Cracking Risk Analysis of Mass Concrete Structures Produced at Constant and Changing Ambient Temperature

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Abstract. The low-heat cured cement-based mass concrete structures need to satisfy some special requirements to avoid crack forming. In this study, the influence of constant and changing ambient temperature on the crack formation is investigated and compared using a finite-element based numerical analysis.

1. Introduction
A real problem is that the quality and the cracking sensitivity of mass concrete structures depend on the changing ambient temperatures and the relative ambient humidity determined by the actual weather conditions. The risk of cracking in concrete structures can be important during summer concreting when thermal stresses are induced due to the hydration heat generation. In the case of winter concreting the low ambient temperature has a decisive influence on the temperature differences developed between the surface and the core of concrete parts. At the beginning of the solidification process in mass concretes, the early-age phase is characterized by an exothermic chemical reaction. During this reaction, the temperature and the volume modification can be observed. These phenomena determine the stress conditions forming between the surface and the core of concretes. Cracking initiates once stresses developed exceed the tensile stress capacity of the concrete.

As it is known, the difference between the surface temperature and the highest temperature of the core influences strongly the risk of crack formation. According to the Eurocode used in the engineering design of concrete parts, the maximum temperature difference is limited, and it cannot exceed 20 °C. Because the design of high performance concrete mixtures is a complex procedure, the technologist should be taken into consideration simultaneously the heat generation, the material properties, and the curing parameters, such as curing temperatures and durations.

During hydration, cement reacts with water and heat is generated. The curing temperature affects strongly the progress of hydration: when the curing temperature is increased, the cement hydrates more rapidly [1]. The amount of heat generated is a function of time and temperature.

Qingbin Li [2] et al. produced concrete specimens in summer and in winter and examined the change of mechanical parameters. It has been observed that the mechanical properties of concrete poured in different time are strongly affected by the external weather conditions (different temperatures). More exactly, fracture parameters are influenced by the coupling effect between temperature and age. According to the fracture test results, they concluded that the fracture properties of concrete poured in summer were better than that of concrete poured in winter at the same age.
Zhou Yunchuan [3] et al. used different curing methods for studying the cracking risk reduction. They applied finite element analysis to describe the solidification process. According to experiments performed at constant ambient temperatures they concluded that the cracking risk depends on the temperature difference forming between the surface and the core of the concrete. The authors recommended the use of a curing procedure to obtain an optimised body temperature field.

Hordijk and Reinhardt [4] performed experiments to investigate the effect of curing conditions on the fracture parameters of concretes. The results obtained indicate that the fracture characteristics are influenced by the applied curing conditions.

Kim et al. [5] studied the age effects, their results demonstrate that the fracture parameters of concretes can be improved with age.

In what follows, to simulate the temperature field in mass concrete structures, experiments by using a finite element software are presented. Based on results obtained the impact of the daily temperature change on the cracking risk in concrete structures is demonstrated.

2. Material and method
As it is known, the composition of the cement belongs to the major contributors to heat hydration. The examined material was a usual concrete with density 2400 kg/m³, it has been made using CEM III B 32.5 N cement. Figure 1 illustrates the heat generation in the concrete as a function of time. The diagram has been determined by calorimetry.

Figure 1. Heat generation curve of the concrete as a function of time

The thermal properties of the material investigated are summarized in Table 1. These parameters values are considered to be constant during the simulation.

Table 1. Material properties of the concrete

| property                      | value     |
|-------------------------------|-----------|
| specific heat                 | 1228 J/(kgK) |
| isotropic thermal conductivity| 3.5 W/(mK) |
| temperature of fresh concrete | 20 °C     |

As usual in the finite element calculations, the geometry of the specimen investigated was represented by a regular cube with size 1m x 1m x 1m [6]. The non-linear finite element model is based on the Fourier law including the internal heat generation due to the exothermic hydration reaction.

Concerning the boundary conditions, in the simulation experiments two cases have been investigated: In the first case it was supposed that the surface temperature is maintained at a uniform constant temperature (at a constant ambient temperature T_s= 20 °C), in the second case we assumed the surface
temperature is changing periodically in the interval (15 °C - 25 °C). In this latter case, the changing ambient temperature $T(t)$ was defined by equation (1).

$$T(t) = T_{amp} \sin \left( \frac{2\pi t}{24} \right) + T_{avg}$$  \hspace{1cm} (1)

where

- $T_{amp}$ is the amplitude of the temperature modification in °C,
- $t$ is the time in hour,
- $T_{avg}$ is the daily average temperature in °C.

The periodical temperature function (1) is depicted in Figure 2.

![Figure 2. The changing surface temperature defined by Eq.(1)](image)

In the model the heat transfer coefficient was considered to be constant: 5 W/(m²K). The simple specimen geometry and the symmetric heat transfer conditions (initial and boundary conditions) enables to take into account only the one-eighth of the unit cube. (See Figure 3.)

![Figure 3. The selected meshing and the convection definition (with yellow)](image)

3. Results

The results obtained by finite element analysis are demonstrated in Figures 4-6. As can be seen in Figure 4, the minimum values of temperature can be observed at the corners of the cube, while central point represents the maximum temperature.
According to diagrams depicted in Figures 5 and 6, due to the hydration heat the minimum and maximum temperatures increase simultaneously.

**Figure 4.** The temperature distribution at constant surface temperature at the end of the hydration process

**Figure 5.** The variation of temperature in the cube as function of time in the case of constant surface temperature

**Figure 6.** The variation of temperature in the cube as function of time in the case of periodically changing surface temperature
The computed results are given in Table 2.

| Table 2. The minimum and the maximum temperatures, the maximum temperature-difference ΔT, and the time \( t_{\text{max}} \) when the temperature-difference obtains its maximum value |
|---|---|---|---|
| | \( T_{\text{min}} \) [°C] | \( T_{\text{max}} \) [°C] | \( \Delta T \) [°C] | \( t_{\text{max}} \) [h] |
| T(t)= const | 29.24 | 41.30 | 12.11 | 51.2 |
| T(t)≠const | 31.05 | 41.65 | 14.36 | 44.07 |

Based on the results of the finite element analysis, it can be concluded that the minimum and the maximum core temperatures are different in the two cases of the selected boundary conditions.

If the surface temperature is constant, lower minimum and maximum temperatures are observed in the body. In the case of periodically changing surface temperature, the difference between the minimum and maximum temperatures in the body is larger. In this latter case it can be observed that there is a shift in times \( t_{\text{max}} \) characterizing the maximum temperature differences (See values 51.2 h and 44.07 h). It should be noted that the maximum value of heat generation is detected at 8 hours, as it is indicated in Figure 1.

For comparison, the results obtained are demonstrated in Figure 7.

From diagram depicted in Figure 7, it can be observed that the maximum temperature difference \( \Delta T \) appears at time 44 h in the case of constant surface temperature, while the maximum \( \Delta T \) temperature is reached at time 51.2 h when the surface temperature is periodically changing.

4. Conclusions
The control and the reduction of hydration heat in concrete structures belong to the technological problems of primary importance. Based on the application of a simplified finite-element based model, from our preliminary results it can be concluded that the cracking sensibility can be decreased by an appropriate selecting of the starting time of concreting and taking into consideration the actual weather conditions.

5. References
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