Liquid moisture transport in combined ceramic brick and natural hydraulic lime mortar samples: Does the hygric interface resistance dominate the moisture transport?

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Abstract
To reduce the energy use of the European building stock, a large potential can be found in the renovation of cultural heritage buildings. However, insulating these valuable masonry facades often increases the risk of moisture-related damage phenomena such as mold growth and frost damage. Therefore, detailed heat, air and moisture simulations are required to quantify and assess these risks. One of the unknown parameters in the simulations for historic masonries is the hygric interface resistance between the bricks and the lime mortars. Consequently, microfocus X-ray scans are performed during a capillary water absorption test on brick–lime mortar–brick samples to increase the insight into the moisture transport over the interface, dependent on the capillary pressure at the interface and the curing conditions of the mortar. The hygric interface resistance is found to be highly dependent on both capillary pressure and the curing conditions of the mortar. For the exact quantification of the interface resistance, highly

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detailed moisture transport and moisture storage properties of the brick and mortar are a prerequisite.

**Keywords**
Heat, air and moisture modelling, hygric interface resistance, masonry walls, natural hydraulic lime mortar, X-ray computed tomography

**Introduction**

The heat, air and moisture (HAM) transport in historical masonries is difficult to predict due to its complex and unpredictable geometry on macro and microscale (Brocken, 1998). First of all masonries consist of multiple materials such as bricks, bed mortars, and pointing mortars each with their own pore structure and hygrothermal properties. Second, within one material the hygric properties often vary significantly. For example, for historic bricks this is caused by inconsistency in the raw materials, the manual production processes, the baking procedure, and so on. For mortars, the type of binder, the purity of the aggregates, the mixing ratio, and the drying conditions are common causes of heterogeneous material properties and behavior (Elsen, 2006). Third, the hygric interaction between porous materials drastically depends on several aspects, which are explained further in detail. Nevertheless, in perspective of hygrothermal simulations masonries are often simplified to solid homogeneous brick constructions to save computational time.

Homogenization of a historic masonry construction occurs on several scales. On the construction scale, neglecting the mortars is commonly done by assuming the whole masonry construction as one brick layer with the properties of the ceramic brick (CB), basically converting the 3D geometry toward a 1D approach. On the material scale, the hygrothermal properties are—in the case material characterization is not performed at all—often partially defined and compared with the existing standard software database of materials that are hygrothermally fully determined. Zhao et al. developed statistical methods to summarize several measurements on similar material samples into one representative material. These detailed materials can further be classified into clusters of similar materials (Zhao et al., 2015). In specific research-oriented studies, parametric analyses on the materials properties are carried out to increase the insight into the sensitivity of the output (Janssen, 2013).

Based on detailed simulations, the above described heterogenic behavior of masonry is found to have a severe impact on several damage functions for specific conditions (Brocken, 1998). Therefore, a better insight into the hygric behavior of historic brickwork is needed to evaluate the validity of the homogenization approach in HAM simulations. One of the least investigated and commonly neglected factors is the hygric interaction between porous materials, also referred to as the interface resistance (IR) in the literature.
In this research, the magnitude of the IRs between homogeneous CBs and natural hydraulic lime mortars (NHLMs) is quantified as a representative of historical masonry. All joints are assumed to be fully filled at once during bricklaying.

First, the moisture storage and moisture transport properties of the materials are intensively characterized based on mercury intrusion, gravimetric absorption, and microfocus X-ray measurements during absorption (Carmeliet et al., 2004; Gómez et al., 2007, 2008; Cnudde and Boone, 2013). Second, HAM simulations are compared with results for these measurement techniques for combinations of bricks and mortars to get insight in the order of magnitude of potential IRs dependent on the curing conditions of the lime mortar. Finally, the dependency of the results on several parameters is discussed, and conclusions are drawn.

Literature

It has been reported extensively in the literature (Derluyn et al., 2008, 2011; Janssen et al., 2012) that the curing conditions of a mortar drastically influence the IR. Consequently, in this research an experimental approach based on three extreme curing conditions, wet, dry and mold cured, is used (please refer to section “Experiments”).

Equations (1) and (2) clarify how state-of-the-art HAM simulations calculate liquid moisture transport, respectively, within a material (equation (1)) and over an interface (equation (2)) (Häupl et al., 1997)

\[
j_{w, \text{material}} = - K_w(\partial \theta_w)(\partial p_w / \partial x + \rho_w g)
\]

\[
j_{IR} = \frac{\partial p_w}{\partial IR}
\]

where \(j_{w, \text{material}}\) (kg/m\(^2\)/s) is the liquid moisture flow over a distance \(\partial x\) (m), \(K_w(\partial \theta_w)\) (s) is the liquid water conductivity of the material at a certain moisture content \((\partial \theta_w)\) (m\(^3\)/m\(^3\)), and \(\partial p_w\) (Pa) the liquid water pressure drop over \(\partial x\). The density of water \(\rho_w\) (kg/m\(^3\)) and the gravitational constant \(g\) (m\(^3\)/(s\(^2\) kg)) are included to take gravity into account. Liquid moisture flow over an interface \(j_{w, IR}\) equals the ratio of the capillary pressure drop over the interface \(\partial p_w\) and the IR (m/s). By the similarity between equations (1) and (2), the IR can theoretically be understood as an extra thickness of material with a certain permeability or resistivity that is included between the two materials, and this also clarifies its unit meter per second (Derluyn et al., 2011). The only difference is that an IR has no moisture capacity. In this article, liquid moisture transport will be expressed in terms of liquid diffusivity and permeability, the conversion from liquid diffusivity to liquid permeability can be found in the study by Carmeliet et al. (2004).

Some authors prefer the approach for which the IR is seen as a separate resistance that hampers moisture transport between two materials (equation (2)) (Qiu et al., 2003; Vereecken and Roels, 2013; Zhou et al., 2018). Other authors have found that for high precision calculations, the IR must be combined with modifications in
the material properties of the adjacent materials as the IR and the adjacent material properties are influenced by the curing conditions of the mortar (Janssen et al., 2012). In perspective of generalization of the IR, the first method is the most applicable but is found to lack precision. Therefore, in this study, the moisture transport properties of the mortars are modified dependent on the curing.

What is the physical concept that causes these hygric IRs to arise? Most common explanations for the disturbance of the hygric transport over the interface have been listed by Derluyn et al. (2011), Guimarães et al. (2018), and Qiu et al. (2003): (i) a mismatch between the physical–chemical properties, (ii) the pore networks, (iii) the surface energy of both systems, (iv) the modification of the hygric properties of the mortar, (v) the transport of fine particles to the interface due to curing, (vi) the creation of compaction pores near the interface, and (vii) cracking of the interface.

Quantifying an IR is a complex procedure and therefore only a limited number of case-specific results are reported in the literature. The IR between a CB and a cement mortar was quantified for several curing conditions by Derluyn et al. (2011), and for a similar combination it was reported for several orientations by Zhou et al. (2018) based on nuclear magnetic resonance (NMR). Qui et al. have defined the IR between aerated autoclaved concrete and a lime cement mortar. As can be seen in Table 1, the magnitudes of the values found for the IR in the literature differ drastically. Zhou et al. (2018) concluded that: “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.” Note that capillary pressure is a suction force and thereby expressed as a negative value. In this perspective, Zhou et al. showed that the hygric IR is lower at lower moisture contents.

Table 1. Hygric interface resistances in literature (m/s).

<table>
<thead>
<tr>
<th></th>
<th>Ceramic brick (CB)—cement mortar (CM)</th>
<th>Autoclaved concrete (AAC)—CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derluyn et al. (2011)</td>
<td>Dry cured 2.5E10</td>
<td>Wet cured 1.25E10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vertical 4.0E9</td>
</tr>
<tr>
<td>Zhou et al. (2018)</td>
<td>Horizontal 8.0E10^a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.0E12^a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20E9^a</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CM-AAC ± 2.5E9</td>
</tr>
</tbody>
</table>

^aThe authors refer to the study by Zhou et al. (2018) for further details concerning the orientation and sample composition.
Unfortunately for historic constructions, the data found in the literature are unfit as typically NHLMs were used which—due to their hygric properties—are expected to entail an IR of a far smaller magnitude. In turn, this would perhaps induce a far smaller impact on the hygrothermal response of historic constructions. However, as hydraulic lime mortars and historic bricks are known for their high liquid moisture transport this small IR may perhaps have a big influence on several damage criteria such as the number of freeze-thaw cycles and mold growth at the interior surface. Note that the impact of a large value for the IR in a brick–cement mortar combination might be superseded by the low moisture transport in the cement mortar, rendering the mere presence of such an IR often irrelevant. In contrast, the impact of a smaller value for the IR in a brick–NHLM–brick might dominate the liquid moisture transport because of the high liquid water permeability of the lime mortar.

Experiments

As noticed in section “Literature,” there is a high dependency of the IR on the hygric properties of the adjacent porous materials, because they influence the curing condition of the mortar. Therefore, in accordance to the study by Derluyn et al. (2008), brick–mortar–brick samples for three extreme curing conditions are made (Figure 1), and the material properties of the brick and the mortar are precisely defined (Table 2). The brick type chosen for this research is an industrially extruded stone with a low variability in hygric properties to avoid highly scattered results. The brick samples are cut at all faces to exclude surface effects. All material samples were taken from a similar location in the bricks to avoid an impact of the compaction during the extrusion process, next to this they are all visually inspected for cracks. The NHLM is composed of 74 wt% of 0/2 mm river sand, 9 wt% of NHL3.5 Lime, and 17 wt% of water. The vapor diffusion resistance factor is measured with dry cup experiments: cylindrical samples are fixed with epoxy resin into a polyethylene ring and screwed with rubber gaskets between the cup, the sample, and the lid (ISO 12571:2000, 2000). This custom system was extensively validated and adopted here because the low cup weight reduces the measurement uncertainty.

The drying condition of the mortars are as follows: (i) dry cured, for which the mortar is cured between two oven dry CBs; (ii) wet cured, where the mortar is cured between two capillary saturated bricks; and (iii) mold cured, where the mortar is cured in a mold, and afterward installed between two brick samples with kaolin. Kaolin is assumed to provide a perfect hydraulic contact between both porous systems (Holm et al., 1996), which by definition would entail an IR equal to zero. For each of the three mortar types and the brick, the pore volume distribution is defined with mercury intrusion by the University of Reims (Figure 2). Mercury intrusion is known to overestimate the volume of small pores, which is also the case for the brick. The unexpected peak at 0.025 μm is therefore disregarded. The
moisture retention curves are based on the mercury intrusion data and described by trimodal functions of the van Genuchten type (equation (3), Table 3) topped of at the capillary moisture content (Carmeliet and Roels, 2002)

\[
\begin{align*}
    w &= w_{cap} \sum_{i=1}^{k} \frac{l_i}{(1 + (a_{pi} w)^{n_i})^{1-n_i}} \\
&= \frac{1}{(1 + (a_{pi} w)^{n_i})^{1-n_i}} 
\end{align*}
\] (3)

The liquid diffusivity of the brick is defined in section “Experiments” with the X-ray measurements. The results are expressed based on equation (4). The fitting parameter \( F \), defining the slope of the liquid diffusivity curve is given in Table 3 (Carmeliet et al., 2007)

\[
D_w(w) = D_w(w_{cap}) \exp \left[ F \left( \frac{w-w_{cap}}{w_{cap}} \right) \right] 
\] (4)

With

\[
D_w(w_{cap}) = \frac{A_{cap}}{2F-1-\frac{F^2}{1-\frac{F^2}{2}}} \exp \left( -F \right) \times \left( \frac{A_{cap}}{w_{cap}} \right)^2 
\] (5)

Due to the lack of multiple vapor diffusivity measurement points, the simplified equations (4) and (5) are used to describe the moisture transport despite the more

Figure 1. Sample dimensions (mm).

Table 2. Material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \theta_{por} ) (m(^3)/m(^3))</th>
<th>( \theta_{cap} ) (m(^3)/m(^3))</th>
<th>( A_{cap} ) (kg/m(^2) s(^{0.5}))</th>
<th>( \rho ) (kg/m(^3))</th>
<th>( \mu_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>0.252</td>
<td>0.192</td>
<td>0.107</td>
<td>1959</td>
<td>5.91</td>
</tr>
<tr>
<td>NHLM-mold</td>
<td>0.281</td>
<td>0.218</td>
<td>0.343</td>
<td>1620</td>
<td>28.30a</td>
</tr>
<tr>
<td>NHLM-wet</td>
<td>0.288</td>
<td>0.184</td>
<td>0.141</td>
<td>1587</td>
<td>28.30a</td>
</tr>
<tr>
<td>NHLM-dry</td>
<td>0.288</td>
<td>0.159</td>
<td>0.127</td>
<td>1710</td>
<td>28.30a</td>
</tr>
</tbody>
</table>

\( A_{cap} \): capillary absorption coefficient; NHLM: natural hydraulic lime mortar.

\( ^a \): Vapor diffusion resistance is assumed equal for the three mortars.
detailed diffusivity model described by Carmeliet et al. (2007). This approach is valid as during the simulated capillary uptake tests, the moisture transport is dominated by high moisture contents at which the simplified method is similar to the detailed model.

The material properties are consistent with the findings of Garijo et al. (2018) except for the porosity: a similar porosity is found for each curing conditions,

![Figure 2. Pore volume distribution defined by mercury intrusion porosimetry. The mortar samples are taken in the center of the mortar.](image)

**Table 3.** Fitting parameters for moisture storage and moisture transport.

<table>
<thead>
<tr>
<th></th>
<th>Brick</th>
<th>NHLM-dry</th>
<th>NHLM-wet</th>
<th>NHLM-mold</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Moisture storage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$l_1$</td>
<td>0.33</td>
<td>0.27</td>
<td>0.19</td>
<td>0.23</td>
</tr>
<tr>
<td>$l_2$</td>
<td>0.36</td>
<td>0.38</td>
<td>0.60</td>
<td>0.18</td>
</tr>
<tr>
<td>$l_3$</td>
<td>0.31</td>
<td>0.33</td>
<td>0.17</td>
<td>0.59</td>
</tr>
<tr>
<td>$a_1$</td>
<td>1.31E–05</td>
<td>2.88E–06</td>
<td>1.55E–05</td>
<td>5.62E–04</td>
</tr>
<tr>
<td>$a_2$</td>
<td>2.86E–06</td>
<td>1.82E–04</td>
<td>3.89E–06</td>
<td>4.77E–06</td>
</tr>
<tr>
<td>$a_3$</td>
<td>1.05E–06</td>
<td>2.86E–06</td>
<td>2.07E–07</td>
<td>9.49E–05</td>
</tr>
<tr>
<td>$n_1$</td>
<td>2.61</td>
<td>4.68</td>
<td>4.65</td>
<td>3.24</td>
</tr>
<tr>
<td>$n_2$</td>
<td>3.63</td>
<td>1.50</td>
<td>2.90</td>
<td>3.56</td>
</tr>
<tr>
<td>$n_3$</td>
<td>6.94</td>
<td>1.59</td>
<td>2.44</td>
<td>1.48</td>
</tr>
<tr>
<td><strong>Moisture transport</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F$</td>
<td>8</td>
<td>12.5</td>
<td>12.5</td>
<td>7</td>
</tr>
</tbody>
</table>
whereas a decrease in porosity with a decrease in W/B ratio was expected. Dry curing conditions can be compared with a low W/B ratio in the study of Garijo et al. (2018) due the absorption of water by the adherent brick. The reduction in absorption coefficient and in the capillary moisture content for dry curing conditions, with a similar porosity, already reveals that in dry cured NHLMs the volume of trapped air is bigger, which is an indication for a poor connectivity between the pores. Based on the mercury intrusion porosimetry data, the presence of water during curing is found to cause an increase in course pores.

Two types of experiments are executed on the combined brick–mortar–brick samples. First, three samples of each curing condition were continuously gravimetrically weighed during an uptake experiment. This allows us to acquire a high precision absorption curve for each sample and gives insight into the potential deviations between the samples. Second, one sample of each curing condition was investigated during a capillary water absorption test during which a microfocus X-ray scanner provided insight into the spatial moisture distribution within the samples. In a third phase, the mortars are sawn away from the bricks and new absorption (gravimetric and X-rays) tests are performed to examine the moisture transport properties of the mortars.

Sample preparation and apparatus of a standard absorption test

Nine brick–mortar–brick samples are made, three for each curing condition (Figure 1). All samples are covered with a damp cloth for 24 h and then stored in the climate chamber for a month at 50% relative humidity and 23°C for curing.

The setup for the capillary absorption test consists of a sample holder that can be suspended below a high precision balance. The holder is made from non-hygroscopic lightweight materials (polymethylmethacrylate (PMMA) and inox) to allow a maximum precision of the balance combined with a maximal sample size. Due to the high absorption rate of the materials studied here, convection at the side of the samples during the test is considered negligible.

X-ray projection method

X-rays are attenuated more by water than by air, thereby the amount of radiation that penetrates through a moist sample can be related to its moisture content. By continuously taking images from a capillary absorbing sample, the moisture front can be visualized and the moisture transport properties can be derived. With the aid of a calibration procedure, the intensity of the penetrated radiation captured by a detector can mathematically be translated into the exact moisture content as a function of time for each location in the sample, whereas the gravimetical absorption test only provides the cumulative moisture content of the whole sample (Roels and Carmeliet, 2006).
**Apparatus and setup.** The micro-computed tomography (CT) scanner called HECTOR at the Centre of X-ray tomography at Ghent University is used because of its high flexibility (Masschaele et al., 2013). HECTOR has a high power reflection tube XWT 240-SE microfocus source that can deliver a target power up to 240 keV with a spot size of 20 μm at 20 W. The large 400 mm × 400 mm detector, PerkinElmer 1620 CN3 CS, is able to generate images up to a resolution of 2000 × 2000 pixels, which results in a camera resolution \( R_d \) of 200 μm. On top of this, the rotational station is able to work with high loads up to 80 kg.

The setup in Figure 3 is assembled at the X-ray facility. It consists of a small PMMA water vessel in which the sample is placed on a fine PMMA structure. This allows free water absorption at the bottom of the sample. The vessel is oblong shaped to avoid as many interactions as possible between the water surface and the X-ray beam by minimizing the depth of the trough. The small trough is connected with a tube to a second trough, which has a much larger surface area. This ensures that the water level cannot decrease during the test due to absorption in the sample. With a frequency-controlled pump, water can be allowed into the second trough (and thereby also the first trough), which is initiated from the outside of the X-ray bunker. Consequently, the water level starts rising in the first trough until it touches the bottom of the sample and the absorption test begins.

**Samples.** One sample of each brick–mortar–brick combination with different curing conditions (dry, wet, and mold cured) is carefully sawn to a thickness of 25 mm. This reduction in depth is necessary to optimize the spatial resolution, as can be derived from equation (6). Unfortunately, only one of the three dry-cured samples remained intact and useful for further analysis. Sample 1, with the highest IR according to the gravimetrical test sequence, detached during transport. Sample 2 detached during sawing. Therefore, from the dry-cured samples only sample 3, the one with the highest absorption rate, the best attachment, and consequently the lowest IR, remained useful.
Settings. The settings of the X-ray apparatus are defined in detail to obtain an optimal spatial resolution. According to the study by Roels and Carmeliet (2006), the optimal spatial resolution can be calculated using equation (6). By adopting equation (6), the spatial resolution $R_x$ ($\mu$m) can be calculated as a function of the resolution of the camera $R_d$ ($\mu$m), the magnification $M$, equation (7), the spot size of the source $l_s$ ($\mu$m), the thickness of the sample $d$ ($\mu$m), and the distance from the center of the beam to the location in the sample $\sqrt{x^2 + y^2}$ ($\mu$m), Figure 2 (Roels and Carmeliet, 2006). To clarify, the spatial resolution represents the number of micrometers on the sample that relates to one pixel on the detector. Hence, a smaller value for $R_x$ yields a better resolution, or differently put, a higher magnification. This might be counterintuitive, as the more common known pixel resolution of commercial displays which represents the number of pixels per inch

$$R_x = \frac{R_d}{M} + (1 - \frac{1}{M}) l_s + \frac{d \cdot \sqrt{x^2 + y^2}}{l_2}$$  \hspace{2cm} (6)$$

With

$$M = 1 - \frac{l_2}{l_1}$$  \hspace{2cm} (7)$$

The detector is positioned at 1100 mm away from the X-ray source, this enables that the whole detector is radiated for optimal magnification. Then, the sample is positioned in between, so that the detector is fully used and the whole sample is visualized. This resulted in a magnification of five, with $l_1$ equal to 880 mm and $l_2$ to 220 mm (Figure 3) using equation (7). Based on equation (6), a spatial resolution varying between 58 and 167 $\mu$m at the center of the specimen and the location of the IR is found, respectively. The spot size of the source cannot exactly be determined due to aging of the filament but a spot size of 20 $\mu$m is commonly assumed for a scan at 20 W at the HECTOR scanner (Masschaele et al., 2013).

A maximum energy of 180 keV and a filter of 0.5 mm aluminum are used. The filter avoids that low energy radiation is projected on the sample as these would not penetrate the sample and would only induce more scatter on the output. The detector is set to generate a 16-bit output image at each alternating second (1 s shutter speed and 1 s rest). Sixteen-bit images contain 65,536 grayscales, which enable a very small moisture mass density resolution. Based on equation (8), and a fixed attenuation coefficient of water of 0.1739 cm$^{-1}$ (mean source energy 90 keV (National Institute of Standard and Technology, 2019)) the moisture content resolution is 0.42 and 0.44 kg/m$^3$ for, respectively, a dry and a capillary saturated sample

$$R_w = -\frac{\mu_w}{\mu_w d} \ln\left(\frac{l_{dry}}{l_{w}}\right)$$  \hspace{2cm} (8)$$

Calibration of the moisture content. As mentioned in several studies (Carmeliet et al., 2004; Roels and Carmeliet, 2006), the attenuation coefficient of water is key in defining the amount of moisture in the image, or in perspective of absorption in porous materials, into the moisture mass density of the material. Most authors use
a simplified method based on a fixed water attenuation coefficient. In this case, Beer–Lambert law, equation (9), is used to define the moisture mass density \( w \) (kg/m\(^3\)) of the sample

\[
w = \frac{C_0}{C_16/C_17} \left( \frac{I_{\text{wet}}}{I_{\text{dry}}} \right)
\]  
(9)

In fact, this constant attenuation coefficient of water (equation (9)) is energy dependent and only valid for monochromatic X-rays, and while an X-ray source radiates a polychromatic beam; therefore, the attenuation coefficient is dependent on the amount of water that is penetrated. In the literature, this is called the beam hardening effect (Ketcham and Carlson, 2001; Roels and Carmeliet, 2006). To overcome the beam hardening effect a calibration setup is constructed to extract the relation between the representative thickness of water penetrated and the logarithmic difference between the intensities of the wet and the dry situations (equation (9), Figure 4). A staircase (eight stairs of ±2 mm)-shaped trough is placed in front of the scanner (Figure 5). Both with and without water, the intensity of radiation through the trough is measured with the same apparatus setting. As pure demineralized water is used in the trough, the moisture mass density \( w \) is equal to the density of water, thereby equation (9) becomes

Figure 4. The correlation between the natural logarithm of the ratio of intensities between a wet and a dry image of a sample is non-linear for a peak source energy of 180 keV. As a comparison between the often assumed constant attenuation coefficient and the above derived correlation, the attenuation coefficients of water for a source of 180 and 90 keV are shown. As expected a constant \( \mu_w \) for 90 keV gives the best agreement as a beam’s mean intensity is always slightly less than half of its peak (Ketcham and Carlson, 2001).
As the X-ray beam has a cone shape, the thickness of the water layer $d_w$ (m) has to be corrected based on triangular geometry to avoid an impact of the position of each specific stair in the beam. The thickness of penetrated water is found to have a power relation through the origin with $-\ln\left(\frac{I_{wet}}{I_{dry}}\right)$ for a source of 180 keV (Figure 4). This relation enables to calculate the moisture content of similarly tested porous samples by translating the found ratio of intensities into a fictional thickness of a water layer $d_w$ (m) which in turn can be translated into the moisture content $w$ (kg/m$^3$) based on the actual thickness of the sample $d$ (m) and the density of water (equation (11))

$$\mu_w d_w = - \ln\left(\frac{I_{wet}}{I_{dry}}\right)$$

(10)

$\mu_w$ is the linear attenuation coefficient of water.

$w = \frac{d_w \rho_w}{d}$

(11)

**Data processing.** To derive correct moisture mass densities and liquid diffusivity from a microfocus X-ray absorption test several calibration and calculation steps are undertaken.

**Step 1.** The gathered images are visually inspected to scan for inconsistencies, and when a false image is detected it is replaced by an average of the previous and the following image. As the time step between two images is only 2 s, this has a negligible effect on the data.

**Step 2.** All images are subtracted by an average image over 120 s taken without X-ray beam (dark image) to cancel out small inconsistencies in the detector.

**Step 3.** The average logarithmic ratio of intensities, equation (10), is plotted over time for a zone in the sample where no absorption occurs, for example, the upper part of the sample. A power function is fitted through these data. The logarithmic ratio intensities $-\ln\left(\frac{I_{wet}}{I_{dry}}\right)$ are then corrected based on this curve. This method excludes the time-dependent behavior of the source and

![Figure 5. Staircase-shaped trough to derive the actual X-ray attenuation of water.](image-url)

$80\text{mm}$
detector at once. The fitting curve, the corrected, and the non-corrected data for the dry-cured case are shown in Figure 6 for the dry-cured sample.

**Step 4.** Based on the correlation derived in Figure 4, the moisture content of the sample is derived in time and over the height of the sample. Figure 10(a) and (b) show these results.

**Step 5.** It was foreseen to scale all moisture contents to achieve a moisture content at the bottom of the sample that equals the capillary moisture content of the brick. However, the analysis of the results showed this was not necessary, which confirms the validity of the gathered data and the reliability of the calibration and attenuation.

**Step 6.** To find the liquid moisture transport properties of the brick the first moisture profiles found in Figure 10(a) and (b) are analyzed. For the mortars, the second X-ray measurements are used. For the lower brick element, which is in contact with the water, the moisture profiles are transformed to a MC-Lambda function, where lambda equals the height in the sample divided by the square root of time (Figure 7). This method is known as the Boltzmann transformation (Roels and Carmeliet, 2006). In a perfectly homogeneous material, all points should coincide in one curve. For the CB, a scatter is found around the curve, but as it is time independent, the scatter is attributed to heterogeneities in the material.

**Step 7.** Validation: based on the moisture profiles derived in step 6, the cumulative absorption in the sample is calculated and compared with the standard absorption data.

**Step 8.** Moisture transport properties: out of all MC-Lambda data points, a single profile central within the random scatter is selected and a Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) fit is made (Figure 7). In the

![Figure 6. Correction for time-dependent behavior of the X-ray scanner in the logarithmic ratio of intensities of the dry and wet images, respectively.](image-url)
literature, often a spline fit is used but the PCHIP is found to better avoid oscillations between the data points. Oscillations have to be avoided as the MC-Lambda function is expected to show a continuous decrease on physical grounds.

**Step 9.** Based on equation (12), the diffusivity of the brick is calculated. Special focus is required at the lower and the higher moisture contents (Carmeliet et al., 2004). At the high moisture’s the MC-Lambda curve is flatted above the capillary moisture content as proposed by Carmeliet et al. (2004). At the lower moisture content end, the X-ray data are unreliable; therefore, the curve is complemented with the water vapor resistance data from the cup measurements

\[
D_w(w) = -\frac{1}{2} \int \frac{\lambda dw}{\partial w/\partial \lambda}
\]  

(12)

With

\[
\lambda = 0 : w = w_{cap}
\]

\[
\lambda \rightarrow \infty : w = w_0 \quad \text{(Carmeliet et al., 2004)}
\]

**Step 10.** The achieved liquid diffusivity curve is now compared with the liquid diffusivity model in equations (4) and (5). Based on the data, the material-dependent constant \( F \) is defined. Afterward, an absorption simulation is ran through to slightly scale the liquid diffusivity curve to achieve the exact absorption coefficient as earlier defined by gravimetrical absorption (Table 2).
Simulations

The simulations are executed in Delphin 5.9, a finite volume HAM simulation software with capillary pressure as driving force (equation (1)) (Häupl et al., 1997). The liquid transport properties are based on the best fit of the simplified liquid diffusivity model on the liquid diffusivity defined by the moisture profiles derived from the X-ray measurements. The moisture storage properties are based on the mercury intrusion data. Further material data are listed in Table 2.

The HAM simulation software is used to replicate the absorption experiment on the combined brick–mortar–brick samples. To achieve this best fit, iteratively IRs are added at both interfaces (equation (2)).

Results and discussion

Standard absorption

Figure 8 shows the high precision absorption curves for the wet- and dry-cured samples. In the beginning (absorption at the bottom piece of brick), all samples seem to show similar results. At a moisture mass density of \( \pm 3 \text{ kg/m}^2 \) the first interface between brick and mortar is reached. For the wet-cured samples, no decline in the absorption rate is found, and one of the samples even shows a slight incline while for the dry-cured mortars absorption of the mortar and the second brick is clearly dominated by the mortar. The decrease in absorption differs significantly between the three dry-cured mortars. It is concluded that the mortar properties and the IRs strongly dominate the moisture transport over the mortar and that the
sample preparation is a major influence factor. By dismantling the dry-cured samples some macroscopic voids are found at the interface due to bad compaction of the dry-cured mortar, which is not the case for the wet-cured samples.

Figure 9 for instance shows the brick surface after a dry-cured mortar was removed from it. At only 30% of the brick surface remaining mortar pieces are present. A rudimental assumption could be that only 30% of the contact surface between brick and mortar was well connected. This lack of contact reduces the moisture transport over the interface. For the wet-cured samples, the mortar brakes before the bond between brick and NHL mortar is broken. Thereby the percentage of contact could not be visually inspected but is assumed to be far bigger. This connection rate between the surfaces is in agreement with finding from the study by Brocken et al. (1998) on dry-cured cement mortars.

Absorption with microfocus X-ray

As described in section “Experiments,” the moisture profiles are derived from the microfocus X-ray measurements (Figure 10(a) and (b)).

The moisture profiles of the wet-cured sample seem to show more fluctuations. This is caused by the fact that the calibration (Figure 6) is executed on the dry-cured sample and applied to both tests for consistency.

Based on the absorption results in Figure 8, a major difference between wet- and dry-cured mortar was expected. This and the expected difference in capillary moisture content are confirmed by the moisture profiles in Figure 10(a) and (b). For the mold-cured sample, the kaolin layer did not induce a perfect hydraulic contact. Probably, small cracks came in the kaolin layers due to manipulation after curing. Therefore, the results are not shown.

Based on iterative fitting, an identical Delphin model to the experimental results of Figure 10(c) and (d) is obtained. The first interface between the brick and mortar seems to have no impact on the absorption rate. At the second surface, the IRs are quantified at 1E9 m/s for the dry-cured sample and 1E8 m/s for the wet-cured sample. This supports the statement of Zhou et al. (2018) that for high capillary
pressure (high moisture contents) the IR is minimal (Zhou et al., 2018) but on first sight contradicts the expectations based on Figure 9. The authors are suggesting that the impact of air voids at the first interface is minimal in this case due to the fact that the voids at the interface are overcome by the higher permeability of the mortar, here the permeability of the first piece of brick remains the bottleneck for moisture transport. While at the second surface a reduction in contact surface between the mortar and the brick reduces the moisture transport to the second brick.

It must be noted that the liquid permeability curve could drastically influence the found magnitudes for the IRs at the second surface of the sample. Therefore, the dependency of the moisture transport to the second brick on modifications in the liquid permeability curve of the brick is illustrated for the dry-cured simulation (Figure 10(c)).
The liquid permeability of the brick is described by the liquid diffusivity (equations (4) and (5)) multiplied by the moisture capacity. The moisture capacity is the derivative of the moisture retention curve as this describes the change in moisture content in respect to a certain change in capillary pressure (equation (13)) (Carmeliet et al., 2004)

\[
K(p_c) = D(w) \cdot C = \left| \frac{\partial w}{\partial p_c} \right|
\]  

By changing the absorption coefficient of the brick in equations (4) and (5), the change in the liquid diffusivity curve is determined. The slope in the diffusivity curve \((F = 12.5, \text{Table 3})\) is kept constant. The analysis shows that the IR at the second surface changes from \(1E9\) m/s to \(0.47E9\) and \(1.44E9\) m/s for \(A_{\text{cap,Brick}}\) standard deviation (SD) and changes to \(0.02E9\) and \(1.85E9\) m/s for \(A_{\text{cap,Brick}}\) \(\pm 2\times\) SD to become a similar cumulative absorption in the second piece of brick (SD = 0.00886, Figure 11), which confirms that rather small deviations in the moisture transport properties of the least permeable material have a significant effect on the magnitude of the IR.

**Conclusion**

Based on gravimetrical and microfocus X-ray absorption experiments, it is found that for NHLMs the curing conditions of the mortar have a significant effect on the moisture transport in combined brick–mortar–brick samples. Both the hygric IR at the surface between the two materials and the changes in material properties

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**Figure 11.** Liquid water conductivity curve of the brick sample (solid line) and the liquid water conductivity corresponding to a variation in the absorption coefficient (dashed lines) to analyze the sensitivity of the hygric interface resistance on the absorption coefficient of the brick.
of the mortars, due to curing, have an impact. Similar to cement mortars, the capillary moisture content and the average pore size decrease, respectively, from dry to wet- and mold-cured mortars due to the decrease in the W/B ratio during curing.

From the X-ray measurements, the statement of Zhou et al. (2018) that the IR is capillary pressure dependent seems to be valid for interfaces between CB and dry-cured NHL mortar as the first interface in a vertical stack of brick–mortar–brick is found negligible under capillary absorption, whereas the second interface is not. For wet-cured NHL mortars, all hygric IR are almost negligible.

The magnitude of the IR itself for the dry-cured interfaces are difficult to assess, as small changes in the moisture transport properties of the materials have a significant impact. Generally, it can be stated that the found hydraulic lime mortar /brick IRs are an order of magnitude smaller than the cement mortars/brick IRs available in the literature.

To conclude, the authors advise in perspective of capillarity absorption simulations of combined brick and mortar setups to mainly focus on precisely defining the moisture storage and moisture transport properties of each material.

Furthermore, note that the conclusions drawn are only valid for liquid moisture transport during capillary absorption. Therefore, in perspective of HAM simulations of masonry constructions under realistic climate conditions, where alternative drying and wetting cycles occur, the impact of the IRs and the moisture transport properties at low moisture contents should be investigated further in detail.

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### Appendix I

#### Notation

- $A$: absorption coefficient
- $C$: moisture capacity
- $d$: thickness
- $D$: diffusivity
- $a_i, F, l_i, n_i$: fitting parameters
- $g$: gravitational constant
- $I$: intensity
- $j$: flow
- $K$: permeability
- $k$: number of modalities of the Van Genuchten function
- $l_s$: spot size
- $M$: magnification
- $p$: pressure
- $R$: resolution
- $w$: moisture mass density
- $x$: distance
- $q$: moisture content
- $\mu_d$: vapor diffusion resistance
- $\mu_w$: attenuation coefficient of liquid water
- $\rho$: density
- $\lambda$: boltzmann variable

#### Subscripts

- $\text{cap}$: capillary
- $d$: diffusion
- $\text{por}$: porosity
- $w$: liquid water