Heat Mass Transfer (2016) 52:2415–2422
DOI 10.1007/s00231-016-1755-z

ORIGINAL

# Water movement in building walls: interfaces influence on the moisture flux

**J. M. P. Q. Delgado**[1] · **V. P. de Freitas**[1] · **A. S. Guimarães**[1]

Received: 9 April 2015 / Accepted: 12 January 2016 / Published online: 16 January 2016

**Abstract** Most building elements are a composite of different material layers; however the majority of the works presented in literature were developed for multi-layered elements with perfect contact interface, without resistance. Experimental results presented in literature showed that a considerable hydraulic resistance could be created by the imperfect contact between two porous building materials. Moisture transport in multi-layered building elements can deviate from the moisture transport found for the combination of the single material elements, so the assumption of perfect hydraulic contact could lead to significant errors in predicting the moisture transport. This work presents an experimental campaign and a critical analysis of water absorption in samples of two different building materials (clay brick and autoclaved aerated concrete) with and without joints at different positions (heights) and different contact configurations (natural contact and air space between layers). The results show that when the moisture reaches the interface there is a slowing of the wetting process due to the interfaces hygric resistance. The interfaces hygric resistance, in the AAC samples, is only observed for the joint located from a distance of 2 cm of the wetting plane. The penetration coefficient of the two building materials analysed is very different. Finally, the evolution of the distribution of liquid in the porous medium was analysed in terms of the Boltzmann transform method and anomalous diffusion equation.

**Keywords** Interfaces · Capillarity · Experimental tests · Moisture diffusion · Moisture transfer

### List of symbols

| | |
|---|---|
| $A$ | Contact area ($m^2$) |
| $A_W$ | Water absorption coefficient ($kg/m^2s^{0.5}$) |
| $B$ | Water penetration coefficient ($m/s^{0.5}$) |
| $D_W$ | Moisture diffusion coefficient ($m^2/s$) |
| $h$ | Penetration depth (m) |
| $m_t$ | Weight of the specimen after time $t$ (kg) |
| $m_0$ | Initial mass of the specimen (kg) |
| $M_t$ | Total amount in time $t$ ($kg/m^2$) |
| $n$ | Real number (-) |
| $P_{c1}$ | Suction pressure of material 1 (Pa) |
| $P_{c2}$ | Suction pressure of material 2 (Pa) |
| $q$ | Moisture flow across the interface ($kg/m^2s$) |
| $Q_{\max}$ | Maximum transport flow ($kg/m^2s$) |
| $R$ | Hygric resistance (m/s) |
| $t$ | Time (s) |
| $x$ | Axial-coordinate (m) |
| $w$ | Volumetric moisture concentration ($kg/m^3$) |
| $w_0$ | Initial volumetric moisture concentration ($kg/m^3$) |
| $w_\infty$ | Equilibrium volumetric moisture concentration ($kg/m^3$) |
| $\alpha$ | Variable given by $\alpha = 1/(n+1)\,(-)$ |
| $\eta$ | Boltzmann variable ($m/s^{0.5}$) |
| $\eta*$ | Similarity variable, $\eta* = x/t^{\alpha}$ ($m/s^{\alpha}$) |
| $\rho$ | Density ($kg/m^3$) |

---

✉ J. M. P. Q. Delgado
jdelgado@fe.up.pt

V. P. de Freitas
vpfreita@fe.up.pt

A. S. Guimarães
anasofia@fe.up.pt

[1] CONSTRUCT-LFC, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal

## 1 Introduction

Moisture damage is one of the most important factors limiting building performance. High moisture levels can damage construction (condensations, mould's development) and inhabitants' health (allergic risks). Rising damp coming from the grounds that climb through the porous materials constitutes one of the main causes of old buildings degradation.

Masonry is the prevalent solution for constructing building envelopes. While its constituent materials (bricks and cement mortar) are reasonably well understood, the hygric behaviour of masonry is often shown to deviate from the normal unsaturated flow theory. In literature, some researchers refer to an imperfect contact and hence an interface resistance in the brick–mortar bond plane.

A building wall, in general, consists of multiple layers, and thus the investigation of the moisture transfer presumes knowledge about the continuity between layers. All of these phenomena enable to explain the retarded water uptake in brick–mortar composites found in experimental investigations [1]. Due to its complexity, the incorporation in numerical models of the retarded water uptake across a (brick–mortar) interface is often done by an implementation of the phenomena mentioned [2]. In literature different approaches were found. Brocken [1] obtained an agreement between numerical and experimental investigations by assuming a perfect hydraulic interface contact in combination with modified mortar properties. In contrast, Qiu [3, 4] neglected the change in material properties and examined the liquid transport across the interface between aerated concrete and mortar and simulated the moisture behaviour by use of an interface resistance. According the authors, this simplification is acceptable if the interface resistance is determined after capillary saturation of the first layer.

Derluyn et al. [5] took an interface resistance as well as a change in mortar properties into account. The authors determined the brick–mortar interface resistance based on the water uptake from the brick layer into the mortar joint. Hence, the values were determined for the liquid transport into a material with a lower absorption. Besides the mortar properties, also the interface resistance was found to depend on the curing conditions. For a dry cured mortar a higher interface resistance was obtained compared to the wet cured composite. Similar interface resistances analytically obtained by Janssen et al. [6] prove the validity of Derluyn's approach.

Although several studies concerning the liquid transport in multilayered composites can be found [1, 3–7], currently only a limited number of values for the interface resistance in multilayered composites are found [1, 3, 7]. These values were determined based on the moisture profiles measured during an imbibition's experiment and can be strongly case-dependent. For instance, the mortar type (e.g. W/C factor, additives), the brick type (e.g. capillarity), the curing conditions (e.g. moisture content of the brick), the thickness of the mortar joint, etc. may have a potential impact on the interface resistance and the modification of the material properties.

Freitas et al. [7] described three kinds of continuity between layers: "Hydraulic continuity" when there is an interpenetration of both layer's porous structure; "Natural contact" when there is a contact without interpenetration and "Air space between layers" when there is an air box of a few millimetres wide between the layer's porous structure. In this work only the natural contact is analysed in detail. In natural contact there is no continuity of the capillary pressure and there is a maximum transport flow (defined as $Q_{\max}$) function of the interface's hydric resistance which conditioned the transfer.

Finally, in this work normal and anomalous diffusion models are analysed, since, this study has particular relevance in hygrothermal numerical simulation and for evaluating the durability of building structures. In literature it is possible to find a significant number of researchers [8–13] that have observed deviation from this behaviour when the infiltrating fluid is water and there is some potential for chemo-mechanical interaction with the material. For example, Küntz and Lavallée [8] discussed the anomalous behaviour and propose a non-Fickian model as a more appropriate physical description.

In conclusion, the major achievements of this work are new experimental values of water absorption in samples of different building materials with and without joints at different positions (only few experiments were presented in literature), new values of maximum transport flow, $Q_{\max}$, function of the interface's hydric resistance and a measurement and analyse of the moisture diffusion coefficient, $D_{\mathrm{w}}$, of two building materials, using normal and anomalous diffusion models.

## 2 Theory

The water penetration into porous building materials is an important physical process in the analysis of the durability of any building structure. The water transport process in building materials has been described exhaustively in literature by many researchers [14, 15] and, during several years, it has been established that the amount of water penetrating the porous medium ($M_t$) is proportional to the square root of elapsed wetting time, $.t^{0.5}$. The slope of this linear variation is called the water absorption coefficient ($A_{\mathrm{w}}$) and can be mathematically written as

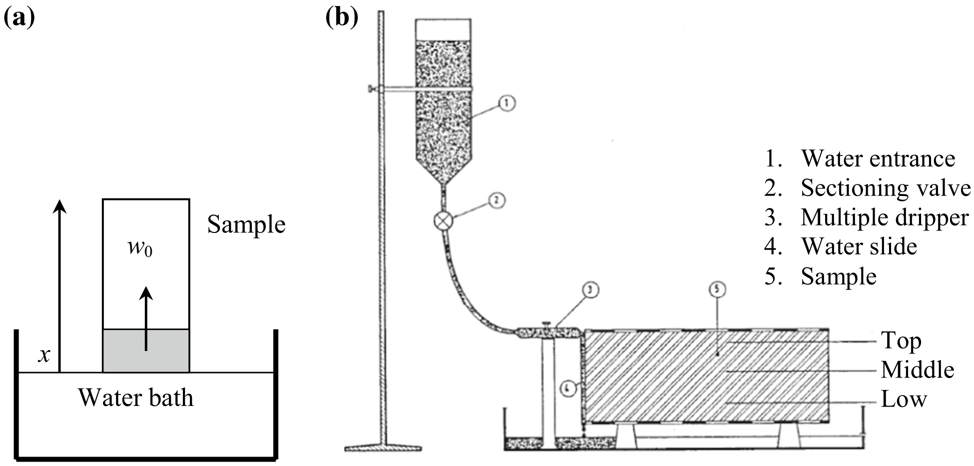

**Fig. 1** Schematic of an absorption test: **a** vertical and **b** horizontal

$$A_{\mathrm{w}} = \frac{m_t - m_0}{A\sqrt{t}} \tag{1}$$

According to Fick's law of diffusion [14], for isotropic materials, the rate of transfer, measured normal to the section, of diffusing moisture through a unit area of a section is proportional to the gradient of moisture concentration. In conclusion, to calculate the average liquid diffusivity ($D_w$) from the water absorption coefficient, it is necessary to establish the relationship between the $A_{\mathrm{w}}$ value and the average liquid diffusivity [14].

$$D_{\mathrm{w}} = \frac{\pi}{4}\left(\frac{A_w}{w_\infty}\right)^2 \tag{2}$$

In this work, Eq. (2) is used to derive the average liquid diffusivity from the water absorption coefficient.

More recently, numerous experimental results have been reported on the violation of the square root of time law [9] and the authors argued that the short-time anomaly in the absorption curve is a manifestation of a deviation from water flux-gradient proportionality (i.e. Darcy's Law). Küntz and Lavallée [8] introduced the following nonlinear diffusion equation to described anomalous diffusion observed:

$$\frac{\partial w}{\partial t} = \frac{\partial}{\partial x}\left[D_{\mathrm{w}}(w)\left(\frac{\partial w}{\partial x}\right)^n\right] \tag{3}$$

where $D_w(w)$ is the capillary diffusivity and $n$ is a real number. For one dimensional water absorption with $w = w_0$ at $x > 0$ and $t = 0$, and $w = w_\infty$ at $x = 0$ and $t > 0$, Eq. (3) can be expressed in terms of a single variable $\eta = x/t^\alpha$, with $\alpha = 1/(n+1)$ [8]

$$-\frac{\eta}{n+1}\frac{dw}{d\eta} = \frac{d}{d\eta}\left[D_{\mathrm{w}}(w)\left(\frac{dw}{d\eta}\right)^n\right] \tag{4}$$

with the following boundary conditions

$$\eta = 0 \; w = w_\infty \tag{5a}$$

$$\eta \to \infty \; w = w_0 \tag{5b}$$

The capillary diffusivity can be determined by integrating Eq. (4) using the boundary conditions (5a) and (5b),

$$D_{\mathrm{w}}(w) = -\frac{1}{n+1}\left(\frac{d\eta}{dw}\right)^n \int\limits_{w0}^{w} \eta dw \tag{6}$$

and the cumulative water absorption $M_t$ is given, at any time, by $M_t = A_{\mathrm{w}}.t^\alpha$, where $A_{\mathrm{w}}$ is the water absorption coefficient of the building material.

Related to moisture transport across interfaces between building materials, two types of interfaces can be distinguished: perfect and imperfect hydraulic contact. If the interface has no effect on moisture transport (perfect hydraulic contact interface) the suction pressure, $P_{\mathrm{c}}$, across the interface is continuous and the hygric resistance is neglected:

$$P_{c1}(w_1) = P_{c2}(w_2) \tag{7}$$

In the case of "natural contact" and "air space" the hygric resistance in the interface can be found. For example, Quiu [3, 4] examined the liquid transport across the interface and simulates the moisture behaviour by use of an interface resistance, $R$, defined as follows:

$$R = \frac{P_{c2} - P_{c1}}{q} \tag{8}$$

where $q$ is the moisture flow across the interface.

**Table 1** Different configurations tested

| Configurations | Interface continuity | Materials |
|---|---|---|
| A | No interface | Clay brick |
| B | No interface | AAC |
| C | Natural contact | Clay brick + Clay brick |
| D | Natural contact | AAC + AAC |
| E | Natural contact | Clay brick + AAC |
| F | Natural contact | AAC + Clay brick |
| G | Air space | Clay brick + Clay brick |
| H | Air space | AAC + AAC |

## 3 Experiments

The moisture uptake process used in the experimental campaign is schematically shown in Fig. 1. During the vertical absorption tests (Fig. 1a), the bottom surfaces of the test specimens 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 specimens analysed, with a constant temperature and relative humidity. The horizontal absorption tests (Fig. 1b) were done in constant hygrothermal conditions (temperature and relative humidity), with the bottom surface permanently in contact with liquid water, fed by the device 1, in Fig. 1b, and with a constant boundary layer of water.

In this work two different building materials, prismatic samples, were tested: clay brick ($\rho = 1925$ kg/m$^3$) and autoclaved aerated concrete, AAC, ($\rho = 525$ kg/m$^3$), density values obtained in [7]. The samples analysed were constructed in the laboratory with a dimension of 70 × 70 × 200 mm$^3$. The experiments conducted in this study are guided by the outline of the partial immersion method as explained in the European Standard CEN/TC 89 [16]. Prior to testing the specimens were placed in a climatic chamber with 22 ± 0.5 °C of temperature and 50 ± 1 % of relative humidity, until the samples reached the equilibrium state, i.e., no weight variation of the specimens, with the time, for the above values of temperature and relative humidity. All surfaces of each test specimen are sealed except the top surface open to the ambient air and the bottom surface in contact with water, to ensure one-dimensional moisture transport.

In this work different configurations were analysed, as showed in Table 1. Configurations A and B are a single piece of clay brick and AAC, respectively. The impact of natural contact interface on moisture transport was evaluated by comparing the moisture flow of Configurations A/B and C to F. 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 a good physical contact (natural contact interface). Finally, Configurations G and H were prepared with an air space of 2 to 4 mm, between the layers of porous structure. During the absorption tests the water

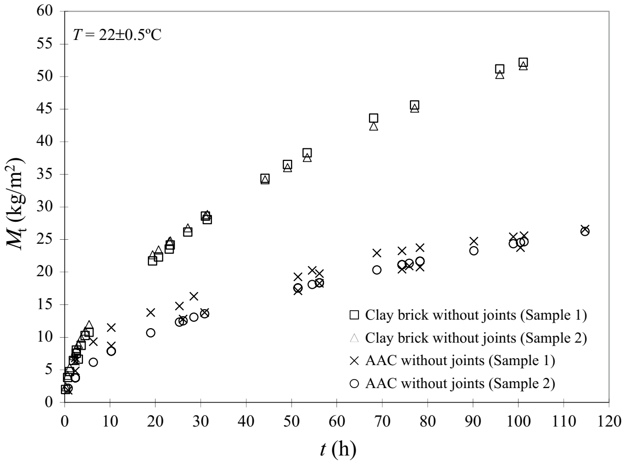

**Fig. 2** Example of the reproducibility observed during the experimental campaign

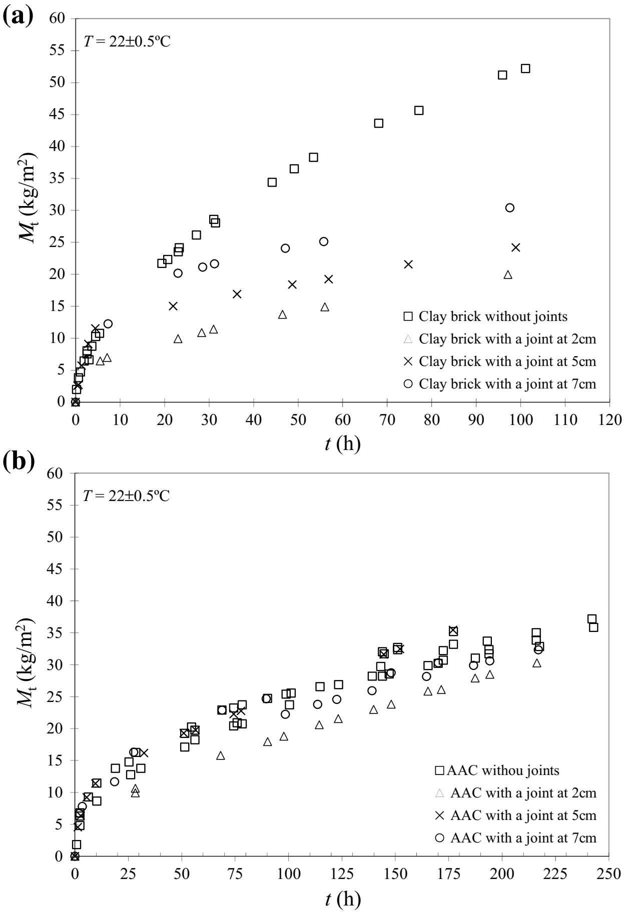

**Fig. 3** Different kinetics of absorption of **a** clay brick samples and **b** autoclaved aerated concrete samples, with joints at different positions

temperature was kept constant at 22 ± 0.5 °C. To guarantee low errors during each experiment, each sample was involved in "aluminium sheet". The "aluminium sheet" could guarantee not only sideways waterproof but also the good connection between layers, for the samples in natural contact and for the samples with an air gap between the layers.

## 4 Results

The building walls are made up of multi-layers of joined materials making up the interface a discontinuity that influences the drying and wetting in a significant way. In this work we analyse the interface impact between layers, using monolithic samples of clay brick and autoclaved aerated concrete (AAC) as well as samples made by two layers of the same sample or of different samples (see Table 1).

The reproducibility of the experiments was tested by independently repeating the measurement of water absorption coefficient, under identical operating conditions, and in the vast majority of cases, repeated measurements of water absorption coefficient did not differ by more than 10 %. Figure 2 shows an example of the reproducibility observed during the experimental campaign.

Figure 3a shows the results obtained for the variation of mass per contact area, in vertical wetting, of monolithic samples of clay brick and samples, of the same building material, with "natural contact" at different distances from the wetting plane ($x = 2$, 5 and 7). It is possible to observe that when the moisture reaches the interface the beginning of the slowing of the wetting process due to the interfaces hygric resistance occurs in different time periods (influence of the joint thickness). From that moment it is possible to observe an increase in mass that is constant for all the 3 cases studied. The same results were observed in Fig. 3b with the AAC samples analysed, however the interfaces hygric resistance is only observed for the joint located from a distance of 2 cm of the wetting plane. It is important to be in mind that the penetration coefficient of the two building materials analysed is very different. The water penetration coefficient, $B$, is defined by the following relation:

$$h = B\sqrt{t} \tag{9}$$

where $h$ is the penetration depth of the water front during sorption process.

In order to know the maximum transport flow between layers of different materials, some mixed samples of AAC/clay brick and clay brick/AAC were prepared and analysed. Figure 4 shows the difference observed during the absorption kinetics of sample with different layers and "natural contact" interface at different positions. The results presented in Fig. 4 show the existence of a hygric resistance associated to a maximum transport flow ($Q_{max}$); when the contact is between 2 layers of clay brick or AAC the $Q_{max}$ values are higher than when the contact is between AAC/clay brick and clay brick/AAC (see Table 2).

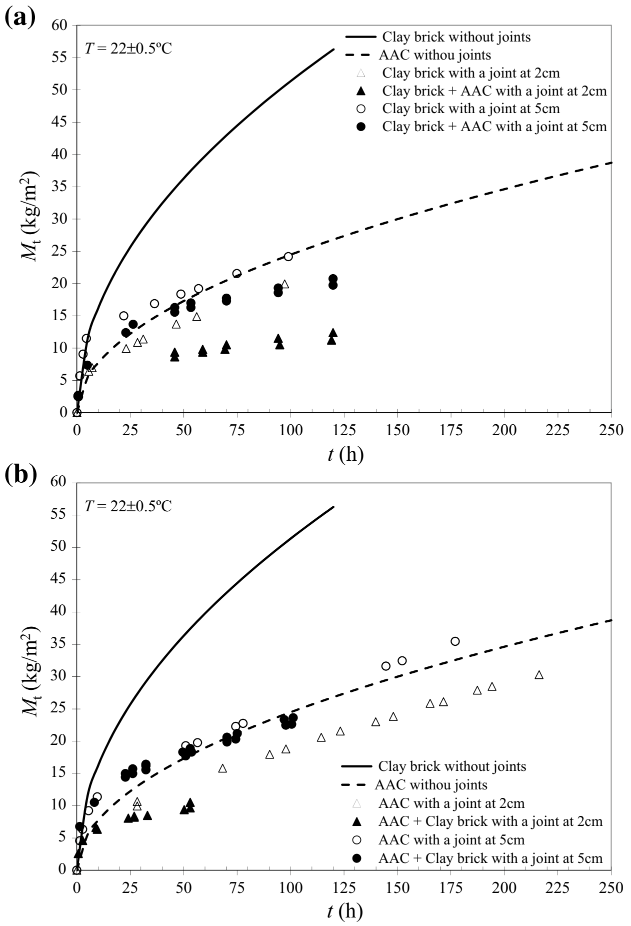

**Fig. 4** Different kinetics of absorption of samples with two different layers (clay brick and autoclaved aerated concrete) and joints at different positions

**Table 2** Values of the maximum transmitted flow, $Q_{max}$, for kinds of contact configurations

| Interface continuity | Materials | $Q_{max}$ (kg/m$^2$s) |
|---|---|---|
| Natural contact | Clay brick + Clay brick | $44 \times 10^{-6}$ |
| Natural contact | AAC + AAC | $30 \times 10^{-6}$ |
| Natural contact | AAC + Clay brick | $23 \times 10^{-6}$ |
| Natural contact | Clay brick + AAC | $15 \times 10^{-6}$ |
| Air space | Clay brick + Clay brick<br>AAC + AAC | $4 \times 10^{-6}$ |

In Fig. 5 it is possible to observe the influence of air space between layers. If the layers of consolidated materials are separated by an air space (2–4 mm), there is a hygric cut that prevents the moisture transfer in liquid phase so the

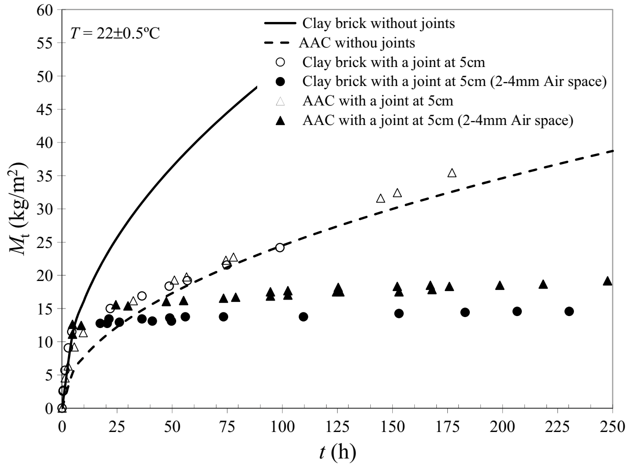

**Fig. 5** Comparison of the absorption kinetics of samples with two different kinds of contact configurations: "natural contact" and "air space between layers"

water transport starts to be in vapour phase. As observed in Fig. 4, these results support the existence of a hygric resistance associated to $Q_{\max}$; when the contact is between 2 layers of clay brick or AAC with "natural contact" interface the $Q_{\max}$ values are higher than when the contact is between the same layers but with air space interface (see Table 2).

Figure 6 shows the gravity forces influence on the absorption kinetics of the building materials analysed. It is possible to observe that for clay brick samples practically no difference were observed and for AAC samples important differences were detected. These results show that in many capillary porous building materials the gravitational forces could not be neglected. If the capillary forces were much stronger than gravitational forces in all building materials the kinetics of capillary rise should be indistinguishable from horizontal capillary absorption on the time. This result observed is in accordance with other experimental results reported in literature [17, 18]. For example, Hall [10] described marked deviations from $t^{1/2}$-scaling behaviour in capillary rise laboratorial experiments with cellular concrete and AAC samples. Similar results were observed in our experimental results and reported in Fig. 7. The water absorption content variation profiles were plotted as a function of the new variable, $t^{0.50}$ for clay brick and $t^{0.42}$ for autoclaved aerated concrete (see Fig. 8). So, it is possible to observe that for autoclaved aerated concrete the motion, during the initial sorption period was faster than the $\sqrt{t}$ behaviour.

It is well-known that the $t^{1/2}$-scaling is only valid for 1-D absorption into a semi-infinite homogeneous porous building material with a constant concentration boundary

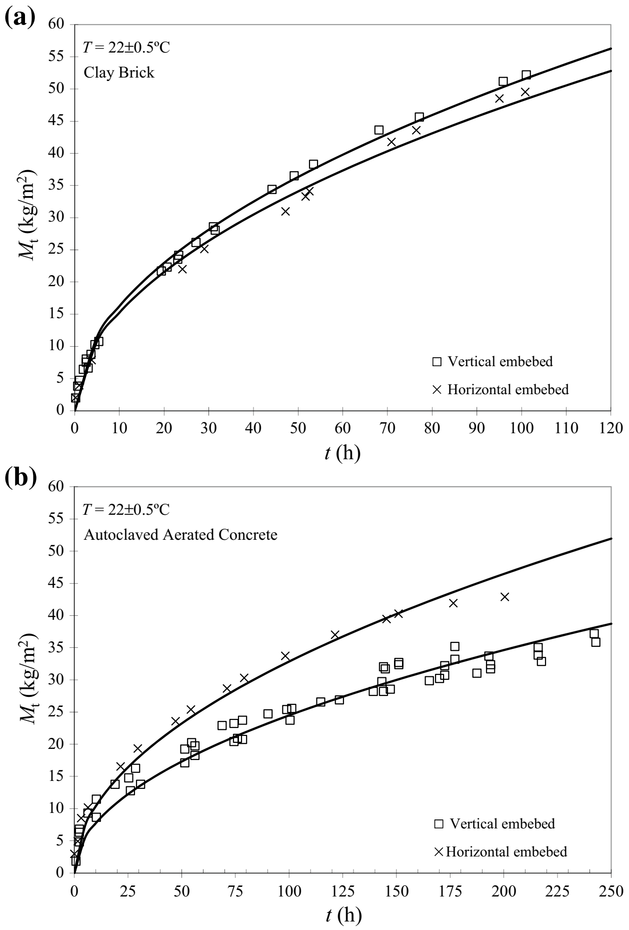

**Fig. 6** Influence of gravity on the absorption kinetics of samples of **a** clay brick and **b** autoclaved aerated concrete. The solid lines represent the equation: $M_t = A_w . t^{0.5}$

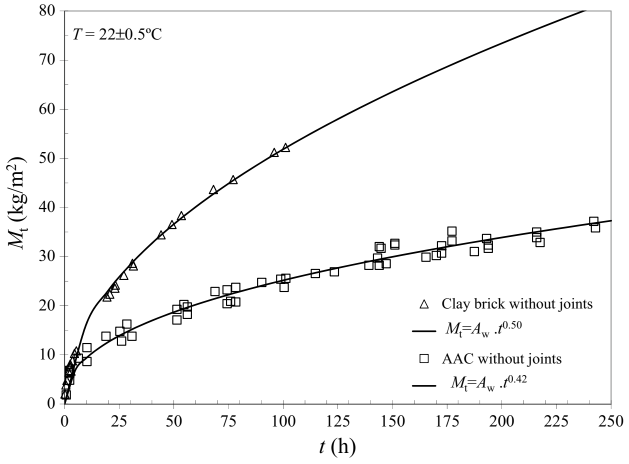

**Fig. 7** Comparison of $\Delta w/A$ predicted from the unsaturated flow theory and from the anomalous diffusion model

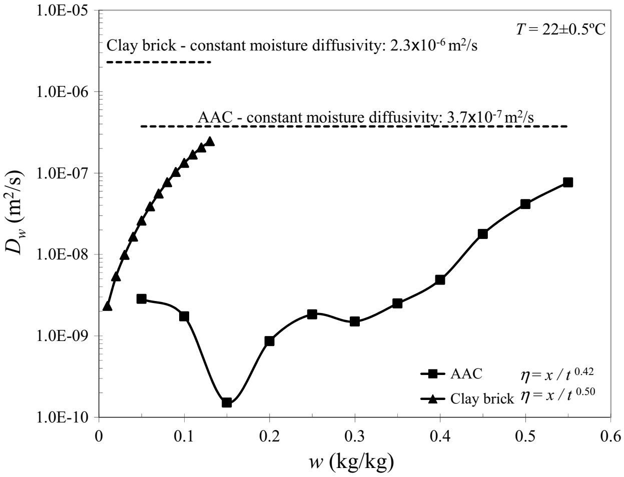

**Fig. 8** Moisture diffusivity coefficients as a function of the moisture content

condition. This homogeneity should be presented in the transport properties and in initial moisture content. Cementitious materials, as AAC, presented relevant variation of properties near the surfaces, as described Krieger [19].

In Fig. 7 it is possible to observe a deviation from the theoretically expected square root of the time behaviour in the cumulative absorption curve of AAC samples. These deviations have been observed in both the short-time and long-time faster. This is clear evidence of water sorptivity anomalies in cement-based materials in comparison with other porous building materials, as clay brick. So, the extended Darcy model and the Richards equation only provide a satisfactory water transport of unsaturated flow in some building materials (for example: clay brick, limestones and sandstones).

More, some classical theories of water sorption in porous media, for example Dullien [20], showed that the distance of the sorption front should be proportional to a square root of time, however, the experimental results showed strong deviations from the classical theory predictions. The initial sorption period the motion was slower ($t > 0.5$) than the $\sqrt{t}$ behaviour for the clay brick and in the case of autoclaved aerated concrete it was faster ($t > 0.5$).

For cementitious materials a time-fractional diffusion equation model of anomalous diffusion is adopted to analyse the experimental data. The superimposition of the profiles is now much better and this indicates that the progression of the water absorption content variation front is different than expected from Fick's analysis [11–13].

## 5 Conclusions

The analysis of moisture migration in building materials and elements is crucial for its behaviour knowledge also affecting its durability, waterproofing, degradation and thermal performance. The mechanisms involved in the transfer of moisture in building elements and components are very complex justifying the development of this studies. It is essential the determination of water content, relative humidity and temperature hydric profiles evolution, predicting the real behaviour of building materials and components when in contact with moisture. With this work it is possible to better understand the moisture transfer process in building materials when in water absorption processes.

A detailed experimental campaign of water absorption in samples of two different building materials (clay bricks and autoclaved aerated concrete) with and without joints at different positions (heights) and different contact configurations (natural contact and air space between layers) were done.

The results show that when the moisture reaches the interface there is a slowing of the wetting process due to the interfaces hygric resistance. The results were observed in clay brick and also with the AAC samples analysed, however the interfaces hygric resistance, in the AAC samples, is only observed for the joint located from a distance of 2 cm of the wetting plane.

It was possible to observe the influence of air space between layers. If the layers of consolidated materials are separated by an air space (2–4 mm), there is a hygric cut that prevents the moisture transfer in liquid phase so the water transport starts to be in vapour phase. The penetration coefficient of the two building materials analysed is very different. There are differences observed during the absorption kinetics of samples with different layers and "natural contact" interface at different positions. It is possible to see that for clay brick samples and for AAC samples no influence of gravity was observed.

Finally, a simple analysis of the anomalous diffusion approach based on the simple absorption test is presented. The, preliminary, results show that the Fickian model underestimates the volume of absorbed water.

**Acknowledgments** The research work presented herein was supported by FEDER funds through the Operational Programme for Competitiveness Factors—COMPETE and by national funds through the FCT—Portuguese Foundation for Science and Technology, under research project. J.M.P.Q. Delgado would like to thank FCT for financial support through the Grant SFRH/BPD/84377/2012.

## References

1. Brocken HJP (1998) Moisture transport in brick masonry: the grey area between bricks. PhD Thesis, Eindhoven University
2. Delgado JMPQ, Ramos NMM, Barreira E, Freitas VP (2010) A critical review of hygrothermal models used in porous building materials. J Porous Media 13:221–234
3. Qiu X (2003) Moisture transport across interfaces between building materials. PhD Thesis, Concordia University
4. Qiu X, Haghighat F, Kumaran MK (2003) Moisture transport across interfaces between autoclaved aerated concrete and mortar. J Build Phys 26:213–236
5. Derluyn H, Janssen H, Carmeliet J (2011) Influence of the nature of interfaces on the capillary transport in layered materials. Constr Build Mater 25:3685–3693
6. Janssen H, Derluyn H, Carmeliet J (2012) Moisture transfer through mortar joints: a sharp-front analysis. Cem Concr Res 42:1105–1112
7. Freitas VP (1992) Moisture transfer in building walls—interface phenomenon analysis. PhD Thesis, FEUP (in Portuguese)
8. Küntz M, Lavallée P (2001) Experimental evidence and theoretical analysis of anomalous diffusion during water infiltration in porous building materials. J Phys D Appl Phys 34:2547–2554
9. Taylor SC, Hoff WD, Wilson MA, Green KM (1999) Anomalous water transport properties of Portland and blended cement-based materials. J Mater Sci Lett 18:1925–1927
10. Hall C (2007) Anomalous diffusion in unsaturated flow: fact or fiction? Cem Concr Res 37:378–385
11. Lockington DA, Parlange JY (2003) Anomalous water absorption in porous materials. J Phys D Appl Phys 36:760–767
12. El Abd AG, Milczarek JJ (2004) Neutron radiography study of water absorption in porous building materials: anomalous diffusion analysis. J Phys D Appl Phys 37:2305–2313
13. Küntz M, Lavallée P (2004) Anomalous diffusion is the rule in concentration-dependent diffusion processes. J Phys D Appl Phys 37:L5–L8
14. Crank J (1975) The mathematics of diffusion. Oxford Science, New York
15. Philip JR (1969) Theory of infiltration. Adv Hydrosci 5:215–296
16. CEN/TC 89/WG10 N70 (1994) Thermal performance of buildings and building components—determination of water absorption coefficient
17. Hall C, Yau MHR (1987) Water movement in porous building materials—IX. The water absorption and sorptivity of concretes. Build Environ 22:77–82
18. Hall C, Hoff WD (2002) Water transport in brick, stone and concrete. Spon, London and New York
19. Kreijger PC (1984) The skin of concrete: composition and properties. Matér Constr 17:275–283
20. Dullien FAL (1979) Porous media: fluid transport and pore structure. New York Academic, New York