Cement and Concrete Research 108 (2018) 167–171

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

Short communication

Transient moisture profiles in cover-zone concrete during water absorption

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ARTICLE INFO

Keywords:
Concrete
Water-absorption
Monitoring
Conductivity
Moisture profiles
Boltzmann transform

ABSTRACT

A number of sophisticated techniques, such as NMR imaging and γ-ray attenuation, have now been used to study moisture transport in porous construction materials. This paper presents initial developments in the application of discretized, electrical conductivity measurements as a relatively simple technique to monitor water movement within cover-zone concrete. Using a 3-phase model and the Archie relationship for porous rock formations, conductivity measurements are used to evaluate moisture-content profiles during water ingress and, through the use of Boltzmann's transformation, it is shown that these profiles *collapse* onto a *master-curve*. Having obtained the master-curve during absorption, the capillary transport coefficient (D_θ) can then be obtained; however, the current work focuses on presenting the methodology as an alternative testing technique.

1. Introduction

The penetration of water into porous construction materials, as well deleterious ions dissolved in it (e.g. chlorides, sulphates), is of considerable importance as virtually all deterioration processes are as a direct result of water ingress. It is thus highly desirable to be able to predict, for a given set of conditions (e.g. environmental exposure, concrete mix), the depth and rate of water penetration and solute concentration profile as they develop over time as this, ultimately, allows estimation of the rate of degradation of the structure and residual service life.

The capillary transport (or moisture diffusion) coefficient (D_θ) is a fundamental moisture transfer parameter and its determination is essential in the simulation of moisture movement. D_θ can be evaluated from the transient moisture profiles obtained during water absorption. Monitoring the time-variant water-content profiles has been undertaken on a range of porous materials such as fired-clay brick, limestone, plaster, cement pastes, mortars and concretes using nuclear magnetic resonance (NMR) imaging [see,for example,1–7], other techniques include γ-ray attenuation [8], X-ray radiography [9,10] and neutron radiography and tomography [11]. When investigating cementitious materials using NMR, complications can occur if the binder contains paramagnetic oxides (e.g. Fe, Mn) hence much work tends to be undertaken using white cement. A more simple gravimetric technique, using a standard water-absorption test, has also been developed to obtain moisture profiles in a clayey aerated concrete [12]; however, this method involves cutting specimens so is destructive in nature.

In this paper we present initial studies on the application of discretized, in-situ, electrical conductivity measurements within the surface region of concrete samples to evaluate the transient moisture profiles during water absorption.

2. Background theory and current developments

The flow of water into a porous surface – concrete in this instance – with a uniform initial water-content is described by Fick's 2nd Law for 1-D, non-linear diffusion,

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial x}\left(D_\Theta \frac{\partial \Theta}{\partial x}\right) \tag{1}$$

where, in this instance, Θ is the reduced or normalised water content, D_Θ is the capillary transport coefficient (diffusivity), t is time and *x* is the spatial distance from the inflow surface where water is applied. The normalised water-content, Θ_t, at time, t, is further defined as,

$$\Theta_t = \left(\frac{\theta_t - \theta_i}{\theta_s - \theta_i}\right) \tag{2}$$

where θ_i is the initial water-content of the material, θ_s is the saturated water-content and θ_t is the water-content at time, t, after the start of absorption. The water-content is expressed on a volumetric basis. Eq. (1) can be transformed into an ordinary differential equation by introducing the Boltzmann transformation $\lambda = x t^{-1/2}$ with the boundary conditions $\lambda = \infty$ ($\Theta = 0$ at time, $t = 0$)), and $\lambda = 0$ ($\Theta = 1$ as $t \to \infty$)). Hence, during water absorption, all moisture profiles are related by a similar $t^{1/2}$ scaling and by plotting the transient moisture profiles, Θ(x, t), against λ produces a master profile which is time invariant. Having

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https://doi.org/10.1016/j.cemconres.2018.04.001
Received 15 December 2017; Received in revised form 3 April 2018; Accepted 3 April 2018

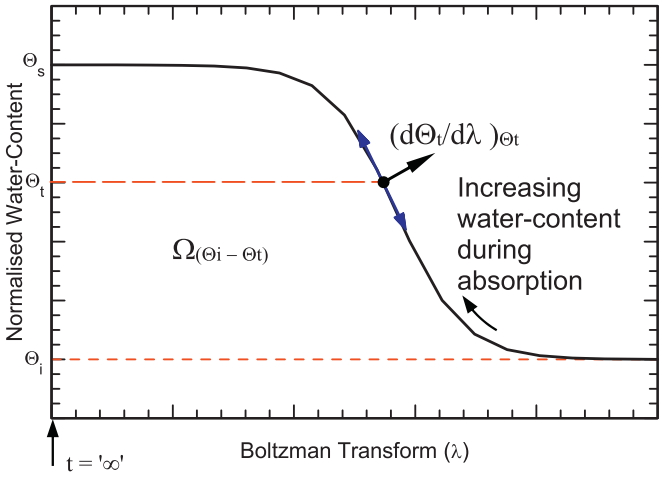

Fig. 1. Schematic diagram showing the normalised water-content as a function of the Boltzmann transform.

obtained the master curve from the experimental data, the capillary transport coefficient, D_Θ, can then be calculated from a derivative and an area of the Boltzmann's curve as follows,

$$D_\Theta = -\frac{1}{2}\frac{1}{\left(\frac{d\Theta}{d\lambda}\right)_{\Theta_t}}\int_{\Theta_i}^{\Theta_t}\lambda d\Theta \quad = -\frac{1}{2}\frac{1}{S_{\Theta_t}}\Omega_{(\Theta_i-\Theta_t)} \tag{3}$$

which is shown schematically on Fig. 1 where $\Omega_{(\Theta i-\Theta t)}$ is the area bounded by the curve $\Theta(\lambda)$ between Θ_i and Θ_t and $S_{\Theta t}$ is the slope of the $\Theta(\lambda)$ curve at a normalised water-content of Θ_t.

In the current study, we have replaced the volumetric water content in Eq. (2) by the electrical conductivity of the concrete obtained from in-situ measurements. With reference to Fig. 2, unsaturated concrete has been simplified as a three phase system comprising solids (aggregate, unhydrated binder and products of hydration), capillary pore-water and air-filled capillary pores. The porosity of the concrete is denoted, ϕ, and the degree of capillary pore saturation is S_r. If the solids (and air) can be assumed to be non-conductive, then the conductivity of the concrete will be directly related to the volume fraction of pore-water and its conductivity, denoted σ_p. If a unit cube of material (unit length into the plane of the page) is placed between a pair of electrodes, the conductivity of the concrete, σ_c, will be,

$$\sigma_c = \frac{L}{R_p A} \tag{4}$$

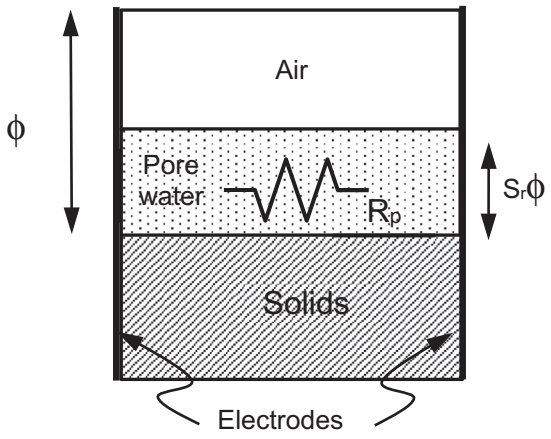

Fig. 2. Concrete considered as a simplified three-phase system comprising air, pore-fluid and solids. In this figure, S_r is the degree of pore saturation and ϕ is the total porosity.

where, for a prismatic sample, L is the distance between the electrodes (=1.0), A is the cross-sectional area of the electrodes (=1.0 × 1.0) and R_p is the resistance of the pore-fluid. The resistance, R_p, of the pore fluid is also given by,

$$R_p = \frac{L}{\sigma_p A'} \tag{5}$$

where L = 1.0 as above, and A′ is the cross-sectional area available for conduction through the pore-fluid. From Fig. 1, A′ = $S_r\phi$ × 1.0 as unit cube is assumed, hence, as a first approximation, the conductivity of the concrete could be written as,

$$\sigma_c = \sigma_p S_r \phi \tag{6}$$

$S_r\phi$ is the volumetric water-content, θ, defined above; however, this assumes a *straight-tube* capillary model and does not take account of the tortuosity, connectedness and constricted nature of the capillary pore network. Adapting Archie's law [13] which was developed for porous rock formations, the cross-sectional area available for conduction will be reduced from $S_r\phi$ to $(S_r\phi)^m$ where the exponent *m* is in the range 1.5–3.0 for rocks. With regards to cementitious materials, values of *m* in the range ~3.0–5.0 have been reported [14,15], hence,

$$S_r\phi = \theta \approx \left(\frac{\sigma_c}{\sigma_p}\right)^{\frac{1}{m}} \tag{7}$$

If it is tacitly assumed that the pore-water conductivity remains constant, then Eq. (2) can be written in terms of conductivity,

$$\Theta(t) \approx \left(\frac{\left(\frac{\sigma_{c,t}}{\sigma_{c,i}}\right)^{1/m} - 1}{\left(\frac{\sigma_{c,s}}{\sigma_{c,i}}\right)^{1/m} - 1}\right) \tag{8}$$

where $\sigma_{c,i}$ is the conductivity of the concrete prior to the start of the absorption test, $\sigma_{c,s}$ is the conductivity of the saturated concrete and $\sigma_{c,t}$ is the conductivity of the concrete at time, t, after the start of the absorption test. A value of m = 4.0 [15] has been adopted in the current work.

3. Experimental programme

In order to monitor both the temporal and spatial changes of moisture movement in concrete a test-cell was designed such that electrical measurements (resistance in this instance) could be made at discrete depths from the exposed surface of the concrete samples.

3.1. Materials

In the work presented, the binders comprised ordinary Portland cement clinker, CEM I 52.5 N to EN197–1 [16] and CEM I cement blended with a low-lime fly-ash to EN450–1 [17]. The concrete mixes used in the current study are presented in Table 1, together with their respective 28-day (f_{28}) and 180-day (f_{180}) compressive strengths after continuous submerged curing at 21°C ± 1°C. A crushed rock (granite) coarse aggregate and matching crushed rock fines were used throughout (100% passing the 5 mm sieve, 8% passing the 150 µm sieve). The aggregate was conditioned to a saturated surface dry state. The aggregate content was adjusted to ensure that the mass of binder

Table 1
Summary of concrete mixes (w/b = water-binder ratio).

Mix Designation	w/b	CEM I kg/m³	FA kg/m³	20 mm kg/m³	10 mm kg/m³	Fine (< 5 mm) kg/m³	f_{28} MPa	f_{180} MPa
PC	0.60	290	–	687	458	765	43.4	54.7
FA	0.60	188	102	674	450	748	25.6	40.8