Magazine of Civil Engineering

journal homepage: http://engstroy.spbstu.ru/

ISSN
2712-8172

Research article

UDC 691.32 + 691.328.1 + 691.335 + 624.042.5

DOI: 10.34910/MCE.124.9

Concrete heat liberation in thermal stressed state analysis

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Keywords: concrete construction, reinforced concrete structures, construction period, thermo-stressed state, concrete heat liberation

Abstract. This paper presents the results of numerical studies of the temperature regime and the thermal stressed state of the reinforced concrete wall of the nuclear power plant foundation block during the construction period with continuous concreting at full height. Calculations were done both using the dependence of the change in heat liberation over time on the hardening temperature, according to the theory of I.D. Zaporozhets, as well as the experimental data. It is established that if Zaporozhets equation is used in calculations, the correction of heat release values should be performed in the first 45 hours of concrete hardening. In order to correct the theoretical values of the specific heat, the last one should be multiplied by the correction factor. The dependence of the factor on the time within the range of 4 to 45 hours is approximated with sufficient accuracy by the obtained fifth degree polynomial. The crack resistance of the structure was determined using a deformation criterion, taking into account the change in the ultimate elongation of concrete over time. In this particular case of concreting a structure it is shown that when the correction function is introduced into the calculation program there is no need to use thermal insulation. The direct economic effect, as well as the indirect one associated with the decrease in the construction period, allow avoiding the rise of the construction costs. It is proposed to use the developed methodology in practical calculations of thermal crack resistance of massive concrete and reinforced concrete structures during the construction period.

Citation: Ivanov, E.N., Semenov, K.S., Barabanshchikov, Yu.G., Akimov, S.V., Kuleshin, A.S., Titov, N.T. Concrete heat liberation in thermal stressed state analysis. Magazine of Civil Engineering. 2023. 124(8). Article no. 12409. DOI: 10.34910/MCE.124.9

1. *Introduction*

The hardening of massive concrete and reinforced concrete structures has a number of features. During the building period, the formation and development of cracks are possible. The main reasons for that are non-uniform temperature distribution in the concrete body and the temperature gradient between the core and surface of the block [1–3]. In turn, temperature non-uniformity is caused by fluctuations of the ambient temperature, the heat release due to cement hydration, as well as difference between the maximum temperature in the block and the temperature of its faces, the rate of block cooling [4–6]. The presence of such damage in structures of high responsibility level is unacceptable.

The problem of assessing the thermal crack resistance of massive concrete and reinforced concrete structures in early period consists of determining the temperature fields based on the solutions of heat conductivity equations [7–10] and stresses, and verifying certain conditions meeting the thermal cracks formation. The allowable core-surface temperature gradient was accepted as a crack resistance criterion in papers [11–13]. The energy [1] and the deformation criterion [13] are more accurate and approved in national design codes of concrete structures. The latter one is used in the current work.

The heat liberation due to the cement hydration contributes greatly to the formation of non-uniform temperature fields of massive concrete and reinforced concrete structures during the building period. Special attention is paid to this factor [14–29].

The theory of I.D. Zaporozhets describes the kinetics of concrete heat release depending on temperature and time of hardening [14]. The experimental studies show that at the initial stage the heat release of concrete differs from the results obtained on the basis of the I.D. Zaporozhets equation used in computer programs [15, 16]. Moreover, the hydration temperature influence on the heat liberation process should be taken into account [13].

Neglecting the above-specified factors causes the error in the concrete thermal stressed state analysis. As a result, the calculated characteristics of concrete protection measures against cracking may be overestimated (thickness of thermal insulation, terms of its removal).

Therefore, the aim of the current work is to develop the procedure for refining the design heat release function based on the experimental data for more accurate application of specific measures against cracking.

2. Methods

2.1. Analysis Procedure

The TERM program developed at the Department of Building Structures and Materials of Peter the Great St. Petersburg Polytechnic University (SPbPU) was used in analysis [13]. An important feature of the program is the ability to take into account the influence of time and temperature on the deformative and thermophysical characteristics of concrete, which is relevant for the construction period.

The first block of the program solves the problem of determining non-stationary temperature fields in a concrete structure in contact with the base and other elements. The inhomogeneous differential heat conductivity equation for 2D calculation cases is as follows:

$$c\gamma = \lambda\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2}\right) + \frac{\partial Q}{\partial \tau} \tag{1}$$

where Q is the heat of the cement hydration exothermic reaction;

c is concrete specific heat capacity;

λ is concrete internal heat conductivity coefficient;

γ is concrete density;

t is temperature;

τ is time.

Concrete heat liberation according to I.D. Zaporozhets is treated as a function of time and temperature not depended on the coordinates of an element:

$$Q(\tau) = Q_{max}\left[1 - (1 + A_T\tau)^{-\frac{1}{m-1}}\right] \tag{2}$$

where Q_{max} is the limit, which the concrete heat liberation goes for;

A_T is the increase rate of heat liberation coefficient providing the constant temperature T in time;

m is reaction order with respect to water, which is 2÷2.3 for Portland cement;

The temperature influence on the heat liberation is taken into account with the temperature function:

$$f(t) = 2^{\frac{t_1 - t_2}{\varepsilon}} \tag{3}$$

where ε is the characteristic temperature subtraction which shows the times of heat liberation velocity alteration providing the temperature variation in ε degrees. The characteristic temperature subtraction depends on temperature: $\varepsilon = kt + l$, where $k \approx 0.13$; $l \approx 8$ are characteristics revealed with experiment.

On the outer contour of structure the 3-d kind boundary conditions are accepted, assuming that the heat exchange between the concrete surface and the air environment occurs according to Newton's convective heat transfer law. In this case, the heat flow, coming from the inner concrete layers to the surface, must be accepted by the environment. This condition is written as equality of two flows:

$$\lambda \frac{\partial t}{\partial n} = -\beta (t_{cs} - t_{em}) \tag{4}$$

where β is the heat exchange coefficient depended on surface heat exchange conditions (wind velocity and direction in the open air, curing conditions: into the temporary hide, the presence on the concrete surface the membrane, thermal insulation, framework);

t_{cs} *u* t_{em} is the concrete surface and environment temperature respectively;

n is the normal vector to the concrete surface.

The reduced heat transfer coefficient allows to take in account the thermal insulation, covering, framework influence:

$$\beta_{np} = \frac{1}{\frac{1}{\beta} + R} \tag{5}$$

where R is the insulation thermal resistance.

At the border of contact with the base or other elements of the concrete structure, boundary conditions of the 4-th kind are accepted. From the condition of the continuity of the temperature field, it follows that at the contact of two bodies in an infinitely thin layer the temperature of the first body is equal to the temperature of the second one. In addition, the equality of heat flows at the border of two bodies must be satisfied:

$$\lambda_1 \left(\frac{\partial t}{\partial n} \right)_1 = \lambda_2 \left(\frac{\partial t}{\partial n} \right)_2 \tag{6}$$

The second block of the program calculates the values of thermal stresses. The resolving system of integral-differential equations is obtained by substituting dependencies describing deformations taking into account the hypothesis of flat sections. Also the relationship between stresses and deformations considers creep through the relaxation function according to the linear hereditary theory of aging, and the condition of static equivalence to zero of the temperature forces across the section. When solving the system, the finite element method and numerical integration are used.

The third block of the program evaluates the thermal crack resistance of a concrete structure. The criterion proposed by P.I. Vasiliev, suggesting the appearance of cracks due to the insufficient ability of concrete to deform under the tensile stresses, is used:

$$\sigma(t) = \gamma_{b3} \gamma_{b6} \varepsilon_{lim} \varphi(t) E_b(t) \tag{7}$$

where $\sigma(t)$ is the thermal stresses at time t;

γ_{b6} is the working condition coefficient;

γ_{b3} is the coefficient taking in account the gradient of strain across the section influence on the strength of concrete in tension;

ε_{lim} is limit concrete elongation;

$\varphi(t)$ is the coefficient taking in account dependence of ε_{lim} from the age;

$E_b(t)$ is initial elasticity modulus of concrete at age less than 180 days.

2.2. Initial Data

We investigated the thermally stressed state of the monolithic reinforced concrete wall of the NPP foundation block, continuously concreted to the entire height with and without taking into account corrections in the heat release equation. Despite the reinforcement of the wall, the work of the reinforcement is neglected due to approximately the same thermal expansion coefficient as that of concrete. Since the length of the wall significantly exceeds its thickness and height, the analysis in plane strain way is considered in this paper. The design characteristics and design parameters are presented in Tables 1 and 2, respectively.

Table 1. Construction parameters.

No	Name	Material	Thickness, m	Height, m
1	Foundation slab	Concrete B40	2.6	–
2	Wall	Concrete B30	2.0	5.4

Table 2. Design parameters for the thermal stress state analysis.

No	Design parameter	Property
1	Concrete strength class	B30
2	Cement consumption for concrete, C	230 kg/m^3
3	Deformation modulus of concrete, E_b	33.1 GPa
4	Environment temperature	10 °C
5	Concrete mixture temperature before casting	20 °C
6	Reduced heat transmission coefficient of 20 mm plywood timbering and 10 mm heat insulation	2.64 W/m^2·°C
7	Concrete maximum heat liberation, Q_{max}	102.4 MJ/m^3
8	Heat liberation growth rate coefficient, A_{20}	0.61
9	Power index, m	2.2

The comparative assessment of the calculation results is presented using Equation (2) in the original and corrected versions. The correction was made by introducing the correction factors equal to the ratio of experimental data to theoretical ones.

2.3. Heat Liberation Experimental Results

The heat release of concrete was determined experimentally: in a semi-adiabatic calorimeter, as well as by calculation: using the temperature function [14] with a reduction to isothermal hardening under a temperature of 20 °C. In order to reveal the dependence of the specific heat release on time, the average values of four samples were used. The laboratory results and theoretical values are presented in Table 3 and Figure 1.

Table 3. Concrete unit heat liberation.

Time τ , h	4.0	8.0	12.1	16.0	20.3	24.2	28.2	32.4	35.8	40.0
q_{test} , kJ/kg	6.0	12.6	32.5	62.2	97.3	125.5	149.6	169.0	181.5	194.4
q_{calc}, kJ/kg	34.5	63.6	89.2	110.1	130.3	146.4	161.5	175.4	185.5	197.0
$\left(q_{calc}-q_{test}\right)/q_{test}$	4.75	4.05	1.74	0.77	0.34	0.17	0.08	0.04	0.02	0.01
$k=q_{test}/q_{calc}$	0.174	0.198	0.364	0.565	0.747	0.857	0.926	0.964	0.978	0.987

NOTE: q_{test} is the experimental specific heat liberation of; q_{calc} is the theoretical specific heat liberation: according to Equation (2).

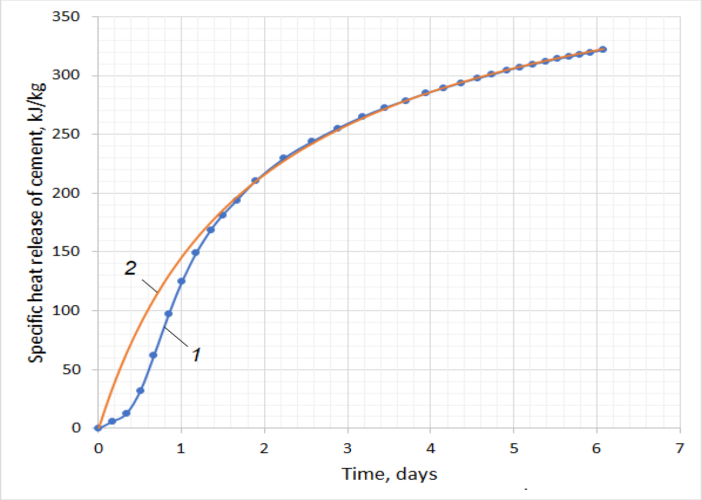

Figure 1. Specific concrete heat liberation: 1 – experimental; 2 – theoretical.

Fig. 1 and Table 3 show that the curves are different from each other in the first 40 hours. The excess of the theoretical value of heat release over the experimental one is from 1 to 475%. The closer the time is to the beginning of concrete hardening, the more significant the distinction is, what may be explained by the impossibility to take into account the retarding action of gypsum, softeners and other additives in Equation (2).

Correction of theoretical values of specific heat release is carried out by multiplying the correction factor k. The dependence of factor k on time τ in the range from 4 to 45 hours with sufficient accuracy ($R^2 = 0.9999$) is approximated with the fifth degree polynomial (Fig. 2).

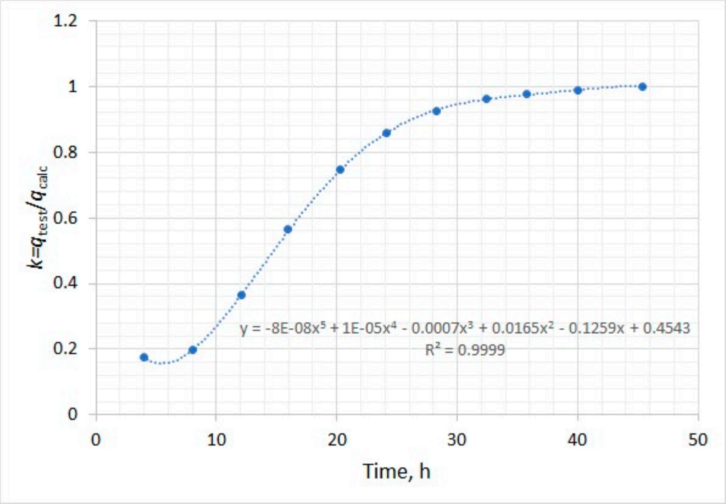

Figure 2 Approximation of the correction factor $k = f(\tau)$ with the fifth degree polynomial.

3. Results and Discussion

The plane problem of determining the temperature fields and stresses of a reinforced concrete wall for two cases of taking into account the heat release of concrete was solved: 1) heat release was taken according to the equation of I.D. Zaporozhets (Eq. (2)); 2) heat release is taken according to the equation of I.D. Zaporozhets with a correcting function $k = f(\tau)$. Thermal insulation and formwork are dismantled 10 days after placing the concrete mixture.

3.1. The first design case

Temperature and stress distributions in the center and on wall surface according to the I.D. Zaporozhets heat liberation theory that was not corrected with the experimental data are presented in Fig. 3 and 4 respectively. The notional strength is the right part of the equation (7).

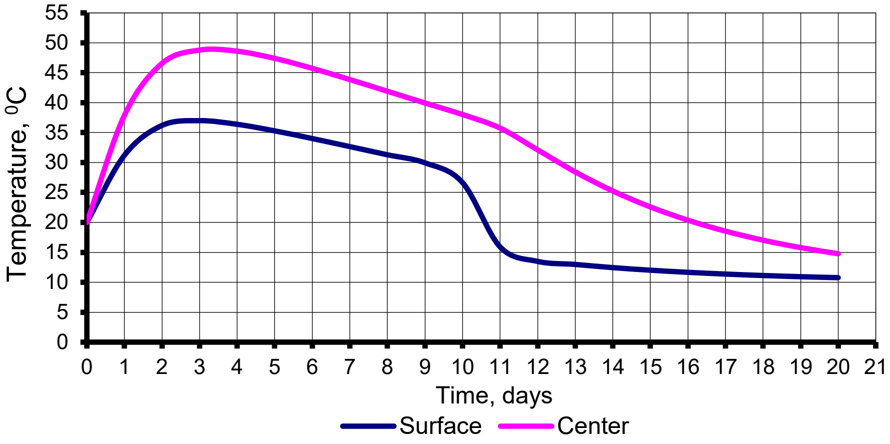

Figure 3. Temperature variation in the center and on the surface of the wall (the 1st case).

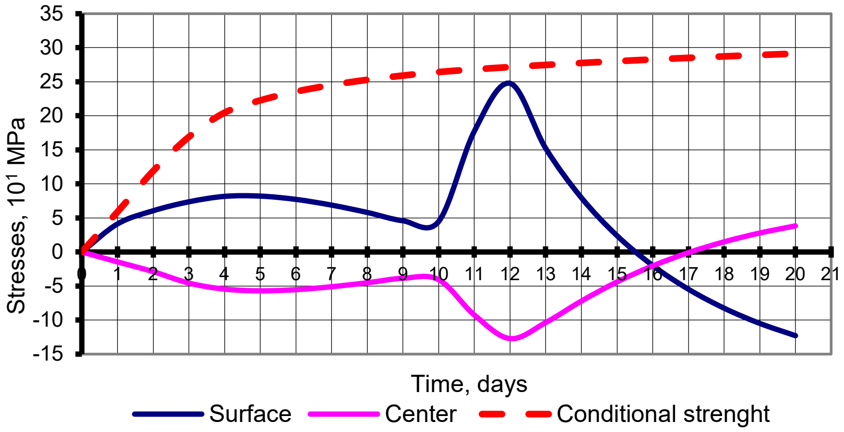

Figure 4. Stress variation in the center and on the surface of the wall (the 1st case).

Figure 3 shows that 3 days later the temperature in the center of the wall rose to a maximum value of 49 °C, and the surface temperature was 37 °C. Ten days later, as a result of thermal insulation and formwork removing, a sharp drop in the surface temperature from 30 °C to 14 °C is observed. Along with it, a sharp jump up to 2.5 MPa of tensile stresses is observed. This phenomenon is called the heat stroke.

3.2. The second design case

Temperature and stress distributions in the center and on the surface of the wall according to the I.D. Zaporozhets heat liberation theory that was not corrected with the experimental data are presented in Fig. 3 and 4 respectively.

Temperature and stress distributions in the center and on the wall surface using the correction function $k = f(\tau)$ to the equation of I.D. Zaporozhets heat liberation theory are presented in Fig. 5 and 6, respectively.

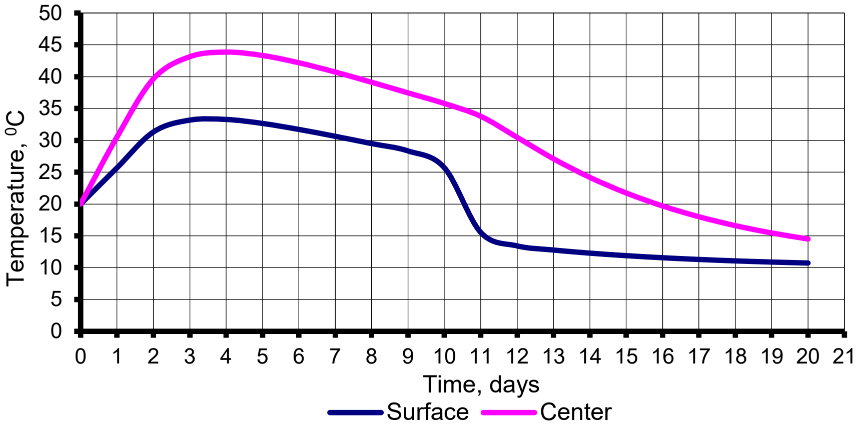

Figure 5. Temperature variation in the center and on the surface of the wall (the 2nd case).

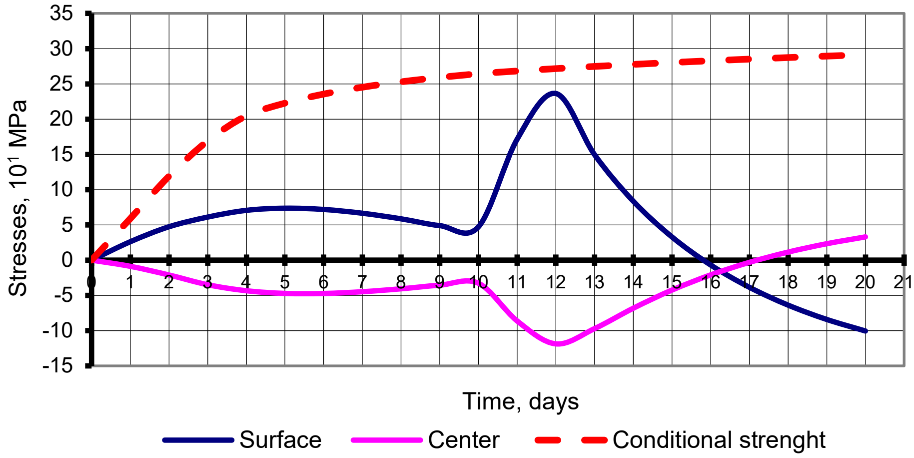

Figure 6. Stress variation in the center and on the surface of the wall (the 2nd case).

In this case, there is a decrease in the maximum temperature in the wall center to 44 °C and in the surface layer to 33 °C. In addition, the temperature drop and the stress jump after the thermal insulation removal decreased to 11 °C and 2.3 MPa respectively.

3.3. Refusal from insulation

Reducing temperature differences and thermal stresses as a result of applying the corrective function and obtaining more reliable results allows us to reject the insulation and reduce the cost of concrete work, which is confirmed by the calculations (see Figures 7 and 8).

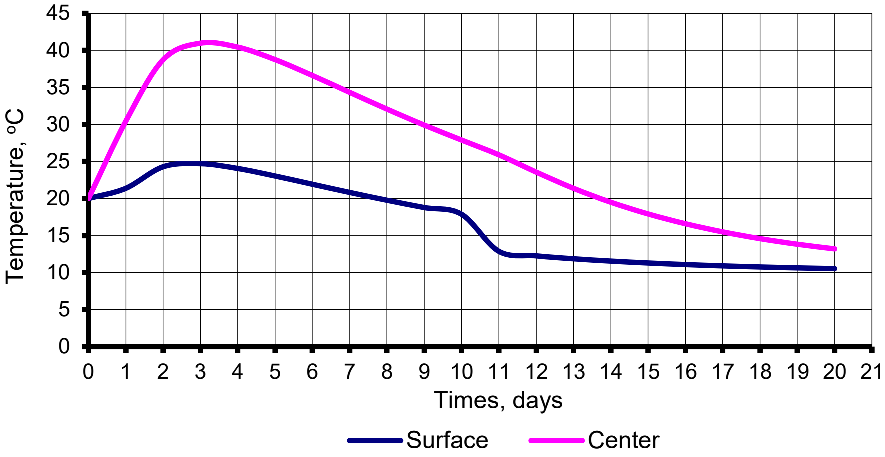

Figure 7. Temperature variation in the center and on the surface of the wall (the 3rd case).

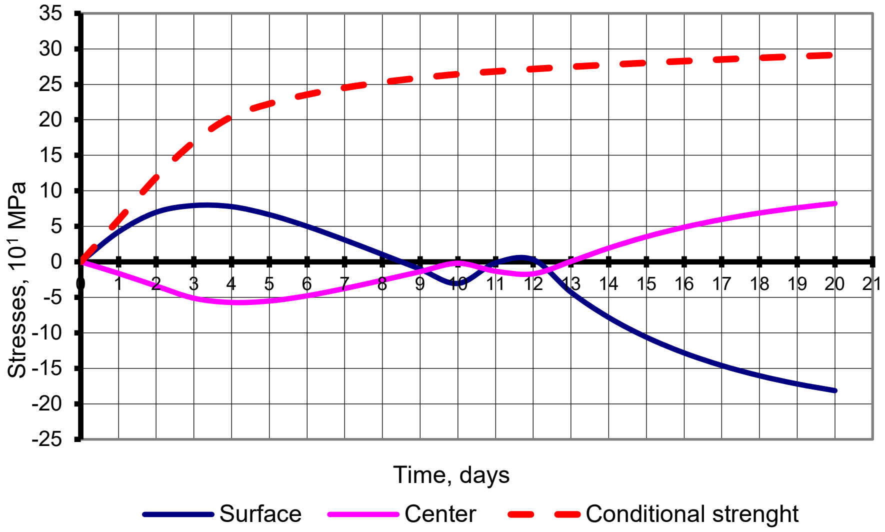

Figure 8. Stress variation in the center and on the surface of the wall (the 3rd case).

The concrete thermal stress state results obtained for the 3 design cases are presented in Tables 4 and 5.

Table 4. Thermal stressed state calculation results on the 1st day after concrete pouring.

No	Calculation case	Time, days	Max temperature center/surface, °C	Max temperature contrast, °C	Tensile stresses, MPa
1	Heat liberation not corrected	1	38/31	7	0.41
2	Heat liberation corrected	1	31/26	5	0.26
3	Heat liberation corrected and without insulation	1	30/21	9	0.42

The results of the thermal stressed state analysis on the 1st day after concrete pouring are presented in Table 4. Such a time step is indicative from comparing the old method of determining the heat liberation of concrete and the new point of view. For this purpose, the crack resistance calculation was carried out separately, taking into account the heat liberation according to the old method in the absence of thermal insulation on the upper face of the wall. As a result, on the 1st day, the crack resistance criterion is not met: the operating stresses are 0.66 MPa, the notional strength is 0.58 MPa, which requires a thermal insulation. When the calculations of crack resistance use a new method for estimating heat liberation (case 3 of Table 4), crack resistance is met and thermal insulation is not required.

Table 5. Thermal stressed state calculation results for the maximum temperature rise.

No	Calculation case	Time, days	Max temperature center/surface, °C	Max temperature contrast, °C	Tensile stresses, MPa	Maximum tensile stresses due to thermal stroke, MPa
1	Heat liberation not corrected	3	49/37	12	0.82	2.5
2	Heat liberation corrected	4	44/33	11	0.74	2.3
3	Heat liberation corrected and without insulation	3	41/25	16	0.78	0.05

Turning attention to Table 5, in the first case, to ensure the thermal crack resistance of concrete, according to the calculation, it is necessary to apply thermal insulation. Here, the largest temperature difference between the center and the wall surface is observed on the 3rd day and amounted to 12 °C, with the corresponding tensile stress of 0.82 MPa. Tensile stresses acquire the highest value (2.5 MPa) on the 10th day after the insulation and formwork removal. However, by this age concrete has time to gain the necessary strength and elasticity to resist cracking.

In comparison with the previous case, the correction of the heat liberation formula gave a delay of one day for the onset of the largest temperature difference and the corresponding stress at their lower values (11 °C and 0.74 MPa). In addition, there was a decrease in the peak of tensile stresses during thermal stroke.

Thus, the refinement of the heat release parameters on the basis of experimental data allows us to obtain more reliable calculation results and reject the unreasonable use of insulation. The removal of the formwork does not lead to the phenomenon of heat stroke (Fig. 8), and the terms of removal can be assigned without consideration of the thermal stressed state of the structure.

Due to the specifics of the study made, the results can be compared with the data of other researchers only without taking into account the introduction of a corrective function, which are close to the similar calculations [2–4].

4. Conclusions

1. The work shows that the theoretical dependence of the heat liberation of concrete on the hardening time used in the calculations of the thermal stress state differs from the experimental one and gives not entirely reliable results on the crack resistance of concrete.

2. Due to the difficulties in the analytical description of the real curve of the cement exotherm, which has a double curvature, the possibility of bringing the theoretical dependence of heat release on time to a

more reliable form is shown by multiplying by correcting function obtained on the basis of experimental data.

3. The work established that, using the equation of I.D. Zaporozhets, heat release values must be corrected in the first 40 hours of concrete hardening. During this period, the actual heat release is lower than the calculated one.

4. It is shown that when the correction function is introduced into the calculation program, in this particular case of concreting a massive structure, there is no need to use thermal insulation. A direct economic effect, as well as an indirect one, associated with a reduction in the construction period of massive structures, will help to avoid a rise in the cost of construction. Therefore, the proposed methodology can be recommended for practical calculations of thermal crack resistance of massive concrete and reinforced concrete structures during the construction period.

5. The offered methodology of estimating the thermal stresses of massive concrete structures during the building period is applicable when the concrete has acquired elastic properties.

References

1. Trapeznikov, L.P. Temperaturnaya treshchinostoykost massivnykh betonnykh sooruzheniy [Thermal cracking resistance of mass concrete structures]. Moscow: Energoatomizdat, 1986. 272 p. (rus)
2. Aniskin, N., Chuc Nguyen, T., Kiet Bui, A. The use of ice to cool the concrete mix in the construction of massive structures. E3S Web of Conferences. Tashkent, 2021. 264. 02047. DOI 10.1051/e3sconf/202126402047.
3. Wang, D.B., Song, X.B., Nie, H.Y. Cracking analysis of massive concrete with large-diameter pipes during construction. Construction and Building Materials. 2022. 338. 127636. DOI 10.1016/j.conbuildmat.2022.127636.
4. Usanova, K., Barabanshchikov, Yu.G., Pakrastins, L., Akimov, S.V., Belyaeva, S.V. Heat release and thermal conductivity of expanded-clay concrete for 3D printer. Magazine of Civil Engineering. 2021. 102(2). Article No. 10210. DOI: 10.34910/MCE.102.10.
5. Maruyama, I, Lura. P. Properties of early-age concrete relevant to cracking in massive concrete. Cement and Concrete Research. 2019. 123. 105770. DOI: 10.1016/j.cemconres.2019.05.015.
6. Lacarrière, L., Knoppik, A., Leal da Silva, W.R., Honorio, T., Šmilauer, V., Asamoto, S., Fairbairn, E.M.R. Hydration and heat development. RILEM State-of-the-Art Reports. 2019. 27. Pp. 13-46. DOI: 10.1007/978-3-319-76617-1_2.
7. Pustovgar, A.P., Lavdansky, P.A., Yesenov, A.V. Research work report. Study of the distribution of temperatures and stresses in selected designs of nuclear power plants during hardening of concrete mix. Concrete production offers. 2012. 137 p.
8. Aleksandrovskiy, S.V. Raschet betonnykh i zhelezobetonnykh konstruktsiy na izmeneniya temperatury i vlazhnosti s uchetom polzuchesti [Calculation of temperature change and humidity in terms of concrete creep in concrete and reinforced concrete structures], Moscow: Stroyizdat, 1973. 444 p. (rus).
9. Lesovik, V.S., Popov, D.Y., Fediuk, R.S., Sabri, M.M., Vavrenyuk, S.V., Liseitsev, Yu.L. Shrinkage of ultra-high performance concrete with superabsorbent polymers. Magazine of Civil Engineering. 2023. 121(5). Article no. 12108. DOI: 10.34910/MCE.121.8.
10. Nemova, D.V., Vatin, N.I., Gorshkov, A.S., Kashabin, A.V., Rymkevich, P.P, Tceitin, D.N. Technical and economic assessment on actions for heat insulation of external envelops of an individual house. Construction of Unique Buildings and Structures. 2014. 23(8). Pp. 93-115. (rus). DOI: 10.18720/CUBS.23.7
11. Teleshev, V.I. Raschet dopustimogo temperaturnogo rezhima betonnoy kladki iz usloviy obespecheniya yeye treshchinostoykosti [Calculation of the permissible temperature regime of concrete masonry from the conditions for ensuring its crack resistance]. Leningrad: LPI, 1985. 37 p. (rus).
12. Teleshev, V.I. Konstruktivno-tekhnologicheskiye meropriyatiya po obespecheniyu treshchinostoykosti i monolitnosti massivnykh betonnykh gidrotekhnicheskikh sooruzheniy [Structural and technological measures to ensure crack resistance and monolithicity of massive concrete hydraulic structures. Leningrad: LPI, 1983. 79 p.
13. Semenov, K.V., Barabanshchikov, Yu.G. Maintenance of thermal cracking resistance in massive concrete base slabs during winter concreting. Construction of Unique Buildings and Structures. 2014. 17(2). Pp. 125-135. (rus). DOI: 10.18720/CUBS.17.10
14. Zaporozhets, I.D., Okorokov, S.D., Pariyskiy, A.A. Teplovydeleniye betona [Heat Liberation of concrete]. Leningrad; Moscow: Stroyizdat, 1966. 316 p. (rus).
15. Pulyaev, S., Pulyaev, I., Korovyakov, V., Sitkin, A. Research of hydration heat of Portland cement used in bridge construction of Kerch Strait. MATEC Web of Conferences. 2018. 251. 7.
16. Linderoth, O., Wadsö, L., Jansen, D. Long-term cement hydration studies with isothermal calorimetry. Cement and Concrete Research. 2021. 141. 106344. DOI: 10.1016/j.cemconres.2020.106344
17. Hai, T.H., Thuc, L.V. The effect of splitting concrete placement on controlling thermal cracking in mass concrete. Journal of science and technology in civil engineering. 2017. Vol. 11. No. 6. Pp. 22-28. http://stce.nuce.edu.vn/index.php/en/article/view/932
18. Vatin, N.I., Gorshkov, A.S., Nemova, D.V. Energoeffektivnost ograzhdayushchikh konstruktsiy pri kapitalnom remonte. [Energy efficiency of envelopes at major repairs. Construction of Unique Buildings and Structures. 2013. 8(3). Pp. 1–11. (rus). DOI: 10.18720/CUBS.8.1
19. Miyazawa, S., Koibuchi, K., Hiroshima, A., Ohtomo, T., Usui T. Control of thermal cracking in mass concrete with blast-furnace slag cement. Concrete Under Severe Conditions. 2010. 7–9. Pp. 1487–1495.
20. Shengxing, W., Donghui, H. Estimation of cracking risk of concrete at early age based on thermal stress analysis. Journal of Thermal Analysis and Calorimetry. 2011. 105(1). Pp. 171–186. DOI: 10.1007/s10973-011-1512-y
21. Zhang, Z., Zhang, X., Wang, X., Zhang, T. Merge concreting and crack control analysis of mass-concrete base slab of nuclear power plant. Applied Mechanics and Materials. 2011. 94–96. Pp. 2107–2110. DOI: 10.4028/www.scientific.net/AMM.94-96.2107
22. Larson, M. Thermal crack estimation in early age concrete-models and methods for practical application. Doctoral Thesis. Division of Structural Engineering, Lulea University of Technology, 2003. 190 p.

23. Lee, M.H., Khil, B.S., Yun, H.D. Influence of cement type on heat of hydration and temperature rise of the mass concrete. Indian Journal of Engineering & Materials Sciences. 2014. 8(5). Pp. 536–542.
24. Usanova, K., Barabanshchikov, Yu.G., Dixit, S. Cementless Binder Consisting of High-Calcium Fly Ash, Silica Fume and Magnesium Chloride. Magazine of Civil Engineering. 2023. 123(7). Article no. 12305. DOI: 10.34910/MCE.123.5.
25. Bingqi, L., Zhenhong, W. Temperature control and crack prevention during constructio in steep slope dams and stilling basins in high-altitude areas. Advances in Mechanical Engineering. 2018. 10(1). Pp. 1–15. DOI: 10.1177/1687814017752480
26. Korotchenko, I.A., Ivanov, E.N., Manovitsky, S.S., Borisova, V.A., Semenov, K.V., Barabanshchikov, Yu.G. Deformation of concrete creep in the thermal stress state calculation of massive concrete and reinforced concrete structures. Magazine of Civil Engineering. 2017. 69(1). Pp. 56–63. DOI: 10.18720/MCE.69.5.
27. Bamforth P.B. Early-age thermal crack control in concrete. CIRIA C660. London. 2007. 113 p..
28. Nguyen, T.C., Huynh, T.P., Tang, V.L. Prevention of crack formation in massive concrete at an early age by cooling pipe system. Asian Journal of Civil Engineering. 2019. 20(8). Pp. 1101–1107. DOI: 10.1007/s42107-019-00175-5
29. Vasilyev, P.I. Svyaz mezhdu napryazheniyami i deformatsiyami v betone pri szhatii s uchetom vliyaniya vremeni [Relationship between stresses and deformations in concrete under compression, taking into account the influence of time]. VNIIG News. 1951. 45. Pp. 78–93.

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Received 01.11.2022. Approved after reviewing 21.11.2023. Accepted 05.12.2023.