ABSTRACT
The moisture transport over brick-mortar interfaces is an important parameter in several degeneration mechanisms of brick masonry and other block constructions. In this study results of the water absorption and drying of masonry indicate that the hydraulic contact at the interface of brick and mortar is not perfect. Experimental moisture profiles as measured using NMR show a (more or less) constant moisture flux over the mortar joint. A macroscopic description of this phenomenon is given by incorporating an interfacial conductivity at the contact of brick and mortar. For water absorption, the value of this interfacial conductivity is determined by tuning the simulated moisture profiles with the measured moisture profiles. The accuracy of the interfacial conductivity as determined in this way, is shown to be mainly affected by the suction curve of mortar joint. Given the moisture diffusivity and the suction curve of the materials, the moisture transport in a masonry segment can be modeled.

1. INTRODUCTION
The moisture transport in masonry is an important parameter in several degeneration mechanisms such as frost, salt attack and growth of algae. Previous research concerning the moisture transport in masonry generally focused on the characteristics, i.e., the suction and the sorptivity of single materials like brick and mortar [1]. However in

Keywords: Brick-mortar interface, Moisture transport, Interfacial conductivity

1Department of Architecture, Building and Planning and 2Department of Physics of the Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, the Netherlands, 3TNO Building and Construction Research, P.O. Box 49, 2600 AA Delft, the Netherlands
masonry, mortar is cured in between bricks. Consequently curing conditions of mortar joints differ and single mortar samples do not represent these mortar joints. Up to now little attention has been given to the study of moisture transport properties of mortar joints and characteristics of hygric contact of brick-mortar interfaces. In this paper the one-dimensional moisture transport across brick-mortar interfaces is studied; a description is given for the moisture transport, accounting for the hydraulic contact between the material layers. Moisture profiles measured by NMR are used to compare simulations based on this description.

2. THEORY OF MOISTURE TRANSPORT

Liquid and vapour transport

The isothermal macroscopic liquid water flux, \( q \) [m s\(^{-1}\)], in porous material can be described by Darcy's law:

\[
q = -K(\theta) \nabla \psi(\theta)
\]  

(1)

In this equation \( K \) [m s\(^{-1}\)] is the hydraulic conductivity and \( \psi \) [m] the suction, which are both a function of the actual volumetric moisture content \( \theta \) [m\(^3\) m\(^{-3}\)]. Neglecting moisture transport due to the gravity, the outside gas pressure and dissolved salts, liquid water is transported because of capillary action only. Combination of equation (1) with the conservation of mass gives:

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left( D_{\theta,1} \frac{\partial \theta}{\partial x} \right)
\]  

(2)

where:

\[
D_{\theta,1} = K(\theta) \left( \frac{\partial \psi(\theta)}{\partial \theta} \right)_T
\]

In this diffusion equation, as first established by Philip and de Vries [2], \( D_{\theta,1} \) [m\(^2\) s\(^{-1}\)] is the isothermal liquid moisture diffusivity which is a function of the actual volumetric moisture content. By volume averaging, an analogous description can be given of the vapour transport, deduced from the microscopic isothermal Fickian vapour flux [2, 3]. Combining these single diffusion equations for liquid and vapour transport, the total moisture transport can be described by:

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left( D_\theta \frac{\partial \theta}{\partial x} \right)
\]  

(3)

In this equation \( D_\theta \) [m\(^2\) s\(^{-1}\)] is the isothermal moisture diffusivity for liquid moisture transport as well as for vapour transport.

Perfect versus imperfect hydraulic contact

In case two porous materials, e.g., brick and mortar are bonded to each other, the macroscopic capillary pressure (or suction) across the material interface will be continuous, hence:
\[ \psi_b(\theta_{t,b}) = \psi_m(\theta_{t,m}) \]  
(4)

In this equation the subscripts 'b' and 'm' indicate the brick and the mortar respectively. Since the suction is a different function of the moisture content for each porous material, condition (4) will result in a discontinuity of the moisture content at the interface of the two materials, hence:

\[ \theta_{t,b} = f(\theta_{t,m}) \]  
(5)

Considering perfect hydraulic contact between the porous materials, the moisture flux across such a material interface will be continuous:

\[ q_b = q_m \]
\[ D_{\theta,b}(\theta_{t,b}) \frac{\partial \theta_{t,b}}{\partial x} = D_{\theta,m}(\theta_{t,m}) \frac{\partial \theta_{t,m}}{\partial x} \]
(6)

On the contrary if the hydraulic contact is imperfect, the suction will not be continuous across the material interface. In that case the liquid moisture flux across this interface is restricted and equation (6) can be rewritten [4]:

\[ q_b (= q_m) = q_{if} \]
\[ D_{\theta,b}(\theta_{t,b}) \frac{\partial \theta_{t,b}}{\partial x} = K_{if}[\psi_{m,if}(\theta_{t,m}) - \psi_{b,if}(\theta_{t,b})] \]
(7)

In this equation \( K_{if} [s^{-1}] \) is the hydraulic interfacial conductivity and \( q_{if} [ms^{-1}] \) the liquid water flux across the interface. Equation (7) states that during moisture transport a discontinuity \( q_{if} / K_{if} \) occurs in the suction across the material interface. Here it is assumed that the interfacial conductivity does not depend on the moisture content.

3. **NMR MOISTURE PROFILES**

Moisture profiles are measured to analyze moisture transport over brick-mortar interfaces in masonry as well as to determine moisture diffusivities of brick and mortar. These moisture profiles are obtained using nuclear magnetic resonance (NMR), offering the possibility to determine moisture content profiles quantitatively, non-destructively and with a high spatial resolution. An extensive description of NMR is given in another paper contributed to the symposium by the same authors [5] and in [6]. Therefore in this section only a short description will be given of the experimental set-up for measuring moisture profiles.

For water absorption this set-up is given in Fig. 1. In this set-up a cylindrical sample of 20 mm diameter and length <180 mm of initially dry material is allowed to freely absorb water through one end. The moisture distribution in a small region (1 to 2 mm) of the sample is measured simultaneously. After determination of the moisture distribution in this small region, the sample is moved vertically over a few mm with the
help of a step motor. This is repeated until a complete moisture profile has been measured. Subsequent moisture profiles are measured by repeating this procedure. For drying, see the inset of Fig. 1, a small cylindrical sample of 20 mm diameter and 25 mm length is placed in a teflon holder of which the upper side is open. In this set-up, the position is selected by the resonance condition [6] so that a profile can be measured without moving the sample. Air of 20°C and 0% relative humidity (RH) is blown over the initial wet sample thus creating a one-dimensional drying experiment.

![Figure 1. Experimental probe head for measuring moisture profiles during absorption and drying (inset).](image)

4. SUCTION AND MOISTURE DIFFUSIVITY OF BRICK AND MORTAR

In order to analyze and to compute the water absorption and drying of masonry, the suction $\psi(\theta)$, and the moisture diffusivity $D_e$, for both brick and mortar (joint) have to be determined. With respect to brick this can be done easily since the structure of this material is not influenced by its application in masonry. However with respect to mortar the structure of the material is strongly influenced (or rather determined) by its application in masonry.

Sample preparation
For the experiments presented in this paper, one type of machine moulded fired-clay brick (type RS) and one type of mortar (type MD) was used. The mortar consisted of portland cement A (CEM I), Dutch river sand (fine grading characteristics according to the Dutch standard 'NEN 3835') and water. Some air entraining agent was added to this mortar: water/cement ratio = 1.2 (by mass), water/additive ratio = $2.9 \times 10^{-5}$ (by mass) and air content = 13.4 (by volume; according to the American standard 'ASTM C185').

In case of fired-clay brick cylindrical bars were drilled whereas in case of mortar, samples with a length of approximately 50 mm were cast in cylindrical moulds. These moulds were open at the top side and the mortar was allowed to cure for at least 28 days at 20°C and 50% RH. For the suction experiments, samples with a diameter of 45 mm and a thickness of 12-20 mm were fabricated. In case of fired-clay brick, slices of 20 mm thickness were first sawn from the bricks whereas in case of mortar, actual
mortar joint slices were fabricated. Therefore, during brick laying, filter paper was placed between the mortar and the brick so that after curing, the mortar joint slices (of 12 mm thickness) and the bricks could be separated easily. Finally, cylindrical bars with a diameter of 45 mm were drilled out of the brick slices and the mortar joint slices.

**Suction curves of brick and mortar joint**

The experimental set-up for the suction experiments is given in the inset of Fig. 2. In this set-up an initially saturated sample is placed on a semi-permeable membrane which seals off an air-tight chamber. This membrane only allows water to penetrate. The curves are measured point by point by applying a certain air pressure (up to 12 bar) on the samples and waiting until an equilibrium moisture content is reached: for each point on the curve this takes about 6 to 8 days. The curves given in Fig. 2 therefore represent an equilibrium situation were no moisture transport occurs. Consequently, the air pressure will be equal to the macroscopic capillary pressure.

The curves that are drawn through the measured points are only given as a guide to the eye. Especially at low capillary pressures, due to the limited number of experimental points for mortar joint MD, there is only minor experimental evidence that in this range, the course of this curve is correct. Compared to mortar joint MD, the suction curve of fired-clay brick RS is less steep, indicating that fired-clay brick RS contain more large pores. From a moisture content of approximately 0.05 m³/m³, mortar joint MD has a higher suction compared to fired-clay brick RS.

![Figure 2. Capillary pressure curve of fired-clay brick RS (□) and mortar joint MD (*). Only the drying curves for capillary saturated samples are measured. The inset shows the set-up of the experiment. For mortar joint MD, the dashed line gives another possible fit through the experimental data.](image)

**Moisture diffusivity of brick and mortar (joint)**

Both water absorption and drying experiments were performed in order to determine the moisture diffusivity, $D_w$. For water absorption the measured profiles for one material can be related to each other by their Boltzmann transformation, $\lambda = x r_{1/2}$ [6, 7]. In Fig. 3 these Boltzmann transformations are plotted for fired-clay brick RS and mortar MD. For both materials the transformation yields a distinct curve on which the data from the various profiles coincide. This indicates that the moisture diffusivity does not depend on the position and supports the modeling of the moisture transport during water absorption by a diffusion equation. For water absorption the liquid moisture diffusivity,
$D_{e,1}$ is commonly approximated by an exponential relation: $D_{e,1} = D_{e,0} \exp(\beta \theta_i)$. For the materials plotted in Fig. 2, the parameters $D_{e,0}$ and $\beta$ are given in Table 1, together with the capillary moisture content, $\theta_{cap}$, and both the sorptivity, $S$, and the initial rate of absorption, $IRA$, for initial dry material. In Fig. 4 the liquid moisture diffusivity of fired-clay brick RS and mortar MD is plotted against the corresponding moisture content. The Boltzmann transformations of the simulated moisture profiles are added in Fig. 3, showing that these simulations give an adequate description of the observed moisture profiles.

For drying, the moisture diffusivity can be calculated numerically from experimental moisture profiles by integration of equation (3) [6, 8]. For both fired-clay brick RS and mortar MD, this calculated moisture diffusivity is added in Fig. 4. At high moisture contents the moisture transport is dominated by liquid transport. Neglecting hysteresis effects, here the moisture diffusivity determined from drying experiments connects to the liquid moisture diffusivity determined from water absorption experiments. With decreasing moisture contents, large pores will be drained and will therefore no longer contribute to liquid transport. As a result, the moisture diffusivity will decrease. Below a certain critical moisture content, the water in the sample no longer forms a continuous phase and both liquid and vapour transport occur. At lower moisture contents, vapour transport is predominant and the drying rate is governed by the vapour pressure.

The cast samples used for the NMR experiments described in this section, do not fully reflect the actual mortar joint as present in brick masonry. Nevertheless, the moisture diffusivity for the mortar samples as determined, will be used as a first approximation for further simulations. For water absorption, additional measurements of the first moisture profile in actual mortar joint samples, indicated that $\lambda = xt^{1/2}$ is approximately 30% less, corresponding to a 50% decrease of the absolute value of the liquid moisture diffusivity (see dashed line in Fig. 4).

![Figure 3](image_url)

**Figure 3.** [left] Boltzmann transformation of the measured moisture profiles for fired-clay brick RS (●) and mortar MD (○). (—) Boltzmann transformation of the simulated moisture profiles based on an exponential moisture diffusivity (see Table 1).

**Figure 4.** [right] Stylistic figure of the moisture diffusivity for fired-clay brick RS (—) and mortar MD (—) as determined from experimental moisture profiles. The dashed line gives an estimate of the liquid moisture diffusivity for mortar joint MD.
Material Do $10^{-9}$ [m$^2$s$^{-1}$] $\beta$ [-] $\theta_{\text{cap}}$ [m$^3$m$^{-3}$] S [kg m$^{-2}$s$^{-0.5}$] IRA [kg m$^{-2}$min$^{-1}$]

<table>
<thead>
<tr>
<th>Material</th>
<th>Do $10^{-9}$ [m$^2$s$^{-1}$]</th>
<th>$\beta$ [-]</th>
<th>$\theta_{\text{cap}}$ [m$^3$m$^{-3}$]</th>
<th>S [kg m$^{-2}$s$^{-0.5}$]</th>
<th>IRA [kg m$^{-2}$min$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>fired-clay brick RS</td>
<td>7.29</td>
<td>29.1</td>
<td>0.26</td>
<td>0.42</td>
<td>3.3</td>
</tr>
<tr>
<td>mortar MD</td>
<td>1.48</td>
<td>39.9</td>
<td>0.19</td>
<td>0.16</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 1: The coefficients of the exponential relation $D_0 = D_0 \exp(\beta \theta)$, describing the liquid moisture diffusivity for absorption, the capillary moisture content, $\theta_{\text{cap}}$, and the sorptivity, S, and the initial rate of absorption, IRA, that are determined using the experimental moisture diffusivity.

5. WATER ABSORPTION IN MASONRY

To investigate the water absorption in brick masonry, small masonry segments of four initial dry fired-clay bricks (type RS) with 12 mm mortar (type MD) in between, were fabricated. Before the actual brick laying, brick surfaces were smoothed, i.e., the sanded sides were sliced off, to improve reproducibility. The masonry segments were cured for one day under damp cloths and thereafter for a period of 28 days at 20°C and 50% RH. The cylindrical bars with a diameter of 20 mm were drilled out of these segments in a direction normal to the mortar joints.

Water absorption experiments

The measured moisture profiles during water absorption in a masonry sample out of fired-clay brick RS and mortar joint MD, are plotted in Fig. 5a and 5b. These figures show that the water absorption front quickly reaches the first brick-mortar interface. Next, moisture profiles develop in the first mortar joint. Since mortar joint absorbs water rather slowly, the first brick quickly gets saturated. When the front reaches the next mortar-brick interface, the water is slowly absorbed by the second brick. Obviously the absorption rate in this brick is reduced, governed by the permeability of the mortar joint. At the second mortar joint, almost no moisture transport occurs across the brick-mortar interface. As a result a flat profile develops in the second brick and the moisture content in this brick starts to increase until saturation. The entire process took about 4 days in this experiment. Fig. 5b reveals that the second mortar joint hardly absorbs any water, even at full saturation of the second brick.

Simulation of water absorption

Using the suction curve and moisture diffusivity of fired-clay brick RS and mortar (joint) MD as given in Fig. 2 and 4, the water absorption in masonry can be simulated. Assuming perfect hydraulic contact between brick and mortar joint, these simulated moisture profiles showed that for the experimental profiles in Fig. 5 the hydraulic contact is imperfect [4]. Therefore, in the simulation, an interfacial conductivity is accounted for according to equation (7). By comparing the simulated and measured total volume of water absorbed by the masonry, the value of this interfacial conductivity $K_i$ is determined. The simulated water absorption profiles, using an interfacial conductivity $K_i = 9 \cdot 10^4$ s$^{-1}$, are plotted in Fig. 6. Comparing Fig. 5 and Fig. 6, with respect to the first mortar joint, the simulated water absorption corresponds with the measured water absorption. However with respect to the second mortar joint, the simulated and measured water absorption apparently differ.
Figure 5. Moisture profiles measured during the absorption of water in a masonry segment. The first 20 profiles were measured continuously during the first 2 hours of absorption (a) whereas the next profiles were measured thereafter at subsequent time intervals of 2 hours (b). The total experiment lasted 4 days. The shaded areas indicate the mortar joint layers.

Figure 6. Simulated moisture profiles for water absorption in brick masonry, assuming imperfect hydraulic contact ($K_r = 9 \times 10^{-4}$ s$^{-1}$). The profiles are calculated at subsequent time intervals of 2 hours.
Note that the interfacial conductivity as used for the above simulation, is not determined independently; for the moment $K_{if}$ disguises all inaccuracies of the moisture diffusivity and the suction curve of both brick and mortar. Especially the approximated moisture diffusivity of mortar joint by means of mortar samples and the suction curve of mortar joint might influence the value of $K_{if}$. To estimate this influence, both the moisture diffusivity and the suction curve were varied. For mortar joint MD, the moisture diffusivity was changed according to Fig. 4 (dashed line). In this case the simulated water absorption process (obtained using the same $K_{if}$ as for the simulations shown in Fig. 6) was somewhat slowed down. Additionally, at low moisture contents, the course of the suction curve of mortar joint MD was changed according to Fig. 2 (dashed line). For this case the simulated water absorption process slowed down even more. These additional simulations therefore suggest that the different water absorption across the mortar joints in Fig. 5 can be ascribed to (slightly) different suction curves.

6. DRYING OF MASONRY

For the drying experiments, masonry samples as drilled out of the masonry segments were sawn at lengths of 25 mm, consisting of 15 mm of fired-clay brick RS and 10 mm of mortar joint MD. These samples were saturated and dried twice, once with the brick on top and once with the mortar joint on top. The measured drying moisture profiles are plotted in Fig. 7. In case the brick dries first, i.e., the brick on top (Fig. 7a), the moisture profiles measured in fired-clay brick RS show a slight receding drying front whereas in mortar joint MD the measured moisture profiles are flat. For the other case, when the mortar joint dries first (Fig. 7b), the thin layer of mortar joint MD almost completely dries within one hour. Now the moisture profiles measured in fired-clay brick RS are flat.

In both cases the moisture profiles in the second material are flat, indicating that for both mortar joint MD (Fig. 7a) and fired-clay brick RS (Fig. 7b), the moisture diffusivity is negligible compared to the drying moisture flux: $\dot{m}_{DS} = \frac{\dot{m}_{DS}}{\phi}$. Since dry air is blown over the samples, vapour transfer at the drying surface will not limit the drying rate. Thus the drying of the second material is governed either by the conductivity of the material interface or by the moisture flux through the first material. Fig. 7b reveals that the drying of fired-clay brick RS is not limited by the moisture flux through mortar joint MD, suggesting that here also an interfacial conductivity is present. However to prove this quantitatively, further analysis of the moisture transport is needed.

7. DISCUSSION AND CONCLUSIONS

A non-linear diffusion model, describing the moisture transport in single porous materials, is used to describe the moisture transport over brick-mortar interfaces. To account for imperfect hydraulic contact between brick and mortar, an interfacial conductivity, $K_{if}$, is added. For water absorption in masonry, the moisture transport was simulated properly. In this case the interfacial conductivity for liquid moisture transport could be estimated quantitatively, tuning the simulated water absorption with the measured water absorption. However for drying of masonry, up to now this interfacial conductivity could not be estimated quantitatively. In this case, further analysis of the moisture transport is needed.
Figure 7. Moisture profiles measured during drying of a brick-mortar sample. The profiles are measured at subsequent time intervals of 1 hour, in case brick dries first (a) and in case mortar dries first (b). The mortar joint layers are shaded.

REFERENCES