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Experience of concreting a massive monolithic foundation slab

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Abstract. The large number of recipe and technological factors affecting the stress-strain state of concrete in the initial period of massive monolithic structures erection predetermines the expediency of using modeling of temperature fields and stresses with software packages based on analytical and numerical solutions when developing technological regulations for concreting. Improving the algorithm for calculating temperature fields and stresses taking into account the kinetics of concrete heat release, heat exchange conditions, ambient temperature and the stages of construction of structures is a pressing task. A comparison was made of calculated, laboratory and natural values of some parameters when concreting a foundation slab with a volume of 1642 m^3, a surface area of 821 m^2, and a thickness of 2 m. Concreting was completed in 13.5 hours with an average intensity of concrete mix placement of 122 m^3/h, and a peak intensity of up to 240 m^3/h. A method for calculating temperature fields and stresses taking into account the staged nature of construction has been developed in the MATLAB environment. It does not require rebuilding the geometry of the finite element model, adding nodes and elements during the process of laying new layers, and allows for the correct consideration of the dependence of the strength and deformation properties of concrete on the degree of its maturity. The results of calculated and measured temperature values excluding heating from solar radiation showed a discrepancy of up to 10 °C on the upper surface at some points in time. Some discrepancy between the calculated and experimental values of stresses and deformations with a qualitative coincidence in the nature of the curves is due to the neglection of shrinkage and rapid creep of concrete and poor study of the deformation properties of concrete with additives based on polycarboxylate esters at an early age.

Keywords: mass concrete, foundation slab, numerical modeling, finite element method, early cracking, temperature stresses

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1. INTRODUCTION

Concreting of massive monolithic reinforced concrete structures is associated with the risk of early cracking caused by temperature and shrinkage deformations, which predetermines the relevance of regulating the temperature regime of concrete curing [1-3]. A mandatory condition for ensuring the monolithicity of massive reinforced concrete structures being erected is the prevention of early cracking by regulating temperature-shrinkage deformations caused by temperature gradients and contraction shrinkage of concrete in the early period [4-6], and at a later stage by shrinkage during drying [7]. To regulate the temperature regime of concrete curing during the construction of massive structures, a combination of formulation techniques, technological and design factors is used. Formulation techniques include the use of low-heat-emitting cements in combination with limiting the cement content in the concrete mix [1, 8, 9], regulation of heat-emitting kinetics using chemical and mineral additives [10-12], and selection of fillers [13]. Technological factors include regulation of temperature gradients [3, 14, 15] and the temperature difference "center-surface" [16] by reducing heat transfer on surfaces and using water cooling. The importance of such measures is confirmed by the experience of constructing massive structures using formulation and technological regulation of temperature fields in order to prevent early cracking [1-3].

Modern technology makes it possible to obtain highly functional concretes with the required level of properties by means of prescription regulation, while ensuring the technological indicators of concrete mixtures in a wide range [9, 15]. Considering the multitude of prescription and technological factors that influence the processes under consideration, it becomes obvious that it is expedient to use modeling of temperature fields and stresses using software packages [17-19] with the use of analytical and numerical solutions [20, 21] when developing technological regulations for concreting.

Numerical modeling of temperature fields allows us to determine the thickness of the near-surface layers of a massive structure, in which the main temperature gradient is realized, as well as the values of temperature differences that can lead to the formation of temperature cracks [22]. When modeling temperature stresses in most software packages, including ANSYS, Abaqus, Lira, etc., the material properties in the user interface can be specified either constant in time or dependent on only one parameter (time or temperature) [23]. However, at an early age, the properties of concrete, including the modulus of elasticity and strength, strongly depend simultaneously on the time and temperature of hardening. Taking this factor into account in some software packages is possible by connecting user extensions [9d]. However, existing commercial calculation packages implementing the finite element method are closed-source software, the modification capabilities of which are severely limited. This encourages the development of our own software aimed at solving the specific problem of modeling temperature stresses at the early age of concrete [24].

Since temperature gradients are one of the main causes of stress formation, improving the algorithm for calculating temperature stresses, including calculating temperature fields in the early period of construction of a structure taking into account the kinetics of heat release of concrete, heat exchange conditions and ambient temperature, as well as the staged nature of construction of structures, is an urgent task. Concreting massive structures with self-compacting concrete mixtures without the use of working joints predetermines the laying of hundreds and even thousands of m^3 of concrete mixture in a relatively short period of time [1-3]. The consequence is the formation of significant temperature gradients [25, 26] and stresses in the hardening massif.

The paper analyzes the calculation results and experimental data obtained during concreting of a massive foundation slab of complex shape. The purpose of the paper is to analyze the possibility of using numerical modeling to determine temperature fields and stresses during the construction of massive monolithic structures.

2. MATERIALS AND METHODS

The general view of the foundation slab (FS) under study are shown in Fig. 1. The volume of the FS is $V = 1642$ m^3, the surface area is $A = 821$ m^2 , the thickness is $h = 2$ m.

Fig. 1. General view of the FS during concreting.

The concreting of the FS was completed in 13.5 hours with an average concrete mix laying intensity of 122 m^3/h (according to the regulations 120 m^3/h) with a peak intensity of up to 240 m^3/h (Fig. 2). The concrete mix was laid in layers with a layer thickness of 25 cm with an estimated layer overlap time of 2 hours.

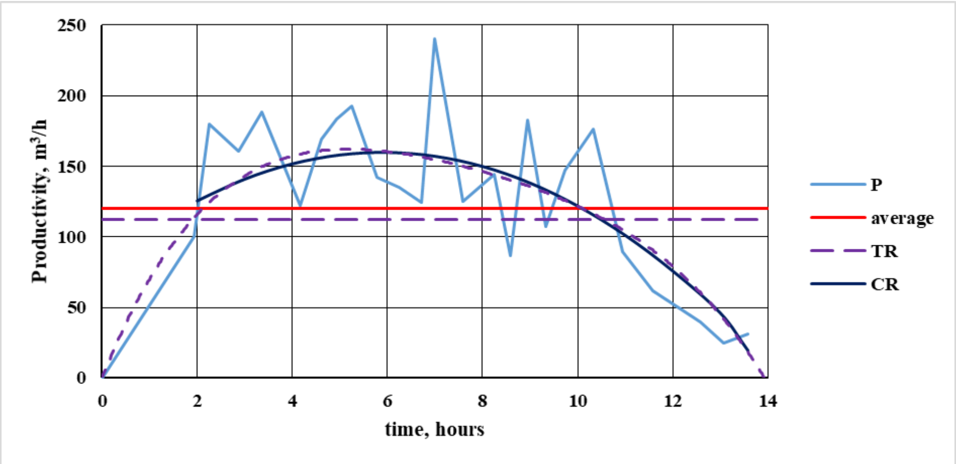

Fig. 2. Productivity of concreting (P), average concreting rate (CR) and technological regulations rate (TR).

The concreting of the FS was performed using concrete grade B25 F100 W8 GOST 26663-2015 . The concrete mix with the workability grade P4 according to GOST 7473-2010 (slump = 18-19 cm) was used, the shelf life of the concrete mix was at least 4 hours. When calculating temperature stresses, the value of the compressive strength R = B +12 was adopted. The actual value of the compressive strength on the slab surface in 28 days was 28.6 MPa.

Portland cement CEM N/A-P 42.5N SS GOST 22266-2013 was used. Cement consumption was 330 kg/m^3. The superplasticizing additive based on polycarboxylate esters "LINAMIX PC" type 2 according to TU 5745-033-58042865-2008 with amendment No. 1 was used.

ANSYS software package, as well as the program developed by the authors in the MATLAB environment were used for calculation of temperatures and stresses. The determination of temperature fields and stresses according to the author's method was performed in a disconnected formulation, i.e. it was assumed that the stress-strain state does not lead to a change in temperature fields. The method for determining temperature fields is based on the differential equation of heat conductivity:

$$\operatorname{div}(\lambda\ \operatorname{grad}T) + W = \rho c\frac{\partial T}{\partial t}, \tag{1}$$

where λ is the thermal conductivity coefficient, *T is* the temperature, ρ is the density, *c* is the specific heat capacity, *t* is the time, *W* is the power of internal heat sources (W/m^3) , $W = \partial Q / \partial t$.

When calculating temperature fields, the heat release function was given by the equation [8]:

$$Q = Q_{28}\exp\left(k\left(1-\left(\frac{28}{t-b}\right)^{x}\right)\right), \tag{2}$$

where Q_{28} is the heat release in MJ/m^3 at the time of 28 days, *t* is the time in days, *k* and *x* are the parameters determining the rate of heat release, *b* is the induction period.

The values of the parameters in formula (2), determined by processing the heat release curves for the laboratory composition of concrete, taking into account the effect of temperature on the kinetics of heat release, were Q_{28} = 140 MJ/m^3, *k* = 0.0546, *x* = 0.564.

When calculating temperature fields, the following thermophysical characteristics were adopted:

- clay soil: density ρ_g = 1800 kg/m^3, specific heat capacity c_g = 750 J/(kg·°C), thermal conductivity coefficient λ_g = 0.9 W/(m·°C);
- concrete: density ρ = 2400 kg/m^3, specific heat capacity *c* = 1000 J/(kg·°C), thermal conductivity coefficient λ = 2.67 W/(m·°C).

The system of FEM equations for calculating temperature stresses taking into account the time-varying deformation properties of concrete is written in increments:

$$[K]\{\Delta U\} = \{\Delta F_T\}, \tag{3}$$

where [*K*] is the stucture's stiffness matrix, changing at each time step, {Δ*U*} is the displacement increment, $\{\Delta F_T\} = \int_V [B]^T [D]\{\Delta\varepsilon_T\}dV$ is the vector of increments of nodal loads caused by temperature deformations, [*B*] is the matrix of gradients of the finite element shape functions, [*D*] is the matrix of elastic constants of the material, $\{\Delta\varepsilon_T\}$is the vector of temperature deformations increments.

When calculating temperature fields and stresses, the layering of concrete mix and the duration of concreting were taken into account. The number of layers was 8 by 0.25 m. The duration of laying one layer was taken to be 6075 s in accordance with the actual duration of concreting work. The layering of concreting in ANSYS was taken into account using the "Element Birth and Death" object. Each layer was "born" after 6075 s after the previous one. In MATLAB, the layer-by-layer increase in the volume of the slab was also taken into account, but without rebuilding the geometry of the finite element model. Before the concreting of a layer was completed, it was assigned zero heat capacity and a very large thermal conductivity coefficient (λ = 1000 W/(m·°C)). After the concreting was completed, the layer was assigned its real characteristics.

The formwork was insulated with a 30 mm thick layer of extruded polystyrene foam, the heat transfer coefficient was 1.04 W/(m^2 · °C). On the upper surface of the foundation slab, the heat transfer coefficient in the calculation was taken to be 13 W/(m^2 · °C) before it was covered and 7 W/(m^2 · °C) after it was covered with a waterproof film and tarpaulin. The moment of covering the upper surface with tarpaulin was taken to be 12 hours after the completion of concreting the upper layer. The average daily ambient temperature, the initial temperature of the concrete mix and the soil temperature under the slab were taken to be 17 °C, 20 °C and 13 °C, respectively.

When calculating the stress-strain state using the author's program in the MATLAB environment , the dependence of the elastic modulus of hardening concrete on time, as well as its strength characteristics, was taken into account. The change in the strength of concrete under compression was taken as a function of its maturity degree DM [27]:

$$DM = \int_0^t T(\tau) d\tau. \quad (4)$$

where $T(\tau)$ is the temperature of concrete at time τ.

The change in compressive strength depending on the given curing time was determined by the equation:

$$R = R_{28} \exp\left(s \left(1 - \sqrt{\frac{28}{\tau_r - b}} \right) \right), \quad (5)$$

where $\tau_r = DM / 20$ is the reduced concrete hardening time, $R_{28} = B+12$ is the average compressive strength at the design age of 28 days, B is the concrete class, $s = 0.25$, b is the induction period.

The modulus of elasticity was specified as a function of the compressive strength at any given time using the formulas:

- N.I. Karpenko [28]:

$$E = \frac{41600 \cdot R}{18 + 0.8R}, \quad (6)$$

- the formula of the authors, obtained during an experimental study of the properties of concrete on the materials used:

$$E_t = 22265 \cdot \left(\frac{R}{10} \right)^{0.28}, \quad (7)$$

which is practically identical (difference less than 2%) with the formula EN 1992-1-1:

$$E_{cm} = 22000 \cdot \left(\frac{f_{cm}}{10} \right)^{0.3}. \quad (8)$$

The values of the elastic modulus according to equation (8) exceed the values according to equation (6) by 1.35 times at 0.5 days, by 1.19 times at 1 day, and by 1.1 times at 2 days. The tensile strength of concrete was specified as a function of the compressive strength at any moment of the given time according to the formula [29]:

$$R_t = 0.29 R^{0.6}. \quad (9)$$

The Poisson's ratio of concrete ν and the coefficient of linear thermal expansion α were taken to be constant and equal to $\nu = 0.2$, $\alpha = 10^{-5}$ 1/°C.

When calculating the stress-strain state, the soil mass was excluded from the calculation scheme, and connections were installed on the lower surface of the slab along the axis z, simulating the work of the piles. Since the pitch of the piles did not exceed the doubled pitch of the triangulation of the slab, the connections were installed along the entire lower surface.

The finite element mesh in ANSYS and MATLAB is shown in Fig. 3 and Fig. 4. The structure was divided into prismatic finite elements (FE) with a side size of 1 m in xOy plane and 0.25 m in thickness, with the exception of the concrete preparation layer, which had a thickness of 0.1 m. This FE size provided an optimal balance between the accuracy and computational complexity of the model.

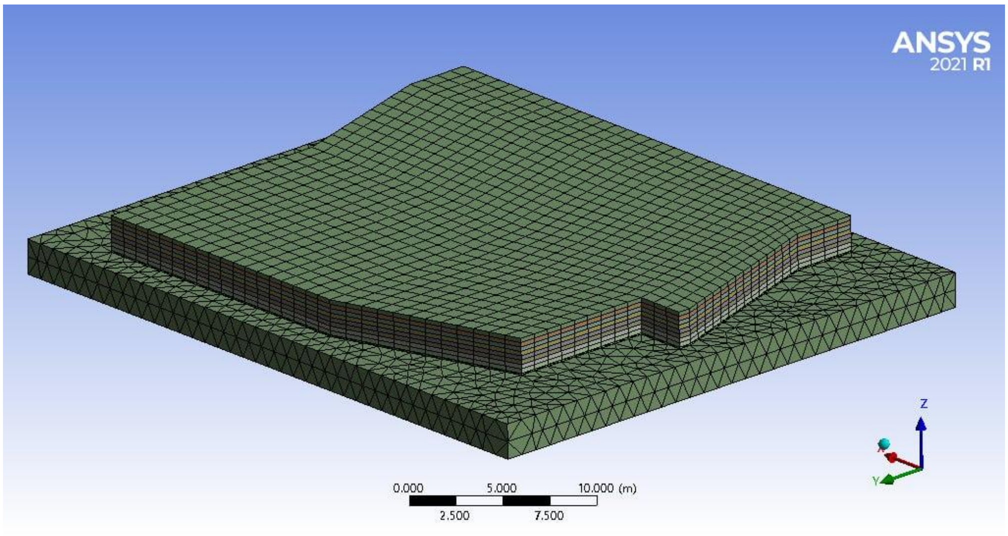

Fig. 3. Finite element mesh in ANSYS.

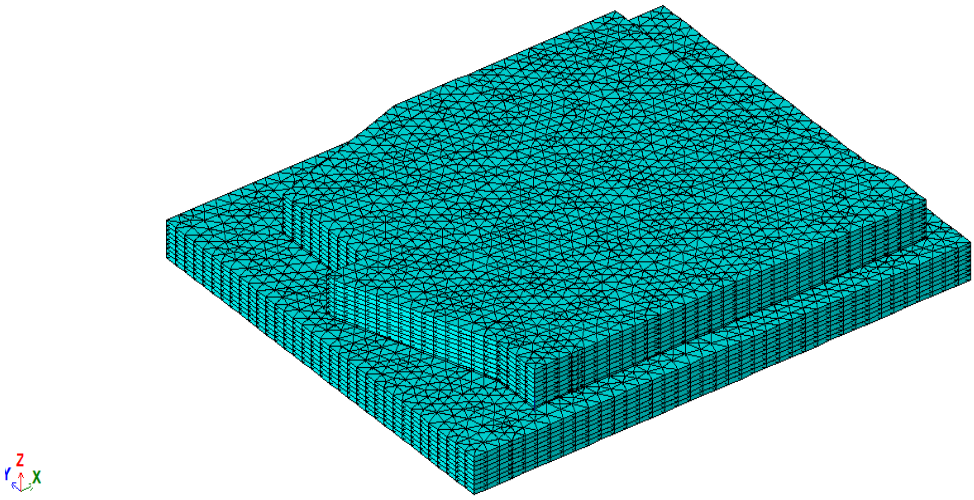

Fig. 4. Finite element mesh in MATLAB.

Since ANSYS does not have built-in tools to take into account time-varying modulus of elasticity of concrete, the calculation was performed with a constant value of $E = 2 \cdot 10^4$ MPa with subsequent recalculation to true stresses using the method given in the work [30].

The temperature in the FS body was measured using sensors with a measurement accuracy of ±0.1 °C. The deformations were measured using embedded string strain gauges (Fig. 5).

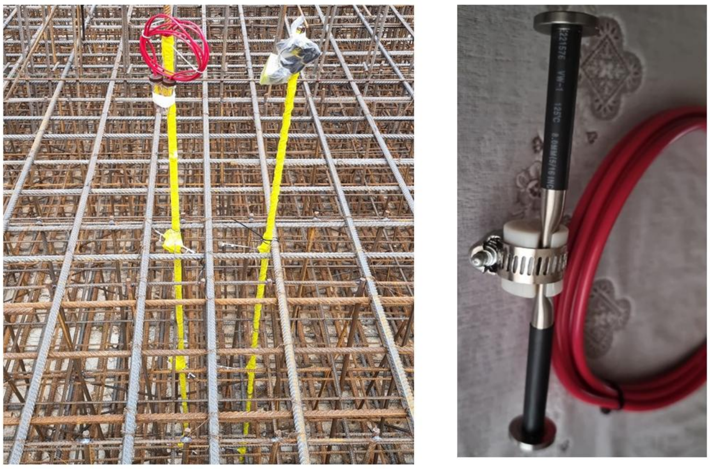

Fig. 5. Sensor for measuring deformations.

All temperature and deformation measurements were made on the upper and lower surfaces at a depth of 50 mm and in the center of the FS body.

3. RESULTS AND DISCUSSION

Fig. 6 shows the change in time of the experimental and calculated values of temperatures in the center of the foundation slab in the middle of the thickness, as well as at a distance of 5 cm from the upper and lower surfaces. From Fig. 6 it is evident that the results obtained in ANSYS and according to the author's method in MATLAB completely coincide for the middle of the thickness, and for points near the upper and lower surfaces they differ within 3%. The method of accounting for the stages of construction proposed by us, in contrast to the method embedded in ANSYS, allows not to reconstruct the geometry of the finite element model when adding new layers of concrete. Satisfactory agreement is observed with the experimental data, within 8% for the middle of the thickness. The maximum temperature according to the experimental results was 68 °C, and according to the calculation results it was 62.8 °C. The discrepancy is due to the difference in the heat transfer parameters adopted in the calculation and the actual ones, as well as the heat release of concrete and the ambient temperature.

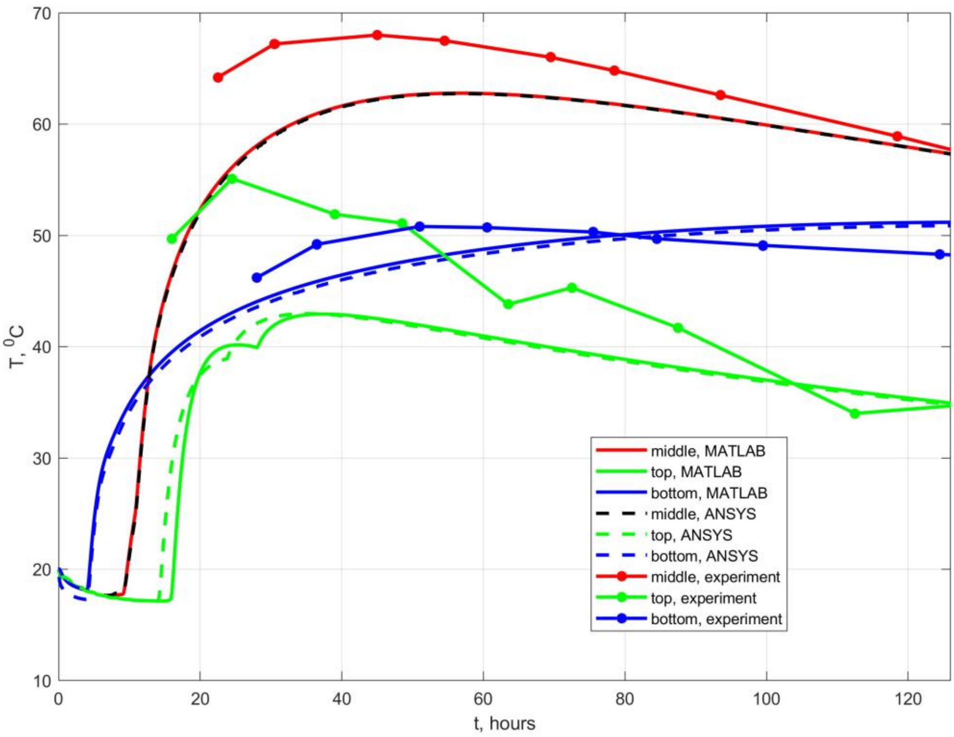

Fig. 6. Comparison of experimental and calculated temperature values.

Fig. 7 shows graphs of changes in stress over time at the same points. Formula (6) was used as the dependence of the elastic modulus on the compressive strength when constructing Fig. 5. The value *b* in formula (5) was taken to be 12 h. The black line shows the current tensile strength of concrete. The dashed lines show the results obtained by recalculating the stresses calculated in ANSYS with a constant elastic modulus over time, using the method given in [30]. From Fig. 5 it is evident that the simplified method [30] gives acceptable results for the upper surface of the slab. For the middle of the thickness and the lower surface, there is a qualitative coincidence of the results, with an overestimation in ANSYS of the maximum tensile stresses at the lower surface by almost 3 times. The reason for this discrepancy may lie in the principles adopted by the authors of the work [30] simplifications for determining true stresses, which turn out to be inapplicable when taking into account the stages of construction of the structure. The results of modeling using the author's method in the MATLAB environment show that at the calculated points the stresses do not exceed the tensile strength of concrete, and thus the crack resistance of the structure is ensured with the adopted measures to regulate heat exchange on the surfaces. No temperature cracks were detected during the in-kind inspection of the structure either.

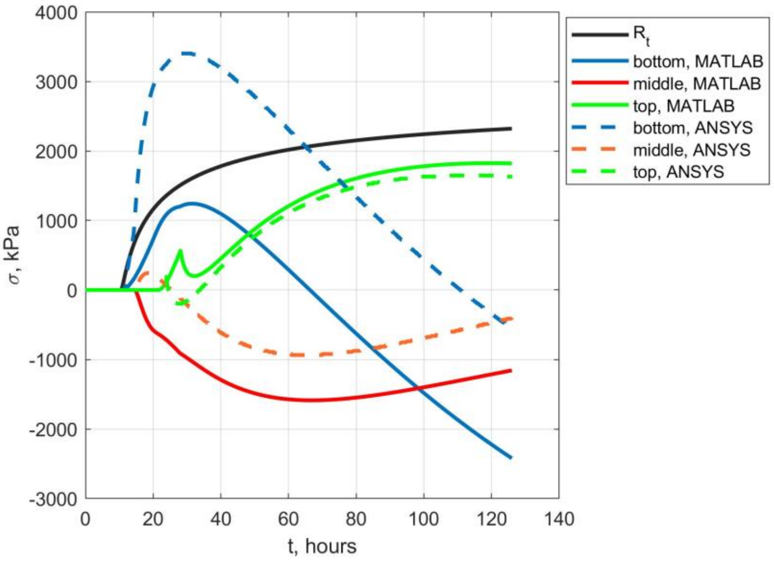

Fig. 7. Change of stresses in the slab over time.

Also provided for comparison are the calculation results using the formula of N.I. Karpenko (6) for the modulus of elasticity and the formula of EN 1992-1-1 (8) (Fig. 8). When using the formula of the authors (7), the maximum tensile stresses at the lower surface are 1.25 MPa, and at the upper surface they are 1.82 MPa. The formula from EN 1992-1-1 gives values of 1.2 MPa and 1.81 MPa, respectively. In the case of using the formula of N.I. Karpenko, the maximum tensile stresses at the lower surface are 0.59 MPa, and at the upper surface they are 1.51 MPa. Obviously, the calculated values of stresses in the early period are very much dependent on the used dependence of the concrete modulus of elasticity. In addition, the calculated values will be affected by taking into account the fast-flowing creep.

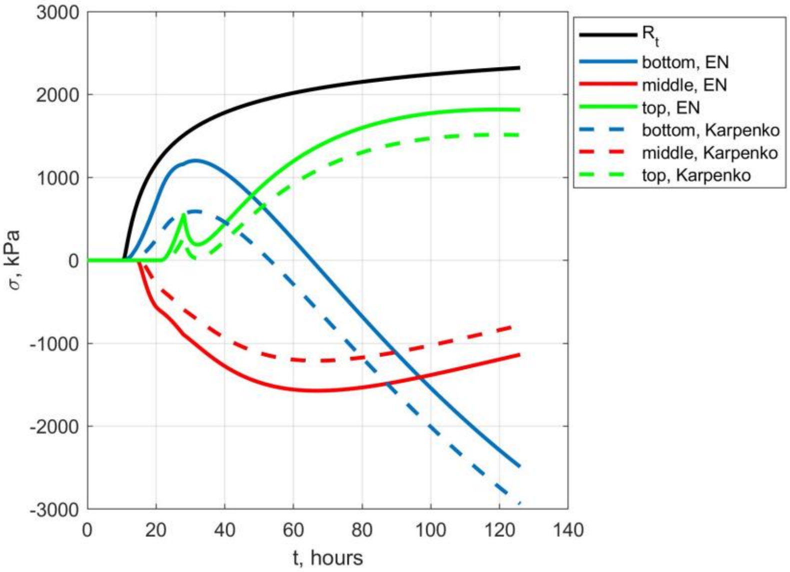

Fig. 8. Comparison of stresses when using the formula of N.I. Karpenko and the formula from EN 1992-1-1 for the modulus of elasticity.

In order to refine the calculation results, the heat release curve was refined under the assumption that the middle of the thickness is in adiabatic conditions until the maximum temperature is reached. The following formula was used:

$$Q(t) = \rho c\left(T_{mid}(t) - T_0\right), \tag{10}$$

where T_0 is the initial temperature of the concrete mixture, equal to 20 °C, $T_{\text{mid}}(t)$ is the temperature in the middle of the thickness.

As a result, the refined values of the parameters in formula (2) were k = 0.02551, x = 0.6019. Due to the reduced cement consumption during concreting of the FS, the heat release of the production concrete composition was, according to laboratory tests, Q_{28} = 132 MJ/m^3 . A comparison of the actual and calculated heat release curve is shown in Fig. 9.

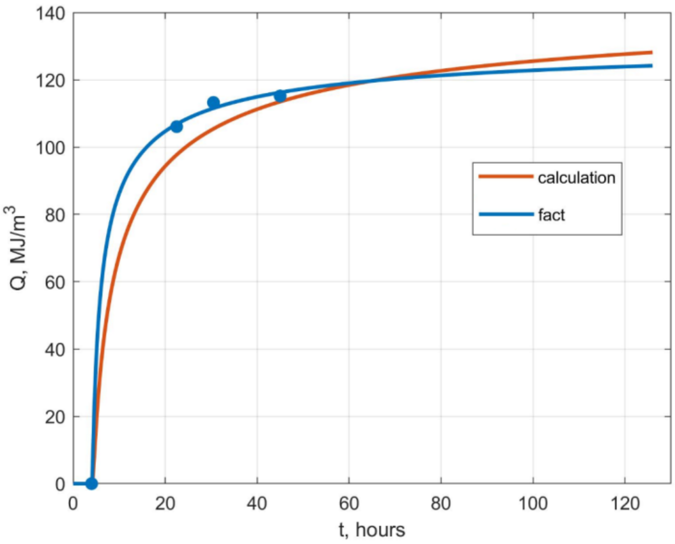

Fig. 9. Comparison of actual and calculated heat release curve.

Also, to clarify the calculation results, actual daily changes in ambient temperature were taken into account (Fig. 10).

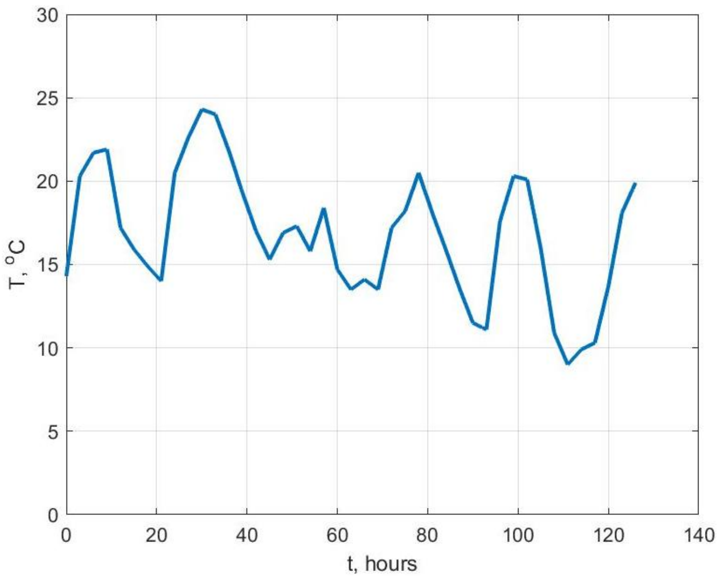

Fig. 10. Change in ambient temperature over time.

The results of calculating the temperature fields with the refined values of the ambient temperature and the parameters of concrete heat release are shown in Fig. 11. The maximum temperature according to the results of the refined calculation was 65.6 °C, which differs from the experimental value by only 3.5%. At the lower surface, the maximum discrepancy in the results is 5.2%. The most noticeable discrepancy, at some points in time reaching up to 10 °C, is observed at the upper surface. This can be explained by additional heating of the upper surface from solar radiation.

Fig. 12 shows the graphs of the calculated stresses refined values, as well as the stresses calculated from the experimental deformations using formula (6) for the elastic modulus. It is evident from Fig. 12 that at the age of 20 hours, only a qualitative coincidence of the nature for the experimental and calculated curves is observed, the quantitative difference is quite noticeable, and for some moments in time can reach up to 2.7 times. Deviations of the experimental results from the calculation can be caused by the following factors:

1. The calculation did not take into account shrinkage and creep deformations of concrete and the work of reinforcement.
2. The presence of a discrepancy between the actual temperatures for the top surface of the slab and the temperatures obtained by calculating the temperature fields, which were then used to calculate the temperature stresses.
3. Complex contact interaction at the boundary between the slab and the foundation, the presence of pile extensions that enter the body of the slab and thereby partially limit deformations of the lower surface.

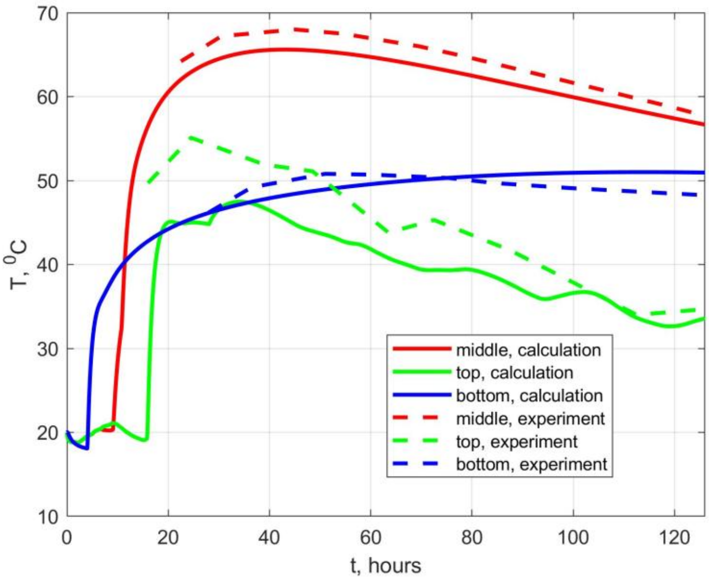

Fig. 11. Calculation results with refined values of ambient temperature and concrete heat release parameters.

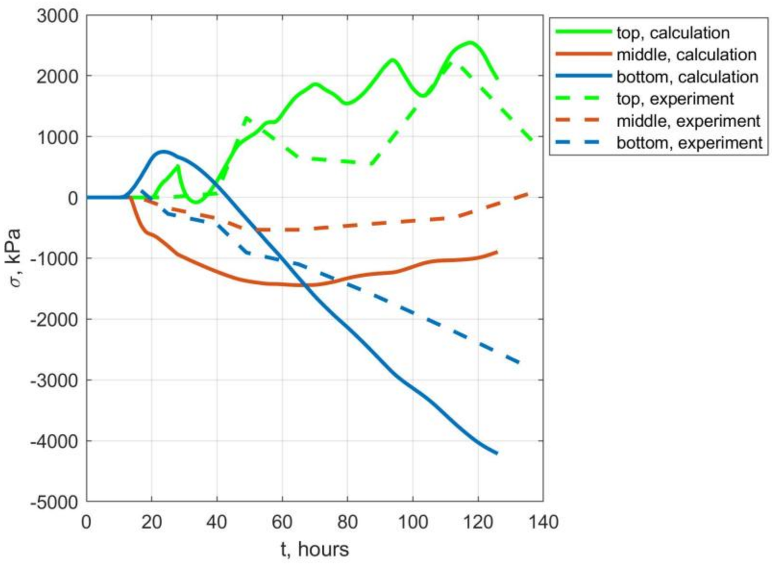

Fig. 12. Comparison of experimental stress values with calculated ones.

4. CONCLUSIONS

1. An experimental study of temperature fields and deformations in a massive monolithic foundation slab of complex shape during construction was conducted.
2. Methodology for calculating temperature fields and stresses during the construction of massive monolithic structures, taking into account the staged nature of construction has been developed and implemented in the MATLAB environment. Unlike existing software packages (ANSYS, Abaqus, etc.), the method and program developed by the authors do not require rebuilding the geometry of the finite element model, adding nodes and elements during the process of laying new layers. The developed program also allows for the correct consideration of the dependence of the deformation characteristics of concrete on the degree of its maturity.
3. Comparison of the results of calculating the temperature fields, taking into account the updated data on the ambient temperature and heat release of concrete with the experimental results showed good agreement between the experimental and theoretical values of temperatures in the center of the foundation slab and at the lower surface. At the upper surface, the discrepancy at some points in time reaches up to 10 °C (18%), which is due to unaccounted additional heating of the surface from solar radiation.
4. Calculated curves of stress changes are in qualitative agreement with the experimental curves, but quantitative differences are up to 2.7 times. These differences are associated with neglecting shrinkage and rapid creep of concrete in the calculation. The deformation properties of concrete with additives based on polycarboxylate ethers (modulus of elasticity, rapid creep, shrinkage) at an early age are currently poorly understood. Our further research will be aimed at identifying patterns of change in time of the specified parameters from prescription and technological factors in order to more accurately model the stress-strain state of massive monolithic structures during construction.

5. ACKNOWLEDGEMENTS

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