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EVALUATION OF THE IMPACT OF PARAMETER INPUTS OF CONCRETE MIX ON THE DISTRIBUTION OF TEMPERATURE IN THE MASS CONCRETE STRUCTURE

PROCENA UTICAJA POČETNIH PARAMETARA MEŠAVINE BETONA NA RASPODELU TEMPERATURE U MASI STRUKTURE BETONA

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Keywords
- heat of hydration
- temperature gradient
- crack
- mass concrete
- mathematical model

Ključne reči
- tolpota hidratacije
- gradijent temperature
- prslina
- teški beton
- matematički model

Abstract

The paper presents the impact of parameters, such as cement content and initial temperature of concrete, on the temperature distribution in the body of the early age mass concrete structure. The cement content and initial temperature of concrete mix used in the study are limited within 250-500 kg/m^3 and 15-25°C, in respect. Thermal analysis is conducted by using Finite Element Midas Civil 2011. Then, the experiment planning method is used to establish a mathematical function that allows determining the maximal temperature in the concrete structure body. The study indicates that the cement content plays a decisive role compared to the initial temperature of concrete in determining maximal temperature. Besides, the achieved function reflects the impact and correlation of mentioned parameters on the temperature profile of the mass concrete structure.

Izvod

U radu je predstavljen uticaj parametara sastava cementa i početne temperature betona na raspodelu temperature u masi betona tokom rane faze teške betonske konstrukcije. Sastav cementa i početna temperatura betonske mešavine korišćene u istraživanju su ograničeni u rasponu 250-500 kg/m^3 i 15-25°C, respektivno. Termička analiza je izvedena primenom alata Finite Element Midas Civil 2011. Zatim je upotrebljena metoda planiranja eksperimenta radi izvođenja matematičke funkcije kojom se određuje maksimalna temperatura u masi konstrukcije betona. Istraživanje pokazuje da sastav cementa ima odlučujuću ulogu u poređenju sa početnom temperaturom betona, pri određivanju maksimalne temperature. Osim toga, izvedena funkcija pokazuje uticaj i vezu spomenutih parametara na temperaturski profil teške betonske konstrukcije.

INTRODUCTION

Due to the hydration heat of cement in the mass concrete structure during the construction phase, a high-temperature gradient between the ambient and the core of the mass structure is produced when the heat from the concrete body cannot dissipate quickly. As a result of this mechanism, cracks form in the concrete surface caused by thermal stress at the early age of concrete /1-3/. Figure 1 shows the mechanism of a thermal crack profile caused by a high-temperature gradient from the cement hydration process.

The maximal temperature in the concrete mass and its evolution with time depends on the following /5/:
- mix concrete properties;
- climatic factors;
- construction period;
- thickness of lifts;
- initial temperature of lifts;
- interval between their successive placements.

There are several ways to reduce the high temperature gradient in mass concrete structures, such as reducing the cement content, using low heat generating concrete mixtures, pre-cooling of concrete, post-cooling of concrete by using cooling piles, surface insulation, or using concrete containing low-thermal-expansion aggregates, /6-8/.

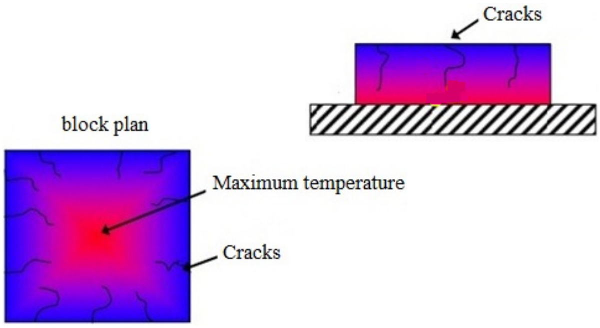

Figure 1. Mechanism of thermal crack formation in the mass concrete structure, /4/.

In addition, using a method of experimental planning to establish a mathematical model is also an appropriate method for controlling the maximal temperature in the mass concrete structure. The mathematical model is used to adjust reasonably the parameters of concrete mix in order to control perfectly the maximal temperature occurring in the mass concrete, /9/.

MATERIALS AND METHODS

Research subjects

In the study, a 3D model includes a mass concrete of size 10×8×3 m, which lays on a foundation 20×12×4 m.

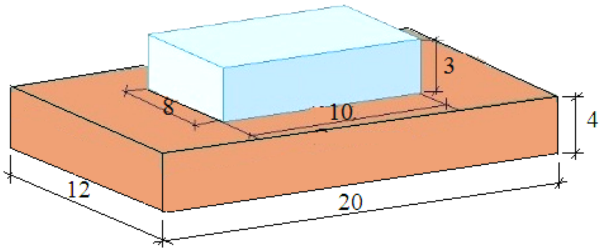

Figure 2. Dimensions of the mass concrete block model.

The ambient temperature significantly effects the maximal temperature. The air temperature which varies by time is calculated by the following Eq.(1), /10/:

$$t_{\text{air}} = 20 + 5\sin\left(\frac{2\pi\tau}{24}\right), \quad (1)$$

where: t_{air}-daily average air temperature (°C); τ-time (hour).

In the study, the initial temperature of the foundation is assumed to be equal to 20 °C. In addition, the properties of concrete and the foundation used as input data for determining the temperature distribution in the concrete mass, are presented in Table 1.

Table 1. Material properties of concrete and foundation.

Property	Concrete	Foundation
Thermal conduction coefficient (W/m°C)	2.31	2.80
Specific heat (kJ/kg°C)	1.15	0.84
Density (kg/m^3)	2400	2700
Convection coefficient (W/m^2·°C	11.5	14.5
Hydration heat of concrete (kJ/kg)	389	–

Mathematical modelling the impact of parameter input of materials

The method of experimental planning is used to build a mathematical model. The effect of parameters of concrete on the temperature field in the mass concrete is considered by establishing the objective function. The objective function of the experimental model is presented by the maximal temperature of concrete T_i ($T_{\max}$, °C). This is the function of the cement content X_1(CC) varying in the range of 200-500 kg/m^3 and initial temperature of concrete mix X_2 (IT), varying from 15-25°C, /11-12/. Table 2 shows the levels of variation of parameters used in first-order planning.

Table 2. Levels of variation of input factors.

Input factors		Variation levels			Interval
Parameter	Variable	–1	0	+1	δ
CC	x_1	200	350	500	150
IT	x_2	15	20	25	5

The number of experiments (N) described in first-order planning can be determined by Eq.(2), /13/:

$$N = 2k + 1, \quad (2)$$

where: k - the number of considered parameters (k = 2); 1 - the number of the experiment at the centre.

Then, the value of N = 5 is adopted.

The mathematical fomula to determine the maximal temperature in mass concrete body can be expressed by second order polynomial as shown in Eq.(3):

$$T = b_0 + b_1 X_1 + b_2 X_2 + b_{12} X_1 X_2 . \quad (3)$$

Finite element method of heat transfer

The governing heat transfer equation in the global Cartesian system can be described by the Fourier equation as shown in Eq.(4), /14-15/:

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{\partial Q_w}{\partial \tau} = \rho c \frac{\partial T}{\partial \tau}, \quad (4)$$

where: T - material temperature (°C); k - thermal conductivity of concrete (W/m°C); Q_w - accumulated internal heat generated in time (J/m^3); $\partial Q_w/\partial \tau$ - rate of internal heat generation per unit volume (W/m^3); c - specific heat (J/kg°C); ρ - density of concrete (kg/m^3); τ - time (hour).

To solve Eq.(4), it is necessary to apply the appropriate boundary conditions, such as Dirichlet boundary conditions, Neumann boundary conditions, the Robin boundary condition, and mixed boundary conditions, /16/.

To solve the complex thermal transfer problem as described in Eq.(4), the FEM - Midas Civil software is an appropriate solution to analyse the thermal-structural behaviour in the concrete mass, /17/. An algorithm for the FE thermal analysis is introduced in Fig. 3.

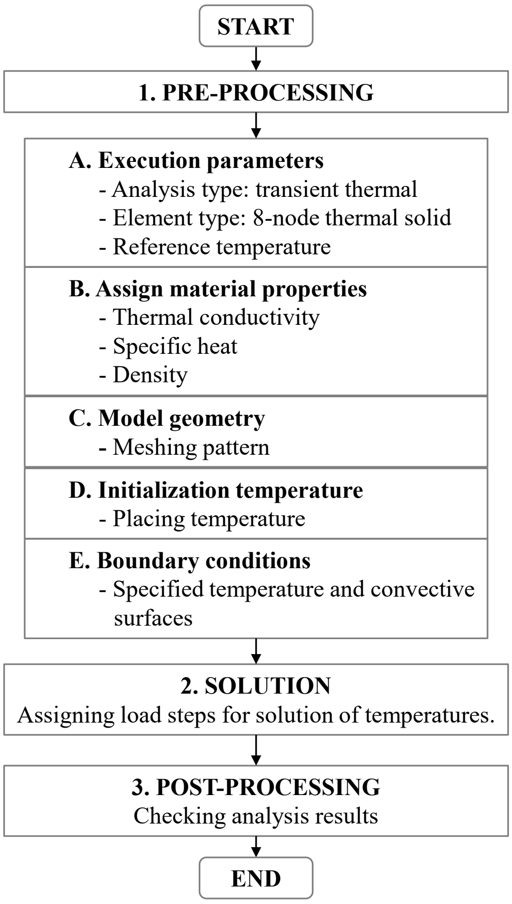

Figure 3. FEM thermal analysis algorithm for mass concrete block.

As the model has symmetry, a quarter of the actual size is used in the FE model as shown in Fig. 4. The mesh of the model with amount number of 1800 eight-node thermal elements, corresponding to 2352 nodes, is used to simulate the transient thermal analysis.

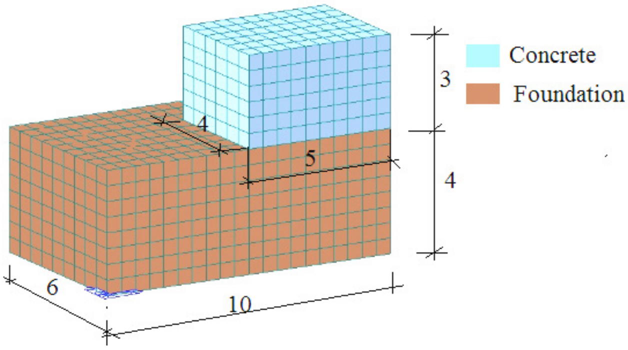

Figure 4. Dimensions of the mass concrete block used in the model, unit (m).

RESULTS AND DISCUSSION

The maximal temperatures obtained from the analytical result are shown in Figs. 5-8 and summarized in Table 3.

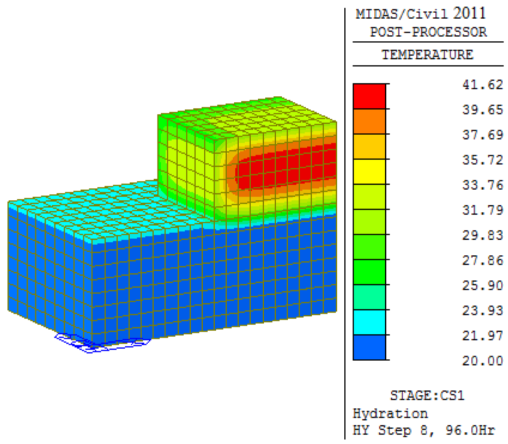

Figure 5. Temperature field in the concrete block at 96 hours (CC = 200 kg/m^3; IT = 15°C).

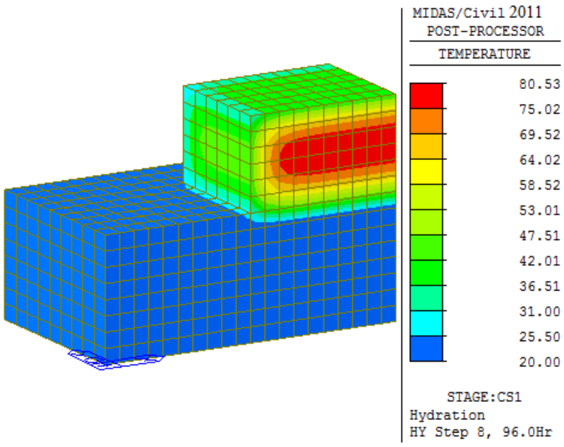

Figure 6. Temperature field in the concrete block at 96 hours (CC = 500 kg/m^3; IT = 15°C).

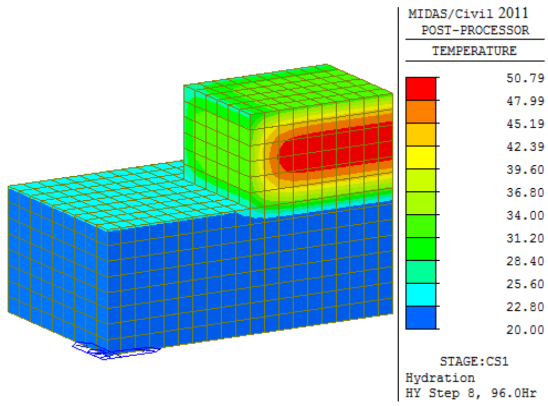

Figure 7. Temperature field in the concrete block at 96 hours (CC = 200 kg/m^3; IT = 25°C).

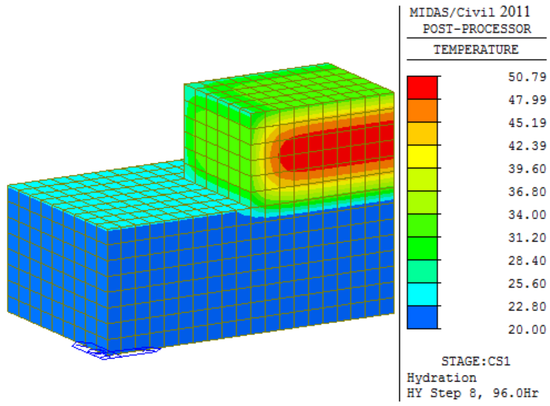

Figure 8. Temperature field in the concrete block at 96 hours (CC = 500 kg/m^3; IT = 25°C).

Table 3. Maximal temperatures in the mass concrete body corresponding to different cement contents and initial temperatures.

In the form of variables		In natural form		T_{max} (°C)
x_1	x_2	CC (kg/m^3)	IT (°C)	
–1	–1	200	15	41.62
+1	–1	500	15	80.53
–1	+1	200	25	50.79
+1	+1	500	25	89.70
0	0	350	20	65.65

It can be seen that an increase in the cement content enhances the maximal temperature more than that caused by an increase of the concrete mix initial temperature. Thus, when the cement content varies in the range 200-500 kg/m^3 of concrete mix, the maximal temperature difference is 38.91 °C (compare Fig. 5 with Fig. 6, and Fig. 7 with Fig. 8). In contrast, the initial temperature of the concrete mix which varies in the range 15-25 °C only contributes a difference of 9.17 °C.

Results of the Matlab program that show maximal temperatures corresponding to the cement contents and initial temperatures can be summarized in Table 3. Then, the regression equation can be adopted as shown by Eq.(5):

$$T_{max} = 65.66 + 19.46 x_1 + 4.59 x_2 \,. \qquad (5)$$

The result obtained in Eq.(5) shows that all the above factors have a fairly large impact on the maximal temperature of the mass concrete. The temperature mostly depends on the factors x_1 (CC). Besides, Fig. 9 allows to quickly determine the maximal temperature (T_{max}) in the mass concrete body, where the parameters of cement content and initial temperature vary in ranges as mentioned in Table 2.

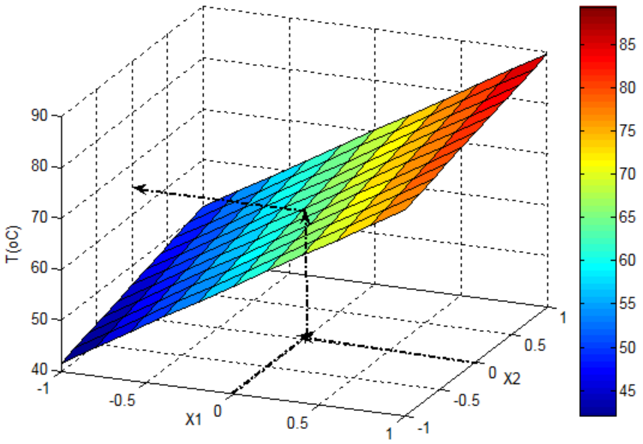

Figure 9. Nomogram used for determining the maximal temperature in the mass concrete.

The case, in which the cement content of 350 kg/m^3 and initial temperature of 20 °C of concrete mix are used (x_1 = 0, x_2 = 0), is considered to determine the maximal temperature in the mass concrete by computer program Midas Civil 2011. An obtained value of the maximal temperature T_{max} = 65.65 °C after 96 hours from the beginning of construction is shown in Fig. 10.

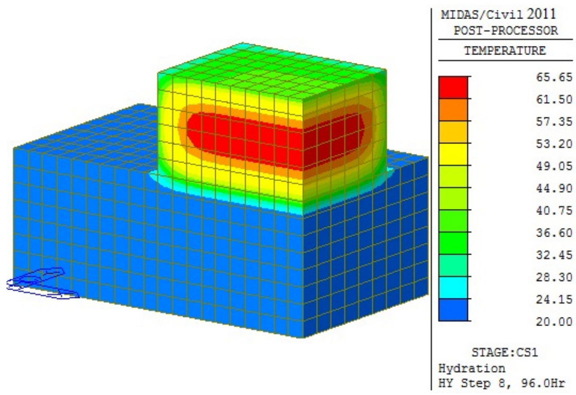

Figure 10. Temperature distribution in the concrete body at 96 hours (x_1 = 0; x_2 = 0, or CC = 350 kg/m^3; IT = 20 °C).

Figure 10 shows the maximal temperature in concrete mass T_{max} = 65.65 °C after 96 hours. The relative error of 0.01 % between the result obtained from the nomogram and that obtained from the FE analysis with Midas Civil 2011 gives a good comparison in the precision of the analytical result.

CONCLUSION

Based on the results of the study, the following conclusions can be obtained:

1) The method of experimental planning used in the model reflects the correlation and impact between cement content and initial temperature of concrete on the temperature distribution in the body of the early age mass concrete structure.

2) The mathematical function T_{max} can be used to calculate the maximal temperature in the mass concrete body with the cement contents and initial temperatures of the concrete mix varying in the range of 200-500 kg/m^3 of concrete and 15-25 °C, respectively.

3) The cement content plays a decisive role in making the maximal temperature in the mass concrete body when compared to that caused by the initial temperature of the concrete mix. Hence, careful consideration is needed for the cement content in the concrete mix when controlling the maximal temperature in mass concrete structures.

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