

## OPTIMIZATION OF CONCRETE CURING CONDITIONS IN MASSIVE MONOLITHIC FOUNDATION SLABS

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**Abstract:** The problem of controlling temperature stresses and preventing early cracking in massive monolithic foundation slabs at the stage of their hardening is considered. Existing methods often fail to account for the lag in concrete strength growth relative to the development of temperature gradients, which can lead to dangerous tensile stresses. The objective of the study is to develop a method for optimizing curing conditions aimed at minimizing tensile stress to strength ratio as an objective function. The method is based on combined numerical modeling of heat transfer and stress-strain problems, taking into account the kinetics of heat generation and concrete strength gain. The variable parameters were a coefficient determining the kinetics of concrete heat generation and the heat transfer coefficient from the upper surface of the slab. The interior point method, pattern search and particle swarm optimization were used to solve the optimization problem. Calculation results for various slab thicknesses and climatic conditions showed that to minimize the risk of cracking, it is necessary to reduce the heat transfer coefficient on the upper surface of the slab to 2.5–4.7 W/(m<sup>2</sup> °C), and to use normal- and rapid-hardening concrete rather than slow-hardening concrete. This is explained by the lag in tensile strength growth behind the development of temperature differences in slow-hardening concrete. Optimization reduced tensile stress levels by 2.2–3.3 times compared to standard conditions, making it possible to concretize slabs up to 3 m thick without the use of artificial cooling systems.

**Keywords:** massive foundation slabs, early cracking, thermal stresses, curing optimization, concrete heat release kinetics, heat transfer, particle swarm method, rapid-hardening concrete, thermal insulation

## ОПТИМИЗАЦИЯ УСЛОВИЙ ТВЕРДЕНИЯ БЕТОНА В МАССИВНЫХ МОНОЛИТНЫХ ФУНДАМЕНТНЫХ ПЛИТАХ

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**Аннотация:** Рассматривается проблема контроля температурных напряжений и предотвращения раннего трещинообразования массивных монолитных фундаментных плит на стадии их возведения. Существующие методы часто не учитывают запаздывание в росте прочности бетона относительно развития температурных градиентов, что может привести к опасным уровням растягивающих напряжений. Целью исследования является разработка метода оптимизации условий твердения, направленного на минимизацию отношения растягивающего напряжения к прочности на растяжение в качестве целевой функции. Метод основан на комбинированном численном моделировании задач теплопередачи и напряженно-деформированного состояния задач, учитывающем кинетику тепловыделения и прироста прочности бетона. Переменными параметрами являлись коэффициент, определяющий кинетику тепловыделения бетона, и коэффициент теплопередачи с верхней поверхности плиты. Для решения задачи оптимизации использовались метод внутренней точки, метод шаблонного поиска и метод роя частиц. Результаты расчетов для различной толщины плит и климатических условий показали, что для минимизации риска раннего трещинообразования необходимо снизить коэффициент теплопередачи на верхней поверхности плиты до 2,5–4,7 Вт/(м<sup>2</sup>·°С) и использовать бетон нормального и быстрого твердения вместо медленно твердеющего бетона. Это объясняется задержкой в росте прочности на растяжение по сравнению с развитием температурных перепадов в медленно твердеющем бетоне. В результате оптимизации уровни растягивающих напряжений снижены в 2,2–3,3 раза по сравнению со стандартными условиями, что позволяет бетонировать плиты толщиной до 3 м без использования систем искусственного охлаждения.

**Ключевые слова:** массивные фундаментные плиты, раннее трещинообразование, температурные напряжения, оптимизация твердения, кинетика тепловыделения бетона, теплоотдача, метод роя частиц, быстротвердеющий бетон, теплоизоляция

## INTRODUCTION

The problem of monitoring thermal stresses in massive concrete and reinforced concrete structures during their construction is a pressing issue in global construction practice [1-3]. When constructing high-rise buildings and structures, as well as multi-story buildings, foundation slabs at least 1 m thick are used, which fall into the category of massive structures, necessitating an assessment of the risk of early cracking and the development of measures to prevent it [4-6].

Traditionally, the use of slow-hardening concrete is recommended to reduce the risk of early cracking, which reduces peak temperature differences [7-11]. However, this approach often fails to account for the lag in the growth of strength properties relative to the development of temperature gradients, which can lead to dangerous levels of tensile stress.

In recent years, considerable attention has been devoted to methods of numerical modeling of thermal and stress fields in massive structures [12-14]. Studies [15-18] demonstrate the effectiveness of using surface thermal insulation for temperature control. However, most studies are limited to analyzing temperature fields without comprehensively considering the kinetics of strength gain and the development of concrete's mechanical properties.

Modern approaches to optimizing curing conditions are based on the combined solution of heat transfer and deformation mechanics problems using numerical optimization methods. Simplified models for assessing the stress-strain state of foundation slabs have been proposed in [19-21]. However, the targeted selection of concrete parameters and heat transfer conditions to minimize tensile stresses remains understudied. In particular, there are no methods for simultaneously optimizing the kinetics of concrete heat release and the intensity of surface heat transfer, taking into account various climatic conditions and geometric parameters of structures.

A literature review revealed a lack of comprehensive methods for optimizing the curing

conditions of massive foundation slabs, aimed at minimizing tensile stress as an objective function. Existing recommendations for the use of slow-hardening concrete do not take into account the effect of delayed strength characteristics on stress, which can lead to suboptimal design solutions. Therefore, developing a method for determining optimal heat generation and heat transfer kinetics from the slab's upper surface for various concreting conditions is a pressing scientific and practical challenge. The results of this study will enable informed selection of concrete compositions and thermal insulation parameters that minimize the risk of cracking.

The purpose of the work is to develop a methodology for optimizing the conditions of concrete hardening in massive monolithic foundation slabs, aimed at minimizing the risk of early cracking by reducing the level of tensile stresses in the initial period of hardening.

Within the framework of the set goal, the following tasks were solved:

1. To develop a calculation model describing the combined influence of the kinetics of heat generation in concrete and heat exchange conditions on the formation of temperature fields and the stress-strain state in massive monolithic foundation slabs.
2. To define the optimization objective function and select the variable parameters.
3. To conduct a series of calculations for various slab sizes and climatic conditions using nonlinear optimization methods (interior point method, pattern search method, particle swarm method).
4. To analyze the obtained optimal parameter values, evaluate the effectiveness of various optimization methods and the influence of initial conditions on the result.
5. To formulate practical recommendations for the selection of concrete and optimal heat transfer parameters to reduce tensile stresses in massive foundation slabs without the use of artificial cooling systems.

**METHODS**

The maximum level of tensile stresses was adopted as the objective function when solving the problem of determining the optimal conditions for concrete hardening in massive monolithic foundation slabs:

$$f = \frac{\sigma}{R_t} \rightarrow \min , \tag{1}$$

where  $\sigma$  is the tensile stress,  $R_t$  is the current tensile strength of concrete.

The determination of the maximum level of tensile stresses was carried out using a simplified method given in [19]. In the first stage, the temperature field was calculated in a one-dimensional formulation using the equation:

$$\lambda \frac{\partial^2 T}{\partial z^2} + W = \rho c \frac{\partial T}{\partial t}, \tag{2}$$

where  $\lambda$  is the thermal conductivity coefficient of the material,  $T$  is the temperature,  $W = \frac{\partial Q}{\partial t}$  is the power of internal heat sources for 1 m<sup>3</sup> of concrete,  $\rho$  is the density,  $c$  is the specific heat capacity.

The temperature field was calculated using the finite element method in conjunction with a soil massif whose thickness was assumed to be constant and equal to 3 m. The values of the thermophysical characteristics of the soil and concrete adopted in the calculation are presented in Table 1.

*Table 1. Thermophysical characteristics of soil and concrete*

	Density $\rho$ , kg/m <sup>3</sup>	Specific heat capacity $c$ , J/(kg·°C)	Thermal conductivity coefficient $\lambda$ , W/(m·°C)
Soil	1600	1875	1.50
Concrete	2400	1000	2.67

On the upper surface, boundary conditions of the third kind were adopted (convective heat exchange with the environment):

$$\lambda \frac{\partial T}{\partial z} + h_{up} (T - T_\infty) = 0, \tag{3}$$

where  $T_\infty$  is the ambient temperature,  $h_{up}$  is the heat transfer coefficient on the upper surface.

At the lower surface of the soil massif, boundary conditions of the first kind were adopted (the temperature is constant and equal to  $T_{bot}$ ). The heat release function of concrete was taken as [22]:

$$Q(t) = Q_{28} \cdot \exp \left[ k \cdot \left( 1 - \left( \frac{28}{t} \right)^x \right) \right], \tag{4}$$

where  $t$  is the time in days,  $Q_{28}$  is the amount of heat released during the first 28 days of hardening (MJ/m<sup>3</sup>), the coefficients  $k$  and  $x$  depend on the rate of hardening of the concrete.

When calculating temperature stresses, the dependence of the mechanical characteristics of concrete on the equivalent age  $t_{eq}$  was taken into account. The equivalent age was calculated by the formula:

$$t_{eq} = \frac{1}{T_{ref}} \int_0^t T(\tau) d\tau, \tag{5}$$

where  $T_{ref} = 20^\circ C$  is the temperature corresponding to normal conditions,  $T(\tau)$  is the temperature at an arbitrary point of the foundation slab at age  $\tau$ .

The function of change in cubic strength under compression was taken as [23]:

$$R = R_{28} \exp \left( s \left( 1 - \sqrt{28 / t_{eq}} \right) \right), \tag{6}$$

where  $t_{eq}$  is the equivalent age of concrete in days,  $R_{28}$  is the compressive strength at the age

of 28 days (when hardening under normal conditions),  $s$  is a coefficient depending on the kinetics of concrete hardening.

Table 2 presents the values of the coefficients  $k$ ,  $x$  and  $s$  according to data [24].

*Table 2. Values of coefficients  $k$ ,  $x$ ,  $s$  according to data [24]*

Classification of concrete according to EN 206.1				
	Rapid hardening	Normally hardening	Slow hardening	Very slow hardening
$k$	$\leq 0.15$	0.16-0.2	0.21-0.24	$> 0.24$
$x$	$\leq 0.45$	0.46-0.51	0.52-0.62	$> 0.62$
$s$	$< 0.25$	0.25-0.43	0.43-0.7	$\geq 0.7$

This table shows a tendency towards an increase in the coefficient  $s$  together with the coefficient  $k$ . The same applies to the coefficient  $x$ . Therefore, the coefficient  $k$  was chosen as the first variable parameter determining the kinetics of heat release of concrete, and the coefficients  $x$  and  $s$  were expressed through the coefficient  $k$  using approximating formulas:

$$\begin{aligned} x &= 17.2 \cdot k^2 - 4.83 \cdot k + 0.787; \\ s &= 4.94 \cdot k - 0.512. \end{aligned} \tag{7}$$

The modulus of elasticity of concrete at equivalent age  $t_{eq}$  was determined as a function of its compressive strength based on the formula [25]:

$$E = 22265 \cdot \left(\frac{R}{10}\right)^{0.28}. \tag{8}$$

Until the equivalent age of 12 hours, it was considered that concrete was not yet a solid body capable of withstanding stress, and the modulus of elasticity was taken to be zero.

Tensile strength, like the modulus of elasticity, was taken as a function of compressive strength [26]:

$$R_t = 0.29R^{0.6}. \tag{9}$$

The calculations were performed at  $R_{28} = 37$  MPa, Poisson's ratio of concrete  $\nu = 0.2$ , coefficient of linear thermal expansion  $\alpha = 10^{-5} 1/^\circ C$ . The value  $Q_{28}$  was taken as constant and equal to  $130 \text{ MJ/m}^3$ .

The second optimized variable was the parameter  $h_{up}$ . In the calculation program, up to the age of 12 hours, the heat transfer coefficient on the upper surface was assumed to be  $23 \text{ W/(m}^2 \cdot ^\circ C)$ , as for an uncovered surface. Subsequently, the heat transfer coefficient was assigned the value  $h_{up}$ .

The search for the minimum of the objective function  $f(k, h_{up})$  was implemented in the MATLAB R2021b environment using three built-in nonlinear optimization methods:

1. Interior point method.
2. Pattern search method.
3. Particle swarm method.

The parameters of the optimization algorithms in MATLAB were set to default values. The values  $k = 0.18$  and  $h_{up} = 23 \text{ W/(m}^2 \cdot ^\circ C)$  were chosen as the starting point for the search, which corresponds to normally hardening concrete and standard heat transfer for external walls, roofs, and ceilings according to Russian design codes SR 23-101-2004. Thermal performance desing of buildings.

For input parameters  $k$  and  $h_{up}$  the following constraints were adopted:

$$\begin{aligned} 0.1 &\leq k \leq 0.4; \\ 0.5 &\leq h_{up} \leq 23. \end{aligned} \tag{10}$$

A series of nine calculations was performed for different values of ambient temperature  $T_\infty$ , soil temperature  $T_{bot}$ , initial concrete mix temperature  $T_0$ , and slab thickness  $h$ . The initial data for each case, as well as the objective function values  $f$  at the initial search point, are presented in Table 3.

*Table 3. Considered variants of initial data for solving the optimization problem*

No.	$h$ , m	$T_{\infty}$ , °C	$T_0$ , °C	$T_{bot}$ , °C	$f$
1	1	5	10	5	0.581
2	1	15	15	15	0.724
3	1	25	20	20	0.927
4	2	5	10	5	1.528
5	2	15	15	15	1.637
6	2	25	20	20	1.769
7	3	5	10	5	2.219
8	3	15	15	15	2.239
9	3	25	20	20	2.277

*Table 4. Results of solving the optimization problem*

No.	Method	$k$	$h_{up}$	$f$
1	Interior point	0.219	3.502	0.261
	Pattern search	0.219	3.474	0.261
	Particle swarm	<u>0.220</u>	<u>3.436</u>	<u>0.260</u>
2	Interior point	<u>0.202</u>	<u>4.726</u>	<u>0.280</u>
	Pattern search	0.182	2.794	0.309
	Particle swarm	<u>0.201</u>	<u>4.561</u>	<u>0.280</u>
3	Interior point	<u>0.159</u>	<u>3.032</u>	<u>0.282</u>
	Pattern search	0.149	2.510	0.288
	Particle swarm	<u>0.159</u>	<u>3.032</u>	<u>0.282</u>
4	Interior point	<u>0.138</u>	<u>2.786</u>	<u>0.519</u>
	Pattern search	<u>0.138</u>	<u>2.795</u>	<u>0.519</u>
	Particle swarm	<u>0.138</u>	<u>2.786</u>	<u>0.519</u>
5	Interior point	0.121	3.011	0.523
	Pattern search	0.128	3.131	0.524
	Particle swarm	<u>0.121</u>	<u>3.034</u>	<u>0.521</u>
6	Interior point	<u>0.113</u>	<u>3.979</u>	<u>0.562</u>
	Pattern search	<u>0.115</u>	<u>4.000</u>	<u>0.562</u>
	Particle swarm	0.100	3.919	0.570
7	Interior point	0.172	2.903	0.819
	Pattern search	0.151	2.820	0.805
	Particle swarm	<u>0.127</u>	<u>2.645</u>	<u>0.802</u>
8	Interior point	<u>0.131</u>	<u>2.687</u>	<u>0.798</u>
	Pattern search	0.144	2.750	0.806
	Particle swarm	<u>0.131</u>	<u>2.687</u>	<u>0.798</u>
9	Interior point	<u>0.122</u>	<u>3.235</u>	<u>0.852</u>
	Pattern search	0.125	3.250	0.853
	Particle swarm	<u>0.122</u>	<u>3.235</u>	<u>0.852</u>

**RESULTS AND DISCUSSION**

Table 4 shows the results of solving the optimization problem in the form of optimal values of parameters  $k$  and  $h_{up}$ , as well as the corresponding value of the objective function  $f$  for each option considered using three methods. The best solutions for each option are underlined.

Table 4 shows that the three methods used yielded roughly the same results. The particle swarm method proved to be the most stable for this problem, providing the best solution in eight of the nine variants considered. However, this method has the highest computational complexity, as it evaluates the objective function value at multiple search points rather than just one at each iteration. It should also be noted that the interior point method finds a local maximum in the vicinity of the initial search point, but not a global one, unlike the other two methods used. As a result of optimization, the maximum values of the tensile stress level were reduced from 2.2 to 3.3 times compared to the initial search point, corresponding to the average heat release kinetics of concrete and the uncovered upper surface.

Based on the obtained solutions, optimal heat transfer coefficient values range from 2.51 to 4.73 W/(m<sup>2</sup>·°C), indicating the feasibility of insulating the upper surface. This method for reducing the risk of early cracking is generally accepted and has been previously discussed in [15-18, 27].

The required thickness of thermal insulation can be calculated based on the formula for the heat transfer coefficient from the insulated surface [27]:

$$h_f = \frac{1}{\sum \frac{\delta_i}{\lambda_i} + \frac{1}{h_{surf}}}, \tag{11}$$

where  $h_{surf}$  is the heat transfer coefficient from an uninsulated surface,  $\delta_i$  is the thickness of the  $i$ -th insulation layer,  $\lambda_i$  is the thermal conductivity coefficient of the  $i$ -th insulation layer. For one layer of insulation, its required thickness can be calculated using the formula:

$$\delta_1 = \lambda_1 \left( \frac{1}{h_f} - \frac{1}{h_{surf}} \right). \quad (12)$$

For example, for the “Penofol” insulation (closed-cell polyethylene foam with a thin layer of aluminum foil) at  $h_{surf} = 23 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$  and  $\lambda_1 = 0.045 \text{ W}/(\text{m} \cdot ^\circ\text{C})$ , the optimal heat transfer coefficient of  $2.51\text{-}4.73 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$  corresponds to a thickness of 7.5 to 16 mm.

The optimal values of the coefficient  $k$ , which determines the heat release kinetics of concrete, range from 0.1 to 0.22, indicating a preference for normal and rapid-hardening concrete over slow-hardening concrete. Furthermore, with increasing slab thickness and ambient temperature, the optimal  $k$  value tends to decrease, suggesting that under these conditions, rapid-hardening and ultra-rapid-hardening concrete are preferable.

This finding regarding the undesirability of using slow-hardening concrete in massive foundation slabs contradicts generally accepted opinion [7-9]. However, authors who postulate the necessity of using slow-hardening concrete in massive structures use the maximum temperature within the structure and the temperature difference between the center and surface of the structure, rather than the level of tensile stress, to assess the risk of early cracking.

Our finding regarding the undesirability of using slow-hardening concrete can be explained by the fact that the rate of increase in strength properties of such concrete lags behind the kinetics of heat release and, consequently, the development of maximum temperature differences between the center and surface of the structure. Let's examine this in detail using option 6 as an example. Figure 1 shows heat release curves plotted for  $k = 0.18$  (initial approximation),  $k = 0.115$  (optimal solution), and  $k = 0.24$  (slow-hardening concrete).

Fig. 2 shows the change in time of the maximum temperature difference  $\Delta T$  between the center and the upper surface of the structure for the initial approximation, at  $k = 0.115$  and  $h_{up} = 4 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$  (optimal solution) and for

slow-hardening concrete at  $k = 0.24$  and  $h_{up} = 4 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$ . A decrease in heat transfer on the upper surface leads to a decrease in the maximum value  $\Delta T$  from 22 to  $11 \text{ }^\circ\text{C}$ . In the case of using slow-hardening concrete, the maximum temperature difference, compared to rapid-hardening concrete, is reduced insignificantly (by only  $0.2 \text{ }^\circ\text{C}$ )

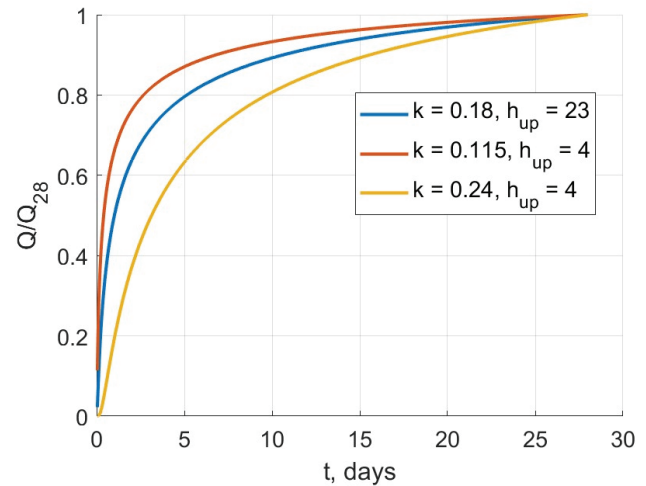


Figure 1. Heat release curves

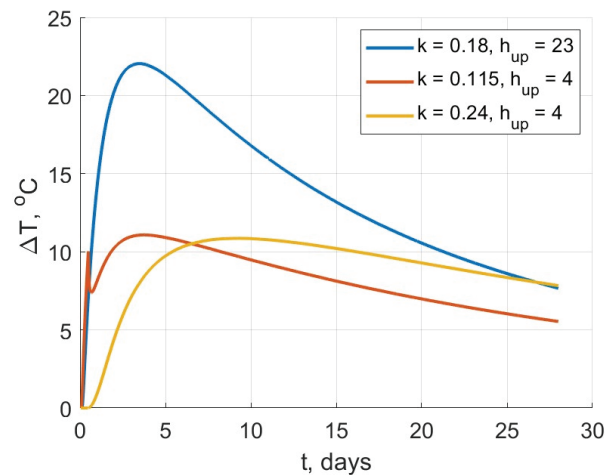


Figure 2. Change in time of the maximum temperature difference  $\Delta T$  between the center and the upper surface of the structure

The maximum temperature difference for rapid-hardening concrete at  $k = 0.115$  is reached at  $t = 3.7$  days, and at this age, the tensile strength is 96% of the strength at 28 days (Fig. 3). For slow-hardening concrete, the maximum temperature difference is reached at

$t = 9.3$  days, and at this age, the  $R_t$  value is 81% of the strength at 28 days, which is significantly less than for rapid-hardening concrete. Moreover, Fig. 3 shows that the growth of the concrete elasticity modulus outpaces the growth of tensile strength. All this taken together leads to the fact that the maximum tensile stress level for slow-hardening concrete, with the same value of the heat transfer coefficient, is significantly higher than for rapid-hardening concrete (1.13 versus 0.56). A comparison of the curves for the change in stress level over time is shown in Fig. 4.

Another important feature should also be noted in Fig. 4. The curves of change  $\sigma/R_t$  at  $h_{up} = 4$  W/(m<sup>2</sup>·°C) (yellow and red lines) have two maximum points and a kink. The kink in these graphs is due to the change in the position of the critical point where the maximum tensile stress is reached (the critical point moves from the upper surface to the lower surface). For the optimized curve (red line), the maximum values at the two critical points coincide, indicating that the structure is of equal strength. It is well known that equal strength of a structure is one of the criteria for its optimality [28-30].

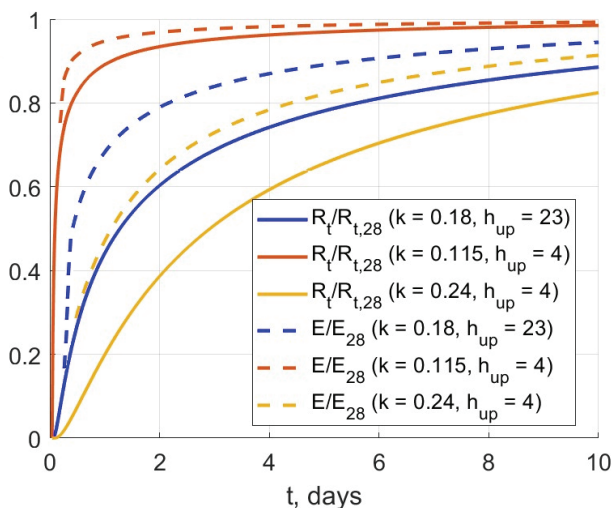


Figure 3. Curves of relative change in concrete tensile strength and elastic modulus over time (values are calculated based on the temperatures of the upper surface of the slab)

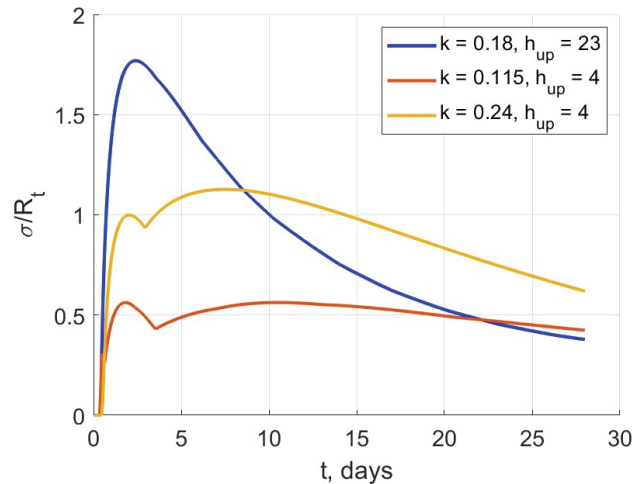


Figure 4. Comparison of stress level change curves over time

The use of the developed optimization methodology makes it possible to determine curing conditions under which it is possible to concrete foundation slabs up to 3 m thick or more without the use of expensive cooling systems.

## CONCLUSION

1. The methodology for optimizing concrete curing conditions in massive monolithic foundation slabs has been developed and tested. This methodology aims to minimize the tensile stress level  $\sigma/R_t$  as an objective function. The methodology is based on a combined solution to the heat transfer problem and the stress-strain state, taking into account the kinetics of heat release and concrete strength gain.
2. It has been established that the most effective way to reduce the risk of early cracking is the combined control of two parameters: the kinetics of heat release from concrete (through the coefficient  $k$ ) and the intensity of heat transfer from the upper surface of the slab (through the coefficient  $h_{up}$ ).
3. Optimization showed that to minimize tensile stresses it is necessary to:
  - reduce the heat transfer coefficient  $h_{up}$  to values of 2.5–4.7 W/(m<sup>2</sup>·°C), which corresponds to the use of thermal insulation coatings on the surface of the slab.

- use normal and rapid-hardening concrete, not slow-hardening concrete.

4. The obtained result contradicts the widespread belief that slow-hardening concrete is preferable for massive structures. It was shown that when using slow-hardening concrete, the increase in tensile strength lags behind the development of temperature changes, leading to higher tensile stress levels compared to rapid-hardening concrete, all other things being equal.

5. The particle swarm method demonstrated the best efficiency in solving the given optimization problem, providing the lowest values of the objective function in 8 of the 9 considered variants, despite the increased computational complexity.

6. The proposed method reduces tensile stress by 2.2–3.3 times compared to typical conditions (uninsulated surface, normally hardening concrete). This opens the possibility of concreting massive foundation slabs up to 3 meters thick or more without the need for complex and expensive artificial cooling systems.

7. The equal strength criterion of the structure, observed with optimal parameters (coincidence of stress maxima at different points of the section), confirms the correctness and effectiveness of the proposed approach to the design of hardening conditions for massive concrete structures.

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## REFERENCES

1. **Li X. et al.** (2023) Investigation of temperature development and cracking control strategies of mass concrete: A field monitoring case study. *Case Studies in Construction Materials*, vol. 18, e02144. doi: 10.1016/j.cscm.2023.e02144
2. **Xie Y. et al.** (2023) Temperature field evolution of mass concrete: From hydration dynamics, finite element models to real concrete structure. *Journal of Building Engineering*, vol. 65, 105699. doi: 10.1016/j.job.2022.105699
3. **Sheng X. et al.** (2023) Experimental and finite element investigations on hydration heat and early cracks in massive concrete piers. *Case Studies in Construction Materials*, vol. 18, e01926. doi: 10.1016/j.cscm.2023.e01926
4. **Bilčík J., Sonnenschein R., Gažovičová N.** (2017) Causes of early-age thermal cracking of concrete foundation slabs and their reinforcement to control the cracking. *Slovak Journal of Civil Engineering*, vol. 25, no. 3, pp. 8–15. doi: 10.1515/sjce-2017-0013
5. **Nesvetaev G.V., Koryanova Yu.I., Shut V.V.** (2024) Specific heat dissipation of concrete and the risk of early cracking of massive reinforced concrete foundation slabs. *Construction Materials and Products*, vol. 7, no. 3. doi: 10.58224/2618-7183-2024-7-4-3
6. **Klemczak B., Żmij A.** (2021) Insight into thermal stress distribution and required reinforcement reducing early-age cracking in mass foundation slabs. *Materials*, vol. 14, no. 3, 477. doi: 10.3390/ma14030477
7. **Afsoosbiria H., Machowska A.** (2025) Development of Sustainable Concrete Using By-Products as a Green Material, and Potential Solutions for Sustainability in Mass Concrete Construction—Comprehensive Review. *Sustainability*, vol. 17, no. 22, 9983. doi: 10.3390/su17229983
8. **Singh M. P. et al.** (2024) Early age cracking relevant to mass concrete dam structures during the construction schedule. *Construction and Building Materials*, vol. 411, 134739. doi: 10.1016/j.conbuildmat.2023.134739
9. **Justnes H., Wuyts F., Van Gemert D.** (2008) Hardening retarders for massive concrete. 5th Int. Conf. on High Perform-

- mance Concrete Location, Manaus, Brazil, pp. 18–20.
10. **De Schutter G., Vuylsteke M.** (2004) Minimisation of early age thermal cracking in a J-shaped non-reinforced massive concrete quay wall. *Engineering Structures*, vol. 26, no. 6, pp. 801–808. doi: 10.1016/j.engstruct.2004.01.013
  11. **Kastornykh L. et al.** (2021) Modified concrete mixes for monolithic construction. *Materials Science Forum*, vol. 1043, pp. 81–91. doi: 10.4028/www.scientific.net/MSF.1043.81
  12. **Smolana A. et al.** (2022) Thermo-mechanical analysis of mass concrete foundation slabs at early age—essential aspects and experiences from the FE modelling. *Materials*, vol. 15, no. 5, 1815. doi: 10.3390/ma15051815
  13. **Smolana A., Jędrzejewska A., Klemczak B.** (2025) Addressing Thermal Cracking in Polish Infrastructure: A Case Study. *International RILEM Conference on Early-age and Long-term Cracking in RC Structures*. Cham: Springer Nature Switzerland, pp. 239–250. doi: 10.3390/ma17153700
  14. **Klemczak B., Smolana A.** (2024) Multi-Step Procedure for Predicting Early-Age Thermal Cracking Risk in Mass Concrete Structures. *Materials*, vol. 17, no. 15, 3700. doi: 10.3390/ma17153700
  15. **Nguyen C.T., Luu X.B.** (2019) Reducing temperature difference in mass concrete by surface insulation. *Magazine of Civil Engineering*, no. 4 (88), pp. 70–79. doi: 10.18720/MCE.88.7
  16. **Chen Y.Y. et al.** (2017) Effects of insulation materials on mass concrete with pozzolans. *Construction and Building Materials*, vol. 137, pp. 261–271. doi: 10.1016/j.conbuildmat.2017.01.059
  17. **Aniskin N.A., Chuc N.T., Khanh P.K.** (2021) The use of surface thermal insulation to regulate the temperature regime of a mass concrete during construction. *Power Technology and Engineering*, vol. 55, no. 1, pp. 1–7. doi: 10.1007/s10749-021-01310-6
  18. **Chuc N.T. et al.** (2018) The effects of insulation thickness on temperature field and evaluating cracking in the mass concrete. *Electronic Journal of Structural Engineering*, vol. 18, no. 2, pp. 128–132. doi: 10.56748/ejse.182722
  19. **Chepurnenko A.S. et al.** (2022) Simplified model for determining the stress strain state in massive monolithic foundation slabs during construction. *International Journal for Computational Civil and Structural Engineering*, vol. 18, no. 3, pp. 126–136. doi: 10.22337/2587-9618-2022-18-3-126-136
  20. **Cha S.L., Jin S.S.** (2020) Prediction of thermal stresses in mass concrete structures with experimental and analytical results. *Construction and Building Materials*, vol. 258, 120367. doi: 10.1016/j.conbuildmat.2020.120367
  21. **Korotchenko I.A. et al.** (2017) Deformation of concrete creep in the thermal stress state calculation of massive concrete and reinforced concrete structures. *Magazine of Civil Engineering*, no. 1 (69), pp. 56–63. doi: 10.18720/MCE.69.5
  22. **Nesvetaev G.V. et al.** (2025) Heat dissipation of cement and design the composition of concrete for massive structures. *Construction Materials and Products*, vol. 8, no. 1, 3. doi: 10.58224/2618-7183-2025-8-1-3
  23. **Nesvetaev G.V., Koryanova Yu.I.** (2023) Prognoz kinetiki prochnosti betona pri tverdenii v usloviyakh, otlichnykh ot normal'nykh [Forecast of concrete strength kinetics under hardening conditions different from normal]. *Sovremennye tendentsii v stroitel'stve, gradostroitel'stve i planirovke territorii*, vol. 2, no. 4, pp. 59–68. doi: 10.23947/2949-1835-2023-2-4-59-68
  24. **Nesvetaev G.V., Koryanova Y.I., Yazyev B.M.** (2024) Autogenous shrinkage and early cracking of massive foundation slabs. *Magazine of Civil Engineering*, vol. 130, no. 6, 13005. doi: 10.34910/MCE.130.5
  25. **Nesvetaev G., Koryanova Y., Chepurnenko A.** (2023) Comparison of the shear strength in heavy and self-

- compacting concrete. *Architecture and Engineering*, vol. 8, no. 2, pp. 63–71. doi: 10.23968/2500-0055-2023-8-2-63-71
26. **Chepurnenko A.S. et al.** (2025) Experience of concreting a massive monolithic foundation slab. *Construction Materials and Products*, vol. 8, no. 5, 2. doi: 10.58224/2618-7183-2025-8-5-2
  27. **Chuc N.T., Nikolay A.** (2020) The effect of formworks on the temperature regime in the mass concrete. *Magazine of Civil Engineering*, no. 7 (99), 9911. doi: 10.18720/MCE.99.11
  28. **Andreev V.I.** (2012) Optimization of thick-walled shells based on solutions of inverse problems of the elastic theory for inhomogeneous bodies. *Computer Aided Optimum Design in Engineering*, pp. 189–202.
  29. **Andreev V.I., Potekhin I.A.** (2017) Equal strength and equal stress structures. *Models and reality. Advances in Engineering Research*, vol. 102, pp. 232–236. doi: 10.2991/icmmse-17.2017.36
  30. **Andreev V., Potekhin I.** (2019) Calculation of equal strength thick-walled concrete cylinder with free ends. *IOP Conference Series: Materials Science and Engineering*, vol. 661, no. 1, 012023. doi: 10.1088/1757-899X/661/1/012023
- СПИСОК ЛИТЕРАТУРЫ**
1. **Li X. et al.** Investigation of temperature development and cracking control strategies of mass concrete: A field monitoring case study // *Case Studies in Construction Materials*. 2023. Vol. 18. Article e02144. doi: 10.1016/j.cscm.2023.e02144
  2. **Xie Y. et al.** Temperature field evolution of mass concrete: From hydration dynamics, finite element models to real concrete structure // *Journal of Building Engineering*. 2023. Vol. 65. Article 105699. doi: 10.1016/j.job.2022.105699
  3. **Sheng X. et al.** Experimental and finite element investigations on hydration heat and early cracks in massive concrete piers // *Case Studies in Construction Materials*. 2023. Vol. 18. Article e01926. doi: 10.1016/j.cscm.2023.e01926
  4. **Bilčík J., Sonnenschein R., Gažovičová N.** Causes of early-age thermal cracking of concrete foundation slabs and their reinforcement to control the cracking // *Slovak Journal of Civil Engineering*. 2017. Vol. 25. No. 3. Pp. 8–15. doi: 10.1515/sjce-2017-0013
  5. **Nesvetaev G.V., Koryanova Yu.I., Shut V.V.** Specific heat dissipation of concrete and the risk of early cracking of massive reinforced concrete foundation slabs // *Construction Materials and Products*. 2024. Vol. 7. No. 3. Article 3. doi: 10.58224/2618-7183-2024-7-4-3
  6. **Klemczak B., Źmij A.** Insight into thermal stress distribution and required reinforcement reducing early-age cracking in mass foundation slabs // *Materials*. 2021. Vol. 14. No. 3. Pp. 477. doi: 10.3390/ma14030477
  7. **Afsoosbiria H., Machowska A.** Development of Sustainable Concrete Using By-Products as a Green Material, and Potential Solutions for Sustainability in Mass Concrete Construction—Comprehensive Review // *Sustainability*. 2025. Vol. 17. No. 22. Pp. 9983. doi: 10.3390/su17229983
  8. **Singh M.P. et al.** Early age cracking relevant to mass concrete dam structures during the construction schedule // *Construction and Building Materials*. 2024. Vol. 411. Article 134739. doi: 10.1016/j.conbuildmat.2023.134739
  9. **Justnes H., Wuyts F., Van Gemert D.** Hardening retarders for massive concrete // *5th Int. Conf. on High Performance Concrete*, Manaus, Brazil. 2008. Pp. 18–20.
  10. **De Schutter G., Vuylsteke M.** Minimisation of early age thermal cracking in a J-shaped non-reinforced massive concrete quay wall // *Engineering Structures*. 2004. Vol. 26. No. 6. Pp. 801–808. doi: 10.1016/j.engstruct.2004.01.013
  11. **Kastornykh L. et al.** Modified concrete mixes for monolithic construction // *Mate-*

- rials Science Forum. 2021. Vol. 1043. Pp. 81–91. doi: 10.4028/www.scientific.net/MSF.1043.81
12. **Smolana A. et al.** Thermo-mechanical analysis of mass concrete foundation slabs at early age—essential aspects and experiences from the FE modelling // *Materials*. 2022. Vol. 15. No. 5. Article 1815. doi: 10.3390/ma15051815
  13. **Smolana A., Jędrzejewska A., Klemczak B.** Addressing Thermal Cracking in Polish Infrastructure: A Case Study // *International RILEM Conference on Early-age and Long-term Cracking in RC Structures*. Cham : Springer Nature Switzerland, 2025. Pp. 239–250. doi: 10.3390/ma17153700
  14. **Klemczak B., Smolana A.** Multi-Step Procedure for Predicting Early-Age Thermal Cracking Risk in Mass Concrete Structures // *Materials*. 2024. Vol. 17. No. 15. Article 3700. doi: 10.3390/ma17153700
  15. **Nguyen C.T., Luu X.B.** Reducing temperature difference in mass concrete by surface insulation // *Magazine of Civil Engineering*. 2019. No. 4 (88). Pp. 70–79. doi: 10.18720/MCE.88.7
  16. **Chen Y.Y. et al.** Effects of insulation materials on mass concrete with pozzolans // *Construction and Building Materials*. 2017. Vol. 137. Pp. 261–271. doi: 10.1016/j.conbuildmat.2017.01.059
  17. **Aniskin N.A., Chuc N.T., Khanh P.K.** The use of surface thermal insulation to regulate the temperature regime of a mass concrete during construction // *Power Technology and Engineering*. 2021. Vol. 55. No. 1. Pp. 1–7. doi: 10.1007/s10749-021-01310-6
  18. **Chuc N.T. et al.** The effects of insulation thickness on temperature field and evaluating cracking in the mass concrete // *Electronic Journal of Structural Engineering*. 2018. Vol. 18. No. 2. Pp. 128–132. doi: 10.56748/ejse.182722
  19. **Chepurnenko A.S. et al.** Simplified model for determining the stress strain state in massive monolithic foundation slabs during construction // *International Journal for Computational Civil and Structural Engineering*. 2022. Vol. 18. No. 3. Pp. 126–136. doi: 10.22337/2587-9618-2022-18-3-126-136
  20. **Cha S.L., Jin S.S.** Prediction of thermal stresses in mass concrete structures with experimental and analytical results // *Construction and Building Materials*. 2020. Vol. 258. Article 120367. doi: 10.1016/j.conbuildmat.2020.120367
  21. **Korotchenko I.A. et al.** Deformation of concrete creep in the thermal stress state calculation of massive concrete and reinforced concrete structures // *Magazine of Civil Engineering*. 2017. No. 1 (69). Pp. 56–63. doi: 10.18720/MCE.69.5
  22. **Nesvetaev G.V. et al.** Heat dissipation of cement and design the composition of concrete for massive structures // *Construction Materials and Products*. 2025. Vol. 8. No. 1. Article 3. doi: 10.58224/2618-7183-2025-8-1-3
  23. **Несветаев Г.В., Корянова Ю.И.** Прогноз кинетики прочности бетона при твердении в условиях, отличных от нормальных // *Современные тенденции в строительстве, градостроительстве и планировке территорий*. 2023. Т. 2. №. 4. С. 59–68. doi: 10.23947/2949-1835-2023-2-4-59-68
  24. **Nesvetaev G.V., Koryanova Y.I., Yazyev B.M.** Autogenous shrinkage and early cracking of massive foundation slabs // *Magazine of Civil Engineering*. 2024. Vol. 130. No. 6. Article 13005. doi: 10.34910/MCE.130.5
  25. **Nesvetaev G., Koryanova Y., Chepurnenko A.** Comparison of the shear strength in heavy and self-compacting concrete // *Architecture and Engineering*. 2023. Vol. 8. No. 2. Pp. 63–71. doi: 10.23968/2500-0055-2023-8-2-63-71
  26. **Chepurnenko A.S. et al.** Experience of concreting a massive monolithic foundation slab // *Construction Materials and Products*. 2025. Vol. 8. No. 5. Article 2. doi: 10.58224/2618-7183-2025-8-5-2

27. **Chuc N.T., Nikolay A.** The effect of formworks on the temperature regime in the mass concrete // Magazine of Civil Engineering. 2020. No. 7 (99). Article 9911. doi: 10.18720/MCE.99.11
28. **Andreev V.I.** Optimization of thick-walled shells based on solutions of inverse problems of the elastic theory for inhomogeneous bodies // Computer Aided Optimum Design in Engineering. 2012. Pp. 189–202.
29. **Andreev V.I., Potekhin I.A.** Equal strength and equal stress structures. Models and reality // Advances in Engineering Research. 2017. Vol. 102. Pp. 232–236. doi: 10.2991/icmmse-17.2017.36
30. **Andreev V., Potekhin I.** Calculation of equal strength thick-walled concrete cylinder with free ends // IOP Conference Series: Materials Science and Engineering. 2019. Vol. 661. No. 1. Article 012023. doi: 10.1088/1757-899X/661/1/012023

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