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Water uptake in masonry: effect of brick/mortar interface

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ABSTRACT
Water transport in masonry walls composed of bricks and mortar joints can be strongly affected by the interface between brick and mortar. In this study, water uptake experiments and numerical simulations are performed to study the effect of interface resistance on moisture transport in masonry samples with horizontal and vertical interfaces. Neutron radiography is used to measure moisture content distribution in different masonry samples. An interface resistance is introduced to consider the imperfect contact between brick and mortar in the numerical model. A good agreement between measured and simulated moisture contents is found for different masonry samples. The orientation, horizontal or vertical, of the interface between brick and mortar has no influence on the value of the interface resistance. However we found that the interface resistance is affected by capillary pressure at the interface. A lower capillary pressure at the interface leads to a larger interface resistance.

KEYWORDS
Masonry, interface resistance, neutron imaging, capillary moisture transport

INTRODUCTION

Liquid water transport in single materials such as masonry, brick or mortar, is well understood and explained with capillary transport theory. However, moisture transport in masonry walls composed of bricks and mortar joints deviates from what is expected from the capillary transport theory. Many researchers attribute the deviation to the imperfect contact and hence the interface resistance at the brick/mortar interface (Qiu et al. 2003, Derluyn et al. 2011, Janssen et al. 2012, Delgado et al. 2016), while some attribute the deviation to a change of the moisture properties of the mortar joint, compared to bulk mortar (Brocken 1998). Nevertheless, most numerical hygrothermal models still use the assumption of perfect hydraulic contact at the brick and mortar interface (Zhou et al. 2016). It is unclear how the interface resistance affects the hygrothermal performance of masonry walls. Moisture flow across the brick/mortar interface needs to be accurately quantified in order to better understand moisture transport in masonry.

The masonry samples used in previous studies on interface effects are quite simplified (Qiu et al. 2003, Derluyn et al. 2011, Delgado et al. 2016). The samples normally consist of a layer of brick, a layer of mortar, and a second layer of brick, where only horizontal interface exists between brick and mortar joint. By comparison, masonry is much more complex than this in reality. There are both horizontal and vertical interfaces between brick and mortar in masonry. The effect of interface resistance on moisture transport in such complex geometry is not yet studied.

The objective of this study is to understand capillary water transport in masonry with horizontal and vertical joints. Neutron radiography is used to measure moisture content distribution. Numerical model is used to study capillary moisture transport and to obtain the interface resistance at different brick/mortar interfaces. The effect of horizontal and vertical interfaces on moisture transport is described.

METHODS

Four masonry samples with horizontal and vertical interfaces between brick and mortar are used for capillary water uptake experiment. Two of them are shown in Figure 1. The type of brick is kiln-fired clay brick. Portland cement mortar is used for making mortar joints. The sand grain size in the mortar ranges between 0.1 and 3 mm. The water-cement ratio is 0.16. The masonry samples are made by joining wet bricks with fresh mortar. Then the masonry samples are covered with vapor tight sheeting for 72 h for initial curing. Afterwards, the plastic sheeting is removed and the masonry samples are let to be cured for 28 days at room condition. Given the power of the neutron beam, the thickness of all the masonry samples is 1 cm. Neutron radiography, a non-destructive imaging technique that uses thermal neutrons to probe the sample, is used to measure the time- and space-resolved moisture content distribution in different masonry samples. The experiments were performed at the NEUTRA (Neutron Transmission Radiography) beamline at PSI (Paul Scherrer Institute) in Villigen, Switzerland. The neutron beam passing through the experimental sample is recorded by a detector system. The detector system consists of a scintillator screen with a CCD camera. The CCD camera has a field of view of 254 x 214 mm^2. The pixel size is 0.196 x 0.196 mm^2. The exposure time in the experiments was 20 s per radiography.

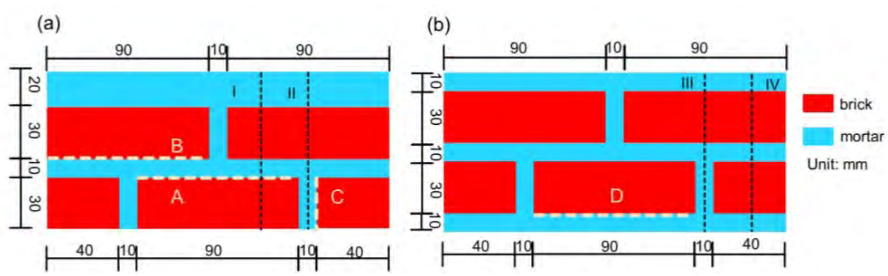

Figure 1. Two masonry samples for water uptake experiments showing the four types of interface (A, B, C and D) considered in this study.

The masonry samples are initially dried in an oven at 60 °C before capillary water uptake experiments. The experimental setup consists of a balance, a support for the samples that rests on the balance and a water reservoir. The sample is first installed on the support. Next, the water surface in the reservoir is brought up to the bottom of the masonry sample and then capillary water uptake starts. The mass of the experimental sample is measured at the start and end of each on a separated balance, as well as during the experiment with the balance in the experimental setup at an interval of 12 s.

The governing equation for 2-dimensional isothermal moisture transport in masonry is described by Richards equation:

$$\frac{\partial w}{\partial p_c}\frac{\partial p_c}{\partial t}+\frac{\partial}{\partial x}\left(K(p_c)\frac{\partial p_c}{\partial x}\right)+\frac{\partial}{\partial y}\left(K(p_c)\frac{\partial p_c}{\partial y}\right)=0 \tag{1}$$

where w is the moisture content (kg/m^3), p_c is the capillary pressure (Pa), $K(p_c)$ is the liquid permeability (s), which is a function of capillary pressure. At the interface between mortar and brick, an interface resistance R (s/m) is introduced. Moisture flow across the interface is described by: $g_f = \frac{\Delta p_c}{R}$, where Δp_c is the capillary pressure difference between the interface (Pa). At the bottom side of the masonry samples, a constant capillary pressure of -10 Pa is applied to represent capillary saturated condition. The capillary pressure curves of brick and mortar are described using a bimodal function of the van Genuchten model. The liquid permeability of the brick is determined based on the method proposed by Carmeliet et al. (2004). The moisture transport equation is solved using the finite element simulation program COMSOL. Rectangular meshes are used to discretize the geometric domain. More meshes are mapped around brick/mortar interface and the lower part of the domain. The COMSOL solver used is the direct solver MUMPS with its default solver options. Numerical time steps are automatically selected by the COMSOL solver.

The interface resistance is obtained by comparing simulated moisture profile results with measured moisture profile results. Only interfaces below the wetting front are considered for numerical simulation in this study. There are four types of interface between brick and mortar that affects moisture distribution in this study (Figure 1). Interface A is the horizontal interface between the first layer of brick and the second layer which is mortar. Interface B is the horizontal interface between this second layer, i.e. of mortar, and the third layer, i.e. of brick. Interface C is the vertical interface between two first layers, of brick and of mortar. Interface D is the horizontal interface between a first layer of mortar and a second layer of brick. Moisture transport in the two samples shows symmetric behavior. For sample (a), two profiles in the right part (profile I and II in Figure 1a) are selected for comparison. For sample (b), two profiles in the right part of this sample (profile III and IV in Figure 1b) are selected.

RESULTS

The moisture content distribution in the uptake experiment in sample (a) is given in Figure 2. The advance of wetting front is symmetric with respect to the middle of the sample. At the time of 409 s, the wetting front in the first layer of brick reaches the top of the brick element. By comparison, the wetting front in the two vertical mortar joints in the first layer shows an inverted bell curve. The wetting front reaches a higher height at the two edges of the mortar joints, while the middle part of the mortar joint shows the lowest height of wetting front. The higher wetting front at the two edges of the mortar is due to moisture transport from the surrounding bricks. At the time of 1525 s, the wetting front is already in the horizontal mortar joint above the first layer of brick, whereas the wetting front shows a shape of inverted triangle in the two vertical mortar joints. At the time of 10027 s, the wetting front is highest in the vertical mortar joint, in the third layer of the sample.

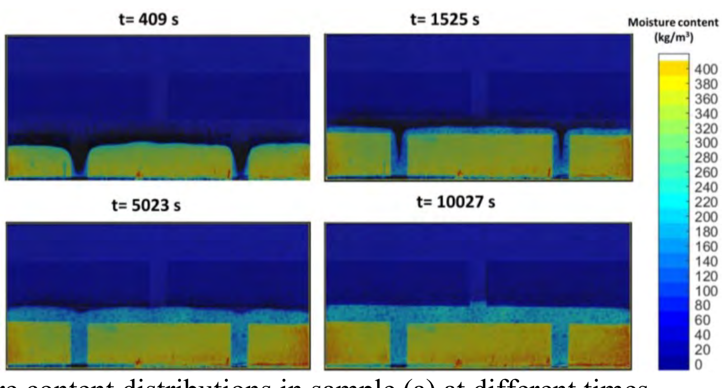

Figure 2. Moisture content distributions in sample (a) at different times.

The moisture content distribution in the uptake experiment in sample (b) is given in Figure 3. As the first layer of the sample is made of mortar, the advance of wetting front is very slow in this sample. For example, at the time of 5012 s, the wetting front only reaches the height of 1 cm. The wetting front shows an almost uniform distribution in the first layer of mortar joint. By comparison, at the time of 10026 s, the wetting front is higher at the location of the two vertical mortar joints than in the brick.

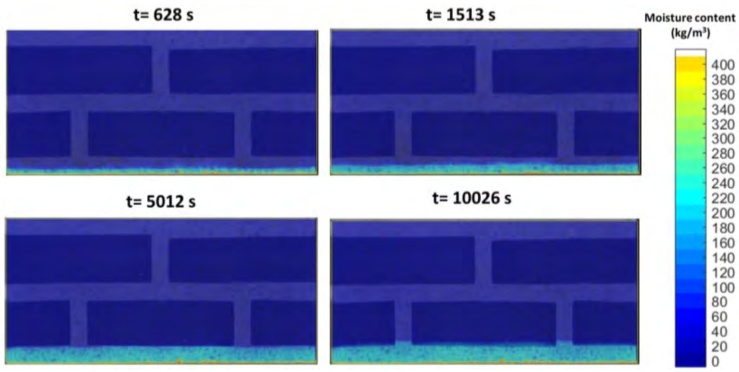

Figure 3. Moisture content distributions in sample (b) at different times

Figures 4 and 5 shows the comparison between simulated and measured moisture profiles in samples (a) and (b). In general, the simulated moisture content profiles agree mostly well with the simulated moisture content profiles. Not only the simulated locations of wetting front agree well with measurements, but also the simulated moisture contents at different locations agree well with the measured moisture contents. However, there are some disagreements between measurement and simulation at some profiles. This might be due to material heterogeneity. In the numerical model, the same brick and mortar material properties are used for each sample. In reality, the material properties of brick and mortar might be slightly different.

The obtained interface resistances for the four types of interface A, B, C and D are: 8.0×10^{9}, 5.0×10^{12}, 4.0×10^{9} and 20.0×10^{9} m/s. A larger value of interface resistance means a larger capillary pressure drop across the interface and a smaller moisture flux across the interface.

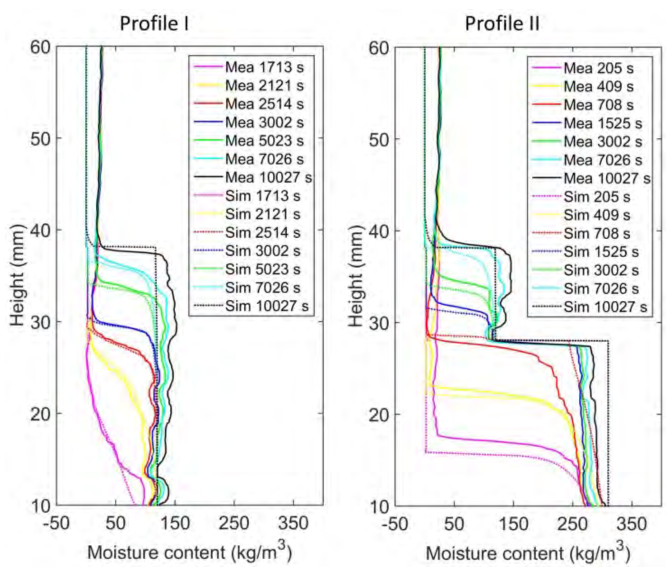

Figure 4 Measured and simulated moisture contents at profiles I and II for sample (a).

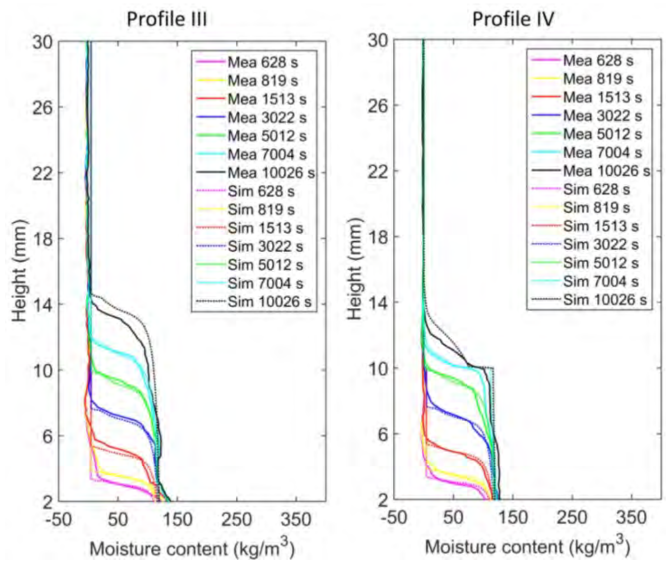

Figure 5 Measured and simulated moisture contents at profiles III and IV for sample (b).

DISCUSSIONS

Based on the results presented above, we propose that the interface resistance may be dependent on capillary pressure at the interface between two materials. A lower capillary pressure at the interface will lead to a larger interface resistance. Interface B has the largest interface resistance. The capillary pressure at Interface B is much lower than at the other types of interface. On the one hand, Interface B is at a higher location above two layers, i.e. of brick and mortar. There is already a large capillary drop when moisture reaches Interface B by capillary transport. On the other hand, the interface resistance at Interface A leads to an additional capillary pressure drop.

The interface resistance at Interface C (4.0×10^9 s/m) is slightly smaller than that at Interface A (8.0×10^9 s/m). Interface A is a horizontal interface between the first layer of brick and the second layer of mortar, whereas Interface C is a vertical interface between brick and mortar in the first layer. When wetting front reaches Interface A, there is already some capillary pressure drop. By comparison, Interface C is along the direction of moisture transport. Capillary pressure at lower location is larger than at higher location. The top location of Interface C is the same as that of Interface A. Therefore, the capillary pressure at Interface A is definitely larger than that at Interface C. The obtained interface resistance at Interface C is the averaged value along this interface. Due to higher capillary pressure at the interface, the interface resistance Interface C is smaller than that at Interface A. There are both horizontal and vertical interfaces between brick and mortar in masonry. Compared to the flow, the magnitude of interface resistance does not seem to be affected by the direction of interface. Instead, the interface resistance is apparently related to capillary pressure during wetting at the interface. The larger the capillary pressure, the smaller the interface resistance at the interface. The datasets offer more result, which will be studied in the next phase.

CONCLUSIONS

Different masonry samples with horizontal and vertical interfaces are used to study the resistance to moisture transport across the brick/mortar interface. Neutron radiography is used to measure the time- and space-resolved moisture content distribution in different masonry samples. A 2-dimensional moisture transport model is built to study moisture transport in masonry samples. An interface resistance is introduced to consider the imperfect contact between brick and mortar. There is very good agreement between measured and simulated moisture contents for different masonry samples. Compared to the flow, the magnitude of interface resistance is not affected by the direction of interface. Horizontal interface or vertical interface between brick and mortar has no influence on the value of interface resistance. It is found that interface resistance seems to be affected by the capillary pressure at the interface, and not by the orientation of the interface. A lower capillary pressure at the interface will lead to a larger interface resistance.

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