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Temperature control in massive concrete for foundation blocks with 2D thermal simulation: case study.

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ABSTRACT
The objective of this study was to analyze the feasibility of casting foundation blocks in one or two stages using 2D thermal simulations with TSA software. A fluid mix with total replacement of mixing water by ice was adopted, considering geometric and technical parameters. Results showed that thermal control kept temperatures below 65 °C, reducing the risk of cracking and delayed ettringite formation. As a limitation, the study is based on two-dimensional simulations. The originality lies in the use of ice as a thermal control strategy in mass concrete. It is concluded that the proposed methodology is feasible and contributes to concrete durability.
Keywords: mass concrete; late ettringite; thermodynamic study; foundation blocks.

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Contribution of each author
In this work, the activity of conceiving the original idea had the contribution of J. R. B. Penha (70%) and E. J. Pazini Figueiredo (30%). In the development of the model, J. R. B. Penha (40%) and P. Candido (60%) participated. S. Jesus (50%) and L. A. Couto (50%) participated in the experimentation. Data collection had the participation of S. Jesus (50%), A. C. R. Oliveira (30%) and L. A. Couto (20%). In the analysis of the results, J. R. B. Penha (35%), A. C. R. Oliveira (25%), P. Candido (20%) and E. J. Pazini Figueiredo (20%) participated. The writing of the manuscript was carried out by J. R. B. Penha (70%) and S. Jesus (30%). The revision of the manuscript was carried out by S. Jesus (40%) and A. C. R. Oliveira (60%). The general supervision of the study was carried out by E. J. Pazini Figueiredo (100%). Finally, the critical revision of the manuscript was carried out by E. J. Pazini Figueiredo (100%).

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Control de la temperatura en hormigón masivo para bloques de cimentación con simulación térmica em 2D: estudio de caso.

RESUMEN

El objetivo de este estudio fue analizar la viabilidad del hormigonado de bloques de cimentación en una o dos etapas mediante simulaciones térmicas en 2D con el software TSA. Se utilizó una mezcla fluida con sustitución total del agua por hielo, evaluando condiciones geométricas y parámetros técnicos. Los resultados indicaron que el control térmico permitió mantener temperaturas inferiores a 65 °C, reduciendo el riesgo de fisuración y formación de etringita tardía. Como limitación, el estudio se basa en simulaciones bidimensionales. La originalidad radica en el uso de hielo como estrategia de control térmico en hormigón masivo. Se concluye que la metodología es viable y contribuye a la durabilidad del hormigón.

Palabras clave: hormigón en masa; etringita tardía; estudio termodinámico; bloques de cimentación.

Controle de temperatura em hormigón maciço para blocos de fundação com simulação térmica 2D: estudo de caso.

RESUMO

O objetivo deste estudo foi analisar a viabilidade da concretagem de blocos de fundação em uma ou duas etapas por meio de simulações térmicas em 2D com o software TSA. Utilizou-se uma mistura fluida com substituição total da água por gelo, considerando parâmetros geométricos e técnicos. Os resultados indicaram que o controle térmico manteve temperaturas abaixo de 65 °C, reduzindo o risco de fissuração e formação de etringita tardia. Como limitação, o estudo baseia-se em simulações bidimensionais. A originalidade está no uso do gelo como estratégia de controle térmico em hormigón massa. Conclui-se que a metodologia é viável e contribui para a durabilidade do hormigón.

Palavras-chave: hormigón massa; etringita tardia; estudo termodinâmico; blocos de fundação.

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1. NOMENCLATURE TABLE

Symbol / Abbreviation	Definition	Unit
fck	Characteristic compressive strength of concrete	MPa
TSA	Thermal Structure Analysis (thermal analysis software)	—
TSA–1D	One-dimensional thermal simulation	—
TSA–2D	Two-dimensional thermal simulation	—
PCE	Polycarboxylate ether (superplasticizer admixture)	—
CP IV 32 RS	Portland pozzolanic cement with sulfate-resistant properties	—
RA1	Type 1 water-reducing admixture	—
RA2	Type 2 water-reducing admixture	—
h_0, h_1	Height of concrete casting layers	m
°C	Degrees Celsius (temperature)	°C
kcal/kg·°C	Specific heat capacity	kcal/kg·°C
m²/dia	Thermal diffusivity	m²/dia

2. INTRODUCTION

The hydration phenomenon of Portland cement has been extensively investigated in recent years. This process results from surface reactions between water and cement particles, involving dissolution–precipitation mechanisms or topochemical reactions (solid-state hydration), both of which are exothermic in nature (Mehta & Monteiro, 2008; Taylor, 1997). These chemical reactions release heat, which may cause significant temperature increases not only in mass concrete structures but also in conventional structures, particularly due to the characteristics of modern concretes, which often contain high cement contents, high characteristic compressive strengths, considerable dimensions, limited heat dissipation conditions and restrained movement.

In addition, the increasing use of special concretes must be considered. These concretes do not necessarily incorporate larger amounts of cement in their composition, as current trends in materials engineering seek to optimize mechanical and rheological performance through the use of supplementary materials and more efficient mix design strategies, aiming to reduce the carbon footprint associated with cement production (Scrivener et al., 2018; Habert et al., 2020). In such cases, the coupled thermochemical-mechanical behavior of the structure becomes a determining factor in its design.

However, within the current context of sustainable construction, the development of special concretes has evolved toward optimizing cement content through the use of supplementary cementitious materials (such as fly ash, slag and limestone filler), with the objective of reducing the carbon footprint without compromising mechanical and rheological performance (Scrivener et al., 2018; Habert et al., 2020).

Nevertheless, depending on design and construction conditions, these concretes may still exhibit significant thermal behavior, especially in large-volume structural elements, maintaining the relevance of thermochemical-mechanical analysis in such structures.

According to Mehta and Monteiro (2008), understanding the amount of heat released is essential, as this phenomenon can be either beneficial or detrimental. Concrete generates heat from the onset of cement hydration and, at early ages, exhibits a low modulus of elasticity while simultaneously gaining strength as its temperature rises. During this stage, compressive stresses develop and generally do not cause cracking. However, once the maximum temperature reached within the structure begins to equilibrate with the ambient temperature, these compressive stresses tend to decrease and eventually transform into tensile stresses. Since concrete possesses relatively low

tensile strength, cracking may occur if these stresses exceed its tensile capacity.
Cracks reduce the load-bearing capacity of the affected structural element and impair concrete durability by facilitating the ingress of aggressive agents. In the case of pile caps and footings, which are essential structural elements responsible for supporting the entire building and transferring loads to deep foundation elements, the occurrence of cracking may seriously compromise structural safety and overall stability. Furthermore, the repair of these critical elements is complex, reinforcing the importance of adopting preventive measures.
The present study aims to concisely present the computational thermal simulation of large foundation pile caps and footings (with volumes ranging from 30 m³ to 400 m³) and characteristic compressive strengths greater than 50 MPa, belonging to a residential development located in Goiânia, Goiás, Brazil. The simulation was carried out by the consulting company JP Prime Engenharia e Consultoria.

3. ASSUMPTIONS AND INPUT DATA

3.1 Preamble.

The thermal study, also referred to as thermal analysis, aims to reduce the risk of cracking in structural elements due to the difficulty of dissipating the heat generated during cement hydration. This type of analysis must be developed specifically for each case, since there are projects in which different structural elements require independent simulations, considering factors such as their particular geometry and construction constraints.
Thermal simulation is performed using computational tools based on a set of input data, among which the following stand out: the dimensions of the element (especially its thickness or height), its geometry, the type of cement (heat release curve due to hydration) and the aggregates used in the proposed mixture (lithology), the type of formwork, the support conditions of the element, the curing method adopted, the ambient temperature and the maximum concrete placement temperature (for example, through the use of ice as a replacement for mixing water).
In this context, the objective was to determine, through computational simulations, the feasibility of casting the analyzed blocks/footings in a single stage using 100% ice as a replacement for the mixing water. For this purpose, the fluid mixture developed through an experimental mix design study carried out on 03/10/2024 was considered, as well as the technical constraints previously mentioned.
JP Prime Engenharia e Consultoria was responsible for carrying out the thermal simulations, the results of which indicated that it would not be feasible to cast all large-volume elements in a single stage given the set of assumptions and scenarios analyzed (considering the combination of the element's height, volume and geometry).
This result highlights the significant influence of the element dimensions on thermal dissipation, indicating that the greater the volume and thickness, the greater the heat accumulation and, consequently, the higher the risk of thermal cracking.
Table 1 presents a summary of the analyzed blocks/footings (highlighted in yellow), the number of layers required for their execution and the number of thermocouples used for thermal monitoring within the concrete. In total, four simulations were performed, focusing on elements with a high potential for heat generation that were considered critical for thermal control. It can be observed that all evaluated elements required casting in two layers, reinforcing the need to segment the concrete placement as a thermal control strategy.

Table 1. Number of casting layers and thermocouples for each analyzed block/footing (Project Development).

Reference Project: Artesano Reserva Marista Development						
Foundation Element	**Side A (m)**	**Side B (m)**	**Total Height (m)**	**Actual Vol. (m³)**	**No. of layers**	**No. of Thermocouples**
Foundation block	10,60	17,00	2,00	360,4	2	6
Footing S14	4,00	9,00	1,45	66,38	2	6
Footing S6+S31	7,00	7,00	2,00	98,00	2	6
Footing S9+S36	7,00	7,00	2,00	98,00	2	6

In this study, the adopted constraints established a maximum temperature limit of 65 °C within each layer, with the objective of preventing both thermal cracking (resulting from stress imbalance) and, more importantly, the deleterious phenomenon known as delayed ettringite formation. Likewise, it was considered essential not to exceed the maximum concrete placement temperature in the fresh state previously defined in the simulations, which was limited to 24 °C.
These criteria made it possible to establish a consistent evaluation basis for comparing single-stage and two-stage concrete casting scenarios.
Finally, it is recommended that all other blocks/footings that are not part of Group 1 be cast using the candidate mixture presented in the JP Prime mix design report, reproduced in a later section of this study, that is, without the use of ice, according to the analyzed mix design.

3.2 Climatic characteristics.

One of the main aspects in the simulation of thermal stresses is the average ambient temperature, which serves as the basis for determining the temperature variation to which the structural element will be subjected.
In this context, it can be observed that the city of Goiânia presents average daily temperatures of 24,6 °C and 24.2 °C during the months of November and December, respectively, with average maximum temperatures of 30,0 °C and 29,4 °C and average minimum temperatures of 18,5 °C and 17,0 °C (the months during which the concrete casting activities will most likely be carried out), according to data available on the website of the Integrated Agrometeorological Information Center (CIIAGRO) of the Government of the State of São Paulo.
These values indicate a climatic scenario characterized by elevated temperatures, which may intensify the temperature rise within the concrete, hindering heat dissipation and increasing the risk of thermal cracking.
These data are presented in Table 2 (highlighted in red) and graphically in Figure 1, which summarizes the environmental conditions adopted as the reference for the thermal simulation.

Table 2. Ambient temperature data (average, maximum and minimum) for Goiânia, in °C.

Month	Days	Average daily temperature (°C)	Average maximum temperature (°C)	Average minimum temperature (°C)
January	1550	24,3	28,9	18,0
February	1412	24,5	28,5	19,5
March	1550	24,6	28,4	18,5
April	1500	24,2	28,2	17,5
May	1522	22,4	27,0	13,0
June	1470	21,1	26,0	10,5
July	1519	21,1	27,0	11,0
Augost	1519	23,1	29,2	13,5
September	1470	25,1	30,5	14,0
October	1519	25,2	31,0	18,0
November	1470	24,6	30,0	18,5
December	1519	24,2	29,4	17,0

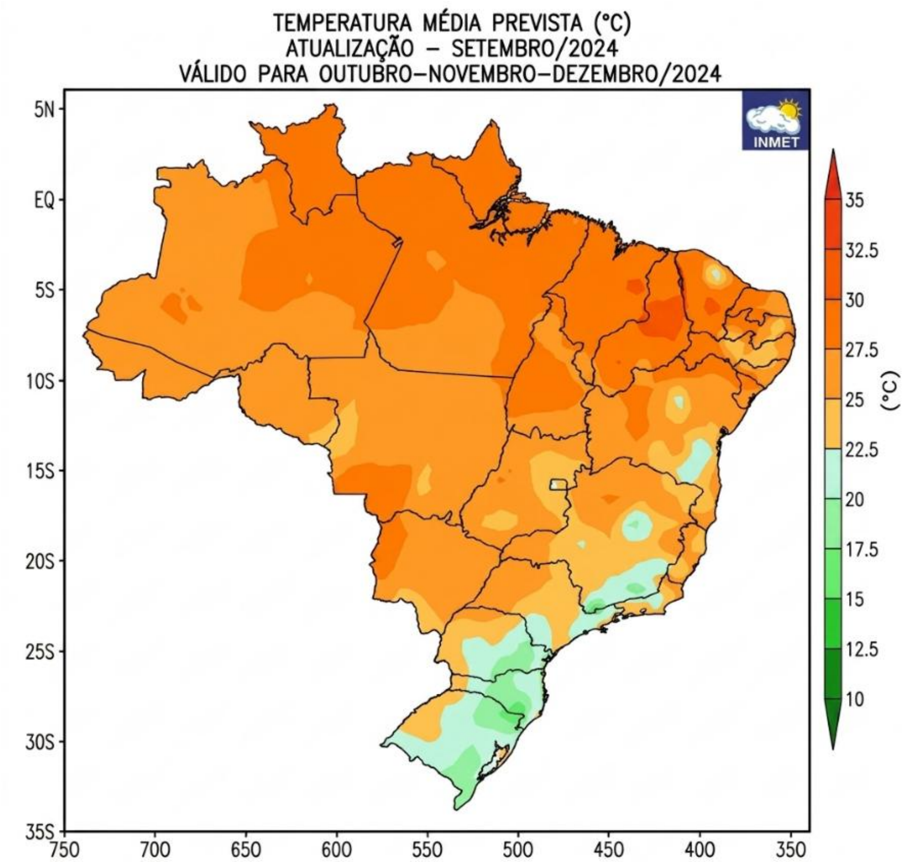

Figure 1. Ambient temperatures (average, maximum and minimum) in Goiânia according to INMET, in °C.

For the thermal simulation, a constant ambient temperature of 30 °C was adopted, considered representative of the most unfavorable conditions for thermal control during the analyzed period. Since the data presented correspond to consolidated historical measurements representative of the local climate, it was decided not to include additional graphical representations, prioritizing clarity and objectivity in the presentation of the parameters adopted for the thermal simulation.

3.3 Concrete and materials.

The concrete used in the production of the footings/blocks that are the subject of this study (Table 1) must be obtained through vigorous and homogeneous mixing of the available materials in order to achieve the minimum characteristic compressive strength specified in the design (fck ≥ 50 MPa), exhibit low heat of hydration, provide favorable thermal dissipation conditions and ensure adequate workability for concrete transportation, placement productivity and casting operations.

In this specific case, a special fluid concrete was proportioned in the laboratory using 100% ice as a replacement for the mixing water as a strategy to reduce the initial concrete temperature and, consequently, mitigate the temperature rise during hydration.

Ciplan, the company responsible for producing this concrete, was consulted and provided the properties and characteristics of the materials to be used in the mixture (materials supplied from the Aparecida de Goiânia/GO plant), as detailed below.

3.3.1 Aggregates:

- Crushed Stone 0 and 1 (Gneiss): coarse aggregate with a nominal maximum size of 16,0 mm and a fineness modulus of 10,43% for Crushed Stone 1 and a nominal maximum size of 16,0 mm and a fineness modulus of 8,43% for Crushed Stone 0. Aggregates supplied by Araguaia Quarry; adopted specific heat capacity: 0,2 kcal/kg·°C.
- Natural Fine Quartz Sand: fine aggregate with a nominal maximum size of 4,8 mm and a fineness modulus of 1,34%. Aggregate sourced from the municipality of Israelândia de Goiás; adopted specific heat capacity: 0,2 kcal/kg·°C.
- Type II Manufactured Sand (Granitic): fine aggregate with a nominal maximum size of 0.6 mm and a fineness modulus of 3,25%. Aggregate sourced from Guapó; adopted specific heat capacity: 0,2 kcal/kg·°C.

3.3.2 Cement:

- CP IV 32 RS cement (supplied by Ciplan Cimento Planalto S/A – Brasília Plant). Test Report No. 158184, Sample 262180, dated March 19, 2024 (sample collected on 29/12/2023), available for consultation in Annex G of this report.

3.3.3 Silica fume addition:

- Tecnosil; adopted specific heat capacity = 1 kcal/kg·°C.

3.3.4 Polycarboxylate Ether (PCE)-based mid-range plasticizing and multifunctional admixture:

- MasterGlenium® 358, BASF; adopted specific heat capacity = 1 kcal/kg·°C.

3.3.5 Total water (ice replacing mixing water + moisture from sands)

- Ice: adopted specific heat capacity = 0,5 kcal/kg·°C.
- Potable Water: specific heat capacity = 1,0 kcal/kg·°C / latent heat = 80 kcal/kg.

3.3.6 Candidate mix design (experimental mix design study)

Table 3. Candidate mix design, based on dry materials, with fck of 50 MPa at 28 days.

Parameter	Value
Concrete mix design	
Cement content (CP IV 32 RS)	432 kg/m³
Water-to-cement ratio	0,44
Silica fume addition (Tecnosil)	48 kg/m³
Total water	190 kg/m³ (120 kg of ice + 70 kg of moisture from the sands)
Effective water	70 kg/m³
Actual ice content	120 kg/m³
Mortar content	55 %
Entrained air	2,0 %
Consistency (slump)	19,0 cm
Specific mass (density)	2386 kg/m³
Fine quartz sand	279 kg/m³
Type II manufactured sand	430 kg/m³
Crushed stone 0 (gneiss)	284 kg/m³
Crushed stone 1 (gneiss)	717 kg/m³
Admixtures (plasticizing + multifunctional)	6,24 kg/m³
Thermal properties of concrete (according to the literature)	
Thermal diffusivity	0,11 m²/dia
Coefficient of thermal expansion	1×10^{-5} 1/°C
Specific heat capacity	0,240 kcal/kg·°C

3.3.7 Ice quantity for blocks and footings.

For practical reasons regarding ice incorporation, it was established that the total mixing water would be replaced, discounting the moisture content present in the aggregates (considering a moisture content of 4,9% for the natural fine sand and 7,9% for the manufactured sand, according to information provided by the concrete plant laboratory). Based on these values, an estimated requirement of approximately 42 bags of ice weighing 20 kg each per truck carrying a 7 m³ load was determined (applicable exclusively to 20 kg bags). This procedure made it possible to significantly reduce the initial concrete temperature, constituting an effective thermal control measure for large-volume elements.

It is recommended that these moisture values be confirmed through the analysis of historical data and tests performed on the date of the concreting operation, as well as by verifying the actual load volume of the mixer truck and the exact mass of each ice bag in order to avoid errors.

According to the thermal balance performed for the candidate mix design (Table 2) and the experimental simulations conducted in the laboratory under conditions similar to those of the project, it was determined that the maximum expected concrete temperature upon arrival at the site should not exceed 24 °C (already considering a margin for the temperature increase resulting from transportation).

In tests carried out at the Ciplan concrete plant, the recorded fresh concrete temperature was approximately 15,2 °C, considering ice at 0,9 °C, an average ambient temperature of 25 °C and a relative humidity of 75%. This temperature was measured after 10 minutes of mixing in a rotating truck mixer, representing a highly favorable scenario. Furthermore, the temperature measured after

30 minutes of mixing did not exceed 18 °C (see the corresponding photographic report). These results confirm the effectiveness of using ice as a strategy for thermal control of fresh concrete.
The consulting team was informed that, in principle, the Ciplan plant in Aparecida de Goiânia/GO would be responsible for supplying the concrete (located approximately 10,2 km away, with an estimated travel time of 30 minutes on business days). In this context, it is recommended that the ice temperature be set at -5 °C at the time of batching at the plant. Under this condition, the expected concrete working temperature is approximately 15 °C, providing a satisfactory safety margin and avoiding the need to reject truckloads solely due to thermal considerations.
Accordingly, a maximum acceptance limit of 23 °C is established for the concrete delivered by each individual truck, with a tolerance of up to 1 °C for trucks corresponding to the second concreting event/second layer of the structural element (in cases of two-stage concreting operations). In other words, trucks with concrete temperatures exceeding 24 °C shall not be accepted, except under second-layer conditions, in which temperatures up to 25 °C are permitted. For single-stage concreting operations, the acceptance limit remains 24 °C.

4. THERMAL STUDY

4.1 Preamble.

The thermal study was performed computationally using the finite element method through the TSA–1D and TSA–2D software packages, which allow the simulation of temperature histories and the stresses generated by thermal differences within the structural element to be cast. TSA (Thermal Structure Analysis) is a finite element-based computational tool developed for simulating thermal evolution in mass concrete structures. Its application enables accurate prediction of internal temperature peaks, thermal distribution over time and the risk of thermal cracking, making it widely used in infrastructure and large-scale building projects. In this study, the TSA–1D and TSA–2D versions were employed to model different geometries and construction scenarios involving foundation footings and blocks.
For the estimation of tensile strength, the software provides the reference values in accordance with the applicable code requirements, as established by ABNT NBR 6118 (ABNT, 2023).
The modeling was carried out considering both single-stage and two-stage casting scenarios. If the internal temperatures exceeded 65 °C or stress imbalance was detected, the remaining alternative would be to divide the element into three or more layers (as a last resort), since the candidate mix design had already been defined (with minimum cement consumption and the maximum feasible amount of ice per cubic meter, that is, parameters that were already fixed).
The computational models considered the interaction between the block and the supporting soil, as well as domain discretization through a refined finite element mesh, allowing an adequate representation of the thermal gradients within the element. Based on this modeling approach, one-dimensional (TSA–1D) and two-dimensional (TSA–2D) thermal simulations were performed to analyze the temporal evolution of temperature and the thermal gradients within the foundation block.
Figures 2 and 3 present the thermal analysis of the block and the two-layer modeling configuration (including soil interaction), as well as the refined finite element mesh adopted for the main block and Footing S14.

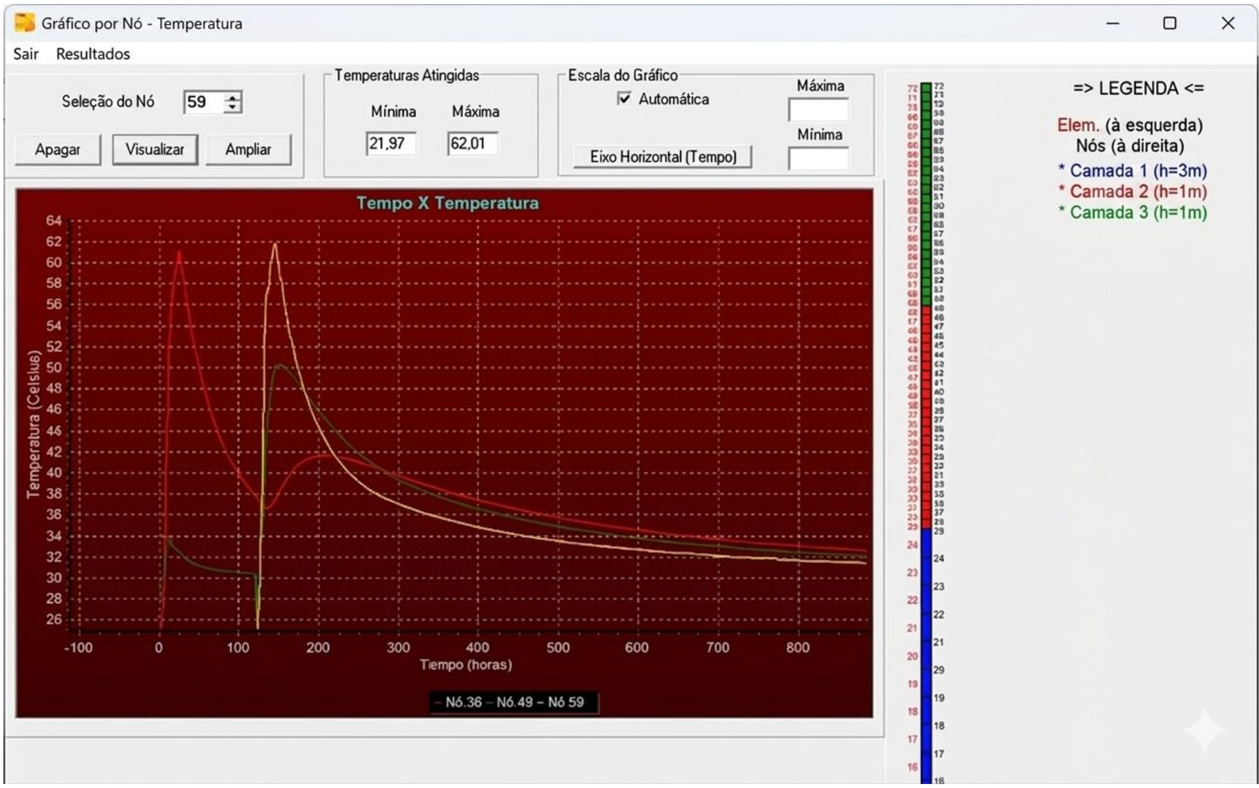

Figure 2. Thermal analysis of the 17,00 × 10,60 × 1,00 m block (TSA–1D).

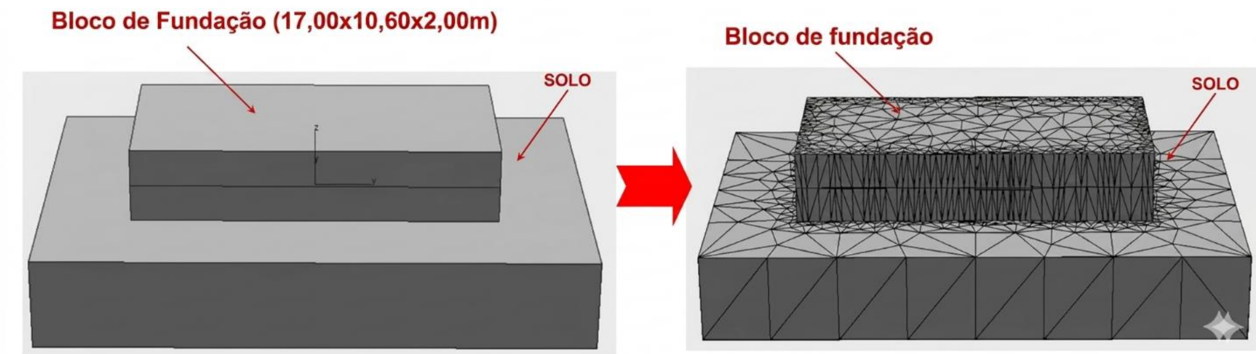

Figure 3. Two-layer modeling adopted for the main block measuring 17,00 × 10,60 × 2,00 m.

In the one-dimensional analysis (TSA–1D), corresponding to the block with dimensions of 17.00 × 10.60 × 1.00 m, temperature-versus-time curves were obtained for different representative points within the element. The results indicated a maximum temperature of approximately 62 °C, reached at early concrete ages, followed by a phase of progressive heat dissipation. This result approaches the adopted critical limit (65 °C), highlighting the need for thermal control strategies to prevent associated pathological phenomena.

In the two-dimensional analysis (TSA–2D), the spatial distribution of temperature was evaluated through the generation of thermal contour maps (isotherms) (Figure 4). The highest temperatures were observed in the central region of the block, where heat dissipation is more restricted, while areas closer to the surface exhibited lower temperatures due to heat exchange with the surrounding environment.

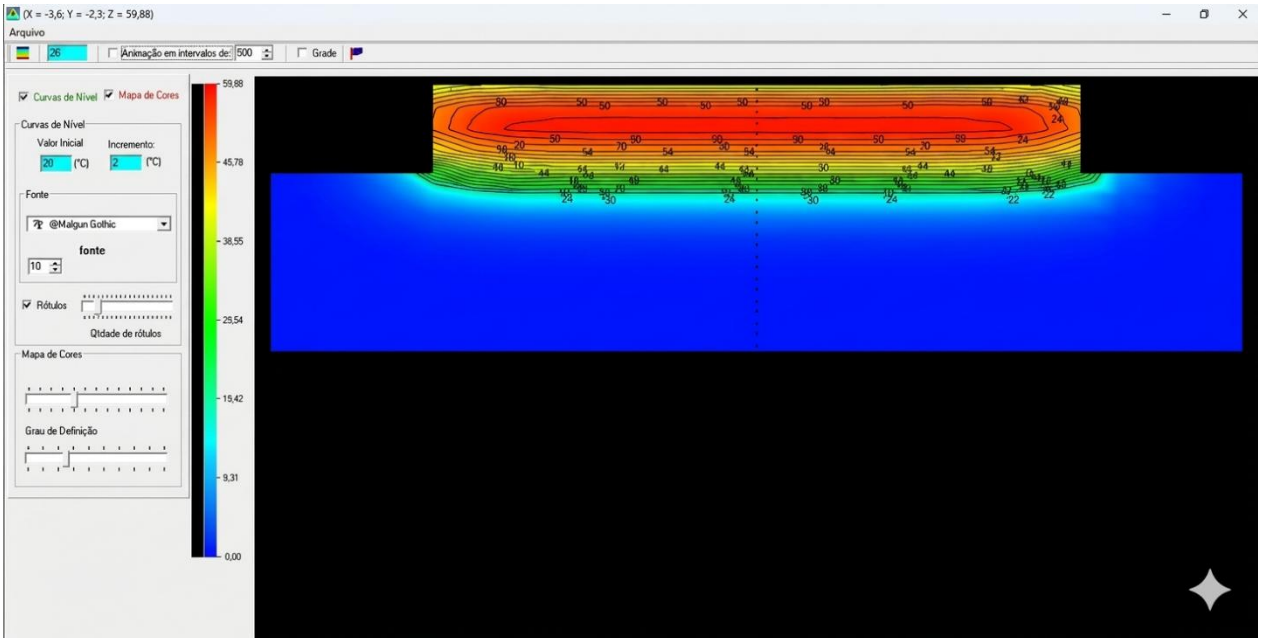

Figure 4. Thermal contour modeling of the 17,00 × 10,60 × 1,00 m block (TSA–2D with mesh refinement).

Additionally, the layered modeling approach made it possible to simulate the thermal behavior of the concrete while considering the construction sequence of the element (Figure 5).

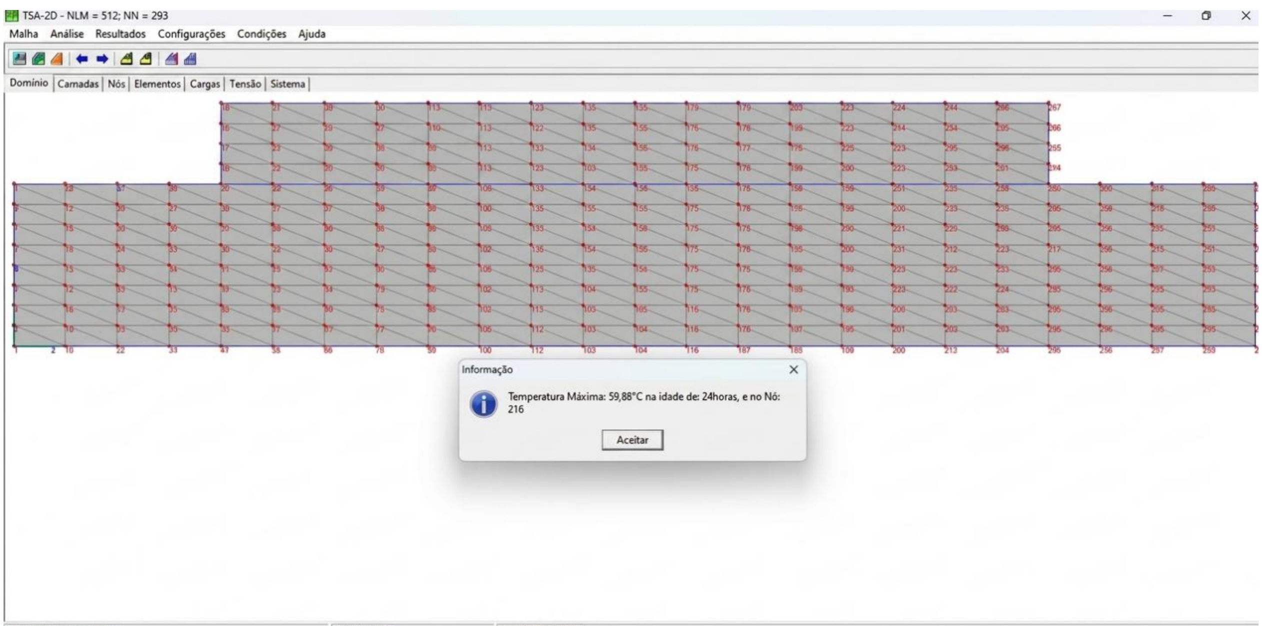

Figure 5. Layered modeling of the 17,00 × 10,60 × 1,00 m block (TSA–2D with mesh refinement).

The results showed that construction in layers contributes to reducing internal thermal gradients, promoting more uniform heat dissipation and decreasing the risk of thermal cracking. In this regard, the construction strategy proved to be a determining factor in the thermal control of mass concrete elements.

The discretization of the domain through a refined finite element mesh enabled the thermal gradients to be adequately captured, ensuring the accuracy of the results obtained from the simulations.

4.2 Concrete footing S14 (simulation 1, in two layers).

The S14 footing of the project was modeled considering casting in two stages, with (equivalent) layers of equal height, h_0 = 1,45 m and h_1 = 1,45 m and internal concrete temperature control through thermocouples, as specified below.

A 5-day interval between the two layers was also considered, together with the use of 20 mm plywood formwork maintained for at least 5 days and the application of continuous water curing during the same period. It is recommended that curing be performed using the ponding method for blocks P5, P8, P10A and P10B, with a water layer of at least 10 cm, so that the actual curing conditions are equivalent to those assumed in the numerical model, thereby reducing the risk of excessive temperature increase due to hydration. For all other footings, the formwork should be maintained for 5 days with blankets kept permanently saturated with water.

Based on the concrete type (aggregates and cement/heat release curve due to hydration), the established placement temperature of 20 °C, the environmental conditions and site constraints, the curing method and the two-stage casting procedure, the software simulates the temperature history generated by the heat of hydration within the element to be cast.

The simulation results indicate critical thermal behavior, with temperature peaks approaching the adopted maximum limit (65 °C), reinforcing the need for thermal control in this type of mass concrete element.

The peak temperature of the first layer occurs 30 hours after the start of casting, reaching 61 °C. The figure also illustrates the peak temperature of the second layer, which occurs 145 hours after the beginning of the work (that is, 115 hours after the second casting operation), reaching a value of 62 °C.

It can be observed that, although the execution in two layers allows a certain degree of control over thermal evolution, the maximum recorded values remain high, indicating that heat dissipation is still limited within the element.

Furthermore, the time lag between the thermal peaks of each layer contributes to reducing abrupt thermal gradients, which may decrease the risk of cracking when compared to a single-stage casting operation.

4.3 Test block 1,5 × 1,5 × 1,5 m (single-layer simulation).

A test block was cast with the objective of verifying the modeling and the study that had been carried out. This experimental test made it possible to compare the results obtained through numerical simulation with actual field measurements, thereby validating the adopted model.

The maximum temperature obtained from the numerical simulation was 62,54 °C after 24 hours (Figure 6).

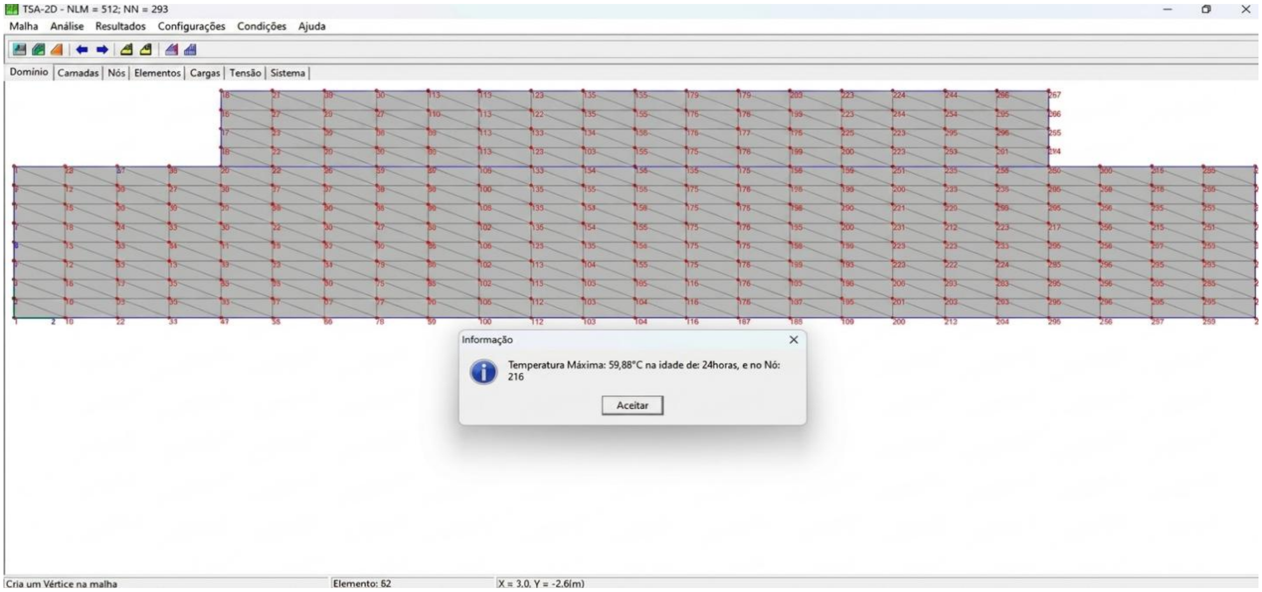

Figure 6. Maximum temperature peak of 62,54 °C in the test block (TSA–2D).

After casting, temperature monitoring was conducted over a 24-hour period and the temperature recorded in the field was 59,4 °C (Figure 7).

Figure 7. Temperature record of T = 59,4 °C after 24 hours in the test block.

It can be stated that the results fall within the expected safety margin for mass concrete. Likewise, a progressive reduction in temperature was observed over time, reaching values on the order of 45 °C after 72 hours, confirming the expected heat dissipation behavior (Figures 8 and 9).

Figure 8. Record of the test block after 72 hours.

Figure 9. Temperature record of T = 45,0 °C after 72 hours in the test block.

It is essential that all variables be carefully controlled in the field, such as the amount of ice used on the day of casting, the transportation time and the maximum placement temperature of 24 °C, with the previously mentioned tolerance (Figure 10).

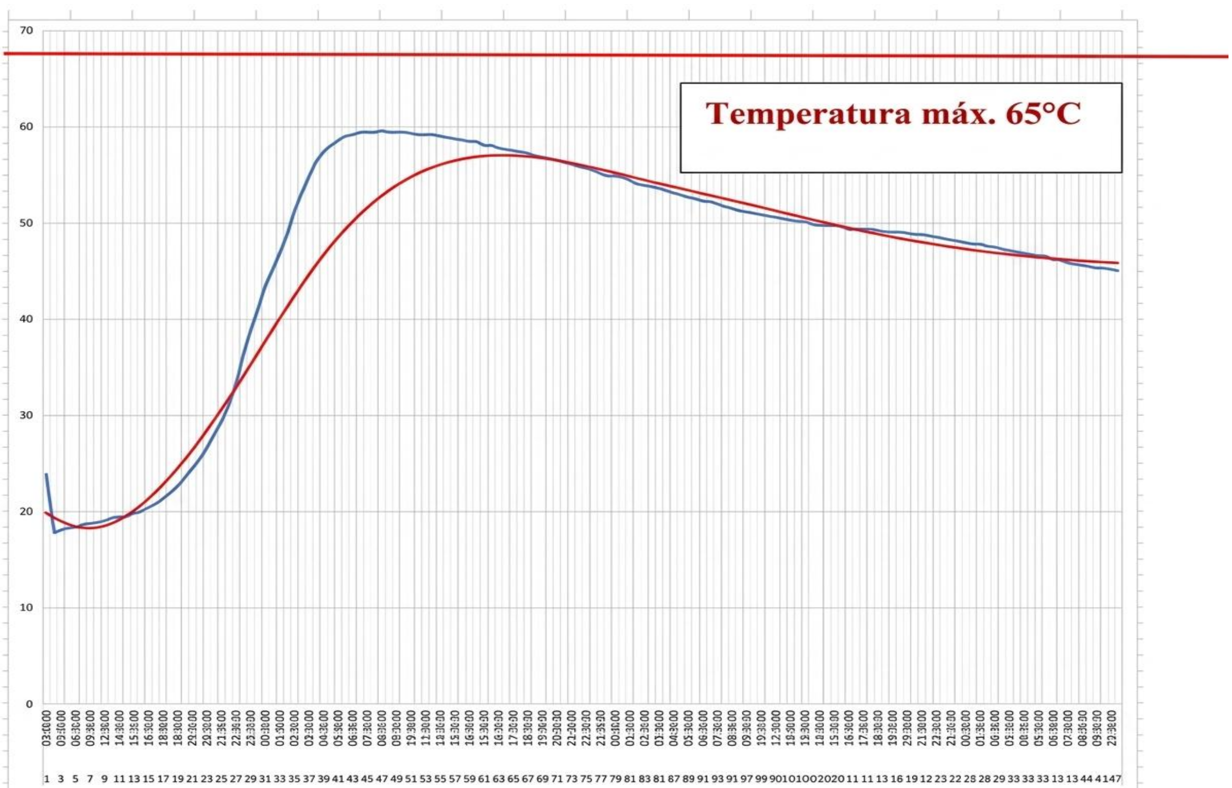

Figure 10. Temperature record of T = 59,5 °C after 72 hours in the test block (cast in place).

These results confirm the effectiveness of the adopted strategy (use of ice and control of the placement temperature) in limiting the temperature rise in mass concrete elements. Finally, the installation of 3 thermocouples within the block is also recommended, positioned in the central plane at the indicated locations, in order to obtain more accurate and representative average values.

The thermocouples shall be located along the block axis, 8,5 m from the lateral face. The height of the first layer is 1,00 m and, vertically, the three (3) thermocouples shall be positioned at elevations of 20,0 cm above the blinding concrete, 50 cm and 80 cm, respectively, as illustrated in Figure 11.

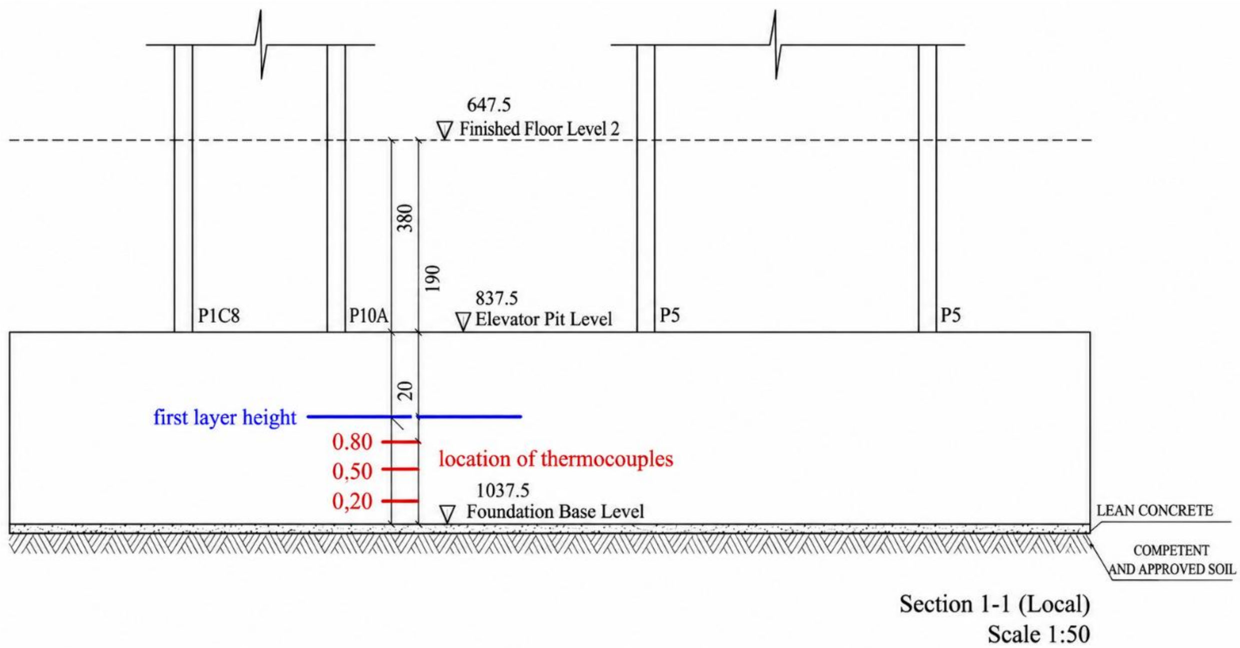

Figure 11. Thermocouple location map.

5. RESULTS DISCUSSION

The results obtained confirm that thermal control in mass concrete elements is a critical aspect for ensuring the structural integrity and durability of large-volume foundations. Recent literature indicates that early-age cracking is directly related to the heat of cement hydration and the thermal gradients generated in thick structural elements, with numerical simulation using the finite element method being a widely adopted tool for predicting these phenomena (Klemczak et al., 2024).

In the present study, the simulations indicated thermal peaks on the order of 62 °C in the analyzed elements, values below the adopted safety limit of 65 °C. This result is significant because it demonstrates that the adopted strategy was able to maintain the maximum temperature within an acceptable range, although close to the critical threshold. From a practical perspective, this indicates that thermal control does not completely eliminate risk but keeps it within safe limits, provided that execution variables are rigorously controlled, such as placement temperature, curing conditions and transportation time (Pessoa et al., 2024). Previous studies have demonstrated that the evolution of hydration heat and its interaction with boundary conditions directly influence the development of tensile stresses capable of inducing cracking in mass concrete (Gambale, 2017).

The thermal distribution observed in the two-dimensional simulations, with higher temperatures concentrated in the central region of the block, is consistent with findings reported in recent studies, which identify the core of mass concrete elements as the region most susceptible to heat accumulation due to limited heat dissipation (Wang and Song, 2024). Conversely, surface regions exhibit lower temperatures, promoting the development of thermal gradients and, consequently, tensile stresses with the potential to cause cracking. In this regard, the use of two-dimensional models provided a more realistic representation of this thermal behavior.

Another relevant aspect is the influence of the construction sequence on thermal control. The

results showed that execution in two layers contributes to the reduction of internal thermal gradients due to the time lag between the temperature peaks of each layer. This behavior has been reported in recent research, which highlights that thermal control in mass concrete depends on the combination of multiple strategies, including the casting sequence, curing procedures and control of the initial material temperature (Tran et al., 2023).
Experimental validation through the test block reinforces the reliability of the adopted model. The difference of less than 5% between the simulated maximum temperature (62,54 °C) and the temperature measured in the field (59,4 °C after 24 hours) indicates good agreement between the numerical model and the actual behavior of the concrete. This result is consistent with recent studies emphasizing the importance of validating thermal models through field monitoring to ensure their applicability under real conditions (Klemczak et al., 2024).
Regarding the pre-cooling strategy, the use of ice as a total replacement for mixing water proved effective in reducing the initial concrete temperature and, consequently, limiting the subsequent temperature increase. This approach is consistent with the literature, which identifies the reduction of initial concrete temperature as one of the most effective measures for controlling hydration heat in mass concrete structures (Aniskin et al., 2021). However, the results also demonstrate that this strategy alone is insufficient to guarantee complete thermal control in large-volume elements.
In this context, the thermal behavior of mass concrete depends on multiple factors, including material composition, cement content, the use of supplementary cementitious materials, element geometry and curing conditions. Recent studies highlight that the incorporation of supplementary cementitious materials and the adoption of combined thermal control strategies are essential for reducing both peak temperatures and internal thermal gradients (Danfour et al., 2024).
From a durability standpoint, maintaining the temperature below 65 °C is particularly important for minimizing the risk of delayed ettringite formation, a phenomenon associated with internal expansion and progressive concrete deterioration. Recent research has shown that exposure to elevated temperatures at early ages may promote microstructural changes capable of compromising the long-term performance of the material (Mohr et al., 2024).
In summary, the results obtained demonstrate that the combination of thermal simulation, control of placement temperature, use of ice, adequate curing and layered construction constitutes an effective strategy for thermal control in mass concrete blocks and footings. The main contribution of this study lies in the validation of these strategies through a real instrumented case study, demonstrating that numerical modeling can be used as a decision-support tool during construction, in accordance with current trends in the design and control of mass concrete structures (Pessoa et al., 2024; Wang and Song, 2024).

6. CONCLUSION

This study presents the technical and operational guidelines for the execution and control of the concreting of large-volume foundation blocks and footings (between 30 m³ and 400 m³), with characteristic compressive strength fck > 50 MPa, applied to the Artesano Reserva Marista project, located in Goiânia–GO, Brazil.
As a general criterion, a maximum concrete placement temperature of 24 °C (with duly justified exceptions) and an internal temperature limit of 65 °C were adopted, considering the effects of cement hydration heat and the balance between induced stresses and allowable stresses. These parameters were established with the objective of mitigating the risk of thermal cracking and preventing deleterious phenomena such as delayed ettringite formation.
The mix design specifications, together with the execution and control procedures for fluid mass concrete using ice, were developed specifically for the structural elements analyzed in this study, considering the particular project conditions, the available materials and the construction

constraints.
The results obtained during the implementation of the thermal control plan demonstrated that the maximum internal temperatures remained below the established limit of 65 °C and that the placement temperatures complied with the defined criteria. Likewise, thermal behavior consistent with the numerical simulations was observed, demonstrating adequate heat dissipation and the absence of critical thermal gradients capable of inducing cracking.
Experimental validation through field monitoring confirmed the reliability of the adopted thermal model, as evidenced by the close agreement between the simulated and measured values. In addition, adequate concrete homogeneity was verified, with no signs of segregation or significant thermal variations among the monitoring points.
In this context, it is concluded that the adopted strategy, based on the combination of numerical modeling, placement temperature control, use of ice, layered construction and adequate curing, proved effective in ensuring the thermal control of mass concrete, contributing to the structural performance and durability of the foundation elements.
Finally, it should be emphasized that the methodology employed can be replicated in similar mass concrete projects, constituting a relevant technical tool for the planning and control of construction works involving large-volume elements.

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