Hygric resistance in multilayer building materials – a prevision new methodology

João Delgado\textsuperscript{1}, António Azevedo\textsuperscript{1}, Isabel Ribeiro\textsuperscript{1}, Ana. Guimarães\textsuperscript{1}, and Vasco Freitas\textsuperscript{1}

\textsuperscript{1}CONSTRUCT-LFC, Faculty of Engineering (FEUP), University of Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal.

Abstract. This work presents the results of an experimental campaign in order to determine the hygric resistance in multilayered building components, with different interface types. The results show a slowing of the wetting process due to the interfaces hygric resistance. The samples with hydraulic contact interface (cement mortar) present lower absorption rate than the samples with lime mortar. The influence of air space between layers was also demonstrated, i.e., the air space interfaces increase the coefficients of capillary significantly, as the distances from the contact with water increase.

The hygric resistance was calculated by three different methods: gravimetric and gamma-ray methods, and the new methodology proposed, an automatic calculation method without human opinion/criteria. The “knee point” was detected, numerically, in water absorption curves and the moisture-dependent interface resistance was quantified and validated for transient conditions. The methodology proposed to detect the “knee point” can be also used in the future for different multilayer materials with an interface, in order to obtain more correct hygric resistance values to be used in future numerical simulations.

1 Introduction

The knowledge of moisture transfer in multi-layered building materials and components using numerical simulations is crucial to predict the moisture behaviour in order to avoid future pathologies and guaranty a correct building performance [1].

There is still a high unfamiliarity concerning the influence of the building components interfaces between layers in moisture transfer processes. The values found in the literature usually neglect the moisture dependency and are based on unlikely boundary conditions.

Some studies which have been carried out [1-3] conclude that it is important to analyse and consider the interface correctly. The hygric resistance can be calculated experimentally by the mass variation curve as a function of time, in a water absorption test, and correspond to the curve obtained after hit the discontinuity, i.e. the interface. The problem is to correctly detect the transition point, knee point. This point can be questionable and its determination is not obvious which means that the hygric resistance measurement can be a difficult task.

In this paper, the moisture transfer was analysed and the hygric resistance was calculated in multi-layered building components. The existence of the interface contributes to a modification on the moisture transport, a moisture transport reduction that crosses the
material interface, in comparison with the same monolithic material. As the hygric resistance calculation seems to be a difficult task and time consuming, it is here proposed and validated a simple methodology to estimate the correct value for each interface type.

Finally, the moisture-dependent interface resistance between brick building components will be quantified and validated which means that can be used for future studies and even as input for numerical simulations. In addition, the methodology to estimate the hygric resistance also can be used in the future for different kind of materials.

2 Materials and methods

Red brick samples have different densities, type “A” with 1800 kg/m$^3$ and type “B” with 1583 kg/m$^3$. The samples area is 40x40mm$^2$ (sectional area), with a height of 100mm, for red brick type “A” and 50x50mm$^2$ (sectional area), with a height of 100mm, for red brick type “B”. In this work, different interface configurations were analysed. The impact of perfect contact interface on moisture transport was evaluated by comparing the moisture flux of these samples with monolithic samples of the same material. For these configurations, a monolithic sample was cut into two smaller pieces and these pieces were put together in a manner that the two cutting surfaces were placed in good physical contact (natural contact interface).

For the study of hydraulic contact interface it was used mortar (lime and cement). Mortar is a common building material used for wall lifting. The dosage is one of the most important factors for the workability of the mortars. The dosage used in this work is in accordance with ASTM C 270 [4], i.e., lime mortar in a proportion of 1:3 (lime and sand) and cement mortar in a ratio of 1:1:6 (cement, lime and sand). The mortar thickness used was 10 mm. Finally, some samples were prepared with an air space interface of 2 mm and 5 mm, between the layers of porous structure, and with the interface at different heights (20, 50 and 70 mm). All the specimens were sealed in the lateral faces with an epoxy coating to avoid the evaporation through these sides and assure the unidirectional moisture flow from the bottom to the specimens’ top surface.

2.1 Gravimetric Method

The Gravimetric Method is a classic method to determine transient moisture content. The bottom surfaces of the test samples were in contact with liquid water. The water level was kept at constant level up to approximately 3 mm above the bottom surface of the samples analysed, with a constant temperature and relative humidity.

Since the goal is to address the effect of the interface in water absorption, the water resistance is measured immediately after the first changing point, which is the time interval of interest. This measurement is calculated experimentally (during a water absorption test) by the slope of the mass variation curve as a function of time, after the knee point.

2.2 Gamma-ray attenuation method

The gamma-ray attenuation method is one of the most widely used non-destructive methods to determine the transient moisture content profile. When gamma rays pass through a material, the adsorption and scattering of gamma rays depend on the nature of the material. A detailed description of the gamma-ray attenuation method can be found in [1].

Figure 1 shows an example of the moisture profiles obtained during the imbibition process, for different times. The hygric resistance values determined by the gamma-ray
method are based in the average values obtained for each moisture profile \((\text{RH})\), after the knee point,

\[
\text{RH}_t = \frac{w_j + 2 \sum_{j=r+1}^{\text{RHm}} w_j + w_{\text{RHm}}}{2}(x_{i+1} - x_i)
\]

(1)

Fig. 1. Example of moisture profile curves during an imbibition process

2.3 New methodology

In the literature, there are several methods of knee or jump point detection [5]. Since the goal is to address the effect of the interface in water absorption, the water resistance is measured immediately after the first changing point, which is the time interval of interest. The final measurement is performed by calculating each hygic resistance (RH). Figure 2a depicts how the several values are measured. Considering this measuring procedure, it is important to detect the exact time instant of the “knee point” automatically and with some precision. The following three methods were taken into consideration to develop the algorithm presented in this work. The choice of these methods took into account the fact that there are discrete methods, intuitive and easy to implement, available in the literature. The following two methods were considered to develop the algorithm presented:

1st Method: This method considers a line which passes through the two extreme points observed \((x_0\) and \(x_n\)). It also considers a set of line segments perpendicular to this line, where each line segment begins at an observed point \((x_i = (t_i, M_{w_i}))\) and ends at a point of the line. The knee point is defined as the point related to the greater segment, as described in Fig.2b.

2nd Method: In this method, the point where the pair of lines that best approaches the curve is called "knee". For its determination, it is necessary to perform, for each point \((x_i = (t_i, M_{w_i}))\) of the curve, two linear fittings, one for all points to the left of \(x_i\) and one for all points to the right of \(x_i\). The knee is considered the point that minimizes the sum of the errors for the two fittings.

3rd Method: This method is a combination of the two methods previously presented. Since the main goal of the algorithm proposed is to find the knee point of a set of points \(x_i = (t_i, M_{w_i}), i=1, 2, \ldots, n\) obtained in the measuring procedure, where the data errors should be taken into account, the combination of the two previously presented methods can give a better knee point. The steps of the developed algorithm are:

1. Use the 1st Method to calculate, for each point obtained in the measuring procedure, the length of the line segment that is perpendicular to the line that connects the two extreme points of the set. Sort the length of perpendicular line segment by a decreasing order. Let \(M1\) be the set of indices of the points corresponding to this ordering.

2. Use the 2nd Method to determine the sum of the errors for the two linear fittings found for each point obtained in the measuring procedure. Sort the sum of the errors for the
two linear fittings by an ascending order. Designate by $M2$ the set of indices of the points associated with this ordering.

3. Determination of the knee point. Find the point $x_i = (t_i, M_{wi})$ whose index, $i$, occupies the best positions in sets $M1$ and $M2$, using the following algorithm:

- **Step 0.** Let $k = 1$ be the position of an element in a set $i = 1$ an index position and $n$ the total number of points obtained in the measuring procedure.

- **Step 1.** If $i > k$, let $j = 1$ and go to Step 3.

- **Step 2.** If $M1(k) = M2(i)$, the knee point is $(t(M1(k)), M_{wi}(M1(k)))$ and stop the algorithm. Otherwise, let $i = i + 1$ and return to Step 1.

- **Step 3.** If $j ≥ k$, go to Step 5.

- **Step 4.** If $M2(k) = M1(j)$, the knee point is $(t(M2(k)), M_{wi}(M2(k)))$ and stop the algorithm. Otherwise, let $j = j + 1$ and return to Step 3.

- **Step 5.** Let $k = k + 1$. If $k > n$ an error message must be sent. Otherwise, let $i = 1$ and return to Step 1.

3 Results and discussion

The water absorption curve increases over time and then presents instants (points of change) where the rate of absorption seems to decrease significantly. These instants correspond to the contact of the water with a different material (contact with the interface). Only 1 knee point was observed for perfect contact and air space interfaces (see Fig.3a), different from what happens with the hydraulic interface (see Fig.3b) where it was observed two discrete knees, one before the interface and another when the interface is saturated.

The results for the determination of the knee point of 30 cases showed: (1) in 5 cases, the 3 methods obtained the same knee point; (2) in 15 cases, each method obtained a distinct knee point; (3) in 1 cases, the 2nd and 3rd methods obtained the same knee point, but the 1st method produced another distinct point; (4) in 9 cases, the 1st and 3rd methods obtained the same knee point but the 2nd method produced another distinct point; and (5) no cases were observed in which the 1st and 2nd methods obtained the same knee point and the 3rd method produced another distinct point.

It should be noted that when the three methods do not obtain the same knee, the point determined by the 2nd method is always to the left of the point calculated by the 3rd method. Meanwhile, the point obtained by the 1st method is always to the right of the point attained by the 3rd method. The 3rd method is an optimization of the existent ones, 1st and 2nd, and showed to be the best method in the experimental cases analysed, with a good detection of the knee point. It is important to keep in mind that in this type of analyse is used with experimental data, which means that there are “discrete” points, and not a curve, with some possible outliers that sometimes contribute to wrong solutions using other methodologies.
Fig. 3. Example of imbibition curves for perfect contact and hydraulic contact interfaces.

Table 1. Hygric resistance values determined by different experimental techniques.

| Material          | Sample / (interface type)         | Hygric Resistance (kg/m²) |
|-------------------|-----------------------------------|---------------------------|
|                   | Gravimetric method                | Gamma-ray method          | New methodology          |
| Red brick Type “A”| Perfect contact (2cm)             | 6.6x10⁻³                  | 8.7x10⁻³                 | 6.2x10⁻²                 |
|                   | Perfect contact (5cm)             | 4.3x10⁻⁵                  | 3.9x10⁻⁵                 | 3.8x10⁻⁵                 |
|                   | Perfect contact (7cm)             | 2.4x10⁻⁵                  | 1.6x10⁻⁵                 | 2.3x10⁻⁵                 |
|                   | Hydraulic contact (cement mortar at 2cm) | 9.7x10⁻⁵               | 1.8x10⁻⁵                 | 7.7x10⁻⁵                 |
|                   | Hydraulic contact (cement mortar at 5cm) | 7.1x10⁻⁵               | 4.4x10⁻⁵                 | 6.9x10⁻⁵                 |
|                   | Hydraulic contact (cement mortar at 7cm) | 4.2x10⁻⁵               | 7.6x10⁻⁵                 | 7.7x10⁻⁵                 |
|                   | Hydraulic contact (lime mortar at 2cm) | 7.9x10⁻⁵               | 4.5x10⁻⁵                 | 7.6x10⁻⁵                 |
|                   | Hydraulic contact (lime mortar at 5cm) | 5.8x10⁻⁵               | 2.2x10⁻⁵                 | 7.5x10⁻⁵                 |
|                   | Air space 2mm at 2cm              | 0.8x10⁻⁵                  | 0.6x10⁻⁵                 | 0.9x10⁻⁵                 |
|                   | Air space 5mm at 2cm              | 0.4x10⁻⁵                  | 0.5x10⁻⁵                 | 0.7x10⁻⁵                 |
|                   | Air space 2mm at 5cm              | 0.9x10⁻⁵                  | 0.8x10⁻⁵                 | 1.0x10⁻⁵                 |
|                   | Air space 5mm at 5cm              | 0.8x10⁻⁵                  | 1.4x10⁻⁵                 | 0.9x10⁻⁵                 |
|                   | Air space 2mm at 7cm              | 0.9x10⁻⁵                  | 0.7x10⁻⁵                 | 0.6x10⁻⁵                 |
|                   | Air space 5mm at 7cm              | 0.4x10⁻⁵                  | 0.2x10⁻⁵                 | 0.4x10⁻⁵                 |
| Red brick Type “B”| Perfect contact (2cm)             | 7.3x10⁻⁵                  | 4.1x10⁻⁵                 | 3.5x10⁻⁵                 |
|                   | Perfect contact (5cm)             | 5.0x10⁻⁵                  | 0.7x10⁻⁵                 | 2.0x10⁻⁵                 |
|                   | Perfect contact (7cm)             | 0.9x10⁻⁵                  | 1.8x10⁻⁵                 | 1.3x10⁻⁵                 |
|                   | Hydraulic contact (cement mortar at 2cm) | 7.9x10⁻⁵               | 3.5x10⁻⁵                 | 6.6x10⁻⁵                 |
|                   | Hydraulic contact (cement mortar at 5cm) | 4.8x10⁻⁵               | 2.9x10⁻⁵                 | 5.0x10⁻⁵                 |
|                   | Hydraulic contact (cement mortar at 7cm) | 3.2x10⁻⁵               | 5.1x10⁻⁵                 | 2.6x10⁻⁵                 |
|                   | Hydraulic contact (lime mortar at 2cm) | 7.9x10⁻⁵               | 4.1x10⁻⁵                 | 7.1x10⁻⁵                 |
|                   | Hydraulic contact (lime mortar at 5cm) | 4.2x10⁻⁵               | 3.3x10⁻⁵                 | 4.8x10⁻⁵                 |
|                   | Hydraulic contact (lime mortar at 7cm) | 4.2x10⁻⁵               | 3.2x10⁻⁵                 | 3.6x10⁻⁵                 |
|                   | Air space 2mm at 2cm              | 0.7x10⁻⁵                  | 1.1x10⁻⁵                 | 0.9x10⁻⁵                 |
|                   | Air space 5mm at 2cm              | 0.8x10⁻⁵                  | 1.1x10⁻⁵                 | 1.0x10⁻⁵                 |
|                   | Air space 2mm at 5cm              | 1.0x10⁻⁵                  | 1.3x10⁻⁵                 | 0.7x10⁻⁵                 |
|                   | Air space 5mm at 5cm              | 0.7x10⁻⁵                  | 1.0x10⁻⁵                 | 1.2x10⁻⁵                 |
|                   | Air space 2mm at 7cm              | 0.7x10⁻⁵                  | 3.9x10⁻⁵                 | 0.7x10⁻⁵                 |
|                   | Air space 5mm at 7cm              | 0.9x10⁻⁵                  | 0.7x10⁻⁵                 | 0.7x10⁻³                 |

The results presented in Table 1 shows good accordance similarity between the RH values obtained by the gravimetric method, gamma-ray method and the new methodology proposed. It is possible to observe that for higher positions of the interface the water absorbed is higher and the hygric resistance is lower. It was expected that considering an interface between layers the water absorption would become lower, and for the case of interfaces located in higher positions the absorption would become higher as the discontinuity is reached latter. In resume:
In samples with perfect contact the absorbed water is lower than in monolithic samples and it is clearly identified the discontinuity. It is possible to observe that for higher positions of the interface the water absorbed is higher. This was perfectly quantified by gravimetric method and the results of the gamma ray’s attenuation technique showed a higher water absorption in the first layer;

The results with hydraulic contact interface (cement mortar) samples present lower absorption rate than the samples with lime mortar, for all techniques used;

The results with the air space interface samples showed, after the interface, that the water absorbed is almost zero, in gravimetric method, and in the gamma-ray method it stays close to the equilibrium water content which means the same;

Finally, for hydraulic contact there are two points of change. As shown in literature [6,7], the changing of porosity in mortar near the transition zone of brick-mortar can be attributed to the flow of water from fresh brick during the bonding process. In the beginning, small binder particles can be transported to the mortar-brick interface and the plaster becomes more compact (enriched in binder) in the interface.

4 Conclusions

In conclusion, the main achievements are the following:

- Two methodologies were studied to detect the knee point and a 3rd methodology is proposed, optimizing the other two, which showed to be the best method;

- The proposed methodology is especially important considering that it is usually used in conjunction with experimental data which means that there are “discrete” points, and not a curve, with some possible outliers that sometimes contribute to wrong solutions using other methodologies;

- In order to make this process even more efficient and effective, the program allows the user to choose whether to define the time frame in which to determine the knee;

- For the interfaces with perfect contact and air space, the model that presented the best fit was the linear model and the hygric resistance is the slope of the equation;

- For the interface with mortar (cement and lime), there are two points of change, and the user can define the time-space in which the knee is to be determined and run the program more than once if you want to determine the two knees.

The main objective, of this work, was to provide a set of values, referring to the hygric resistance in masonry walls of buildings, for advanced simulation programs of moisture transfer.

References

1. V.P. Freitas, V. Abrantes, P. Crausse, Build. Environm. 31, 99 (1996).
2. H. Derluyn, H. Janssen, J. Carmeliet, Constr. Build. Mater. 25, 3685 (2011).
3. X. Qiu, F. Haghighat, K. Kumaran, J Therm Envelope Build Sci 26, 213 (2003).
4. ASTM C 270, Standard Specification for Mortar for Unit Masonry, Rev. 14A (2014).
5. Christopoulos, D.T., Reliable computations of knee point for a curve and introduction of a unit invariant estimation (2014), DOI: 10.13140/2.1.3111.5844.
6. H. Brocken, L. Pel, K. Kopinga, Moisture transport over the brick/mortar interface. In: Nuclear Magnetic Resonance Spectroscopy of Cement-Based Materials. Springer, Heidelberg, (1998).
7. N. Shahidzadeh-Bonn, A. Azouni, P. Coussot, J. Phys: Cond. Matter, 19, 112 (2007).