XLVI CILAMCE
VITÓRIA - ES - BRAZIL - 2025
XLVI IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING

Cracking analysis caused by temperature rise in foundation block

Eduardo de M. R. Fairbairn[1], Bruno B. de Oliveira[1], Mariane R. Rita[1], Alfredo Quiroga Flores[1]

[1]*COPPE, Federal University of Rio de Janeiro*
Athos da Silveira Ramos Avenue, 149, Cidade Universitária,
Zip-Code: 21.941-611, Rio de Janeiro/RJ, Brazil.
eduardo@coc.ufrj.br,bruno.barroso@coc.ufrj.br,
mariane_rita@coc.ufrj.br, alfredo.quirogaf@pet.coppe.ufrj.br

Abstract. This study investigates the behavior of massive concrete structures and the stresses induced by temperature variations resulting from the hydration reaction at early ages. This article also uses the enhanced massivity index proposed by RILEM Technical Committee 254 CMS [1], which aids in identifying the most suitable analysis for each structural element. As a case study, a real concrete foundation block was analyzed. Temperatures within the block were monitored using thermocouples, and the experimental data were compared with results obtained from a numerical analysis performed using the commercial software DIANA FEA. Once the model was validated against the experimental results, a mechanical analysis was conducted to predict the cracking behavior.

Keywords: massive structures, temperature, hydration reaction, cracking.

1 Introduction

According to Fraga [2], mass concrete structures can be defined as elements with a large concrete volume and, consequently, a low surface-area-to-volume ratio, which hinders heat dissipation. Since the cement hydration reaction is exothermic and thermally activated, the hydration process causes a temperature rise, which in turn leads to deformations. When these deformations are restrained, stresses develop in the structural element, potentially leading to cracking.

In this context, it is crucial to carry out thermal studies of mass concrete structures to support proper concreting planning and to prevent cracking. However, in the execution of foundation blocks in buildings, these elements are often massive and thermal analysis is frequently neglected.

In this study a preliminary massivity analysis of a foundation capping block was conducted using the Enhanced Massivity Index (EMI), which was proposed initially by Kanavaris et al. [3]. Field temperature monitoring of the block was performed using thermocouples and a data logger. The block was then modeled using DIANA FEA software, allowing comparison between numerical and experimental temperature behavior. The model was calibrated using experimental data, adjusting parameters like adiabatic heat rise and thermal properties. Finally, a mechanical analysis using the cracking index was performed to predict the likelihood and timing of cracking, with values above one indicating potential cracks.

2 The experimental program

The experimental program presents an experimental analysis performed in a concrete foundation block of a 14 story residential building with dimensions of 4m x 2,50m x 1,50m supported by five continuous flight auger (CFA) piles. The block is a reinforced concrete structural element whose function is to connect the foundation piles to the columns of the building's superstructure, ensuring proper load distribution and providing rigidity to the system, which helps prevent potential differential settlements.

For temperature monitoring, four type K thermocouples connected to an Instruterm TH 096 data logger were used. Thermocouples 1 and 2 were placed at a height of 75 cm, corresponding to the geometric center of the block. Thermocouple 3 was placed at a height of 1.25 m. Thermocouple 4 was positioned outside the block to measure the ambient temperature. In figure 1 are presented images of the block's concreting process.



Figure 1. Block before concreting and after insulation layers were removed

The block was monitored throughout 300 hours since the beginning of concreting process. The results are presented in figure 2, which shows the concrete temperature as well as the environment temperature.

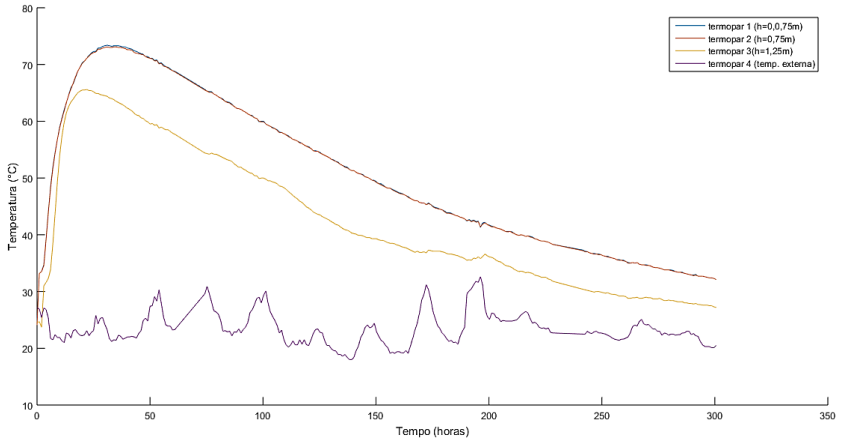


Figure 2. Temperature results

3 The Enhanced Massivity Index

The enhanced massivity index was proposed by Kanavaris et.al [3] and consists in an effective way to assess how likely a concrete element is to suffer with thermal cracking. Thus, the index takes into account some relevant factors that influence the temperature rise, for instance, binder type and content, casting and ambient temperature. It can be obtained from equation 1:

$$M = \frac{ms}{kf * kb * k\Delta T} \tag{1}$$

Where kf, kb and kΔT are dimensionless corrective factors accounting for cement type, binder content and temperature differential. Ms is the surface modulus, which is given by the ratio between the area of exposed surfaces and volume.

Based on the concepts presented, the EMI is calculated for the pile cap. The following section presents the calculations of these factors, which were carried out using the mix design data provided by the concrete supplier.

Given the concepts presented by Oliveira et.al [4], it its well established that the Enhanced Massivity Index is an effective way to assess how likely a concrete element is to suffer with thermal cracking, Although cracking can be strongly influenced by restraint conditions, the EMI of the block points towards a massive element, which is likely to cracking. The calculations of the correction factors and the surface modulus will not be detailed, but will follow the same principles adopted in Oliveira et al. [4] and Kanavaris et al. [3].

From equation 1, the Enhanced Massivity Index (M) is computed as:

$$M = \frac{ms}{kf * kb * k\Delta T} = \frac{1{,}97}{1{,}00 * 1{,}12 * 1.02} = 1{,}72\ m^{-1} \tag{2}$$

According to the classification proposed by Kanavaris et al. [3]:

- For $M \leq 2\ m^{-1}$, structures are categorized as massive, with thermal deformations being the dominant concern;
- For $2\ m^{-1} < M \leq 15\ m^{-1}$, structures are considered semi-massive, where thermal and drying shrinkage effects are of comparable magnitude;
- For $M > 15\ m^{-1}$, structures are classified as thin-walled concrete elements, and thermal deformations are regarded as negligible.

Based on this preliminary assessment, the block analyzed in this study, with an EMI value of $1.72\ m^{-1}$, qualifies as a massive structure, indicating that thermal effects are significant and warrant a more detailed thermal analysis.

4 The numerical program

The numerical program consisted of developing a finite element analysis of the foundation block using the DIANA FEA software. Initially, the thermo-chemical model was implemented. For this, parameter values for the concrete properties already validated experimentally by Fairbairn and Rita [5] were used, such as thermal conductivity, heat capacity, Poisson's ratio, Arrhenius constant, among others. Regarding the adiabatic temperature rise curve, it was calibrated based on experimentally obtained results and adjusted according to Hill. In table 1 the used data is presented. It is worth noting that the ambient temperature adopted was 23.48°C, which corresponds to the average of all readings taken by thermocouple 4 (external temperature). The initial temperature of the concrete was measured on-site at the beginning of the casting.

Table 1. Properties of concrete and boundary conditions

Thermal conductivity	2.6 W/mK
Thermal capacity	2.525e+06 J/ m³K
Coefficient of thermal expansion	1e-05 1/K
Activation energy (Arrhenius constant in DIANA input)	4300 k
Young's modulus	2.6e+10 N/m2
Poisson	0.2
Initial concrete temperature	24,7 °C
External temperature	26°C
Convection coefficient with the environment	h = 10 w/m²°C
Convection coefficient considering wood panel.	0,61 W/m²°C

To determine the size of the mesh elements, a sensitivity analysis was performed and quadrilateral elements of 200mm were adopted, since a further refinement would not increase significantly the precision of results. Therefore roughly 2000 quadrilateral elements were used.

Once the thermo-chemical model was validated through the experimental data, the mechanical model was

defined.

To develop an accurate mechanical model, it is essential to incorporate the behavior of the mechanical properties of concrete, such as the elastic modulus, compressive strength, and tensile strength. Since the cement hydration reaction is thermally activated, these mechanical properties directly depend on the degree of hydration. Thus, the higher the thermal activation, the faster these mechanical properties will develop.

To model this behavior, the equations proposed by RILEM [1] are used, which adopt the variable βc(t), defined by equation 3:

$$\beta c(t) = \frac{\propto (t) - \propto_0}{\propto_\infty - \propto_0} \tag{3}$$

Therefore, the hydration degree curve from the central node of the thermo-chemical model was used to calculate the mechanical property curves through the aforementioned equations.

Since the main objective of the mechanical model is to determine whether thermal cracking will occur, particular attention is given to the cracking index, which can be simply defined by equation 4 as the ratio between the maximum principal stress (σ_1) and the tensile strength (f_t).

$$Icr = \frac{\sigma 1}{ft} \tag{4}$$

Therefore, for values greater than 1, the concrete tends to crack at that location.

5 Results

5.1 Temperature behavior

Once the thermo-chemical model was completed, the temperature curve behavior at the central node — that is, at the geometric center of the block — was compared. The results can be seen in the figure 3.

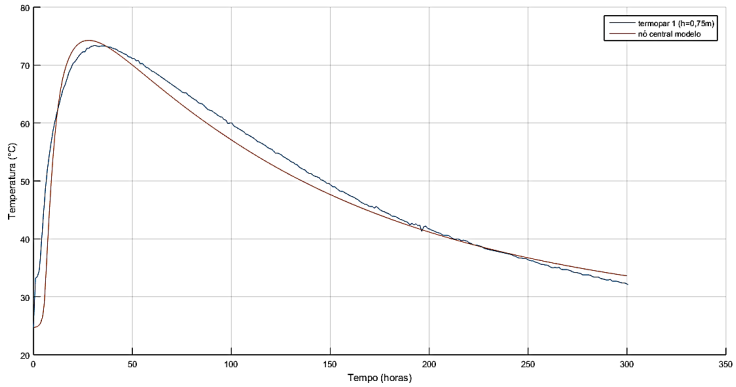


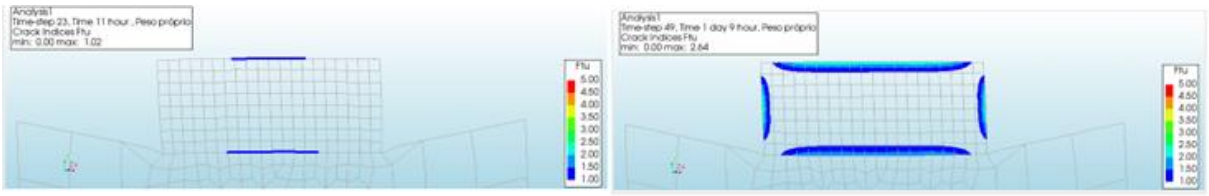
Figure 3. Experimental x numerical results

Taking a closer look at the peak of the curves, it is worth noting that, according to the experimental results from thermocouple 1, the peak temperature was 73,40 °C and occurred at 31 hours. In contrast, the numerical model predicted a peak temperature of 74,27 °C at 28 hours. Despite this slight difference, the numerical model can be considered validated, as the temperature trends in both the experimental and numerical analyses are closely aligned.

Given the peak temperature recorded, in addition to the thermal stresses generated by the temperature gradients, the potential for delayed ettringite formation (DEF) becomes a significant concern, given that, as noted by Mehta and Monteiro [6], DEF primarily occurs when concrete is exposed to temperatures exceeding 65°C during the early stages of hydration, as ettringite becomes unstable under such conditions. Consequently, its initial formation is suppressed, leaving aluminate and sulfate ions unreacted. At later ages, ettringite may reprecipitate within the hardened concrete, leading to internal expansion and subsequent cracking.

5.2 Cracking index

The figures 4 - a and 4- b highlight the regions where the cracking index exceeded 1.It can be observed in Figure 4 – a that the first instance of cracking indicated by the model occurs at 11 hours. on the top and bottom surfaces. After that moment, the model shows a maximum cracking index of 2.64 at 33 hours as shown in Figure 4-b.



a) b)

Figure 4. Cracking index at 11 hours (a) and 33 hours (b)

After this instant the cracking index starts to decrease until it becomes lower than one at 5 days and 19 hours.

By analyzing the results related to the cracking index of the mechanical model, cracking was observed on all four surfaces of the block. The cracking process began at 11 hours from the start of concreting, peaked at 33 hours, and ceased after 5 days and 19 hours. Such cracking is commonly observed on the surface of blocks a few hours after concreting and is mainly due to the temperature gradient with the external environment. This process can be explained through the following analogy: it is known that temperatures are naturally higher at the center of the block. Therefore, the surfaces can be imagined as simply supported beams, as illustrated in Figure 5.

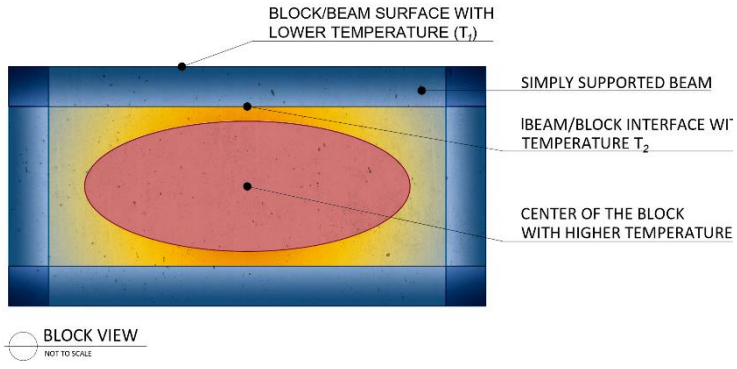


Figure 5. Supported beams analogy.

Thus, there is a simply supported beam for each surface, in which the temperature T2 of the bottom face, or inner face, is always higher than the temperature T1 of the top face, or outer face as we can see in figure 6.

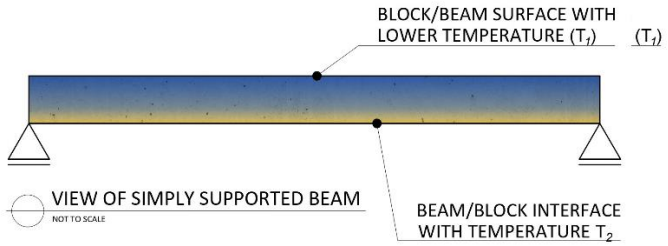


Figure 6. Supported beam with temperature gradient

Such a thermal gradient will naturally cause greater deformation in the lower fibers of the beam. If there were no restraints, the deformation would occur as presented in figure 7:

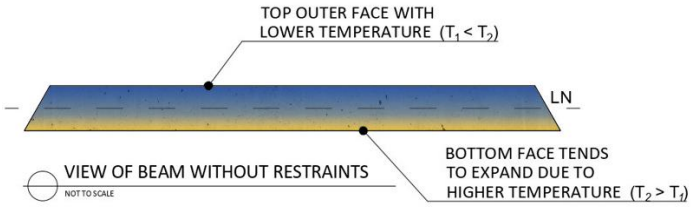


Figure 7. Strains caused my temperature gradient given a no restraint situation

Since this deformation is restrained, tensile stresses develop in the upper fibers, which are consistent with the introduction of a bending moment. That is, the bending moment generates tensile stresses in the upper fibers, leading to cracking.

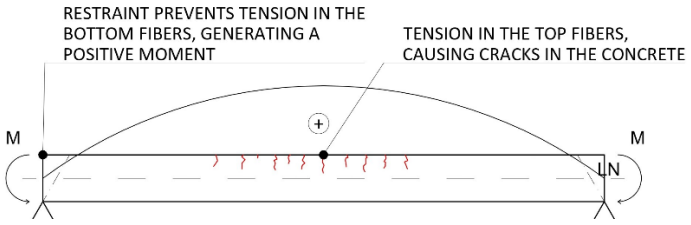


Figure 8. Positive bending moment caused by temperature gradient associated with restraints

Although it was not observed expressive cracking on this particular block, the cracking behavior presented though the numerical model is considered to be accurate since similar cracking is often observed on the surface of foundation blocks.

Conclusions

This study evaluated the thermochemical behavior of a foundation block, as well as its mechanical behavior and the occurrence of cracking. To this end, the first step was to analyze the Enhanced Massivity Index (EMI). The purpose of the massivity index is to quickly assess whether the structure under analysis requires a thermal study to mitigate cracking and how thorough this study needs to be. Even though the EMI does not take into account restraint conditions, which strongly influences the cracking behavior as it was shown by Oliveira. et. al

[4], the EMI already points towards a massive element, which is likely to suffer with early age cracking.

Regarding the thermochemical and mechanical models, the results were very close to the experimental data, which indicates that the model is well-calibrated and accurately represents the structure. Concerning temperature, the results showed that even for a foundation block of a medium-sized structure, the peak temperature reached approximately 74°C. This is concerning not only due to the stresses introduced by the thermal gradient but also because of the potential occurrence of delayed ettringite formation (DEF).

With regard to cracking behavior, the numerical model predicted the formation of surface-level cracks, primarily resulting from the stresses induced by external thermal gradients. These cracks tend to diminish progressively after a few days. Although no cracks were observed in the block in the days following concreting, the model is considered representative, as the simulated crack pattern is commonly observed in foundation blocks lacking adequate curing procedures. It is worth noting that curing procedures were applied, which may have mitigated the appearance of surface cracks.

Therefore, the results demonstrate that even in foundation blocks with a relatively small concrete volume, it is essential to conduct proper thermal studies to mitigate the development of cracks and, consequently, the appearance of pathological manifestations or compromise of the structure's durability.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] F. Benboudjema, J. Carette, B. Delsaute et al., "Mechanical Properties". In: E. M. R. Fairbairn and M. Azenha (ed.), *Thermal cracking of massive concrete structures.* State of the Art Report of the RILEM Technical Committee 254-CMS, Springer, 2019.

[2] I. Fraga. "Análise de sensibilidade do modelo termoquímico-mecânico para estruturas de concreto massa", Rio de Janeiro, 2018.

[3] F. Kanavaris, A. Jedrzejewska and I. P. Sfikas, et al., "Enhanced massivity index based on evidence from case studies: Towards a robust pre-design assessment of early-age thermal cracking risk and practical recommendations". *Construction and Building Materials*, vol. 271, pp. 1-18, 2021.

[4] B. B. Oliveira et al. "Massivity index and numerical analysis of concrete specimens". *CILAMCE*, Maceió, 2024.

[5] R. D. Toledo Filho, E. M. R. Fairbairn, O. A. M. Reales, et al., "Transdutores de nanotubos de carbono-pastas de cimento para monitoramento de deformações estáticas e dinâmicas em barragens de concreto". *Relatório Técnico de Atividades 6 - Relatório Final*, Fundação COPPETEC, 2024.

[6] P. K. Mehta and P. J. M. Monteiro. *Concreto - Microestrutura, propriedades e materiais*. Nicole Pagan Hasparyk, 2014.