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Heat dissipation of cement and design the composition of concrete for massive structures

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Abstract. Introduction. When designing a concrete composition depending on the type of structure, cement content is determined taking into account regulatory requirements for the minimum cement content depending on the operating environment. The maximum cement content is limited by economic indicators and technical conditions depending on the methods and conditions of work; the limitation on the amount of heat dissipation is not considered. Research objective: to develop a methodology for accounting for the heat dissipation of cement when assigning its consumption in concrete compositions for massive structures depending on their parameters and construction conditions. Methods. Experimental studies and analysis of regulatory documents and literary data on heat dissipation of cements and concretes. Modeling the parameters of temperature fields and stress fields depending on the class of concrete and its specific heat dissipation using the example of a foundation slab with specified dimensions and parameters of heat exchange with the environment. Results: An approach is proposed to standardizing the value of the maximum heat dissipation of concrete when designing a concrete composition for massive reinforced concrete structures. The article substantiates the position that the value of the level of tensile temperature stresses is less significantly affected by the concrete class than by its specific heat dissipation, since it is the heat dissipation of concrete that forms the temperature field and the temperature difference "center – top". Prevention of the risk of early cracking is associated not with slowing down heat dissipation, but with the value of specific heat dissipation, which determines the parameters of temperature fields, temperature gradients and stresses. The example shows that for a massive flat foundation slab with an accepted permissible level of tensile stresses of 0.67, the value of specific heat dissipation of concrete should not exceed 140 mJ / m^3. A principle is proposed for determining the maximum class of concrete for compressive strength depending on the properties of cement. A dependence between the level of tensile temperature-shrinkage stresses and the criterion of thermal crack resistance of Zaporozhets I.D., independent of the concrete class, is revealed.

Keywords: design of concrete composition, specific heat dissipation, massive structures, thermal crack resistance criterion, stress level, early crack formation

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1. INTRODUCTION

The purpose of designing the concrete composition is the justified selection of materials and the assignment of a rational ratio of components to ensure the required technological properties of the concrete mix depending on the concreting parameters and concrete quality indicators, taking into account the operating environment. In connection with the improvement of traditional and the emergence of new materials, the design procedure is constantly being improved [1, 2]. Algorithms are developed and numerical methods are implemented to take into account numerous factors that determine the rational composition of concrete [3], including when using antifreeze admixtures [4]. Known provisions and calculation dependencies for designing the concrete composition for a given compressive strength [5], flexural strength, splitting tensile strength, creep and frost resistance of concrete [6, 7] are being improved, including when using admixtures of various purposes and efficiency, as well as taking into account the structural and mechanical properties of materials [8, 9]. Methods are being developed for designing concrete compositions for structures operated in aggressive environments, including under the influence of hygroscopic inorganic salts [10]. One of the key issues in designing the composition of Portland cement concrete is the justified appointment of rational cement content:

$$C_{min} < C < C_{max}, \quad (1)$$

where: C_{min} – minimum cement content, standardized according to the condition of ensuring the durability of reinforced concrete structures depending on the operating environment, for example, according to SP 28.13330.2017, GOST 31384-2017, EN 206-1:2013, as well as according to technical conditions during the performance of work, for example, during transportation and laying of concrete mixture by concrete pumps, while in the latter case the standards are usually of a recommendatory nature;

C_{max} –maximum cement content is standardized for economic reasons (SNiP 82-02-95), the technical conditions also limit the value of C_{max}, for example, according to the condition of limiting shrinkage deformations, while the standards are usually of a recommendatory nature.

When limiting the value of C_{max} according to technical conditions, the limitation on the heat dissipation of concrete is practically not considered, which is very important when constructing massive structures in order to prevent early cracking [11, 12]. The heat dissipation of concrete is determined by the specific heat dissipation and cement content, while the criterion of thermal crack resistance proposed by Zaporozhets I.D. and co-authors can be considered as a criterion [12]:

$$k_{crc} = \frac{[\varepsilon_t] \cdot C \cdot \rho}{Q \cdot \alpha}, \quad (2)$$

where $[\varepsilon_t]$ – ultimate tensile deformation of concrete;

C, ρ, α – specific heat capacity, average density and coefficient of linear thermal expansion of concrete;

Q – specific heat dissipation of concrete.

Modeling and experimental determination of the parameters of temperature fields and stress fields when developing concreting regulations is performed for hydraulic structures [13, 14], massive foundation slabs [15-18], walls [19, 20] and other massive structures [21, 22]. According to Russian Federation standards, structures with a top area to volume ratio of less than 3 or 2 according to different standards can be classified as massive structures, in connection with which flat foundation slabs with a thickness of more than 0.75 m can already be classified as massive structures. The importance of taking into account the heat dissipation of concrete when developing concreting technology is noted in [22]. Studies of the effect of various admixtures on the heat dissipation parameters of self-compacting concrete are presented in [23]. An assessment of the heat dissipation of concrete in comparison with the indicators standardized by SP 41.13330.2012 is presented, for example, in [24]. However, comparison of concrete heat dissipation parameters with stress-strain state parameters in the early period of hardening of a massive monolithic structure is insufficiently presented in the literature. In connection with the above, the purpose of this work is to substantiate the approach and develop a methodology for assigning restrictions on cement content taking into account its heat dissipation, parameters and conditions of construction of a massive reinforced concrete structure.

2. MATERIALS AND METHODS

The studies on heat dissipation used data on 6 quick-hardening cements from four manufacturers with heat dissipation values at the age of 28 days from 332 to 400 kJ/kg [25], as well as cements whose heat dissipation data are presented in Table 1.

Table 1. Heat dissipation of the investigated cements.

№	PC	Heat dissipation of cements, kJ/kg, at age, h				
		24	48	72	120	672
1	CEM I 42.5N[1]	227.0	287.1	305.7	326.6	378.1
2	CEM I 42.5N[2]	255.7	291.3	309.8	330.5	381.6

Notes: 1 – Russian Federation, GOST 31108-2020; 2 – South Korea.

All the cements studied in [25] are quick-hardening according to GOST 31108-2020 and belong to cements of types 1–3 according to ACI 207.2R-07. The following data were also used in the analysis of heat dissipation. According to SP 41.13330.2012, the heat dissipation values of Portland cement at the age of 28 days are 345 and 385 kJ/kg for cements of classes 32.5 (M400) and 42.5 (M500), respectively. According to GOST 23464-79 (1992), low-heat cements are those with heat dissipation up to 230 and 270 kJ/kg in 3 and 7 days, respectively, and medium-heat cements are those with heat dissipation up to 315 kJ/kg in 7 days. According to ACI 207.2R-07, for cements of types 1–4, the heat dissipation at 28 days is no more than 87 cal/g (364.5 kJ/kg), 76 cal/g (318 kJ/kg), 105 cal/g (440 kJ/kg), 60 cal/g (251 kJ/kg), respectively. The cements according to Table 1 belong to type 3. Table 2 presents the values of specific heat dissipation of Portland cements at the age of 28 days according to some literary data.

Table 2. Specific heat dissipation of Portland cements according to some literary data.

Indicator	Specific heat dissipation of cements, kJ/kg, according to data						
	ACI 207.2R-07	[26]	[27]	[28]	[29]	[30]	[31]
Q, kJ/kg	251 - 440	235 - 290	243 - 513	482	120 - 350	237 - 290	235 - 339

According to the data of [25], out of 31 batches of cement analyzed over 5 years, in 20 batches the heat dissipation value was from 386 to 460 kJ/kg.

The specific heat dissipation of concrete depends on the heat dissipation of cement, cement content and concrete curing conditions. In [21], the modeling was carried out for concrete with a specific heat dissipation of 140 mJ/m^3. In [12], the modeling was performed for concrete with a specific heat dissipation of 167 and 66.8 mJ/m^3. Respectively, the Zaporozhets I.D. criteria at the age of 7 days were 144 and 359. Since in massive structures concrete hardening occurs under conditions different from normal, in the present study, when determining the parameters of temperature fields and stresses, the equivalent age was used, determined by the indicator of the degree of maturity of concrete [15, 25]. In this work, the method according to GOST 310.5-88 is implemented in the experimental determination of heat dissipation of cements, including those with admixtures, since in massive structures the process occurs under conditions closer to adiabatic. The procedure for determining the value of heat dissipation is described in [25].

The stress-strain state is assessed using the example of a flat foundation slab 1.5 m thick with side dimensions greater than 25 m. The methodology is presented in [15, 16, 25]. The equation describing the kinetics of heat dissipation is the dependence presented in [25]:

$$Q_\tau = Q_{28} \cdot \exp\left(k \cdot \left(1 - \left(\frac{28}{\tau - \tau_s}\right)^d\right)\right), \tag{3}$$

where k, d – coefficients;

τ_s – parameter that is adjusted to take into account the different setting times due to different temperatures of the mixture caused by the use of retarding/accelerating admixtures,

ensuring, as shown in [25], good agreement with the frequently used equations of Zaporozhets I.D. [30, 31] in various interpretations or the Knudsen equation [32]. Dependence f. (3) is in accordance with the classification of EN 206-1:2013 by hardening rate [25].

For modeling in this work, the calculation apparatus presented in [25] was used, and the following equations were used to clarify the dependence of the change in the modulus of elasticity over time:

$$E_0 = f(R_t);\ R_t = f(R);\ R = f(T, \tau), \tag{4}$$

$$E_0 = 12270 \cdot \ln(R_t) - 12100, \tag{5}$$

providing complete agreement with the results according to f. (17) in [25] at $\tau > 12\ h$ and better agreement with the experimental data at $\tau > 4\ h$ for quick-hardening concrete.

Since the main task in modeling was to identify the effect of specific heat dissipation of concrete on the level of temperature stresses using a specific example, in order to simplify the problem, the ambient temperature was conventionally assumed to be constant and equal to 20 ºC, the heat transfer coefficient from the upper surface of the slab was assumed to be constant for an uninsulated surface in the absence of wind and equal to 23 W/(m^2 ºC). The stress state was assessed based on the resulting value of the stresses "temperature + autogenous shrinkage" [15, 16].

3. RESULTS AND DISCUSSION

The simulation results presented in Fig. 1 clearly show that the value of the temperature-shrinkage stress level in the early period of hardening of a massive structure is less significantly affected by the concrete class than by its specific heat release, which is natural, since it is the heat release of concrete that forms the temperature field and the temperature difference "center – top" [25]. In the example under consideration, the value of specific heat release is taken from 131 to 205 mJ/m^3. The limit value of the tensile stress level is 0.67 ($R_{bt} = R_t/1.5 = 0.67R_t$).

In the case of using slow-hardening concrete (45 S - 205 in Fig. 1), the risk of early cracking also occurs with high heat dissipation of concrete, but it occurs later. Preventing the risk of early cracking is not associated with slowing down heat generation and, naturally, with slowing down concrete hardening, but with the value of its specific heat dissipation, which determines the parameters of temperature fields, temperature gradients and stresses in the structure. Chapter 5.3.8 of SP 412.13330.2018 states that "Concrete for massive foundation slabs must have *minimal exothermy*...", but the concept of "minimum" is not specified. It is also stated that "concrete... must have... slowed-down hardening kinetics at an early age under normal temperature and humidity conditions". The latter provision is debatable, since the level of temperature-shrinkage stresses depends on the growth rate of the tensile strength.

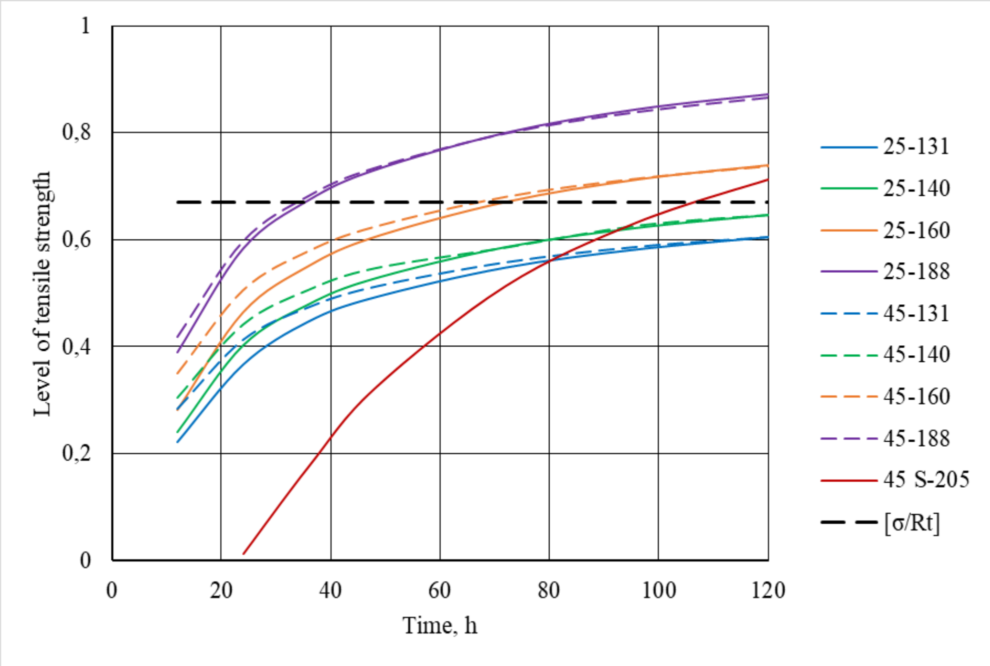

Fig. 1. Development of the level of temperature-shrinkage stresses over time depending on the class, rate of hardening and heat dissipation of concrete. 45 S-205 is concrete of class B45 GOST 26633-2015 (C35/45 EN 1992-1-1), slowly hardening with heat dissipation of 205 mJ/m^3 at the age of 28 days; [σ/Rt] is the permissible level of stresses; all other concretes are fast-hardening.

Fig. 2 shows the dependence of the level of tensile stresses due to temperature-shrinkage deformations on the specific heat dissipation of concrete.

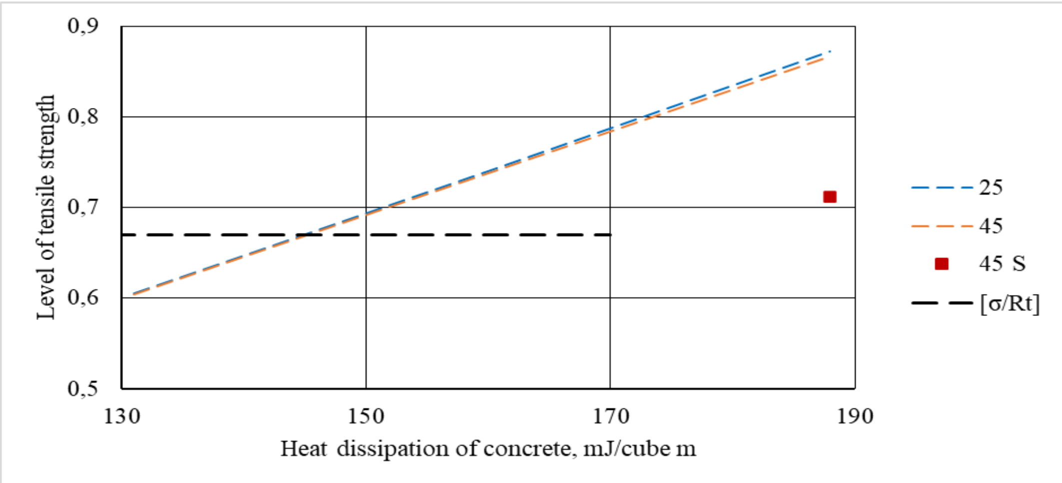

Fig. 2. Dependence of stress level on heat dissipation of concrete at the age of 28 days. 45 S is concrete of class B45 GOST 26633-2015 (C35/45 EN 1992-1-1), slowly hardening; [σ/Rt] is the permissible level of stresses; all other concretes are fast-hardening.

It is obvious that for the accepted limitation of the tensile stress level [σ/R_t] = 0.67, the heat dissipation value of concrete in the example under consideration should not exceed approximately 140 mJ/m^3.

Fig. 3 shows the calculated and standard dependencies of cement consumption on the concrete class. The calculated values were obtained using the equation:

$$R = \frac{k_a \cdot k_c R_c}{(\frac{W}{C})^{1,89}}, \quad (6)$$

where R_c – cement activity according to GOST 31108-2020 in the example under consideration is 42.5 N/mm^2;

k_a – the coefficient taking into account the quality of fillers in the example under consideration is 0.32;

k_c – coefficient taking into account different values of cement activity when determining according to GOST 310.4-81 and GOST 31108-2020, in the example under consideration 1.17;

W – water content, kg/m^3;

C – cement content, kg/m^3.

To move from concrete class B to the design strength value R, the following approaches were used:

$$R = B + 12, \quad (7)$$

$$R = B/k_1, \quad (8)$$

$$R = k \cdot B. \quad (9)$$

The values of the coefficients k, k_1 and the calculated values of W/C for concretes of the classes under consideration are presented in Table 3. The values of k = 1.28 and 1.43 are adopted according to GOST 18105-2018, Table A1 with a variation coefficient of 13% and 16%. The value of k_1 = 1/0.8 is adopted according to GOST 18105-2018, clause 8.4.4. The value of k_1 = 1/(0.8·0.8) is adopted taking into account the difference in the conditions of concrete structure formation at the facility and in the laboratory. Fig. 3 also shows the values of cement content depending on its specific heat dissipation q_c and the permissible value of concrete heat dissipation in the example under consideration of 140 mJ/m^3:

$$[C] = \frac{140}{q_c}. \quad (10)$$

Table 3. Calculated values of *W/C.*

Class of concrete	*W/C* при calculated value of the quantity *R*, N/mm^2				
	R = B[1] + 12	*R* = B/0.8	*R* = B/0.8*0.8	*R* = 1.28B	*R* = 1.43B
B25 (C20/25)[2]	0.547	0.615	0.525	0.607	0.56
B30 (C25/30)[2]	0.5	0.542	0.46	0.535	0.492
B35[1]	0.46	0.485	0.415	0.477	0.44
B40[1]	0.427	0.44	0.375	0.432	0.4
B45 (C35/45)[2]	0.4	0.405	0.345	0.397	0.365

Note: 1 – B – concrete class according to GOST 26633-2015; 2 – concrete class according to EN 1992-1-1.

Fig. 4 shows the proposed limitations of cement heat dissipation for the example under consideration depending on the class of concrete and the specific heat dissipation of cement q_c, for which the values of 385 kJ/kg according to SP 41.13330.2012 and the minimum value for the cements studied by the authors according to Table 1 and [25] – 332 kJ/kg were adopted for Fig. 4.

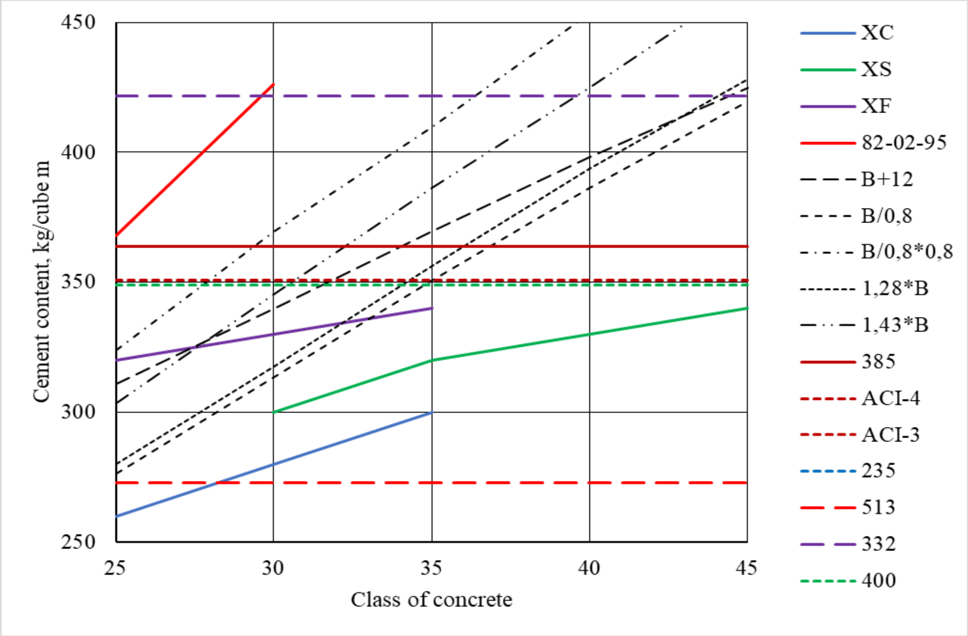

Fig. 3. Dependence of cement consumption on concrete class XC…XF – minimum values for operating environment classes according to GOST 31384-2017
R_m + 12…R_m/0.64 – according to Table 1; 235…513 – minimum and maximum heat dissipation of cement, respectively, according to Table 2; 332…400 – minimum and maximum heat dissipation of cement, respectively, according to the authors' experimental data; 385 – according to SP 41.13330.2012 for cement class 42.5; ACI-3 (4) – according to ACI 207.2R-07 for cements of groups 3 and 4; 82-02-95 - according to SNiP 82-02-95.

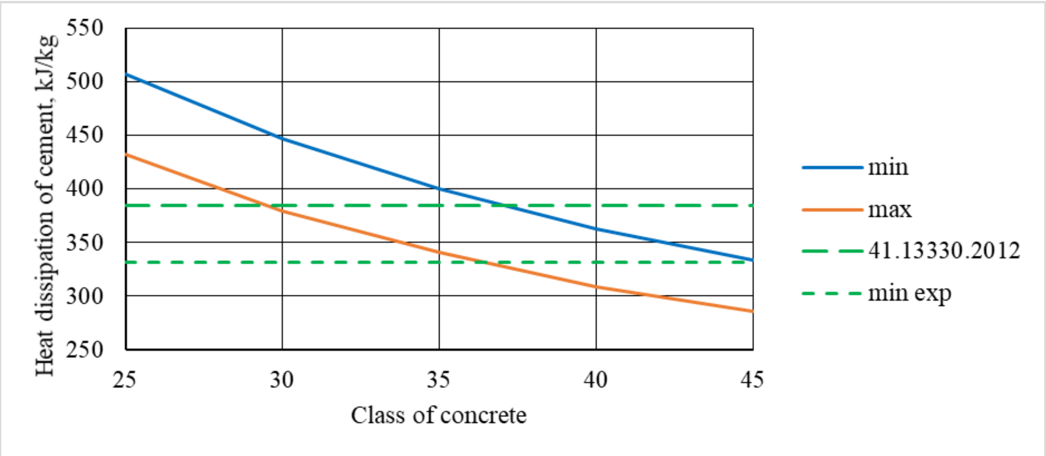

Fig. 4. Limitation of heat dissipation of cement depending on the class of concrete min, max – respectively, the minimum and maximum consumption of cement according to the formulas of Table 3; min exp – cement with minimum heat dissipation according to the experimental data of the authors; 41.13330.2012 - according to SP 41.13330.2012.

The analysis of the results presented in Fig. 4 shows that in the considered example, with the maximum cement consumption according to the *W/C* values in Table 3 and its specific heat dissipation according to SP 41.13330.2012, there is a limitation on the class of concrete used to B30, and with the specific heat dissipation of cement of 332 kJ/kg, the value of the permissible class of concrete will be up to B35. With the minimum cement consumption according to the *W/C* values in Table 3 and its specific heat dissipation according to SP 41.13330.2012, there is a limitation on the class of concrete used to C30/37, and with the specific heat dissipation of cement of 332 kJ/kg, the value of the permissible class of concrete will be up to B45. The presented results should be considered only as an interpretation of the proposed method for limiting the maximum cement content [*C*] depending on the permissible value of the specific heat dissipation of concrete [*Q*], mJ/m^3, and the specific heat dissipation of the cement used q_c, kJ/kg in a particular case:

$$[C] = \frac{[Q]}{q_c}. \tag{11}$$

Fig. 5 shows the dependence of the level of temperature-shrinkage stresses at the age of 24, 72 and 120 hours depending on the criterion f. (2).

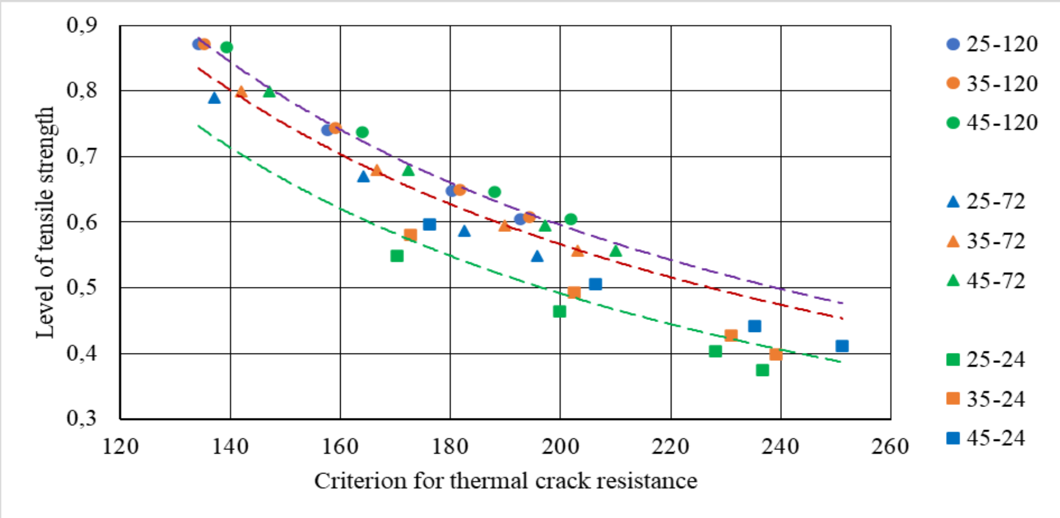

Fig. 5. Dependence of the level of tensile stresses on the criterion of Zaporozhets I.D. 25, 35, 45 – concrete class; 120, 72, 24 – concrete age, h.

Between the level of tensile temperature-shrinkage stresses $u\ (\sigma_t)$ and the K_{crc} criterion in f. (2) there is a dependence that does not depend on the concrete class:

$$u(\sigma_t) = a \cdot K_{crc}{}^x, \tag{12}$$

the values of the coefficient a and the exponent x are presented in Table 4.

Table 4. Parameters of the equation f. (12).

Time, h	Parameters of the equation f. (12)		Approximation reliability index R^2
	a	x	
24	127	-1.05	0.875
72	99	-0.975	0.945
120	107	-0.98	0.988

With increasing age (maturity level of concrete), the reliability index of approximation of equation f. (12) increases, i.e. the dependence becomes more unambiguous. According to [19], tensile stresses σ_T due to the temperature difference "center – top" ΔT are determined as:

$$\sigma_T = \frac{k_T \cdot E \cdot \alpha \cdot \Delta T}{(1+\varphi)}. \tag{13}$$

Taking $\Delta T = b \cdot Q$, and expressing Q from f. (2), after some transformations we obtain an equation similar to f. (12):

$$u(\sigma_T) = \frac{\sigma_T}{R_t} = \frac{d}{K_{crc}}, \quad (14)$$

where:

$$d = \frac{0{,}83 \cdot 0{,}41 \cdot b \cdot C \cdot \rho \cdot E^{0,14}}{(1+\varphi) \cdot R_T^{0,14}}, \quad (15)$$

where:
kr – degree of restriction on the upper top of the plate (0.83 [19]);
E – modulus of elasticity of concrete, MPa;
φ – creep coefficient of concrete;
C, ρ – specific heat capacity and average density of concrete.

The value of d in f. (14) is not a constant, i.e. the equation f. (14) describes a family of curves, and the value of d changes in the example under consideration within the limits of up to d_{max}/d_{min} = 1.3. The ratio of stress levels according to the equations in Table 4 is quite close values from 1.18 to 1.23, the difference does not exceed 10%.

4. CONCLUSIONS

An approach to standardizing the maximum specific heat dissipation of concrete when designing the concrete composition for massive reinforced concrete structures is proposed. It is substantiated that the value of the level of tensile temperature stresses is less significantly affected by the concrete class than by its specific heat dissipation, since it is the heat dissipation of concrete that forms the temperature field and the temperature difference "center - top". Prevention of the risk of early cracking is associated not with slowing down heat dissipation, and, naturally, with slowing down concrete hardening, but with the value of specific heat dissipation, which determines the parameters of temperature fields, temperature gradients and stresses. The example shows that for a massive foundation slab with an accepted permissible level of tensile stresses [σ/R_t] = 0.67, the value of specific heat dissipation of concrete should not exceed approximately 140 mJ / m^3. The principle of determining the maximum class of concrete for compressive strength depending on the properties of cement is shown. A dependence between the level of tensile temperature-shrinkage stresses $u\ (\sigma_t)$ and the criterion of thermal crack resistance of Zaporozhets I.D., independent of the concrete class, was revealed.

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