Moisture transfer through mortar joints: interface resistances or hygric property changes ?

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Abstract

This paper investigates the deviating hygric behaviour of mortar joints, based on a combination of hygric property measurements, numerical simulations, sharp-front analysis and microscopic imaging. Comparison of the hygric properties of mould and joint mortars reveals significant differences. Further analysis with numerical simulations indicates however that an interface resistance must be attributed to the brick-mortar bond plane, which is further corroborated by sharp-front analysis of free water uptake in masonry samples.
While the deviating hygric behaviour of mortar joints previously has been ascribed to hygric property changes or interface resistances, the current study points out that both are at play, and it demonstrates the influence of the curing conditions on these phenomena.

Introduction

In large parts of the world, masonry forms an essential part of the building envelope. Damage to masonry facades is frequently moisture related: spalling caused by frost-thaw cycles, cracks due to hygric expansion-contraction, or aesthetic damage as a result of salt efflorescences are just a few examples. To correct or prevent damage to masonry constructions, a detailed knowledge of the hygrothermal response of masonry is required. Hygrothermal simulations form a useful tool [1] but require hygrothermal material properties as input. Realistic material properties for mortar joints are often lacking though.

While several sources offer such hygrothermal material properties for mortars [2,3], these are commonly determined from mortar samples cured in moulds. It is however generally accepted that the hygric behaviour of mortar joints deviates from that of mould cured mortars. Some authors attribute these deviations to an interface resistance between brick and mortar [4,5], others to changes in the hygric properties of mortar joints [6]. The water extraction from the fresh mortar by the bricks is named as the primary reason for changes in the hygric properties, due to the decreased availability of curing water, but also for the interface resistance, due to the advection of fine cement particles to the interface and into the brick pores. Other authors refer to a mismatch between the two pore systems to justify an interface resistance.

This paper reports on an experimental and numerical investigation of the hygric behaviour of mortar joints, consisting of the standard determination of hygric material properties, numerical simulations of moisture transfer in masonry samples, quantitative analysis of X-ray visualised moisture transfer in masonry samples and of microscopic imaging of the interfaces between brick and mortar. The combined results of these four techniques allow a further discussion of the interface resistances versus hygric property changes issue.

Sample preparation

A standardised cement mortar was applied for all samples, obtained by mixing six parts (by weight) of river sand, two parts of P42.5 Portland cement and one part of tap water. For the mould mortar samples, mortar was poured in wooden moulds (50 x 30 x 15 cm^3), and cured for 24 hours under damp cloth. The moulds were removed after that initial curing interval, and the mortar was moved to a curing chamber at 80 % RH and 20 °C.

Since the extraction of water out of the fresh mortar joint by the bricks is commonly indicated as the prime reason for the deviating hygric behaviour of mortar joints, two extreme curing conditions were applied: mortar joints were cured between oven-dry bricks (resulting in maximal water extraction) and between capillary saturated bricks (virtually no water extraction).

Ceramic bricks were cut lengthwise, yielding two halves of 0.2 x 0.1 x 0.025 m. Mortar was applied on the sawed surface, with an intended thickness of 1 cm. After spreading of the mortar – to minimise the joint's unevenness – the second half of the brick was planted on top, and slightly pressed into the mortar. These joined bricks were similarly cured for 24 hours under damp cloth, and were then moved to the curing chamber.

After 28 days of curing, the exterior edges (approximately 1 cm) of the mould mortar and the joined bricks were cut away, in order to avoid edge disturbances. Appropriately sized mould mortar samples were obtained by further sawing. The mortar joint samples were obtained by sawing away the bricks, paying attention that the loss of mortar material was minimal. The masonry samples – for the X-ray moisture transfer visualisation – were obtained by slicing of the joined bricks. Conclusively all samples were dried at 50 °C and 3 % RH. Low temperature drying was favoured to avoid removing chemically bound water from the cementitious materials. Illustrations of the joined bricks, the mortar joint samples, and a masonry sample are shown in Figure 1.

Figure 1: illustrations of the joined bricks (left), mortar samples (centre) and masonry samples (right).

Determination of hygric properties of mould and joint mortar

Introduction

Six different measurements were performed on the three mortars considered (mould mortar, wet cured mortar and dry cured mortar):

- vacuum absorption test: open porosity, bulk density;
- free water uptake test: capillary absorption coefficient, capillary moisture content;
- sorption measurements: sorption isotherm;
- mercury intrusion porosimetry: moisture retention, pore size distribution;
- X-ray profile measurements: moisture diffusivity;
- dry and wet cup tests: vapour permeability;

For reasons of conciseness not all results can be included here. The analysis must be limited to the results of the vacuum absorption and free water uptake tests: the open porosity, the bulk density, the capillary absorption coefficient, and the capillary moisture content.

Open porosity and bulk density

Vacuum absorption was carried out for 5 mould mortar samples, 10 x 5 x 0.5 cm³, and for 6 wet and 6 dry cured mortar samples, 8 x 4 x 1 cm³. Opposite to more permeable materials, a long-term approach was required to obtain complete vacuum and saturation of the mortar samples. After placing the dry samples in the clock, the air pressure was pumped to a near-vacuum, which was maintained for 24 hours. After that interval the water supply was opened, and the clock was allowed to fill at a very low rate, while the pump kept working. Once the water level superseded the samples' top surface, the water supply was closed and the pump turned off. This low-pressure, submersed state was maintained for 72 hours. After that period, the air pressure was restored, but the mortar samples were kept submersed for two more weeks. Discrete measurements in that period show that the initial state – after 72 hours of submersion – of the samples was still below 'total saturation': the samples' weight increased continuously. It is assumed that this very slow evolution must be attributed to the very fine porosity of the mortars. The obtained open porosities and bulk densities are gathered in Table 1: they demonstrate the difference between mould mortar and mortar joints, and the pronounced influence of the curing conditions.

Capillary absorption coefficient and capillary moisture content

Free water uptake tests were performed on 10 mould mortar samples, 5 x 5 x 2.5 cm³, of which a 5 x 5 cm² face was put in water, and on 6 wet and 6 dry cured mortar joint samples, 8 x 4 x 1 cm³, of which a 8 x 4 cm² face was put in water. The capillary absorption coefficients are thus measured perpendicular to the mortar joint, in agreement with the direction of moisture transport analysed further on in this paper. The resulting capillary absorption coefficients and capillary moisture contents are collected in Table 1. The values confirm the former trend: the mould mortar is most (coarse) porous and permeable, while the dry cured mortar demonstrates the lowest (coarse) porosity and permeability.

Table 1: overview of the hygric properties (averages in bold, minimum and maximum between brackets)

	mould mortar	wet cured mortar	dry cured mortar
open porosity [-]	**0.193** (0.184-0.198)	**0.158** (0.156-0.161)	**0.138** (0.133-0.143)
bulk density [kg/m³]	**2092** (2082-2118)	**2166** (2155-2170)	**2232** (2215-2249)
capillary absorption coefficient [$kg/m^2s^{0.5}$]	**0.0193** (0.0175-0.0213)	**0.0154** (0.0135-0.0174)	**0.0098** (0.0071-0.0133)
capillary moisture content [kg/m³]	**147** (138-158)	**134** (130-137)	**97** (92-103)

Conclusion

For reasons of conciseness, not all results can be included here. All complementary measurement results confirm the general trend though: the hygric properties of the three mortars differ considerably. The mould mortar is most (coarse) porous and permeable, while the dry cured mortar demonstrates the lowest (coarse) porosity and permeability. This indicates that the deviating hygric behaviour of mortar joints must, at least partially, be attributed to differences in hygric properties. It moreover shows that the curing conditions have a substantial effect. Surprisingly though, even the wet cured mortar properties deviate from the mould mortar, while water extraction must have been minimal.

It is reasoned here that the observed changes affect the complete mortar joint and not only a surface layer of limited thickness. The differences in Table 1 are too substantial to be caused by deviations in thin surface layers only. The evolution of the moisture accumulation, observed in the free water uptake tests, moreover agreed fairly well with the theoretical square root of time behaviour. Conclusively, free water uptake tests in the direction of the joint plane gave similar absorption coefficients.

Numerical simulation of free water uptake in masonry

Moisture retention curves and moisture permeabilities were derived for the wet cured and dry cured mortar and numerical simulations of free water uptake in wet cured and dry cured masonry samples were performed. Masonry samples were oriented as shown in Figure 1 (right), and thus moisture transfer perpendicular to the mortar joint is investigated, in correspondence with the previously measured capillary absorption coefficients. Simulated moisture content profiles are compared with measured profiles – visualised with X-ray tomography – in Figure 2.

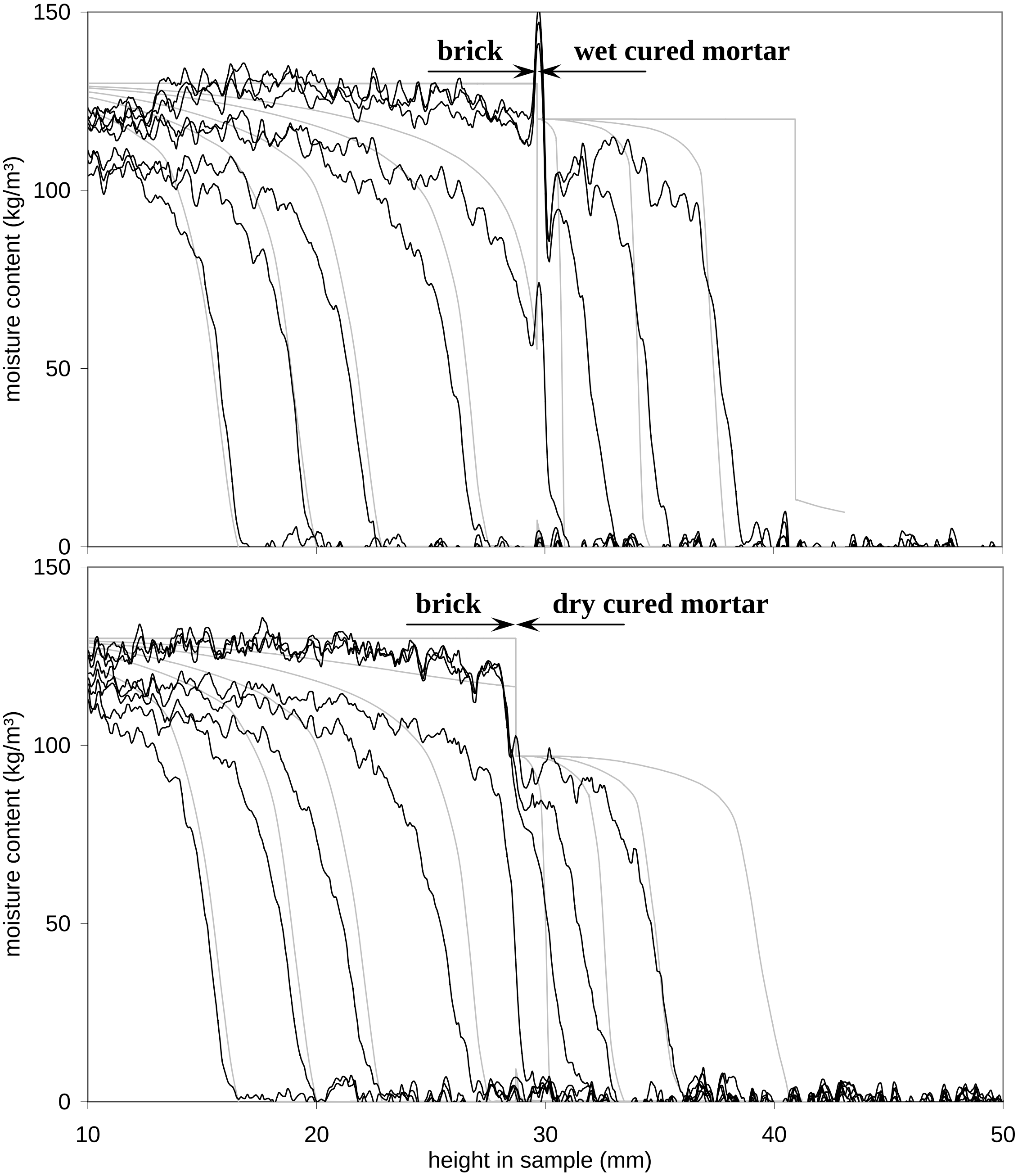

Figure 2: comparison of the numerically (grey) and experimentally (black) determined moisture content profiles during free water uptake in wet cured (top) and dry cured (bottom) masonry samples. Moisture content profiles are shown at 4, 6, 8, 12, 16, 30, 60 and 150 minutes.

Figure 2 clearly shows that the hygric behaviour of mortar joints cannot be entirely captured by changes in the hygric transfer properties only: the simulations in Figure 2 take the decreased porosity and permeability of the wet cured and dry cured mortar into account, but they still overestimate the moisture absorption into the mortar joints. It appears that an additional moisture transfer resistance needs to be considered to properly describe the hygric behaviour of mortar joints, even for the wet cured mortar. As it was reasoned above that there is no experimental evidence to support the existence of deviating surface layers of the mortar joints, this additional moisture transfer resistance can only be deemed an interface resistance, to be ascribed to the bond plane between brick and mortar. Before elaborating this issue however, the existence of such interface resistances is corroborated by a quantitative analysis of the experimentally determined moisture content profiles.

Sharp front analysis of free water uptake in masonry

Moisture content profiles during free water uptake were visualised with X-ray tomography for three different samples: a wet cured and a dry cured masonry sample, and a combined sample with mould mortar. In the latter, a mould mortar joint was hydraulically joined to two brick facets by use of kaolin clay, assumed to yield perfect hydraulic contact [4].
The visualised moisture content profiles were then analysed quantitatively by application of the sharp front theory for absorption into a two-layer composite [7]. In short, by simplifying the moisture transport in a porous material to the movements of a sharp moisture front – separating the wet and the dry material zone –, it can be established that the moisture accumulation during free water uptake in a two-layered composite is proportional to the square root of time for the bottom layer, and is proportional to the square root of an ‘adapted’ time for the top layer:

$$i = S_A \cdot t^{0.5} \tag{1}$$

$$i = S_B \cdot \left(t + {L_A}^2 \cdot X\right)^{0.5} + L_A \cdot Y \tag{2}$$

$$X = \left(\frac{f_B}{S_B}\right)^2 \cdot \left(\frac{K_B}{K_A}\right)^2 - \left(\frac{f_A}{S_A}\right)^2 \qquad Y = f_A - f_B \cdot \frac{K_B}{K_A}$$

where i is the total absorbed volume per unit surface [m], t is the time [s], S is the sorptivity [m/s$^{0.5}$] (capillary absorption coefficient A [kg/m²s$^{0.5}$] is obtained by multiplying with the liquid density), L is the length [m], f is the porosity [-], K is a permeability [m/s], and $_A$ and $_B$ refer to the bottom and top material. Equation (2) can also be represented as:

$$l_B = S_B \cdot \tau^{1/2} - L_E \tag{3}$$

$$\tau = t + {L_A}^2 \cdot X \qquad L_E = L_A \cdot \frac{K_B}{K_A}$$

where l_B is the distance between the front and the materials’ interface [m] and L_E is material A’s ‘equivalent length’ [m]: the hydraulic resistance of the bottom material expressed as a length of the top material. The approximation of the measured moisture content profiles with equation (3) allows to independently determine the capillary absorption coefficient of the mortar materials, but also the equivalent length of the underlying brick facets. Evaluation of these equivalent lengths for the mould, wet cured and dry cured mortar allows assessing potential interface resistances.
The approximation is shown for the free water uptake in the dry cured masonry sample in Figure 3. It is observed that the sharp front paradigm forms an acceptable approximation of the real absorption process, given the fair agreement between the measured results and the expected square root of τ behaviour.

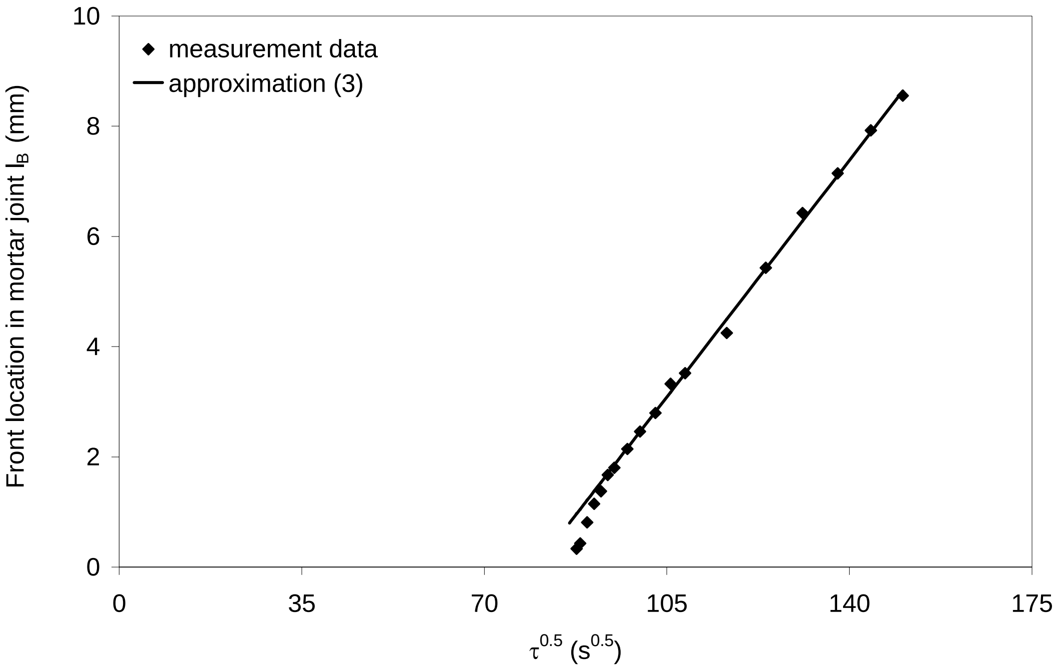

Figure 3: approximation of the measured front locations with the sharp front description (3).

The capillary absorption coefficients A_{mortar} and equivalent lengths L_E, resulting from the least-squares-approximation of the measured data with equation (3), are gathered in Table 2. When A_{mortar} and L_E are both considered fitting parameters, the resulting A_{mortar} all fall in the range of the directly measured values (Table 1) although they are at the high end of the range. Such overestimation can be attributed to the approximation of rounded moisture content profiles (see Figure 2) by vertical moisture fronts.

The L_E increase for the wet cured and dry cured mortar, when compared to the equivalent length of the mould mortar, is a clear indication that an interface resistance is present between brick and mortar joint: without such resistance, a diminishing L_E is expected, since $L_E = L_A K_B / K_A$ and K_B can be assumed to decrease for the wet cured and dry cured mortar, given the decrease in capillary absorption coefficients seen in Table 1. Again, surprisingly, the wet cured mortar also exhibits the presence of such interface resistance.

When all deviation in hygric behaviour of the mortar joints is attributed to an interface resistance, the traditional approach in literature, the second set of values in Table 2 is obtained. For these approximations the capillary absorption coefficient of the mould mortar is assumed applicable for all three mortars. It is evident that neglecting the change in hygric properties of the mortar joint results in a misleadingly high interface resistance. All in all though, the values for the equivalent length of the brick facets confirm the findings of the previous paragraph.

Table 2: overview of the fitted capillary absorption coefficients and equivalent lengths

free fitting of A_{mortar} and L_E	mould mortar	wet mortar	dry mortar
absorption coefficient (kg/m²$s^{0.5}$)	0.0215	0.0175	0.0119
brick equivalent length (mm)	3.90	5.65	9.79

avg A_{mould}, free fitting of L_e	mould mortar	wet mortar	dry mortar
absorption coefficient (kg/m²$s^{0.5}$)	0.0193	0.0193	0.0193
brick equivalent length (mm)	2.66	7.66	26.89

Discussion

The previous paragraphs have clearly demonstrated that the deviating hygric behaviour of mortar joints has two complementary causes: the curing of mortar between bricks (1) results in a significant change in the hygric material properties, and (2) leads to an interface resistance between brick and mortar. Where previous authors [4][6] have opted for one or the other explanation, the presented results indicate that their combined action determines the hygric behaviour of mortar joints.

All common explanations apply for the dry cured mortar. Water extraction from the fresh mortar during curing reduces the water/cement ratio, yielding a less porous and hence less permeable mortar. That same water extraction transports fine cement particles toward the bond plane, hence leading to an interface resistance between brick and mortar. The latter may also result from the mismatch between the two pore systems involved.

Microscopic images of the brick-mortar interfaces in Figure 4 however bring about an additional possible explanation for the interface resistance. At the magnification shown, the bond between brick and mortar is far from perfect for the dry cured mortar: a lot of small air voids are observed. When mortar is applied on dry brick, water extraction reduces the mortar's workability and deformability, near the interface, almost instantly. Pressing the upper brick into the mortar bed may smooth the upper surface of the mortar joint, but leaves the lower contact surface uneven, as shown in Figure 4 (left). The disturbances in the bond plane form an additional explanation for the detected interface resistance. Such disturbed bond plane also explains the frequently experienced detachment of the brick facets for the dry cured masonry samples.

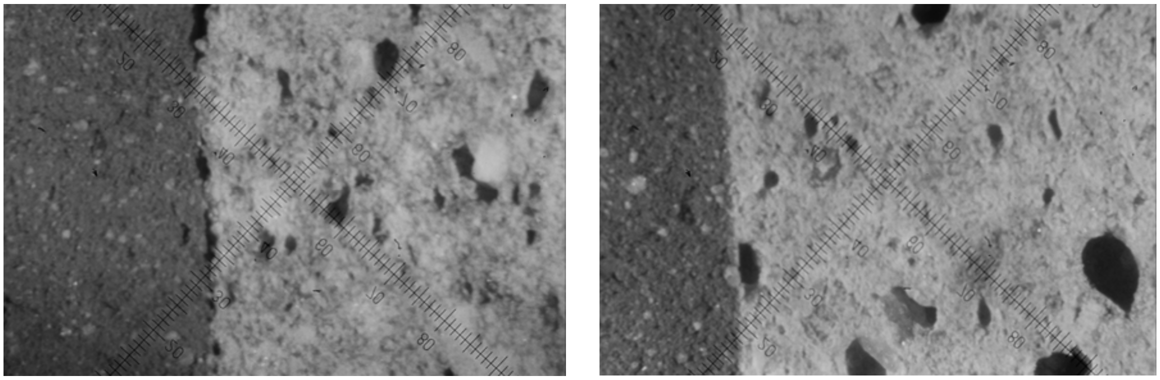

Figure 4: magnified (15 x) images of the brick-mortar bond planes for the dry cured (left) and wet cured (right) masonry samples.

The findings for the wet cured mortar cannot be so easily explained however: whereas the water extraction should have been very small, both changes in the hygric properties as the presence of an interface resistance are observed. Such resistance can neither be explained by disturbances in the bond plane, since Figure 4 (right) reveals that, at the magnification shown, the brick-mortar bond is fairly satisfactory. The noted interface resistance may be a consequence of solely the porosity mismatch, but this phenomenon does not explain the changes in the hygric properties. Two possible explanations are put forward here:

- the wet bricks have lost some moisture by evaporative drying during the handling, prior to the mortar application, which has resulted in a minor amount of water extraction during the first minutes of the curing process;
- not only the water extraction from the fresh mortar by the bricks, active during the first minutes of the curing process, plays a role, but also the long-term drying and curing conditions affect the final hygric behaviour of the mortar joint;

Further research is however required to corroborate these hypothesises.

Conclusions

This paper presented the results of hygric property measurements, numerical simulations, sharp-front analysis and microscopic imaging, in order to investigate the deviating hygric behaviour of mortar joints in more detail, with particular attention for the ‘interface resistances versus hygric property changes’ issue.

It was shown that the deviating hygric behaviour of mortar joints, as compared to the behaviour predicted by mould mortar transport properties, is to be attributed to both factors: there is evidence supporting the difference in the basic hygric transport properties and the existence of an interface resistance between brick and mortar joint.

By determination of the standard hygric properties, it was demonstrated that the curing of mortar joints between bricks yields a mortar material different from mould mortars, even when cured between wet bricks. The mould mortar exhibited the largest (coarse) porosity and permeability, while the dry cured mortar was least porous and permeable.

Comparison of numerical simulation of free water uptake in masonry samples with experimental results did however demonstrate that the changes in hygric properties do not fully capture the deviating hygric behaviour of mortar joints. An additional moisture transfer resistance was required to correct the overestimation of the absorption process by numerical simulation, which were attributed to the bond planes between brick and mortar.

The presence of such interface resistance was further corroborated by quantitative analysis of the experimentally obtained moisture content profiles. Approximation with the sharp-front equations for free water uptake in a two-layered composite supported the hypothesis of an extra resistance between brick and mortar, for both the wet cured and dry cured masonry.

The common explanations all apply for the dry cured brick, and these were supplemented with the disturbed brick-mortar bond, detected in microscopic images. A full explanation for the deviating behaviour of the wet cured mortar is lacking though: as water extraction must have been minimal, particularly the change is hygric material properties remains unresolved.

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