Pergamon

Cement and Concrete Research 30 (2000) 1559–1563

CEMENT AND CONCRETE RESEARCH

Estimation of the capillary transport coefficient of Clayey Aerated Concrete using a gravimetric technique

M.S. Goual[a], F. de Barquin[b], M.L. Benmalek[a], A. Bali[c], M. Quéneudec[a,*]

[a]Laboratoire des Transferts et Réactivité dans les Milieux Condensés, IUT de Génie Civil, UPJV, Avenue des Facultés, 80025 Amiens Cedex 1, France
[b]Division Matériaux, Centre Scientifique et Technique de la Construction, Av. Pierre Holoffe 21, 1342 Limelette, Belgium
[c]Département de Génie Civil, Ecole Nationale Polytechnique d'Alger, 16000, Algeria

Received 22 July 1999; accepted 31 July 2000

Abstract

Knowledge of the capillary transport coefficient is important to the study of moisture migration in building materials and therefore essential to the simulation of moisture movements predicted by mathematical models. In this paper, an experimental technique based on gravimetric measurements of capillary water absorption is developed in order to determine water content profiles and estimate the isothermal capillary transport coefficient D_θ of Clayey Aerated Concrete (CAC) at various porosities using the Boltzmann transform resolution method. All experiments have been conducted at room temperature. A comparison of the evolution in capillary transport coefficient as a function of volumic water content obtained using this technique with the evolution obtained using the γ-ray attenuation for similar materials [J.A. Da Cunha Neto Bellini, Transport d'humidité en matériau poreux en présence d'un gradient de température: Caractérisation expérimentale d'un béton cellulaire, PhD thesis, Université Joseph Fourier-Grenoble I, 1992, 69 pp.; A. Bouguerra, Contribution à l'étude d'un procédé de valorisation de déchets argileux: Comportement hygrothermique des matériaux élaborés, PhD thesis, INSA de Lyon, 1997, 116 pp.] confirms the relative reliability of this technique in estimating isothermal hydraulic diffusivity as a function of volumic water content.

Keywords: Clayey Aerated Concrete; Hydraulic profiles; Volumic water content; Capillary transport coefficient

1. Introduction

Moisture transport in porous media plays an important role in building environment. Many building materials are, in fact, porous, if water and its transport are not taken into account, considerable consequences in building materials may appear to be sizeable; this can affect the materials' durability, degradation and thermal performance. Rain or inundation penetration, water vapor condensation and drying shrinkage are some examples. The durability of building materials is very sensitive to humidity, and both high and low moisture content, and rapid changes may cause problems, damage the materials and diminish their performance. A better understanding of moisture transfer can therefore reduce or prevent damage in building materials. These phenomena are of interest to physicists and engineers working on heat and mass transfer [1,2], as well as on building materials [3–6].

The moisture transport coefficient D_θ (m^2 s^{-1}) represents a fundamental parameter in the moisture transfer equations; this coefficient is variable with respect to both temperature and moisture content. Its determination is essential to the simulation of moisture movements predicted by mathematical models. In general, the value of this coefficient can be determined once the moisture profiles obtained from either γ-ray attenuation or nuclear magnetic resonance (NMR) have been identified and through use of the Boltzmann transformation as a resolution method [7,8]. These techniques require an equipment that is not yet available in all laboratories.

In this paper, a gravimetric technique has been developed in order to determine moisture profiles and estimate the isothermal capillary transport coefficient of clayey concretes lightened by means of reaction with aluminum powder. This technique involves a very simple series of laboratory ex-

* Corresponding author. Tel.: +33-3-22-53-40-16; fax: +33-3-22-53-40-16.

E-mail address: michele.tkint@iut.u-picardie.fr (M. Quéneudec).

0008-8846/00/$ – see front matter
PII: S0008-8846(00)00379-3

periments, which merely require a laboratory scale, accurate to within 0.01 g, a watch and a drying oven. The experimental process is similar to that used in sorptivity measurements [4].

2. Theory of capillary water suction

The flow through a saturated homogeneous material under the action of a pressure gradient is described by the well-known Darcy law (Eq. (1)) as follows:

$$\vec{u} = -K_S \nabla P \quad (1)$$

where $\vec{u}$ is the vector flow velocity, K_S the conventional saturated permeability and P the potential pressure.

In the case of unsaturated flow, the flow is described by the extended Darcy equation [9]:

$$\vec{u} = -K(\theta)\nabla\psi \quad (2)$$

where ψ is the capillary potential and $K(\theta)$ is the unsaturated permeability.

The idea behind this extension stems both from the experience that in porous media, for example, the permeability is heavily dependent on the water content of the material and from the assumption that capillary transport can be described like a diffusion process.

Combining Eq. (2) with the continuity equation and then writing the resultant equation in terms of θ by using the substitution $D_\theta = K(d\psi/d\theta)$ for "hydraulic diffusivity", or more exactly, "capillary transport coefficient", the following is obtained:

$$\frac{\partial\theta}{\partial t} = \nabla(D_\theta \nabla\theta) \quad (3)$$

For a one-dimensional flow, Eq. (3) becomes:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left(D_\theta \frac{\partial\theta}{\partial x}\right) \quad (4)$$

where θ (m^3/m^3) is the moisture content, t (s) the time, x (m) the space coordinate and D_θ ($m^2\ s^{-1}$) the capillary transport coefficient for a volumic water content of θ.

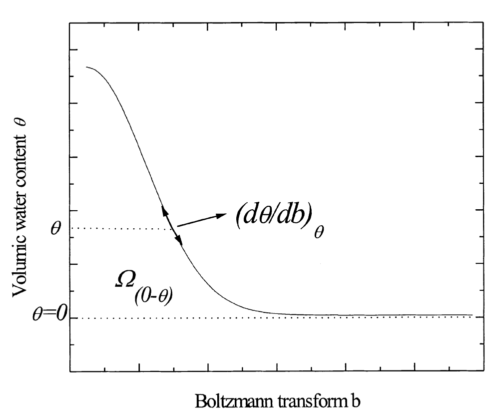

Fig. 1. Schematic curve of the evolution in volumic water content as a function of the Boltzmann transform.

Table 1
Characteristics of the various CAC mix designs included in this study

Sample type	Al/(Cl+C) (%)	Bulk density	Porosity	28-day Compressive strength σ_{28} (MPa)	Dry-thermal conductivity at 20°C ($Wm^{-1}K^{-1}$)
A	0.00	1.038	0.579	3.850	0.280
C	0.40	0.953	0.619	2.400	0.234
E	0.80	0.876	0.663	1.200	0.215
F	1.00	0.843	0.675	0.950	0.195

Al: aluminium; Cl: clay; C: cement.

Using the Boltzmann transform $b = x/\sqrt{t}$, Eq. (4) is reduced to an ordinary differential equation:

$$-\frac{b}{2}\left(\frac{d\theta}{db}\right) = \frac{d}{d\theta}\left(D_\theta \frac{d\theta}{db}\right) \quad (5)$$

and the capillary transport coefficient at a water content of θ is obtained by integrating Eq. (5), hence:

$$D_\theta = -\frac{1}{2}\frac{1}{\left(\frac{\partial\theta}{\partial b}\right)_\theta}\int_0^\theta b\,d\theta \quad (6)$$

Eq. (6) can be interpreted geometrically by the following formula:

$$D_\theta = -\frac{1}{2}\frac{1}{p_\theta}\Omega_{0-\theta} \quad (7)$$

where p_θ is the slope of the average curve $\theta(b)$ for a volumic water content of θ and $\Omega_{0-\theta}$ is the area delimited by the curve $\theta(b)$, the vertical axis and the horizontal line $\theta = 0$ and θ, as diagrammed in Fig. 1.

3. Materials and experimental technique

3.1. Materials

The clayey concrete described in this study is a new building material manufactured under normal conditions. It is composed of clay (kaolinite), extracted from quarry wastes and a CPA CEM 52.5 (EN 196-1) cement made with the following proportions: 75% clay and 25% cement, mixed using potable water whose percentage by dry weight (of the clay–cement mix) is 65%. In order for these concretes to yield improved thermal performance, they were lightened by reaction with an aluminum powder (gap-grading ≤ 100 μm and purity of 99%, supplied by the Prolabo Company) upon mixing. Many cells were created from the hydrogen gases released by the chemical reaction between the aluminum and the lime freed due to cement hydration during setting. Thus, this material has been called Clayey Aerated Concrete (CAC). Four mix designs for CAC were developed with the following percentages of

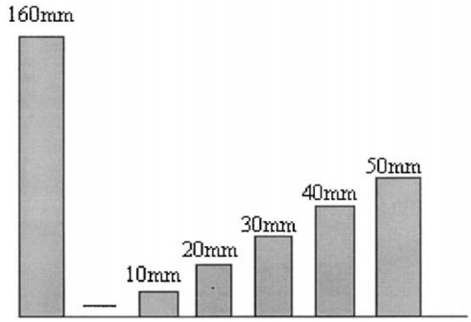

Fig. 2. Cutting of a 160-mm-long CAC specimen into several elements.

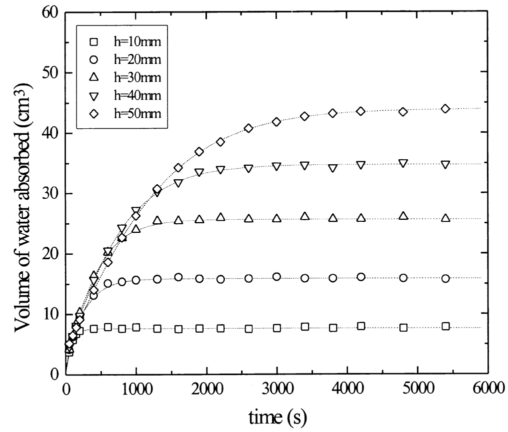

Fig. 4. Evolution in the volumic water content absorbed by various lengths of CAC type A as a function of time.

aluminum: 0%, 0.40%, 0.80% and 1%, with respect to the dry mass of the clay–cement mix. It is important to establish the characteristics of the mixing procedure because of the dominant influence they will exert on the density, distribution, shape and size of the cells created. In our experiment, clay and cement were mixed in a standard mixing machine (EN 196-1) at low speed for 2 min. Water was then gradually added and the mixing was continued at low speed for another 2 min, followed by a 2-min period at medium speed until a homogeneous mixture had been obtained. Then, aluminum powder was added to the mixture while maintaining the mixer at low speed for 1 min, followed by medium-speed mixing for another minute. Three specimens from each mix were cast into $40 \times 40 \times 160$ mm^3 moulds.

After removal from the moulds 48 h later, the samples were maintained in a humid room at 20°C and 90% RH for 28 days. They were then dried in a drying oven at 70°C until constant mass had been reached before beginning the experiments. Table 1 lists the characteristics of the various CAC mix designs used in this study.

3.2. Experimental technique

The principle of the technique employed is to determine the evolution in the volume of water absorbed by the material as a function of time for different heights of the test specimen. In the experiments, the height of the local volume (representative volume) considered in determining the evolution in water content was set equal to 10 mm. For this method, it has been assumed that the material is homogeneous and the front separating the dry and wet zones of the specimen is horizontal. The various stages of this method are the following.

(i) The first stage consists of cutting the 160-mm-high specimen into several elements with heights of 10, 20, 30, 40 and 50 mm, respectively, as shown in Fig. 2. These elements are then sealed laterally with a plastic film in order to eliminate water vaporization from the faces and to yield a one-dimensional water diffusion.

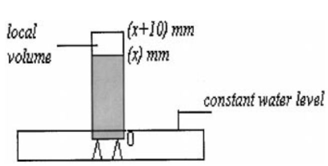

Fig. 3. Schematic diagram of capillary absorption.

(ii) The second stage consists of determining, for each of these elements, the evolution in the volume of water absorbed by capillarity as a function of the amount of time they are in contact with the water surface, as presented in Fig. 3. Weighing is carried out at the same time intervals for all elements until stabilization of the absorption process. It is assumed that a mass of l g of water corresponds to 1 cm^3 of volume.

(iii) In the third stage, the volumic water content profiles are determined relative to the local volume ($40 \times 40 \times 10$ mm^3) at various abscissas by applying the following formula:

$$\theta(x,t) = \frac{V_w(x+10,t) - V_w(x,t)}{V_{local}} \tag{8}$$

where $x = 10$, 20, 30 and 40 mm, $V_w(x,t)$ is the volume of water absorbed by the element of height $h = x$ (mm) at time t, and V_{local} is the local volume being studied.

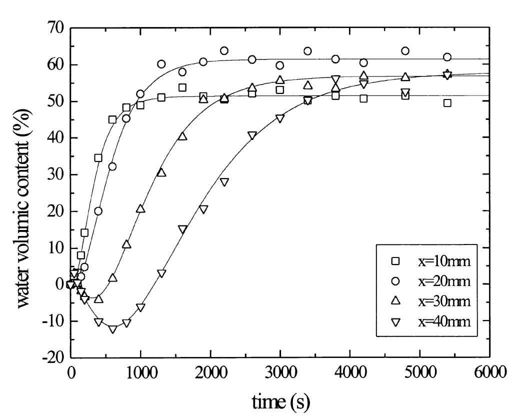

Fig. 5. Volumic water content of a local volume located at various levels as a function of time for CAC type A.

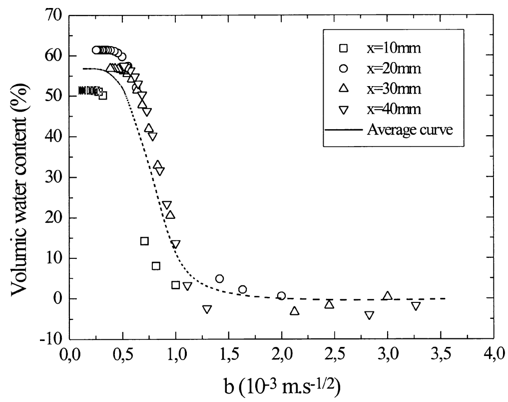

Fig. 6. Volumic water content of a local volume located at various levels as a function of the Boltzmann transform for CAC type A.

(iv) The hydraulic profiles established in stage (iii) are combined here into a single hydraulic profile using the Boltzmann transform, through deriving the correspondence between the volumic water content $\theta(x,t)$ and the volumic water content $\theta(b=x/\sqrt{t})$.

(v) Determination of the capillary transport coefficient.

In establishing the average hydraulic profile $\theta(b)$ from the results obtained in stage (iv), the capillary transport coefficient D_θ at a volumic water content θ can be determined by applying the formula given in Eq. (7).

3.3. Experimental results

The different stages of this technique are illustrated using the matrix (composition A) of CAC as an example. Fig. 4 presents the evolution in the volume of water absorbed by the various elements of CAC type A with respective lengths of 10, 20, 30, 40 and 50 mm as a function of time; the volume measurements used to derive this figure have been determined by weighing at equal time intervals. Fig. 5 displays the local evolution in volumic water content as a function of time at levels $x = 10$, 20, 30 and 40 mm, as calculated from the results presented in Fig. 4 and using the formula given in Eq. (8).

By applying the Boltzmann transform ($b = xt^{-1/2}$) to the results given in Fig. 5, the series of curves $\theta(x,t)$ can be combined into a single average curve $\theta(b)$ (see Fig. 6).

The average capillary transport coefficient D_θ of the studied material is then derived by applying the relation provided in Eq. (7) to the average curve $\theta(b)$ given in Fig. 6.

These same stages have also been applied to the other CAC compounds (C, E and F); the entire set of results of hydraulic diffusivity measurements as a function of volumic water content have been presented in Fig. 7.

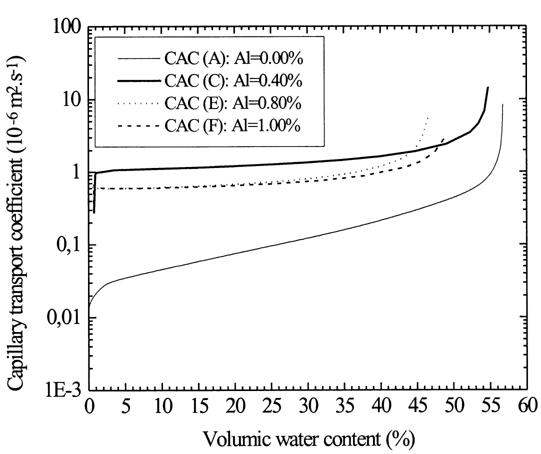

Fig. 7. Average capillary transport coefficient as a function of volumic water content for the studied CAC mix designs.

4. Discussion

In comparing the capillary transport coefficient curves of various CAC compound mix designs derived using this technique (see Fig. 7) to those given in the literature [10,11] obtained by γ-ray attenuation for the autoclaved aerated concrete (AAC) and the clayey wood concrete (CWC) matrix (see Fig. 8), a distinct similarity in the evolution of the D_θ curves can be noted. This finding confirms the

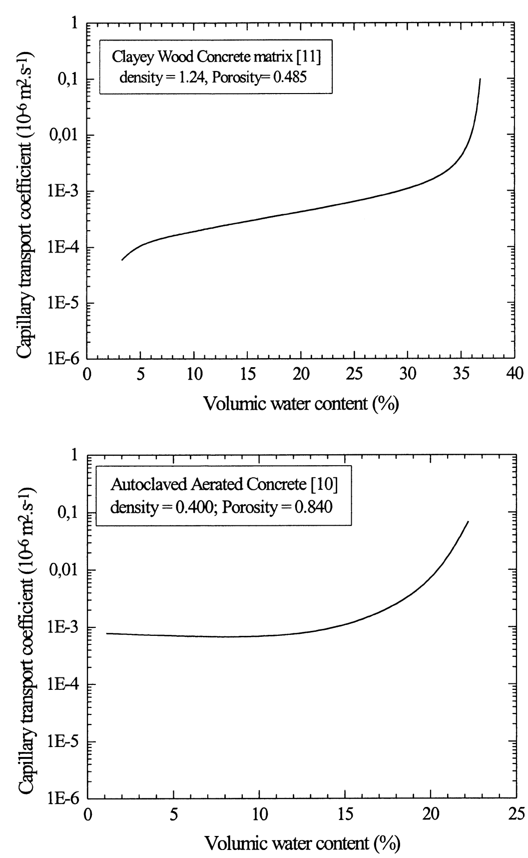

Fig. 8. Capillary transport coefficient as a function of the volumic water content of the CWC matrix [11] and of AAC [10], as obtained by the γ-ray attenuation technique.

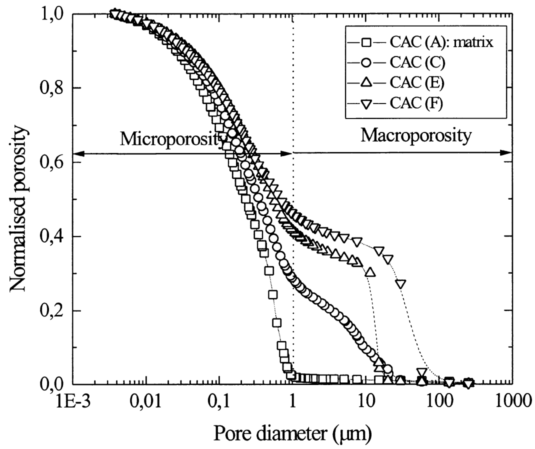

Fig. 9. Normalized porosity as a function of pore diameter for various CAC mix designs.

relative accuracy of the capillary transport coefficient evolution, as a function of volumic water content, estimated using this technique.

Fig. 7 shows that for lower water contents $\theta < 1\%$, the capillary transport coefficient D_θ increases more rapidly. According to the literature [12–14], this feature concerns the vapor phase transfer. Capillary transport coefficient increases even more rapidly as capillary absorption rises. Over the range of 2–50% of volumic water content, a mixed liquid–vapor diffusion appears. The transport coefficient during the liquid phase increases to the detriment of the transport coefficient during the vapor phase. Capillary transport coefficient increases almost linearly for all mix designs with a significant slope for the CAC (A) matrix. This is due to the presence of macropores resulting from the aluminum powder reaction in the C, E and F compounds; the macropores serve to create an increasingly tortuous path for liquid flow, in accordance with the proportion of aluminum. This tortuosity tends to dampen the diffusion phenomenon. Fig. 9 presents the cumulative normalized pore volume distribution as function of the pores diameter obtained by the mercury porosimetry technique. Two categories of pores can be distinguished: micropores ($D < 1$ μm) and macropores ($D \geq 1$ μm). It should be pointed out that the matrix is exclusively composed of micropores, while the other mix designs are composed of both micropores and macropores. In contrast, Fig. 7 reveals that capillary transport coefficient decreases as the macroporosity ratio increases, which is obvious from the higher level of tortuosity. When the volumic water content has reached the percentage of capillary saturation, around 45–55% for all mix designs, a rapid increase in capillary transport coefficient occurs, as shown in Fig. 7. This phenomenon is probably due to the decrease in water vapor pressure in the capillary pores until the capillary pressure equals the liquid water pressure, which favors the ease of liquid diffusion.

5. Conclusion

A technique based on gravimetric measurements for evaluating the capillary transport coefficient of a CAC at different porosities has been presented herein. This technique can be applied to other consolidated porous materials. The level of precision is much greater when the test material exhibits rapid capillary absorption (plaster, clay). Faster absorption reduces the errors committed whenever the duration required to obtain the straight line characterizing the stability absorption of the test specimen turns out to be high. The precision of this technique, with respect to the other automatic acquisition techniques, cannot be quantified however because of the lack of appropriate equipment. Yet, a comparison of the capillary transport coefficient as function of volumic water content, obtained using this technique with the evolution obtained using γ-ray attenuation for similar materials [10,11] has confirmed the relative reliability of this technique.

References

[1] J.B. Chaddock, B. Todorovic, Heat and mass transfer in building materials and structures, 21st Symp. of the Int. Center for Heat and Mass Transfer, in: J.B. Chadduk, B. Torodovic (Eds), Hemisphere, New York, 1990.

[2] B. Kari, B. Perrin, J.C. Foures, Mater Struct 25 (1992) 482.

[3] A. Hillerborg, Cem Concr Res 15 (1985) 809.

[4] H. Cristopher, K.T. Thomas, Build Env 21 (2) (1986) 113.

[5] W. Bu-Xuan, F. Zhao-Hong, Int J Heat Mass Transfer 31 (2) (1988) 251.

[6] F.H. Wittmann, H. Sadouki, F.H. Wittmann, Determination of hygral diffusion of AAC: A combined experimental and numerical method, in: Wittmann (Ed.), Advances in Autoclaved Aerated Concrete, Balkema, Rotterdam, 1992, pp. 113–118.

[7] P. Crausse, Etude fondamentale des transferts couplés de chaleur et d'humidité en milieux poreux non saturé, PhD thesis, INP de Toulouse, 1983, 209 pp.

[8] B. Perrin, Etude des transferts couplés de chaleur et de masse dans les matériaux poreux consolidés non saturés utilisés en Génie Civil, PhD thesis, Université Paul Sabatier, Toulouse, 1985, 267 pp.

[9] J. Kaufmann, Mag Concr Res 49 (180) (1997) 157.

[10] J.A. Da Cunha Neto Bellini, Transport d'humidité en matériau poreux en présence d'un gradient de température: Caractérisation expérimentale d'un béton cellulaire, PhD thesis, Université Joseph Fourier-Grenoble I, 1992, 69 pp.

[11] A. Bouguerra, Contribution à l'étude d'un procédé de valorisation de déchets argileux: Comportement hygrothermique des matériaux élaborés, PhD thesis, INSA de Lyon, 1997, 116 pp.

[12] D.A. De Vries, Trans Am Geophys Union 39 (5) (1958) 909.

[13] J.F. Daian, Processus de condensation et de transfert d'eau dans un matériau méso et macroporeux: Etude expérimentale du mortier de ciment, PhD thesis, Université Scientifique, Technologique et Médical de Grenoble, 1986, 319 pp.

[14] L. Pel, Moisture transport in porous building materials, PhD thesis, Eindhoven University of Technology, Netherlands, 1995, 127 pp.