Building Materials Capillary Rise Coefficient: Concepts, Determination and Parameters Involved

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Abstract The presence of water is one of the main decay factors in buildings. Capillary rise is the most important mechanism of water penetration into building materials in liquid phase. The free capillary water uptake experiment, used for the estimation of the capillary water absorption coefficient, a crucial materials property, is widely used for the characterization of building materials. The capillary water absorption coefficient was calculated according to three different European standards and recommendations. The three methods were compared in order to investigate which is the most appropriate for the calculation of the capillary water absorption coefficient. In addition, the effect of temperature on the estimation of the capillary water absorption coefficient of different building materials such as stones, bricks and mortars, was investigated for three different room temperatures (20, 25, 30 °C). From the results it was found a linear dependence between temperature T and the capillary water absorption coefficient.

Keywords Capillary rise coefficient · Temperature · Stones · Bricks · Mortars · Building materials

Nomenclature

ε_o	Total porosity (%)
g	Gravitational constant (m/s^2)
h	Capillary moisture equilibrium height (m)
σ	Water surface tension (dyn/cm)
T	Air Temperature (°C)
V_p	Total pore volume (mm^3)
V_b	Material bulk volume (mm^3)
V_s	Material total volume (mm^3)

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J.M.P.Q. Delgado (ed.), *New Approaches to Building Pathology and Durability*, Building Pathology and Rehabilitation 6, DOI 10.1007/978-981-10-0648-7_2

ρ_b Material bulk density (kg/m^3)
ρs Material true density (kg/m^3)
ρ Water density (g/cm^3)
r Material average pore radius (μm)
θ Liquid-solid contact angle
A_w Capillary water absorption coefficient ($mg/cm^2s^{1/2}$)
A Specimen surface area (cm^2)
ΔB Mass of the absorbed water (mg)

1 Introduction

Water can reach a building material through the material pores in several ways. It originates from e.g. driving rain, condensation of air humidity, run off from roof and facade and/or capillary rise of ground water (Arnold 1982; Karoglou et al. 2005). Building materials usually contain an amount of physically bound water without affecting their durability. But if the material's moisture content is above a certain percentage, the deterioration effect of moisture is activated causing an amount of physical, chemical and biological issues (Oliver 1997; Avoletti 1997; Moropoulou et al. 2014):

- Physical issues: Water will transport contaminants such as soluble salts. If wet, the material can become susceptible to freezing damage. In this case, major decay phenomenon is the formation of ice in low temperatures.
- Chemical issues: While water penetrates into a building material, salt crystallization may occur at the surface, or just under the surface. Some salts are hygroscopic, facilitating water vapor absorption and in many cases causing further structural damages.
- Biological issues: Moisture may also act as a substrate for the growth of bacteria, fungi, or algae with possible physical and chemical damages, but also possible health risks.

Thus, the knowledge of the water movement within a building material is of great importance to determine the degradation mechanism in question.

Main decay mechanisms are: hydrolysis, dissolution, hydration, oxidation, capillary rise, salt transfer and crystallization, hygroscopicity, cycles of wetting/drying; while main types of decay caused are: spalling, peeling, delamination, blistering, shrinkage, cracking, crazing, irreversible expansion, embrittlement, strength loss, staining discoloration, bio-decay of building materials (Connoly 1993).

Potential sources of water are: the ground, the environment (rain, sea, water vapor etc.), possible water sewage leakages, use of water for the production of building materials, interventions with the use of extensive quantities of water, salts hygroscopicity (Oxley and Gobert 1998). Best way to "fight" moisture related problems in buildings is the prevention of the entrance of moisture at the design phase. However, the elimination of the problem in existing structures, especially historical ones, is more complicated.

1.1 Capillary Rise

Capillary rise is the main mechanism by which water penetrates into a building material. Capillary rise is, by definition, the upward vertical movement of ground water through a permeable wall structure (Alfano et al. 2006) causing the appearance of rising damp into the structure.

Building materials have pores of different shapes and different diameters, which means that they contain air voids. The main parameter of each material microstructure is the total porosity ε_o of the material, which is defined as the ratio of the material empty space V_p divided by the material's total volume V_s (Amoroso and Camaiti 1997):

$$\varepsilon_o = \frac{V_p}{V_s} = 1 - \frac{V_b}{V_s} = 1 - \frac{\rho_b}{\rho_s} \tag{1}$$

where ρ_b, ρ_s are the bulk and the true density of the material and V_b the material bulk volume.

However, some material pores behave like closed ones (Fig. 1) and do not play a significant role in the water movement into the material. This is the reason why the estimation of the effective or open porosity is more representative. This refers to the fraction of the total volume in which fluid flow is effectively taking place and includes catenary and dead-end pores and excludes closed pores (or non-connected cavities).

The pore structure, meaning pore shape, size, distribution, and networking of pores is very difficult to define. Capillary rise takes place inside the capillary pores of a building material. The capillary pore radius is a controversial issue among researchers but, in general, its range is considered to be from about 10 nm to 10 μm (Table 1). A very useful classification of pores based on their diameter according to researchers (Mehta 1986; Mindess et al. 2003) and IUPAC is listed in Table 1.

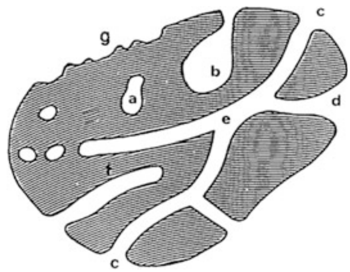


Fig. 1 Schematic pores classification, according to their accessibility to surroundings (*Legend* *a* closed pores, *b*, *f* pores open only at one end, *c*, *d*, *g* open pores, *e* open at two ends (through) pores)

Table 1 Pore classification based on their diameter *d* (nm)

According to IUPAC		According to Mehta (1986)		According to Mindess et al. (2003)	
Name	Size range	Pore type	Size range	Name	Size range
Micropores	up to 2 nm	Interparticle space between C-S-H sheets	1–3 nm	Micropores "inter layer"	Up to 0.5 nm
				Micropores	0.5–2.5 nm
Mesopores	2–50 nm	Capillary pores (low w/c)	10–50 nm	Small (gel) capillaries	2.5–10 nm
		Capillary pores (high w/c)	3–5 µm	Medium capillaries	10–50 nm
Macropores	>50 nm	Entrained voids	50 µm–1 mm	Large capillaries	50 nm–10 µm
				Entrained air	0.1–1 mm

Pores can also be classified according to their accessibility to surroundings (Fig. 1). The pores communicating with the external surface are named open pores, like (b), (c), (d), (e) and (f). They are accessible for molecules or ions in the surroundings. Some are open only at one end (b, f). These are described as blind pores. Others may be open at two ends (through pores, (e)) (Zdravkov et al. 2007; IUPAC 1994).

Ground water can rise into the pore structure of a building material driven by the force of capillarity. Capillarity is greater for small capillaries and inversely proportional to the pore radius according to Jurin's law. Jurin's law is referred to the height h of the vertical rise in a capillary pore and is given by the following equation (Gennes et al. 2004):

$$h = \frac{2\sigma \cos\theta}{\rho g r} \tag{2}$$

where r is the mean radius of the capillary pore, σ the surface tension of the liquid, θ the water contact angle, ρ the water density and g the gravity acceleration (Fig. 2).

1.2 Capillary Water Absorption Coefficient

Capillary water absorption coefficient, or *A*-coefficient, is one of the most important features of a building material because it governs the liquid moisture movement into it and expresses the rate of absorption of water due to capillary forces for building materials. Thus, it must be taken into consideration when determining the hydrometric properties of the material.

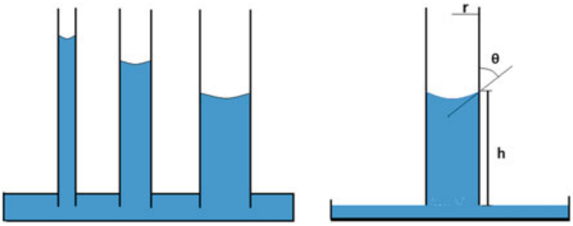


Fig. 2 Capillary action depends on the radius of a capillary tube. The smaller the tube, the greater the height reached

1.3 Estimation of the Capillary Water Absorption Coefficient

There are many European and international standards and recommendations by which researchers estimate the capillary water absorption coefficient of building materials. The majority of these standards are related to building materials and materials used in cultural heritage protection. European standard EN 1925 (2000) refers to natural stones, while EN 1015-18 (2002) refers to hardened mortars. European standard EN 13057 (2002) describes the measurement of the capillary water absorption of hardened concrete. Normal 11/85 (1985) refers to materials and conservation interventions of cultural heritage and it was replaced by the UNI 10859 (2000) standard, which refers to natural and artificial stones. Finally, EN 15801 (2009) refers to porous inorganic materials used for and constituting cultural property and the European standard EN 480-5 (2005), describes the determination of the water capillary absorption coefficient of concrete, mortars and grouts.

The experimental setup for a water absorption experiment as described in the EN standards and recommendations is quite common (Hall 1989). After drying each sample at 60 °C to constant mass in a hot-air oven, its dry mass is measured. Each sample is cooled to room temperature and is putted on a tray of distilled water. The position of the waterfront is gradually approaching the opposite side of the sample and the water intake is governed by capillary and viscous forces. The quantity of the absorbed water is measured at standard time intervals by weighing the specimen. Each weighing should be completed as quickly as possible (typically within 30 s). The capillary water absorption coefficient is determined with three different ways.

According to EN 1925 and EN 1015-18, the capillary water absorption coefficient is the gradient of the straight line obtained by plotting the cumulative mass of water absorbed per unit area against the square root of time *t* obtained from this first stage according to the following equation:

$$A_w = \frac{\Delta B}{A\sqrt{t}} \tag{3}$$

where A_w (mg/cm^2 s$^{1/2}$) is the water absorption coefficient, A (cm^2) is the surface area of the cross section of the specimen and ΔB (mg) is the mass of the absorbed water. This estimation way is known as the one tangent method.

The Italian UNI 10859 standard refers to natural and artificial stones and indicates that the capillary water absorption coefficient should be calculated according to the following equation:

$$A_w = \frac{Q_{30} - Q_0}{\sqrt{t_{30}}} \quad (4)$$

where, Q_{30} is the cumulative mass of water at 30 min, Q_0 is the cumulative mass of water at the beginning of the experiment and t_{30} is the time of 30 min. This estimation method is known as the 30 min method.

Finally, in Italian Normal 11/85 the two tangents method is described. According to this method, the capillary water absorption coefficient should be determined according to the following equation:

$$A_w = \frac{M^*}{\sqrt{t^*}} \quad (5)$$

where A_w (mg/cm^2 s$^{1/2}$) is the capillary water absorption coefficient, M^* (g/cm^2) is the asymptotic value of the absorbed water per unit area of the sample and t^* (s) is the abscissa of the point of intersection between the straight line passing through the asymptote and the tangent to the straight portion of the curve measured in seconds.

Many researchers have investigated the capillary water absorption coefficient as a part of their research works, however using each time one of the precedent standards.

Plagge et al. (2005) described an experimental method of an automated water uptake test. Moreover, they used this method to determine the capillary water uptake coefficient A_w according to EN 15148. Candanedo and Derome (2005) conducted capillary absorption tests to measure the water absorption coefficient in the longitudinal, radial and tangential directions and the capillary moisture content for one softwood species, Jack Pine, according to the one tangent method. Fronteau et al. (2010) studied the sedimentological and petrophysical properties of some Lutetian limestones of the Paris Basin. In this study, the building stones were characterized and their petrophysical characterizations were carried out using normalized tests recommended for building stones. They also determined the water uptake coefficient by capillary according to EN 1925. Juhász et al. (2014) analyzed the migration characteristics of Bacillus cereus in porous limestone, as well as the capillary absorption and elevation properties of porous limestone and they measured the water absorption coefficient according to EN 1925. Sengun et al. (2014) determined the capillary water absorption coefficients of 118 different natural stone types having different structural and textural features in accordance with the EN 1925 standard and related these coefficients with other rock properties such as bulk density, apparent porosity, total porosity, seismic velocity, etc.

Calcaterra et al. (2000) studied Piperno, a Late Quaternary magmatic rock, from different points of view, namely mineralogy, petrography and engineering geology and they measured the capillary water absorption coefficient of this rock according to the Normal 11/85. Stefanidou and Papayianni (2005) examined the role of aggregates on the structure and behaviour of lime mortars by studying the influence of the aggregate content and the grain size on strength, porosity and volume stability of the mortars. They also measured capillary water penetration by suction according to the Normal 11/85. Karoglou et al. (2005) developed a first-order capillary rise kinetic model for predicting the water capillary rise of several building materials. In this work, the experimental procedure for the calculation of the moisture content of the materials followed the instructions of Normal 11/85. Karoglou et al. (2013) also studied the water vapor transfer rate of repair coated and uncoated plasters, used for masonries suffering by rising damp phenomena. Moreover they performed an ageing test with repeated cycles of capillary absorption of sodium sulphate solution, on brick–plaster-coating systems in accordance with Normal 11/85. Dei and Salvadori (2006) in their study, tried to evaluate the effectiveness of inorganic compatible treatments, based on nano-sized particles of calcium hydroxide (slaked lime) dispersed in alcoholic medium, as consolidants for limestones and painted surfaces. Both in situ and laboratory tests were carried out on carbonatic, low-porosity stones and on frescoes. The measurements of water absorption by capillarity in two classes of stones, both for the untreated and consolidated samples were conducted according to the Normal 11/85.

Maravelaki-Kalaitzaki et al. (2005) conducted a research with hydraulic restoration mortars for a historic masonry in Crete, Greece. They also presented the results of the physico-chemical characterization of original mortars and plasters and the evaluation of the repair ones prepared with natural hydraulic lime (NHL) as binding material and siliceous sand and crushed brick as aggregates. Water absorption measurements were carried out and the test was performed according to the methodology described in the normal UNI 10859. Vandevoorde et al. (2009) proposed an alternative method, the contact sponge method, which was tested on non-treated porous stone materials in a laboratory environment. Moreover, the results of this method were compared with results obtained via the capillary rise method according to UNI 10859 in order to evaluate its accuracy. Vandevoorde et al. (2013) also presented a comparison of non-destructive techniques for analysis of the water absorption behavior of seven lithotypes, in order to develop a methodology for the selection and application of method and an adequate comparison of the results. In this work capillary rise measurements were performed according to UNI 10859. Ksinopoulou et al. (2012) investigated the performance of particle modified consolidants (PMC) applied on two types of porous stones used in historical structures in Greece. In order to evaluate the consolidation effect, changes in properties of treated specimens were estimated through several methods such as SEM, mercury intrusion porosimetry, water absorption by capillarity, etc. More specifically, the water absorption coefficient was estimated through capillary rise tests according to UNI 10859.

While, the experimental procedure estimating the capillary water absorption coefficient of building materials remains unquestionable, the comparison of *A*-coefficient values is difficult due to different estimation methods. Indeed, as it is often observed, a building material presents a different *A*-coefficient value depending on the estimation method. Thus, different materials *A*-coefficient cannot be compared based on different estimation methods.

2 Materials and Methods

Three main types of building materials were selected and studied (bricks, stones, and natural hydraulic mortars) with different microstructural characteristics. Bricks are symbolized with codes starting with the letter *B*, stones with *S* and mortars with *M*. Two different types of clay brick have also been investigated. One was a traditional handmade clay brick (*BRM*) and the other one was a typical solid clay brick (*BRI*). Two sedimentary quarry stones originated from Rethymno, Crete island (*SRY*) and from Rhodes island (*SRH*) respectively were the stones investigated. The mortars examined were prepared by using two different types of natural hydraulic lime (*NHL2 and NHL3.5*) in accordance to EN 459-1 (2010), in 3 different binder/aggregate ratios. The materials dimensions were 5 × 5 × 5 ± 0.1 cm^3. The materials characteristics are summarized in Table 2.

The aim of this work was the estimation of the *A*-coefficient according to three different European standards and recommendations. Additionally, the dependency of the capillary water absorption coefficient with the temperature was investigated.

Among the European standards and recommendations, the regulations chosen were: EN 1925 and EN 1015-18 in which the one tangent method is described, UNI 10859 in which the two tangents method is described and Normal 11/85 recommendation in which the 30 min method is described.

A building material was chosen for examination and capillary rise experiments were conducted at 20 °C. The choice was the *BRI* brick because it exhibited the most linear first and second stages among all materials examined and because of its high homogeneity. Following the experimental procedure, the capillary rise coefficient was calculated according to the three different aforementioned methods.

Table 2 Materials description

a/a	Materials	Description
1	mca25/75	25 % NHL 2 and 75 % river sand
2	mca30/70	30 % NHL 2 and 70 % river sand
3	mca20/80	20 % NHL 2 and 80 % river sand
4	mcb25/75	25 % NHL 3.5 and 75 % river sand
5	mcb30/70	30 % NHL 3.5 and 70 % river sand
6	mcb20/80	20 % NHL 3.5 and 80 % river sand
7	BRI	Typical solid clay brick
8	BRM	Traditional handmade clay brick
9	SRH	Rhodes quarry stone
10	SRY	Rethymno quarry stone

Following this, capillary rise experiments were carried out with the rest of the materials described in Table 2, at the temperature of 20 °C, as suggested in most European standards and recommendations.

In order to investigate the dependence of the capillary water absorption coefficient on the temperature, a series of capillary rise tests were carried out at three different air temperatures of 20, 25 and 30 °C for all the examined materials. All the capillary rise experiments were performed at controlled relative humidity conditions. The water temperature was determined about 2 ± 0.5 °C lower than the air temperature while the relative humidity was 45 ± 5 % during the experiments.

At least, three specimens of each material were tested for each of the selected air temperatures.

3 Results and Discussion

In Table 3 the capillary water absorption coefficient values according to the three different estimation methods, at the air temperature of 20 °C for all the examined materials are presented. In addition, the estimation of the *A*-coefficient based on the three different estimation methods for building material *BRI* is shown in Figs. 3, 4 and 5.

Bricks presented the highest capillary water absorption coefficient values (>20) whatever the calculation method was. On the contrary, *SRY* stones and *mca25/75* mortars exhibited the lowest water absorption coefficient values probably due to their different nature and different microstructural characteristics. *BRM* bricks, *SRY* stones and *mca30/70* mortars exhibit almost the same capillary water absorption coefficient values with all the estimation methods. Moreover, in many cases (*mca20/80*, *mca30/70* and *mcb20/80* mortars) the two tangents method and the

Table 3 Water absorption coefficient A_w (mg/cm^2 s$^{1/2}$) values for building materials at 20 °C

	A_w (mg/cm^2 s$^{1/2}$) (20 °C)					
Materials	One tangent method	SD	Two tangent method	SD	30 min method	SD
mca20/80	19.2	0.59	17.6	0.89	17.9	1.07
mca25/75	7.90	0.80	8.00	0.42	7.20	1.00
mca30/70	17.5	1.02	16.0	2.08	16.1	2.37
mcb20/80	12.3	0.70	10.6	0.45	10.0	0.05
mcb25/75	9.10	0.10	7.10	0.00	5.10	0.00
mcb30/70	9.20	0.43	6.50	0.26	3.60	0.10
BRI	27.0	1.18	25.2	0.69	26.1	0.83
BRM	20.5	0.05	20.6	1.33	20.7	0.75
SRH	10.1	0.00	12.3	0.25	7.00	0.00
SRY	8.90	0.80	8.30	0.59	9.00	1.84

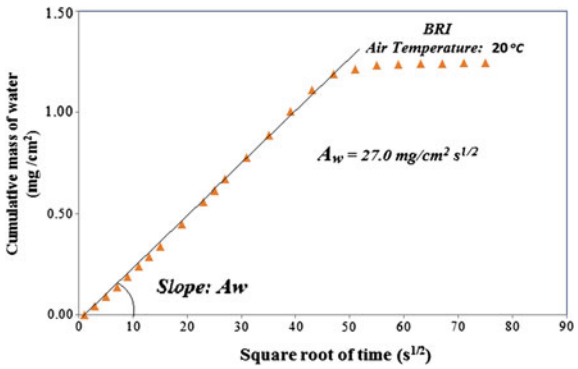


Fig. 3 Determination of water absorption coefficient due to capillarity according to EN 1925

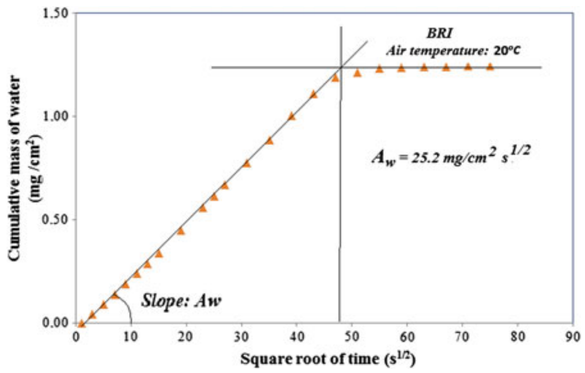


Fig. 4 Determination of water absorption coefficient due to capillarity according to normal 11/85

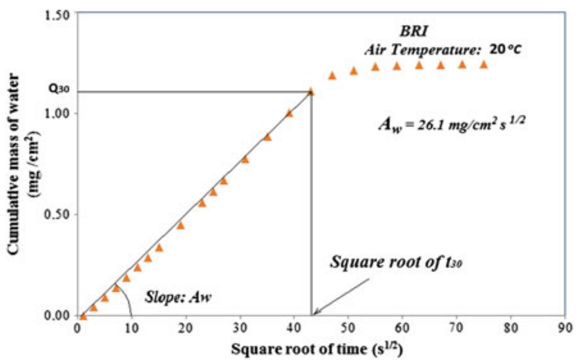


Fig. 5 Determination of water absorption coefficient due to capillarity according to UNI 10859

30 min method presented almost the same results. However, some building materials (*mcb30/70* and *mcb25/75* mortars) exhibit a slow initial water absorption rate and thus, the 30 min method estimates smaller values compared to the values given with the other two estimation methods. In Fig. 6, the capillary rise kinetics, at 20 °C

is presented for all the examined materials. In general, *mca* mortars have higher water absorption coefficients than *mcb* mortars probably due to their different type of binder.

The main results of the capillary rise experiments for all the examined materials at the temperatures of 20, 25 and 30 °C are summarized in Fig. 6.

From the diagrams in Fig. 6, a dependence of the *A*-coefficient with the temperature is observed in all samples. More specifically, it was found that the water absorption coefficient increases with the increase of temperature. In the case of *BRI* and *BRM* bricks kinetics, the initial part is very well defined by a straight line at all the temperatures and their curve shape is the same at every temperature examined. Moreover, *BRI* brick exhibits higher capillary saturation than *BRM* brick. *SRH* stones exhibit a first stage not sufficiently defined by a straight line (see Fig. 6) and this makes the calculation of the *A*-coefficient according to the one tangent method very difficult. *SRY* stones present higher sorptivity values than *SRH* stones. Some irregularities are also observed in the curve shape of some mortars (*mca25/75*, *mcb25/75* and *mcb30/70* mortars) probably due to their different microstructure. Moreover, the two tangents method seems to be the most appropriate for the estimation of the capillary water absorption coefficient not only in the case of building materials with high homogeneity but also in the case of materials with anomalous microstructure.

Table 4 presents the results of the linear regression analyses with their R-squared values according to the two tangents method. The dependence of the water absorption coefficient values with the temperature for some of the examined building materials according the one tangent method is shown in Fig. 7.

According to the results as exhibited in Table 4 and in Fig. 7, it is evident that the capillary water absorption coefficient exhibits a linear dependence with the temperature in all the samples. In almost all the calculations standard deviation was under 10 %.

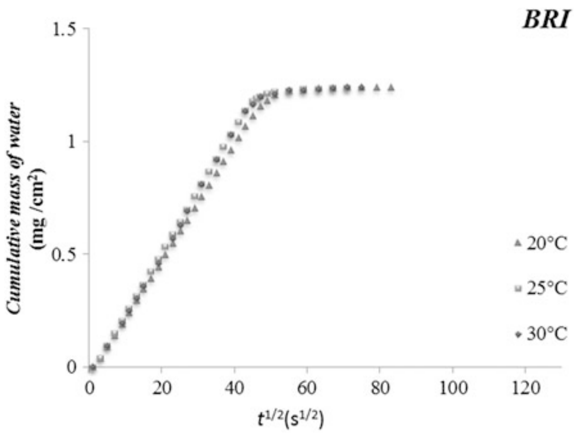


Fig. 6 Cumulative mass of capillary water uptake versus time for different building materials

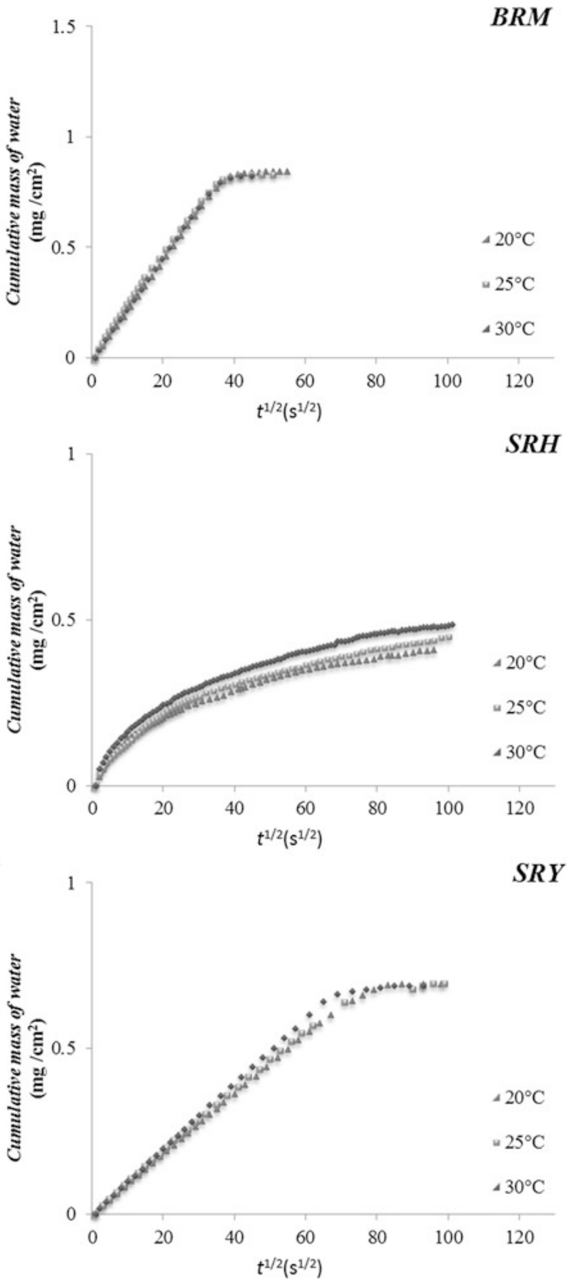
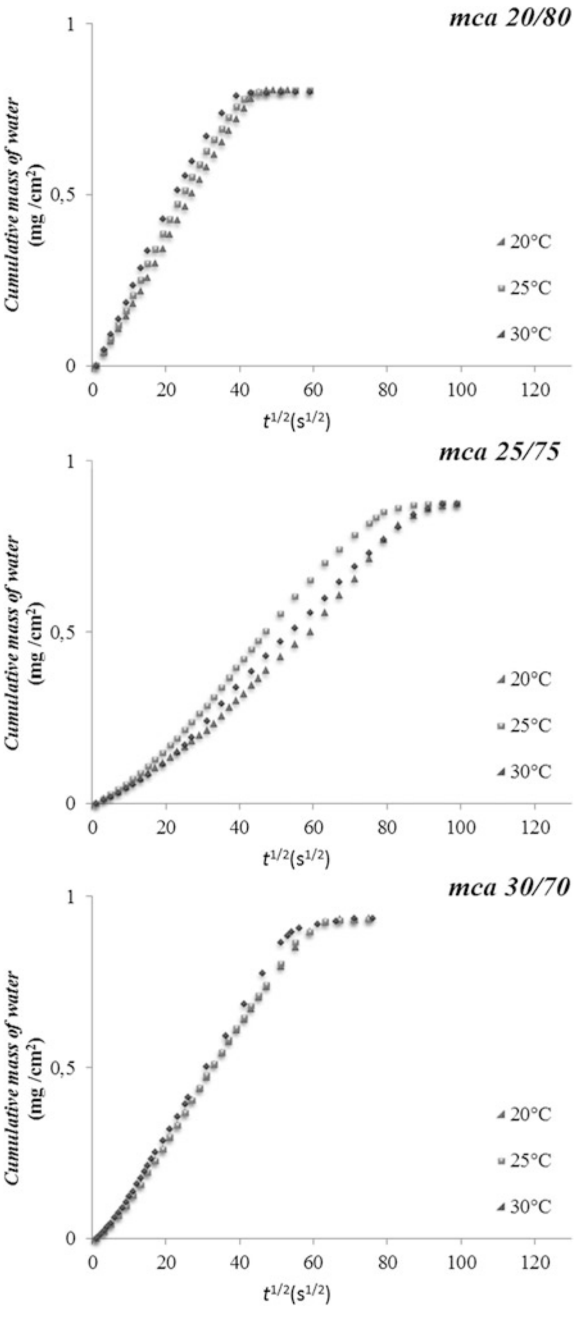


Fig. 6 (continued)



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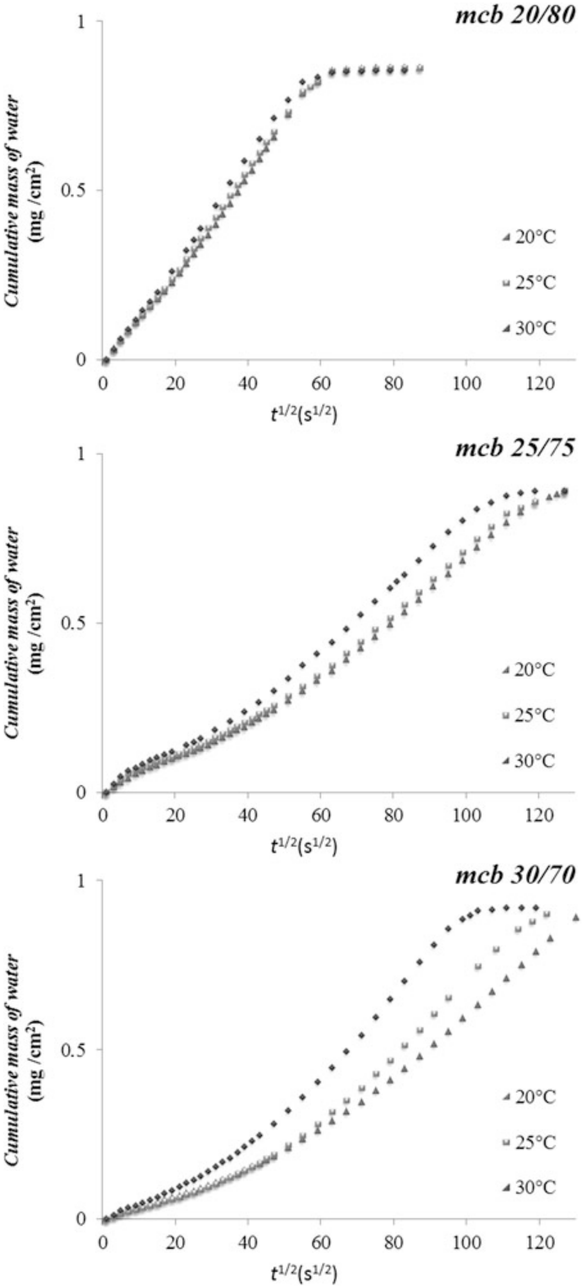

Fig. 6 (continued)

Table 4 Linear regression equations and R-squared values for the examined building materials according to the two tangents method. The *A*-coefficient is the slope of the linear regression equation

	Two tangents method	
Materials	Linear regression equation	R^2-value
mca25/75	y = 0.241x + 3.030	0.803
mca30/70	y = 0.245x + 10.80	0.967
mca20/80	y = 0.171x + 14.08	0.991
mcb25/75	y = 0.108x + 4.87	0.993
mcb30/70	y = 0.049x + 5.74	0.792
mcb20/80	y = 0.088x + 9.11	0.858
BRI	y = 0.133x + 22.91	0.914
BRM	y = 0.146x + 17.62	0.958
SRH	y = 0.612x + 0.10	0.990
SRY	y = 0.163x + 5.20	0.974

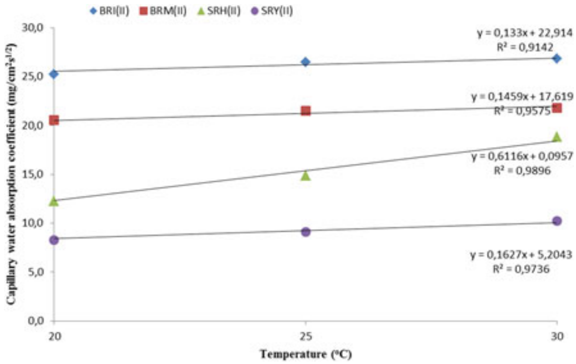

Fig. 7 Absorption coefficient values at different temperatures and use of linear regression for bricks and stones according to the two tangents method

3.1 *Case Study*

In order to evaluate the validity of the predicted values, the capillary water absorption coefficient of *BRI* and *BRM* bricks was measured at 15 °C. After this, a calculation of the water absorption coefficient was made, using the equations obtained from the linear regression given in Table 4 according to the two tangents method.

The results from the comparison of the experimental values with the predicted values of the capillary water absorption coefficient are shown in Table 5.

From the above reported results is evident that experimental values of the *A*-coefficient are in very good agreement with the predicted ones using the equations given in Table 4.

Table 5 Experimental and predicted estimation of the capillary water absorption coefficient A for bricks BRI and BRM at 15 °C

Temperature 15 °C		
Materials	Predicted *A*-coefficient (mg cm^{-2} $s^{-1/2}$)	Experimental *A*-coefficient (mg cm^{-2} $s^{-1/2}$)
BRI	24.9	25.1
BRM	19.8	19.7

4 Conclusions

In the literature, different standards and recommendations are utilized for the estimation of the capillary water absorption coefficient of building materials. Each one of them derives from a different calculation basis and gives different final results. In this paper, the capillary water absorption coefficient was estimated according to three European standards and recommendations. The two tangents method seems to be the most appropriate for the estimation of the *A*-coefficient especially in cases in which building materials have a first absorption stage deviating from the linearity.

The effect of air temperature on the progress of the capillary rise of various building materials was also investigated and a linear relationship between the capillary water absorption coefficient values with the temperature was observed. Moreover, a case study at a different temperature of 15 °C was performed, in order to validate the linear dependency of the A-coefficient with the temperature. Experimental A-coefficient values were found in very good agreement with the predicted ones. Hence, a prediction of the value of the water capillary rise coefficient in every air temperature using appropriate linear equations could be made.

In addition, the assumption of a constant water absorption coefficient, independent of temperature, that is often adopted, is clearly inaccurate. This dependence should be taken into account by all researchers and practitioners who use the water absorption coefficient as a mean to characterize a building material.

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http://www.springer.com/978-981-10-0647-0

New Approaches to Building Pathology and Durability
Delgado, J.M.P.Q. (Ed.)
2016, VIII, 207 p., Hardcover
ISBN: 978-981-10-0647-0