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Temperature regime during the construction massive concrete with pipe cooling

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Abstract. Pipe cooling is one of the effective measures in order to reduce the exothermic heating of massive concrete structures. In this paper, analyzing the influence parameters of the pipe cooling system on the temperature regime and the thermal stress state in mass concrete to be built. The concrete mass was considered as a pillar with dimensions in plan (10×10) m and a final height of 30.0 m. The effect of the following parameters was investigated: the height of the concrete column from the elevation of the foundation is used for the cooling pipe system; the step of cooling pipe system according to the height and width of the concrete block; the temperature of water supplied to the pipe cooling system. Then, numerical studies were carried out by using the Midas civil software package based on the finite element method in order to solve the temperature problem and determine the thermal stress state of the block. From that will be collected the numerical results from pictures of changes in the temperature regime and the thermally stressed state in mass concrete during construction. The influence of each of those factors is considered in order to evaluate the change in temperature regime and thermal stress of the concrete mass. So, the results obtained are of practical importance and can be used to assign parameters of the pipe cooling system.

1. Introduction

As is known, due to the process of cement hydration heat during construction of massive concrete structures is the temperature at the center of mass concrete significantly increased. At «an early age» concrete this heating causes free expansion of plastic material [1]. The surface of mass concrete under the influence of ambient temperature is cooled faster at the center of mass concrete. As a result, there is a significant temperature difference between the center and the surface of the mass concrete [2, 3]. In that case, if concrete enough strength, its deformability is limited, and the temperature drop causes tensile thermal stresses. This is likely to occur in the contact area between the concrete and foundation [4]. When these tensile stresses exceed the tensile strength of the concrete, thermal cracks are formed. To prevent thermal cracking of massive concrete during construction, thermal stress and temperature difference to be controlled is necessary [5].

There are methods and measures to control the temperature regime of the mass concrete during construction period [6, 7]. One of the most effective methods reduced the maximum temperature of the mass concrete in the process of its construction is applied by pipe cooling system. This method is typically used for large-scale concrete structures such as dams, massive foundations and bridge supports, etc. In fact, advantages include the innermost heated parts of the mass concrete structures are exposed to the cooling pipe. In addition, it is possible to control the maximum temperature by changing the operation of the cooling pipe system. This method allows to quickly reducing the maximum temperature in a mass concrete to the desired values at an early age. Hence, in order to achieve effective cooling, the pipes cooling systems are designed parameters exactly during the operation period. It is important to choose the material and diameter of the cooling pipes, cooling height, the distance between pipes, cooling temperature control, the start time and the end of the cooling system, etc [8].

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For the first time, the pipe cooling system was applied in the construction by American Hoover Dam in 1933 [9]. For examples of the later were applied of pipe cooling system can be observed such as during the construction of the Xiang Hong Dian dam in China (1955), the Bureyskaya hydroelectric power in Russia (1978), the Seo-He Bridge in Korea (2000), Tuyen Quang dam in Vietnam (2002), Dagangshan dam in China (2013), etc [10–15].

This paper presents the temperature regime during the construction of massive concrete with varying the parameters of the pipe cooling system. The analysis of the influence of the height of the pipe cooling, the distance between pipes, and the temperature of the cooling water on the temperature field and the thermal stress of the concrete during construction. The construction of mass concrete in this study with dimensions 10× 20× 30 m was considered. The research results can be applied in the design of mass concrete structures with the optimal parameters of the pipe cooling system in order to reduce thermal stress and improving the thermal crack in a mass concrete at an early age.

2. Materials and methods

The temperature field in a mass concrete with the cooling pipe systems is determined based on solving two differential equations Fourier according to the principle of energy balance [16]. One of them is the basic equation of the theory of thermal conductivity, taking into account the release of heat due to cement hydration is expressed as:

$$k_c \nabla^2 T_c + Q_h = \rho_c c_c \frac{\partial T_c}{\partial t}, \tag{1}$$

where T_c is the temperature of concrete at age *t* days (°C);

k_c is the thermal conductivity of concrete (W/m.°C);

Q_h is the heat of hydration (W/m^3);

c_c is the specific heat of concrete (kJ/kg.°C);

ρ_c is the mass density of concrete (kg/m^3);

t is time (day).

The second equation takes into account the heat exchange between the pipe cooling system and the concrete is expressed as:

$$\rho_w c_w \left(\frac{\partial T_w}{\partial t} + \vec{u} \nabla T_w \right) = k_w \nabla^2 T_w, \tag{2}$$

where T_w is the temperature of water at age *t* days (°C);

k_w is the thermal conductivity of water, (W/m.°C);

c_w is the specific heat of water (kJ/kg.°C);

ρ_w is the mass density of water (kg/m^3).

These Fourier equations (1) and (2) can be solved by using initial, boundary conditions and a given graph of cement heat release during the hydration of cement [17, 18].

The formation of the temperature regime in a mass concrete not only depends on exothermic heating due hydration of cement but also on many other factors. The process of developing a temperature regime in a mass concrete is influenced by changes in environmental temperature such as convection and radiation.

Convection at the boundary of the concrete with ambient air is expressed using Newton's law. He shows that the rate of heat loss of the body is proportional to the temperature difference between the body in mass concrete and its surroundings. The boundary condition of convection is given by equation (3) [19–21]:

$$q_{\text{convec}} = h_c (T_c - T_{\text{air}}), \tag{3}$$

where T_c is the temperature of the body of concrete (°C);

T_{air} is the air temperature (°C);

h_c is the convection coefficient of concrete surface with ambient air (W/m^2.°C).

The main complication in solving this problem is to take into account the removal of heat released as a result of exothermic be moved in the pipe system with water. Figure 1 shows a diagram of the interaction of mass concrete with cooling pipe system. Due to the absorption of heat from the concrete in during cement hydration, the water temperature will gradually increase and its heat absorbing capacity will decrease because to the decreasing temperature difference between the concrete and the water. Heat transfer between the concrete and the water can be considered using Newton's law of convective heat transfer (2) [22].

The heat transfer from concrete through a small section of the cooling pipe with a flow rate of q during a small time interval dt was considered is shown in Figure 1. The amount of heat transferred from mass concrete to water through the inner surface of the pipe along the length of the pipe from the inlet to the outlet can be written as:

$$dQ_1 = \iint 2\pi r_0 dl Q_{c\to w} dt = -\lambda_c \iint \frac{\partial T_c}{\partial n} dl dt, \tag{4}$$

where $Q_{c\to w}$ is the amount of heat transferred from concrete to water;

r_o is the radius of the cooling pipe;

$\lambda_c \partial T / \partial n$ is the specific heat flow at the border of concrete – water pipe;

n is the normal to the inner surface of the pipe.

The heat energy entering through the inlet and outlet sections of the cooling system pipe by the equations (5), (6).

$$dQ_{\text{inlet}} = \rho_w c_w q T_{\text{inlet}} dt, \tag{5}$$

$$dQ_{\text{outlet}} = \rho_w c_w q T_{\text{outlet}} dt, \tag{6}$$

Using the condition of heat equilibrium by assumption water is incompressible and, therefore, there are no change in the internal energy of water is given by equation (7).

$$dQ_{\text{outlet}} = dQ_{\text{inlet}} + dQ_1. \tag{7}$$

After substitution (5) and (6) into (7), it is possible to obtain the change in water temperature when passing through mass concrete ΔT is given by equation (8).

$$\Delta T = T_{\text{outlet}} - T_{\text{inlet}} = dQ_1 = \frac{2\pi r_0 \lambda_c}{\rho_w c_w q} \iint \frac{\partial T_c}{\partial n} dl dt, \tag{8}$$

The given mathematical dependencies are incorporated into the algorithm for the numerical solution of the temperature problem of the mass concrete with the cooling pipe system by Midas civil software [23]. This complex was used for research in this work. In this study, three-dimensional finite-element models of the “Midas civil” were used both in order to solve the temperature field and thermal stress in a mass concrete with a cooling pipe system.

3. Results and Discussion

3.1. Object of study

In this paper, was analyzed the influence of the parameters of the pipe cooling system on the temperature field and the thermal stress state in a mass concrete during the construction period. The dimensions of massive concrete as column shape with a size 10×20×30 m are considered. Taking advantage of the axial symmetry of the concrete block, 1/2 of the concrete block model has been divided into finite element mesh. The temperature field and thermal stress of points were considered (Figure 2). The concrete block was placed by ten lifts (each lift is 3 m thick) and construction schedule according to the thick of 0.3 m/day. Thus, the total time of construction of the concrete column was considered about 100 days. In the calculations, the following values of temperature are assumed: ambient temperature – 26.5 °C; temperature of foundation – 20 °C, the initial temperature of the concrete – 30 °C.

In the paper, the cement used has the maximum heat generation cement (389 kJ/kg), which is classified as large-heat cement. Most of the heat from the cement hydration process (up to 90% of the total heat) is released in the first 6 days after concreting. The maximum heat release rate of cement occurs in the first days after the laying of concrete and is approximately 200 kJ/kg.day. In this case, the highest intensity of heat release is on the first day [24].

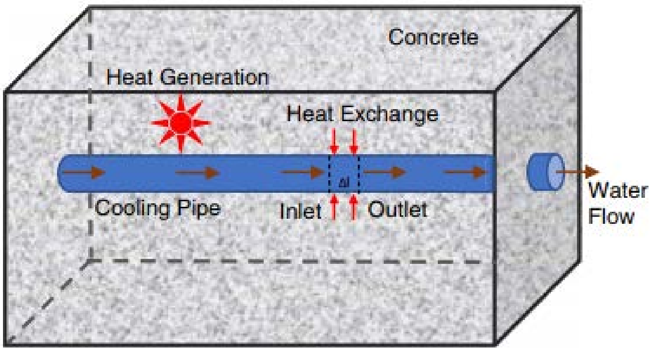


Figure 1. Scheme of interaction of concrete with the cooling pipe system.

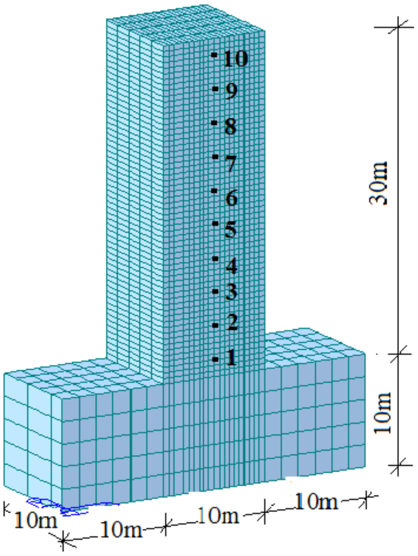


Figure 2. Finite element discretization of the concrete block.

The thermophysical characteristics of the concrete and the foundation were used in the numerical analysis and are shown in Table 1. The parameters and properties of the pipe cooling system are shown in Table 2.

Table 1. Thermophysical characteristics of the materials in the model.

Parameters	Concrete	Foundation
The coefficient of thermal conductivity (W/(m.°C)	2.65	1.98
Specific heat (kJ/kg.°C)	0.95	0.85
Density of the material (kg/m^3)	2400	1800
The coefficient of convective heat transfer (W/m^2.°C)	12.0	13.5
Modulus of elasticity (N/m^2)	2.7×10^{10}	1.8×10^{10}
The coefficient of linear expansion (1/°C)	1×10^{-5}	1×10^{-5}
Poisson's ratio	0.20	0.28
Cement content (kg/m^3)	289	–
Maximum heat release during hydration of cement (kJ/kg)	389	–

Table 2. Characteristics of the pipe cooling system.

Parameters	The pipe cooling
Heat transfer coefficient on the border with concrete (W/(m^2.°C)	282
Specific heat (kJ/kg.°C)	4.2
The coefficient of thermal conductivity W(m.°C)	0.64
Volume (m^3/h)	1.08
The water velocity in the pipe (m/s)	0.6
The water temperature in pipe (°C)	10÷20
Water density (kg/m^3)	1000
Section area (m^2)	0.00008
Diameter of pipe (m)	0.0254
Cooling duration (days)	7

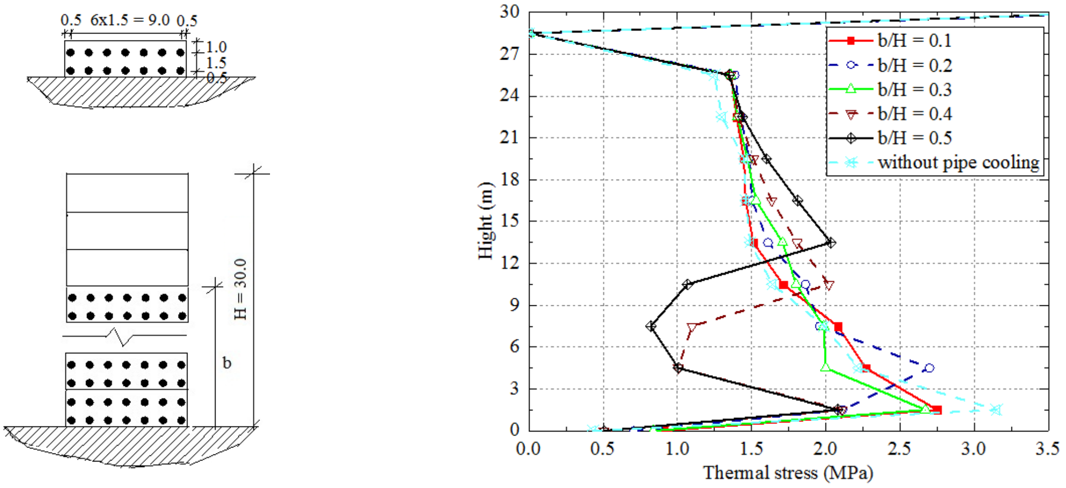
There are many parameters and properties of the cooling pipe system effects on the temperature field and the thermal stress in a mass concrete during construction [25–27]. In this paper, the influence of the following parameters was studied:

- The height of the concrete column from the level of the foundation is used for the cooling pipe system.
- The step of cooling pipe system according to the height and width of the concrete block.
- The temperature of the water is supplied to the cooling pipe system.

3.2. Research results

As a result of the numerical simulation in during construction of concrete block by using software Midas civil has been obtained the temperature regime and thermal stress in a concrete block at different points in time during its construction. The most dangerous from the point of view about the capacity for work in the mass concrete is the values of the greatest tensile stresses. The study results show changes largest tensile stresses arising in the concrete block at the corresponding points in the period considered. For each point, the thermal stress was appeared at a certain time and in a certain direction are given in Figures 3–5.

Influence of the height of the pipe cooling zone on the thermal stress of the massive concrete. The ratio of the height of the pipe cooling zone (b) to the total height of concrete column (H) changed and was taken to be equal to the following values b/H – 0.1, 0.2, 0.3, 0.4, 0.5. The pipe distance according to the height and width of the concrete block is 1.5×1.5 m. Vertical layout schematic of the cooling water pipe is shown in Figure 3a. The number of layers of concrete laid from the foundation using a pipe cooling system varied from 1 to 5, which corresponds to a change in the ratio of b/H. The temperature of the cooling water entering the pipe cooling system was adopted t_w = 15 °C. Time operation of the pipe cooling system after laying each layer of concreting was taken to be 7 days. The results of calculations of the distribution of the maximum thermal stress over the height of the concrete massif for the considered variants of the b/H are given in Figure 3b. For comparison with the cases of using the cooling pipe system, stress distribution in the concrete block without the cooling pipe system have been analyzed.



a) b)

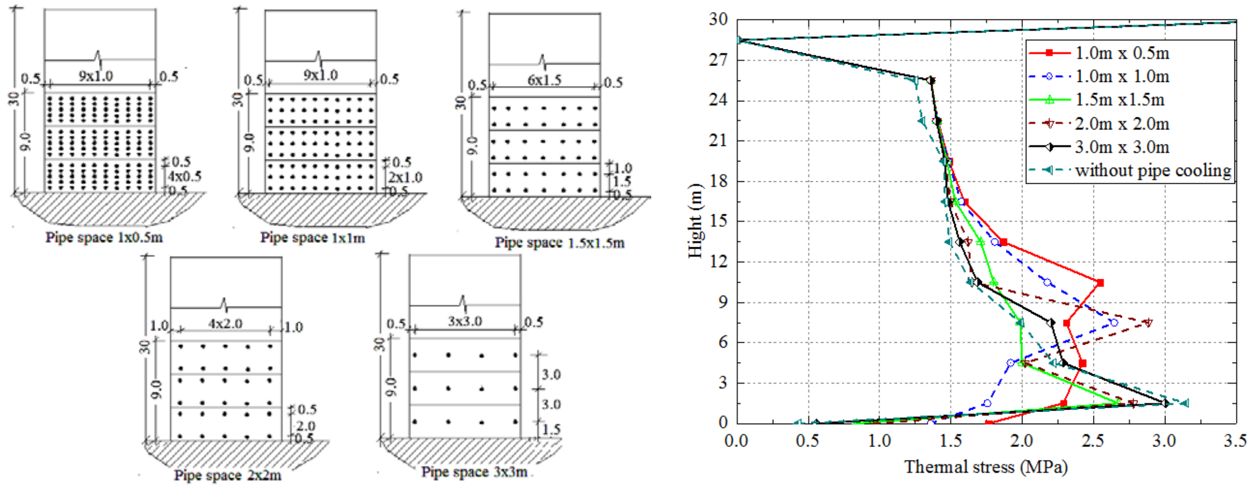
Figure 3. Influence of the height of the pipe cooling zone on the thermal stress of the massive concrete: a) the layout of pipe cooling system; b) maximum thermal stress at the center of mass concrete with a different cooling height.

As clearly observed in Figure 3b, we can give the following analysis. The thermally stressed state of concrete blocks for all variants is characterized by maximum tensile stresses in the contact zone. The maximum thermal stress depending on the height of the zone using the cooling pipe system. Thermal stress are 2.75, 2.70, 2.67, 2.11, 2.08 MPa, respectively when height of the cooling system zone b/H = 0.1, 0.2, 0.3, 0.4, 0.5. When the height of the pipe cooling zone increases, the maximum tensile thermal stress is reduced. Besides that, for comparison with the cases of using the cooling pipe system, the maximum tensile thermal stress when concrete block without cooling pipe system is 3.2 MPa is shown in Figure 3b. Furthermore, it is also possible to note that changes in the distribution of thermal stress on the height of the concrete column are presented in Figure 3b. So, when the height of the pipe cooling zone is 15.0 m (b/H = 0.5) in the lower part of the column (the zone from the level of 3.0 m to the level of 12.0 m from the foundation), the thermal stress decreases and has a minimum thermal stress value of 0.78 MPa at the level of 7.5 m from the foundation. From the calculation results show that when the selected height of the pipe cooling zone reasonable, it is possible to reduce tensile stresses in the concrete mass and to obtain a favorable distribution of thermal stresses.

The influence of the pipe spaces on the thermal stress in mass concrete. The following cases of distances between pipes were considered (the first digit is the distance between pipes in the horizontal direction, the second is in the vertical): 1.0×0.5 m, 1.0×1.0 m, 1.5×0.5 m, 2.0×2.0 m, 3.0×3.0 m. The schemes of these cases are shown in Figure 4a. The height of the cooling zone in these calculations was assumed to be constant at 9 m (b/H = 0.3). The water temperature in the pipes at the entrance to the system is t_w = 15 °C. The duration of the cooling system after each layer concreting is 7 days.

Some results of the calculations obtained are shown in Figure 4b, which shows the distribution of maximum thermal stress along the height of the concrete column (at the points in the center of the concrete block is shown in Figure 2). It can be seen that thermal stress changes depending on the distances between the pipes of the cooling system (with cases are shown in Figure 4a – 1.0×0.5 m, 1.0×1.0 m, 1.5×1.5 m, 2.0×2.0 m and 3.0×3.0 m). It is clear that in terms of the above five different distances between the pipes, the maximum tensile stress of the concrete are 2.55, 2.65, 2.67, 2.88 and 3.00 MPa respectively is shown in Figure 4b.

Research shows that when the most common pipe space (the case with the pipe space of 1.0 × 0.5 m), the maximum thermal stress of 2.55 MPa was obtained at the level of 10.5 m from the foundation (the area near the contact boundary between the concrete cooling zone and the layer on the concrete without the cooling pipe system). Figure 4b shows that the area near contact with the foundation, thermal stress is reduced to 2.30 MPa at 1.5 m from the foundation. Along the axis of the concrete block, when the distance of points from the foundation increases then the thermal stress decreases, as can be seen in Figure 4b.



a) b)

Figure 4. a – The layout of pipe cooling system with different distance between pipes; b – The effect of the distance between the cooling system pipe on the maximum thermal stress state of the concrete mass during construction.

In the case of the concrete block without pipe cooling system the maximum tensile thermal stress of 3.2 MPa was obtained at a height of 1.5 m from the foundation. Obviously, the correct choice of the step between the cooling pipes will help prevent necessary crack formation and economic efficiency.

Influence temperature of water in pipes on the thermal stress state in a mass concrete. In these studies, the height of the pipe cooling zone is b/H = 0.30, the pipe distance is 1.5×1.5 m. The cooling duration after laying each 3 m layer of concreting was taken to be 7 days. In this paper, the temperature parameters of the cooling pipe system are assumed to vary from 10 to 20 °C.

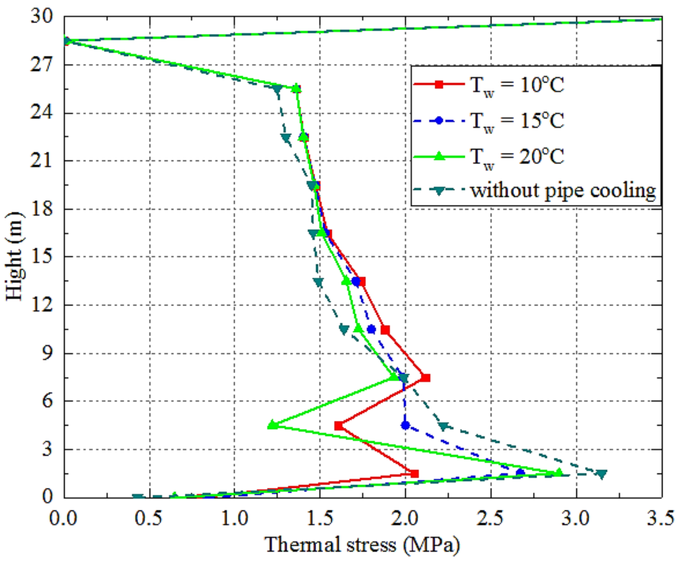


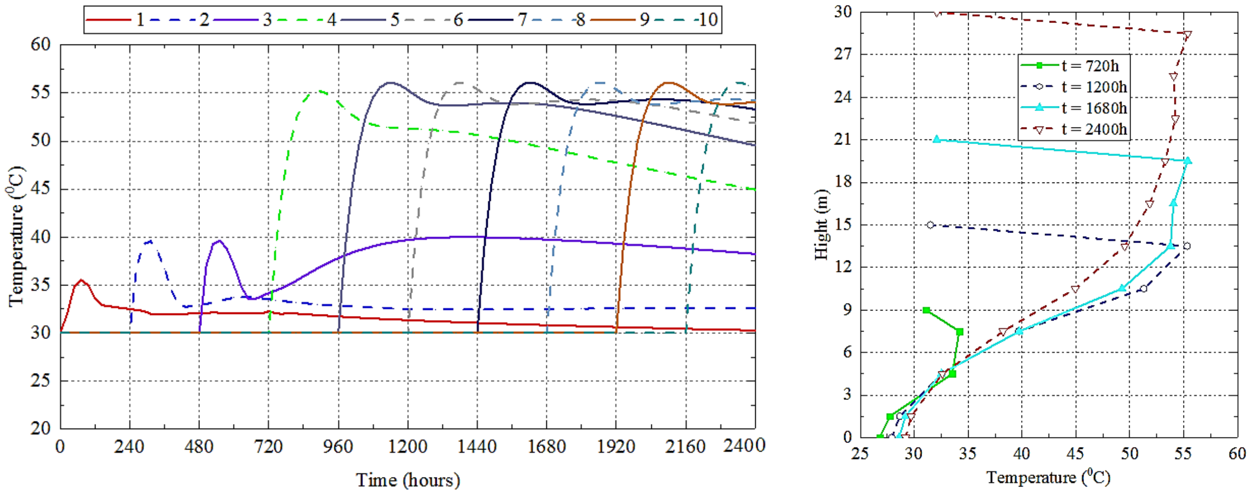
Figure 5. Distribution of horizontal thermal stress along the height of the concrete column for different values of temperature of water in pipes.

Figure 5 shows that maximum thermal stress distribution at the center section of the concrete column (at points 1–10 in Figure 2). The maximum thermal stress are 2.12, 2.67, 2.90 MPa respectively when the temperature of water in pipes 10, 15, 20 °C.

It should be noted that the use of cooling pipes can also have negative effects such as significant temperature difference, large local tensile stresses may occur around the cooling pipe. In order to avoid this, it is necessary to limit the minimum values of water temperature.

The temperature regime and the thermal stress in a concrete block with pipe cooling during construction were calculated with average values of the parameters of the cooling pipe system: $b/H = 0.3$, the pipe distance is 1.5×1.5 m and water temperature in pipes t_w = 15 °C. The results of these numerical calculations are presented in Figures 6–8.

The temperature of all the nodal points (10 nodes in Figure 2) changes over time during the construction of a concrete block are presented in Figure 6a. Analyzing the results it can be noted that the nodes 1, 2 and 3, which located in the zone of pipe cooling, the maximum temperature is significantly reduced: 36 °C (node 1) and 40 °C (nodes 2, 3) at the moment of time about 70 hours after corresponding to each layer of concrete. Besides that, the nodes (4÷10) in the concrete block, the maximum temperature is reached about (55÷56) °C at the time after 160 hours each of the concrete pours.



a) b)

Figure 6. Temperature regime of the concrete mass during construction: a – the graph changes the temperature of the nodes (1÷10) in the mass concrete over time; b – the graph changes the temperature along the height of the concrete mass at different times.

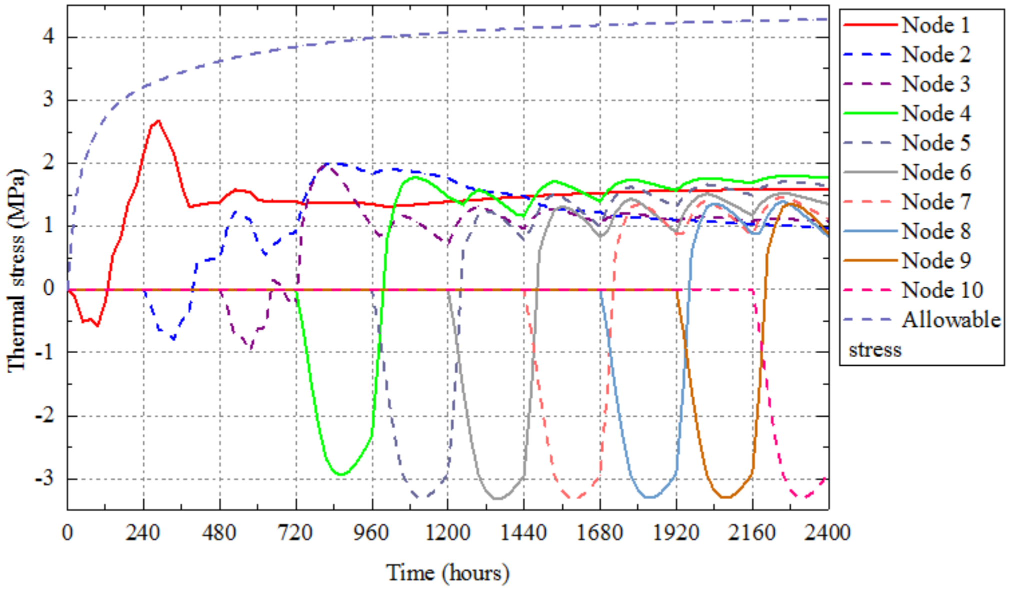


Figure 7. The graph of the maximum thermal stress changes at the nodes (1÷10) in the mass concrete over time, MPa.

Figure 6b presents the results of temperature field changes at 10 nodes (see Figure 2) along the axis of the concrete block during construction. At elevation 9 m from the foundation, the maximum temperature is about 34 °C after 720 hours of pour concrete mixture. The maximum temperature in the concrete block is reduced when using the cooling pipe system. Besides, when concrete placing by large thickness without cooling pipe system, the maximum temperature in the concrete block is about 56.5 °C is shown in Figure 6a. Thus, the concrete block with the cooling pipe system has significantly reduced the risk of cracking in the mass concrete.

Furthermore, it can be noted that due hydration of cement raises the temperature at the center of each of the concrete pours, creating a temperature difference between the center and the surface of the concrete block reaching (22–24) °C, which induces a risk of through cracking at an early age.

The results of the calculation of thermal stresses at nodes along the axis of the concrete block are shown in Figure 7. The formation of cracks in mass concrete is possible when the maximum tensile stress exceeds the allowable tensile stress value. Allowable tensile stress is determined depending on the type of concrete and time. The graph of change of this tensile stress value in time is presented in Figure 7. For the considered problem, the maximum tensile stresses are observed near the base of the concrete block (node 1). However, the thermal tensile stress of node 1 σ= 2.67 MPa is lower than the allowable value (about 3.2 MPa), so thermal cracks do not occur in the concrete block during construction.

4. Conclusions

Based on the results of the study lead to the following conclusions:

1. The cooling pipe system was applied in the during construction of the mass concrete can significantly reduce the maximum temperature due to increased temperature of the cement hydration process and reduce the risk of thermal cracks.

2. When the mass concrete was applied to the pipe cooling system during construction, in order to obtain the optimal result for control the temperature field and economic efficiency, it is necessary to correctly assign the parameters of the cooling system such as the height of the pipe cooling zone, the distance between pipes and the temperature of water in pipes.

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Температурный режим возводимого бетонного массива с трубным охлаждением

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Ключевые слова: температурный режим, экзотермический нагрев, максимальная температура, перепад температуры, трещинообразование, трубное охлаждение, массивный бетон

Аннотация. Трубное охлаждение является одним из эффективных мероприятий по снижению экзотермического нагрева массивных бетонных конструкций. В данной работе выполнен анализ влияния параметров системы трубного охлаждения на температурный режим и термонапряженное состояние возводимого бетонного массива. Бетонный массив рассматривался в виде столба с размерами в плане (10×10) м и окончательной высотой 30,0 м. Исследовалось влияние следующих параметров: высоты зоны бетонного столба от отметки основания, где используется система трубного охлаждения; шаг труб системы охлаждения по высоте и ширине бетонного массива; температура подаваемой в систему трубного охлаждения воды. Были проведены численные исследования с использованием программного комплекса «Midas civil» на основе метода конечных элементов как при решении температурной задачи, так и при определении термонапряженного состояния массива. В результате численных исследований получены картины изменения температурного режима и термонапряженного состояния бетонного массива в процессе его возведения. Проведена оценка влияния каждого из рассмотренных факторов на изменение температуры и температурных напряжений бетонного массива. Полученные результаты имеют практическое значение и могут быть использованы при назначении параметров системы трубного охлаждения.

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