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A Study of Thermal Cracking in The Buttresses Blocks in Itaipu Dam: Thermochemical-Mechanical Numerical Analysis

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Abstract. The Itaipu hydropower plant is a world leader in clean and renewable energy. One of the main structures is the right bank dam, which is composed of buttress blocks. It was built in 1978 and in 1980 the first cracks were already observed. The thermo-mechanical model, which predicts an increase in temperature inside the concrete mass due to the hydration of the cement, explains the thermal stresses in these dam blocks. In order to validate this model and verify if those cracks in Itaipu buttresses are thermal cracks, the block was modeled in DamThe software in 3D simulating the D38 block. The 3D simulation achieved results that are close to those observed in the field regarding the position of cracks in the blocks and the temperature developed inside the blocks, compared to the temperatures observed in the thermometers. The model, already verified in previous works, was validated, as it was able to predict the temperatures and the tendency to crack. This indicates that it is a reliable program for designing structures and anticipating undesirable cracks in massive concrete structures. It was also noticed that the cracks have a thermal origin and may have a mechanical contribution, but not exclusively.

Keywords: Thermal cracking, massive concrete structures, Itaipu Dam

1 Introduction

The combination of heat of hydration and environmental conditions, autogenous shrinkage and boundary conditions can cause volumetric changes or thermal stresses. Whenever these stresses reach the tensile strength of concrete, cracking occurs, which may impair the maintenance and durability of massive structures.

There are several types of structures that can be considered massive structures. This term is defined by Fairbairn and Azenha [1] as structures for which the effects of cementitious materials at early ages, such as heat generation and autogenous shrinkage, can lead to cracking [20]. Some examples of these structures are: concrete dams, slabs, retaining walls, bridges and pillars, spillways, etc.

Thermal cracking of massive structures is a common problem and can be analyzed by modeling the structure, using, for example, FEM software. The simulation can predict the thermal stresses that could become greater than the tensile strength, causing the cracks. Therefore, it is important to model the structure prior to construction and, if necessary, add some preventive measures to avoid cracking.

2 Numerical modeling of the concrete

The cement matrix is a reactive porous medium according to Coussy [2]. In this medium, the clinker grains are hydrated, forming Hydrated Calcium Silicates (C-S-H), Portlandite (Calcium Hydroxide), in addition to generating heat. Cement hydration is highly exothermic and is also thermoactivated, which means that the evolution of temperature influences the kinetics of hydration. Cement hydration is shown in eq. (1) below:

$$cement + H \rightarrow C - S - H + CH + heat. \tag{1}$$

The concept of hydration degree is defined by Silva [3] as the advancement of hydration reactions. The experimental determination of this parameter can be made by adiabatic tests. In these experiments there isn't any external source of heat, and the exothermic nature of the hydration reaction is the only responsible for the increase in temperature in the system. This phenomenon can be described by the formulation of the thermochemical coupling Ulm and Coussy [4, 5] presented in eq. (2):

$$C_{\varepsilon} \cdot \frac{dT}{dt} = Q^{0} + L \cdot \frac{d\xi}{dt}. \tag{2}$$

where Cε = thermal capacity; T = temperature; t = time; Q0 = heat transfer rate from external environment; L = constant of the material, which is always positive due to the exothermic nature of the hydration reaction; ξ = degree of hydration. Water microdiffusion is controlled by the thermodynamic imbalance between free water and the combined water in the solid skeleton. This phenomenon of chemical affinity is also amplified by thermoactivation and Arrhenius' Law is used to model this process, as shown in eq. (3):

$$A_{m} = \eta \cdot \frac{dm}{dt} \cdot \exp\left(\frac{E_{a}}{RT}\right). \tag{3}$$

where Ea = activation energy; R = universal gas constant; η = viscosity measurement.

In the formulation of thermochemical coupling of Ulm and Coussy [4, 5], some properties that govern heat transfer and the consequent changes in temperature in the system are presented. The thermal properties of the concrete depend on the individual properties of each component and the dosage of the mixture. Some of the properties that influence temperature increase are: thermal conductivity, thermal capacity, and coefficient of thermal expansion. This last coefficient is responsible for predicting the volume change in structures due to thermal gradients. For the calculation of stresses, the thermochemical coupling is presented in eq. (4), combining the thermochemical coupling model of Ulm and Coussy [4, 5] and the creep effects of Hellmich [6] and Sercombe et al. [7].

$$d\boldsymbol{\sigma} = \mathbf{C}(\xi) : (d\boldsymbol{\varepsilon} - d\boldsymbol{\varepsilon}^{P} - d\boldsymbol{\varepsilon}^{f} - d\boldsymbol{\varepsilon}^{v} - \mathbf{a}dT - \mathbf{b}dm). \tag{4}$$

where C(ξ) = tensor of elastic stiffness as a function of the degree of hydration; ε = deformation tensor; εP = plastic deformation tensor; εf = long-term creep tensor; εv = short-term creep tensor; a = CTD . 1 , CTD is the coefficient of thermal dilation; b = β . 1 is the tensor of the chemical dilation coefficient and β is the coefficient that correlates hydration with autogenous retraction. At the origin of thermal stresses, two types of different thermal gradients that occur in massive structures can be highlighted. One is relative to time, since as time passes, there is a stage when the temperature is increasing and other when it is decreasing due to cement hydration. In the first stage, the concrete is younger than in the following stage, so the mechanical properties are lower. This means that in the second stage, when cooling down, the stresses are greater than the first stage. If this difference reaches tensile strength (also dependent on the degree of hydration), cracking can happen. The second gradient is the spatial gradient, since at a given time, there may be a temperature difference between different points of the structure. If the structure has constraints in the direction of these points, the stresses are generated to compensate for the tendency to expand or shrink.

3 Case study

Itaipu Binacional is the world leader in clean and renewable energy, because it has produced more than 100 million MWh of annual generation and more than 2.5 billion MWh since it began operating (1984). Itaipu has 20 generating units, each capable of generating 700MW. Totaling, the hydroelectric plant has 14,000 MW of installed power and supplies 15% of the energy consumed in Brazil and 86% of the energy consumed in Paraguay. The Itaipu reservoir, with a flooded area of 1350 km², is the seventh largest in Brazil, but has the best water utilization coefficient for the generation of electricity of all large Brazilian reservoirs [8]. The dam is the structure that serves to harness the water and get the difference in levels of 120 m that allows the operation of the turbines. There are structures made of concrete, rock fill and embankment. The complex is 7919 meters long and a maximum height of 196 meters. During construction, it consumed 12.3 million cubic meters of concrete. The concreting was quite fast and the volume of concrete placed in just one day reached 15,000 m³ and, in a single month, 340,000 m³ [8]. The buttress dam constitutes the Right Bank Dam and the right and left side connection dam, as shown in the General Plant in Fig.1. The construction of the right bank dam began in November 1978, when the first blocks of buttresses (D27 to D30) were built. The first cracks were noticed in these same blocks by visual inspection in August 1980. There were cracks in 34 of the 47 blocks built beyond El. 190m on the right bank. There were also cracks in the connection dams in the right and left sides. The cracks were located mainly in the buttresses and sometimes on the heads of the blocks. They were vertical, began at the foundation and were located in the thirds upstream or downstream of the base. The cracks were not deep, had an opening of 0.3 to 0.9 mm and the most significant were 10 to 20 m long. At the time, a research and control program was developed, which included mapping, samples extraction and other monitoring tests, according to Betioli *et al.* [9].

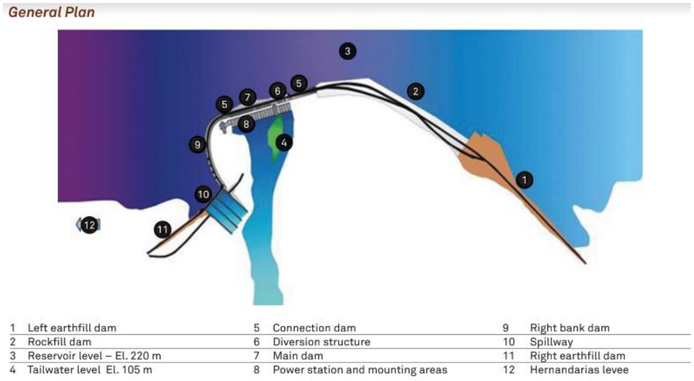


Figure 1. General Plan Itaipu hydropower plant – Andriolo and Bertioli [8]

3.1 Concrete properties

The characterization of the concrete used in the construction site was carried out by the Itaipu Laboratory, where several technological tests were made, such as adiabatic tests, tests to obtain thermal properties, shear test, bending tensile strength, compressive strength, creep, autogenous shrinkage, etc. The detailed characterization combined with the extensive experience in the construction of dams in Brazil determined the proper dosage of concrete.

The value of activation energy E_a/R was admitted as 4000K, according to Fairbairn and Azenha [1], and the main values of the properties are summarized in Tab. 1.

Table 1 - Characterization of concrete types A-140f and A-210f

Property	A-210f	A-140f
Cement (kg/m³)	162	108
Fly ash (kg/m³)	19	13
Water (kg/m³)	86	85
w/c	0.45	0.67
Dmax (mm)	152	152
Design compressive strength at 360 days (MPa) $f_{ck,360}$	21	14
Thermal conductivity (W/m.K)	1,6987	2,05
Specific heat (J/kg.K)	1029,95	1021,58
Thermal expansion coefficient	9x10-6	9x10-6
Specific mass (kg/m³)	2622	2622
Young's Module (GPa)	41,76	44.70
Tensile strength by diametral compression (MPa)	2,96	2.03
Poisson coefficient	0,198	0.21

J_{∞}^{ve}	9,75x10-12	14,25x10-12
$\tau_{w,\infty}$ (days)	8,5	10
H_V	0,25	0,14
$\overline{T}$ (°C)	20	20

Source: Itaipu [8, 10, 11, 12, 13]

Data on adiabatic tests were adjusted in a Hill Function, given in eq. (5):

$$\text{For a given } T^{ini} \qquad \Delta T^{ad}(t) = \Delta T^{ad}_{max} \cdot \frac{t^n}{k^n + t^n} \tag{5}$$

where T^{ini} is the pouring temperature; ΔT^{ad}_{max} is the maximum temperature rise obtained in the adiabatic test; t is time; k and n are adjustment parameters.

The adjustment parameters used in the concrete curves are given in Tab. 2 and the adiabatic rise curve in Fig. 2.

Table 2 – Parameters of Hill Function

Parameter	A-210f	A-140f
ΔT^{ad}_{max}	25,4 °C	16,54 °C
T^{ini}	7,87 °C	7.18 °C
k	2,598325	2,193955
n	1,528765	1,075983

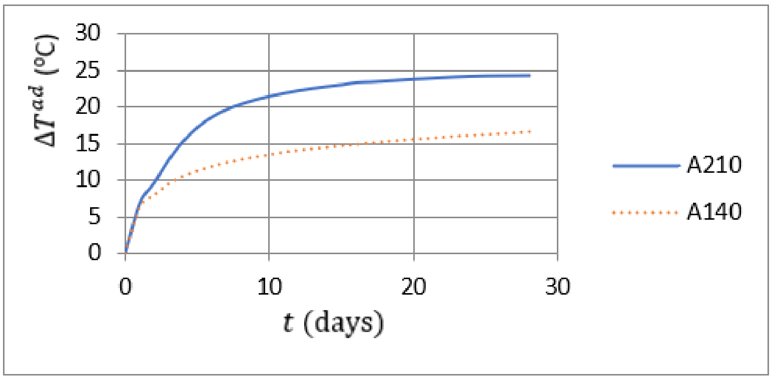


Figure 2. Adiabatic raise of concretes A-140 and B-210

4 Methodolody

A block of the right bank dam was chosen to simulate its construction using the DAMTHE Finite Element software implemented in the Fortran language, developed by PEC / COPPE / UFRJ [14, 15]. This software contains a high-performance numerical model for the problem of thermos-chemo-mechanical concrete couplings in the early ages, and can be applied to simulate large constructions such as dams. The model combines, within thermodynamics, the various phenomena that intervene in the hydration reaction, such as: exothermicity, thermo-activation and dependence of thermal and mechanical properties in the advancement of the hydration reaction [16]. The computational code also allows the simulation of construction by layers, considering variations in geometric and boundary conditions with the time elapsed since the beginning of the analysis.

The buttress block chosen was the D38, because it is well instrumented and has 3 surface thermometers and an internal one, besides having the cracking map. The block was modeled in 3D, applying specific boundary conditions of concrete mass structures. The effects of creep, as proposed by Hellmich [6], and Sercombe et al, were also considered. [7]. The output data of the problem were temperature and cracking index at each instant. A period of 1370 days was simulated since 90 days before the beginning of the construction of block D38 and different time intervals were used at each construction stage to observe the phenomena. The geometry was discretized with 77722 nodes and 429372 tetrahedral elements. The simulations observed the characteristics of the concretes used, the history of the ambient temperature on the site, and also the construction schedule of the block. Several simulations were made to test hypotheses and make a sensitivity analysis of the model. Only 1 was chosen to be reported in this study, because it presented interesting conclusions about the use of the model, other interesting results without finding in the thesis of Valentim [17].

The cracking index represents the tendency to crack for any element at any time, as shown in eq. (6):

$$I_{cr}(\alpha(t,x,y,z),x,y,z) = \frac{\sigma_1(x,y,z,t,\alpha(t,x,y,z))}{f_t(x,y,z,t,\alpha(t,x,y,z))} \tag{6}$$

in which: σ_1 is the maximum positive principal stress at a given point (x,y,z) at time t,which is as a function of the degree of hydration α at this point and time; and f_t is the tensile strength at the same point and at the same time, which is also a function of the degree of hydration at this point and time.

The cracking index is calculated in the elastic band for each time interval and for each element, even if it is greater than 1, when the tensile stresses exceed the tensile strengths. The program does not compute the post-cracking behavior (evolution of the crack) of the structures. The goal is basically to know if, at any time, the structure was cracked, so there is no need to use a sophisticated model of fracture mechanics, which simulates the evolution of the damage caused by the cracked concrete. In this case, the cracking index was computed cumulatively, which means that if at any time the value of 1 is reached, the index will receive this maximum value.

5 Results

5.1 Temperature evolution

This simulation was developed with the data collected in Itaipu, considering the history of environmental temperature and the creep model of SERCOMBE *et al*. [7]. Fig. 3 shows the cracking index for this simulation, and the triangles represent the elements that cracked at some point during the simulation.

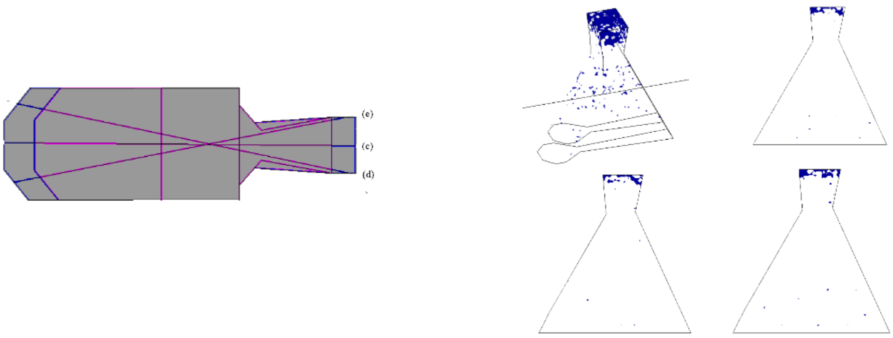
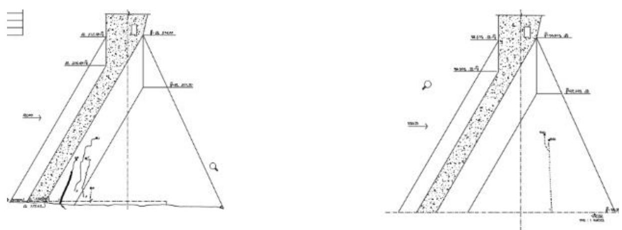


Figure 3. Cracked elements in simulation

On the right side there are few cracked elements in the head of the block. On the left side, there are some cracked elements in the buttress. Some of these cracks extend into the middle of the block as seen in the central cut. The surface that presents many cracked elements shows that it suffers from seasonal variations, but it is noted that these cracks are only superficial, because 20 cm inside, it is no longer possible to visualize them. If they happened, they probably weren't even visible and closed quickly with cement hydration. Fig. 4 and Fig. 5 show the mapping of the cracks on the right and left faces, respectively.



Figures 41 and 5. Crack mapping - Block D38 - Right and left face- Source: Menezes And Akio [18, 19]

There were cracks in the head on the right side and in the buttress on the left side as shown in the simulation. In the result, the top of the block had a significant crack, which occurred mainly after 400 days, as can be seen in Fig. 6, with the block at 350 days. These cracks also did not penetrate deep into the block. In the cracks mapping seen in loco, this behavior was not observed. This can be explained by the fact that above the block, there is actually a concrete slab that allows the transit of vehicles on the top of the entire dam. The protection of this structure and the static and dynamic overload of the vehicles were not applied in this and any of the simulations of this work. Visualizing the slab in loco, it is quite cracked due to seasonal variations and vehicle traffic, among others. However, it is important to note that the itself block is intact and the cracks on the road do not cause any damage to the structure. What the simulation is revealing is one of the phenomena that happens with the road, which is the action of temperature. How the block is protected by the slab, the cracking presented in the simulation should not be worrisome.

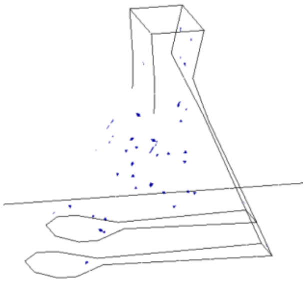


Figure 6. Cracked elements in simulation 1 at 350 days

Figure 7 shows the comparison of the internal temperature obtained by the simulation and the temperature of the internal thermometer TI-D-001. This graph illustrates that there was a difference of 3°C between the temperature curve obtained by the simulation and the temperature history extracted from the internal thermometer. This difference can be explained by the fact that this environmental temperature was extracted from a station. It is reasonble to say that in the vicinity of the construction site the temperature was 3°C higher. Nevertheless, the waves that represent the internal temperature of the concrete mass and the temperature of the internal thermometer have the same kinetics: same amplitude, same phase and wave period. They are only displaced from this value of 3°C on the vertical axis.

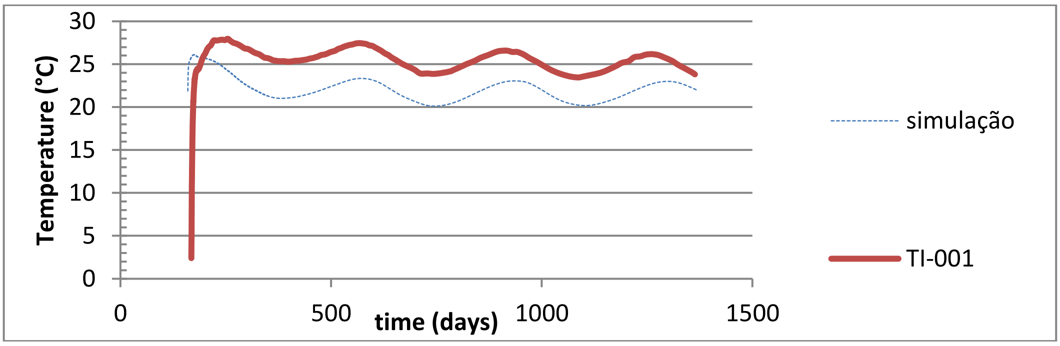


Figure 7. Simulation - D38 - Internal Temperature x Time

6 Conclusions

In this study that 3D simulations were conducted, the data were collected within Itaipu Binacional and it was possible to choose a specific block to model, the D38 in the right bank dam. More than 60 simulations were made as a test to choose the ones that presented robust results, with only 1 of them presented here. The simulation reproduced several data of the material used in the construction, in addition to the schedule of construction of the block and boundary conditions, with satisfactory results, since the internal temperature obtained was similar to that measured by the internal thermometer and the cracks were also located in regions similar to those of the cracking maps drawn at the time of observation. It is worth mentioning that this work aimed to study the case of cracking the buttress block of the Itaipu dam and to validate the model that predicts cracking in massive concrete structures. The study was relevant, because it was possible to observe the real cracks in the block. This way, the results obtained by the model and on the construction site could be compared and the model implemented in DamThe was validated. DamThe software can be used safely to predict structural cracks in the design phase, avoiding future pathologies and expenses with structural repair or recovery.

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