Methods of construction of objects taking into account the simulation of the temperature regime of hardening concrete

I S Pulyaev* and S M Pulyaev
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

E-mail: ivanes50@mail.ru

Abstract. The article is devoted to the use of different methods of construction of the object, depending on the boundary conditions set in the process of its design and construction. The aim of this work is a compilation of the various methods of investigation of the temperature regime of hardening concrete, aimed at providing the required timing of the turnover of a formwork, with a view to ensuring the consumer properties of the structures. The scientific novelty of the work lies in the updating and testing of methods for regulating the heating of hardening concrete, ensuring the formation of the required consumer properties of structures not previously used in transport and civil construction, based on preliminary modeling of thermal processes occurring in the hardening concrete, through the calculation software. The use of modern calculation and analytical complex allowed to obtain the results as accurately as possible comparable with the observations obtained during construction, which allowed to develop projects for the production of works on concreting objects erected in different conditions, with the necessary consumer properties.

1. Introduction

It is known that the physical modeling of the concrete hardening process allows to optimize the technology of construction production, to prevent unwanted defects and cracks caused by unaccounted critical temperature drop, as well as to increase the economic feasibility of the work associated with the projected turnover of the formwork and reduce the cost of repairs if necessary [1,2,3]. However, it is not enough to take into account only the experience and knowledge that are associated exclusively with various technologies of construction production and the use of which is applicable for unified class facilities [4]. Often in the construction of complex and unique structures it is necessary to take into account factors that directly relate to the internal structure of concrete as a material and assess its condition over time throughout the manufacturing process – from the preparation of the concrete mixture to the concrete set the required strength. Practice shows that the underestimation of these factors often leads to an increase in the construction time, reduce the economic feasibility and, as a consequence, the rise in the cost of construction of the entire facility, as well as to unjustified costs for repair and restoration work in the case of defects and cracks [5,6,7,8]. The purpose of this work is to summarize the experience of using different methods of studying the temperature regime of hardening concrete, which are aimed at meeting the necessary terms of turnover of formwork and technological equipment, in terms of ensuring the quality of the erected structures in year-round construction, and testing of these methods, not previously used in transport and civil construction, allows us to talk.
about the mutual possibility of their application for different types of objects without reference to a specific classification. The article shows that the use of certain technological methods in combination with the theory of its own thermally stressed state of concrete can provide the required consumer properties of the entire structure, taking into account the specified conditions and construction technology, compliance with a certain rate of construction of the object, using as a basis of the process under consideration the use of physical modeling of technological processes occurring in the hardening concrete in time.

2. Methods
The study of the temperature regime of hardening concrete in conditions of artificial cooling through the use of water, taking into account the complex initial boundary causes some difficulties, and in some cases it is impossible [9]. This issue is particularly acute in transport construction, where the most common large-scale objects, the construction of which is carried out in difficult climatic conditions, in a confined area and in a short time [10]. In particular, the chosen technology of construction of a bridge across the Oka river in Murom using adjustable formwork could be justified and effective only in the case of pipe cooling of the lower tiers of the upper parts of the pylons with water. To simulate the draft tube cooling of hardening concrete by water was only possible on the basis of determining the results of the study of the heat transfer occurring in the tubes of water with the surrounding hardened concrete.

In hydraulic engineering at the time, similar problems were solved using approximate methods of calculation, which, however, gave significant errors [11]. In addition, in the construction of massive hydraulic dams are used at most low-grade concrete with low heat, and high-quality concrete – the most common in transport construction - do not apply. As a result, the use of nomograms, developed at the time for water cooling of low-grade concretes when used in modern real conditions of transport construction of high-class concretes was simply impossible. The application of the method of direct modeling of technological processes of cooling concrete with water using the theory of similarity, partially based on the method of hydraulic analogies, developed by Professor V. Lukyanov and improved Professor A. Solovyanchik. Helped to solve mathematical difficulties to a certain extent. This method has been successfully used to calculate the pipe cooling of hardening concrete dams of hydroelectric power plants, showed a sufficiently high efficiency and validity [12].

To date, the method of hydraulic analogies is practically not used, but on its basis, a calculation program has been developed, which with a sufficiently high accuracy allows to solve the problems of Thermophysics of hardening concrete in one-dimensional, two-dimensional and three-dimensional formulations with given boundary conditions. This software package is based on the algorithm of numerical solution of boundary value problems proposed by V. Velichko [13,14], the flexibility of which is achieved through the use of special technological methods, which are a further development of the method of hydraulic analogies, previously developed by Professor V. Lukyanov. However, when setting the task, the authors of the article needed to make certain changes and additions to the program [15], which are as close as possible to the real ones, and take into account changes in time that occur with the hardening concrete depending on the temperature of the outside air, the environment and the temperature of its laying in the formwork.

It is known that in the construction of hydraulic structures, artificial cooling pipes in the concrete array are laid in horizontal rows of coils. In the construction of the bridge under consideration, such a method proved to be ineffective, and in this regard, it was decided to vertically arrange the pipes in a corridor or staggered order. In this case, the concrete array was divided into finite trace elements, each of which consisted of a conditionally accepted concrete block in the form of a rectangular or hexagonal prism with a cooling pipe passing in the center. Schematic illustration of a concrete mass with a water cooling system of pipes is shown in figure 1.
It follows from the similarity theory that the thermophysical calculation of the temperature regime of hardening concrete in a rectangular field when using artificial water cooling can be carried out by solving the problem for a certain cylinder with a radius $R_n$, where $R_n$ is the radius of the cylinder under consideration, transformed from a rectangular prism figure. The radius of the cylinder is determined from the condition of equality of the cross-sectional areas of the prism and the cylinder.

When the pipe-line order

$$ R = \frac{\sqrt{BH}}{\pi} , $$

where $B$ and $H$ are the specified distance between the installed pipes in the block in the horizontal and vertical directions, respectively.

Accounting for changes in temperature and the processes occurring in the cylinder can be divided into two tasks: the definition of heat transfer in the plane of the cross section of the cylinder and the definition of the temperature process along the length of the pipe in question. Assuming that the heat exchange in the concrete along the pipe is practically absent, and the change in the temperature of the cooler in this section is slow enough in view of the given rate of its supply, it is permissible to assume that the pattern of temperature distribution in the cross-sectional plane and its average value for the first flat problem can be expressed through the initial temperature of the concrete to cooling, the temperature of the cooler (water) and the adiabatic rise in the temperature of the concrete from the exothermy of the cement. In the construction of the object in question in the calculations considered the flat problem of cooling the cylinder with a given radius $R$. At the first stage it was assumed that the radius $R = 0.56$ m (at a distance between the pipes is about 1 m). At the same time, a number of assumptions were made in the process of solving the problem, including:

- the value of the surface temperature of the tubes was taken to be equal to the value of the temperature of the refrigerant in the pipe, and was constant in time;
- the initial temperature of the concrete was the same throughout the section and the upper surface of the design cylinder was in adiabatic conditions.

Taking into account the above parameters, the differential equation and the boundary conditions characterizing the process of temperature change in the design cylinder will be as follows:

$$ \frac{\partial T}{\partial \tau} = a \left[ \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right] + E_c - B $$

Initial and boundary conditions:

$$ \begin{align*}
\text{when } \tau = 0 & \quad \text{for } r_0 \leq r \leq R \quad T = t_c; \\
\text{for } r < r_0 & \quad T = t_w; \\
\text{for } r = R & \quad \frac{\partial T}{\partial x} = 0.
\end{align*} $$
where $r$ - is the distance from the center of the cylinder, m;
$r_0$ – radius of the installed pipe, m;
$R$ – radius of the design cylinder, m;
$T$ – the desired temperature at a certain point, °C;
$t_w$ – temperature of the cooler (water), °C;
$t_c$ – initial temperature of the laid concrete, °C.

When carrying out calculations for the centers of elementary layers, their centers of gravity were taken, the definition of which was carried out according to the following formula:

$$ r_{n+1} = r_{n-1} + \xi, $$

where $\xi = l \cdot \frac{3r_{n+1} + 2l}{6r_{n-1} + 3l}$ – the distance of the center of gravity of the calculated layer from its inner surface, m.

$$ l = r_n - r_{n-1}, $$

where $r_n$ – the radius of the outer surface of the layer, m;
$r_{n-1}$ – the radius of the inner surface of the layer, m.

The thermal resistance $R$ between adjacent layers was determined by the following formula:

$$ R = \frac{1}{n} \frac{\lambda}{r_{(n)} - r_{(n-1)}}, $$

where $\lambda$ – coefficient of thermal conductivity of concrete, W/(m·°C);
$r_{(n)}$, $r_{(n-1)}$ – radii of surfaces passing through the center of gravity of an arbitrary $n$-th layer and the adjacent layer $n-1$, m.

With this breakdown of the temperature field, the heat capacity of the elementary layers is concentrated in cylindrical surfaces passing through the centers of gravity of these layers, the value of which is determined by the formula:

$$ C_n = C_c \gamma_c \cdot \frac{r_n^2 - r_{n-1}^2}{2}, $$

where $C_c$ - is the specific heat capacity of concrete;
$\gamma_c$ – average concrete density, kg/m$^3$;
$r_n$ – radius of the outer surface of the layer $n$, m;
$r_{n-1}$ – the radius of the inner surface of the layer $n$, m.

Now let’s consider an example of modeling of technological processes occurring in the hardening concrete, associated with the holding of concrete in certain climatic conditions, for example, during winter concreting. This problem is widely consecrated in various sources [16,17], including in the writings of B. Krasnovsky [18], but the technology of construction of structures made of monolithic reinforced concrete, taking into account the re-preservation of the object, in which the concrete is laid on the previously erected structure, taking into account the given pace of construction, is not sufficiently consecrated. Such technology, in particular, was applied at construction of Academy of judo in the Moscow region Zvenigorod where in the conditions of the accelerated rates of construction of object the decision to apply at work in winter conditions heating of concrete for designs of walls and partitions by means of thermal generators, and for overlappings was made – with the use of a combined method, including the provision of the required temperature regime of the air in the room under the ceiling with the help of thermal generators and electric heating of the concrete floor using heating wires in the presence of thermal insulation with thermal resistance $R=1,15m^2\cdot°C/W$ on the upper surface of the floor.

Separately, it is worth noting the factor that often in the construction of large industrial and civil facilities requires the operational use of various methods associated with the use of modern technological methods aimed at ensuring the specified properties of reinforced concrete structures based on the conditions of construction of an object [19]. Such an example is the development by the
authors of measures for the heat treatment and aging of concrete in the manufacture of beams of self-compacting concrete mixture in the city of Rostov-on-Don under different climatic conditions without additional heating and heating in the cold season, recommendations for the management of heating concrete, the creation of automatic control and quality control. This work was carried out on the basis of the condition that the concrete work was carried out in landfill conditions and by modeling the processes in the application of non-heating concrete aging in the warm season and the development of modes of electric heating of concrete, and the required rate of production of beams with the rational use of electricity was provided.

The application of the above measures without physical modeling of the processes occurring in the hardening concrete would be incomplete, and often impossible. And, unfortunately, in the design and construction of a large number of facilities currently being built in our country, this factor is not always taken into account. And experience shows [20,21] that for the correct assessment of the processes occurring in the hardening concrete, it is necessary to make it by means of application of the modern settlement and analytical complexes allowing to trace in real time the processes occurring in the hardening concrete.

3. Results
Several series of calculations were carried out to study the temperature process in the cooled cylinder during the calculation of water-tube cooling. The following technological parameters were set:
- concrete temperature (initial) - 10°C ... 20°C;
- water temperature (cooled) - 5°C ... 20°C;
- the radii R of the cylinders (calculated) is equal to 0.56 ... 0.8 m;
- the radius of the tube \( r_0 = 12.5 \text{ mm} \) (with the subsequent change on \( r_0=20 \text{ mm} \)).

Thermal properties of concrete: heat conductivity of \( \lambda=2.1 \text{ W/m·°C} \); heat capacity \( C_c=0.96 \text{ kJ/kg·°C} \); the average density \( \gamma_c=2600 \text{ kg/m}^3 \). The consumption of cement is 400 kg/m\(^3\). The scheme of water cooling of hardening concrete, adopted during the calculations, at a distance between the pipes of 1 m is shown in figure 2.

![Figure 2](image)

Figure 2. Design scheme for cooling the hardening concrete around the pipe at a distance of 1 m between the pipes with a pipe diameter of 25 mm

In the process, the authors conducted several series of thermal calculations, which changed the speed of water movement in the pipes and the distance between them. Calculations have shown that at a water speed of 0.6 m/s in pipes in the summer period of the year, the required turnaround time of the formwork is not provided, and only at a temperature of the concrete mixture of 15°C, at a water speed of 1 m/s and a coolant temperature of 20°C, heated from the exothermy of cement, the concrete is cooled to 40°C, at which it is allowed to decompress the structure, for 10 .. 12 days, that is the time that provides the required construction time of the object. Studies have shown that the distances between the pipes should be assigned taking into account the massiveness of the structural elements.

To determine the timing of the aging of concrete by using thermal generators and using the heating wires were also produced by the thermal calculations of hardening concrete by means of a program.
complex "ZA 200". For example, when calculating the parapet with a section of 300x1000 mm (figure 3), the structural element was divided into elementary blocks, after which the program considered the thermal interaction between these blocks and the environment. As a result of the calculations, graphs of the temperature and strength of the hardening concrete were constructed, one of which is shown in figure 4. According to these graphs, it is easy to determine the holding time of concrete to achieve the required strength.

Prior to commencement of works has also been produced by thermal calculations of the temperature regime of hardening concrete for the conditions of heating using the heating wires, which allowed us to determine how the maximum temperature of heating of the concrete and the timing of its aging to set the desired strength.

At the same time, at the stage of preparation of computational models in the software package "ZA 200" the authors have made some adjustments to the physical modeling associated with the task of the initial boundary conditions. Thus, the initial temperature of the concrete mixture laid in the structure was taken from the calculation

\[ t_c = t_{c,m} - (t_{c,m} - t_o)0.01 \tau_{mp} \]

where \( t_c \) – the initial temperature of the concrete mixture laid in the structure, °C;
\( t_{c,m} \) – the temperature of the concrete mixture released from the concrete mixing unit, °C;
\( t_o \) – outside air temperature, °C.

Was separate computational models were developed as a direct warm-up slabs and slabs with beams. The model of the last element is shown in figure 5, and one of the calculation results is shown in figure 6.
Special attention during concreting of structural elements of floors, columns and crossbars was paid to concrete holding. It turned out that when holding concrete floors and crossbars laid concrete in the warm period of the year should be covered with a thermal barrier coating with thermal resistance $R = 0.30 ... 0.50 \text{ m}^2 \cdot ^\circ \text{C} / \text{W}$ (moisture-proof film layer, covering material layer thickness 3 ... 5 mm, moisture-proof film layer).

When concreting the floor heating wires were installed on the reinforcement in proportion to the thickness of the protective layer of concrete from the top and from the bottom surfaces of the floors of the structure. The approximate scheme of electric heating of overlapping of Academy of judo by the heating wires is given in drawing 7.

**Figure 5.** Calculation scheme of the floor plate of the bolt when concreting with electrical heating up of wires with a pitch of 200 mm

**Figure 6.** Graphs of temperature change (a) and strength of hardening concrete crossbar

4. Conclusion
On the basis of the conducted researches technological regulations on production of preparatory, shuttering, reinforcing and concrete works, and also specifications on the device of pipe cooling of the
hardening concrete of pylons water on which working drawings, and the device and connection of heating wires in concrete during winter concreting were developed.

To cool the water, it was decided to use steel pipes with an internal diameter of \( d = 40 \text{ mm} \), which were installed vertically. When cooling the lower tiers of the upper parts of the pylons, the pipes were installed at a distance of not more than 1 m from each other. When cooling the lower—less massive tiers of the upper parts of the pylons—the pipes were installed at a distance of 1 ... 1.2 m apart. In particular, the layout of the cooling pipes on one of the pylon grips is shown in figure 8. Water in the pipes was supplied from the river by a pump through the registers, and removed from the pipes through the registers. Pipes were connected from below in pairs with the device of rounding in order to avoid formation of sharp corners. Horizontally located at the bottom of the tier of the pipe were at a distance of no more than 0.3 ... 0.5 m from the surface of the previously concreted tier. The pipes were securely fastened to prevent their sliding in the process of laying the concrete mixture. It should be noted that the fundamental differences in the order of concreting the structure using water-tube cooling from the usual conduct of concrete works, as well as additional requirements, except as described above, are not provided. The discharge of water from the registers back into the river was arranged in such a way that the water when removed from the cooling system did not fall on the previously concreted tiers of the upper parts of the pylons and the lower part of the pylon. We should also say about the requirements for pumps for water supply. The power of the pump for the water cooling system was selected taking into account the total water consumption during the construction of the gripper with the maximum volume of laid concrete. The speed of water flow through the pipes when the cooling system was 0.6 ... 0.9 m/s. The volume of water supplied for each capture was determined taking into account the total cross-section of vertically installed pipes on the capture and the accepted minimum speed of water movement in the pipes. The pumps provided the possibility of their continuous operation for 15 days (with possible interruptions in operation according to the requirements of the technological regulations for the production of concrete works).

![Figure 8](image_url)  
**Figure 8.** Schematic diagram of the installation of water cooling pipes of the lower tiers of the upper parts of the pylon

The project was implemented, in particular, during the construction of a bridge across the Oka river in the city of Murom in compliance with the required terms of turnover of formwork and concreted structures had no defects and cracks. As a result of this work it was found that for the purpose of simulation of the hardening process of concrete, its dissipation, and timing of strength development to ensure accelerated modes of erection of the pylons and reduce the time of turnover of a formwork is possible to apply various methods, including tube cooling of hardening concrete by water.

A physical modeling of the process of heating concrete with the help of heat generators and heating wires and the practice of its use in the construction of the Academy of judo allowed to significantly reduce the need for electricity, reduce the construction time of the facility and get ready-made structural elements of high quality.
It is also shown that in relation to the out-of-class structures for each structural element it is possible to establish an individual approach to the process of concreting by means of rational physical modeling of thermal processes occurring in the hardening concrete structures, using different methods of studying the temperature regime of the hardening concrete, depending on the boundary conditions specified in the design and construction of the object, which together have a significant impact on the guarantee of obtaining the required consumer properties of the entire construction.

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