Chapter 1
Introduction

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Abstract This chapter provides an introduction to the State of the Art Report (STAR) produced by RILEM Technical Committee 254-CMS 'Thermal Cracking of Massive Concrete Structures'. Several recent developments related to the old problem of understanding/predicting stresses originated from the evolution of the hydration of the concrete are at the origin of the creation of this technical committee. Having identified that there was a lack in the organization of up-to-date scientific and technological knowledge about cracking induced by hydration heat effects, it was decided to establish this STAR. It aims to provide both practitioners and scientists with a deep integrated overview of consolidated knowledge, together with recent developments on this subject.

1.1 General Introductory Remarks

Massive concrete structures are structures for which the effects of hydration of the cementitious materials at the early ages, such as heat generation and autogenous shrinkage, can lead to cracking. Considering the percolation threshold as the very moment when concrete becomes a solid, early-age concrete can be defined as the period after this threshold when the properties of the material are rapidly changing under the influence of hydration.

Thermal cracking of massive concrete structures is an important phenomenon, which is mostly originated and induced by matters related to the hydration reaction of the cementitious binder present in the concrete mixture.

As the hydration 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

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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. Taking into account the thermal dilation of concrete, and structural restraints to free deformations, both the 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.

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.

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. The set of aforementioned matters adequately back the claim that the temperature rise due to hydration is a very important issue in what concerns the durability of the structure.

In the past, cracking risks at the early ages were commonly faced in large structures in which hydration heat dissipation is normally slow, and therefore, high temperature rises were observed (quasi-adiabatic conditions). The types of concretes used in such types of structures had relatively high w/c ratios and therefore did not endure significant additional strains caused by autogenous shrinkage.

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 STAR, 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 tetrapods breakwaters may experience cracking induced by the hydration reaction (see Fig. 1.1).

Some examples can be taken from the literature. One very significant case was reported by Betioli et al. (1997) and concerns the Itaipú hydroelectric power plant. Itaipú, built in 1975, is the second largest power plant in the world for installed capacity (14,000 MW) and the first one for annual generation (2.3×10^9 MWh) (see Fig. 1.2).

During the construction of the buttress dam, thermal cracks have been observed, most of them vertical in the bulk of the block, and a few were located in the head of the buttress (see Fig. 1.3).

At that time, the analyses indicated that such cracking was induced by the heat of hydration observed in the field, which was considerably higher than the one assumed during the design of the dam (Rosso and Piazentin 1997). It was also

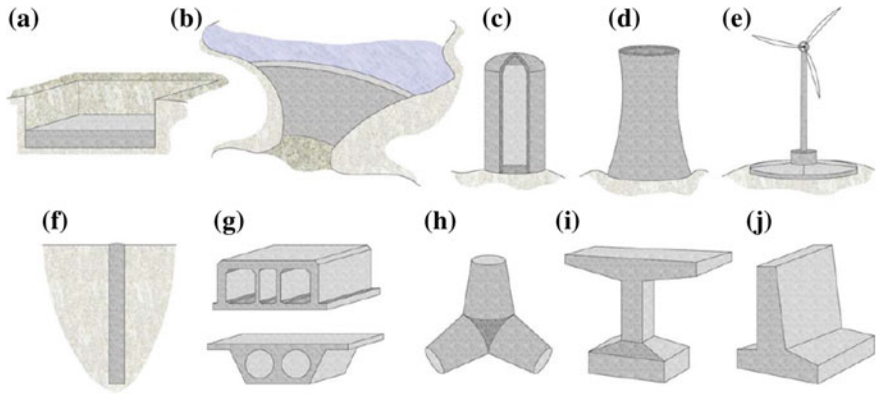


Fig. 1.1 Examples of concrete structures that can benefit from thermal simulation: **a** ground slabs; **b** concrete dams; **c** silos/containment structures; **d** cooling towers; **e** wind turbine foundations; **f** piles; **g** precast segments (top: immersed tunnel, bottom: bridge deck); **h** tetrapods units; **i** bridge piers; and **j** retaining walls. (From Sifkas et al. 2017)

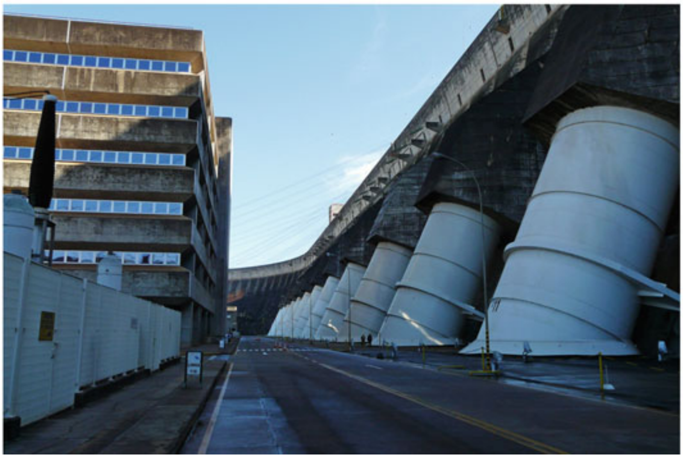
found that the models used to simulate the early-age behaviour of massive concrete were very simplified and did not take into account stress concentrations induced by the geometry. Besides limiting the placing temperature of the concrete to 7 °C, several additional measures have been undertaken such as (i) introducing a contraction joint parallel to the upstream face; (ii) changing the concrete mix design, reducing the heat of hydration and Young´s modulus for the five first lifts above the foundation; (iii) changing the height of the first three lifts from 0.7 m, 1.5 m, 1.75 m to 0.75 m, 0.75 m, 1.00 m, respectively; (iv) introducing additional reinforcement in some regions.

The existing cracks were injected with epoxy resin, and the correspondent structures have been surveyed by an intense monitoring programme. After several years of observation, it was verified that the behaviour of the cracked blocks was similar to that of the sound blocks, showing that the measures taken were sufficient to ensure the stability and safety of the dam.

Another example of cracking in massive concrete has been reported by Funahashi and Kuperman (2010) in the spillway of a small hydropower plant (see Fig. 1.4). In this case, the cracks developed in the 35 m × 15 m × 7.5 m spillway block were found to have been caused by heat of hydration-induced effects.

The analysis carried out by the authors aimed to prove that the cracks were caused by the thermal gradients originated by the heat of hydration of the cementitious material. The authors did not have detailed information about the thermo-chemical-mechanical properties of the materials, such as adiabatic temperature rise, a fact that is still relatively common in dams with lower concrete volume. However, a three-dimensional finite element analysis was performed, using estimated values based on information from materials similar to those used in the construction. This analysis considered the construction of the lifts C1 to C5 built

(a) General view of the concrete dam



(b) View of the intake

Fig. 1.2 Itaipú hydroelectric power plant. (Photographs by E. M. R. Fairbairn)

every 3 days with a placing temperature of 32 °C. The construction scheme and the finite element mesh are shown in Fig. 1.5.

Temperatures of about 61 °C were computed by the thermal analysis, and stress calculations indicated the appearance of principal tensile stresses that reached the tensile strength in the regions where the cracks were actually observed in the field. The authors concluded that the cracks could be avoided by changing the concrete mix design by reducing the cement content and consequently the heat of hydration,

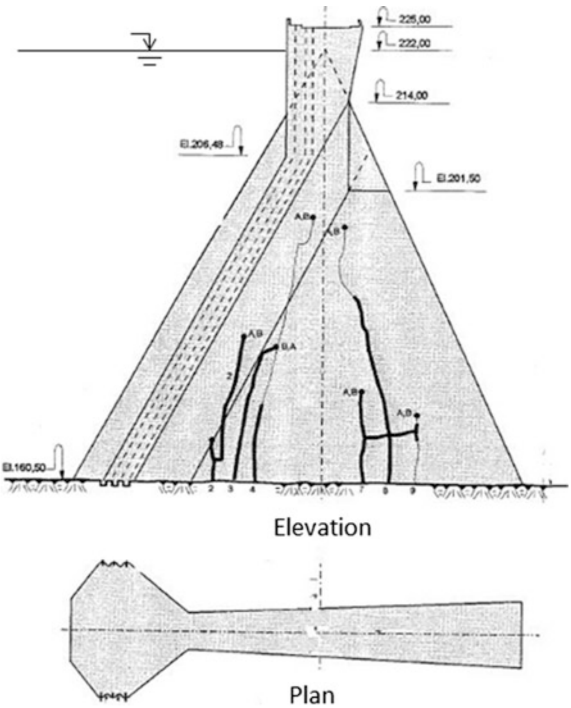


Fig. 1.3 Vertical cracks in the buttress of Itaipú Dam. (Adapted from Betioli et al 1997)

Fig. 1.4 Spillway of small hydropower plant and thermal cracking (Funahashi and Kuperman 2010)

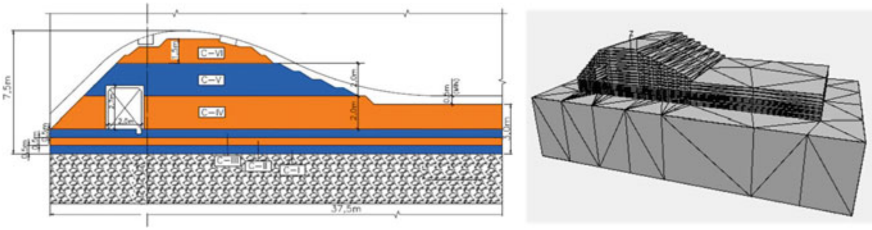


Fig. 1.5 Construction scheme and finite element mesh (Funahashi and Kuperman 2010)

and reducing the placing temperature of concrete. The authors remarked that the amount of cement could have been reduced even further if the concrete strength was not limited by minimum values at 28 days according to standards. If standards had allowed minimum compressive strength to be verified at later ages (e.g. 90 days), significant reductions of cement consumption might have been attained.

Therefore, the construction phase and the period that follows it should be accurately analysed. If cracking tendency is detected, many actions can be adopted to minimize early-age stresses, such as slowing the construction speed allowing higher heat dispersion; reducing the placement temperature of concrete; decreasing the concrete temperature by circulating water or air on pipes embedded in the bulk (post-cooling systems); and choosing a material composition that gives lower rates of hydration.

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 (Fairbairn et al 2012) (see Fig. 1.6).

The evolution of theory and modelling has naturally been accompanied by advances in the experimental methods related to the early-age phenomena in massive concrete. As an example, the mechanical analyses should initiate at the very moment when concrete can bear structurally relevant stresses, and the properties of the material must be known since then. Therefore, it has been worthy to

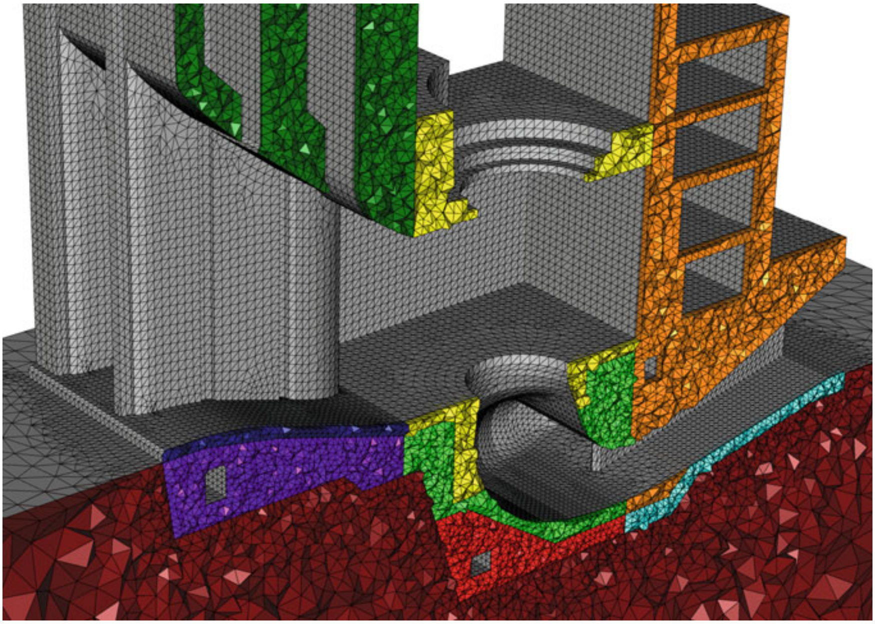


Fig. 1.6 Finite element mesh for the 3D model for the phased construction of the powerhouse of Tocoma Dam (approximately 5,000,000 elements)

develop new experimental methodologies that are dedicated to determine thermo-mechanical characteristics since the very early ages. Examples of such experimental tests can be seen in Boulay et al (2010) from where Fig. 1.7 was taken, representing a sophisticated apparatus for characterizing the early development of E-modulus of concrete (BTJASPE method).

Several other scientific and technological advances have been verified in other areas related to the control of concrete cracking in massive structures. In such context, it is relevant to mention: new techniques for temperature control and on-site monitoring; new advanced models for mix design and methods that allow the mixture proportioning optimization using computer codes; new requirements of sustainability introducing the use of a new category of green materials and practices that can contribute to the reduction of greenhouse gases emissions.

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’. Having identified that there was a lack in the systematization of recent scientific and technological knowledge about thermal cracking of massive concrete, RILEM has created this committee to provide both practitioners and scientists with a deep overview of the recent developments on this subject.

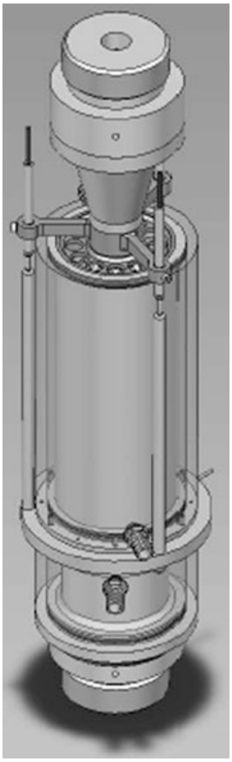


Fig. 1.7 Sketch of BTJASPE, a new testing device was designed at IFSTTAR aimed at measuring automatically the evolution of the stiffness of a concrete cylinder in compression at early age (since the setting time up to a couple of days) (Boulay et al 2012)

1.2 Presentation of 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 Chap. 2. In this chapter, the velocity 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 predict the hydration evolution of a given concrete mix, and forecast the heat release and the consequent temperature rise.

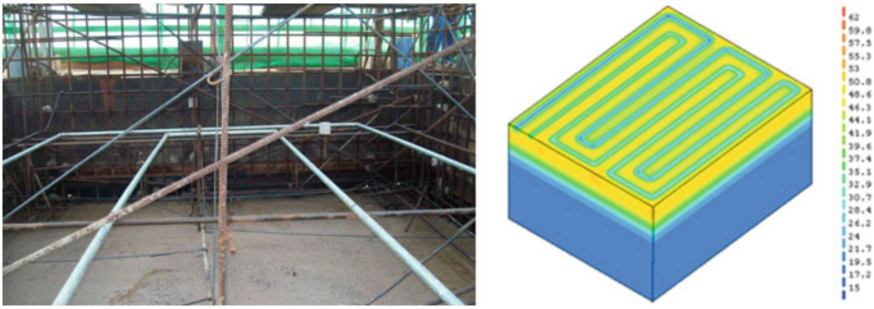
In order to better understand and predict the thermal behaviour of massive concrete structures, a sound fundamental knowledge is necessary in regard to the thermal properties of concrete. The thermal properties described in Chap. 3 are grouped into properties responsible for transport of heat and corresponding 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, taking into account both thermal and shrinkage deformations. This chapter is structured into three main subsections:

- 'Quasi-static behaviour 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.
- 'Shrinkage', covering topics of plastic shrinkage, autogenous shrinkage and drying shrinkage.
- '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. Discussions are held about the underlying creep mechanisms, with emphasis on the distinction between basic and drying creep. A final note is given to the effects of temperature on creep behaviour, normally referred as 'transient thermal creep'.

In Chap. 5, the nature, the physical–chemical properties and the contents of the concrete constituents are discussed for the understanding of the way of making an optimized concrete mix-design for massive structures, where the temperature rise must be minimized. The chapter initially makes a systematic review of materials and their relation to crack avoidance, covering aggregates, water, admixtures, cement, supplementary cementitious materials and fibres. It also incorporates two specific sections of practical issues related to mix design for conventional mass concrete and mix design for roller compacted concrete.

Temperature rises are definitely one of the most important driving forces for thermal cracking in mass concrete, together with the restraint to deformation. Therefore, amongst the most widespread measures that can be taken to minimize the risks of thermal cracking, the temperature control of concrete since its production and throughout construction is of utmost significance. Following Chap. 5 where temperature control of concrete by limiting the heat generation potential of the binder in the mixture has already addressed, Chap. 6 is dedicated to a review on measures that can be taken to control concrete temperature at several levels, mainly focused on 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 (Fig. 1.8).



(a) In the field (photograph of W. P. Andrade) **(b)** Numerical simulation (T in ºC)

Fig. 1.8 Temperatures are reduced by post-cooling system

Chapter 7 deals with the problem of modelling the behaviour 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 not only on the scale level considered but also on which phenomena/processes are taken into account. In this chapter, we limit the description to approaches/models that can be implemented using the Finite Element Method, which is still the most used numerical technique worldwide in the context of simulations for structural concrete. 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 behaviour of the material, to more sophisticated approaches which consider 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 behaviour 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 detailed information about crack spacing and opening in concrete structures in service life conditions.

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 with regard to 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 with regard to different measurement systems as well as types of structures.

The last chapter, Chap. 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 and demolition waste, as well as natural fibre alternatives to steel and synthetic reinforcements is discussed in detail.

Material 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.

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