Design of reinforced concrete structures in the early stages of construction taking into account heat dissipation of concrete

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Abstract. Foundation slabs and other massive reinforced concrete structures in the process of their construction experience temperature effects as a result of heat release during concrete hardening. In combination with variable environmental conditions there is an uneven distribution of temperatures in the massive structures thickness, which can cause cracks in the process of concrete strengthening. The heat of concrete is mainly influenced by several factors: the cement specific content, type of cement, water-cement ratio etc. Numerical methods provide the most complete way to estimate thermally stressed state of structures. This paper suggests method of 3-D temperature field calculation for temperature regime estimation of the most typical cast in place reinforced concrete structures (foundation slabs). The influence of sample size, ambient temperature and thermal insulation parameters of the samples outer faces was studied. The program for the ANSYS is developed, which allows estimating the temperature regime of reinforced concrete structures at the early stages of concrete hardening.

1. Introduction
Currently, a construction of high-rise buildings and large-scale engineering structures like dams, bridge structures, etc. is a global trend. A volume of concrete which is poured at the same time in these structures is often thousands or thousands dozens of cubic meters. With this volume of concrete there is a significant release of heat during its hardening, which leads to an uneven distribution of temperatures in the thickness of massive structures in combination with variable environmental conditions, and therefore to a thermal stresses state appearance, a cracks formation, and initial stresses in reinforcement.

Numerical methods provide the most complete way to estimate thermally stressed state of structures. Usually it includes the use of computer software systems that implement the finite element method (FEA-analysis). Licensed software (ANSYS, COSMOS, ABACUS, etc.) and also free programs (Calculix) may be used these calculations. Some researchers solve this problem with a simplified thermo elastic question [1-3], and the influence of the hardening temperature on the heat release of concrete is not taken into account in the vast majority of methods used in practical calculations at the present time [3, 4], and the deformation parameters influence of concrete is also not taken into account [5-7].

Numerical modeling and real structures observations show that structures with the smallest size exceeding 1.5-1.8 m can be considered as massive structures from the point of view of the temperature influence on the structure stress state. A foundation slab of considerable thickness is the most characteristic element of this type.
The main factors affecting the concrete heat release while hardening are the following:

- a specific content of cement in concrete mix;
- a type of cement (the slag-portland cement has a smaller heat release, approximately for 15% per unit mass of cement than portland cement);
- an initial temperature of a concrete mixture (reducing of a concrete mixture initial temperature is an effective method to reduce the concrete heat release per unit time);
- a specific cement surface area (fineness of cement);
- water-cement ratio (at relatively low temperatures (20-40°C) a higher water-cement ratio leads to an increase of a heat release rate, at high temperatures (60-80°C), in contrast, a lower water-cement ratio leads to an increase of a heat release rate;
- an accelerating agents or hardening retarders presence in a concrete.

2. Stages of heat release
The concrete heat release happens due to hydration reactions in hardening concrete and it is customary to divide heat release kinetics into several stages (Figure 1).

![Figure 1. The concrete heat release rate to time relation.](image)

2.1. Stage 1. The initial hydrolysis
This stage lasts for 15-30 minutes after an addition of water to a concrete mix and is characterized by a fairly rapid increase of a concrete mixture temperature by several degrees. Thus, the concrete mixture temperature will be several degrees higher than the temperature of mixture initial components at the end of this stage. From the point of construction works view in construction site conditions, the heat release of this stage is not taken into account if the concrete initial temperature is taken at the end of this stage (for example, when obtaining concrete at the construction site).

2.2. Stage 2. Induction period
This stage lasts about 4 hours after the addition of water to a concrete mix and is characterized by low heat release. During this period, the mixture has essential workability. At this stage the temperature is almost unchanged (in the absence of heat loss to the environment).

2.3. Stage 3. Accelerated hydration
At this stage there is an accelerated flow of hydration and, accordingly, heat release and hardening. This stage continues approximately until 12 hours after the addition of water to a concrete mix.
2.4. Stage 4. Period of slowdown
This stage continues until about 4 days after the addition of water to a concrete mix. During this period of time the heat release and strength gain rate is gradually reduced.

2.5. Stage 5. The slow strength gain period
During this stage, there is a relatively slow heat release and strength gain. The given above time parameters can significantly vary from the temperature of the concrete and the agents presence slowing or accelerating the cement hydration process.

3. Methods of heat release modelling and assessment
Real heat release curves are approximated by various mathematical functions for calculations performance convenience and implementation in software. In particular, the function proposed by I. D. Zaporozhets is adopted in Russian Federation:

\[ Q = Q_{\text{max}} \left[ 1 - \left( A_T \tau \right)^{\frac{1}{m-1}} \right] \]  \hspace{1cm} (1)

where \( Q_{\text{max}} \) is total heat dissipation of concrete; \( A_T \) is the coefficient characterizing the heat release rate at temperature \( t \); \( m \) is an order of the hydration reaction; \( \tau \) is time elapsed since the addition of water to a concrete mix.

The parameters \( Q_{\text{max}}, A_T, \) and \( m \) can be determined by approximate empirical function (see below) and must be corrected by testing concretes of the production composition.

It should be taken into account that the function (1), proposed by I. D. Zaporozhets, the concrete heat release at the age of more than 3 days is quite well described, but this function application for heat release determine in early stages of hydration (less than 3 days) should be done with great caution. The form of the curve obtained by the I. D. Zaporozhets equation (1) is shown in Figure 2.

![Figure 2](image-url)

Figure 2. General view of the heat release function gained by the Zaporozhets’s equation.

Concretes currently used are modified to a large extent in order to give them additional predefined positive properties: increased strength at a lower consumption of cement, high water resistance, hardening accelerating or decelerating, etc. At the same time, these admixtures to the concrete make it almost impossible to determine a theoretical heat dissipation of the concrete only by cement chemical compound. The chemical composition of admixtures and their action mechanism are now often hidden by manufacturers for commercial reasons.
The mentioned factors lead to the conclusion that the assessment of concrete heat release should be made only of the production concrete composition, i.e. of the same composite, which will be used in the real structure. The most accurate assessment of the concrete heat release can be made in a laboratory using adiabatic calorimeters. This device allows drawing an accurate function curve of the concrete heat release in time. A significant disadvantage of adiabatic calorimeters is their relative rarity in construction laboratories.

Currently, assessment of heat release of production concrete composition is commonly made on trial samples without adiabatic calorimeters. In this case, trial samples should meet following requirements:

- The sample should be of significant size so that the internal heat dissipation would be much greater than the heat loss through the outer surface. On some construction sites, samples were made in the cube form with an edge of up to 3 meters.
- The specific surface area of the sample (the ratio of the external surface area to the sample volume) should be minimal, but since the production of samples in the ball form is technically difficult to implement, it is recommended to use samples in a cube form.
- The outer surface of the cube should be covered with effective heat insulation. The used insulation should not be hygroscopic, and also should have a minimum heat capacity itself. In accordance with the experiments, the ideal insulation for these purposes is polystyrene foam.

Heat transfer coefficients into the external environment should be estimated with sufficient accuracy, it’s a room, where the test sample is located (preferably positive) temperature should be at a constant, the sample itself should be protected from wind.

Numerous samples of production composition concrete were tested by specialists from Ural Federal University in the period from 2010 to 2018. The most numerous studies were conducted for the concreting massive structures purpose of the Central stadium in Yekaterinburg. In parallel, a program for the ANSYS software was developed to assess the temperature regime of reinforced concrete structures. The basis of the program is the theoretical formula by Zaporozhets, which was refined on the basis of the samples tests results and real structures studies. The developed program allows more precise evaluating of the temperature regime of reinforced concrete structures at the early hardening stages.

4. Conclusion
One of the most important results of full-scale experiments, numerical calculations and measurements of the parameters of full-scale structures is the evaluation of the optimal parameters of trial samples, which provide sufficient accuracy of measurements for further design of real structures. Also these test helped to evaluate following parameters:

- the minimum dimensions of the sample must correspond to a cube with an edge of 1m;
- the formwork of the test sample can be made of waterproof plywood;
- the inner surface of the formwork (including the bottom and the cover) should be covered with a layer of polystyrene foam with a thickness of 200 mm.

Also, specialists from the Institute of Civil Engineering and Architecture of UrFU developed a method of selection of the necessary parameters of heat release taking into account the actual temperature in the sample and the calculated heat loss through the outer surfaces of the insulated sample. The obtained data are used in the design of massive structures. The measurements carried out on real structures show a significant correspondence of experimental and calculated data both on the temperature inside the structure (within 2-5°C) and on the hardening period, in which the maximum temperature of the structure is set (within 3-7 hours).

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