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Experimental validation of a framework for hygro-mechanical simulation of self-induced stresses in concrete

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ABSTRACT

An accurate simulation of the internal stresses that develop in concrete structures in service demands the explicit consideration of the internal heat and moisture movements that induce strains, which in turn have the potential to cause relevant internal stresses. Following a previous exploratory work from the authors, in which a thermo-hygro-mechanical simulation framework had been proposed, the present paper focuses on the validation of the proposed methodology through an experimental program targeted to assist prediction of the evolution of bulk drying shrinkage (and the corresponding internal stresses) in three specimens of different sizes. This paper presents the entire experimental program, which involved extensive concrete characterization using three distinct sizes of specimens, namely: moisture diffusion with internal humidity sensors, compressive strength, E-modulus, creep and shrinkage on three distinct specimen sizes. The program also included characterization of cement paste shrinkage, which was accomplished employing a newly proposed methodology based on the use of very thin specimens monitored with a handheld microscope. Finally, the obtained experimental data was used for partial validation of predictive capacities of the above mentioned simulation framework, mostly in regard to the prediction of bulk shrinkage. It is noted that the validation does not focus on thermal modelling, since this is a matter that has been addressed by the authors in previous works.

1. Introduction

The service life of reinforced concrete (RC) structures is strongly affected by cracking, not only with regards to aesthetics, but mainly due to the durability hazard that cracking represents. Cracking of concrete is known to have reduced the lifespan of many structures by decades, and also has imposed costly repairs and increased maintenance paces [1]. Even though prediction/control of cracking due to applied loads is relatively well mastered both in the scientific and practising communities [2–5], concrete cracking due to imposed deformations such as drying shrinkage has not yet been studied thoroughly, particularly in the case of simultaneous occurrence together with applied loads. It is therefore frequent to find inadequate service life behaviour in regard to cracking in several RC structures, particularly those that have geometrical/support conditions that promote restraint to free deformations [6]. In view of this problem, several research works have been carried out in order to enhance understanding of concrete cracking due to self-imposed deformations through experimental approaches [7–13], or even through processes of multi-physical simulations of the relevant phenomena that drive shrinkage, particularly the moisture distribution within concrete [14–16]. In spite of the considerable quantity of efforts concerning multi-physical approaches to monitoring, analysis and simulation of self-induced stresses in concrete structures, very few integrative approaches were found to focus on the entire problem as a whole, including a combination of both numerical prediction and experimental characterization/validation [17,18]. Most existing works focused on drying stresses, are either fundamentally based on experiments [19,20], or are solely focused on application of numerical simulation approaches using third party results [15,21]. It is however worth highlighting two contributions that have made integrative efforts by combining measurement, analysis, and modelling of strain

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variation of drying specimens: the works of Grasley et al. [17] and Kim et al. [18]. Even though such works provided insights into the non-uniform development of stresses within drying specimens, they still leave issues unresolved, particularly in regard to the validation and study of more than a single size of specimen.

This paper intends to fill the above identified research gap by expanding a previous research focused on the proposal of a thermo-hygro-mechanical framework [14], supporting it with material characterization and validation through comparison of numerical predictions with experimentally observed behaviour. The entire study is focused on the experimental characterization of moisture fields in concrete prisms, together with the observation of their bulk shrinkage, with a special focus on observing the effect of specimen size. No specific emphasis is given to the characterization of thermal properties, or the validation of thermal simulations, as the expected temperature variations are very low, and this concern has been extensively addressed by the authors in previous publications that used the same basic framework [9,22]. A strong emphasis is given to the establishment of a valid experimental technique that allows relating the reduction of internal humidity of concrete to its natural tendency to shrink. This newly proposed technique is based on tests with cement pastes, where shrinkage strains are calculated from optical measurements assisted by a microscope, and are thereafter up scaled to concrete level via a homogenization model.

Finally, the entire set of experimental data is used to provide a validation of the above-mentioned thermo-hygro-mechanical framework to make good predictions of bulk shrinkage of the concrete specimens (which were measured experimentally), when fed with adequate parameters that are robustly supported by the overall experimental program. However, it is to be noted, that the parameters for simulation of moisture fields were attained through back-analysis of the measured data, following a procedure consistent with [23].

As far as the organization of this paper is concerned, Section 2 deals with the general description of the modelling framework that was utilized. The experimental program that was carried out is described in detail in Section 3, comprising experiments on both concrete and cement paste specimens. Section 4 deals with the numerical simulation of the thermo-hygro-mechanical behaviour of the tested concrete prisms, highlighting the internal stresses that were developed, and the validation of the predictive capacities by comparing calculated shrinkage with the measured results. Section 5 wraps up the paper with prominent conclusions and possibilities for future development of research work.

2. Modelling framework for thermo-hygro-mechanical simulation

The thermo-hygro-mechanical modelling framework adopted in this research is the one proposed by the authors and described in detail in Refs. [14,24]. Nonetheless, the general highlights of the model, namely the governing equations, are provided in this section. The overall modelling strategy consists of a staggered analysis in which the thermal, relative humidity (H) and mechanical fields are computed sequentially, with information being transmitted among them. Full coupling among models (thermo-hygro-mechanical) might be considered necessary in cases where there is: (i) a very early exposure of concrete to drying, which hinders heat generating chemical reactions at their initial stages; (ii) an extensive cracking in concrete that may change thermal transmission and moisture diffusion properties; and (iii) an elevated cement content that might lead to intense self-desiccation in concrete, hindering the proper progress of hydration. These situations do not apply to the scope of this validation, which was centred in relatively low cement content (low self-desiccation) and exposure to drying at the age of 28 days sans expected macro-cracking. Due to these reasons, the thermal, hygral and mechanical models were not fully coupled and calculations were performed sequentially.

2.1. Thermal model

The thermal energy balance equation that includes the release of cement hydration heat is given by:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{Q}=\rho c\dot{T} \tag{1}$$

where $\dot{Q}$ is the heat generation rate, k is the thermal conductivity of concrete ($\mathrm{Wm^{-1}K^{-1}}$), T is the temperature (K), $\dot{T}$ is the temperature rate, c is the specific heat of the material ($\mathrm{Jkg^{-1}K^{-1}}$), ρ is the specific mass ($\mathrm{kgm^{-3}}$) and x, y and z are the spatial coordinates (m).

The heat generation rate $\dot{Q}$ is expressed through an Arrhenius-type function based on the degree of heat development, α_T (normalized degree of hydration established as a function of total heat generation that the hydration reaction can actually generate), as [25]:

$$\dot{Q}=f(\alpha_T)A_T e^{\frac{-E_a}{RT}} \tag{2}$$

where $f(\alpha_T)$ is the normalized heat generation function, A_T is a rate constant, R is the ideal gas constant (8.314 $\mathrm{Jmol^{-1}K^{-1}}$) and E_a is the apparent activation energy ($\mathrm{Jmol^{-1}}$). Boundary conditions that express direct contact with the surrounding environment are expressed with a Neumann-type formulation that includes a lumped convection/radiation coefficient h_{cr}:

$$q_h=h_{cr}(T-T_{env}) \tag{3}$$

where q_h is the heat flux due to convection and longwave radiation (per unit area), and T_{env} is the temperature in the environment. In the presence of thin elements that cover the surface of concrete (e.g. formwork), the value of h_{cr} can be adjusted to include the effect of such elements through an electrical analogy detailed in Refs. [24,26].

2.2. Humidity field model

The driving potential selected for simulating the moisture field is the average pore humidity, according to the reasons forwarded in Ref. [14]. The governing equation has strong affinities with the proposal for moisture diffusion of MC2010 [3]:

$$\frac{\partial H}{\partial t}=\left(\frac{dW}{dH}\right)^{-1} div(D_H\, grad(H))+\frac{\partial H_s}{\partial t} \tag{4}$$

where H is the relative humidity in the pores, t is the time (s), $\left(\frac{dW}{dH}\right)$ is the moisture capacity, D_H is the diffusivity and $\frac{\partial H_s}{\partial t}$ represents the changes in H due to internal water consumption in the chemical hydration reactions. If it is considered that the influence of self-desiccation in the pore humidity is negligible and that moisture capacity of cementitious materials at usual environmental relative humidity (H>50%) is fairly constant [27], it is possible to simplify Eq. (4) by neglecting the term $\frac{\partial H_s}{\partial t}$ and by lumping the moisture capacity, $\left(\frac{dW}{dH}\right)$, and the diffusivity D_H into a single coefficient, D_{H^*}:

$$\frac{\partial H}{\partial t}=div(D_{H^*} grad(H)) \tag{5}$$

The diffusion parameter D_{H^*} is modelled according to the