AC, as shown in Figure 5. Therefore, there was a jump of capillary pressure across the interface due to the same material properties of two layers. That is, the interface between two pieces of AC is imperfect hydraulic contact. Furthermore, moisture accumulation in the second layer of specimen **B** was noticeably slower than that of corresponding part in the integrated specimen **A**: indicating that imperfect hydraulic could significantly resist the moisture transport. Therefore, the assumption of perfect hydraulic contact may result in significant error in predicting moisture accumulation in multi-layered building materials.

Since the composing materials of specimen **C**, i.e., AC and PCLMS, are different, it is difficult to identify whether there is discontinuity of capillary pressure across the interface from Figure 6 directly. However, based on moisture retention curves, the capillary pressure can be derived from moisture content. Therefore, based on moisture retention curves of AC and PCLMS, the capillary pressures of composing materials close to the bonded interface in the specimen **C** is derived from Figure 6 and shown in Figure 7. As shown in Figure 7, the capillary pressure across the bonded interface between AC and PCLMS is discontinuous. Therefore, the bonded interface between AC and PCLMS is not perfect for moisture transport either. Therefore, for both bonded and natural contact interfaces between building materials, it is more accurate and appropriate to assume imperfect hydraulic contact than perfect hydraulic contact.

All tests performed were predicted using the model developed. The results are shown in Figures 8 – 10. Besides the properties of AC and PCLMS known, the mass transfer coefficient and partial vapor pressure of the air were determined with the experimental conditions. Mismatching resistance was determined with the least error between modeling and experimental results. The capillary moisture content of AC and PCLMS referenced to the moisture content corresponding at 50%RH are 263 kg/m^3 and 155 kg/m^3, respectively.
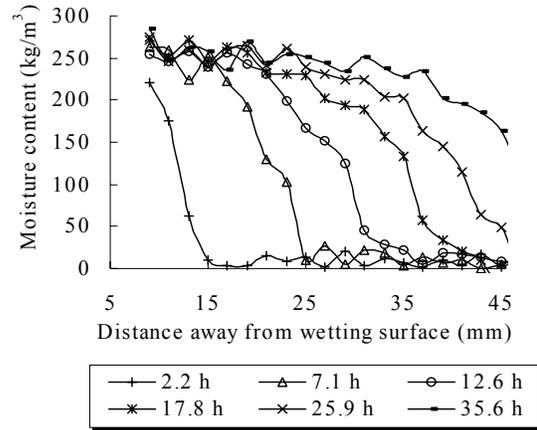
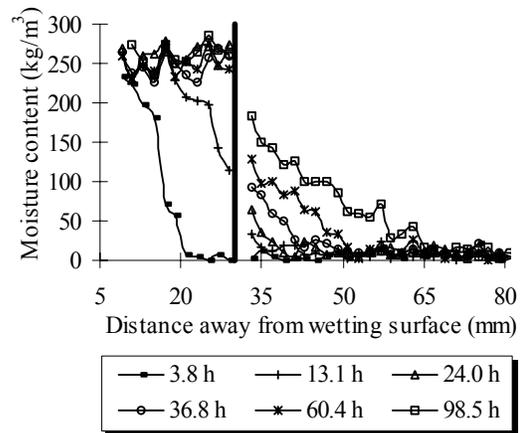Figure 4.   Moisture content profile of specimen *A*.

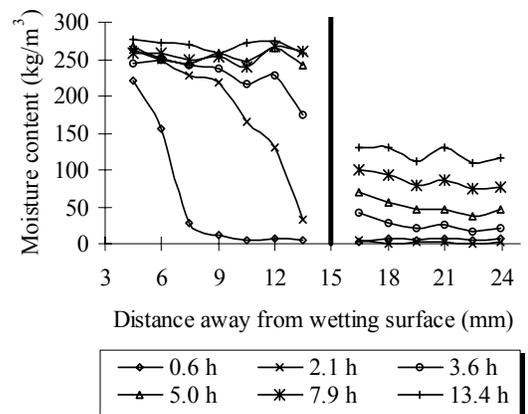Figure 5. Moisture content profile of specimen *B*.

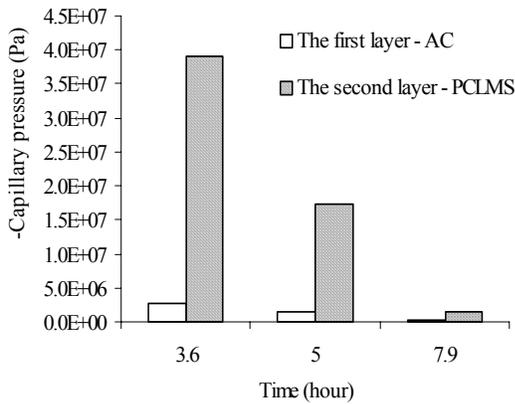Figure 6.   Moisture content profile of specimen *C*.

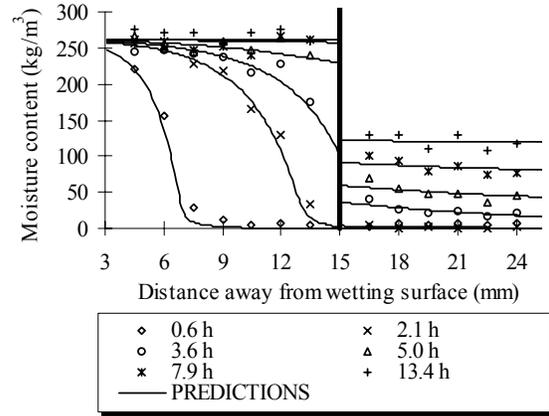Figure 7. Capillary pressures of AC and PCLMS at 1.5mm away from the bonded interface in specimen **C**.

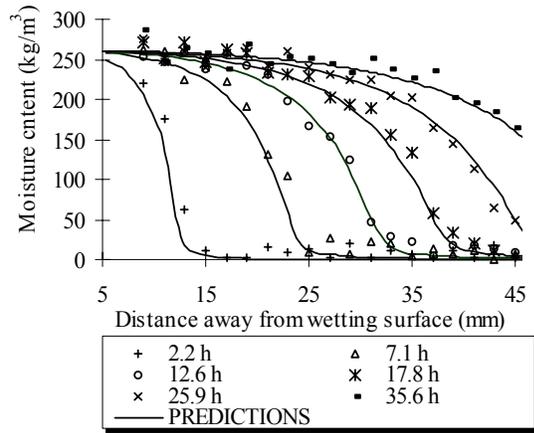Figure 10.Comparisons of moisture content profile of specimen **C**.

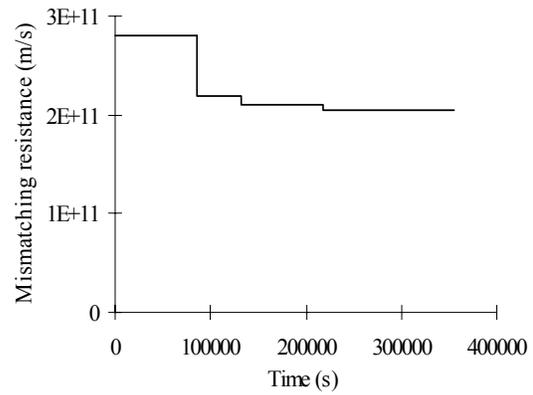Figure 8. Comparisons of moisture content profile of specimen **A**.

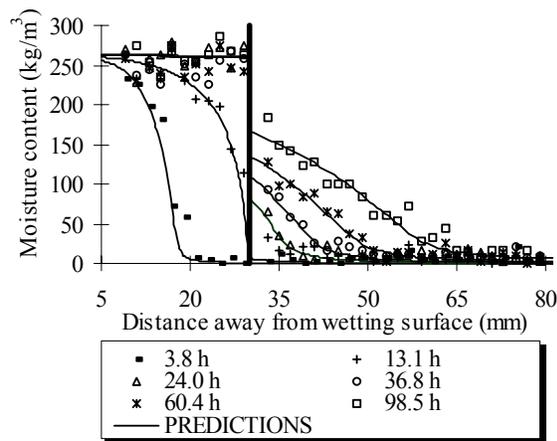Figure 11. Mismatching resistance of specimen **B**.

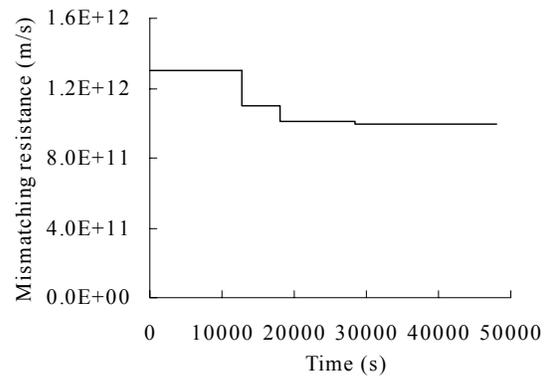Figure 9. Comparisons of moisture content profile of specimen **B**.

Figure 12. Mismatching resistance of specimen **C**.

Figure 8 compares the predictions of the model with the experimental results on moisture transport in a single piece of AC. Figure 9 compares the model predictions with experimental results on moisture transport across the natural contact interface between

two pieces of AC. Figure 10 compares predictions of the model with experimental results on moisture transport across a bonded interface between AC and PCLMS. Figures 11 and 12 show the mismatching resistance used in the predictions.

As shown in Figure 8, the model predictions on the moisture transport in a single material agree with the experimental results well. Therefore, by comparing predictions made by model with experiments involving moisture transport across imperfect hydraulic contact interfaces, mismatching resistance can be estimated. If the mismatching resistance utilized is appropriate, the good agreement between predictions made by the model and experimental results is expected. As shown in Figures 9 and 10, indeed, there is good agreement between experimental results and predictions of the model on the moisture transport across a bonded or natural contact interface between AC and PCLMS. Therefore, the mismatching resistances utilized in these predictions, as shown in Figures 11 and 12, are appropriate and reasonable.

As shown in Figures 11 and 12, mismatching resistance varies with experimental time period. However, by comparing Figures 9 and 10 with Figures 11 and 12, it is found that the mismatching resistance, in fact, mainly depends on the moisture content of the first layer. This is because the moisture reaching the contact surface of the first layer is distributed to both the layers. Due to mismatching, some pores on the contact surfaces are not available for moisture transfer. As a consequence, at the initial stage, the requirement of the second layer could not be fully satisfied. Therefore, the mismatching resistance is relative high at this moment. With the increasing moisture accumulated in the first layer, more moisture could be transferred to the second layer and requirement of the second layer could be satisfied more and more. When the first layer reached capillary saturation, the second layer could be satisfied as much as possible. Consequently, variation of mismatching resistance is smaller after the first layer reached capillary saturation than before. Other factors such as experimental time period and thickness of the composing materials affect the moisture content, which in turn affect the mismatching resistance.

CONCLUSIONS

A numerical model based on the assumption of imperfect hydraulic contact was developed. This model considers the increased length of the moisture path due to mismatching as the source of interface imperfection. The predictions of the model were compared with experimental results. The results indicated that there was good agreement between predictions of the model and experimental results. In addition, the experimental results showed that the bonded or natural contact interfaces between AC and PCLMS are imperfect hydraulic contact. Furthermore, the present study found that the mismatching resistance significantly varies with moisture content of the first layer until the first layer reaches capillary saturation.

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