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BELO MONTE HYDROPOWERPLANT - TEMPERATURES AND THERMAL STRESSES ANALYSIS OF THE INTAKE

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Abstract. *The total concrete volume of the Belo Monte hydropower plant is 2.847.720* m^3. *In order to minimize the probability of occurrence of thermal cracking as well as to avoid the eventual formation of delayed ettringite formation, maximum temperatures of fresh concrete were specified in the several concrete structures of the project.*

This paper presents an evaluation of the thermal behavior of the concrete structure of the intake of Belo Monte HPP during its construction and compares the temperatures measured by installed thermometers and the calculated theoretical temperatures. Theoretical temperatures and derived stresses were calculated using a three dimensional finite element method software.

Thermal stresses analysis considered several parameters such as the constructive methodology, thermal and mechanical properties of concrete, type of curing and formwork, heat of hydration of cement, adiabatic temperature rise of concrete and local environmental conditions. The thermal analysis was fundamental to define the concreting plan. Derived from the calculated temperatures the resulting thermal stresses were important to fix the concrete cooling plan to be adopted and to reduce the risk of thermal cracking.

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1 INTRODUCTION

The Belo Monte hydroelectric plant, built in Altamira and Vitória do Xingu, in the state of Pará, is one of the largest engineering works executed in the last decade in Brazil. The total concrete volume of the Belo Monte HPP is 3,570,000 m^3. It is the third largest installed power plant in the world, behind the Three Gorges hydropower plant in China, and Itaipu, between Brazil and Paraguay. The Belo Monte HPP has been in operation since April 2016 and with 14 of its 24 generating units in full operation. It will have eighteen generating units in the main powerhouse, with an installed capacity of 11,000 megawatts (MW), and six in the complementary powerhouse in Pimental area, with 233 MW, totaling 11,233 megawatts.

Maximum temperatures of concrete placements were set in for several structures of the project in order to minimize the probability of occurrence of thermal cracking as well as to avoid the eventual formation of delayed ettringite.

In mass concrete structures, the evolution and distribution of temperatures in any section of the structure, allied to the thermal gradient either internal or external, at any instant can result in thermal cracking. One of the most important factors associated with thermal cracking in mass concrete structures is the evolution and distribution of temperature increase throughout the section at any time after its placement. The temperature increase is a direct consequence of the evolution of the hydration heat of the cement. [1]. Since concrete is a solid body, the temperature and heat flux distributions follow the principle of energy conservation, which can be described by the Fourier model. In this way, concrete tends to equate its temperature with the ambient temperature, resulting in a thermal gradient and consequently in a thermal shrinkage that, when restrained, can generate tensile stresses higher than those supported by the material.

The tensile stresses resulting from high temperature gradients can form a crack in massive concretes. The formation of this framework impairs both the bearing capacity and the durability of the structure and, in hydraulic constructions, leaks can occur through these cracks, impairing its performance and durability. In order to avoid its occurrence, it is necessary to use suitable materials, including concrete cooling, besides the study and elaboration of a suitable executive plan to minimize this type of pathology.

The thermal studies consist of analyzes of temperatures and stresses arising respectively from the release of heat generated by the cement hydration and the respective thermal shrinkage of the concrete. Basically, the thermal studies are divided in two stages: a) calculation of the temperature changes of the concrete and b) analysis of the resulting thermal stresses and / or deformations in the structure when it cools.

In practice, the main challenges of mass concrete design are how to fix the maximum height of concrete layers and time intervals between placements without resulting in the occurrence of cracking. [2]

The basic parameters that influence the design and analysis of mass concrete structures in general are: cement type (heat of hydration); cement content per m^3 of concrete (adiabatic temperature rise); aggregate lithology (thermal diffusivity); room temperature; concrete placement temperature; geometry of the concrete structure; height of concrete layers; placement time interval between the concrete layers; coefficient of superficial transmission of temperature (type of cure and forms), among others.

2 SCOPE

This work presents an evaluation of the thermal behavior of the concrete structure of the water intake slab of the Belo Monte Power Plant between EL. 60.50 and EL. 64.50, located at the Belo Monte site during its construction. A comparison is made between the temperatures measured through installed temperature sensors and the temperatures calculated through a three-dimensional finite elements model. The b4cast software, version 5.10, was used for the studies of temperature and stresses evolution, in which a simulated construction method similar to the one applied at the site with three-dimensional thermal flow, was simulated.

3 CONCRETING SCHEDULE

For the mathematical modeling of the water outlet structure, it was considered the heights and volumes of the concrete layers listed on Table 1 and Figure 1.

Lift number	Maximum lift height (m)	Initial elevation (m)	Concrete volume (m³)	Concrete class	fck (MPa/days)
C61	0.40	60.50	311	G	25/90
C62A	1.50	60.90	1159	G	25/90
C63	1.60	62.40	527	G	25/90
C64A	0.50	64.00	386	G	25/90

Table 1: Concrete schedule adopted for thermal calculation

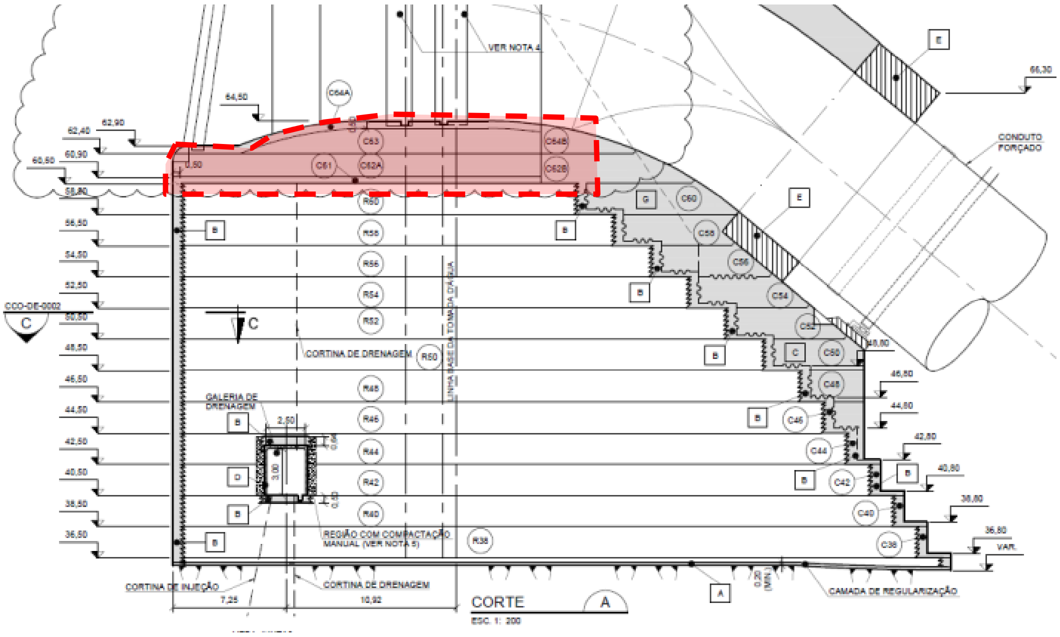


Figure 1. Longitudinal section of water intake slab UN01 to UN18 (Belo Monte site) - Simulated region and concreting layers [5]

For the study of possibility of cracking, it was considered the concreting of the slab of the water intake from elevation 60.50 to elevation 64.50, adopting the total length of the structure of 23.6m upstream, to the joint construction and a width of 33m.

It was adopted the use of fixed forms considering the maximum release interval of 5 (five) days between the concrete layers.

Figure 2 shows the concrete zoning and layers adopted for the slab of the water intake and used in the simulations.

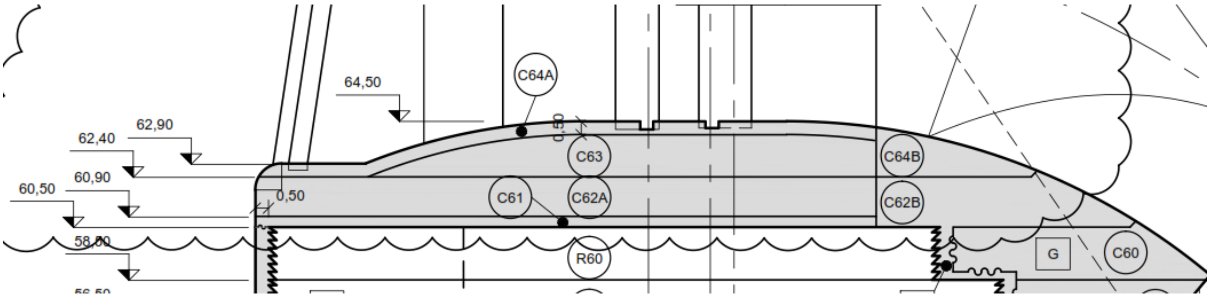


Figure 2. Zoning of concrete lifts - Detail of the longitudinal section of part of the water intake slab from Unit 01 to Unit 18 (Belo Monte site), Belo Monte site indicating the concrete lifts. [5]

4 THERMAL AND MECHANICAL CHARACTERISTICS - THERMAL STUDY

Table 2 shows the concrete mix design used in the thermal simulations.

Material f_{ck}=25MPa at 90 days	Mix design G class (thermal study)	 G class (site)
Cement	179	154
Fly Ash	59	51
Cement Equivalent	**261**	**224**
Water	138	114
Natural sand	172	-
Artificial sand	407	465
Aggregate 25 mm	565	318
Aggregate 50 mm	846	566
Aggregate 64 mm	-	727
Admixture 1	2.096	1.800
Admixture 2	0.180	0.200
Water-cement equivalent ratio	0.529	0.508
Specific mass	2391	2416

Notes: f_{ck} = characteristic compressive strength;

Table 2: Concrete mix design - Slab of the water intake - Belo Monte HPP [6]

Table 3 shows the estimated compressive strength, tensile strength and modulus of elasticity data for thermal simulations. The average tensile strength was calculated as 10% of the compressive strength.

Age (days)	f_{ck}=25 MPa/90 days f_{cj} (MPa)	 f_{ct} (MPa)	 E_c (MPa)
1	1.6	0.2	0
3	18.1	1.8	21700
7	24.1	2.4	25100
14	26.1	2.6	26125
28	28.1	2.8	27150
90	31.4	3.1	28500

Notes: f_{cj} = average compressive strength; f_{ct} = average tensile strength; E_c = average modulus of elasticity

Table 3: G class concrete - Mechanical characteristics of concretes adopted for the thermal study [6]

The Poisson coefficient adopted was 0.21 for all concrete classes. For the calculation of thermal stresses the effect of the concrete creep was not considered.

From the expected mix design, the values of specific heat (c) and thermal conductivity (k) of concrete were estimated considering the weighted average of the individual values of specific heat of each material constituent. The specific heat and thermal conductivity values were estimated to be 0.98 kJ/kg ° C and 8.95 kJ/m.h°C, respectively.

The coefficient of adiabatic temperature rise for the concrete class G (°C/kg/m³) was obtained from the tests of adiabatic temperature rise for the reference concrete with the same type of cement and a content of 357 kg/m³. The coefficient of adiabatic temperature rise of the class G concrete was estimated as shown in Figure 3.

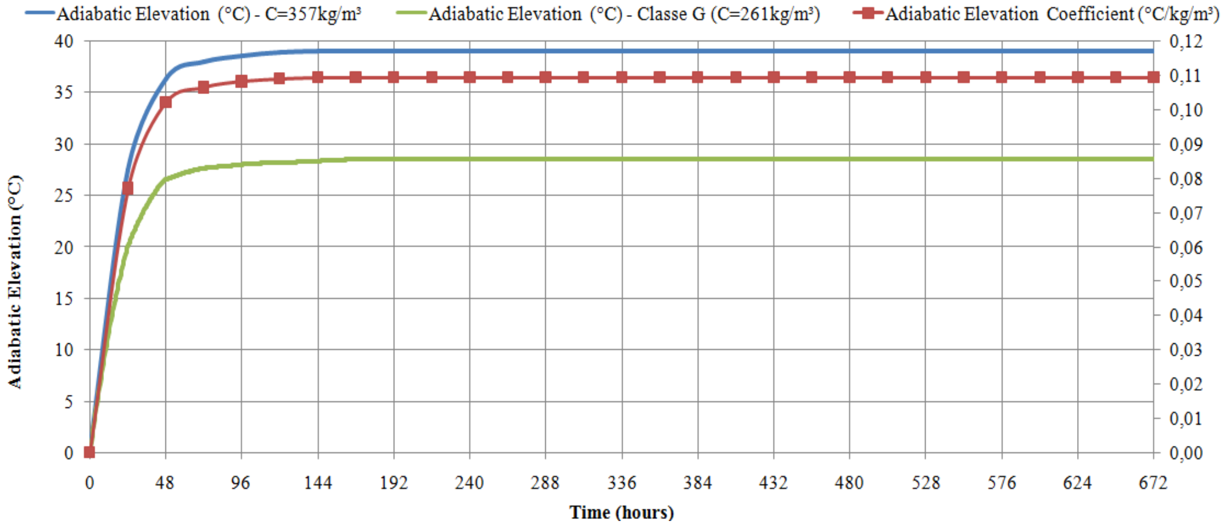


Figure 3. Estimated coefficient of adiabatic temperature rise for the concrete class G [6]

The coefficient of thermal expansion was calculated from the weighted average of the coefficients of thermal expansion of each material present in the concrete, as shown by the following expression:

$$\alpha = \frac{m_{paste} \cdot \alpha_{paste} + m_{sandi} \cdot \alpha_{sand} + m_{gravel} \cdot \alpha_{gravel}}{m_{paste} + m_{sand} + m_{gravel}} \qquad \textbf{(Equation 1)}$$

Where: m_i = mass of each component (kg/m³) and α_i = coefficient of thermal expansion of each component (x10-6/°C). The coefficient of linear thermal expansion of the paste (α_{pasta}) was calculated according to the water/cement ratio (w/c) [3]. The estimated value for the linear coefficient of thermal expansion for concrete class G is 9.4×10^{-6}/°C.

4.1 BOUNDARIES CONDITIONS

The slab of the water intake was considered to be placed over an old concrete base and its characteristics are shown in Table 4.

Characteristics of hardened concrete	
Parameters	Values
Specific mass (kg/m³)	2391
Specific heat (kJ/kg.°C)	0.90
Thermal conductivity (kg/m.h.°C)	9.60
Modulus of elasticity (GPa)	28.5
Compressive strength (MPa)	31.4
Coefficient of Thermal expansion(10^{-6}/°C)	9.4
Poisson coefficient	0.21

Table 4: Characteristics of hardened concrete [6]

For the calculation of thermal stresses it is relevant to know the history of the temperatures of the region. The average ambient temperature for the thermal simulations was adopted for the Altamira-PA region ranging from 25°C to 27°C, in addition to the average wind speed of 10 km/h. The formworks were simulated as being placed at the beginning of the concreting and removed 120 hours after the concreting of each layer. Curing with water was started 5 hours after the end of the concreting of each layer and finished 2 hours before the beginning of the next layer. The maximum curing period was 14 days, by flooding. The coefficients of surface transmission adopted are shown in Table 5.

Heat transfer coefficient	
Type of exchange	Surface heat transfer (kJ/m².h.°C)
Concrete - air	48.6
Concrete - curing water	1256.0
Concrete - form + wind	16.4

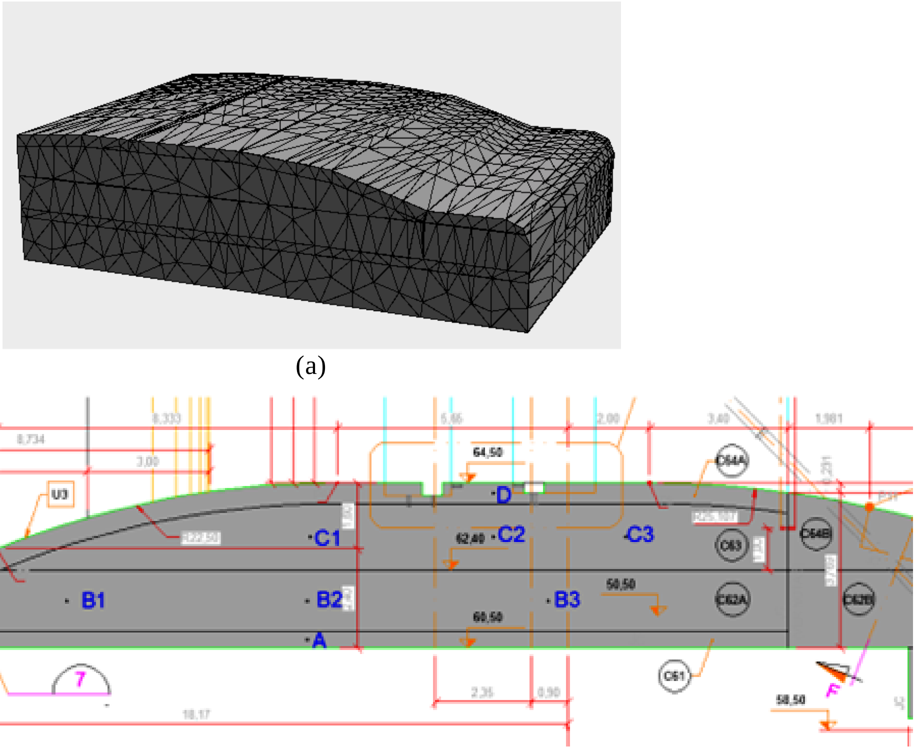
Table 5: Heat transfer coefficient [6]

5 MODEL ANALYSIS

Temperatures and stress changes that would occur in a three-dimensional model of finite elements, were simulated within the most critical sections of the water intake slab, considering the placement temperature of fresh concrete at 15°C, 20°C, 25°C and 30°C. The finite element mesh is automatically formed by tetrahedral elements, developed by the software through probabilistic models. The tetrahedral elements are formed with 10 nodes for thermal analysis and 20 nodes (each with 3 degrees of freedom) for stress analysis. [4] [5]. The three-dimensional calculation of temperatures in the concrete element assumes that the heat propagation occurs in the cross-section and longitudinal section simultaneously approaching a real situation. The finite element mesh adopted and the isotherms and isostresses calculated from the software in the cross sections are shown in Figure 4.

Through the simulation it was possible to analyze the development of the maximum temperatures and stresses that occurred in the structure for the placement temperatures considered. From the isotherms and isostresses obtained from the simulations were chosen the points of maximum temperatures and stress in the slab of the water intake. From this analysis the maximum admissible temperature of fresh concrete for the studied layers in order to minimize thermal stresses and considering a 5-day interval is 30°C.

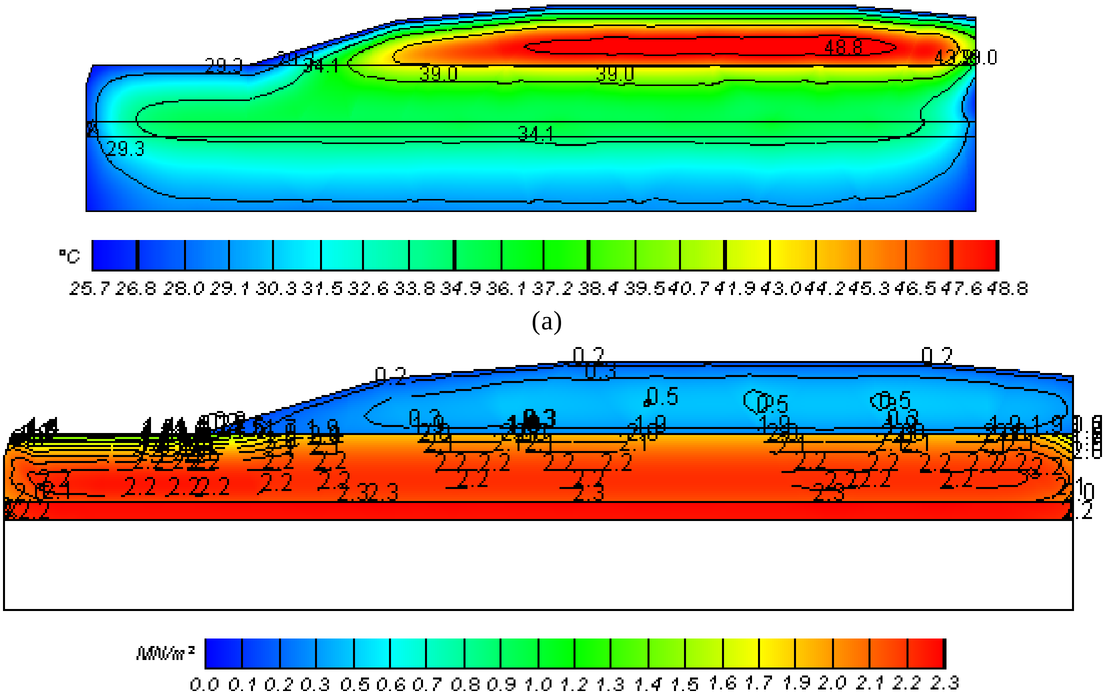
Figure 6 shows the results of maximum temperatures and stresses of the points studied.



(a)

(b)

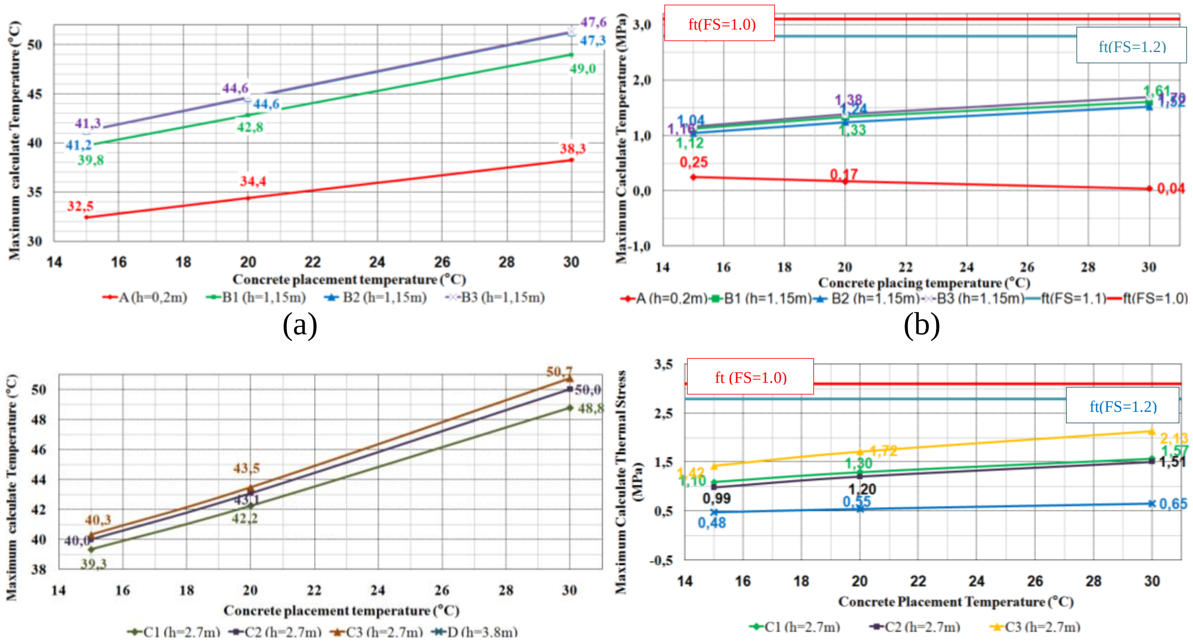
Figure 4. (a) Finite element mesh and (b geometry for evaluation of layer heights - Slab of the water intake - From elevation 60.50 to elevation 64.50 - Placement interval = 5days – Studied points



(a)

(b)

Figure 5. (a) Isotherms and (b) isostresses resulting after 346 hours from the start of the concreting considering the placement temperature of fresh concrete of 30°C [6]



(a) (b)

(c) (d)

Figure 6. (a) Summary of maximum temperatures at points A, B1, B2 and B3; (b) summary of the major maximum stresses at points A, B1, B2 and B3 considering safety factor FS = 1.1 and FS = 1.2; (c) summary of maximum temperatures at points C1, C2, C3 and D; (d) summary of major maximum stresses at points C1, C2, C3 and D considering safety factor FS = 1.1 and FS = 1.2. [6]

6 COMPARISON BETWEEN MEASURED AND CALCULATED TEMPERATURES

For temperature monitoring, two thermometers were installed on the slab of the water intake (TA-06) when it was built and installed in the C62A layer between the EL. 60.50 and EL. 62.40. Table 6 shows the sensors information.

Thermometers	Installation date	Structure	Distance from dam baseline (m)	Unit axis distance (m)	Installation elevation
TE-BM-ES-07	22/01/2014	TA-06	8.16 (upstream)	0.19 (to the right)	62.00
TE-BM-ES-08	22/01/2014	TA-06	7.20 (upstream)	0.71 (to the right)	62.00

Table 6 Installation date of the thermometers - TA-06 - Belo Monte site

Figure 7 shows the approximate location of the PT-BM-ES-07 and TE-BM-ES-08 thermometers type PT 100 brand MSI installed in the upstream intake slab of the Belo Monte site.

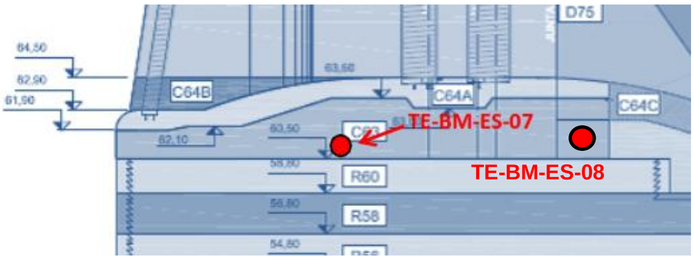


Figure 7. Location of the thermometers TE-BM-ES-07 and TE-BM-ES-08 upstream intake slab of the Belo Monte site. [5]

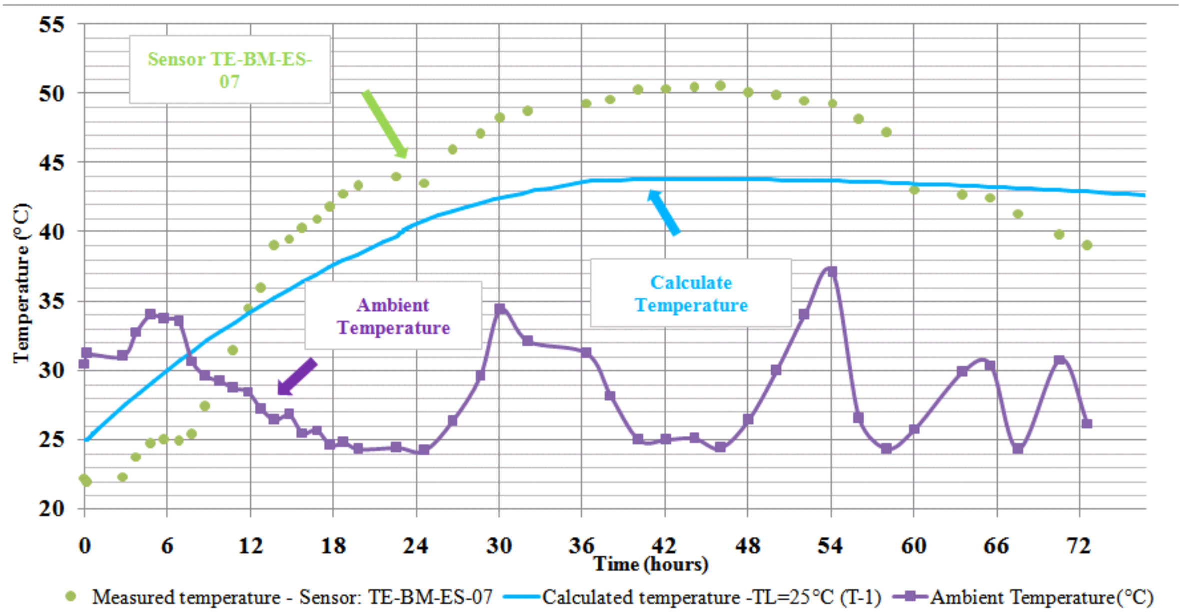


Figure 8. Comparison between measured and calculated temperatures – temperature sensor: TE-BM-ES-07 x Point T-1 – Intake slab of the Belo Monte site [5][6]

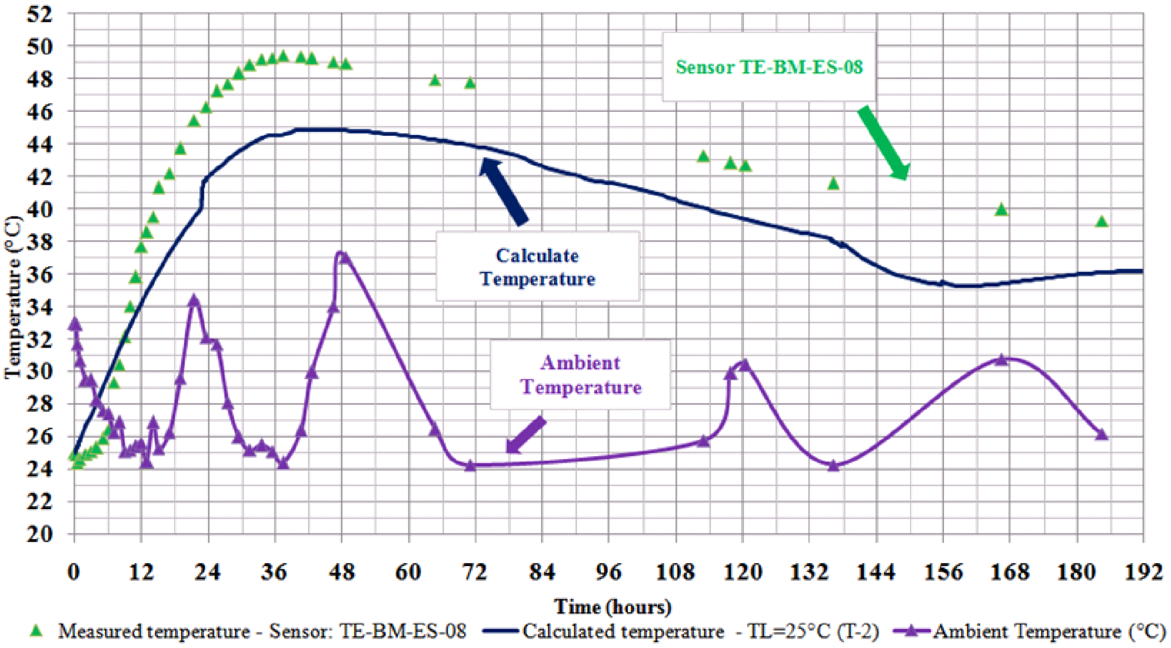


Figure 9. Comparison between measured and calculated temperatures – temperature sensor: TE-BM-ES-08 x Point T-2 – Intake slab of the Belo Monte site [5][6]

Table 7 presents a summary of the measured and calculated maximum temperatures, as well as the main differences between the thermal study and measurements at the real structure. The T-1 and T-2 points adopted from the model used in the thermal study are located at the same locations of the temperature sensors installed in the structure.

The maximum temperature reached by the concrete and measured by the sensors installed in the slab of the water intake was 50.5°C and do not present a risk of thermal cracking. From the comparison between the measured and calculated temperatures it was verified the good correlation between the points analyzed from the mathematical modeling and the measured temperatures between the sensors with a difference of 4,5°C between the T-2 point and the TE-BM-ES-08. At the T-1 point, the difference is 6.7°C in relation to the TE-BM-ES-08 sensor. Even considering higher cement content of the concrete adopted for the thermal studies compared to the one applied during construction, of 37 kg/m³, it can be verified that the slightly higher temperatures observed in the structure can be related to the smaller placement interval between the layers and greater height of concrete layers.

Parameters	**Thermal study**		**Construction**		**Thermal study x Construction**	
Study points	**T-1**	**T-2**	**TE-BM-ES-07**	**TE-BM-ES-08**	**T-1 x TE-BM-ES-07**	**T-2 x TE-BM-ES-08**
Maximum Temperature (°C)	43.8	44.9	50.5	49.4	6.7	4.5
Time to reach the maximum temperature after the concrete placement (hours)	44.4	42.5	46	37.5	1,6	5.0
Placement temperature	25	25	22.3 (1)	25.0(1)	2.7	0.1
Placement interval between concrete layers	5	5	3	3	2	2
Cement content (kg/m³)	261	261	224	224	37	37
Concrete layer height C62A (m)	1.5	1.5	1.9	1.9	0.4	0.4

Note (1) First reading of the thermometer

Table 7 Comparison between the thermal calculation and the real slab structure of the water intake

7 CONCLUSIONS

From the comparison between the temperature sensors and the results of the thermal studies, it can be concluded that the results showed good representativeness, proving the usefulness of its application for thermal studies in massive structures. Other thermal studies were carried out for other structures of the Belo Monte HPP and also showed the correctness in the adoption of cooling with ice flakes and cold water, which was indicated by the thermal studies.

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