



Identification of early-age concrete temperatures and strains: Monitoring and numerical simulation

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ABSTRACT

Concrete at early-ages experiences thermal deformations due to the heat generation caused by the cement hydration reactions. These deformations may lead to cracking of concrete, for which the use of numerical models in order to foresee and prevent this problem is of crucial importance. However, these numerical models must be appropriately validated by monitoring the young concrete behaviour. The conducted research regards an experimental work carried out with two main goals: (i) to evaluate the performance of different kinds of strain gages, in order to determine the more adequate ones for monitoring concrete deformations during early-ages after casting; (ii) to interpret the experimental measurements of temperatures and strains in concrete, by using a numerical model. Two different vibrating wire strain gages were used to measure early-age deformations in a concrete prism tested in the laboratory: one with a metallic housing and the other with a plastic one. The instant of solidarization of the sensors to concrete and the temperature sensitivity of their signals during the pre-solidarization period are key points as far as measurement of concrete early-age strains is concerned, which were examined for the present work. A thermo-mechanical numerical model was used to simulate the early-age concrete behaviour of the specimen. After a brief description of the model background, a comparison of the numerical predictions with the experimental results is made.

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1. Introduction

Early-age concrete behaviour is a problem of great concern nowadays, closely related to the increasing use of high performance concrete, where cracking may arise not only due to autogenous shrinkage, but also in result of deformations caused by the heat generated during the cement hydration reactions. Therefore, it is important to have numerical tools for predicting temperatures and stresses in early-age concrete, in order to foresee – and if possible to avoid – premature cracking of thermal origin. The thermo-mechanical methodology used in this paper is based on the Finite Element Method (FEM), and it accomplishes a thermal analysis, followed by a mechanical one. The thermal analysis assimilates the heat of the cement hydration as an internal heat source, and it accounts for the energetic flows by convection and radiation between concrete and the environment. As far as the mechanical analysis is concerned, the evolution of concrete mechanical properties, as well as the influence of creep, are considered.

In this regard, it is essential to develop suitable monitoring practices for evaluating temperatures and strains in early-age concrete, so as to validate the numerical models. As during early-ages concrete has evolving mechanical properties, there are difficulties

related to measurement of strains, while concrete stiffness and temperature vary significantly and are largely amplified as compared to the final hardened stage. Doubts about the adequacy of using strain sensors developed for hardened concrete in early-age measurements still persist, based on two main concerns: the instant of solidarization of the sensor to concrete is difficult to determine, and the temperature sensitivity of the strain sensor when embedded into a material ranging from a liquid to a solid state can only be roughly estimated. Solidarization of the strain sensors to concrete is a fundamental dilemma within the early-age monitoring context, depending mostly on the ratio of stiffnesses between the concrete and the sensor. Solidarization is here defined to occur when the strain gage is capable of reproducing variations in concrete deformations, which is only foreseeable when concrete stiffness is sufficiently high to ensure the sensor to be perfectly attached.

Electrical strain gages with ceramic insulation have wide spread usage among large-scale applications on civil engineering, due to their economy and sturdiness. Nevertheless, for early-age strain measurements these resistive electrical sensors revealed some problems [1]. One of the main reasons for this inadequacy is that these sensors are made from a material with the same thermal dilation coefficient of hardened concrete, in order to perform an “auto compensation” of concrete thermal deformation. Another problem with these sensors, and based on the authors’ experience,

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is that the existence of electrical apparatus in the sensors vicinity may cause current peaks that interfere with the signals, being this an important problem when monitoring campaigns are to be performed on real site constructions.

On the other hand, vibrating wire strain gages embedded in hardened concrete require temperature compensation procedures that strictly depend on the thermal dilation coefficient of the wire placed internally, which is constant and known.

Few references were found on the theme of concrete strain monitoring at early-ages. Even so, some practical applications concerning in-field early measurements are reported in the literature. An overview of field measurement techniques and data analyses on early-age concrete structures is acutely discussed by Cusson [2]. Concerning field applications, Anson and Rowlinson [3] reported the use of vibrating wire strain gages in early-age strain measurements in concrete tank walls, which were successful only when the internal temperature stabilized. Another application reported by Heimdal et al. [4] regards a concrete box culvert in Norway, instrumented with embedded vibrating wire strain sensors and electrical strain gages, where reliable results were obtained after the age of 15 h. Morabito [5] reports an early-age concrete monitoring application on a dam sluice gate, in which embedded vibrating wire strain gages and electrical strain gages welded to the reinforcement were used, revealing that along the heating and cooling periods of cement hydration measurements from both types of sensors were quite dissimilar, although following similar tendencies from then on. Temperature measurements during the concrete curing of the viaduct deck of the Öresund Link are reported in Cervera et al. [6], where cracking risk scenarios are analyzed with a thermo-mechanical model. Also, Azenha and Faria [7] reported a case study of a reinforced concrete foundation of a wind tower, where temperatures and stresses due to cement hydration were evaluated. As far as laboratory experimental work is concerned, O'Moore et al. [8] have used vibrating wire strain gages with a plastic housing on early-age monitoring of industrial pavements, reporting that incoherent measurements of strains were obtained at the very early-ages.

More recently, optical fibre technology is reported to be a good solution in early-age concrete temperature and strain measurements, because of its high precision and resolution, insensitivity to electromagnetic fields and mechanical robustness [9–12]. In terms of in-field applications, this technology was used by Glisic and Inaudi [13] for monitoring temperatures and deformations in early-age concrete cast above a hardened element, and in composite steel-concrete structures during cement hydration [14].

All the above cited works report difficulties in identifying concrete strains during the heating phase of cement hydration, approximately around the first 12–15 h after casting. When the cooling phase commences, the output signals from different strain gage sensors start to have consistent and similar evolutions.

Based on the experience of the authors of this paper, the major difficulty on early-age concrete monitoring relates also to measurement of strains [1,15]. Inadequacy of most of the standard strain gages for this early stage of concrete, where high variations of temperature and stiffness are present, adding up to problems of characterizing the developing material, are the main causes of the unsuccessful strain monitoring during the cement hydration of concrete. The key issues that persist are: (i) the instant of solidarization of the sensor to concrete and (ii) the thermal sensitivity of the strain gage before and after the solidarization.

In this paper a laboratory campaign was performed on a concrete prism, and had the following two goals:

- To evaluate the performance of different types of strain gages. One of the kinds of sensors selected for this research was the vibrating wire strain gage with a metallic casing,

because of its robustness for *in situ* applications (where mechanical injuries due to concrete vibrators are frequent). In order to identify the instant of solidarization to concrete of this metallic housed strain gage, a vibrating wire strain gage with a plastic (and thus less stiff) casing was also used.

- To use a thermo-mechanical numerical model as a tool for better interpreting the experimental results, taking advantage of the temperatures and strains measured at various points of the concrete prism during the cement hydration stage.

In this experimental work, detailed in Section 2, concrete deformations refer to 'total strains', that is, the sum of the 'mechanical' and 'thermal' components.

An additional important outcome of this study is to support the determination of stresses in early-age concrete, in order to compare the maximum principal tensile stresses with the evolving tensile strengths, and finally to predict the cracking risk in concrete. This is accomplished by using a thermo-mechanical model, briefly outlined in Section 3, and applied to the above-referenced concrete prism in Section 4.

2. Experimental campaign on a prismatic concrete specimen

2.1. Geometry, materials and monitoring

An experimental monitoring campaign for measuring early-age temperatures and strains on a concrete prism was carried out, fulfilling the following requisites: (i) the prism should have geometry allowing for an easy and accurate numerical discretization, with dimensions compatible with the laboratory work, and (ii) at the same time it should engender a heat generation potential high enough to cause significant temperature and strain gradients. The geometry of the concrete prism, whose dimensions are $0.60 \times 0.30 \times 0.60 \text{ m}^3$, is presented in Fig. 1. Lateral faces and base of the element were insulated with 6 cm thick polystyrene plates and 2.1 cm thick plywood formworks. The mix composition of the concrete was as follows: 1134 kg m^{-3} of calcareous gravel, 263 kg m^{-3} of recycled concrete sand, 264 kg m^{-3} of natural sand, 400 kg m^{-3} of cement type I 42.5R and 200 kg m^{-3} of water. Concrete casting and the experimental procedures took place inside a climatic chamber with a constant temperature $T = 20^\circ\text{C}$ and relative humidity $RH = 50\%$; data acquisition started at the end of the casting operations.

Regarding the experimental monitoring measurements, different types of sensors were placed at symmetrical positions in relation to plane *B-B'* of Fig. 1, where identical temperatures and strains are to be expected, in order to compare their measurements, performances and aptitudes. Concerning the temperature sensors, two types were adopted: the thermocouple type K (TC), very easy to use and economical, but with a low precision of $\pm 2.2^\circ\text{C}$, and resistive temperature sensors (PT100), housed with a material with high thermal conductivity (copper), with a high precision of $\pm 0.1^\circ\text{C}$. As far as the strain sensors are concerned, two types of vibrating wire strain gages with rather dissimilar casings were used: one with a metallic and stiffer housing (VWM) and the other with a plastic and less stiff casing (VWP). Vibrating wire strain gages have internal resistive temperature sensors, so they are able to monitor strains and temperatures at the same time and location. All these strain gages were embedded into concrete.

Sensor locations are schematically represented in Fig. 1. Temperature sensors were placed in the lateral faces and base of the concrete prism, as well as between polystyrene layers, in order to validate the thermal boundary conditions of the numerical model; in the concrete element itself 16 TC and 2 PT100 were placed at

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