XLIII CILAMCE
21–25, November, 2022
FOZ DO IGUAÇU – PR – BRAZIL

# Computational modeling of a mass concrete structure using a post-cooling system

Igor A. Fraga[1], Ana B. C. G. Silva[1], Eduardo M. R. Fairbairn[1]

[1]*Programa de Engenharia Civil (PEC/COPPE), Universidade Federal do Rio de Janeiro (UFRJ)*
*Av. Horácio Macedo, 2030 - Bloco I-116 - Cidade Universitária, Rio de Janeiro - RJ*
*ifraga@coc.ufrj.br, anabeatrizgonzaga@coc.ufrj.br, eduardo@coc.ufrj.br*

**Abstract.** 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. The generation of heat during hydration and the consequent increase in the temperature of concrete are important, not only because they can generate thermal gradients in space and time, responsible for the appearance of high initial stresses, but also because deleterious phenomena such as delayed ettringite formation (DEF) have been shown to be associated with the existence of thermal fields in the early ages of cementitious material. In this sense, this work will present the simulation of the construction of a mass concrete structure, on a mesoscopic scale, in which the temperature of the material is reduced during hydration by the circulation of water in pipes embedded in the formwork by a postcooling system. The simulation was based on data obtained from the construction of a concrete slab, previously builded and tested in the laboratory of FURNAS (Goiânia/GO). The computational modeling was performed using the finite element method (FEM), in a parallel environment, developed in FORTRAN programming language, by PEC/COPPE/UFRJ.

**Keywords:** post-cooling, mass concrete, numerical model, finite element method, cooling pipes

## 1 Introduction

Mass concrete structures are characterized by their differentiated behavior due to their high volume of concrete and consequently high consumption of cement. Because of that, they are more prone to cracking due to the temperature rise during the cement hydration reaction. Therefore, due to the exothermic and thermoactivated nature of the hydration reaction, such structures are subject to volume variations, which, when restricted, cause tensions that can lead to cracking of the material. In this sense, RILEM [1] defines these structures as “those in which the hydration effects of cementitious materials at early ages, such as heat generation and autogenous shrinkage, can lead to cracking”.

Thus, an in-depth and specific understanding of the behavior of such structures is fundamental for the prediction of material cracking, a fact that has motivated several researches in this field, whether applied in the experimental and/or computational area, in order to study the effects of thermal and mechanical phenomena on mass concrete, as shown in Ulm and Coussy [2], Ulm and Coussy [3], Ulm and Coussy [4], FAIRBAIRN et al. [5] and AZENHA [6].

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: one is relative to time, that is, a given point of the structure has its temperature varying over time; and 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 can be responsible for the generation and evolution of strain and stresses in the concrete elements. If such strains or stresses reach a certain limit, undesirable thermal cracks can occur.

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 prove 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

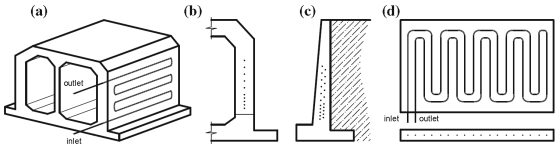


Figure 1. Examples of structures with post-cooling systems.

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 decreasing the concrete temperature by circulating water or air in tubes embedded in the formwork (post-cooling systems).

Post-cooling of concrete with embedded tubes has been applied since 1930 [7]. The objective is to control the internal temperature of the concrete within the limits specified in the project through the active circulation of water (or other cooling fluid) or air through the tubes embedded in the material, to mitigate the risk of the appearance of cracks of thermal origin. It is generally oriented towards reducing peak concrete temperatures during the hydration period, thus minimizing the volumetric variations associated with the corresponding temperature variations. The design of post-cooling systems comprises the optimization of tube properties (geometric layout, heat transfer, fluid flow, inlet/outlet temperatures) to achieve the desired peak temperature reduction with the least possible energy consumption .

Examples of structures and their corresponding typical tube layouts can be seen in Fig. 1 [8]. The technique is quite effective [1], but it has considerable design, material acquisition, installation, and effective operation costs. For this reason, its general application area is limited to larger ones, such as dams that mold internal cooling before filling/ sealing the joint [9]. The cooling system can be activated in the first days after concreting, allowing thermal control of the concrete. Other post-cooling applications include, but are not limited to, production of concrete segments for immersed tunnels, retaining walls and slabs [10] [11] [12], which are commonly used today.

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 [13].

This work will present the simulation of the construction of a mass concrete structure, on a mesoscopic scale, in which the temperature of the material is reduced during hydration by the circulation of water in pipes embedded in the formwork by a postcooling system. The simulation was based on data obtained from the construction of a concrete slab, previously builded and tested in the laboratory of FURNAS (Goiania/GO). The computational modeling was performed using the finite element method (FEM), in a parallel environment, developed in FORTRAN programming language, by PEC/COPPE/UFRJ, using the post-cooling simulation model, developed by FRAGA et al. [14].

## 2 Numerical modeling of mass concrete and post-cooling system

The numerical model used in this work is based on the theory of thermochemical and mechanical coupling proposed by Ulm and Coussy [2] in which the equations that govern the problem are deduced within the thermodynamic theoretical framework for porous media and consider the cross-effects between the hydration reaction, temperature evolution, deformations and changes in concrete properties.

Ulm and Coussy [3] consider the concrete a chemically reactive porous medium. In its initial phase it is a fluid formed by free water and air, becoming a porous solid after reaching its percolation level.

The degree of hydration $\alpha \in [0, 1]$ is a normalized variable that expresses the evolution of the hydration reaction. It can be written as a normalization of the variable $m_c$ that expresses the skeletal mass variation:

$$\alpha = \frac{m_c(t)}{m_{c_{t=\infty}}}, \quad \alpha \in [0, 1] \tag{1}$$

where $m_{c_{t=\infty}}$ corresponds to the solid skeleton mass formed $m_c(t)$ at time $t = \infty$ when hydration is complete.

According to the theory developed by Ulm and Coussy in their studies ([2]; [3]; [4]), given a mass of concrete, the description of the evolution of the hydration reaction is given, in order to consider the exotherm and thermoactivation of the reaction, from the solution of the equation of evolution of the thermal fields in a given

volume. Thus, the equation of heat over time, considering the thermochemical coupling (hydration heat generation with thermoactivation) following the theoretical framework of thermochemical couplings, can be placed in the form:

$$C_{pc}\dot{T} = \dot{Q} + L\dot{\alpha} + \lambda\nabla^2 T \tag{2}$$

where $C_{pc}$ is the specific heat of concrete, $\dot{Q}$ the flow of heat originating from some heat source (e.g. post-cooling system), $\lambda$ is the thermal conductivity, $L$ is a material constant, positive because of the exothermic nature of the reaction and $\dot{\alpha}$ is the reaction speed represented by the speed that the degree of hydration increases (derived from $m_\alpha$ with respect to time).

The term corresponding to the thermochemical coupling is $L\dot{\alpha}$ which represents the generation of heat by the hydration reaction, that is, the exotherm.
The initial fields are given by:

$$T(x, t_0) = T_0 \quad \text{em} \quad \Omega \tag{3}$$

And the boundary conditions are:

$$T = \bar{T}(\Gamma_T, t) \quad \text{em} \quad \Gamma_T \tag{4}$$

$$\mathbf{q}.\mathbf{N} = \bar{q}(\Gamma_q, t) \quad \text{em} \quad \Gamma_q \tag{5}$$

$$\mathbf{q}.\mathbf{N} = h_{pr}.(T - T_{amb}) \quad \text{em} \quad \Gamma_{C,R} \tag{6}$$

where $\bar{q}(\Gamma_q, t)$ is the flow in the $\Gamma_q$ part of the contour, $\bar{T}(\Gamma_T, t)$ is the temperature prescribed in $\Gamma_T$, a Eq. 6 represents the heat exchange by convection and radiation at the boundaries of the continuum with the environment considering an average exchange coefficient ($h_{pr}$), $\Gamma = \Gamma_T \; cup \Gamma_q \cup \Gamma_{C,R}$ and $\mathbf{N}$ is the normal outside the boundary.

Through the Eq. 2 it is possible to calculate the temperature field as a function of the heat generated, represented by the term $L\dot{\alpha}$.

It is also noted that to find the numerical solution of the Eq.2 it is necessary to calculate the hydration field, that is, it is necessary to know $\alpha$ for all time steps that you want to obtain the field of temperatures $T$. Thus, it is concluded that to solve the Eq. 2, it is necessary to first determine the hydration kinetics ($\dot{\alpha}(\alpha)$) for each time step.

Considering then the kinetics of this hydration reaction in an integrated way, through the basic model for cementitious materials, in a law like *Arrhenius*, it is writed the Eq. 7 proposed by Ulm and Coussy [2], Ulm and Coussy [3], Ulm and Coussy [4], as the equation for the evolution of the cement skeleton mass, measured by the variation of the degree of hydration with time.

$$\dot{\alpha} = \frac{d\alpha}{dt} = \tilde{A}(\alpha) \exp\left(-\frac{E_a}{RT}\right), \tag{7}$$

where $\tilde{A}(\alpha)$ is called normalized affinity and encompasses the physical effects corresponding to the increase in hydrate mass, diffusion, viscosity and the chemical affinity itself. This is the only property of concrete that is independent of temperature.

The thermoactivation effect is represented in the equation by the exponential factor as a function of temperature, $\exp\left(-\frac{E_a}{RT}\right)$, explaining that the reaction intensifies when temperatures are higher. The terms $E_a$, $R$ and $T$ are defined as the activation energy, universal constant of perfect gases and temperature, respectively. It should be noted that in this model $E_a$ is considered constant over time.

Thus, it is evident that if there is knowledge of a curve $\tilde{A}(\alpha)\; x\; \alpha$, it will be possible to solve the Eq. 2, as long as there is, for each time step, in addition to the temperatures $T$, the degrees of hydration $\alpha$.

The values of $\tilde{A}(\alpha)$, which are an intrinsic measure of the reaction kinetics, can be obtained experimentally, through adiabatic tests or through uniaxial compression isothermal tests performed at different ages.

Applying the theoretical formulation proposed by Fraga et al. [15] to implement a numerical solution of the post-cooling system, an arbitrary volume is considered, as shown in Fig. 2, consisting of two distinct materials: concrete and fluid.

It is considered this volume as a single isolated element, in order to simplify the fluid-solid interaction. Time $t_0$ is considered the instant that the fluid enters in the element, and $t_i$ the instant the fluid exits the element, determined as a function of the fluid velocity and the length of the tube section. The $\delta t$ is characterized by the exchange time between both materials, defined by the lenght of stay of a given fluid control volume inside the solid, according to Eq. 8 and Fig. 3.

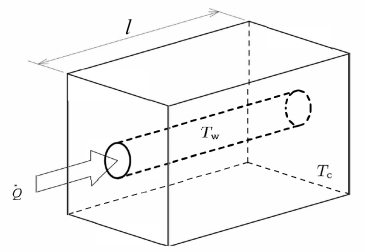


Figure 2. Concrete and tube+fluid volume specimen.

$$\delta t = t_i - t_o = \frac{l}{v} \tag{8}$$

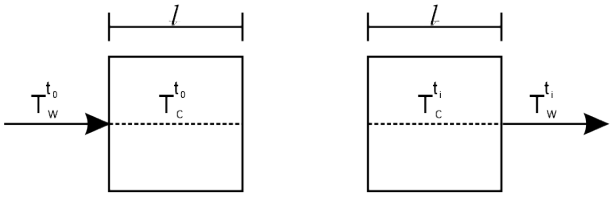


Figure 3. Temperatures at the instant $t_0$ and $t_i$.

The value of the mean velocity of the fluid $\upsilon_w$ in a tube is determined from the requirement that the conservation of mass principle be satisfied. That is,

$$\dot{m} = \rho \upsilon_w A_w \tag{9}$$

where $\dot{m}$ is the mass flow rate, $\rho$ the density of the fluid and $A_w$ is the cross sectional area.

The conservation of energy for the steady flow of a fluid in a tube can be expressed as:

$$\dot{Q} = \dot{m} C_{pw} (T_w^i - T_w^0) \tag{10}$$

where $T_w^i$ and $T_w^0$ are the mean fluid temperatures at the exit and inlet of the tube, respectively, $\dot{Q}$ is the rate of heat transfer to the fluid and $C_{pw}$ is the specific heat of the fluid.

The thermal conditions at the surface was approximated to be constant surface heat flux ($\dot{q} = constant$) and surface heat flux is expressed by Newton's law of cooling as

$$\dot{q} = h(T_c - T_w) \tag{11}$$

where $h$ is the local transfer coefficient.

Knowing that the mean fluid temperature increases linearly in the flow direction in the case of constant surface heat flux ($\dot{q} = constant$), and the surface area increases linearly in the flow direction ($A_s$ is equal to the perimeter ($P$), which is constant, times the tube length($l$)), the rate of heat transfer can also be expressed as

$$\dot{Q} = \dot{q} A_s = \dot{m} C_{pw} (T_w^i - T_w^0) \tag{12}$$

Considering that $h$ and thus $T_c - T_w$ are constant, as the fluid properties remain constant during flow, the slope of the mean fluid temperature $T_w^i$ can be determined by applying the steady-flow energy balance. In this sense, assuming $\dot{m} = \rho \upsilon_w A_w = \rho \dot{V} = \rho \frac{V}{\delta t}$, where $V$ is the fluid volume, is obtained:

$$T_w^i = T_w^0 + \frac{h(T_c^0 - T_w^0) P l}{\rho V C_{pw}} \delta t \tag{13}$$

$$\dot{q} = -\frac{\rho V C_{pw} (T_w^i - T_w^0)}{P l \delta t} \tag{14}$$

Finally, the heat flow generated is distributed in the volume of the element and is added as a new heat source to the thermochemical coupling of the program, as shown in Eq. 15.

$$Q = -\rho V C_{pw} (T_w^i - T_w^0) \tag{15}$$

In order to implement the model in the finite element program DAMTHE, the representation and application of the tube mesh is by interconnected hexahedral elements, coupled to the mass concrete structure mesh geometry, and each element will represent a control volume. Thus, to simulate the fluid flow along the pipe, the fluid inlet temperature in a given element will always be given by the outlet temperature of the previous element, according to Eq. 16 and Fig. 4.

$$T^0_{w_n} = T^i_{w_{n-1}} \tag{16}$$

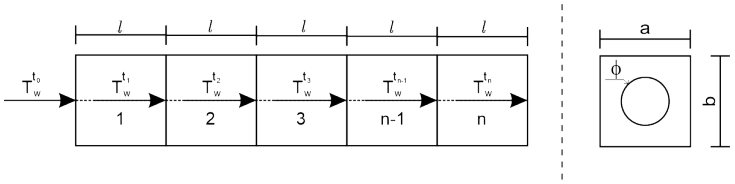


Figure 4. Longitudinal view of $n$-elements arrangement and orthogonal section of the element.

Considering that the initial temperatures at time $t_0$ will be prescribed for both materials, and that the fluid inlet temperature in the first element $T^0_{w_1}$ will always be constant, for each time step $\delta t$ a new exit temperature is calculated for each $T^i_{w_n}$ element and a heat source in the $Q_n$ element.

## 3 Application

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. 5) - as described in FAIRBAIRN et al. [17] - 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 developed post-cooling system model.

Figure 5. Slab shape tested and monitoring thermometers coupled to the LYNX platform (COPPE/FURNAS).

The temperatures measured during the experimental test were automatically obtained using the LYNX equipment from COPPE/LABEST (Fig. 5) and performed by FAIRBAIRN et al. [17]. Temperatures were recorded at the center and edge of the slab, with thermometers at variable heights.

Fig. 6 presents the geometry used for the numerical simulation of the slab. Three different materials were considered, with different thermal and mechanical properties: the soil, the concrete base and the concrete of the slab itself. Material properties are shown in the table 1.

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.7.

After this step, the temperature rise of the model was simulated using the post-cooling system.

The mesh of both simulation is defined by 145380 nodes and 132225 hexahedral elements, as shown in Fig. 6 with the first conditions of the concrete $T^0_{c_1} = T^0_{c_n} = 293K$. The inlet cooling water temperature is constant $T^0_{w_1} = 283K$ throughout the entire simulation.

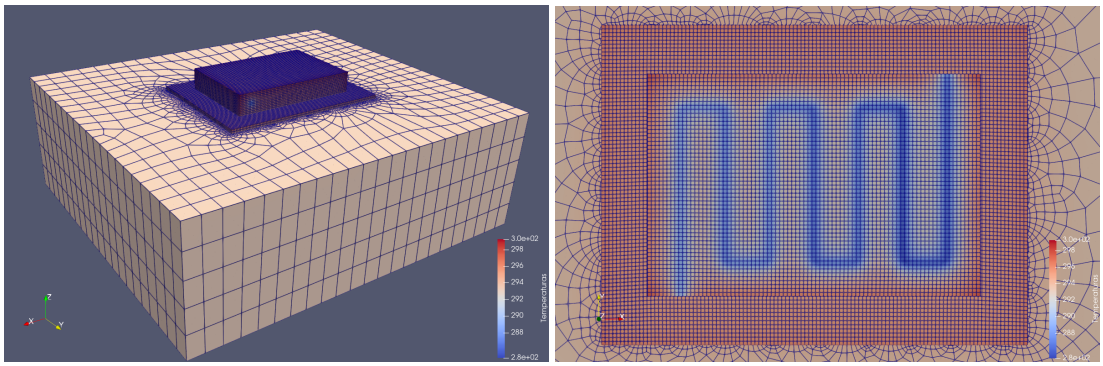

Figure 6. The finite element geometry mesh with post-cooling elements.

Table 1. Material properties: concrete and coolant (water).

| | Concrete | Tube + coolant (water) | Concrete base | Soil |
|---|---|---|---|---|
| $\sum l\ (m)$ | 12.8 | | - | |
| $l\ (m)$ | 0.036 | | - | |
| $a\ (m)$ | 0.036 | | - | |
| $b\ (m)$ | 0.036 | | - | |
| $\delta t\ (s)$ | 0.072 | | - | |
| $m\ (kg/m^3)$ | 2532 | 1000 | 2443 | 2500 |
| $C_p\ (J/kg.K)$ | 1086 | 4184 | 1005 | 800 |
| $\lambda\ (W/m.K)$ | 1.562 | 0.61 | 1.562 | 2.500 |
| $v_w\ (m/s)$ | - | 0.5 | - | |
| $\phi\ (m)$ | - | 0.0254 | - | |
| $h\ (W/m^2.K)$ | 10 | 2000 | 10 | |
| $Ea/R\ (K)$ | 4000 | - | - | |

In order to validate the model and verify the obtained results, the same conditions of the problem were simulated in the commercial finite element software *DIANA FEA*.

The Fig. 7 presents the temperature results obtained by the proposed model compared with the temperature data obtained by *DIANA FEA* to post cooling-system. In addition, the temperatures of the simulation without the post-cooling system were also presented for both softwares (DAMTHE and DIANA), and compared with the experimental data in order to validate the mesh and the simulated parameters. It is possible to verify that both results show similar behavior.

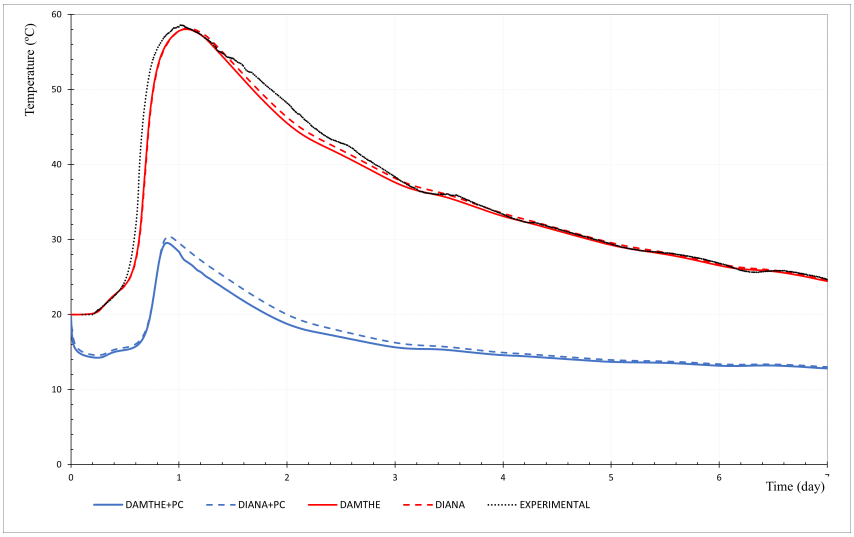


Figure 7. Temperature results at the center of the structure (25 cm) for the simulations - with and without post-cooling system - and the experimental measurements.

## 4 Conclusion

The temperature results obtained by the implemented model, compared with the temperature data obtained by *DIANA FEA* show similar behavior, both for the hydration model without the post-cooling system, as well as for the use of coolant during the hydration period.

In this way, the formulation and implementation proposed by the authors shows a promising approach that will allow a significant reduction in the computational processing time of macro-scale models, thus enabling the analysis of structures in less time and at a lower computational cost.

Numerical modeling of post-cooling allows significant savings in the construction of large structures. Thus, developing a predictive cracking model that incorporates concrete cooling at early ages is extremely important to minimize the appearance of stresses that exceed the resistive capacity of the element and future pathologies.

In the future, the model will be assign to simulate the construction of a mass concrete structure that used post-cooling system during its construction. The experimental data obtained during its execution will be used as input parameters for the simulation and comparison of the temperature rise over the time will be made.

## References

[1] RILEM. *Thermal Cracking of Massive Concrete Structures: State of the Art Report of the RILEM Technical Committee 254-CMS*. Springer International Publishing, 2018.

[2] F. J. Ulm and O. Coussy. Modeling of thermochemomechanical couplings of croncrete at early ages. *Journal of Engineering Mechanics (ASCE)*, pp. 785–794, 1995.

[3] F.-J. Ulm and O. Coussy. Strength growth as chemo-plastic hardening in early age concrete. *Journal of Engineering Mechanics (ASCE)*, vol. 122, pp. 1123–1132, 1996.

[4] F.-J. Ulm and O. Coussy. Couplings in early-age concrete: from material modeling to structural design. *International Journal of Solids and Structures*, vol. 35, pp. 4295–4311, 1998.

[5] E. FAIRBAIRN, M. SILVOSO, R. TOLEDO, J. ALVES, and N. EBECKEN. Optimization of mass concrete construction using genetic algorithms. *Computers and Structures*, vol. 82, pp. 281–299, 2004.

[6] M. AZENHA. *Numerical Simulation of The Structural Behaviour of Concrete Since Its Early Ages*. PhD thesis, Faculdade de Engenharia da Universidade do Porto, Porto, 2009.

[7] A. C. I. ACI. *Guide to mass concrete.* ACI Manual of Concrete Practice, 2005a.

[8] I. P. Sfikas, J. Ingham, and J. Baber. Msimulating thermal behaviour of concrete by fea: state-of-the-art review. vol. , 2016.

[9] ICOLD. Bulletin 76, conventional methods in dam construction. vol. , 1990.

[10] J. Baber, T. A. M. Salet, and J. K. Lundberg. Øresund tunnel control of early age cracking. vol. , 1998.

[11] J. K. Kim, K. H. Kim, and J. K. Yang. Thermal analysis of hydration heat in concrete structures with pipe cooling system. vol. , 2001.

[12] R. Lunniss and J. Baber. Immersed tunnels. vol. , 2013.

[13] E. M. R. Fairbairn, M. M. Silvoso, E. A. B. Koenders, F. L. B. Ribeiro, and R. D. Toledo-Filho. Thermo-chemo-mechanical cracking assessment for early-age mass concrete structures. *Concrete International*, vol. 34, pp. 30–35, 2012.

[14] I. FRAGA, A. SILVA, and E. FAIRBAIRN. Computational modeling for simulation of post-cooling systems in mass concrete structures. *Proceedings of the XLII Ibero-Latin-American Congress on Computational Methods in Engineering ISSN 2675-6269*, 2021.

[15] I. A. Fraga, A. B. C. G. Silva, and E. M. R. Fairbairn. Formulação numérica para simulação de sistemas de pós-resfriamento em estruturas de concreto massa. *XLI Ibero Latin American Congress on Computational Methods in Engineering*, vol. , 2020.

[16] Y. A. CENGEL. *Heat transfer: a practical approach*. Mcgraw-Hill, 2002.

[17] E. FAIRBAIRN, R. TOLEDO, M. SILVOSO, and E. SILVA. Fissuração do concreto a poucas idades: modelagem mecânica, numérica e experimental. *Relatórios Diversos, Fundação COPPETEC*, 2009.