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Thermal cracking resistance in massive foundation slabs in the building period

Термическая трещиностойкость массивных фундаментных плит в строительный период

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Ключевые слова: модуль деформации; массивные бетонные и железобетонные конструкции; термонапряженное состояние; термическая трещиностойкость; температура твердения

Abstract. The article deals with the research of the thermal cracking resistance of massive concrete and reinforced foundation slabs of buildings and structures in the building period. The article examines the results of the analysis of the thermal stress state of a massive foundation slab with a fixed thickness of thermal insulation as well as the results of changing the minimum thickness of the insulation on a surface, providing the cracking resistance of the structures on different plate heights, with and without taking into account the hardening temperature influence on the concrete modulus of the deformation. The article authors determined that the solution of the problem of definition the thermal stress state of the massive foundation slab in the building period without the hardening temperature influence on the modulus of deformation may cause a significant distortion of the real diagram of the thermal stresses and elongation deformations in the structures body. It was indicated that the calculation error essentially depends on the height of the foundation slab. Additionally it was established that in case the slab height exceeds 1.25 m the problem should be solved in a strict setting, which would allow to minimize the insulation layer.

Аннотация. Работа посвящена исследованию термической трещиностойкости массивных бетонных и железобетонных фундаментных плит зданий и сооружений в строительный период. В статье рассматриваются результаты анализа термонапряженного состояния массивной фундаментной плиты при фиксированной толщине теплоизоляции, а также результаты изменения минимальных толщин поверхностной теплоизоляции, обеспечивающих трещиностойкость конструкции, при различных высотах плиты с учетом влияния температуры твердения смеси на модуль деформации бетона и без данного учета. Авторами установлено, что решение задачи определения термонапряженного состояния массивных фундаментных плит в строительный период без учета влияния температуры твердения бетона на модуль деформации может привести к существенному искажению действительных эпюр распределения термонапряжений и деформаций удлинения в теле конструкции. Показано, что погрешность в расчетах существенно зависит от высоты фундаментной плиты. Также определено, что при высотах плит, превышающих 1,25 м, расчеты необходимо проводить только в строгой постановке задачи, что приводит к существенной экономии необходимой специальной теплоизоляции.

Introduction

In general practice the calculation of thermal fields is often based on the heat equation solution as well as thermal stresses definition [1–7], linked with calculation of cracking resistance massive of concrete in construction period. A change in the thermal state of such structures occurs due to the heat

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liberation from cement hydration during the concrete hardening process, as well as outside temperature fluctuations, solar exposure, various technological factors, etc. [8–13]. Emerging thermal stresses may cause damage to the structural integrity [14–20].

Due to a number of technological and manufacturing reasons, it is preferable to concrete massive foundation mats and other massive structures as a single block of equal height. However, it causes a considerable heat rise in the mass concrete as the result of an exothermic reaction during the concrete hardening. Consequently, the irregular temperature distribution arises along with the block height, which leads to the dangerous tensile strain first on the surface of the foundation slab and then in its central zones [21–29].

Deal with a problem of cracking it applied a complex of technological measures (the heat enclosure, a peripheral electric heating, cooling of concrete mix, tubing cooling of concrete etc.). However, before setting the optimal complex of measures it necessary to calculate the thermal stressed state of construction in a strict definition of the problem. Such a formulation presupposes taking into account the hardening temperature influence on thermophysical [30] and deformation characteristics of concrete.

The modulus of deformation is important characteristic of concrete, which has a significant running value in the building period. Many researches explored the modulus of deformation [31–37].

Modulus of elasticity is part of many static calculations and has close relation to other physical and mechanical characteristics of concrete as are creeping, shrinking, frost resistance etc. Final value of the modulus of elasticity of concrete depends on many influences [37], for example concrete aggregate [35–36]. One of the most important factors influencing the modulus of elasticity is the ambient temperature during concrete setting and hardening [31–34].

Nowadays in practice of calculating the thermal stressed state of the building period used function [17]:

$$E(t) = E_{max}\left(1 - e^{\alpha t^{\gamma}}\right) \tag{1}$$

where E_{max} – is the limit value of deformation of concrete, setting by rules;

α, γ – are functional dependency parameters;

t – current time.

The paper [31] deal that modulus of deformation significant depend on temperature of hardening. There is also suggested to take into account the dependency of «reduced time» hypothesis, which a real time replaced on reduced time a function of hardening temperature. The temperature function is of the form:

$$f_T = 2^{\frac{(T_1 - T_2)}{\varepsilon}} \tag{2}$$

where *ε* – is the characteristic temperature difference.

For the foregoing reasons, estimation of hardening temperature influence on modulus of concrete deformation in calculating the thermal cracking resistance of massive reinforced concrete structured in the building period is the vital task. Since the solution of the problem of definition the thermal stress state of the massive foundation slab in the building period without the hardening temperature influence on the modulus of deformation may cause a significant distortion of the real diagram of the thermal stresses.

The purpose of article is estimation of hardening temperature influence on modulus of concrete deformation in calculating the thermal cracking resistance of massive reinforced concrete structured in the building period and calculated validity of the necessity of such accounting.

As initial data (thermophysical and stress-related characteristics of concrete, cement heat radiation) the results or research, obtained in laboratory “Polytech-SKiM-Test” in CUBS department by professor Barabanschikov Y.G. were accepted.

Methods and Materials

This paper demonstrates calculation of the foundation mat thermal stressed state with the help of TERM software developed by the Institute of Civil Engineering at the Peter the Great St.Petersburg Polytechnic University [18]. This software calculates nonstationary fields of temperature and thermal stresses in slabs. An essential feature of the TERM software is the consideration of temperature influence on thermophysical and stress-related concrete characteristics.

Considering horizontal mats sizes significantly exceed their height, we can study a one-dimensional structural model for the mat central part with the reasonable degree of accuracy. In this model, stress and temperature are functions of the vertical coordinate space [38].

In order to estimate the cracking resistance of the foundation mat, we would use the deformation criterion suggested by P.I. Vasiliev [21]. According to this criterion, concrete elongation deformations, determined in view of the concrete creep factor and variable deformation modulus, should not exceed the ultimate concrete elongation.

The article examines the results of the analysis of the thermal stress state of a massive foundation slab with a fixed thickness of thermal insulation as well as the results of changing the minimum thickness of the insulation on a surface, providing the cracking resistance of the structures on different plate heights, with and without taking into account the hardening temperature influence on the concrete modulus of the deformation.

Consider B35 foundation slab 2 m high with the cement consumption of 340 kg/m^3 constructed in summer. The foundation slab is supported by the concrete bedding layer B12.5 with the grade foundation.

Thermal and physical characteristics of the concrete B35 are defined by the concrete thermal conductivity $\boldsymbol{\lambda}$ = 2.67 W/(m·^{0}C) and thermal capacity c = 1.0 kJ/(kg·^{0}C). For modulus of concrete deformation E_{max} = 34500 Мпа, α = –0.37, γ = 0.72 [17].

Concrete creep account according to straight line inherited theory of aging using the relaxation function:

$$R(t,\tau) = A\left(1 - e^{-\beta\tau^{\alpha}}\right) + \left(B_1 + D_1 e^{-\beta\tau^{\alpha}}\right)e^{-\gamma_1(t-\tau)} + \left(B_2 + D_2 e^{-\beta\tau^{\alpha}}\right)e^{-\gamma_2(t-\tau)} \quad (3)$$

Where functional dependency parameters are as follows: A = 0.7; B_1 = 0.2; D_1 = 0.4; B_2 = 0.1; D_2 = 0.3; α = 0.67; β = 3.61×10^{-6} c^{-1}; γ_1 = 1.17×10^{-5} c^{-1}; γ_2 = 2.33×10^{-7} c^{-1}.

The heat dissipation process follows the I.D. Zaporozhets equation [16].

$$Q_T(\tau) = Q_{max}\left\{1 - \left[1 + A_{20}\int_0^t F_Q[T(\tau)d\tau]\right]\right\}^{-\frac{1}{m-1}} \quad (4)$$

The equation parameters I.D. Zaporozhets gets from experimental evidence on concrete heat dissipation [20] Q_{max} = 157500 kJ/m^3, A_{20}=4.1×10^{-6} c^{-1}.

The following technological specifications of concrete pouring were taken into account: inside the heat enclosure, the concrete mix is poured as a single 2.0 m high block with the concrete mix temperature is 20 ^{0}C and air temperature is 20 ^{0}C. After concreting the surface is covered with insulation, which thickness is determined by the cracking prevention condition.

Results

Evaluation of thermal stressed state with a fixed thickness of thermal insulation

Calculations of this paragraph provide for the same thickness of thermal insulation layer for the case with influence of hardening temperature on modulus of concrete deformation and without such influence. Figure 1 shows graphs of variation in time the thermal stresses in the control points of the base slab without the special insolation. Solid line is the thermal stresses determined with the influence of temperature of hardening on modulus of deformation. Dash line is the thermal stresses without of such influence.

Analyze of a result show us:

1. Character of changing the thermal stresses with time is the same in cases with and without temperature influence on modulus of deformation;
2. The maximum stresses without taking into account the influence of temperature on the modulus deformation for exothermal heating moment (3 days) is: tensile on the surface of the slab is 2.25 MPa, compressive in the center of the slab is 0.86 MPa;
3. Similarly, in the case with taking into account the influence of temperature: tensile stresses on the surface is 3.41 MPa, compressive in the center is 1.38 MPa;

In such a way, problem solution in the simple definition leads to decrease of tensile stresses on the surface to 1.16 MPa (or to 34 %), but compressive tensile to 0.52 MPa (or to 38 %).

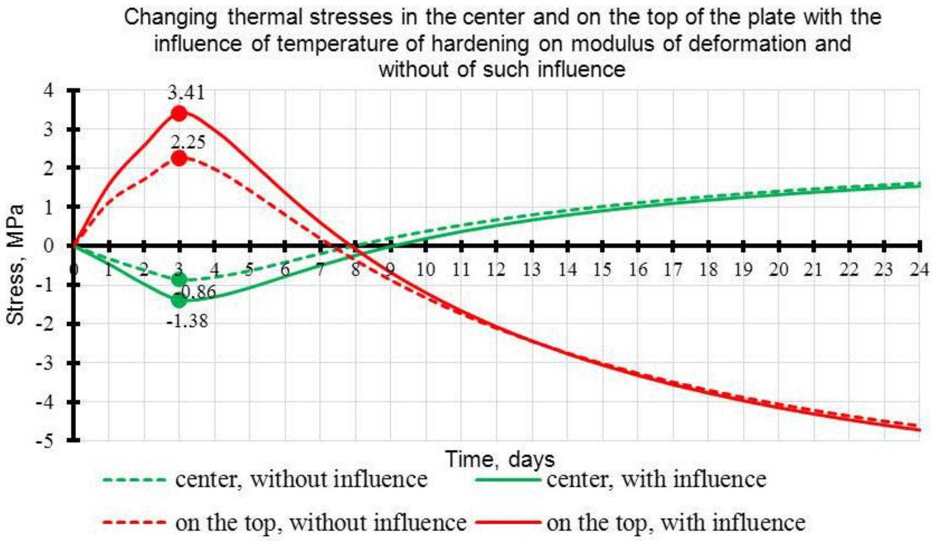

Figure 1. Graph of changing thermal stresses in the center and on the upper surface of the slab (solid line with the influence of temperature of hardening, dash line without of such influence)

With a special heat insulation on the surface of the foundation slab the relative elongation deformations changed not so obviously (Fig. 2). Deformations calculated with the hardening temperature influence on the modulus become less than deformation determined without such influence. If a thickness of insulation layer is 4.7 cm than such reducing is 3.9×10^{-4} (or 8 %). This is effect because relative deformations calculate as stresses divided by modulus of deformation. Using of the heat insulation reduce the temperature difference “center-surface of the slab” and accordingly the stresses themselves. Reducing of numerator (that is stresses) equally for methods with taking into account temperature influence and without that. At the same if we use the hypothesis of “reduced time” than denominator (modulus of deformation) increase in a greater degree.

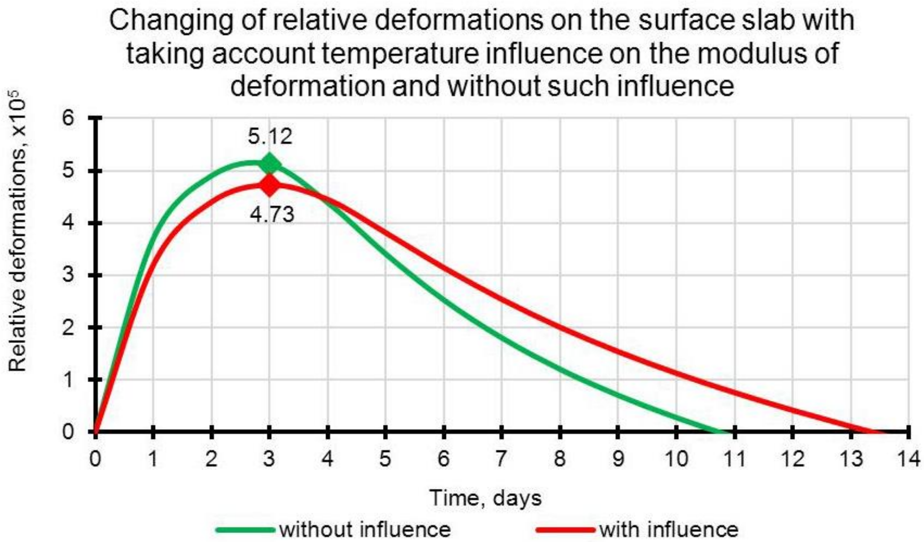

Figure 2. Dependency graph of relative deformations on the surface slab by time with taking account temperature influence on the modulus of deformation and without such influence (thickness of heat insulation 4.7 cm)

Selection of the required insulation thickness

Calculation is performed for the thermal insulation of foam polystyrene density 40 kg/m^3, with a coefficient of heat conductivity: λ = 0.030 W/m×°C. In this part of the work for more information thicknesses of the foundation slabs varied in the range from 1.0 to 2.5 m at a pitch of 0.5 m. Figure 3 shows graphs of the minimum safe (in terms of cracking) surface insulation thicknesses depending on the thickness of the foundation slab.

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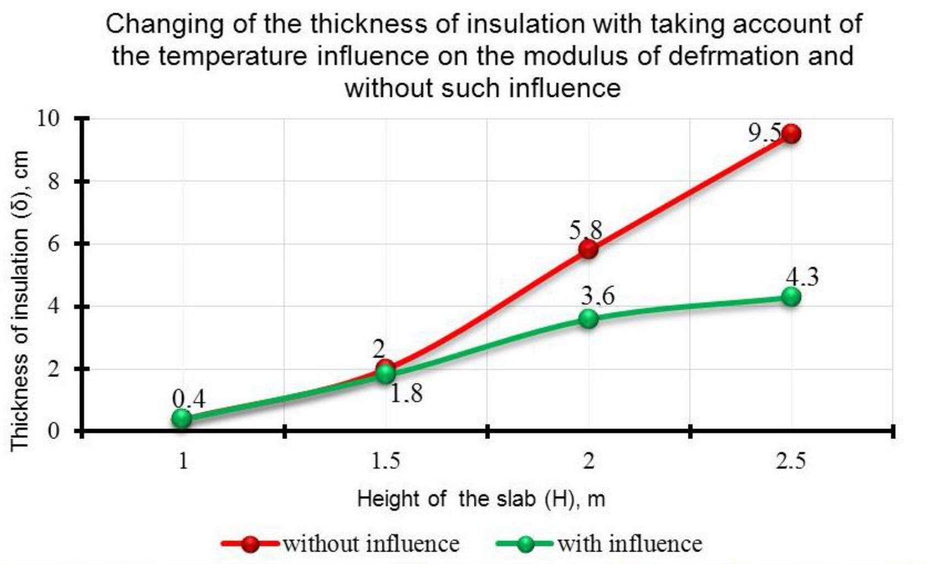

Figure 3. Graph of changing the required thickness of insulation on the surface of the slab

Analyze of a results show us:

1. At low heights of the foundation slab (1.0–1.25 m) the effect of the hardening temperatures on the thickness safety insulation layer is not significant, solve the problem in a simplified variant will cause an error not exceeding the accuracy of the base line (5 %);
2. For the thickness of the slabs from 1.5 m the effect of hardening temperature becomes very significant: so for a foundation slab thickness of 2.0 m not taking into account the hardening temperature influence leads to an overestimation of the necessary thickness of thermal insulation by 2.2 cm (or by 38 %) and for a foundation slab thickness of 2.5 m by 5.2 cm (or 55 %).

Discussion

According to the work [31–37] the elastic modulus is not a constant, in fact, it can reach very different values in concrete of the same strength class. It is thus important to have knowledge of aspects, which have the greatest influence on it. According to studies, the solution of the problem of definition the thermal stress state of the massive foundation slab in the building period without the hardening temperature influence on the modulus of deformation may cause a significant distortion of the real diagram of the thermal stresses and elongation deformations in the structures body. Thereby one of the most important factors influencing the modulus of elasticity is the hardening temperature during concrete setting and hardening [31–34].

Conclusion

The results of the conducted experiments allow us to make following conclusions:

1. Solving the problem of thermal stressed state of the massive foundation slabs in the building period without taking into account the influence of concrete hardening temperature on the modulus of deformation may cause to significant deviation of the real diagram of the thermal stresses and elongation deformations in the structures body;
2. The calculation error significant depends on the heights of the foundation slab. At the heights from 1 to 1.5 m calculations of thermal cracking resistance can make in the simple definition without taking into account the influence of the hardening temperature on the modulus of deformation. At heights of slabs large 1.5 m calculations must be carried out only in the strict definition of problem;
3. Calculation of thermal cracking resistance of foundation slab with taking into account the influence of hardening temperature on the modulus of concrete deformation leads to (for the slabs higher than 1.5 m) significant economy of the special required heat insolation. Volume of economy depends on thickness of the foundation slab because for a slab of 2.0 m height it is 38 %.

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