Masonry brick-cement mortar interface resistance to water transport determined with neutron radiography and numerical modelling

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Abstract

Masonry is one of the most common building envelope systems in the world, providing an excellent water protection solution against rain. Water transport in masonry walls composed of bricks and mortar joints can be strongly affected by the nature of the interface between brick and mortar. In this study, two dimensional 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 document the time- and space-resolved moisture content distribution in different masonry samples. In the simulation of moisture transport, an interface resistance models the imperfect contact between brick and mortar. A good agreement between measured and simulated moisture content distribution is observed for different masonry samples. Moisture transport in masonry could be strongly affected by the interface resistance, when interface is in proximity to moisture source. The orientation, horizontal or vertical, of the interface between brick and mortar does not have an influence on the value of the interface resistance. However, the interface resistance depends on the capillary pressure at the interface. In the range of capillary moisture transport, a lower capillary pressure at the interface will lead to a larger interface resistance.

Keywords: masonry, interface resistance, neutron imaging, capillary moisture transport

1 Introduction

Masonry is one of the most common building envelope systems in the world, in part due to its excellent water management behavior of multiple-wythe masonry (Hall & Hoff, 2009). One of the main factors affecting durability of masonry is moisture. Liquid water sources in masonry can be wind-driven rain, rising damp and, to a lesser degree, condensation. High moisture levels in masonry walls can give rise to several types of damages, such as salt crystallization, efflorescence, spalling and freeze/thaw damage (Pel et al., 1995). Masonry consists of brick, a coarse pore material, and mortar a fine porous material. Brick with coarse pores has a fast water uptake, and as such the first brick in masonry works as a buffering material during rain preventing run-off. Moisture transport from a fine porous material as mortar to a coarse porous material as brick is hindered due to the high viscous forces in the fine porous material (mortar) and the low capillary forces in the coarse pore material (brick) according to Laplace law. In three-wythe masonry, this phenomenon leads a capillary break, where the inside brick layer is protected from rain and remains dry. This is why it is important to study the capillary break principle in the setup brick-mortar-brick and the possible role of interfaces. This paper proposes to analyze the role of interfaces between brick and mortar in order to better understand moisture transport and capillary break principle in masonry wall materials and, consequently, to prevent moisture-related damage.

Liquid transport in a single material, such as 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 this theory. Many attribute the deviation to the imperfect contact and, hence, the interface resistance at the brick/mortar interface (Delgado et al., 2016; Derluyn et al., 2011; Guimarães et al., 2018; Janssen et al., 2012; Qiu et al., 2003), while some attribute the deviation to a change of the moisture properties of the mortar, compared to bulk mortar (Brocken, 1998). Derluyn et al. (2011) studied the influence of curing conditions on interface resistance and found that the interface resistance is larger for a dry cured mortar than a wet cured mortar. Janssen et al. (2012) confirmed the finding from Derluyn et al. (2011) with an analytical sharp-front-theory. Qiu et al. (2003) carried out research to study moisture transport across the interface between autoclaved aerated concrete and mortar. They proposed that the interface resistance varies with moisture content and mortar characteristics at the interface. Delgado et al. (2016) studied moisture transport in building materials for a brick/mortar interface at different positions in the samples. Despite the evidence of a contact resistance present in masonry, most heat and mass transport simulations using numerical models still assume perfect hydraulic contact at the brick and mortar interface (Johansson et al., 2014; Künzle et al., 2004; Zhou et al., 2017, 2018), and neglect the role of an interface resistance on the hygrothermal performance of masonry walls. Therefore, moisture flow across the brick/mortar interface needs to be accurately quantified in order to better understand moisture transport in masonry walls and to validate hygrothermal models. The masonry samples used in previous studies on interface effects are quite simple, with layered brick-mortar-brick samples displaying only a horizontal interface (Delgado et al., 2016; Derluyn et al., 2011; Qiu et al., 2003). Actually, masonry is much more complex containing both horizontal and vertical interfaces.

Gravimetric test could measure accurately moisture transport in building materials. However, this method only measures total moisture weight in a sample and no information about moisture content distribution in the sample could be obtained. By comparison, imaging of moisture content in porous media is a powerful mean to analyze distribution of moisture content during moisture transport. Gamma-ray attenuation method, X-ray radiography, and nuclear magnetic resonance have been used to visualize water distribution and sometimes to determine quantitatively the moisture content in porous building materials (Derluyn et al., 2011; Guimarães et al., 2018; Pel et al., 1995; Qiu et al., 2003). Moisture content can be measured accurately with gamma-ray attenuation method, but only along one dimension. X-ray projection or computer tomography can document the presence of water in pores, however, as water does not interact strongly with X-rays, the reduced signal makes quantification challenging in a time and spatial resolved way. In contrast, neutron radiography is a powerful technique to measure moisture content with excellent time and spatial resolution in a non-destructive way. As neutrons are very sensitive to hydrogen, even small amounts of water in a porous structure can be detected. Many studies have successfully used neutron radiography to measure moisture variation in porous building materials (Guizzardi et al., 2016; R. Hassanein et al., 2006; Lal et al., 2014).

The objective of this study is to understand capillary water transport in masonry in presence of horizontal and vertical joints in order to determine the role of these interfaces. Neutron radiography is used to measure the moisture content distribution at high spatial and temporal resolution in different samples from simple to complex configurations. A numerical model is used for the accurate determination of the interface resistance of different brick/mortar interfaces. The effect of horizontal and vertical interfaces on moisture transport is then described.

2 Capillary water uptake experiments

2.1 Experimental setup and Procedure

2.1.1 Materials

Masonry samples with horizontal and vertical interfaces between brick and mortar, as shown in Figure 1, are used for capillary water uptake experiments. Sample A has only horizontal interfaces between brick and mortar, whereas samples B, C and D have both horizontal and vertical interfaces. The type of brick is a kiln-fired clay brick. Cement mortar is used for the mortar joints. The sand grain size in the cement mortar ranges between 0.06 and 3.0 mm and the water-cement mortar ratio is 0.16 by mass according to the manufacture. The different bricks are first cut to their correct thickness to avoid the possible damage to brick/mortar interface caused by cutting after curing. 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 during initial curing. Afterwards, the plastic sheeting is removed and the masonry samples are let to be cured for 28 days at room condition, i.e. around 22°C and 40% RH. Given the energy of the neutron beam used in this experiment, the thickness of all the masonry samples is 1 cm. The material properties of brick and mortar are given in Table 1.

Table 1 Material properties of brick and mortar

	Bulk density (kg/m ³)	Open porosity	Water absorption coefficient (kg/m ² s ^{0.5})	Capillary moisture content (kg/m ³)	Moisture retention parameters			
					N	k	a	n
Brick	1564	0.389	0.455	309.9	1	1.0	1.6e-6	1.8
Mortar	2146	0.195	0.051	120.1	1	1.0	0.7e-7	1.5

Figure 1 Schematic representation of the masonry samples A, B, C and D, used for water uptake experiments, showing the three generic interfaces considered in this study.

2.1.2 Neutron Radiography

Neutron radiography, a non-destructive imaging technique that uses thermal neutrons to probe the sample, allows to measure the time- and space-resolved moisture content distribution in the different masonry samples. The experiments were performed at the NEUTRA (Neutron Transmission Radiography) beam line at PSI (Paul Scherrer Institute) in Villigen, Switzerland. Neutrons with an average energy around 25 meV and velocities around 2200 m/s are emitted by spallation by the Swiss Neutron Spallation Source (SINQ). The neutron beam is controlled by a collimator and the sample is located in the beam path at a distance from the collimator. Neutrons interact with the atomic nuclei of experimental sample. The intensity of the transmitted neutron beam, I , can be described with the Beer–Lambert law:

$$I = I_0 \times e^{-\Sigma z} \quad (1)$$

where I_0 is the intensity of the incident beam (W), z is the thickness of the sample (m), Σ is the neutron attenuation coefficient of the sample (1/m). For composite materials, each component, from 1 to n , can be considered to have a thickness and the above equation becomes:

$$I = I_0 \times e^{-\Sigma_1 z_1 - \Sigma_2 z_2 \dots - \Sigma_n z_n} \quad (2)$$

For the case here, where we only consider as components the dry porous building materials brick/mortar (subscript d) and water (subscript w), we get:

$$I = I_0 \times e^{-\Sigma_d z_d - \Sigma_w z_w} \quad (3)$$

The intensity of the transmitted neutron beam for the initial dry material is:

$$I_{dry} = I_0 \times e^{-\Sigma_d z_d} \quad (4)$$

Therefore, the water thickness for a given wet condition can be calculated as

$$z_w = \frac{1}{\Sigma_w} \ln\left(\frac{I_{dry}}{I}\right) \quad (5)$$

The moisture content m_w (kg/m³) at each pixel can be calculated as following:

$$m_w = \frac{z_w \Delta x^2 \rho_w}{z \Delta x^2} \quad (6)$$

where ρ_w is the water density (kg/m³) and Δx is the pixel size (m).

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 mm². The pixel size is 0.196 x 0.196 mm². The exposure time in the experiments is 20 s per radiography. The quantitative correction is performed with the Quantitative Neutron Imaging (QNI) algorithm developed at PSI (R. K. Hassanein, 2006).

2.1.3 Capillary uptake experiments

The masonry samples, after curing for 28 days, are initially dried in a convection oven at 60 °C before the capillary water uptake experiments. The experimental setup consists of a balance (resolution: 0.001 g), a support for the samples that rests on the balance and a water reservoir that is held on a separate support and remotely controlled with two elevating pistons (Figure 2). The measured weight from the balance is used to calibrate the weight measured with neutron radiography. The two elevating pistons are used to control water level in the water reservoir. The weight of dry sample is first weighted on a separated balance. The sample is then installed on the support. Special care is taken to keep the sample on the support immobile throughout the water uptake experiment. The dry sample is imaged before capillary water uptake starts. After imaging of the dry sample, the reservoir is brought up until the water surface touches the bottom of the masonry and then capillary water uptake starts. The mass of the experimental sample is measured during the experiment at 12 s intervals. Neutron radiographs are acquired every 20 s during the water uptake experiments. When the wetting front in the sample does not move anymore over a certain period, the reservoir is brought down and images are still taken for the wet sample. Finally, neutron imaging is stopped and the wet sample is removed from the support and weighted on the separated balance.

Figure 2 Photo of capillary water uptake experiment setup inside the NEUTRA beamline showing sample C in the frame resting on the balance and the water reservoir with its two remote-controlled elevating pistons. The whole experimental set-up lies on a moveable stage that is translated upwards to bring the sample in front of the scintillator.

2.2 Results

We consider the four uptake experiments successively, presenting results for masonry systems of increasing complexity. For the simplest configuration of brick/mortar layers, the moisture content distribution in sample A at four time steps are shown in Figure 3. The wetting front at these different times is mostly uniform and almost horizontal, indicating that water uptake occurs as a one-dimensional water flow in the vertical direction. At time 413 and 674 seconds, the wetting front is in the first layer of brick. At the time of 1256 seconds, the wetting front is in the second layer of the system, the mortar layer. The advance of the wetting front is much slower in the mortar layer than in brick, as water absorption coefficient of mortar is much smaller than that of brick. At the time of 10028 seconds, the water front is still in the mortar layer approaching the brick.

We now consider the moisture content profiles over the height of the sample versus time. To remove heterogeneity and noise effects, these profiles are obtained by averaging the moisture content in the horizontal direction over a width of 2 cm in the middle of the sample. Moisture content profiles in the center part of sample A evolve versus times, as shown in Figure 4. The first three profiles are all within the brick layer and the next four are in the mortar layer. There is a clear jump down in moisture content across the interface between the brick and mortar layers. Moisture content reached in the brick is larger than that in the mortar, as the capillary moisture content of the brick is larger than that of the mortar.

Figure 3 Moisture content distributions in sample A at four times

Figure 4 Measured moisture content profiles in sample A at different times with simulated moisture contents. Simulation results are discussed below. (The grey area shows the position of mortar joint)

Compared to sample A, sample B is much more complex. The vertical mortar joint in the first layer yields two vertical interfaces between brick and mortar. The horizontal mortar joint in the second layer yields two horizontal interfaces. The moisture content distributions during the water uptake experiment in sample B are given for different times in Figure 5. The distribution of moisture content at early stage (from 63 until 302 seconds) is significantly affected by the presence of cracks in the brick and at the interface brick-mortar. It is clearly shown that the advance of wetting front in the first layer is much faster at the interface between the vertical mortar joint and brick at the right brick. In this case, there is most likely a crack between the vertical mortar joint and the right brick, which results in a preferential pathway for liquid water uptake. The crack between the vertical joint and the right brick is probably due to the shrinkage during binding and hardening of the cement mortar. In addition, there are also two small cracks in each brick, bottom left and right. The advance of the wetting front is initially faster at the location of these cracks. At 622 seconds, the wetting front at the interface between the vertical mortar joint and the right brick reaches the top of the brick, while the wetting front at the interface between the vertical mortar joint and left brick did not reach the top yet. In general, the difference of the location of the wetting front for the two interfaces becomes smaller when the wetting front reaches the horizontal layer of mortar.

The moisture content profiles at the locations II and III, as indicated in Figures 1 and 5, are shown in Figure 6. The moisture content profiles II and III are similar until 5012 seconds from start of the uptake process (Figure 6). At 10015 seconds, the wetting front of Profile II is slightly higher than that of Profile III. This is due to the fact that at Profile II, after passing the first brick, the capillary uptake continues over the mortar layer extending until the top of the sample. On the other hand, at Profile III, we have a change

from brick to mortar and again to brick showing an additional interface resistance mortar-brick. Moreover, the capillary suction of the brick, which is a coarse pore material, is not sufficiently high enough to overcome the high viscous forces in the fine porous material, as such blocking the capillary transport from a fine to a coarse porous material.

Figure 5 Moisture content distributions in sample B at different times. (The dashed box shows the displayed area at other time steps)

Figure 6 Measured moisture content profiles at profile III and II in sample B at different times with simulated moisture contents. (The grey area shows the position of mortar joint)

Sample C is similar to sample B, however with two vertical mortar joints in the first layer. The moisture content distributions in the uptake experiment in sample C are given in Figure 7 and the moisture profiles at the location of profiles IV and V are shown in Figure 8. Compared to sample B, there are no evident cracks in this sample. Up to 205 seconds, the wetting front is slightly faster in the middle brick. Then, from the 409 seconds, the advance of wetting front is almost flat across the sample. At 708 seconds, the wetting front reaches the top of the first layer of brick. By comparison, the wetting fronts in the two vertical mortar joints show an inverted bell curve. The wetting front is higher at the two edges of the mortar joints, while the middle part of the mortar shows the lowest height of wetting front. The higher wetting front at the two edges of the mortar joint is due to moisture transport from the brick to the mortar joint. At time 1541 seconds, the wetting front is crossing the horizontal mortar layer above the first layer of brick, whereas the wetting front shows a shape of inverted triangle in the two vertical mortar joints. The wetting front in the mortar joint at Profile IV advances quite fast from 1713 to 3002 s (Figure 8). Afterwards, the advancing rate decreases. This is due to the loss of water contribution from the surrounding bricks to the mortar joint, as the wetting front by then reached the horizontal mortar layer. There is an observable difference of the wetting fronts at Profiles VI and V at the time of 3002 seconds (Figure 8), where the front is behind in the mortar compared to the brick-mortar composition. However, the difference of wetting front between the two profiles becomes smaller at 5023, 7026 and 10043 seconds. At the time of 10043 s, Figure 7 shows that the wetting front enters the vertical mortar in the top brick layer. At the mortar-brick interface, the presence of the capillary break and an additional interface resistance blocks further moisture transport. The same observations can be made in Figure 8.

Figure 7 Moisture content distributions in sample C at different times. (The dashed box shows the displayed area at other times)

Figure 8 Measured moisture content profiles at profile V and IV in sample C at different times with simulated moisture contents. (The grey area shows the position of mortar joint)

Sample D is similar to sample C, with a first layer of mortar at the bottom. The moisture content distributions in the uptake experiment in sample D are given in Figure 9 and the moisture profiles at the location of profile VI and VII are shown in Figure 10. It can be seen in Figure 9 that moisture distribution is very uniform in the first layer of mortar. The moisture content at profile VI and VII are very close to each other in the first 5012 seconds. 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 seconds, the wetting front only reaches the height of 10 mm. After 5012 seconds, there is difference of moisture content at profile VI and VII. The moisture front advances faster in the mortar at Profile VI than at Profile VII. The faster uptake in mortar at Profile VI illustrates the absence of interface resistance while the mortar continues. At profile VII, the moisture content at 10 mm height shows clearly a moisture drop due to the capillary break and the presence of an interface resistance (Figure 10).

Figure 9 Moisture content distributions in sample D at different times. (The dashed box shows the displayed area at other times)

Figure 10 Measured moisture content profiles at profile VI and VII in sample D at different times with simulated moisture contents. (The grey area shows the position of mortar joint)

3 Numerical simulations

Water uptake in the four samples is simulated with an isothermal moisture transport model, considering 2-dimensional moisture transport, as the samples are homogeneous in the third (thickness) direction.

3.1 Governing equation

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

$$\frac{\partial w}{\partial p_c} \frac{\partial p_c}{\partial t} + \frac{\partial}{\partial x} \left(K(p_c) \frac{\partial p_c}{\partial x} \right) + \frac{\partial}{\partial y} \left(K(p_c) \frac{\partial p_c}{\partial y} \right) = 0 \quad (7)$$

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. Since the pore size of both brick and mortar are sufficiently small gravity may be neglected. Here the capillary pressure p_c is defined as the pressure difference between the liquid and the gaseous phase and is thus negative for unsaturated conditions (Janssen et al., 2007).

Two artificial boundaries are created at the interface between brick and mortar to consider moisture flow across the interface. One boundary is at the brick side and the other is at the mortar side. There is continuity of moisture flux at these two boundaries. Moisture flux (kg/s) at the boundary is described by:

$$g_f = \frac{\Delta p_c}{R} \quad (8)$$

where Δp_c (Pa) is the capillary pressure difference between brick and mortar across the interface and R (s/m) is the interface resistance between brick and mortar.

The initial condition is a capillary pressure of -10^{10} Pa to represent dry initial condition. In the first layer of brick, for the case of numerical stability, the initial capillary pressure is set to $-10^{8.5}$ Pa, also representing very low initial moisture content of 2.1 kg/m^3 . At the bottom side of the masonry samples, a constant capillary pressure of -0.1 Pa is applied to represent capillary saturated condition. The top boundary condition is set as no-flux condition.

The moisture transport equation is solved using the finite element simulation software COMSOL. The time-dependent problem is solved by integration of the partial differential equations in time according to an implicit backwards differentiated formula (BDF) method. The COMSOL solver used is the direct solver MUMPS (MULTifrontal Massively Parallel Sparse direct Solver) with its default solver options. Numerical time steps are automatically selected by the COMSOL solver, depending on relative or absolute tolerance for the accuracy of the integration. Rectangle meshes are used to discretize the modeling domain. Finer meshes are generated at the boundary and interface. Due to larger capillary pressure change in the vertical direction, more elements are applied in the vertical direction than horizontal direction.

3.2 Material properties

The capillary pressure curves of brick and mortar are described using van Genuchten model (1980):

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$$w = w_{cap} \sum_{i=1}^N \frac{1}{(1 + a_i \cdot abs(p_c)^{n_i})^{m_i}} \quad (9)$$

289 where w_{cap} is the capillary saturation moisture content (kg/m^3); a_i and n_i are the fitting parameters, $m_i = 1 -$
 290 $1/n_i$. As capillary moisture content, we take the maximal moisture content reached in the first layer of
 291 brick and mortar. The capillary moisture contents are, respectively 309.9 and 120.1 kg/m^3 for brick and
 292 mortar (Table 1). The relation between capillary pressure and moisture content for brick is based on data
 293 obtained from pressure plate apparatus and vapor sorption isotherm, while the relation between capillary
 294 pressure and moisture content for mortar is measured only with vapor sorption isotherm as no moisture
 295 change could be observed in the pressure range of pressure plate apparatus. The other parameters for
 296 describing capillary pressure curve of brick and mortar are included in Table 1. Figure 11a shows the
 297 capillary pressure curve for the brick and mortar.

298 The liquid permeability of the brick is determined based on the method proposed by Carmeliet et
 299 al. (2004). Liquid permeability is calculated as the product of moisture capacity and moisture diffusivity.
 300 Moisture diffusivity is determined from moisture content profile measurements measured in the first
 301 layers of brick and mortar. Figure 11b shows the liquid permeability for brick and mortar.

302

303 Figure 11 Capillary pressure curve (a) and liquid permeability (b) of brick and mortar

304 The interface resistances are considered only in the first and second layers as measurement results
 305 are only available in these two layers. We identify three generic interfaces between brick and mortar that
 306 affect moisture distribution in this study (Figure 1). Interface 1 is the horizontal interface between the first
 307 layer of brick and the second layer of mortar in samples A, B and C. Interface 2 is the vertical interface
 308 between the first layer of brick and the first layer of mortar in samples B and C. Interface 3 is the
 309 horizontal interface between the first layer of mortar and the second layer of brick, which is present only
 310 in sample D. The interface resistance is obtained indirectly by comparing simulated moisture profile

results with measured moisture profile results. Simulations are performed to find the interface resistance that leads to best agreement between simulation and measurement results.

3.3 Simulation results

We first discuss the selection of the location of interest, where moisture content profiles are used to determine the interface resistance. As sample A is subjected to one-dimensional moisture transport, the location is selected in the middle part of the sample (profile I in Figure 1a) for comparison between measurement and simulation. In sample B, the left side of the sample shows preferential liquid water flow due to the existence of a crack in the brick. Thus, the two locations selected for comparison are in the right part of this sample (profile II and III in Figure 1b). Moisture transport in sample C shows symmetric behavior. Two locations in the right part of this sample (profile IV and V in Figure 1c) are selected for comparison. For profile IV, the first and second layers are mortar, while for Profile V the first layer is brick, and the second layer mortar. For sample D, two locations in the right part of this sample (profile VI and VII in Figure 1d) are selected for comparison. Only the second layer is different for the two locations. This second layer is made of mortar for profile VI and of brick for profile VII.

Figures 4, 6, 8 and 10 show the comparison between simulated and measured moisture profiles for samples A, B, C and D, respectively. In general, the simulated moisture content profiles agree quite well with the simulated moisture content profiles. For example, there is a good agreement between measurement and simulation at profile I for sample A. Not only the simulated locations of wetting front agree well with measurements, but also the simulated moisture content profiles agree well with the measured moisture content profiles. The simulated moisture contents at profiles II and III in sample B are also very close to measured moisture contents. At profile IV in sample C, the moisture transport is influenced by moisture transport properties of mortar and brick, and the vertical interface resistance mortar-brick. A good agreement between measurement and simulation results is obtained at this profile. Furthermore, the two-dimensional distribution of the wetting front agrees well with the measurement (Figure 12). The simulated shape of wetting front in the vertical mortars displays the same shape, a V with rounded edges that is seen in the measurement. Both measurement and simulation show that the lowest wetting front is in the middle of the two vertical mortar joints. At profile VI in sample D, the moisture transport is mainly influenced by material properties of mortar. The good agreement between measurement and simulation at this profile indicates that the moisture transport properties of mortar are well represented in the numerical model. However, there is some disagreement between measurement and simulation for some profiles at different time. This might be due to differences in material properties of the mortar from sample to sample due to material heterogeneity. In the numerical model, the same brick and mortar moisture transport properties are used for each sample, while in reality, the moisture transport properties of brick and mortar might be slightly different. For example, although the materials in the different layers in profiles I, III and V are totally the same, the agreement between measurement and simulation is better for profiles I and III than for profile V, which may indicate slightly different moisture properties of the mortar at this location.

Figure 12 Comparison of measured and simulated wetting front at 2121 seconds for sample C

The interface resistances obtained for Interface 1, 2 and 3 are 8.0×10^9 , 3.5×10^9 and 80.0×10^9 m/s, respectively. Interface 3 shows the largest value of interface resistance while interface 2 shows the smallest interface resistance. A larger value of interface resistance means a larger capillary pressure drop across the interface and a smaller moisture flux across the interface.

4 Discussions

From the experimental results, we observe that moisture transport across interface 2 is very fast whereas moisture transport is much slower at interface 3. Interface resistance may be dependent on capillary pressure at the interface between two materials. We analyze how the interface resistance depends on capillary pressure at the interface of the source material. Figure 13 shows as an example the capillary pressure at the locations P1, P2 and P3 (Figure 1) during the water uptake experiments. The points P1, P2 and P3 are located in the source material in the middle of Interface 1, 2 and 3, respectively. The capillary pressure in the brick at P2 shows an earlier increase and slightly larger value than at P1 during the total wetting process. From our analysis, we observed that the capillary pressure at Interface 2 in average is larger than that at Interface 1. We also found that the interface resistance at Interface 2 is smaller than that at Interface 1. This indicates that the interface resistance is smaller when the capillary pressure is higher. The same is found for interface 3. When the moisture front reaches the interface, the capillary pressure in the mortar at P3 increases and then during the wetting period remains much smaller than at P1 and P2. Since the capillary pressure at Interface 3 is much smaller compared to the other two interfaces, the interface resistance at this interface is found to be much larger. In principle, the interface resistance changes with capillary pressure, and a larger capillary pressure at the interface of the source material will lead to a smaller interface resistance and a smaller jump in capillary pressure at the interface. The following explanation may explain why the interface resistance is smaller at higher capillary pressure. Assuming the interface between two materials consisting of a bundle of capillary pores of different size, more coarse pores will be filled by water at higher capillary pressure showing a higher permeability. Thus, the interface resistance becomes smaller at higher capillary pressure due to increased liquid permeability

of pores connecting over the interface tubes. There are both horizontal and vertical interfaces between brick and mortar in masonry. Compared to the moisture 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.

Figure 13 Capillary pressures at the locations P1, P2 and P3

Figure 14 shows the influence of interface resistance at Interface 2 on moisture content distribution at profile IV in sample C. Moisture transport across the interface between brick and mortar is observed to be very sensitive to interface resistance. Even a small change of interface resistance will lead to very different moisture content distributions at profile IV. For example, a small increase of interface resistance from 3.5×10^9 to 7.0×10^9 m/s will lead to much slower wetting at profile IV in sample C. Therefore, we conclude that the interface resistance needs to be determined accurately to predict moisture transport in masonry walls.

Figure 14 Influence of interface resistance on moisture content distribution at profile IV for sample (c). IR: interface resistance.

5 Conclusions

Water uptake experiments in masonry samples are performed to study the effect of interface resistance on moisture transport across the brick/mortar interface. Different masonry samples with horizontal and vertical interfaces are studied. Neutron radiography is used to measure the time- and space-resolved moisture content distribution in different masonry samples with horizontal and vertical interfaces. A 2-dimensional moisture transport model is built to study moisture transport in masonry samples with horizontal and vertical interfaces. A constant 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. Moisture transport in masonry could be strongly affected by the interface resistance, when interface is proximity to moisture source. A small change of interface resistance will lead to quite different moisture content distributions. The magnitude of interface resistance is not affected by the direction of interface. Interface resistance is determined by the value of the capillary pressure at the interface. In the range of capillary moisture transport, a lower capillary pressure at the

interface will lead to a larger interface resistance. More study is needed to quantify the relation between capillary pressure and interface resistance.

Cracks regularly exist at the interface between brick and mortar which can act as preferential flow path for moisture into masonry. A fracture flow model is needed to predict moisture distribution and transport in masonry wall with cracks (Michel & Pease, 2018; Roels et al., 2003).

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