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Short communication

FEA model for the simulation of the hydration process and temperature evolution during the concreting of an arch dam

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ABSTRACT

Temperature plays a significant part in the cracking phenomenon of mass concrete structures, and therefore thermal analysis is of major importance, especially during construction, due to the heat of hydration of the cement. A transient coupled 3D finite element analysis of the thermal behaviour of Alqueva dam during construction is presented in this paper. The method used for the thermal analysis is described in detail, along with the simulation of the different actions. The thermal state of the dam is affected not only by climatic actions but also by concrete's constituent materials and by the construction methods. The chemo-thermal problem is solved using a heat transfer model. An exponential function was calibrated taking into account the heat of hydration of the cement at 3, 7 and 28 days and the function obtained was then used to establish the chemical affinity relationship. The temperatures predicted using the numerical model are compared with the actual temperatures recorded *in situ. Despite the uncertainties characteristic of this type of problem, results lead to the conclusion that the methodology applied in this paper can be effectively used for the chemo-thermal analysis of concrete arch dams, which is particularly relevant during the construction phase.*

1. Introduction

Concrete hydration is an exothermic reaction that can produce high amounts of heat during curing, especially in the first few days or weeks after concreting. In large volumes of concrete, such as mass concrete structures, this heat production can generate high temperatures at the core of the concrete's mass due to the insulating effect of the concrete. When the surface temperatures decrease, due to heat dissipation into the environment, temperature gradients appear. These thermal gradients are likely to generate undesirable thermal stresses, which may result in cracks at the exterior concrete surfaces.

Mass concrete is defined as a volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking [1]. These structures are *e.g.* massive foundations (blocks or slabs in industrial and high-rise residential buildings), bridge supporting elements (piers and abutments), massive retaining structures such as retaining walls and, especially, large concrete dams.

Premature cracking in early age concrete is particularly relevant in mass concrete structures that are in contact with water, such as concrete dams, because it affects the durability of the structures, requiring expensive repair, and thus control of cracking is essential. Temperature-induced cracking in a large mass of concrete can be minimized if proper measures are taken to reduce the amount and rate of temperature change. This need for controlling concrete temperatures was recognized by the Bureau of Reclamation soon after the first large concrete structures were built [2]. Measures commonly used include precooling, post-cooling (or a combination of the two), and thermal insulation to protect exposed surfaces. Also, proper construction processes should be adopted, namely placing successive layers of concrete at a controlled rate. In mass concrete structures, contraction joints are usually provided to allow for volume changes caused by temperature drops. In arch dams, grouting of the vertical contraction joints at the end of the construction is necessary in order to ensure that, once injection is concluded, the dam behaves as a monolithic block and the reservoir load is transferred to the abutments by arch effect. It is normally required that an embedded pipe system is used to cool the concrete artificially, so that contraction joints are wide open while the grouting is carried out.

Early age cracking in massive concrete structures due to the heat of hydration is not a new issue. This has historically been a problem in dams, and numerical methods of predicting temperatures throughout mass concrete elements have been available since the 1920s, *e.g.* Schmidt in 1924 (*apud* [3]), as mentioned by Bobko et al. [4] and by Riding et al. [5]. Glover [6] highlighted that heat retention is favoured

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both by large dimensions and rapidity of construction, and he introduced formulas and diagrams developed in order to estimate the magnitude of the temperature changes to be expected. Later, he devised a method for calculating temperature distributions in a succession of layers [7]. Carlson [8] concluded that the precise prediction of temperature distribution in concrete is practically impossible due to the inexactness and complexity of the conditions, and presented an approximate method, which is sufficiently accurate for engineering purposes.

Among the methods of predicting temperatures in mass concrete elements, one of the most widely used is the one presented by Schmidt in 1924. This method is a simplified finite difference explicit formulation which allows the heat conduction problem to be solved by a simple averaging process. This can often be done by hand or by graphical constructions. Based on a previous work by Rawhouser [9], the Committee on mass and thermally controlled concrete of the American Concrete Institute [10] gives guidance on how to model the temperature rise associated with the concrete hydration reaction using the Schmidt method. A newer version of this method has also incorporated the thermal activated character of the hydration reaction using the equivalent age of the cementitious material [4]. However, the Schmidt method is better suited to rectangular shapes with little variation in other dimensions, and should only be considered as a first rough estimate for more complicated geometries. Moreover, it does not consider the effects of solar radiation, convection, or other sources of heat (or heat dissipation) on boundary elements.

More detailed analyses of early-age behaviour of massive concrete structures can be carried out using finite element models, where convective and radiative boundary conditions and the construction sequence are easy to model.

In the finite element modelling, the temperature evolution is obtained by solving the heat equation considering the heat release due to the hydration reaction (through a heat source term).

Based on the experimental results on hardening concrete samples in adiabatic conditions, different analytical expressions to approximate the observed evolution of heat over time have been proposed to represent the heat source term as a function of time. In the dam engineering field, the research work of Ishikawa [11], Jaafar et al. [12], Luna and Wu [13] and Malkawi et al. [14], among others, may be highlighted. However, under practical circumstances, the hydration does not evolve adiabatically and the heat source is significantly affected by the actual values of the temperature that develops inside the concrete. Therefore, the time parameter only is not enough to correctly describe the progress of the hydration reaction. The mutual dependency between the rate of hydration and the concrete temperature implies that the calculation of both the temperature development and the hardening process are to be carried out using a stepwise calculation procedure in which the effect of the actual temperature and the rate of reaction are modelled explicitly [15].

In order to analyse the coupled chemo-thermal behaviour of early-age concrete, various finite element formulations written in the framework of thermodynamics of chemically reactive porous media, and based on the chemical affinity concept introduced by Ulm and Coussy [16], have been presented in the last fifteen years. The evolution of the chemical affinity as a function of the degree of hydration can be determined by means of adiabatic test or from the evolution of the compressive strength. Examples of these are the formulations written by Cervera et al. [17] and by Fairbairn et al. [18], which obtain the normalized affinity by means of an adiabatic test, and that written by Lackner and Mang [19], which evaluates the chemical affinity from the evolution of the compressive strength.

In the above-mentioned approach, the degree of hydration is part of the output of the numerical prediction. In addition to being a more realistic simulation of the temperature development during hydration, the knowledge of the degree of hydration in the hardening concrete allows the evolution of the material properties to be determined as a function of this state parameter [20].

In dams, the temperature field produced by hydration heat is affected by environmental thermal actions specific to the dams' location. In order to obtain accurate results, it is therefore fundamental to properly model these actions. As regards climatic actions, solar radiation and convection heat transfer are the two main factors that affect temperature distribution on the faces of dams. Recent publications have focused particularly on the simulation of solar radiation [21–26]. Three-dimensional (3D) analysis is particularly relevant in the thermal analysis of arch dams as, due to the curved geometry of this type of structures, there are areas of the upstream and downstream faces of the dam that do not absorb solar radiation, depending on their inclination.

This paper aims at modelling the hydration process and temperature evolution during the concreting of arch dams. It is based on the thermodynamic framework of the multiphase porous media proposed by Ulm and Coussy [16]. From the different empirical relationships to represent the normalized affinity, namely those presented by Hellmich et al. [27], Lackner and Mang [19] and Cervera et al. [28], the latter was preferred due to its chemical meaning. The adopted theory is presented in Section 2. Since in real cases the available data of heat of hydration is restricted to a few points, an analytical expression to fit the data points has been proposed in Section 3, allowing the definition of the normalized affinity function. The numerical implementation of the solar radiation action is presented in Section 4. The several angles describing the incidence of the solar irradiance and the implemented radiative model are described in detail. Finally, the case study of Alqueva dam is reported in Sections 5–7.

2. Chemo-thermal model

2.1. Evolution of the hydration reaction

In this study, the hydration kinetics model based on the thermodynamics of multiphase porous media, which was first proposed by Ulm and Coussy [16], was adopted. According to these authors' model, the concrete is considered as a reactive porous media composed of a solid skeleton of anhydrous cement grains, calcium silicate hydrates (CSH) and pores that may be filled by either air or water. Within this framework, the hydration process of concrete can be viewed, from a macroscopic level, as a chemical reaction in which the free water is a reactant phase that combines with the unhydrated cement to form combined water in the hydrates as a product phase. This implies that the micro-diffusion of water through the layers of already formed hydrates can be considered as the dominant mechanism in the kinetics of the reaction [28].

The evolution of the hydration reaction is represented by an Arrhenius-type equation, which takes into account the thermo-activation and exothermic nature of the reaction:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{1}{\eta} A \exp\left(-\frac{E_a}{R\,T}\right) \tag{1}$$

where $\frac{\mathrm{d}m}{\mathrm{d}t}$ is the *variation of the skeleton mass* (reaction velocity [mol/s]); η is a *viscosity* term representing the increase in physical barrier of CSH, which tends to isolate the cement grain from the free water, and depends on the state of the hydration reaction; A is the *affinity of the chemical reaction* or, in other words, the *thermodynamic force associated to the rate of hydration formation*, which also depends on the state of the hydration reaction; E_a is the *apparent thermal activation energy*, which is considered to be constant with relation to the hydration degree; R is the *universal constant of gases* [8.314 J/(mol K)], and T is the *temperature* in K. The SI unit system is used in this paper.

For practical purposes, it is convenient to rewrite the model in terms of the *hydration degree*, defined as the ratio between the mass of the skeleton at time t normalized by the mass of the skeleton when hydration is complete, *i.e.*, $\xi(t) = \frac{m(t)}{m_\infty}$: