Peculiarities of Thermal Treatment of Monolithic Reinforced Concrete Structures

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Abstract. A mathematical program has been developed that allows one to determine the parameters of heat treatment of monolithic structures. One of the quality indicators of monolithic reinforced concrete structures is the level of temperature stresses arising in the process of heat treatment and further operation of structures. In winter at heat treatment the distribution of temperatures along the cross-section of the structure is uneven. A favorable thermo-stressed state in a concrete massif occurs when using the preheating method, providing the concrete temperature in the center of the structure is greater than at the periphery. In this case, after the strength is set and the temperature is later equalized along the cross-section, the central part of the structure tends to decrease its dimensions more but the extreme zones prevent it. Therefore, the center is in a state of tension, and the extreme zones on the periphery are compressed. In compressed concrete there is a lesser chance of cracks or defects. The temperature gradient over the section of the structure, the stress in the concrete and its strength are determined. When calculating the temperature and strength fields, the stress level was determined - a value equal to the ratio of the tensile stresses in the section under consideration to the tensile strength of the concrete in this section at the same time. The nature of the change in stress level is determined by the massive structure and power of the formwork heaters. It is shown that under unfavorable conditions the stress level is close to the critical value. The greatest temperature gradient occurs in the outer layers adjacent to the heating formwork. A technology for concrete conditioning is proposed which makes it possible to reduce the temperature stresses along the cross-section of the structure. The time for concrete conditioning in the formwork is reduced. In its turn, it further reduces labor costs and the cost of concrete work along with the cost of heat treatment. The authors conduct the technical and economic comparison of heat treatment options for the structures. The duration of monolithic structures erection with the use of combined heat treatment decreases in comparison with the method of peripheral heating. The economic effect consists of the reduction of the cost to organize and perform temperature control, insulation, electricity.

1. Introduction
One of the indicators of the quality of monolithic reinforced concrete structures is the level of temperature stresses arising in the process of heat treatment and further operation of structures [1]. In winter at heat treatment, the distribution of temperatures along the cross-section of the structure is uneven. A favorable thermo-stressed state in a concrete massif occurs when the temperature of the concrete in the center of the structure is greater than at the periphery [2,3]. This temperature distribution is observed when the concrete mixture is preheated [4].
Technologies for maintaining monolithic structures in winter are devoted to the work of S.G. Golovneva, B.M. Krasnovsky, A.S. Arbenieva, S.A. Mironova, A.I. Gnyrya, B.A. Krylov and other domestic scientists [5-11]. The preservation of high rates of growth in construction production while ensuring the quality of building structures is an urgent task. The solution of this problem is possible by expanding the raw material base of concrete by using industrial wastes. An example of this is slag-alkaline concretes, the field of application of which is the production of prefabricated concrete and reinforced concrete structures (foundation blocks, slabs, etc.), the erection of monolithic supporting structures of buildings (columns, walls, slabs) [12].

2. Method for calculating the parameters of heat treatment

The aim of the work was the development of regulations for the heat treatment of monolithic structures. To achieve this goal, various tasks were accomplished. One of them is the development of mathematical models describing the development of temperature and strength fields in structures, arising temperature stresses.

One of the effective ways of heat treatment of monolithic structures from slag-alkali concrete is the combined method. It includes preheating the concrete mix in the tank, laying in the formwork, peripheral heating using the heating formwork. In comparison with preheating, when using the combined method, there is less temperature difference across the cross-section of the structure, and, hence, the temperature stresses. It is possible to exclude the possibility of freezing of peripheral zones, the angles of the structure.

Investigations of the influence of various factors on the physical and mechanical properties of slag-alkali concretes have been carried out. It is established that the coefficient of linear thermal expansion of concrete depends on the consumption of slag and is within \((0.76–1.25) \cdot 10^{-5} \, \text{1/}^\circ \text{C}\). The strength of slag-alkali concrete for stretching is 10–25% greater than that of Portland cement concrete. The dependences of the modulus of elasticity of slag-alkaline concrete on the composition and conditions of aging.

A computer program was developed to calculate the temperature, concrete strength, temperature stresses and deformations along the cross-section of the structure. The following heat treatment methods were modeled: preheating, peripheral heating in the heating form, combined method including heating and subsequent heating. Similar studies for concrete on clinker binders have been carried out earlier [13,14].

To determine the stresses at the point X of the cross-section of the structure, we used the expression

\[
\sigma_{x, t} = \alpha E \left( t_{p, t} - t_{X, t} \right) / \left( 1 - \nu \right)
\]

where \(\sigma_{x, t}\) – temperature stress at X time point \(t\), MPa, \(\alpha\) – coefficient of linear thermal expansion of concrete, \(1/\circ C\), \(E\) – module of elasticity of concrete, MPa, \(t_{p, t}\) – average temperature of concrete along the section of the structure at the moment of time \(t\), \(\circ C\), \(t_{X, t}\) – temperature of concrete at a point with the coordinate X at the time moment \(t\), \(\circ C\), \(\nu\) – Poisson's ratio.

In the course of the calculations, the influence of the following factors was considered: the type of binder - slag-alkali and clinker; module surface design - 3, 4, 6.7, 10 m\(^{-1}\); temperature of heating of concrete mix - from 40 to 80 \(\circ C\); heat transfer coefficient of formwork from 1 to 5 W/(m\(^2\)·\(\circ C\)); outside air temperature - from minus 5 to minus 30 \(\circ C\); specific power of heaters of heating formwork - from 25 to 400 W/m\(^2\).

During the calculations, we analyzed how the technological parameters change: the temperature and strength of concrete, the stresses arising along the cross-section of the structure, and the stress level.

After laying in the formwork of the heated concrete mix, it is recommended to start the peripheral heating not immediately, but after the end of the irregular cooling period. This period lasts from 4 to 20 hours, depending on the massive structure.
After the end of the irregular cooling period, heating starts from the periphery. The specific power of the formwork heaters is first assigned a minimum (25 W/m²). At each time step, the following conditions are checked:

1) \( t_x < t_{max} \), where \( t_x \) – temperature of concrete at the given point with coordinate \( X \), \( t_{max} \) – permissible temperature of concrete heating;

2) \( \sigma_{p,x} < R_{t,x} \) – tensile stresses in any section should not exceed the tensile strength of concrete.

3. Results of calculation

Stresses in concrete appear after it acquires the properties of an elastic body. Concrete acquires elastic properties when strength is reached 22–30 % from \( R_{28} \) [15]. The temperature distribution over the cross section is called the temperature curve of zero voltages. In the course of the calculations, it is established that 0.5-2 hours after the start of heating, the temperature of the outer layers of the structure becomes higher than in the center. The outer layers tend to increase their dimensions more than the inner layers, but the latter restrain this expansion and are, therefore, in a stretched state. The outer layers are in a compressed state. This favorably affects the quality of concrete structures [16,17].

The magnitude of tensile stresses in the middle plane is determined mainly by the massive structure, the type of binder and the specific power of the formwork heaters. Stretching stresses in the center and compressing in the outer layers reach the highest values at the end of heating, when the greatest temperature drop across the section is observed. So, when heating a structure with a surface modulus of 6.7m⁻¹ (for example, a wall thickness of 0.3 m) from slag-alkali concrete after 12 hours from the beginning of heating by heaters of 200 W/m² the stresses reached 1.05 MPa, for concrete on clinker binder this value was 0.67 MPa. The data are given for the heat transfer coefficient of the formwork \( \alpha = 2 \text{ W/(m}^2 \cdot \text{°C}), \) outside temperature \( t_{at} = –20 \text{ °C}. \)

The magnitude of the tensile stresses can be adjusted by specifying a specific heat flux. Reducing the power of heaters from 200 to 50W/m² led to a decrease in the greatest value of stresses from 1.05 to 0.12 MPa.

Along with other indicators, the calculation of the temperature and strength fields was used to determine the stress level \( \sigma_{p}/R_{t} \) – the values equal to the ratio of tensile stresses in the section under consideration to the tensile strength of concrete in this section at the same time. The nature of the change in the stress level is determined by the massive structure and power of the formwork heaters [18,19].

For structures with a surface module 3 m⁻¹ and 6,7 m⁻¹ the pattern of stress level changes \( \sigma_{p}/R_{t} \) is given in the table. A sharp increase in the value \( \sigma_{p}/R_{t} \) in the first 2-4 hours from the beginning of the heating is explained by the relatively small rate of growth of the strength of concrete in tension during this period of time. When heating the structure with a surface module of 6.7 m⁻¹ with heaters of 300 W/m² the stress level is close to the critical one and is 0.95. Therefore, it is reasonable to approach the design of the power of the formwork heaters.

| Surface module, m⁻¹ | Specific power of formwork heaters, W/m² | Heating time, h |
|---------------------|----------------------------------------|----------------|
|                     |                                        | 3  | 6  | 9  |
| 3                   | 100                                    | –0,15 | 0,08 | 0,25 |
| 3                   | 300                                    | –0,15 | 0,35 | 0,65 |
| 6,7                 | 100                                    | 0,35 | 0,3 | 0,2 |
| 6,7                 | 300                                    | 0,95 | 0,75 | 0,6 |

The greatest temperature gradient occurs in the outer layers adjacent to the heating formwork. Its value does not remain constant during heating: in its beginning it grows faster, by the end of heating it is slower with subsequent stabilization. As the calculation results show, the magnitude of the
maximum temperature gradient depends to a small extent on the massiveness of the structure, the initial temperature of the concrete, the heat exchange conditions with the surrounding environment, but is determined by the specific heat flux from the formwork heaters and by the kind of binder. This dependence is close to linear.

In accordance with the requirements of the Sanitary rules when using in winter methods of electric heating, heating in the heating formwork, the rate of rise of concrete temperature should be no more than 5–10 °C/h [20]. If the mixture is preheated before laying in the formwork, it is possible to reduce the temperature gradient of the concrete along the section of the structure. At the same time, the temperature stresses decrease. This allows you to assign a higher rate of temperature rise on the surface of the structure. The recommended values for the rates of temperature rise are in the range 15–20 °C/h.

4. Conclusion
The technical and economic comparison of heat treatment options for structures is carried out. The duration of the erection of monolithic structures with the use of combined heat treatment is reduced by 25-30% due to the reduction of the time of the concrete curing in the formwork (in comparison with the method of peripheral heating). The economic effect consists of reducing the cost of organization and performance of temperature control, insulation, electricity. The cost of electricity compared to the method of electric heating is reduced by 10-20%.

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