Civil Engineering

DOI: 10.23968/2500-0055-2024-9-4-75-86

THERMOPHYSICAL PROCESSES IN HARDENING CONCRETE AS A FACTOR FOR QUALITY ASSURANCE OF ERECTED REINFORCED CONCRETE STRUCTURES OF TRANSPORT FACILITIES

Sergey Fedosov[1], Ivan Pulyaev[2]*, Olga Aleksandrova[1], Nadezhda Cherednichenko[3], Evgeniya Derbasova[2], Yuliya Lezhnina[4]

[1]Moscow State University of Civil Engineering (National Research University), Moscow, Russia
[2]Moscow Polytechnic University, Moscow, Russia
[3]Russian University of Transport (MIIT), Moscow, Russia
[4]MIREA – Russian Technological University (RTU MIREA), Moscow, Russia

*Corresponding author's email: ivanes50@mail.ru

Abstract
Introduction. This paper presents the main issues of maintenance of structural properties of concrete depending on the effect of temperature factor and heat and mass transfer processes in contact with the environment during the construction of transport facilities erected from monolithic reinforced concrete under different initial and limiting conditions. **Purpose of study:** quality assurance of preliminary design studies of reinforced concrete structures, including full-scale modeling of the considered thermophysical processes in hardening concrete, including use of modern calculation and analytical software packages. **Methods:** application of a special software package for calculation of temperature changes and strength of hardening concrete, estimation of temperature factor impact on the following concrete properties: frost resistance, water resistance, strength and crack resistance. **Results:** it is shown that recording of the thermal stressed state of hardening concrete allows to ensure required operational properties of structures: quality, reliability, durability, including prevention of appearance of temperature and shrinkage cracks, — one of the most common defects in transportation construction, that reduce quality of the erected surface. The studies described in this paper have been widely tested at Russian transportation facilities in Moscow, St. Petersburg, Kuban, Crimea and other regions, the obtained results have resonated with the transport industry. The paper will be interesting and useful for persons involved in the processes of quality assurance of defect-free concreting of multi-mass concrete structures of transportation facilities, as well as for engineers and technicians engaged in the real sector of construction.

Keywords: concrete; thermal stresses; thermophysical processes; crack resistance; modulus of structure surface.

Introduction

The radical changes in the economic conditions of the operation and development of the country's production sector that took place in Russia at the end of the 20th century led to the priority use of road transport in our country. This in turn required the construction of appropriate motorways, flyovers, bridge crossings, tunnels, numerous road junctions and other types of transport facilities throughout its territory (Ginzburg, 2014; Kosmin et al., 2014; Vasiliev and Veitsman, 2015; Solovyanchik et al., 2006; Balyuchik and Cherny, 2010).

The required scope of construction works since the end of the 90 s has been met mainly due to the large-scale use of monolithic reinforced concrete in transport construction, which successfully provides architectural expressiveness and diversity of design solutions used in practice.

Wide application of monolithic reinforced concrete was mainly facilitated by supply of highly efficient and highly productive equipment to the transport market for preparation, transportation and delivery of concrete mixtures to the place of paving, as well as wide use of new modern additives of different effect. (Sokolov, 2002; Passek et al., 2002; Komandrovsky, 2003; Velichko and Cherny, 2013; Solovyanchik and Shifrin, 2000).

However, the initial experience of large transportation facilities construction, including reconstruction of the Moscow Ring Road, showed that in the process of construction of structural elements of different masses, various defects began to appear on their surface in the form of cracks, spalls, sinks, which led to intensive and consistent destruction of the erected structures at the initial stage of their active operation and loading (Pryakhin, 2009; Sokolov, 2002; Solovyanchik et al., 2002; Solovyanchik et al., 2003; Kosmin and Mozalev, 2014).

It turned out that, during the use of concrete of high classes in combination with the intensive pace

For citations: Fedosov, S., Pulyaev, I., Aleksandrova, O., Cherednichenko, N., Derbasova, E., Lezhnina, Yu. (2024). Thermophysical processes in hardening concrete as a factor for quality assurance of erected reinforced concrete structures of transport facilities. Architecture and Engineering, No 4 (9), pp. 75–86. DOI: 10.23968/2500-0055-2024-9-4-75-86.

of concrete works and the need to erect structures in massive blocks, a fundamentally new integrated approach is required to ensure the necessary quality, reliability and durability of transport structures, related to the effects of a whole series of thermophysical processes both on the hardening concrete and on the erection of individual structural elements and the structure as a whole (Pryakhin, 2009; Tarasov et al., 2007; Velichko, 1987; Evlanov, 2019).

However, the current rules and regulations with its requirements regarding thermal processes occurring in hardening concrete reflects only restrictions in permissible heating temperature of the concrete mixture and on critical temperature differences between the concrete and the environment during formwork removal from concrete structures (Concu and Trulli, 2018; Zvorykin et al., 2017). At the same time, the latter limitation is formulated only for structures with a surface modulus of 2 m^{-1} or more.

Physical picture of the thermal processes development in the system 'hardening concrete plate — formwork', can be presented in the form of a graph in Fig. 1.

The curves illustrate development of temperature fields in the model plate and formwork. It is assumed that inside the plate (in its entire area) there is a distributed source of heat — $q_{VT}(\tau)$, due to the effects of hydration of cement components. From the side surface the heat flux — $q_l(\tau)$ is discharged. This flux is transferred by heat conduction through the formwork layer of size — δ_f and then from the outside of the formwork is removed to the environment by the mechanism of convective heat transfer.

Based on the above stated physical and mathematical picture of the processes occurring in a solidifying monolithic reinforced concrete slab, we synthesize a mathematical model of the processes of interconnected heat and mass transfer in a plate of limited dimensions, complicated by the thermal effect of hydration reactions of binder components (Fedosov, 2010; Fedosov et al., 2024):

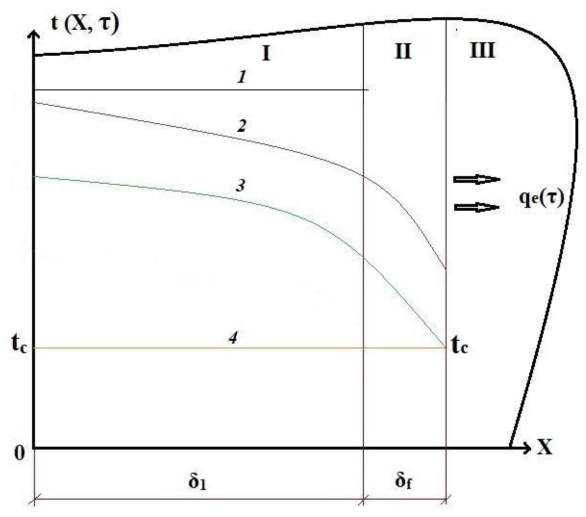

Fig. 1. Illustration of the dynamics of heat exchange processes

$$\frac{\partial t}{\partial \tau} = \nabla(a\nabla t) + \varepsilon \frac{r^*}{c}\frac{\partial u}{\partial \tau}; \quad (1)$$

$$\frac{\partial u}{\partial \tau} = \nabla(k\nabla u) + \nabla(k\delta_T \nabla t). \quad (2)$$

Equation (1) is a differential equation of non-stationary heat conduction and reflects the fact that in a given point of space of the hardening concrete mass, the temperature change — $t(x,y,z,\tau)$ — occurs both in time t and in coordinates — x,y,z.

At the same time, both temperature (in particular) and temperature field (in general) are impacted by material properties: density (ρ_o), heat capacity (c^*), thermal conductivity (λ), which also generally depend on temperature and humidity and, therefore, vary both in time and in coordinates

Equation (2) is a differential equation of unsteady moisture conduction; it shows that moisture transport in a given point of space is determined by mass conduction (diffusion in solid k), as well as by such phenomena as thermodiffusion δ_T and pressure transfer δ_p.

As a rule, the initial conditions for nonstationary heat and mass transfer problems are the values of potentials at the moment of time taken as the origin:

$$t(x,y,z,\tau)|_{\tau=0};\ u(x,y,z,\tau)|_{\tau=0};\ \rho(x,y,z,\tau)|_{\tau=0}, \quad (3)$$

The limiting conditions, in general, should be recorded in the form of conditions of the III kind, they define the conditions of heat and mass transfer at the plate boundaries:

$$\alpha\left[t_c(\tau) - t(R,\tau)\right] = \lambda\nabla t(R,\tau) + q_m(\tau)r^*; \quad (4)$$

$$q_m(\tau) = \beta\left[u_{nc}(\tau) - u_c(\tau)\right]\rho_g = -k\left[\nabla u(R,\tau) + \delta_T \nabla t(R,\tau)\right], \quad (5)$$

where $q_m(\tau)$ is the moisture flux from a unit of material surface kg/m^{2}s.

In thermal treatment processes of the greater part of construction materials, the temperature does not reach the value of 100 °C (otherwise, moisture boiling occurs in the material, leading to a change in the B/C ratio and the subsequent procedure of structure formation). Taking this into consideration, the system of equations (1), (2) may be transformed to a simpler form:

$$\frac{\partial t}{\partial \tau} = \nabla(a\nabla t) + q_{VT}; \quad (6)$$

$$\frac{\partial u}{\partial \tau} = \nabla(k\nabla u) + \nabla(k\delta_T \nabla t). \quad (7)$$

At the same time, we pay attention to the fact that in absence of internal moisture evaporation (Σ = 0), the last element of the right-hand side in equation (1) turns to zero. But, at the same time, there are processes of hydration of binder components in the concrete mixture. They are accompanied by the release of reaction heat. This phenomenon is characterized by a new element in the right part of equation (6) — a volumetric source of heat due to chemical transformations.

In accordance with the stated physical concepts of the process, let us consider the mathematical model of heat transfer in the system under study in one-dimensional formulation.

In this case, it is logical to assume symmetry of the temperature field in the model plate. In this case, the boundary value problem of heat conduction for the plate is written as follows:

$$\frac{\partial T_1(\bar{x},Fo_1)}{\partial Fo_1}=\frac{\partial^2 T_1(\bar{x},Fo_1,)}{\partial \bar{x}^2}+Po(\bar{x},Fo_1);$$

$$Fo_1>0;\ 0\le\bar{x}\le 1; \quad (8)$$

$$T_1(\bar{x},Fo_1)|_{Fo_1}=T_{1.0}(\bar{x}); \quad (9)$$

$$\frac{\partial T_1(\bar{x},Fo_1)}{\partial \bar{x}}|_{\bar{x}=0}=0; \quad (10)$$

$$\frac{\partial T_1(\bar{x},Fo_1)}{\partial \bar{x}}|_{\bar{x}=1}=-Ki_l(Fo_1). \quad (11)$$

The equation (9) shows that, in general, the initial temperature distribution is non-uniform along the coordinate. Equation (10) represents a symmetry condition. Equation (11) shows that there is a heat flux at the boundary of the concrete slab with the formwork, the magnitude of which is generally a function of time variable.

The heat conduction requirement for the formwork may be represented as follows:

$$\frac{\partial T_2(\bar{x},Fo_2)}{\partial Fo_2}=\frac{\partial^2 T_2(\bar{x},Fo_2,)}{\partial \bar{x}^2};\ Fo_2>0;\ 0\le\bar{x}\le 1; \quad (12)$$

$$T_2(\bar{x},Fo_2)|_{F>2}=T_{2.0}(\bar{x}); \quad (13)$$

$$\frac{\partial T_2(\bar{x},Fo_2)}{\partial \bar{x}}|_{\bar{x}=0}=-Ki_l(Fo_2); \quad (14)$$

$$\frac{\partial T_2(\bar{x},Fo_2)}{\partial \bar{x}}|_{\bar{x}=1}=-Ki_r(Fo_2). \quad (15)$$

Together with the condition of temperature equality, they constitute the limiting condition of the IV kind. Equation (15) characterizes the condition of heat exchange of the external surface of the formwork with the environment.

For dimensionless values and similarity criteria we shall use the following formula:

$$T_1(\bar{x},Fo_1)=\frac{t_1(x,\tau)-t_{1,0}}{t_e}; \quad (16)$$

$$T_2(\bar{x},Fo_2)=\frac{t_2(x,\tau)-t_{2,0}}{t_e}; \quad (17)$$

$$\bar{x}=\frac{x}{\delta},\ \delta=\left[\delta_1,\delta_f\right]; \quad (18)$$

$$Fo_1=\frac{a_1\tau}{\delta_1^2};\ Fo_2=\frac{a_2\tau}{\delta_f^2}. \quad (19)$$

Pomerantsev criterion:

$$Po(\bar{x},Fo_1)=\frac{q_{VT}(\tau)\delta_1^2}{\lambda_1 t_e}. \quad (20)$$

Kirpichev Criteria:

at the edge of the formwork:

$$Ki_l(Fo_1)=\frac{q_l(\tau)\delta_1}{\lambda_1 t_e}; \quad (21)$$

at the interface between the formwork and the medium:

$$Ki_r(Fo_2)=\frac{q_r(\tau)\delta_f}{\lambda_2 t_e}. \quad (22)$$

The solution of the limiting value problem (8)–(11) obtained by methods of mathematical physics is given in (Fedosov, 2010). This equation is used for non-uniform initial temperature distribution and heat transfer criteria (*Po*, Ki_r), varying in coordinate and time.

The mathematical record of the solution is rather tedious.

Below is an equation for the uniform initial temperature distribution and constant values of the criteria:

$$T_1(\bar{x},Fo_1)=T_{1.0}+\frac{Ki_l}{6}\left[6Fo_1+3\bar{x}^2-1\right]+$$
$$+\frac{1}{6}Po\left[6Fo_1+3\bar{x}^2+1\right]. \quad (23)$$

Accordingly, the solution of the boundary value problem (12)–(15) will have the form:

$$T_2(\bar{x},Fo_2)=$$
$$=T_{2.0}+\frac{1}{2}\left\{Ki_l\left[(1-\bar{x})^2-\frac{1}{3}\right]-Ki_r\left[\bar{x}^2-\frac{1}{3}\right]\right\}-$$
$$-\left[Ki_l-Ki_r\right]Fo_2-\frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\left[Ki_l-(-1)^n Ki_r\right]\times$$
$$\times\operatorname{coscos}(\pi n\bar{x})\exp\left(-\pi^2 n^2 Fo_2\right). \quad (24)$$

Some results calculated according to the above equations are shown in Fig. 2.

Some results of calculations according to equations (23) and (24) are shown in Figs. 1–2. It should be noted that the calculations were done for constant values of the transfer coefficients, for greater clarity of the physicality of the processes. At the same time, when using numerical and analytical methods of calculation, to which can be referred the *"zonal method"* (Fedosov, 2024; Rudobashta, 2015) and the *"method of microprocesses"* (Fedosov, 2010; Fedosov et al., 2020), it becomes possible to create mathematical models and engineering calculation methods of heat and mass transfer processes occurring at any dependencies of thermophysical

Table 1. **Hardening parameters of concrete mixture during erection of 2.0 m diameter piers**

$t_{c.m}$, °C	t_{aver}, °C	t_{max}, °C		Δt at t_{max}, °C	Time of gaining strength R = $0,7R_{28}$, h	
		core	surface		core	surface
10	5	66	46	20	56	72
10	10	69	49.5	19.5	56	70
15	10	73	52	21	48	54
15	15	75.5	56	19.5	48	54
20	20	82	62	20	40	48

coefficients on temperature and humidity of the material and the external environment. It should also be noted that these methods allow us to use the originated mathematical models with the reference to available experimental information on the kinetics and dynamics of thermal effects of hydration reactions in the medium of hardening concrete mass (Usherov-Marshak, 2002). Some data illustrating and supporting these opportunities are presented below in the *Results and Discussion* section.

Subject matter, Purposes and Methods of the Study

The impact of the temperature factor on such basic properties as frost resistance, water resistance, strength and cracking resistance of hardening concrete has been studied with the use of a special software package "*ZA*" (Solovyanchik et al., 1992) for calculation of temperature changes and strength of hardening concrete. It has been established that when the surface modulus of the structure is less than 5 m^{-1}, a temperature gradient of more than 10 °C in the concrete structure is observed. This gradient is even more critical at edges and faces as well as at the other corner areas of the structure, which should be used as a reference for setting of time for demoulding of the element covered with concrete. Otherwise, underestimation of the non-uniformity of concrete heating can lead to early freezing of the material and to surface cracks formation (Solovyanchik et al., 1989; Kollegger et al., 2018).

When the structure is massive with a surface modulus below 2.0 m^{-1}, there is a problem with high concrete warm-up, limits of which to ensure the design frost resistance are 70 °C for non-surface conditions of the structure and 80 °C for severe conditions (Baluchik et al., 2012).

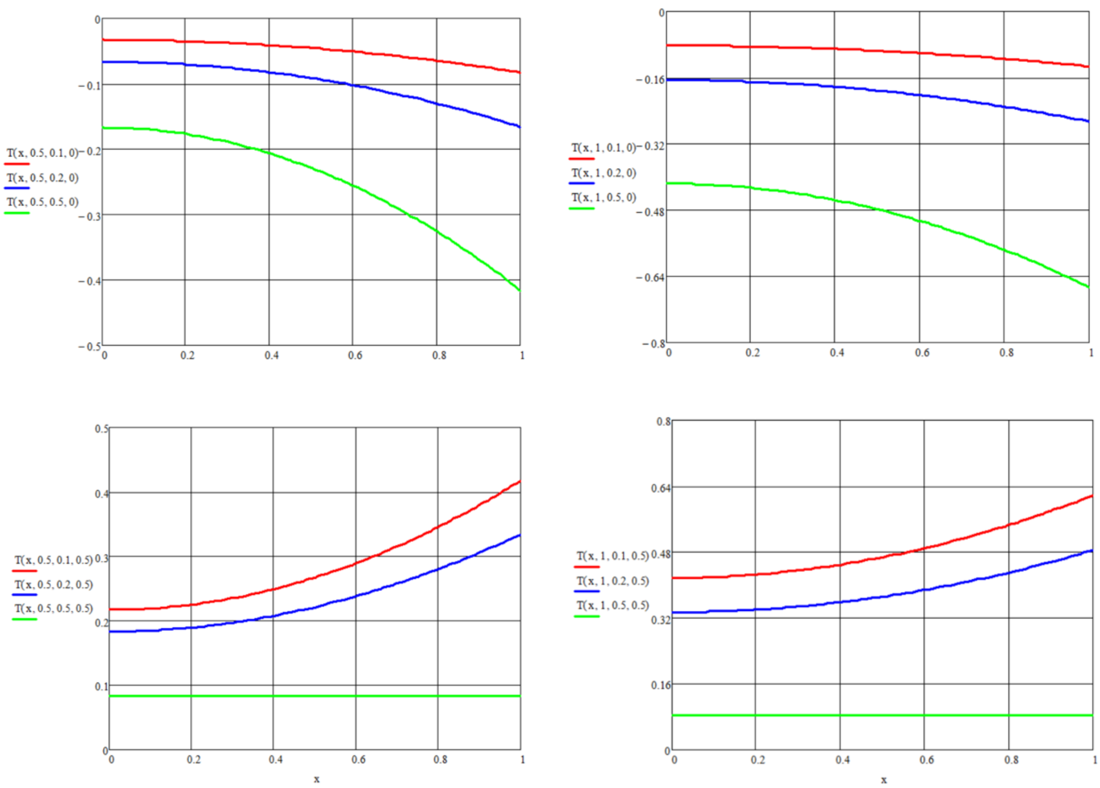

Fig. 2. Uniform initial distribution: a) T_o = 0, K_i = 0.1; 0.2; 0.5. F_o = 0.5; P_o =0; b) T_o = 0, K_i = 0.1; 0.2; 0.5. F_o = 1; P_o =0; c) T_o = 0, K_i = 0.1; 0.2; 0.5. F_o = 0.5; P_o =0.5; r) T_o = 0, K_i = 0.1; 0.2; 0.5. F_o = 1; P_o =0.5

The nature of temperature non-uniformity, which arises, for example, in pillars construction of a diameter of 2.0 m (surface modulus of 2.0 m^{-1}) may be explained by the data from Table 1, which show that the problem of concrete heating decrease in structures of this type arises at a medium temperature above 10 °C.

The current solution to the problem of reduction of concrete heating consists mainly in the timely prediction of maximum temperatures in specifically considered units or elements of a transport structure, since the performed researches allowed to identify modern modifiers, which provide reduction of concrete heating either by slowing down the hydration process at a certain stage of its hardening, or by using super plasticizers or organo-mineral complexes, which provide the possibility of essential reduction of the concrete heating. On top of this, calorimetric measurements of the heat release of concrete have shown that the reduction in the heating of concrete is directly proportional to the reduction in the cement consumption in it.

In order to illustrate the effect of introduction of organomineral additives into the concrete composition, Fig. 3 shows the change of temperatures in the process of its hardening during the thermophysical calculation of the foundation slab of a residential building with a thickness of 1500 mm and the foundation slab of the air terminal building with a thickness of 1400 mm. In the first instance, the concrete class was assumed to be B40 and a complex modifier such as "*Embelit"* was used in the selection of concrete mix composition; and in the second instance, when the design class of concrete was B35, only traditional super plasticizer and air-entraining agent were used in its composition.

Results and discussion

Comparison of the presented data shows that during construction of the foundation slab with the use of concrete based on the modifier "Embelit 8-100" the maximum heating as a result of exothermic processes occurring during the hardening of cement in the core of the foundation slab is 9...14 °C lower than in similar situation with the use of traditional composition concrete, even despite the higher class of concrete and greater thickness of the structure under consideration (Fig. 4).

The second important impact of the temperature factor for provision of marketable properties of concrete is associated with conditions of formation of its own thermal stress state, which is determined by the specifics of the impact on the structural formation of the matrix and by temperature increase in the volume of the structure during its hardening, depending on external and internal heat and mass exchange processes occurring in the concrete structure.

The emergence of thermal stressed state of concrete is explained by the fact that due to the process of uneven distribution of temperature gradient over the maximum cross-section of the concreted structure, its individual elements (as a rule, ribs and faces) undergo significant deformations. Under the conditions of the ongoing concrete hardening process, despite the fact that he observed difference in strain magnitude is recorded, the strain changes are not clearly demonstrated. This ultimately leads to formation and separation of residual (intrinsic temperature) stresses, which in certain conditions are the main cause of intensive and uncontrolled cracking.

Prof. V.S. Lukyanov (Lukyanov and Denisov, 1970) in the old days experimentally proved that the

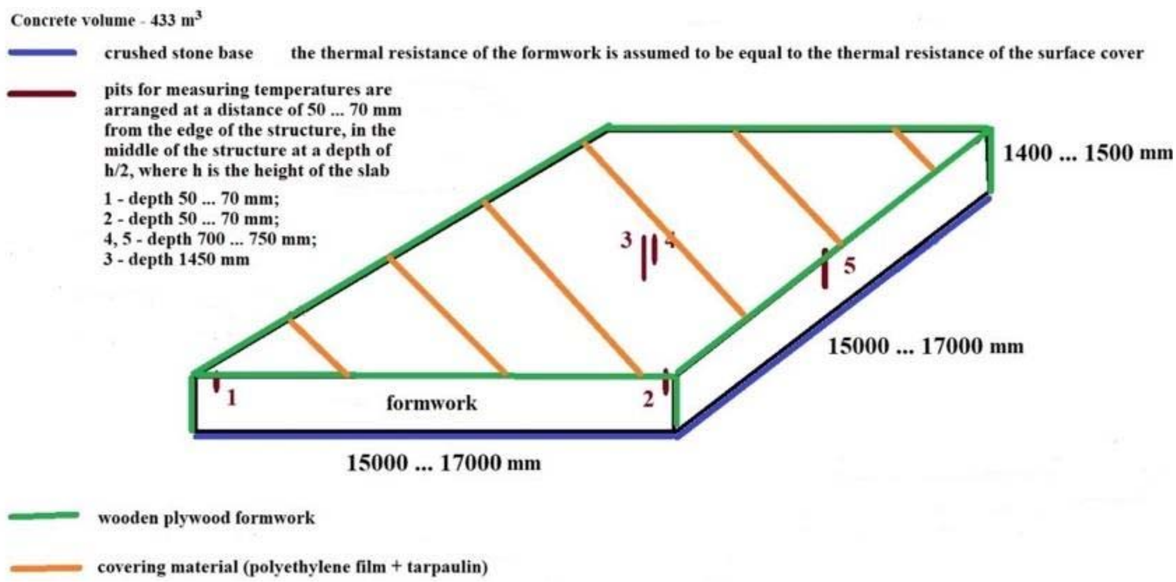

Fig. 3. Schematic diagram of the foundation slab

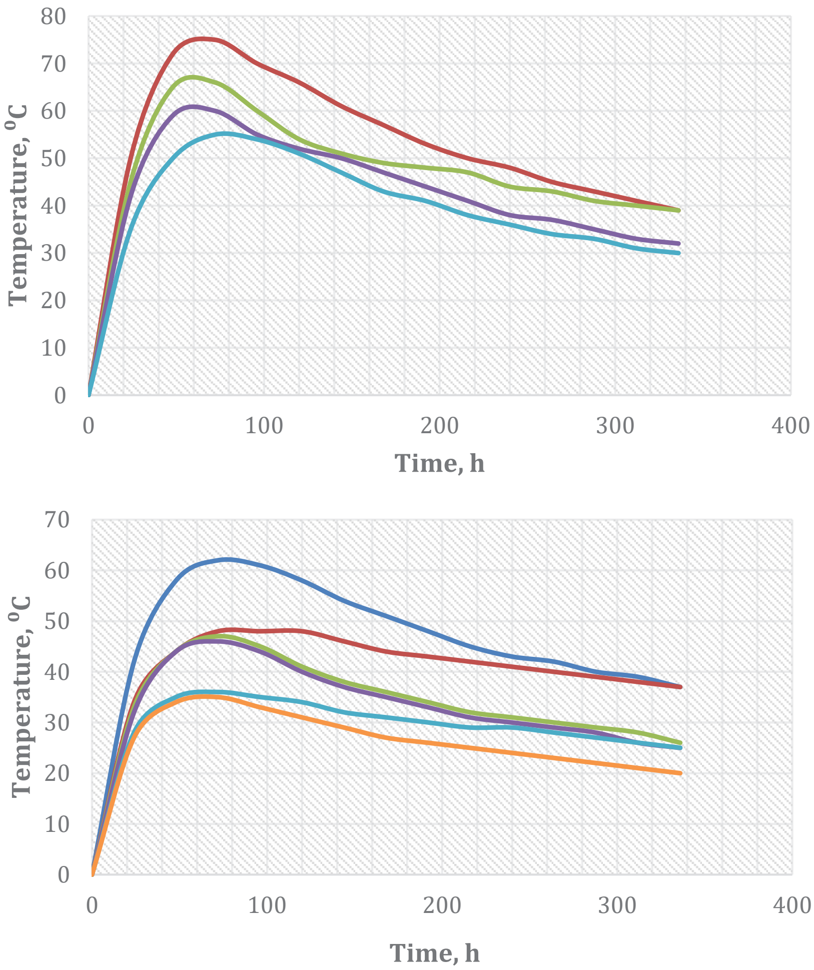

Fig. 4. Graphs of temperature gradient in concrete hardening during construction of foundation slabs with the use of different types of concrete: a) 1400 mm thick (concrete class B35, without special modifiers); b) 1500 mm thick (concrete class B40, with *"Embelit 8-100"* modifier).

intrinsic temperature macro stresses in a concreted structure should be considered at the moment of temperature gradient equalization in its entire mass and under the condition of absence of external mechanical effects and phenomena of uneven shrinkage throughout the thickness during this period of time. Prof. V.S. Lukyanov proposed and later justified the hypothesis, according to which the nature and magnitude of the effect of intrinsic temperature stresses has a direct dependence on the formed temperature gradient across the cross-section of the concrete structure, while at this point in the structure such stresses are completely absent. This temperature distribution is called the temperature field (or more often - temperature curve) of zero stresses. A diverse understanding of the nature of emergence of thermal stress state under the direct impact of the temperature factor on the concrete structure, conducted by Prof. A.R. Solovyanchik (Lukyanov and Solovyanchik, 1972), showed that the time of formation of the temperature curve of zero stresses corresponds to the time of transition of primary unstable structures from hydrosulfoalumoferritic and hydroalumoferritic new formations into secondary stable ones from calcium hydrosilicates in zones of the structure with the greatest lag in temperature. At this time, the strength of concrete is in the range of 25...30 % of R_{28} (Solovyanchik et al., 1994).

Estimation of the concrete's own thermal stress state is made by the calculated temperature difference between the most and the least heated zones of the structure, which is calculated by reduction of the temperature difference at the most unfavorable temperature distribution over the cross-section of the structure by the temperature difference at the moment of formation of the temperature curve of zero stresses. An example of such estimation can be traced on the characteristics of concrete mixture hardening in the columns of channel piers of the bridge crossing over the Oka River, presented in Table 2.

The calculations of this structure, which has a surface modulus Mn = 0.95 m^{-1}, showed that at the consumption of cement per cubic metre of concrete mixture equal to 425 kg/m^3 in both winter and summer periods of the year during the placement

Table 2. **Values of concrete intrinsic thermal stress state during construction of bridge supports piers over the Oka River in Nizhny Novgorod Region**

Calculation parameters			Formwork design		Maximum heating temperature, °C		Temperature gradient, °C			Time of cooling down to acceptable temperature, day
Cement consumption, kg/m^3	$t_{concrete}$, °C	t_{aver}, °C	steel w/o heat insulation	steel with heat insulation	surface	core	at strength of 0.3 R_{28}	at the moment of maximum heating	design	
425	9	4	+	-	29	72	16	42	25	2,9
425	9	4	-	+	64	74	1	9	7	6,4
425	18	18	+	-	27	74	11	46	34	1.9
425	19	19	-	+	61	85	8	23	14	4.4
375	9	4	+	-	24	56	11	31	19	2.9
375	9	4	-	+	39	52	3	12	8	4.4
375	18	18	+	-	34	67	9	32	12	1.6
375	19	19	-	+	49	67	5	16	10	3.4

of concrete mixture in the formwork made of metal, the value of non-uniform temperature distribution in the concrete appeared to be the most dangerous, first of all, in terms of the probability of formation of temperature cracks in the structure, because the temperature difference exceeded 15 °C. Additional heat insulation of the formwork system makes it possible to provide the required temperature differences, which in this situation vary within 9...16 °C.

It is obvious that the achievement of a greater effect on reduction of the gradient of uneven heating of concrete in the process of its hardening in the construction of low-mass bridge piers is directly achieved with a systematic reduction in cement consumption from 425 to 375 kg/m^3 respectively. In this case, when concrete works are carried out in the hot period, the permissible temperature difference can be guaranteed without additional formwork insulation, including steel formwork.

The intrinsic thermal stress state of concrete has a direct impact on the quality and reliability not only of individual elements of the erected structure covered with concrete, but also on the specified properties of concurrently concrete-enveloped, diverse in mass and configuration elements, as well as on the force interaction of the considered element with the previously concrete-enveloped element. This interaction as a rule takes place at stage-by-stage construction of tunnels, bridges, other facilities, when at each subsequent stage of concreting the hardened concrete becomes "*restrained*" by the previously placed and hardened concrete, and this restraint, limiting the manifestation of free deformations of hardened concrete, leads to emergence of thermal stresses, the value of which forms the maximum allowable size of the concrete structure and, accordingly, the distance between the construction joints, at which it does not form defects and cracks.

The distance between construction joints is directly related to the permissible temperature difference in the mass of hardening concrete, as well as in the zone of restraint into the foundation, which, in the event of assessment of the intrinsic thermal stress state of concrete, occurs at the time when the concrete forms a secondary structure of calcium hydrosilicates, i.e. when the strength of hardening concrete in this zone is 25...30 % of the strength at the age of 28 days R_{28}.

The performed calculations have shown that if the temperature difference between the concrete placed in the formwork in the restrained zone and the foundation at the moment when the concrete has gained strength equal to 30 % of the strength R_{28}, not more than 20 °C, the acceptable length of the blocks to be covered with concrete shall not exceed 15–17 m. However, contrary to this, a proper thermophysical expertise of the emerging temperature conditions of concrete hardening is not provided during development of design documentation (MS), as a result of which the sizes of concrete blocks are often assigned arbitrarily, in relation to which through-temperature cracks with opening width up to 1.0 mm are inevitably formed in the erected structure at the commencement of active operations.

At present a number of thermal engineering methods have been developed, including by the authors, which help to carry out pouring of blocks restrained in the base up to 35 m long, and in the event of the possibility of partial concrete compression — up to 50 m long. The proposed methods were used for concreting of walls and slabs (with the length 30–35 m) of a number of tunnels in Moscow, which provided almost one and a half times reduction of the construction time of these facilities in critical segments of the schedule of concrete works.

The need to consider the probability of temperature cracks and develop appropriate measures to eliminate and minimize them often arises during simultaneous concreting of structures with elements of different massiveness, for example, during the construction of overpasses with slab-and-ribbed spans.

In structures of such type, there are significant variations during concrete heating, which, on the one hand, lead to formation of significant heterogeneity in its physical and mechanical characteristics, and on the other hand, require additional assessment of the interaction between intrinsic thermal stress states of the bearing rib and the slab part of the span structure.

In this situation, the problem of thermal stress reduction may be solved with the use of formwork systems and additional thermal and moisture protective coatings with variable thermal resistance of thermal insulation, the values of which are set by a special thermophysical calculation. Such approach ensures complete elimination of cracking during construction of overpasses with slab-on-ribbed spans, and it has been implemented at various transportation facilities.

In addition to the temperature factor, formation of structural properties of concrete is primarily impacted by the process of heat and mass transfer during its placement in the concrete structure being erected. One of the most important factors from this point of view is the process of moisture exchange between the exposed concrete surface and the environment. Underestimation of this process can lead to plastic shrinkage of concrete and, as a consequence, to irreversible process of moisture loss of the whole erected massif.

Thermal and humidity regime of the concrete of a structure during its construction plays an almost dominant role in formation of stresses arising in concrete and leading to its shrinkage and plastic deformations, as well as in the process of determination of physical and mechanical properties of the hardening concrete. These features have a direct impact on the periods of interruption in the overlay of concrete mixture layers, and this factor directly depends on many factors, one of which is the shape of the structure, its architectural design features, speed of placement of the concrete mixture into the formwork, guarantee of uninterrupted logistic flows, as well as variability of concrete and environmental temperatures, including the factor of solar radiation, also directly affecting the level of moisture loss. These factors shall be taken into consideration during approval of restrictive measures for construction works.

The conducted studies have allowed to establish that the period of direct environmental impact on the concrete surface in the process of its hardening should be regulated by the time period from the start of the concrete placement into the formwork until the moment when moisture loss by the end of the process of overlapping layers does not exceed for concrete class B30 — 10.5 % of the volume of mixing water and 10 % — for concrete class B40. The above remark is valid provided that the workability of the concrete mixture previously placed in the formwork system is not less than 2.5 cm of the Abrams standard cone settlement, and the time of joint vibro-compaction of two adjacent layers varies within the limits equal to 25...30 s. At the same time for the top - the final layer of concrete mixture to be placed in the formwork system, the allowable level of the moisture loss, at which the gain of the design strength of concrete is guaranteed with a security of 0.98, and there is no reduction in the grade of concrete frost resistance, is about 6.9 % of the volume of mixing water for concrete class B30 and 6.4 % — for concrete class B40.

The adopted limits on the permissible moisture loss boundaries allowed to outline the optimum period of environmental exposure on the poured concrete. The results are presented in Table 3.

The critical challenge related to the care and handling of fresh concrete by the time the formwork is completed and the exposed surface of the structure is finished can be divided into two key sub-challenges.

The first is the need for absolute elimination of further moisture loss from the concrete surface. Bearing this in mind, the hardening concrete maintenance period shall be calculated according to the time of critical strength gain relative to moisture loss in the surface layers of the placed concrete. The physical determination of the values of this parameter is recommended to be carried out on the concrete mixture compositions selected in advance in laboratory conditions and planned for use. If performance of such tests is unavailable, the above value should be taken as 75 % of the concrete strength at R_{28} age.

Implementation of the method described above shall be carried out by covering the exposed concrete surface of the structure under consideration with prepared polymeric materials, which are fixed on the concrete surface as appropriate.

The second sub-challenge is to ensure the required conditions for formation of temperature homogeneity across the cross-section of the erected structure. For its solution, it is sufficient to use various covering materials having a certain thermal resistance, the number of layers of which, including an additional layer of PE film protecting the covering material from getting wet, shall be determined in advance by a special thermo-physical calculation.

It should be noted that pooled data on methods of reduction of the degree of inhomogeneity of concrete temperatures in different massiveness of elements can only be indicative. Therefore, for each newly designed structure, it is necessary to carry out individual calculations on simulation models in search for options that ensure exclusion of formation of through-temperature cracks.

Table 3. **Regulated period of environmental exposure of the concrete surface when the structure is concreted in layers**

No	Concrete class	Concrete structure temperature, °C	Medium parameters			Regulated period of environment exposure, min	
			temperature, °C	mobility, m/s	radiation, W/m²	top layer	layer-by-layer laying
1	B30	14	9	-	-	115	146
2	B30	18	24	-	-	35	87
3	B30	19	25	1.0	-	22	24
4	B40	14	9	-	-	145	175
5	B40	19	24	-	-	37	62
6	B40	20	25	1.0	-	19	29
7	B40	21	26	1.0	300	21	31
8	B40	22	27	0	300	27	38

Conclusions

The described features of the impact of processes related to thermal physics on ensuring the necessary structural properties of transportation structures should be taken into consideration in the development of process regulations as part of Method Statements, which are an integral part of the industry quality management system in relation to transportation infrastructure facilities.

The primary goal of the developed rules for a particular construction facility is to determine and fix the conditions and techniques that ensure reduction of defects and cracks, including in conditions of discontinuity of technical processes, and with reference to compliance with the requirements to ensure performance of work at a fast pace.

It is important to note that the implementation of these techniques, depends on availability of research and technical support of the construction of transport infrastructure structures, the main purpose of which is to validate reliability of the decisions on the formation of the specified structural properties of concrete in practice with possibility of making operational adjustments to the decisions taken (if appropriate), with reference to thermophysical processes, which is directly evidenced by a sufficient degree of coincidence between the calculated and experimentally obtained data on the temperature difference of concrete during hardening at those facilities where this support was carried out, as well as absence of defects and cracks in structures for which the provisions of process regulations were perfectly observed.

References

Balyuchik, E. A. and Chernyi, K. D. (2010). Increasing crack resistance of monolithic concrete bridge supports by structural methods. *Collection of scientific papers of the Central Research Institute of Structural Engineering*, No. 257, pp. 49–57.

Balyuchik E.A., Velichko V.P., and Chernyi K.D. (2012). Manufacturing of facing blocks in winter period of bridge construction across the river Angara. *Transport construction,* No. 10, pp. 4-7.

Concu, G. and Trulli, N. (2018). Concrete defects sizing by means of ultrasonic velocity maps. *Buildings*, Vol. 8, Issue 12, pp. 176. DOI: 10.3390/buildings8120176.

Evlanov, S. F. (2002). Technological cracks on the surface of monolithic span structures. *Scientific works of JSC CRITC "Problems of standardization and research of consumer properties of bridges"*, No. 208, pp. 27-36.

Fedosov, S. V. (2010). Heat and mass transfer in technological processes of the construction industry: Monograph. Ivanovo: IPK "PressTo". p. 363.

Fedosov, S. V. (2024). Methods of the Theory of Heat Conduction in Applications to Problems of Modeling the Processes of Drying and Heat Treatment of Solid Materials: Monograph. Moscow, Vologda: Infra-Engineering. p.212.

Fedosov, S. V. and Mizonov, V. E. (2020). Fundamentals of the theory and mathematical modeling of mechanical and thermal processes in the production of building materials, Switzerland: Palmarium Academic Publishing. p. 256.

Ginzburg, A. V. (2014). Ensuring high quality and efficiency of the worksin the process of constructing the tunnels of in-situ concrete. *Vestnik MGSU,* No. 1, pp. 98–110.

Kollegger, J., Kromoser, B., and Suza, D. (2018). Erection of bridges and shells without formwork-challenges for the computational modeling. *Computational Modeling of Concrete Structure*, pp. 43-54.DOI: 10.1201/9781315182964-4.

Komandrovsky, A. F. (2003). Experience in constructing span structures from monolithic prestressed reinforced concrete. *Bulletin of Bridge Construction*, No. 3–4, pp. 24–29.

Kosmin, V. V. and Mozalev, S. V. (2014). Problems of research, design and construction of large-span bridges. *Bulletin of Bridge Construction*, No. 1, pp. 19–24.

Lukyanov, V. S. and Denisov, I. I. (1970). Calculation of thermoelastic deformations of massive concrete bridge supports for the development of measures to improve their crack resistance. *Collection of scientific papers of the Central Research Institute of Structural Engineering*, No. 36, pp. 4-43.

Lukyanov, V. S. and Solov'yanchik, A. R. (1972). Physical bases of forecasting proper thermal stress state of concrete and reinforced concrete structures. *Collection of scientific works of the Central Research Institute of Structural Engineering,* No. 73, pp. 36-42.

Passek, V. V., Zakovenko, V. V., Antonov, E. A., and Efremov, A. N. (2002). Application of artificial cooling in the process of temperature control of erected reinforced concrete arches. *Scientific works of JSC CRITC "From hydraulic integrator to modern computers"*. No. 213, pp. 73–75.

Prjakhin D.V. (2009). Investigation of stay cable span bridge structure work by physical modelling. *Transport construction,* No. 10, pp. 11–13.

Rudobashta S. P. (2015). Thermal Engineering. Moscow: "Pen". p. 672.

Sokolov, S. B. (2002). The influence of air temperature fluctuations in greenhouses on the temperature of hardening concrete during the construction of monolithic slab-ribbed span structures in the cold season. *Scientific works of JSC CRITC "From a hydraulic integrator to modern computers"*, No. 213, pp. 167-172.

Solov'yanchik, A. R., Shifrin, S. A., Ilyin, A. A., and Sokolov, S. B. (2006). Selection of technological parameters for the production of concrete works during the construction of massive grillages and supports of the arch pylon of the cable-stayed bridge across the Moskva River. *Scientific works of JSC CRITC "Research of transport structures"*. No. 230, pp. 24-30.

Solov'yanchik, A. R. and Shifrin, S. A. (2000). Management of thermally stressed state of monolithic reinforced concrete structures in high-speed year-round construction of transport facilities. *Scientific works of the Central Research Institute of Structural Engineering*, No. 203, pp. 25–32.

Solov'yanchik, A. R., Korotin, V. N., Shifrin, S. A., and Veitsman, S. G. (2002). Experience in reducing crack formation in concrete from temperature effects during the construction of the Gagarin Tunnel. *Bulletin of Bridge Construction*, No. 3-4, pp. 53-59.

Solovyanchik, A. R., Krylov, B. A., and Malinsky, E. N. (1994). Inherent thermal stress distributions in concrete structures and method for their control. Thermal Cracking in Concrete at Early Ages. *Proceedings of the International RILEM Symposium. Munich.* pp. 5.

Solov'yanchik, A. R., Shifrin, S. A., Korotin, V. N., and Veitsman, S. G. (2003). Implementation of the concept of "quality" in the construction of the Gagarin tunnel in Moscow. *Scientific works of JSC CRITC "Technologies and quality of erected structures from monolithic concrete"*, No. 217, pp. 206-212.

Solov'yanchik, A. R., Velichko, V. P., and Zorina, V. A. (1992). Development of a new methodology for studying the temperature regime, strength of hardening concrete and thermal stress state of transport structures using a PC. *Collection of scientific papers of the Central Research Institute*, No. 112, pp. 75–77.

Solov'yanchik, A. R., Velichko, V. P., and Zorina, V. A. (1989). Calculation of thermal and thermally stressed state of concrete and reinforced concrete structures with modified geometry during their manufacture. (ZA200). Collection of scientific papers of *CRITC*, No. 108, pp. 10–15.

Tarasov, A. M., Bobrov, F. Yu., and Pryakhin, D. V. (2007). Application of physical modeling in the construction of bridges and other structures. *Bulletin of Bridge Construction*, No. 1, pp. 21–26.

Usherov-Marshak, A. V. (2002). Calorimetry of cement and concrete. Kharkov: Selected works. p.180.

Vasiliev, A. I. and Veitsman, S. G. (2015). Modern trends and problems of domestic bridge construction. *Bulletin of Bridge Construction*, No. 1, pp. 2–17.

Velichko, V. P. (1987). Methodology of using hydraulic analogies of V. S. Lukyanov in developing an algorithm and solving transport construction problems on a computer. *Collection of scientific papers of the Central Research Institute of Structural Engineering*, No. 100, pp. 15–22.

Velichko V.D. and Chernyi K.D. (2013). Consideration of stress-strain state in precast monolithic bridge pillars at its construction. *Transport construction,* No. 2, pp. 11–13.

Xu, G., He, C., Lu, D., and Wang, S. (2019). The influence of longitudinal crack on mechanical behavior of shield tunnel lining in soft-hard composite strata. *Thin-Walled Structures*, Vol. 144, pp. 106282. DOI: 10.1016/j.tws.2019.106282.

Zvorykin, A., Mahdi, M., Popov, R., Barati, F. K., and Pioro, I. (2017). Heat transfer to supercritical water (liquid-like state) flowing in a short vertical bare tube with upward flow. *International Conference on Nuclear Engineering. London, England: Proceedings, ICONE 9*. pp. 14. DOI: 10.1115/ ICONE26-81608.

ТЕПЛОФИЗИЧЕСКИЕ ПРОЦЕССЫ В ТВЕРДЕЮЩЕМ БЕТОНЕ КАК ФАКТОР ОБЕСПЕЧЕНИЯ КАЧЕСТВА ВОЗВОДИМЫХ ЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ ТРАНСПОРТНЫХ ОБЪЕКТОВ

Сергей Федосов[1], Иван Пуляев[2]*, Ольга Александрова[1], Надежда Чередниченко[3], Евгения Дербасова[2], Юлия Лежнина[4]

[1]Национальный исследовательский Московский государственный строительный университет, г. Москва, Россия
[2]Московский политехнический университет, г. Москва, Россия
[3]Российский университет транспорта (МИИТ), г. Москва, Россия
[4]МИРЭА – Российский технологический университет (РТУ МИРЭА), г. Москва, Россия

*E-mail: ivanes50@mail.ru

Аннотация
Введение. В настоящей статье рассмотрены основные вопросы обеспечения конструкционных свойств бетона в зависимости от воздействия на него температурного фактора и тепломассобменных процессов в контакте с окружающей средой при строительстве транспортных объектов, возводимых из монолитного железобетона при различных начальных и граничных условиях. **Цель исследования:** обеспечение качества предпроектных исследований железобетонных конструкций, включающих натурное моделирование рассматриваемых теплофизических процессов в твердеющем бетоне, в том числе с использованием современных расчётно-аналитических комплексов. **Методы.** Применение специального программного комплекса для расчета изменения температур и прочности твердеющего бетона, оценки влияния температурного фактора на обеспечение свойств бетона: морозостойкости, водонепроницаемости, прочности и трещиностойкости. **Результаты.** Показано, что учёт термонапряженного состояния твердеющего бетона позволяет гарантированно обеспечить требуемые эксплуатационные свойства конструкций: качество, надежность, долговечность, в том числе в части недопущения появления температурных и усадочных трещин, как одних из самых распространенных в настоящее время в транспортном строительстве дефектов, снижающих качество возводимой поверхности. Описанные в настоящей статье исследования были неоднократно апробированы на транспортных объектах России в Москве, Санкт-Петербурге, на Кубани и в Крыму, других областях и нашли широкий отклик в транспортной индустрии. Статья будет интересна и полезна лицам, интересующимся процессами обеспечения бездефектного бетонирования разномассивных конструкций транспортных объектов, а также инженерно-техническим работникам, занятым в реальном секторе строительства.

Ключевые слова: бетон; температурные напряжения; теплофизические процессы; трещиностойкость; модуль поверхности конструкции.