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Recent advances in numerical modeling of massive concrete structures

Eduardo M. R. Fairbairn[1], Miguel Azenha[2], Fragkoulis Kanavaris[3]

[1] *Dept. of Civil Engineering, Federal University of Rio de Janeiro*
Rio de Janeiro, RJ, Brazil
eduardo@coc.ufrj.br
[2]*Dept. of Civil Engineering, University of Minho*
Guimarães, Portugal
miguel.azenha@civil.uminho.pt
[3]*ARUP Group Limited*
London
Frag.Kanavaris@arup.com

Abstract. This paper presents recent advances in numerical modeling of massive concrete structures resulting from the conclusions of the Technical Committees of RILEM TC 254-CMS "Thermal cracking of massive concrete structures" and RILEM TC 287-CCS ‘‘Early-age and long-term crack width analysis in RC structures’’, committees chaired by the authors. The TC 254-CMS Committee met for 7 years (2013-2019) and involved the participation of approximately 30 researchers and professionals from different continents. In addition to several meetings, symposia and participation in Conferences, the Committee has published a book on the state-of-the-art and also some articles in specialized journals that indicate procedures pertinent to the construction of massive structures that are of fundamental importance for designers and constructors. Therefore, in the present paper, several conclusions about the best practices in numerical modeling of the problems related to the hydration of early-age concrete will be addressed. The concept of massivity index will also be discussed which determines the need to analyse a structure considering the hydration effects at the early ages.

Keywords: massive structures, concrete, numerical modeling

1 Introduction

Thermal cracking of massive concrete structures is an important phenomenon originated by the hydration reaction of the cementitious materials. As the reaction is exothermic, and the thermal conductivity of concrete is relatively low, it normally endures temperature rises that have special relevance in massive concrete structures. Two types of relevant thermal gradients can be identified in mass concrete: (i) one is relative to time, i.e., a given point of the structure has its temperature varying throughout 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 dilation of concrete, and structural restraints to free deformations, both above mentioned gradients can be responsible for the generation and evolution of strains and stresses in concrete elements. If such strains/stresses reach a certain limit, undesirable thermal cracks can occur. The heat generation and consequent temperature rise of the concrete bulk are very important, not only because it can generate thermal gradients in space and in time, but also because deleterious phenomena such as the Delayed Ettringite Formation (DEF) have been proved to be associated with the existence of thermal fields at the early ages that reach temperatures of the order of 65 °C.

Furthermore, since there is volume unbalance between reactants and products of reaction, autogenous shrinkage also imposes additional strains to concrete that may cause the cracking tendency to increase. With the advent of high-performance concretes, cracking at the early ages is no longer a peculiarity of massive structures. Higher contents of cementitious materials associated with lower w/c ratios result, respectively, in higher heat of hydration and microstructures with finer pores, thus potentiating greater amplitudes of thermal gradients and autogenous shrinkage. In this way, in the present paper, the term ‘massive concrete’ is used in a broad sense, comprising all types of concrete elements for which the effects of cement hydration can lead to thermal cracking risks. In practice, it happens that several massive concrete structures such as hydroelectric and nuclear power plants, thick foundations, bridge pier columns and caps, thick walls, and breakwater accropodes may experience cracking induced by the hydration reaction [1]. Due to the high costs and safety requirements of building and infrastructure works, thermal cracking of early-age concrete has been a concern of the engineering community since the first applications of massive concrete. The evolution of knowledge on the subject has led to the development of theories that consider the hydration reaction as exothermic and thermally activated. This means that, concerning the specific heat generation, there is a second-order effect, since the rate of heat generated by a unit mass, at a given point and at a given time, depends on the extension of the reaction, which varies as a function of the thermal history at the considered point. Also, the properties of the material and phenomena related to hydration evolution, such as strength, Young’s modulus, autogenous shrinkage and creep, will vary according to the extension of the reaction. Such theories led to sophisticated numerical models that, together with the evolution of computer hardware and software, allowed the development of very complex simulation models that successively get closer to reality both in terms of geometry and phenomenological models considered.

All these recent developments related to the old problem of the stresses originated from the evolution of the hydration of the concrete are at the origin of the creation of RILEM Technical Committee 254-CMS ‘Thermal Cracking of Massive Concrete Structures’[2]. Having identified that there was a lack in the systematization of recent scientific and technological knowledge about thermal cracking of massive concrete, the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM, from the name in French) has created this committee to provide both practitioners and scientists with a deep overview of the recent developments on this subject. Three main publications of this Committee constitute major contributions to the field of the behavior of early age concrete: (i) The state of the art report [1], a book published by Springer with the up to date information about thermal cracking of massive structures; (ii) the introduction of the enhanced massivity index based on evidence from case studies, a robust pre-design assessment of early-age thermal cracking risk and practical recommendations [3]; (iii) the Recommendations of RILEM TC 287-CCS: thermo-chemo-mechanical modelling of massive concrete structures towards cracking risk assessment [4] a guide for numerical modeling of hydration governed structures. In the next paragraphs some details will be given about these three outstanding contributions.

2 State-of -the art report (STAR): thermal cracking of massive concrete structures [1].

The chapter division of the STAR was a dynamic process throughout the life of the TC with an initial proposal being forward by the management, which was refined during the several meetings. The chapter structure is the following:

Ch. 1 – Introduction
Ch. 2 – Hydration and heat development
Ch. 3 – Thermal properties
Ch. 4 – Mechanical properties
Ch. 5 – Mixture proportioning for crack avoidance
Ch. 6 – Temperature control
Ch. 7 – Numerical modelling
Ch. 8 – Cracking risk and regulations
Ch. 9 – On-site monitoring of mass concrete
Ch. 10 – Sustainability aspects in mass concrete

Chapter 1 provides an introduction to the STAR.

The development of the hydration reaction of the cementitious materials is the main phenomenon that commands the thermal cracking of concrete at early ages. This physical-chemical phenomenon is presented in Chapter 2. In this chapter the velocity of the evolution of the reaction, and consequently the heat generation, are shown to be strongly influenced by thermal activation. This can be regarded as a second order effect since the heat released by the reaction activates the reaction itself. One of the main problems to simulate the evolution of the temperature fields and to compute stresses and strains is that several thermo-chemo-mechanical properties are dependent on the state of the hydration. Chapter 2 presents a survey of the main chemical properties in relation to the evolution of the hydration, the affinity, and the activation energy. It also presents several types of models that are dedicated to predicting the hydration evolution of a given concrete mix and forecast the heat release and the consequent temperature rise.

To better understand and predict the thermal behavior of massive concrete structures, a sound fundamental knowledge is necessary regarding the thermal properties of concrete. The thermal properties described in Chapter 3 are grouped into properties responsible for transport of heat and corresponding temperature changes (effective thermal conductivity and heat capacity, heat exchange parameters), and thermal expansion coefficient, which allows relating the temperature changes to thermal deformations of concrete. A special focus is given to the most recent developments that have been recently achieved in the characterization of all thermal properties at very early ages.

Chapter 4 gives a description of the main mechanical properties that will govern cracking due to the restraint of imposed deformations in massive concrete structures, considering both thermal and shrinkage deformations. This chapter is structured in three main sub-sections: (i) Quasi-Static behavior of concrete and steel/concrete bond - covering a review on relevant properties such as: compressive strength, tensile strength, Young's modulus, Poisson's ratio, strain capacity, fracture energy, steel/concrete bond and the effects of multi-axial stress states; (ii) Shrinkage - covering topics of plastic shrinkage, autogenous shrinkage and drying shrinkage; (iii) Creep - focusing on the viscoelastic features that concrete endures since its early ages, with particular focus on the elevated creep strains that are expectable in the very first hours after setting.

In Chapter 5, the nature, the physical and chemical properties, and the content of the concrete constituents are discussed for the understanding of the way of making an optimized mixture proportioning of the concrete for massive applications where the temperature rise must be minimized.

Chapter 6 is dedicated to a review on measures that can be taken to control concrete temperature at several levels, mainly focused in limiting temperature rises due to cement hydration heat: (i) pre-cooling of mix constituents; (ii) cooling concrete during the mixing procedures; (iii) controlling temperature during transport and placement; (iv) selecting and designing suitable surface measures for temperature control; (v) scheduling of construction stages; (vi) post-cooling with water or air.

Chapter 7 deals with the problem of modelling the behavior of massive concrete structures. In the last decades, the developments in the field of computational mechanics were very significant, so nowadays several numerical techniques are available for this goal, depending on the scale level considered but also on which phenomena/processes are considered. In this chapter we limit the description to approaches/models that can be implemented using the Finite Element Method. The chapter presents two distinct groups of models: in the first, some "deterministic" models are described starting from the simplest ones, which consider simply the thermo-chemo-mechanical behavior of the material, to more sophisticated approaches which considers also the fluid phases, i.e., they consider concrete as a multiphase porous material. In this first part, a specific section is dedicated to mechanical behavior modelling considering damage of the material, plasticity, etc. The second group of the models taken into consideration have a "stochastic" nature. These models are formulated specifically for giving a detailed information about cracks spacing and opening in concrete structures in service life conditions. At the end of the chapter, the reader can find a short section about modelling of environmental conditions, which are particularly important for massive concrete structures.

Chapter 8 is focused on the cracking risk at early ages. After general considerations about cracking, the cracking risk prediction is discussed. Two main ways to assess this risk are considered: through an evaluation of the tensile stresses and through an evaluation of the strains. Finally, the evaluation of crack opening at early ages and the reinforcement design in regulations are presented. Special focus is given to a broad coverage of the aspects by which each regulation is specifically distinctive.

Chapter 9 is devoted to display the benefits of on-site monitoring of mass concrete. An important outcome is the assurance that adequate conditions for the evolution of the desired concrete properties were maintained. This refers mainly to the monitoring of the concrete temperature in the phases of warming and cooling down, but it is also possible to obtain mechanical parameters for further considerations. Besides, the measurement results provide important data to verify the calculation models and assumptions applied for crack assessment of the considered structure as well as to improve these calculation models and assumptions for future projects. Next to very general information on monitoring affairs, this chapter presents different levels of measures about the purpose and expected insights of each level, available instruments, and least requirements on practical application as well as possibilities for result verification. This focuses on both established techniques with comprehensive experiences in many applications, as well as comparably new techniques available on the market. Finally, the presented techniques and approaches were exemplified on three different application examples regarding different measurement systems as well as types of structures.

The last chapter, Chapter 10, addresses potential alternatives for base raw materials as well as potential solutions for sustainability in mass concrete. Issues like material selection and environment, material properties and mix design, durability, carbon footprint and life-cycle analysis (LCA) of mass concretes are reviewed. The focus is put on recycling. Beside the use of conventional SCMs, non-conventional biomass pozzolans, based on combustion of renewable source of energy, like woody ashes, sugarcane bagasse ash and rice husk ash are covered. The synergic use of several mineral SCMs as a partial substituent of Portland cement is addressed. Furthermore, reuse of aggregates from Construction Demolition Waste, as well as natural fibre alternatives to steel and synthetic reinforcements is discussed in detail. Materials selections and the consequence of it on the properties that affect the mix design and material properties, specifically related to durability are summarized. An introduction on life cycle assessment (LCA) is given with its pros and cons, followed by its review on different mass concrete mixtures, separately addressing LCA of binders, aggregates, concretes, and reinforced concrete structures with placement technologies. Limitations and further research directions are highlighted.

3 Enhanced massivity index [3]

The decision about which structure should be analyzed considering the risk of cracking as a function of stresses due to the hydration reaction is of fundamental importance for the engineering of massive concrete structures. This was a concern of the RILEM TC-254 Committee, which led to the proposal of a massivity index capable of guiding engineers on when to carry out a detailed numerical calculation considering the effects of hydration. This study was published in a 2021 paper [3] that is based on the evidence collected by the members of TC 254 and relate to 7 distinct, representative large-volume concrete structures in which hardening-induced cracking was reported. The structures in question are described in detail in the paper. For all considered case studies the observed cracking was predominately attributed to hardening induced thermal stresses reaching the tensile capacity of concrete. These thermal stresses were formed in the volume of the elements due to temperature differentials caused by dissipation of heat that is generated by hydration of cement during hardening of these elements. High magnitude of thermal gradients was mainly caused by the combination of large dimensions of the structural elements and the material characteristics.

It is evident that the designer must make a difficult, yet responsible decision about the potential risk of early-age thermal cracking in any large volume of concrete and the need of performing thermal analysis. This decision can be potentially aided through the concept of quantifying proneness to cracking using massivity indexes. Different approaches in evaluating the massivity that can be used to support this decision process are described in the paper, namely: (i) the characteristic length approach; (ii) the surface area approach; (iii) the equivalent thickness approach; and (iv) the surface modulus approach. A critical analysis of the different indices is carried out in the light of the case studies carried out to verify the relevance of these indices. It is then suggested that the concept of surface modulus, m_s, is used and corrected since it also provides boundaries. This modulus is defined as:

$$m_s[\mathrm{m}^{-1}] = \frac{S}{V} \tag{1}$$

where S is the total area of surfaces through which heat dissipates and V is the volume of concrete. These variables are defined in detail in [3].

The structures are then divided into three groups:

- for $m_s \leq 2\mathrm{m}^{-1}$ structures are classified as massive with a predominant impact of thermal strains and close-to-adiabatic conditions in the core;
- for $2\ \mathrm{m}^{-1} < m_s < 15\ \mathrm{m}^{-1}$ structures are classified as semi-massive with a comparable impact of

thermal and drying shrinkage strains;

- for $m_s \geq 15\ \mathrm{m}^{-1}$ structures are classified as thin-walled concrete structures with negligible impact of thermal strains.

To encompass the effects of binder type and content, casting and ambient temperature and temperature drop, the surface modulus, m_s, is then modified. As such, the enhanced massivity index can be obtained from:

$$M_{cor} = \frac{m_s}{k_f \cdot k_b \cdot k_{\Delta T}} \tag{2}$$

where $k_f,\ k_b$ and $k_{\Delta T}$ are dimensionless correction factors accounting for cement type, binder content and temperature differential, respectively.

The k_f coefficient is given in relation to cement type I (CEM I) of the European standard EN 197. Indicative values of mixtures with fly ash (FA) and ground-granulated blast-furnace slag (GGBS) are given in a table in [3] for different contents of FA and CGBS. As an example, for pure cement $k_f = 1$ and for a blending with 70% of CGBS $k_f = 0.43$.

It has been well established that the binder content has a decisive influence on the potential temperature evolution within a section; the temperature effectively increases with binder content. As a general quantification, it was then proposed in [3] to keep a value of:

$$k_b = \frac{bindercontening[\mathrm{kg/m^3}]}{300[\mathrm{kg/m^3}]} \tag{3}$$

The coefficient $k_{\Delta T}$ represents the temperature differential in the member resulting from the interplay between fresh concrete temperature, peak concrete temperature and ambient temperature. It is given by the following equation:

$$k_{\Delta T} = \frac{T_{fresh} + T_{ambient} + T_{adi,rise}}{T_{adi,rise}} \tag{4}$$

where: T_{fresh} is the temperature of fresh concrete; $T_{ambient}$ is the expected ambient temperature at time of maximum concrete temperature; and $T_{adi,rise}$ is the temperature increase due to hydration under adiabatic conditions, that can be approximated by the following equation:

$$T_{adi,rise} = 0.12\ \frac{[^{\mathrm{o}}\mathrm{C}]}{[\mathrm{kg/m^3}]} \cdot bindercontening[\mathrm{kg/m^3}] \tag{5}$$

The enhanced massivity index was validated with several real structures that showed thermal cracking and with structures that did not crack. The reader will be able to verify in [3] details of the analyzed structures, among which two are dams located in Brazil, one of which is the Itaipú hydroelectric plant.

The enhanced massivity index was validated with several real structures that showed thermal cracking and also with structures that did not crack. The reader will be able to verify in [3] details of the analyzed structures, among which two are dams located in Brazil, one of which is the Itaipú hydroelectric plant. In addition, a flowchart that helps engineers decide which decision to make regarding whether or not to consider the effects of hydration on structures is presented.

The article [3], which is an output of the RILEM Technical Committee 254, constitutes an important contribution to the engineering of massive concrete structures, providing elements for decision making regarding the depth of the thermo-mechanical calculations to be performed.

4 Recommendations for thermo-chemo-mechanical modelling of massive concrete structures [4]

The use of thermo-chemo-mechanical models for the study of massive concrete structures during construction is still relatively recent, especially when finite element codes are used that allow the simulation of complex geometries in three-dimensional models. In this way, when such models are used in real works, the contractors may demand that the consultants follow some standardization with national or international recognition. Such a demand occurred, for example, when the team of COPPE/UFRJ carried out studies based on numerical analysis for the construction of massive structures for the Angra III nuclear power plant [5]. However, such standards are non-existent, and their elaboration is not a simple task that can be accomplished in a short time by a single team.

Within this perspective, RILEM's technical committees, based on STAR [1] developed the recommendations for thermo-chemo-mechanical modelling of massive concrete structures towards risk assessment [4].

These recommendations have been prepared by the corresponding working group within RILEM TC 287-CCS ‘‘Early-age and long-term crack width analysis in RC structures’’, following work by the previously ceased RILEM TC 254-CMS ‘‘Thermal cracking of massive concrete structures’’. This recommendations document was developed in complementarity to the state-of-the-art report [1] of RILEM TC 254-CMS and aims to provide expert advice and suggestions to engineers and scientists interested in modelling the thermo-chemo-mechanical behavior of massive concrete structures since concrete casting. Recommendations regarding geometrical characteristics and complexities, concrete properties and appropriate material models, boundary conditions and loads, and numerical model peculiarities with relevance to the simulation of the thermo-chemo-mechanical behavior of massive concrete structures are given in the document. The recommendations have been reviewed and approved by all members of the TC 287-CCS (more than 45 at the time of publication).

This document applies to massive concrete structures, understood as concrete structures with significant volume or thickness, which can cause significant temperature variations at early ages, owing to the heat of hydration release of cement. The duration scope of analysis is limited to the period when internal temperatures of concrete are still influenced by the temperature rise inherent to cement hydration. To decide which structure should be calculated by such a model, the reader can refer to the enhanced massivity index presented in the previous section.

Several aspects of numerical modeling of concrete subjected to hydration are addressed in these recommendations and can be highlighted:

- The concepts of degree of hydration and degree of heat development and its consideration when the scope of simulation extends to longer term analyses (months or even years).
- The choice of the instant at which the numerical simulation starts, named as $t_{0,analysis}$.
- The stiffness to consider for the concrete in the very early ages before setting.
- The choice between 2D plane simulations in opposition to 3D modelling.
- The consideration of formwork.
- How to consider the terrain underlying the analyzed structural element.
- How to consider the initial temperature of the soil.
- How to consider reinforcement.
- Concrete properties and assumptions.
- Exothermy and thermos-activation of the hydration reaction.
- Dependence of thermal and mechanical properties to the hydration evolution.
- Consideration of autogenous and desiccation shrinkages.
- Consideration of creep.
- Boundary conditions and loads.
- Calculations/procedures.

These recommendations constitute an extremely important document for the engineering of massive concrete and serve as a guide for contractors and consultants to carry out structural analysis studies when the effects of hydration become relevant, especially in the early ages. Such studies aim to indicate the tendency of the so-called massive concrete structures to crack and guide engineers to the best way to organize the construction in layers with possible cooling of the concrete.

5 Concluding remarks

The three documents described above published between 2019 and 2021 are important recent references for the engineering of massive concrete structures. All these documents were produced within the framework of RILEM's technical committees with the participation of highly qualified professionals from different parts of the world. Such documents can guide contractors and consultants to the best practices of design and construction of massive structures, avoiding the cracking caused by hydration phenomena such as those caused by thermal effects and autogenous shrinkage.

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