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Early-age behaviour of the concrete surrounding a turbine spiral case: Monitoring and thermo-mechanical modelling

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ABSTRACT

Within massive structures hydration reactions of the cement present in the mixture promote an internal heat release. Due to the low thermal conductivity of concrete, the dissipation rate of this thermal energy is lower than the rate of production of hydration heat, so considerable temperature gradients occur. Therefore, thermal stresses arise as a consequence of differential thermal expansions or contractions. These self-induced stresses may be even higher in the scenario of additional external restraints (such as support conditions). If not adequately controlled, the self-induced tensile stresses may induce cracking of concrete at early ages. This paper describes the in-depth analysis of the concrete surrounding the spiral case of a hydroelectric turbine constructed in Brazil, with a comprehensive approach that includes: laboratory characterization of the concrete properties, numerical analyses to predict the temperature and stress fields, and the corresponding in-field monitoring. The consistency obtained between numerical results and *in situ* observations is discussed in detail. The thermally induced cracking risk is also evaluated.

1. Introduction

The exothermic chemical reactions that occur in concrete due to cement hydration at early ages foment high temperature gradients between the core regions and the surfaces of the structural elements. Due to the induced differential concrete strains on the core and surface regions, as well as to external restraints, these temperature gradients may lead to tensile stresses that reach the tensile strength of the young concrete, and thereby cause thermal cracking which jeopardizes concrete durability, has detrimental effects on aesthetics, and may even limit the intended service-life performance (e.g. leakage in a reservoir). These effects are prominent in massive concrete structures, such as bridge footings, nuclear containments and dams. Evaluation of the thermo-mechanical behaviour of massive concrete during construction is a relevant challenge that structural engineers may be faced with, as demonstrated by the several attempts dealing with this issue published in recent years [1–8].

In hydroelectric power plants the powerhouse substructure supports the turbines and generators, as well as the superstructure. The substructure contains the water passages, includes rooms and galleries needed for mechanical and electrical equipment, and provides the mass needed for stability (see Fig. 1a) [9]. Normally, in the vicinity of the steel spiral cases, it is necessary to guarantee recesses in the substructure for accommodation of the spirals, and to devise the construction phasing of the power plant in such a way that concreting operations can continue without interruption during installation of the spiral components [9]. Therefore, the overall concrete placement is made in two stages: first, all the elements that do not contain turbine parts are cast, and afterwards the concrete surrounding the steel spiral is placed. Generally, the substructure concrete is placed in lifts 1.5 m thick or less, in order to minimize thermal cracking; on the other hand, massive concrete placements are necessary where concrete needs to be watertight, such as in spiral cases [9]. The significant volumes of concrete involved in the second phase necessarily lead to large amount of heat release due to the exothermic nature of cement hydration reactions. Temperature gradients between the core and the surface regions of the hardening concrete are thus expected. In addition, the hardened concrete of the first stage restrains the deformation of the hardening concrete of the second stage.

Numerical predictions of the temperature and stress fields in the concrete surrounding spiral cases were published by few

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authors in recent years [10–13], but so far comparisons of numerical predictions against monitored results are still lacking. Moreover, an accompanying extensive characterization of the concrete properties by laboratory tests, such as thermal diffusivity, rate of cement hydration, elastic E-modulus growth, tensile strength, basic creep and autogenous deformation, has not yet been presented in this context. The present paper aims to provide further information about the thermo-mechanical performance of this type of massive structures, based on the real study case of the Batalha Hydroelectric Power Plant (Batalha HPP), built in the San Marcos River (Brazil), in which the concrete around the spiral case was monitored during the construction phase. To this end, the following research methodology was applied: (i) characterization of concrete properties via laboratory testing, (ii) *in situ* monitoring of concrete temperatures and strains, (iii) thermo-mechanical modelling of the concrete that encases the steel spiral and evaluation of the concrete cracking risk. The concrete spiral case under investigation is made up of lightly reinforced concrete (massive concrete), with dimensions of 13.90 m × 14.15 m × 5.83 m (see Fig. 1b). The steel spiral case was embedded in concrete under pressurized conditions, i.e., the spiral was filled with water and pressurized to the test pressure, before the pouring of concrete. The thermo-mechanical modelling described in this paper consists on the initial computation of the thermal field, and subsequent evaluation of the corresponding strain field. The thermal problem was reproduced using a transient model, which allows determining concrete temperatures taking into account the internal heat generated by cement hydration reactions, the thermal conductivity and specific heat of concrete, the heat losses towards the surrounding environment, and the influence of the temperature of the water encased inside the spiral.

The time-dependent mechanical behaviour of concrete is described by the theory of linear viscoelasticity for aging materials. The mechanical problem encompasses the evolution of concrete mechanical properties, as well as the influence of thermal and autogenous deformations and basic creep. This thermo-mechanical methodology, based on the Finite Element Method (FEM), is similar to the ones reported in [14–16]. Special attention is paid to the material properties and modelling assumptions, which are validated by comparing the predicted temperatures and strains with the monitored results. Finally, evolutions of the concrete stresses and corresponding cracking risks are analysed in detail.

2. Thermal–mechanical modelling

2.1. Thermal problem

The evolution of temperatures is calculated from the heat balance equation [17]

$$k\nabla \cdot (\nabla T) + \dot{Q} = \rho c \dot{T} \tag{1}$$

where k is the thermal conductivity, T is the temperature, $\dot{Q}$ is the rate of internal heat generated by cement hydration and ρc is the volumetric specific heat. At a macro-scale, that is, at the engineering level at which large real concrete structures are analysed, the rate of internal heat generation, which reflects the thermo-activated nature of cement hydration reactions, can be expressed with an Arrhenius-type law [18]:

$$\dot{Q} = a\, f(\alpha)\, e^{-E_a/(RT)} \tag{2}$$

where a is a constant, $f(\alpha)$ is a function representing the normalized evolution of the heat production rate, the hydration degree α is the ratio between the total heat $Q(t)$ generated until instant t and the total heat that can be released upon completion of hydration reactions Q_∞, E_a is the apparent activation energy and R is the universal gas constant (8.314 J mol^{-1} K^{-1}). In the application of this paper E_a is taken as a constant, being denoted as 'apparent' as it provides a simplified macro representation of the complex set of individual chemical reactions that really occur at a micro-scale level in cement hydration (a more complete representation of those individual chemical reactions is performed by several authors, like in Refs. [19–21]). The simplification of considering E_a as a constant is backed by the proposal of Wadsö [22] and validated with experimental results by Azenha [23].

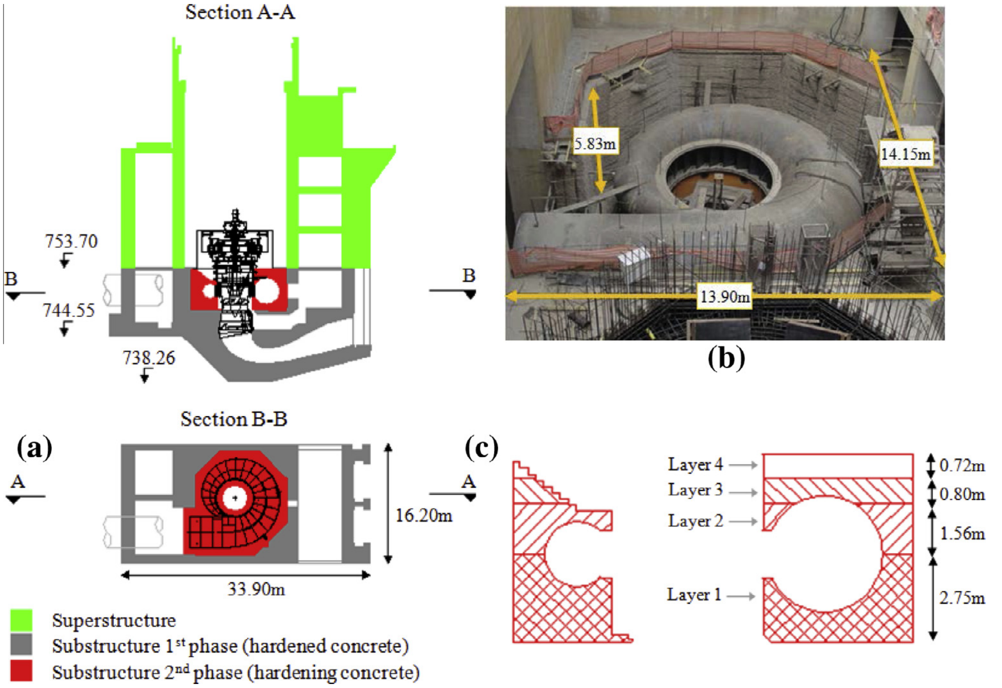

Fig. 1. Batalha hydroelectric power plant: (a) overall structure; (b) spiral case; (c) casting layers of the spiral case (section A-A).