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Do interface resistances matter in historic masonries? -Analysis based on X-ray tomography and heat, air and moisture modelling -

Klaas Calle[1,*] and Nathan Van Den Bossche[1]

[1]Faculty of Engineering and Architecture, Ghent University, Ghent, Belgium

[*]*Corresponding email: Klaas.Calle@ugent.be*

ABSTRACT
For hygrothermal simulations it is often advised to homogenize masonry wall constructions into a 1D solid brick construction. This saves computational time, but it may lead to an underestimation of moisture related risks. Some literature states that the impact of mortar is negligible, but no specific attention was paid to historic masonries, which often have high absorptive mortars (e.g. lime) and/or bricks. Hence, this study investigates the impact of the interface resistance between brick and mortar, in relation to the properties of the adjacent materials during absorption as well as under real climate conditions. As expected the impact of interface resistances is more pronounced during an absorption test compared to under real climate conditions. Nevertheless, due to the interface resistance, increased frost risks do arise in a number of cases subjected to real climate conditions. The results are found to be highly dependent of the climate, the sequence of rain and frost events, and the properties of the adjacent materials. In conclusion, one can state that there can be an increased risk of frost damage due to the effect of interface resistances in historic masonries. However, deriving generic guidelines on the impact of these effects remains a challenge due to a high dependency on climate and material parameters.

KEYWORDS
Interface resistance, HAM simulations, Masonries, Frost damage

INTRODUCTION
The hygrothermal response of porous materials has been studied and documented intensively. (Pel, 1995; Künzel,1995; Grunewald,1997) These studies have led to an increased reliability of risk assessment on building facades due to Heat, Air and Moisture (HAM) modelling software. In these models it is often advised to homogenize masonry constructions from a combination of mortar and bricks to solid brickwork to simplify the model and thereby save computational time (Dephin User Manual, 2006; Vereecken et al, 2013). This approach raises several questions. For instance, what happens in the mortar, which represents in reality +/- 20% of the masonry?

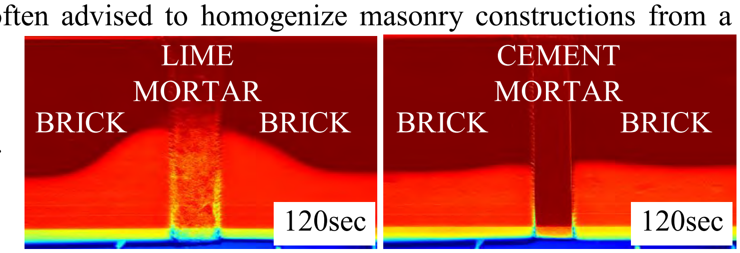

Figure 1. X-ray visualization of absorption in a brick/mortar sample. Left: Hydraulic lime mortar, Right: cement mortar. Red/blue= Low/high moisture content. In collaboration with UGCT.

To answer this question, Vereecken investigated the impact of the simplification in the article 'Hygric performance of a massive masonry: How mortar joints influence the moisture flux?'(Vereecken et al., 2013). This publication reported that for the investigated material properties massive masonry constructions can be homogenised to a solid brick construction in perspective of HAM modelling. The statement is based on several simulations and measurements on ceramic brick and cement mortar. However, it can be assumed that the impact of mortars in historic constructions may be bigger, as mortars generally have higher absorption coefficients in comparison to cement mortars. This is visualized by means of tests with X-ray attenuation (Figure 1). It can be seen that the hydraulic lime mortar (often used in historic constructions) serves as a capillary highway and humidifies the brick sideways, which is not the case for the cement mortar. Due to these capillary highway, the moisture penetrates deeper into the structure, which may perhaps increase the frost risk. In (Figure 1, left) it is clear that the brick and the mortar influence each other's moisture content over the interface between them. Here the so called interface resistance (IR) will be decisive for the moisture flux. From this visualisation it can be concluded that the potential impact of mortars and their adjacent IR may be bigger for high absorptive mortars.

What is an IR between porous materials? Qui et al, 2003; Derluyn et al, 2011 and Guimarães et al, 2018 have listed several causes: a mismatch between the physical-chemical properties, the pore network and the surface energy of both systems, the modification of the hygric properties of the mortar and the transport of fine particles to the interface due to curing, the creation of compaction pores near the interface, and cracking of the interface due to hygric tensions.

The amount of research that addresses the impact of interface resistance (IR) between porous media is limited (Qui et al, 2003; Derluyn et al., 2011). The order of magnitude of an IR found by Derluyn et al, 2011 is between 0 and 5E10 m/s. It must be noted that the highest IR was found for the combination of a ceramic brick and cement mortar, for a sample where the mortar was cured in contact with oven dried bricks. It can be discussed whether these values derived by Qui and Derluyn are representative for the combination of ceramic brick and hydraulic lime mortar. Next to that, to date the dependency of the IR on the moisture content and flow direction is unknown. On the other hand, it can be argued that these results provide at least an order of magnitude of the potential impact, which should suffice to indicate the impact on the hygrothermal performance of masonry constructions. This study will therefore proceed with adopting an IR of 5E10 m/s. In preliminary simulations the IR was modified to see the impact, and it showed that the presence of the IR is more important than its magnitude in perspective of the amount of absorbed moisture.

Where does this interface resistance occur?

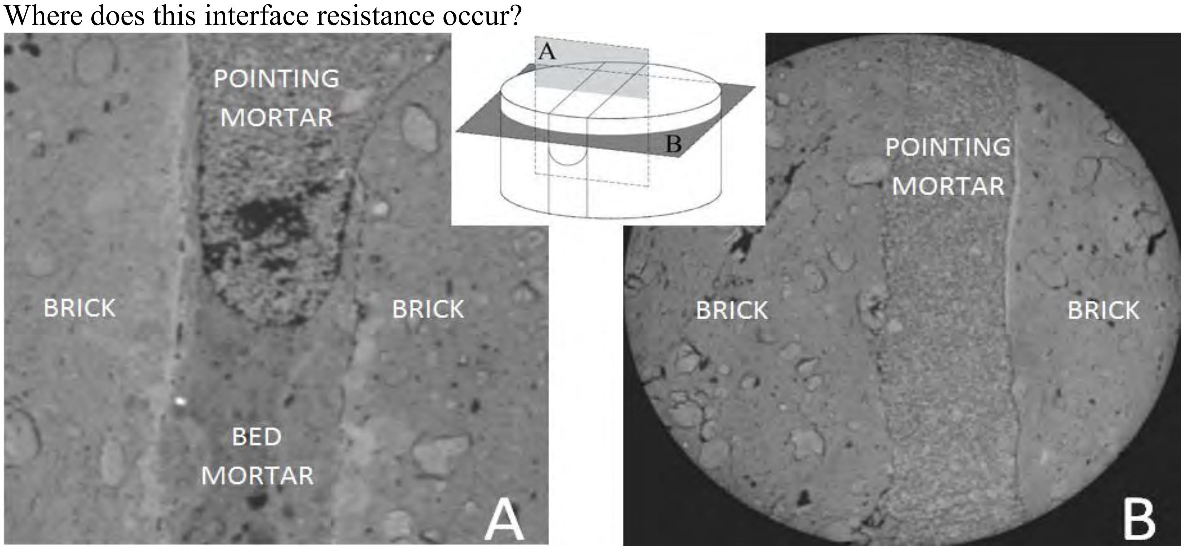

Figure 2. X-ray tomography, voxel size 90 μm A) perpendicular section to the building facade with the facade at the top side. B) parallel section to the building facade through the bed mortar. In collaboration with UGCT and the Belgian Royal Institute for Cultural Heritage.

With X-ray tomography a historic masonry core of a Flemish church was investigated to visualise the interfaces between the pointing mortar, the bed mortar and the bricks. From the images, shown in Figure 2, the following aspects can be deduced:

- pointing mortar – brick(A/B): very clear separation of materials, interface appears fractured (±0.3mm).
- bed mortar – brick(A): very diverse interface; some places seem in perfect contact whereas in other places cracks are visible. Around the interface the attenuation changes. This may be the effect of a changed density/porosity at the interface (0-0.5mm).
- pointing mortar – bed mortar: poor compaction of the pointing mortar results in a poor contact.

To summarize, traditionally masonry constructions are homogenised in HAM simulations. This seems to be a valid approach based on the state-of-the-art literature, but no specific attention has been given yet to high absorptive mortars and interface resistances, which are as shown in figure 2 on different ways present in historic constructions. This study aspires to contribute to this understanding, in order to develop in depth guidelines for HAM simulations for historic masonry constructions.

METHODOLOGY

First, six types of historic bricks commonly found in historic buildings in Belgium are characterized by their density, capillary moisture content, absorption coefficient and vapor diffusion resistance. The same is done for three historic mortars, based on replicas made from contemporary raw materials.

Subsequently, some combinations of bricks and mortars were simulated in Delphin 5.9, mimicking a simple absorption test. The section of the materials was based on the absorption coefficients, extreme values are preferred to indicate clear but at the same time realistic differences. The material functions (moisture retention curve, liquid water conductivity and vapor permeability curve) were scaled based on the materials available in the software database. As a reference, the materials used by Vereecken (ceramic brick/cement mortar) were approximated as good as possible based on the available data and added to the simulations.

In a third phase, simulations under realistic climate conditions (Essen, Bremerhaven and Munich) were executed for four brick/mortar combinations and three types of interface resistances. To investigate the impact of the interface resistances in the construction, a combination of moisture saturation degree, freeze thaw cycles (FTC) and ice mass density outputs were analyzed.

Based on the literature reported above and the X-ray tomography (Figure 2), three variations on the interface resistances in the setups are simulated: 1) perfect hydraulic contact is assumed (IR0), 2) an interface resistance of 5E10 m/s is added at all interfaces between brick – mortar (IR5), 3) on top of the IR's in IR5 an additional IR of 5E10 m/s is added in the mortar at a depth of 20mm from the surface, to represent poor contact between the pointing mortar and the bed mortar (IR5PM).

RESULTS

Table 1 (the abbreviations represent brick type B_V: Veldovensteen (Dutch, literal translation: Field oven stone), M_H: Hydraulic lime mortar, B_REF/M_REF: Reference material from Vereecken Roels et al, 2013) shows the results of the material characterization for the materials which are used in the simulations. Generally, the absorption coefficients of the historic bricks and mortars are higher than for the reference materials.

Table 1. Material properties bricks and mortars: Mean (Standard deviation)

	Density [kg/m³]	A_W [kg/m².s$^{0.5}$]	Θ_{cap}* [m³/m³]	μ_{dry}** [-]	Mat. func.*** /
B_V	1786 (87)	0.486 (0.237)	0.165 (0.058)	10.394 (3.652)	ID 97
B_REF	2087	0.116	0.130	24.79	ID 97
M_H	1459 (31)	0.518 (0.033)	0.180 (0.016)	28.302	ID 718
M_REF	1823	0.091	0.252	20.97	ID 717

*Capillary moisture content, **Vapor diffusion resistance, *** The material functions are scaled based on the software database, the material ID is shown.

Absorption

From the normalized (based on capillary moisture content) absorption curves it is clear that the absorption occurs in several linear phases (Figure 3). The number and transitions of these phases depends on the obstructions the moisture front has to overcome. These obstruction can be a low absorptive mortar (M_REF), an IR (IR5, IR5PM) or the top of the specimen. For example Figure 3A shows the moisture content of B_REF-M_H after 3.5 hours. At that point in time the moisture front reaches location 1, where the IR and the mortar result in a decline of the water absorption (point A). A similar observation can be made when the water front reaches location 2 after 16h for the same configuration (3B). The large difference in the absorption curves for high absorptive mortars (M_H) without (IR5) and with (IR5PM) pointing mortar IR are due to reduced moisture buffering in the mortar. In cases with the low absorptive reference mortar (M_REF) these difference are negligible.

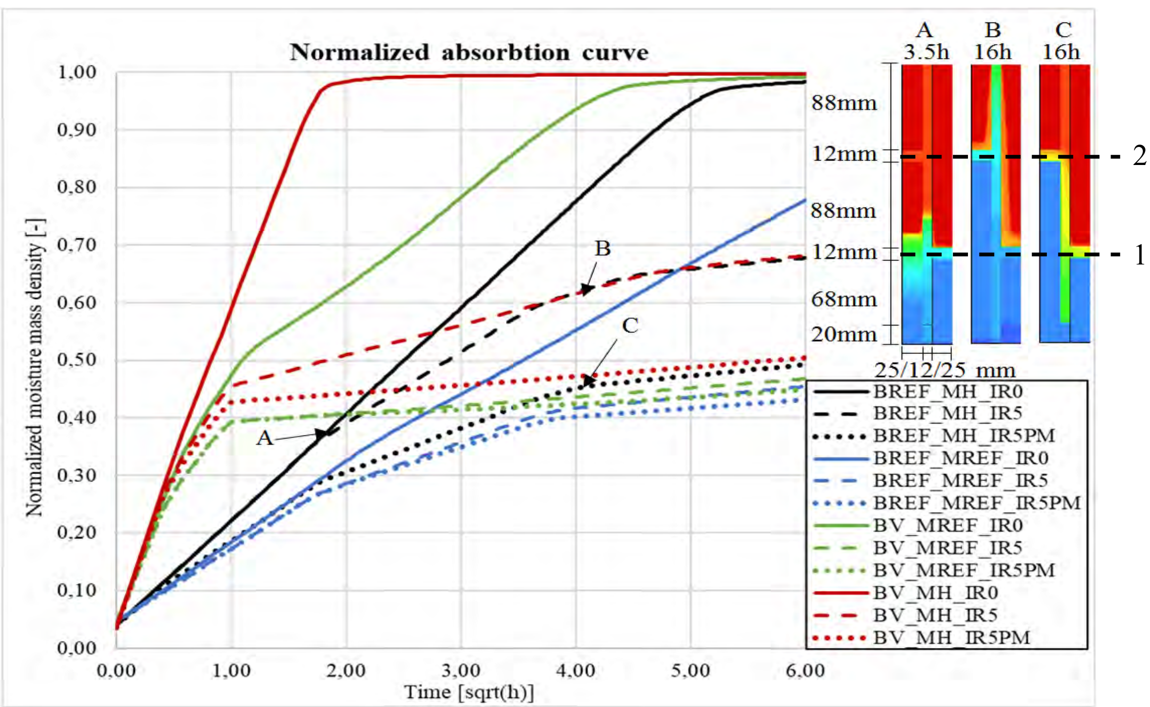

Figure 3. Normalized absorption curves, ABC moisture saturation degree after 3.5h/16h/16h of respectively BREF_MH_IR0/ BREF_MH_IR5/ BREF_MH_IR5PM

It is clear that in all cases the absorption is slowed down by the interface resistances, especially in combination with high absorptive mortars, which could insinuate a decreased frost damage risk. But is this also the case under real climate conditions?

Real climate conditions

For these simulations with realistic exterior climate conditions (Essen, Munich, Bremerhaven) the same configuration as shown in Figure 3 (A) was used, except for the lime plaster of 10 mm, which was added to the interior side. The normalized average moisture mass density reveals that the interface resistances affect the moisture distribution in the brickwork, especially during rain events, as well as during the convective drying fase (Figure 4). The interface resistances decreases the amount of absorbed water during a rain event due to a reduced redistrubtion of the moisture in the masonry, and the drying potential shortly after the rain event is increased as well. But in the second drying phase, indicated in figure 4 as zone a, the drying potential is decreased due to the hampering of moiture redistribution which makes the brickwork more vunerable to critical frost cycles for a longer period of time after a rain event. To conclude the sequence of wetting and drying, and the trade-off between reducing absorption and hampering drying yields a complex balance that is very sensitive to material properties and boundary conditions.

In the analysis several effects of the interface resistances were found that induce increased frost risks:

- moist trapped in the bed mortar behind the IR between a pointing mortar and a bed mortar (Figure 4 A/B and zone a)
- generally a slight increase in of freeze thaw cycles due to a decreased redistribution and drying, biggest impact for case B_V, M_H due to higher moisture contents deeper in the construction
- reduced drying of the brick to the mortar due to the IR, especially in case of high absorptive mortars (Figure 4 DEF, case B_REF,M_H).
- reduced drying of the mortar to the brick, especially in case of high absorptive bricks combined with a low absorptive mortar (Figure 4 G/H/I, case B_V, M_REF).

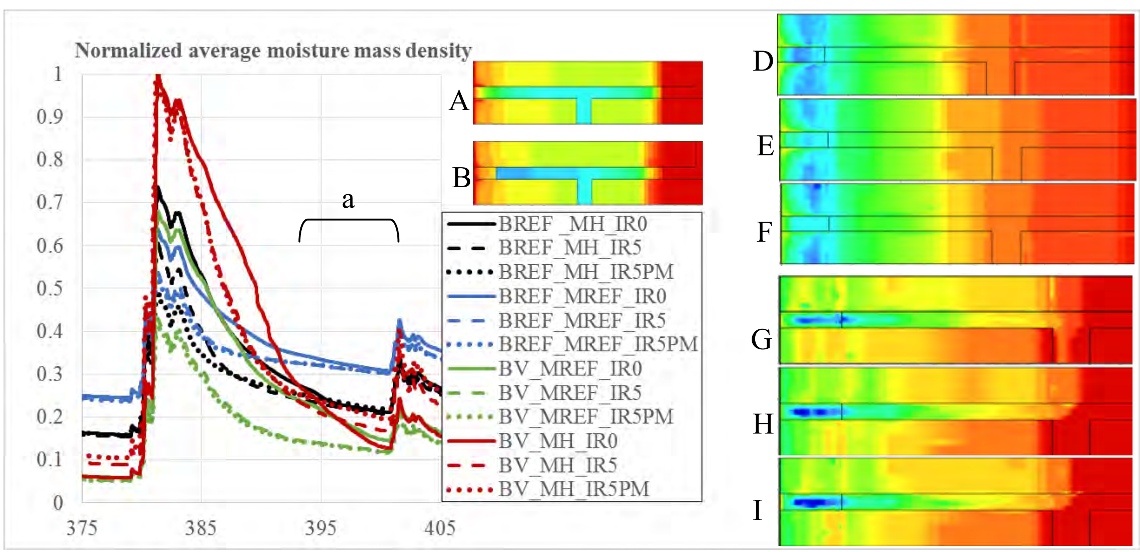

Figure 4 Normalized average moisture mass density during and after a rain event (Munich) based on the capillary moisture content, A/B: Ice mass density for respectively BREF_MH IR0/IR5PM at day 393.5 (Munich), D/E/F: cumulative critical FTC for respectively BREF_MH IR0/IR5/IR5PM (Munich) and G/H/I cumulative FTC for respectively BV_MREF IR0/IR5/IR5PM (Bremerhaven)

Despite the effects discribed above, it must be noted that the overal differences between IR0, IR5 and IR5PM are limited for the combinations that were studied here.

The risk for mould growth at the interior surface was investigated as well, the IR seems to have reduce the risk on mould growth in all cases. As expected, masonries with hydraulic lime mortar are far more vulnerable to mold growth at the interior surface due to the capillary highway effect discribed in (Figure 1).

CONCLUSIONS

Homogenisation of historic masonries whit lime mortars in HAM simulations can lead to an underestimation of several risks. Therefore it is advised to avoid homogenisation if possible in perspective of historic constructions.

Next to that, the described effects are found to be strongly dependent on several parameters such as the sequencing of wetting/freezing and the properties of the adjacent materials which hampers straight forward conclusions.

The impact on the moisture content of interface resistances in brickwork in real climate conditions seems rather limited compared to absorption tests. Therefore it is plausible that IR can be neglected but further validation of the reliabliltity of this approach should be made. Follow up research is planned to validate the IR between historic matrials more in depth based on CT(computerized tomography).

Due to the large number of uncertainties and highly sensitive trade-off between wetting and drying effects, additional research should also further investigate what the impact is of the variation in the material properties (pointing mortars, bed mortars and bricks), the interface resistances, and the climate conditions.

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