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FINITE ELEMENT ANALYSIS OF TEMPERATURE AND STRESS FIELDS IN THE CONCRETE MASS WITH PIPE-COOLING

ANALIZA TEMPERATURSKOG I NAPONSKOG POLJA BETONSKE MASE SA CEVNIM HLAĐENJEM METODOM KONAČNIH ELEMENATA

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Keywords
- temperature field
- stress field
- crack
- mass concrete
- pipe cooling

Abstract

The reduction of heat during cement hydration and the prediction of the formation of temperature field and stress fields in mass concrete should be considered and studied. The main objective of the paper is analysis of temperature and stress fields in the concrete mass with and without the cooling pipe system by finite element method. When the mass concrete contains the cooling pipes system, the maximum temperature, temperature difference is significantly reduced compared to the mass concrete without the cooling pipe system. At the same time, cracks do not form on the surface of mass concrete blocks. The analysis method in this study can help engineers choose one of the most effective measures to prevent the cracking formation in mass concrete structures, as is the cooling pipe system.

Ključne reči
- temperatursko polje
- naponsko polje
- prslina
- betonska masa
- hlađenje cevima

Izvod

Potrebno je istraživati smanjenje toplote kod hidratacije cementa i predviđanje obrazovanja temperaturskog i naponskog polja betonske mase. Osnovni cilj rada je analiza metodom konačnim elementima temperatursko i naponsko polje betonske mase, sa ili bez sistema hlađenja cevima. Kada betonska masa ima sistem hlađenja cevima, maksimalna temperatura i temperaturska razlika se u velikoj meri smanjuju u poređenju sa betonskom masom bez sistema hlađenja cevima. Istovremeno, prsline se ne formiraju na površinama blokova betonske mase. Metoda analize ovde predstavljena može koristiti inženjerima u izboru najefikasnijih mera za sprečavanje obrazovanja prslina kod betonskih konstrukcija, kao što je sistem hlađenja cevima.

INTRODUCTION

Currently, construction technologies are actively developing. The problem of crack formation caused by temperature effects is not completely solved. It is known that there are values of maximum temperatures inside a concrete massif, based on the requirements for crack formation, /1-3/.

Besides, in addition to increasing the strength of concrete, the cement hydration process takes place with the release of large amounts of heat, which depends on the shape, the cement composition, and other factors. Generated heat causes thermal deformation and thermal stress, which leads to the appearance of internal and external cracks.

There are several methods to reduce the temperature in large concrete structures: reducing the composition of cement, cooling the concrete mix, laying the concrete block over the seizures, pipe cooling, etc. One of the more effective methods, particularly for really large structures such as concrete dam walls, is to install an interconnected pipe network inside the concrete during construction, /4-6/. The cooling pipe system was first used at Owyhee Dam in Oregon in 1931, /7/. Then, the cooling pipe system has been used in the construction of the Hoover Dam in 1936 in the US, /8/. Today, cooling pipe systems are commonly used in mass concrete structures in order to reduce the maximum temperature in mass concrete blocks during cement hydration, /9, 10/. However, when using the cooling pipe system in mass concrete, it is important to note the adverse effects such as the formation of local cracks around the cooling pipes due to an extreme temperature gradient.

Here three-dimensional (3D) finite-element code Midas Civil 2011©, /11/, is used to determine temperature and stress field in the concrete mass with two cases: with and without pipe cooling, thus suggesting the best measure for reducing cracking risk in such a concrete structure.

MATERIALS AND METHODS

Research subjects

The size of the concrete block 12×8×3 m, is shown in Fig. 1. Ambient temperature is 25 °C, soil temperature is 20 °C and initial temperature of concrete is 25 °C. The concrete mix is shown in Table 1. Mechanical properties of concrete depend on the age of concrete are presented in Table 2.

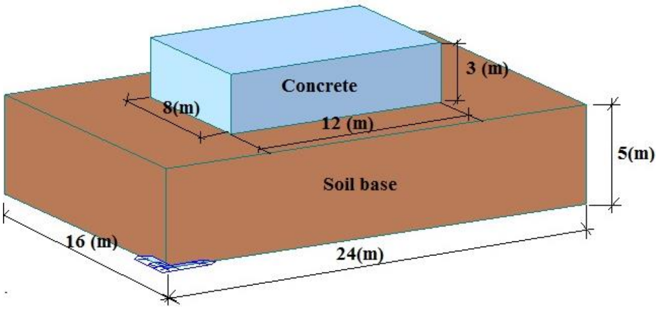

Figure 1. Size of the concrete massif.

Table 1. Mix design of concrete.

W	C	FA	Slag	Sand	Grave	W/C
kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	
160	405	50.50	40.12	740	1068	0.39

Table 2. Mechanical properties of concrete.

Days	1	3	7	28
Compressive strength (MPa)	23.2	30.3	43.4	60.0
Tensile strength (MPa)	2.11	3.22	3.89	3.95

Table 3 provides the thermal properties of concrete and soil base, used as input data for 3D thermal analyses.

Table 3. Thermal properties of concrete and soil base.

Physical properties	Concrete	Soil
Heat conductivity coefficient (W/(m·°C)	2.65	1.98
Specific heat (kJ/kg·°C)	0.95	0.85
Density (kg/m^3)	2400	1800
Convection coefficient (W/m^2·°C)	12.00	13.50
Elastic modulus (N/m^2)	2.7×10^{10}	1.8×10^{10}
Coefficient of thermal expansion (1/°C)	1×10^{-5}	1×10^{-5}
Poisson's ratio	0.20	0.25
Max. heat of cement hydration, 28 days (J/g)	305	-
Concrete compressive strength, 28 days, (MPa)	60	-

Typical values of pipe radius and velocity of water flow r_0 = 2.5 cm, u = 10 cm/s, step of pipes 1.0 m, duration of cooling, water temperature T_w = 15 °C, coefficient of heat conduction of pipe h = 220 W/m^2·°C. Practical layout of cooling pipes in a mass concrete are shown in Figs. 2 and 3, /11/.

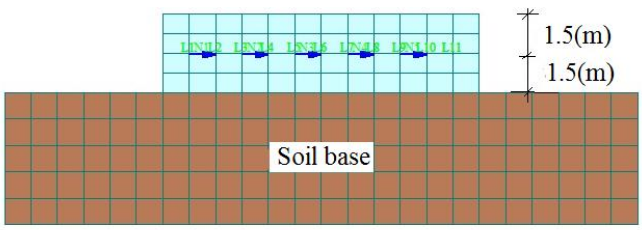

Figure 2. FE meshing of concrete and cooling pipes.

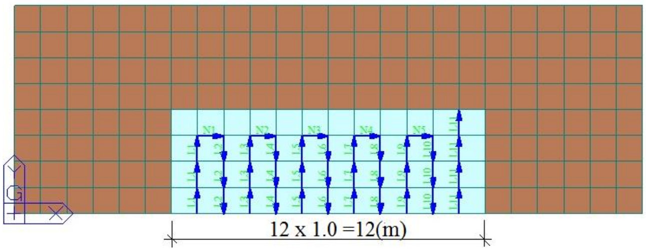

Figure 3. Cooling pipe system.

Finite element method to solve the heat problem

The equivalent equation of heat conduction. According to researchers, /12, 13/, the differential equation of heat conductivity as shown by Eq.(1):

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)+q_v=\rho c\frac{\partial T}{\partial t}, \qquad (1)$$

where: k_x, k_y, k_z - coefficients of thermal conductivity of the material in directions of coordinate axes 0x, 0y, 0z, (k_x = k_y = k_z = $\lambda/c\rho$) (m^2/s); λ - thermal conductivity of the material (W/m°C); c - specific heat coefficient (J/g°C); ρ - density of concrete (kg/m^3); q_v - amount of heat generated by internal sources at a given time, i.e. during the cement hydration process (kJ/m^3).

In /14/, the heat generation per unit volume and unit time is determined by Eq.(2):

$$q=\frac{1}{24}c\rho T_{\max}e^{-\alpha t}\,,\ T(t)=T_{\max}(1-e^{-\alpha t})\,,\ T_{\max}=\frac{qC}{c\rho}\,, \qquad (2)$$

where: C - amount of cement (kg/m^3); $T(t)$ - temperature (°C) at time 't' (days); $T_{\max}$ - final amount of adiabatic temperature rise acquired by test (°C); α - coefficient of temperature rise (reaction rate).

While solving Eq.(1), it is necessary to know the boundary conditions, /15/:

- boundary conditions of the 1st kind: $T = T_p$ (T_p is the known value of nodal temperatures on the boundaries);
- boundary conditions of the 2nd kind: value of the potential's normal derivative on the boundary is given;
- boundary conditions of the 3rd kind: condition of heat exchange of the body with the external environment:

  – on the surface of concrete:

$$-\lambda\frac{\partial T}{\partial n}=\beta(T-T_a)\,, \qquad (3)$$

where: λ - thermal conductivity of the material (W/m°C); n - outward normal of the surface; β - heat transfer coefficient (W/m^2 °C); T_a - environment temperature (°C).

  – at the pipe boundary:

$$-\lambda\frac{\partial t}{\partial n}=h(T-T_w)\,,\quad h=\frac{\lambda_1}{r\ln\left(\frac{r}{r_0}\right)}\,, \qquad (4)$$

where: λ_1 – the heat conductivity coefficient of the pipe (W/m°C); h - coefficient of heat conduction of pipe (W/m^2 °C); T_w - water temperature (°C); r - outer radius of pipe (m); r_0 - inner radius of pipe (m).

- boundary conditions of the 4th kind: on the boundary of two bodies, there is a dense thermal contact,

$$T_{1k}=T_{2k}\,,\quad \lambda_1\frac{\partial T_1}{\partial n}=\lambda_2\frac{\partial T_2}{\partial n}\,, \qquad (5)$$

where: T_{1k}, T_{2k} - temperature of the first and second bodies, respectively (°C); λ_1, λ_2 - thermal conductivity of these bodies (W/m°C).

In this paper, the finite element discretization of Eq.(6) with implementation of the aforementioned boundary conditions results in, /16/:

$$[C]\left\{\frac{\partial T}{\partial t}\right\}+[K]\{T\}=\{Q\}\,, \qquad (6)$$

where: [C] - specific heat matrix; [K] - heat conductivity matrix (conduction, convection); {Q} - total heat flux vector for internal hydration and heat convection; {T} - nodal temperature vector; {∂T/∂t} - time derivative vector of above nodal temperatures.

Now the Galerkin method, $T(t) = T_i(t)N_i + T_j(t)N_j$ is used for each element, $N_i = 1-\frac{t}{\Delta t}$, $N_j = \frac{t}{\Delta t}$, /17/. After each time step, Eq.(6) is rewritten:

$$\left(-\frac{[C]}{2\Delta T}+\frac{[K]}{3}\right)\{T\}_{(n-1)t}+\frac{2[K]}{3}\{T\}_{nt}+$$
$$+\left(\frac{[C]}{2\Delta T}+\frac{[K]}{6}\right)\{T\}_{(n+1)t}=\{Q\}\,. \qquad (7)$$

The solution of Eq.(7) provides the temperature field.

According to the results of studies, /18, 19/, the relationship between the stress and temperature in materials is determined by Eq.(8):

$$\sigma = R\times E\times\alpha\times\Delta T\,, \qquad (8)$$

where: σ - temperature stress (N/mm^2); R - restrain ($0 < R < 1$); ΔT - drop in temperature (°C); α - thermal expansion coefficient of concrete (1/°C); E - modulus of elasticity of concrete (N/mm^2).

An analysis of the temperature field during hardening of such massive concrete blocks with pipe cooling is rather complicated in view of the spatial shape of the structure and the influence on the process of many internal and external factors. In this paper, a finite element method is used to solve this problem using the computer program Midas Civil 2011©, /20/. It can be divided into the following three steps:

- establish a numerical model and confirm the necessary parameters;
- analysing temperature field and stress field;
- result analysis.

RESULTS AND DISCUSSION

Since the mass concrete has investigated symmetry properties, in order to reduce the number of calculations in this work a 1/2 part of its structure is analysed and shown in Fig. 4. The total number of elements is 1152 including the soil base. Analysis of results of time-dependent temperature and maximum temperature is carried out using the 3D-FEM software Midas Civil 2011, and is shown in Figs. 5-6.

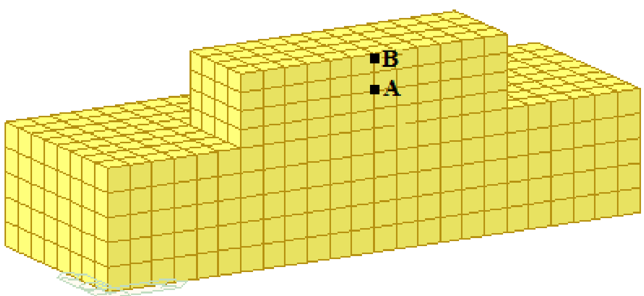

Figure 4. 3D FEM model for analysis.

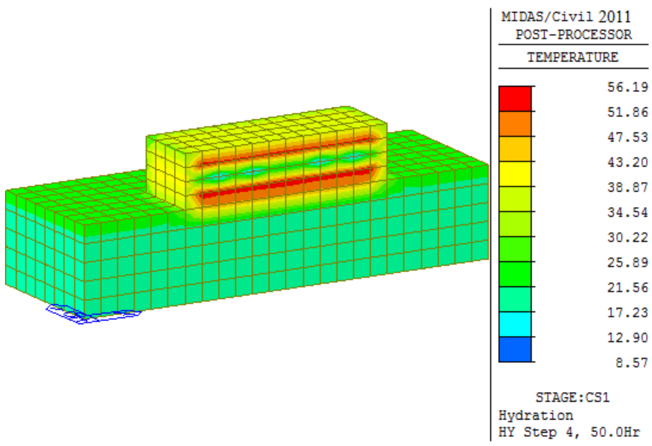

Figure 5. Maximum temperature in a mass concrete with cooling pipe system after 50 hours of hardening concrete.

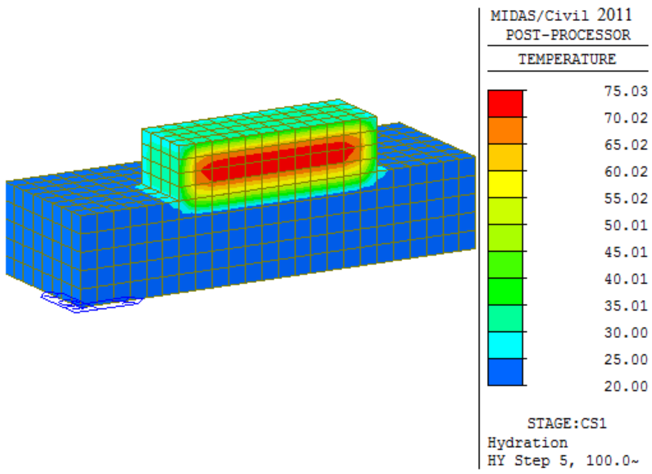

Figure 6. Maximum temperature in a mass concrete without pipe cooling after 100 hours of hardening concrete.

Maximum temperatures in the concrete mass without cooling pipe 75.03 °C reached after 100 hours from the start of construction, and with pipe-cooling 56.19 °C after 50 hours from the start of construction. Results show that the use of cooling pipes in concrete blocks is reduced by 25 % compared to concrete blocks without cooling pipe systems.

The temperature difference between the concrete block centre and surface exceeds the allowable limitation leading to excessive stresses due to the appearance of extreme temperature gradients during concrete hardening. As a result, cracking will often appear in the structural body or surface. Analysis of the temperature field in 2 dangerous places (see Fig. 4) in the design under investigation, including the location in the centre (A) - node (179) and on the external surfaces in the structure (B) - node 27, are shown in Fig. 7. These two nodes are used to preliminarily assess the risk of cracking in mass concrete structures. To prevent the formation of cracks, the temperature difference between the centre and the surface of mass concrete blocks is as low as possible.

In the research model, the temperature difference between the centre and the surface of mass concrete without the cooling pipe is equal to 29 °C and was reached at 100 hours after casting. The risk of cracking will appear on the surface of concrete blocks. Besides, the temperature difference between the centre and the surface of the concrete block with the cooling pipe system equals 14.5 °C and 12.5 °C and was reached at 50 and 100 hours after casting, in respect.

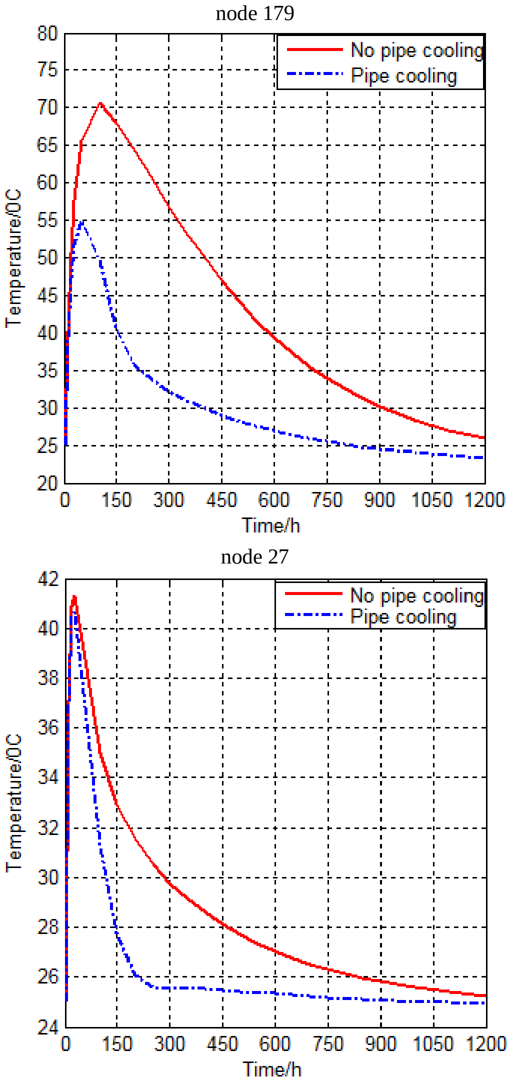

Figure 7. Temperature field in nodes 179 and 27 of a mass concrete vs. time.

To accurately assess the formation of cracks, it is necessary to consider the stress field distributed in the concrete block at a time when the risk of cracking is high. In this study, the time after 100 hours after casting is the time when the risk of cracking is high due to the maximum temperature difference. Figure 8 shows the distribution of the stress field for the mass concrete with and without the cooling pipe system at 100 hours after casting.

The outer surface is cooled by air so that it tends to contract. However, the central part of the concrete massif expands and prevents compression of the outer part of the concrete massif, so the tensile stress appears in the first stages in two cases. Tensile stress on the surface of mass concrete with the cooling pipe system is observed to be 1.64 MPa less than the allowable tensile stress of concrete after 100 hours of hardening concrete (3.45 MPa). Therefore, cracks do not form on the surface of mass concrete with cooling pipes at an early age. Besides, in mass concrete without cooling pipes, the thermal stress on the surface of mass concrete blocks is 3.76 MPa and exceeding the permissible tensile stress (3.45 MPa). Therefore, cracks are formed on the surface of the concrete block.

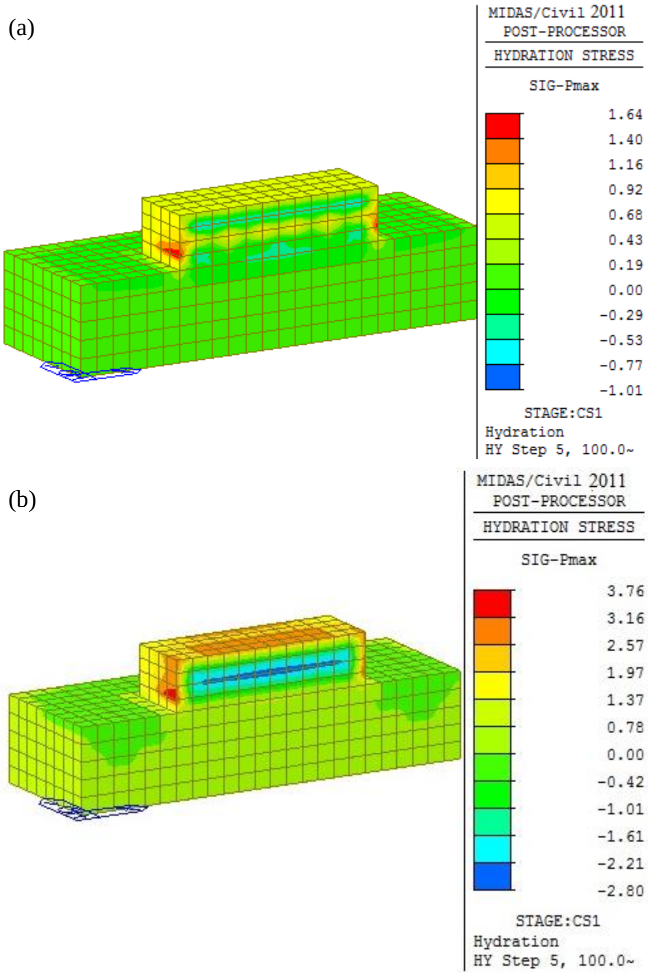

Figure 8. Thermal-stress state in concrete massif after 100 hours after casting: a) with cooling pipe system; b) without pipe cooling.

CONCLUSIONS

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

- usage of the program Midas Civil 2011© enables to solve problems of thermal conductivity and thermoelasticity, taking into account pipe cooling,
- the temperature in the centre of the concrete massif with pipe cooling is significantly less than in the case without pipe cooling. Maximal temperatures in concrete massif without pipe cooling reach 75.03 °C, and with pipe cooling 56.19 °C, with cooling duration of 7 days.
- compressive and tensile stresses during pipe cooling are smaller than without the cooling. Therefore, the occurrence of cracks is limited,
- in the case of the concrete massif without cooling, at node 27 of the investigated massif up to 100 hours of concrete hardening, the tensile stress value exceeds its permissible value, leading to the formation of cracks on the surface of the concrete massif. In the case of a concrete array with

pipe cooling, the tensile stress is below ultimate tensile strength of concrete, making it impossible to form cracks.

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