Massivity index and numerical analysis of concrete specimens

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Abstract. This study focuses on the behavior of massive concrete structures and the stresses induced by temperature variations due to the hydration reaction at the early ages. Before conducting an analysis of effects due to cement hydration, it is essential to determine whether the structure qualifies as massive. This article uses the enhanced massivity index proposed by RILEM Technical Committee 254 CMS [3], which aids in identifying the most suitable analysis for each structural element. As a case study aiming to assess cracking behavior, a concrete block was modelled and the results of the numerical model were compared with the experimental results obtained in the laboratory. Once the model was validated by those results, different restraint conditions were applied, demonstrating that the boundary conditions play an important role regarding cracking occurrence.

Keywords: massive concrete structure, temperature, hydration, restraints, boundary conditions.

1 Introduction

Regarding massive concrete structures, it is of utmost importance to have a proper pre-design assessment of early age thermal cracking. That said, this study addresses the importance of the enhanced massivity index in order to determine if the structural element is massive or not and what kind of thermal study should be applied.

That said, the massivity index aims to assess whether a thermal analysis of a given element is necessary to mitigate potential thermal cracking. According to Kanavaris et.al [1], the most commonly used methods for calculating the index are: characteristic length of hydration heat diffusion, basic massivity equivalent thickness and surface modulus. In table 1 is a summary of each method.

In this paper, we present examples that complement those presented in Kanavaris et.al [1]. These are case studies conducted by LABEST/NUMATS, as-built analyses of massive structures, and other complementary studies. To this end, enhanced massivity indices were calculated, and thermo-chemical and mechanical analyses were performed using the DIANA-FEA computational code. The analyzed models served as a basis to examine the influence of the restraint conditions of the structural element concerning the occurrence of thermal cracking.

Table 1. Methods for calculating the index

Basic massivity	Calculated as a ratio between the volume of concrete and total area of surfaces	$M_{basic=}\frac{Vconcrete}{S\,total}\,(m)$
Massivity	Calculated as a ratio between substitute volume (volume of concrete + volume representing insulation layers) and total area of exposed surfaces	$M_{=}\frac{Vconcrete+Vins}{S\,p}\,(m)$
Equivalent thickness	Calculated as a product of Massitity M and a shape factor	$Deq_{=}\gamma a * M$
Surface modulus	Calculated as a ratio of total area of exposed surfaces and volume of concrete	$Ms_{=}\frac{Sp}{Vconcrete}\,(m^{-1})$

2 The enhanced massivity index

The enhanced massivity index was proposed by Kanavaris et.al [1] 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:

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

(1)

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

$$ms = \frac{sp}{V\ concrete},$$

(2)

2.1 Relative heat correction factor, kf

This factor is related to the heat generated during the hydration process. It can be defined as the ratio of heat output of blended cement with supplementary cementitious materials (SCMs) to that of pure Portland cement (CEM I). Typical values of kf are given in Table 2.

Table 2 – Exemplar relative heat factors according to cementitious binder (Kanavaris et.al [1])

Cement Type/ Combination	Heat evolved at 72 h [j/g] (Q)	Relative heat factor (kf)
CEM I 42.5	366	1,00
CEM I 42.5 + 10% FA	325	0,89
CEM I 42.5 + 30% FA	200	0,55
CEM I 42.5 + 50% FA	112	0,31
CEM I 42.5 + 10% GGBS	334	0,91
CEM I 42.5 + 30% GGBS	255	0,70
CEM I 42.5 + 50% GGBS	232	0,63
CEM I 42.5 + 70% GGBS	157	0,43

2.2 Binder content correction factor, kb

Binder content has a significant influence on the temperature development. Thus, considering an average binder content of 300 kg/m³, kf can be defined as:

$$kb = \frac{binder\ content\ (\frac{Kg}{m^3})}{300\ (\frac{kg}{m^3})} \tag{3}$$

2.3 Correction factor for temperature differential, kΔT

This factor takes into account the fresh concrete temperature, ambient temperature and the adiabatic temperature rise.

$$k\Delta T = \frac{Tfresh - Tambient + Tad,rise}{Tad,rise}, \tag{4}$$

where:

Tfresh is the fresh concrete temperature or placing temperature;

Tambient Expected ambient temperature at the time of maximum concrete temperature;

Tad,rise is Temperature rise due to hydration under adiabatic conditions.

Once the correction factors are properly calculated and applied on equation 1, the proposition of Kanavaris et al. [1] is that for those values for $M \leq 2m^{-1}$ structures are classified as massive with a predominant impact of thermal strains. For values $2m^{-1} \leq M \leq 15m^{-1}$ structures area classified as semi massive of comparable impact of thermal and drying shrinkage strains. For $M \geq 15m^{-1}$ structures are classified as thin-walled concrete structures and the impact of thermal strains are negligible.

3 Case studies

3.1 Concrete block 40x40x40 cm, free for thermal deformations

A block was cast at the LABEST/NUMATS laboratory at the Federal University of Rio de Janeiro with the boundary conditions of the laboratory. The block consists in a cube of dimensions 40 x 40 x 40 cm monitored with thermocouples. The walls of the block were made of 18 mm thick wood panel reinforced with expanded polystyrene boards and aluminized self-adhesive asphalt blanket. The initial external temperature was 26° C and the concrete placing temperature was 29°C.

Figure 1. Block concreting being carried out at the LABEST/NUMATS laboratory (Toledo Filho et al. [2])

Once the experimental results were obtained, a model of the block was developed using DIANA-FEA computational code with the very same boundary conditions of the laboratory, which are resumed below.

Table 3 – Properties of concrete and boundary conditions

Binder content	440 kg/m³
Fly ash content	132 Kg/m³
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	29 °C
External temperature	26°C
Convection coefficient with the environment	h = 10 w/m²°C
Convection coefficient considering wood panel and polystyrene boards	0,61 W/m²°C

To determine the size of the mesh elements, that is, the mesh refinement, a sensitivity analysis was performed and hexahedral elements of 100mm were adopted, sense a further refinement would not increase significantly the precision of results.

We now calculate the enhanced massive index. First, we need to calculate the correction factors kf, kb and kΔT.

Considering that we have 132 kg of fly ash and 440 kg of cement, which results in an addition of 30%, the results of Table 2 can be used as this cement is close to a CEM I 42.5 + 30% FA. Using data obtained from Table 3 of Kanavaris et al.[1]. That results in a factor kf=0.55.

The factor kb can be calculated as follows.

$$kb = \frac{binder\ content\ (\frac{Kg}{m^3})}{300\ (\frac{kg}{m^3})} = \frac{440}{300} = 1.467$$

And the factor kΔT:

$$k\Delta T = \frac{Tfresh - Tambient + Tad, rise}{Tad, rise} = \frac{29 - 26 + 43.5}{43.5} = 1.068$$

Now the next step is to calculate the surface modulus:

$$ms = \frac{sp}{V\ concrete} = \frac{6 * 0.4^2}{0.4^3} = 15$$

Then, M is given by:

$$M = \frac{ms}{kf * kb * k\Delta T} = \frac{15}{0.55 * 1.467 * 1.068} = 17.407$$

So, taking into account the reference values previously presented, the cube would not be considered a massive structure. Therefore, at first, a thermal analysis would not be necessary.

Next we present the model that was built using DIANA-FEA computational code. The main goal of this model is to develop a mechanical model of the structural element that is capable of determining its behavior in terms of cracking. In order to achieve that goal first we establish a thermo – chemical model that represents the block's behavior regarding temperature and degree of hydration. Then, we can use this data to calculate the behavior of the mechanical properties throughout time, such as young' modulus, compressive strength and tensile strength using the equations proposed by RILEM Technical Committee 254 CMS (Benboudjema et al. [3]) on chapter 4. This step is necessary because the behavior of such properties over time directly depends on the temperature, as the cement hydration reaction is thermally activated.

Once the behavior of temperature and degree of hydration over time is known, we can use that as an input on the mechanical model and, then, obtain the results.

Below are the results of the thermochemical model and the comparison with the experimental results.

Comparing experimental and numerical results, we can observe that the temperature development and the temperature peak were very close. Taking thermocouple TP-04, for instance, it registered a temperature peak of 57.5°C at a time of 27 hours. The numerical model pointed to a temperature peak of 60.6ºC at a time of 26 hours. A node in the geometric center of the block was taken as reference, in order to be comparable to data obtained by TP-04. Therefore, we can conclude that the results are consistent and the model is validated.

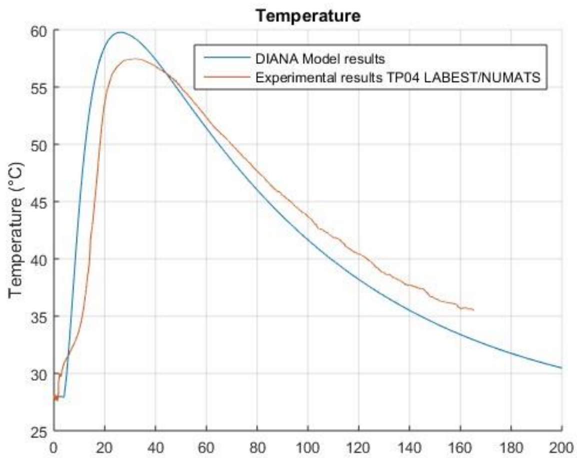

Figure 2. Temperature obtained experimentally and temperature obtained from the model.

It is noteworthy that, since the goal is to reproduce the very same boundary conditions of the laboratory, there are no external restraints. That is, the block is free do deform.

Since the main goal of the mechanical model is to determine whether or not thermal cracking will occur, we are particularly interested in the cracking index, which can be simply defined by the ratio between the applied stress and the tensile strength.

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

Where σ1 is the applied stress and ft is the tensile strength. Therefore, for values greater than 1, the concrete tends to crack.

Therefore, if the index is greater than 1, the concrete tends to crack at that point. That said, we can now evaluate if at some point of the analysis period the ICR becomes greater than one.

After running the model, the conclusion was that the greatest ICR found was 0.06. Thus, the block does not crack at all. That is an expected result since the Enhanced Massivity Index had already pointed towards a non massive element and there were no external restraints. It is important to note that no cracks were observed in the laboratory block, which validates the model.

3.2 Concrete block 40x40x40 cm, with restrictions in the base

This time we run again the exactly same model, with the same boundary conditions, except the base restrictions. Now we assigned supports that do not allow the base to undergo displacements. The EMI is precisely the same.

After running the model we concluded that by simply adding a base support that restrains displacements, the cracking index achieves 2.34 at the peak. The following figure shows color contours in the areas where cracking will occur. That is, where ICR is greater than one.

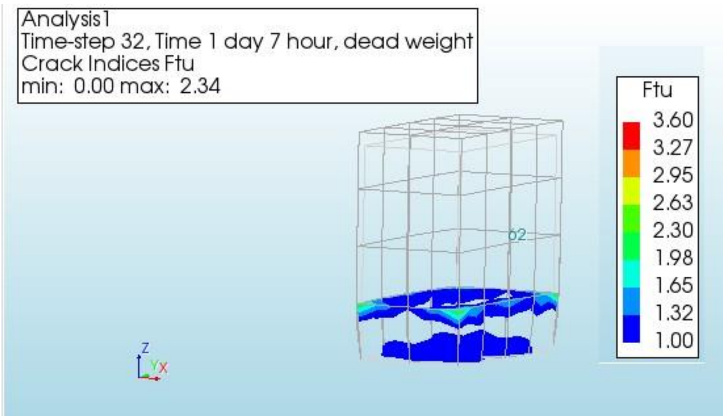

Figure 3. Cracking index results.

3.3 Concrete block 40x40x40 cm, all restricted

Now we aim do study an upper bound case where, besides the base, all faces are restrained.

In this scenario the cracking index achieves 2.96, showing that the block will crack at several points.

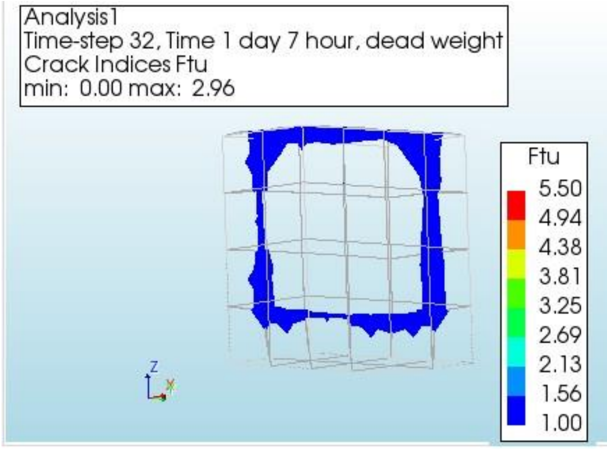

Figure 4. Cracking index results

4 Discussion and conclusions

The enhanced massivity index was designed for real structures such as dams or containment structures that, in some way, will have restraints on horizontal displacements at their foundations. Perhaps for this reason, restraints are not parameters that intervene in the EMI. However, in the case of the block tested in the laboratory, the restraints on horizontal movements at the base are not very similar to those that would occur in a foundation block when the structure is bonded to the soil or rock layers where they are supported. In the case of the cube studied here, the tendency to crack is highly influenced by the boundary conditions, since the case study demonstrated that external restraints increase considerably the crack index and, therefore, cracking occurrences. But this fact does not invalidate the EMI since the most common case of base restriction indicates no cracking in the early ages.

Therefore, considering that restraint conditions had a great influence on the appearance of cracks in the block, it is suggested that these be taken into account in the calculation of the massivity index. This consideration is due to the fact that even an element that is not considered massive by the already established methodologies for calculating the index, when severely restricted, becomes prone to cracking.

It is important to emphasize that 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. Thus, taking into account the restraint conditions make the index more accurate and closer to the reality of structures, preventing structures that initially are not considered massive from presenting cracks due to the stresses imposed by thermal loads.

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