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Numerical modeling of mass concrete structures: practical applications and relevance to society

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Abstract. Computational analysis has become crucial in almost all disciplines of our society, together with theory and experimental analysis. In civil engineering, the thermal cracking of young concrete, associated with the high costs and safety requirements of infrastructure works, has been a concern of the engineering community since the first applications of mass concrete. It happens that several massive concrete structures such as hydroelectric and nuclear power plants, thick foundations, bridge pier columns and caps, thick walls, and tetrapods breakwaters may experience cracking induced by the generation of heat during hydration reaction (hardening). Considering the nature of this type of work, whose risk, cost, and predictability of behavior are extremely important factors for our community, accurate models are necessary to guarantee the success of the project. In this sense, this work will considerer the most commonly used numerical method – Finite Element Method (FEM) - in practical applications for numerical modeling of concrete structures developed by PEC/COPPE/UFRJ in several engineering works, showing its impact and importance for society.

Keywords: numerical modeling, mass concrete structures, finite element method, practical application

1 Introduction

Cement, in general, can be described as a material with adhesive and cohesive properties that make it capable of joining mineral fragments in the form of a compact solid unit [1]. In civil construction, the meaning of the term cement is restricted to binding materials used in mixtures with gravel, sand, and water to produce mortars and concrete. As they are limestone-based compounds, they react chemically when in contact with water, hardening. In this way, they are called hydraulic cements.

The cement hydration reaction is an exothermic and thermo-activated chemical reaction. This means that at the same time that the thermal fields of the concrete mass are altered by the evolution of the reaction, the kinetics of this reaction itself is altered as a function of the temperature of the heated concrete mass. In addition, the evolution of the hydration reaction is directly related to the evolution of material properties such as modulus of elasticity, strength, creep, shrinkage, etc. This evolution can be defined by the term "aging" of concrete.

Hydraulic cements are mainly composed of calcium silicates and aluminates. They can be classified, in general, as natural cements, Portland cements, and aluminous cements. In the context of this work, the term cement will be associated with Portland cement, the material with the greatest application in engineering works.

If we consider that, from the percolation threshold (term used to describe the change of state of the paste, from fluid to solid), the fluid in which the mixture is initially constituted (cement, gravel, sand, and water) is transformed into a skeleton with two networks of pores (one nanometer and the other micrometer). These pores can be filled with water or air. Also, if we consider that this skeleton is formed by hydrates that are the result of the reaction of free water with anhydrous cement (the hydration reaction), we find that the skeleton is evolving, and we can consider concrete as a chemically reactive porous medium.

The formalism proposed by ULM and COUSSY [2], based on the thermodynamics of porous media, allows the deduction of constitutive equations that consider the various thermochemical-mechanical couplings and the elaboration of numerical models for the consequent computational implementation of the hydration reaction.

In the past, the term mass concrete was applied only to large structures, such as gravity dams. However, nowadays, according to RILEM [3], the technological aspects of mass concrete are relevant for any, "structures in which the hydration effects of cementitious materials at early ages, such as heat generation and autogenous shrinkage, can lead to cracking". Therefore, the fundamental aspect of mass concrete is its thermal behavior, being one of the objectives of the project to avoid/reduce and control the opening of cracks.

As the hydration reaction is exothermic and the thermal conductivity of concrete is relatively low, it usually endures temperature rises that are especially relevant in massive concrete structures. Two types of relevant thermal gradients can be identified in mass concrete: (i) one is relative to time, that is, a given point of the structure has its temperature varying over time; (ii) another is a spatial gradient that corresponds to the temperature difference, at a given instant, between two different points of the structure. Considering the thermal expansion of concrete and the structural restraints to free deformations, both gradients mentioned above can be responsible for the generation and evolution of strain and stresses in the concrete elements. And undesirable thermal cracks can occur if such strains or stresses reach a certain limit.

The generation of heat and the consequent rise in the temperature of concrete are very important, not only because they can generate thermal gradients in space and time, but also because deleterious phenomena such as the Delayed Ettringite Formation (DEF) have been proved to be associated with the existence of fields thermals in the early ages that reach temperatures of the order of *65 ºC*. The set of issues mentioned adequately supports the claim that the increase in temperature due to hydration is a very important issue with regard to the durability of the structure.

Therefore, the construction phase and subsequent period must be accurately analyzed. If the tendency to cracking is detected, many actions can be taken to minimize early stresses, such as: (i) decreasing the construction speed, allowing higher heat dispersion; (ii) reducing the placement temperature of the concrete; (iii) decreasing the concrete temperature by circulating water or air in tubes embedded in the formwork (post-cooling systems); and (iv) choosing a material composition that gives lower heat of hydration rates.

Due to the high costs and safety requirements of construction and infrastructure works, thermal cracking of young concrete has been a concern of the engineering community since the first applications of massive concrete. The evolution of knowledge on the subject led to the development of theories that consider the hydration reaction as exothermic and thermally activated. Such theories led to sophisticated numerical models that, together with the evolution of hardware and software, allowed the development of very complex simulation models that approached reality in terms of geometry and phenomenological models considered [4].

In the past, early age cracking risks were commonly faced in large structures where heat dissipation from hydration is normally slow and, therefore, high temperatures are observed (almost adiabatic conditions). The types of concrete used in such types of structures had relatively high water/cement ratios and therefore did not support significant additional stresses caused by autogenous shrinkage.

With the advent of high-performance concretes, cracking in the early ages is no longer a peculiarity of massive structures. High contents of cementitious materials associated with lower water/cement ratios result, respectively, in greater heat of hydration and microstructures with fine pores, enhancing greater amplitudes of thermal gradients and autogenous shrinkage. Thus, the term mass concrete is used in a broad sense, in this work, comprising all types of concrete elements for which the effects of cement hydration can lead to thermal cracking risks.

In practice, it turns out that various massive concrete structures, such as hydroelectric and nuclear power plants, thick foundations, bridge abutments, thick walls, and tetrapod breakwaters, can present cracks induced by the hydration reaction (Fig.1).

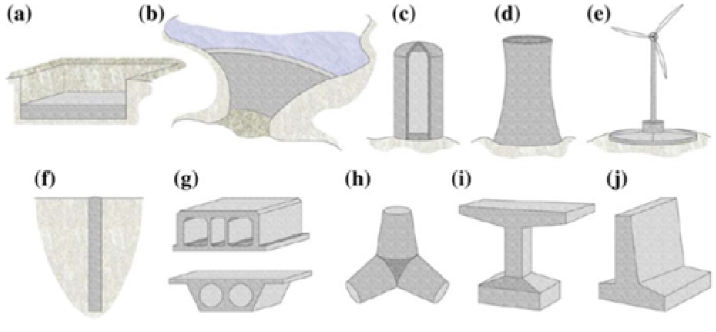

Figure 1. Examples of concrete structures that can benefit from thermal simulation: (a) foundation slabs; (b) concrete dams; (c) silos / containment structures; (d) cooling towers; (e) wind turbine foundations; (f) stakes; (g) precast segments (top: current artwork (culvert), below: special artwork deck (bridge/viaduct)); (h) tetrapod blocks; (i) mesostructures of special works of art; and (j) retaining walls. [5]

Several other scientific and technological advances were verified in other areas related to crack control in mass concrete structures. In this context, it is relevant to mention: new techniques for temperature control and monitoring *in loco*; new advanced models for dosage and methods that allow its optimization using computer codes; new sustainability requirements introducing the use of a new category of materials and sustainable practices that can contribute to the reduction of greenhouse gas emissions.

Thus, an in-depth and specific understanding of the behavior of such structures is essential for the prediction of material cracking, a fact that has motivated several researchers in this field, whether applied in the experimental and/or computational area, in order to study the effects of thermal and mechanical phenomena on concrete mass (ULM and COUSSY [2]; ULM and COUSSY [6]; ULM and COUSSY [7]; SILVOSO [8]; FAIRBAIRN et al. [9]; DE FARIA [10]; AZENHA [11]).

In research using computer simulations, programs have been developed to map the temperature in the concrete solid and also its transient stress and strain fields, which enables the prevention of cracking, through the establishment of strategies to prevent it.

In this sense, this work will consider the most commonly used numerical method – Finite Element Method (FEM) - in practical applications for numerical modeling of concrete structures developed by researchers of the PEC/COPPE/UFRJ in several engineering works, showing its impact and importance for society.

2 Numerical modeling of concrete structures

Computational analysis has become crucial in almost all disciplines, together with theory and experimental analysis. Every model is a simplification of reality intended to promote its understanding. A model uses a simplified physical formulation, mathematical framework, and numerical tools in order to find the solution. Successful models pass the validation stage, where modelling results correspond sufficiently well to reality.

Computational approaches are also playing an increasing role in the industry. In fact, validated models can save a significant amount of experiments, time, and resources, mitigate potential problems, and even find the optimal solution. For instance, in the case of massive concrete structures, numerical modelling often follows objectives such as: determination of temperature field during hardening, effect of concrete composition, estimation of cracking potential with consequences to durability, economical benefits [3].

In civil and environmental engineering, most of the processes/phenomena are mathematically described by a set of partial differential equations (PDEs), usually nonlinear in material laws. For example, a set of PDEs describes heat and mass transfer, mechanical effects, hydrodynamic effects, electric and magnetic fields, and all their interactions (multiphysics problems). There exists a significant amount of numerical techniques for solving such a kind of complex mathematical systems, some of them limited to the research world. In the context of this work, we consider the most commonly used numerical method — the Finite Element Method.

Hardening concrete is undoubtedly one of the most difficult structural materials for modelling. The difficulties arise from a complex concrete microstructure, which is additionally subjected to transformations as a result of cement hydration. Initially, it is a mixture of liquids and solids of varying diameters and shapes. Such a multiphase medium is characterized by strong viscous and plastic properties. With progressing cement, hydration concrete becomes a solid, with elastic, viscous, and plastic characteristics, where the mutual proportions of these features depend on the progress of the concrete hardening process. Moreover, in addition to the chemical reactions resulting in the hydration of the material, several physical phenomena take place (e.g. phase changes) and numerous fields are interacting with each other (thermal, hygral, mechanical, etc.) making the problem a typical multifield–multi-physics problem [12].

In RILEM [3], is shown that concrete represents a multiscale material which spans characteristic lengths from about 10^{-10} to $10^{-2}m$. Taking into account only concrete scale and its changes during hardening, two possibilities appear to model its early-age behaviour:

- to use pure thermo-chemical, and possibly mechanical, models;
- to formulate a multifield model.

In the first class of models, concrete is treated as a continuum at the macroscopic level, and only the solid phase of the material is considered, taking into account the thermal field and the chemical reactions (e.g. the hydration process), which affect the mechanical performance of the material for a large extent. The second group of models is based on the multifield concept; i.e., they consider one or more phases: not only the solid phase, which is typically the concrete skeleton, but also the liquid and gaseous components filling the pores of the material. Depending on the number of phases considered and the scale level chosen for the initial formulation of the mathematical model, the multifield models can be subdivided into two main groups corresponding to two different approaches.

The first approach is related to phenomenological models, where concrete is treated as a continuous medium. A detailed analysis of physical processes related to phase transitions and chemical processes occurring in hardening concrete is neglected in these models, and a macroscopic description of the thermal–moisture–mechanical phenomena is used as a multiphysical description.

The second approach is related to multiphase models based on Multiphase Porous Media Mechanics (MPMM), in which a precise analysis of the physical phenomena and the influence of the material's internal structure on these phenomena are made. Starting from the microscopic level, appropriate constitutive equations are defined for the solid, liquid, and gaseous phases of the medium and then averaged at the macroscopic scale for a multiphase medium.

3 Practical applications

3.1 Sensitivity analysis of the computational model (FURNAS)

In this work, the construction of a concrete slab (3.0 x 2.0 x 0.5 m), built on a 10 cm concrete base was simulated. The finite element program used was DAMTHE, implemented in FORTRAN programming language and developed by researches of PEC/COPPE/UFRJ. The objective was to use data from experimental tests carried out on a slab - built and tested at the FURNAS laboratory in Goiânia/GO (Fig. 2) as described in FAIRBAIRN et al. [13] - as a starting point for adjusting the numerical model, so that could be obtained a reference simulation that represented the tests performed as accurately as possible and, later, perform an analysis of the influence of some parameters (variables) of the program's input, referring to the thermal properties of the material, on the behavior of the structure.

Figure 2. Slab shape tested and monitoring thermometers coupled to the LYNX platform (COPPE/FURNAS).

This analysis of the influence of parameters can be called *sensitivity analysis* and can be characterized in general terms as a study that evaluates the effect caused by the change of a stipulated variable within a model, analyzing the result of this variation on its initial design. Thus, this work sought to identify, through numerical simulations, among the properties of concrete, namely: (i) activation energy, (ii) specific heat, (iii) thermal conductivity and (iv) rate of heat exchange by convection, which cause significant impacts on the result of the simulations, evaluating the disturbances caused in the temperature rise and in the volume of cracked elements in comparison with the reference simulation.

The temperatures measured during the experimental test were automatically obtained using the LYNX equipment from COPPE/LABEST (Fig. 2) and performed by FAIRBAIRN et al. [13]. Temperatures were recorded at the center and edge of the slab, with thermometers at variable heights.

Fig. 3 presents the geometry used for the numerical simulation of the slab. In this model, the bilateral symmetry of the problem was used, representing only a quarter of the slab under study. Three different materials were considered, with different thermal and mechanical properties: the soil, the concrete base and the concrete of the slab itself. The finite element mesh used has 29474 nodes and 163673 linear tetrahedral elements.

As a criterion for validating the developed numerical model, the temperature rise in the central node of the structure was compared with the built slab and plotted in Fig.4.

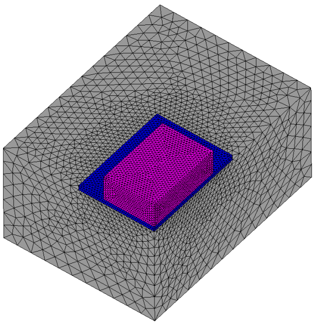

Figure 3. Features of finite element geometry and mesh.

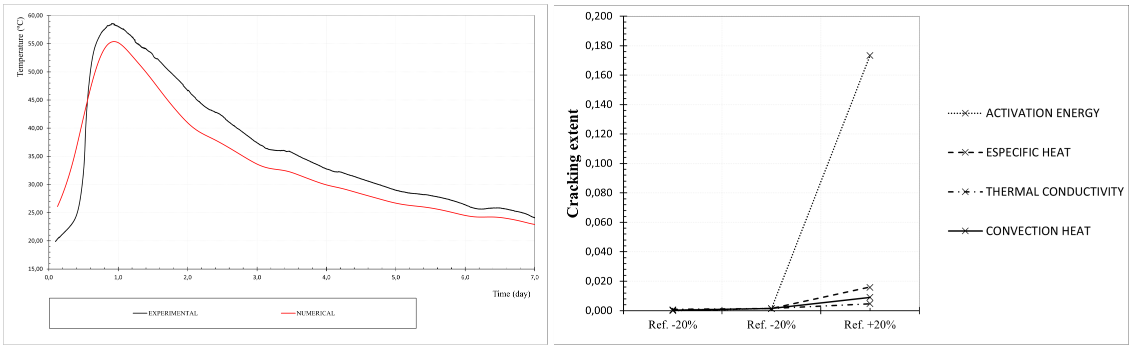

Figure 4. Comparison of the temperature rise of the numerical model and experimental data for 7 days.

In order to analyze the influence of the selected parameters, three possible values were adopted for them: the reference value (Ref.), a minimum and a maximum value, and based on the input values admitted for the materials, a fixed variation was adopted of 20% for the reference values, thus guaranteeing a standardized variation for all parameters and the guarantee of not extrapolating values, decharacterizing, for example, the experiment.

Finally, to properly characterize the influence of material properties on the structure, the cracking extension, proposed by RITA et al. [14], was adopted as the response variable. This variable represents the sum of finite element mesh elements that at some point in the simulation were cracked, that is, the stresses acting on the element exceeded its resistive capacity at that moment, divided by the total mesh elements that represent the analyzed material. The results can be seen in Fig. 4.

A factor analysis, with overlapping factors and more information can be found in FRAGA [15].

3.2 Tocoma Hydroelectric Power Plant

As presented in FAIRBAIRN et al. [16], the basic project was conceived originally under the concept of using scaffolding with the technique of conventional climbing formworks of wood or metal, with a height of 1.5 m. The methodology was viable in some areas, however, for situations where it was necessary to make the formwork with great heights, it was very difficult to proceed with the conventional climbing formwork system. In addition, the massive structure of the pillar had the same geometry, and stopping it, generally every 1.5 m (or in some cases 3 m), to assemble a new segment equal to the previous one, associated with repair work on routine and joint treatment, would delay the continuity of the work in the foreseen execution times.

Therefore, the work's production team, together with the COPPE/UFRJ technical team and external consultants, evaluated the implementation of the sliding formwork technique, carrying out the concreting continuously, in order to guarantee the safety, costs and deadlines of the project. A large number of technical-scientific studies were carried out, with the idea of observing the thermochemical-mechanical behavior of the main structures of the spillway of the Tocoma Hydroelectric Power Plant, in Venezuela - the most critical structure - and the use of the post-cooling system as a technique of dissipation of thermal stresses in the concrete at the time of its hardening, which generates a greater degree of safety.

Stress or strain analyzes were performed based on the results of the temperature calculations made for each launch condition studied. For each condition, the stresses or strain resulting from the thermal gradients that will act on the structure were determined, for which the concrete will have to resist.

Furthermore, the cracking potential of the pillar of the spillway of the HPP Tocoma was numerically analyzed, by FAIRBAIRN et al. [16], using the geometry of the main pillar "PP08" (Fig. 5). The thermal properties obtained experimentally were used in the analyses. The analysis of the thermochemical-mechanical behavior of the concrete, during the construction phase of the analyzed pillar, was carried out considering the continuous concreting with sliding forms up to a height of 22 meters, at a rate of 10 cm/hour. The launch temperatures analyzed were 10°C, 15°C and 20°C, with cooling through a pipe at a height of 80cm from the foundation. For each launch temperature, a post-cooling pipe temperature at 10°C and 20°C was considered. In this model, the symmetry of the problem was considered, representing half of the pile with a plane of symmetry on its main axis.

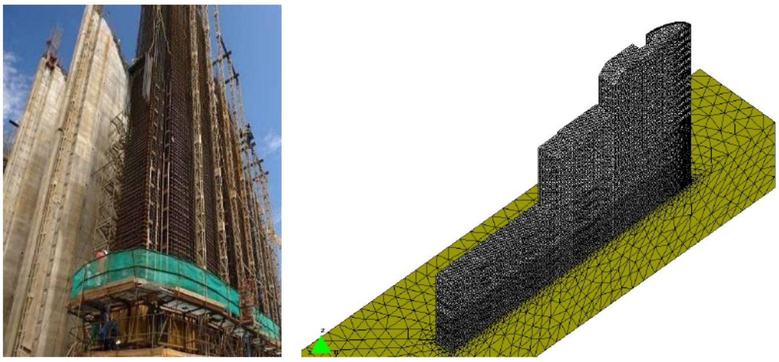

Figure 5. PP08 pillar and the finite element mesh of Tocoma HPP.

The finite element mesh used incorporated post-cooling tubes, considered as thermal load at the nodes at the prescribed temperatures. In this mode, the finite element mesh used was composed of 122,526 nodes and 647,515 elements, as shown in Fig. 5 [16]. With the results obtained, the safety parameters were established and it was verified that there were low rates of cracking for the condition of launching the concrete at 10°C. In addition, it was found that with the use of cooling tubes at a temperature of 10°C, the concrete could be launch at 15°C, without affecting the cracking rates allowed in the safety of the project. After construction, the temperatures measured during construction were analyzed and compared with the temperatures predicted in the computational model. The results are shown in Fig. 6.

Currently, FRAGA et al. [17] are developing a numerical model for post-cooling simulation of mass concrete structures implemented in finite elements. In this way, they seek to simplify and improve the results obtained in numerical simulations.

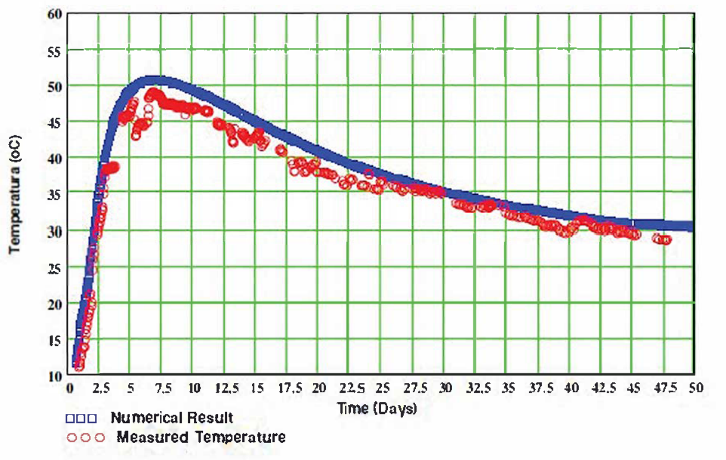

Figure 6. Temperatures rise measured during construction and in the numerical model.

4 Conclusions

The computer models allow the simulation of the construction of massive concrete structures with extreme accuracy. In this way, using a computational model is a fundamental part of the previous analysis of mass concrete structures in order to identify the appearance of cracks and eventual pathologies caused by concreting at high temperatures, even before its physical execution. In addition to guaranteeing safety parameters, numerical modeling allows significant financial savings in the construction of large structures, allowing the choice of the best construction techniques to be applied to the structure under analysis. This kind of solution can be seen in the work developed by RITA et al. [14], which presents an optimization procedure for the constructive phase of massive structures through a genetic algorithm. Therefore, due to the relevance of numerical modeling, the scientific community constantly develops new models seeking to improve the precision of numerical analysis to increasingly reduce the risks and uncertainties of simulations and expand its applications.

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