Magazine of Civil Engineering. 2024. 17(6). Article No. 13005

Magazine of Civil Engineering

ISSN 2712-8172

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

Research article

UDC 693.547

DOI: 10.34910/MCE.130.5

Autogenous shrinkage and early cracking of massive foundation slabs

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Keywords: kinetics of heat dissipation, autogenous shrinkage, stress level, massive monolithic structure

Abstract. The risk of early cracking due to temperature gradients in the early period of concrete hardening of massive monolithic reinforced concrete structures determines the relevance of research into the possibilities of regulating temperature-shrinkage stresses. An important task is to improve the algorithm for calculating temperature-shrinkage stresses due to temperature gradients and autogenous shrinkage, taking into account the kinetics of heat dissipation of concrete, heat exchange conditions, and ambient temperature. Numerous factors influencing the formation of temperature-shrinkage stresses determine the relevance of the use of numerical methods for modeling temperature fields and stresses, which requires dependencies of changes in heat generation and temperature gradients over time, temperature deformations and autogenous shrinkage deformations, tensile strength of concrete, elastic modulus, creep coefficient. *Purpose of the study*: obtaining dependencies describing changes in the kinetics of heat dissipation and strength, taking into account the properties of cements and the presence of additives; methodology for taking into account autogenous shrinkage deformations when calculating stress values; modeling the stress-strain state of a massive monolithic structure in the early period of hardening and comparison of calculated and experimental values, taking into account the influence of autogenous shrinkage of concrete on the stress level. *Materials and methods*: modeling temperature fields and stresses from temperature differences and autogenous shrinkage depending on the class and kinetics of heat dissipation and hardening of concrete; experimental studies of temperature fields and stresses in the early period of hardening. *Results*: the equations describing the kinetics of heat dissipation, strength, and autogenous shrinkage of concrete up to 5 days old depending on concrete hardening rate are proposed. It is shown that failure to take autogenous shrinkage into account can lead to an overestimation of the tensile stress level, depending on the concrete class and the autogenous shrinkage value by up to 30 %. An algorithm is proposed for calculating the kinetics of the stress level in the early period of hardening of massive monolithic structures, taking into account the deformations of autogenous shrinkage, the class, and hardening rate of concrete. The expediency of limiting the temperature difference "center-top" depending on the required reliability in the range from 20...23 °C to 26...28 °C is substantiated.

Citation: Nesvetaev, G.V., Koryanova, Yu.I., Yazyev, B.M. Autogenous shrinkage and early cracking of massive foundation slabs. Magazine of Civil Engineering. 2024. 17(6). Article no. 13005. DOI: 10.34910/MCE.130.5

1. Introduction

The risk of early cracking due to temperature gradients in the early period of concrete hardening of massive monolithic reinforced concrete structures determines the relevance of regulating the temperature regime of concrete hardening. Particularly effective is the combination of prescription (limiting cement content, using low exothermic cements and hardening retardant additives) and technological factors, for example, regulating heat loss to level out temperature gradients [1–3].

An important task is to improve the algorithm for calculating temperature stresses due to temperature gradients in the early period of construction of a massive monolithic structure, taking into account the kinetics of heat dissipation of concrete, heat exchange conditions, and ambient temperature. According to [4], the level of tensile stresses $u = \sigma_t / f_{ctm}$ (R_{bt} in the Russian Code of Regulations 63.13330.2018 “Concrete and reinforced concrete structures. General provisions”) > 1 was noted after approximately 3.5 days of aging. In [5], the level of tensile stresses $u = \sigma_t / f_{ctm}$ (σ_t / R_{bt} in the Russian Code of Regulations 63.13330.2018) > 1 at a design concrete strength of 80 MPa was recorded after approximately 54 hours of hardening. In [6], when the maximum temperature in the center of the slab was reached after 72 hours, the value σ_t = 2.43 MPa was recorded, which is higher than the axial tensile strength of class C20/25 (B25 in the Russian Code of Regulations 63.13330.2018) concrete at design age. The maximum temperatures in the center of the structures can exceed 70 °C, the time to reach the maximum temperature can be from 24 to 72 hours or more, and the “center-top” temperature difference, which determines the level of tensile stresses, according to the authors, can exceed 30 °C with standardized permissible values up to 20 °C.

The above predetermines the relevance of research in the field of regulating the temperature regime of hardening and preventing early cracking of massive monolithic reinforced concrete structures [7]. The numerous prescription and technological factors influencing the formation of temperature stresses in the early period of concrete hardening of monolithic structures determines the relevance of using modeling to study temperature fields and stresses using numerical methods [1, 3, 8]. Calculation of the stress level requires the dependencies of the change in the “center-top” temperature gradients and temperature deformations, the tensile strength of concrete, the elastic modulus, and the creep coefficient over time [1, 9]. Calculation of temperature gradients requires data on the kinetics of heat dissipation of hardening concrete. In addition, when calculating temperature stresses, with rare exceptions [1], the deformations of autogenous shrinkage of concrete are ignored, especially when the overlap time of layers is more than 4 hours, when using concrete mixtures from different suppliers (with different cements), the values of which depend on prescription factors and can make certain adjustments to the assessment of stresses. The value of autogenous shrinkage of concrete at any time depends on the class of concrete, the properties of cement [10–12]. Some factors can influence on the kinetics [13] and the value of autogenous shrinkage, for example the different additives and conditions, such as internal curing [14], calcium carbonate whiskers [15], nanofibrillated cellulose [16], temperature rising inhibitor [17], and others. And, with increasing class of concrete, it can exceed the shrinkage deformation during drying [18, 19], and depending on the class of concrete can be 0.5…0.83 of the total shrinkage (shrinkage during drying + autogenous shrinkage) [18], and according to [19] – 0.32…0.38. Since the use of high-strength concrete is finding increasing application in the construction of building foundations due to the increase in the number of storeys, assessing the contribution of autogenous shrinkage to the formation of the stress field in the early period of hardening of massive monolithic structures is an urgent task. In this regard, the purpose of this work is:

- obtaining dependencies describing changes in the kinetics of heat dissipation and strength, taking into account the properties of cements and the presence of additives;
- methodology for taking into account deformations of autogenous shrinkage, when calculating the magnitude of stresses;
- modeling the stress-strain state of a massive monolithic structure in the early period of hardening and comparing of calculated and experimental values.

2. Materials and Methods

The research included modeling and experimental determination of the parameters of temperature fields and concrete deformations of a massive monolithic structure. The modeling methodology is based on the principles presented below.

The determination of temperature field parameters was carried out according to the method [20] depending on the concrete class C20/25 – B40 (B40 in the Russian international standard GOST 25192-2012 “Concretes. Classification and general technical requirements”, between C30/37 and C35/45) with specific heat dissipation at the age of 28 days respectively from 130 to 190 mJ/m^3 (for example, in [21], the simulation was performed for concrete with a specific heat dissipation of 140 mJ/m^3). In order to exclude factors that do not have a significant impact on the result of this study, the main objective of which is to assess the effect of autogenous shrinkage of concrete, taking into account the properties of cement, on the level of stress in the early period of hardening, the following assumptions were made:

- uninsulated upper surface, ambient temperature of 20 °C and initial concrete temperature of 20 °C;
- a statically determinate slab is erected on a concrete foundation.

Since the Russian Codes of Regulations (63.13330.2018, 70.13330.2012, 435.1325800.2018) do not contain quantitative criteria for crack resistance in the early period of hardening, the following condition is adopted as a criterion:

$$\sigma_\tau < R_{t,\tau}/1{,}5, \tag{1}$$

where σ_τ is the value of tensile stress at time τ; $R_{t,\tau}$ is the ultimate strength of concrete under axial tension at time τ; 1,5 is the safety factor for concrete under tension (in the Russian Code of Regulations 63.13330.2018).

The relative heat dissipation of hardening concrete due to the hydration of Portland cement under normal conditions is described by the equation [20]:

$$Q_\tau = Q_{28} \cdot \exp\left(k \cdot \left(1 - \left(\frac{28}{\tau}\right)^d\right)\right),\ \tau > 1, \tag{2}$$

where τ is the time (days); k, d are the coefficients, the values of which proposed by the authors are presented in Table 1.

In this case, the relative heat dissipation is considered as an indicator of the degree of cement hydration:

$$\frac{\alpha_\tau}{\alpha_{28}} = f\left(\frac{Q_\tau}{Q_{28}}\right). \tag{3}$$

When hardening under normal conditions, the change in the relative compressive strength of concrete $f_{c,\tau}/f_{c,28}$ (R/R_{28} in the Russian international standard GOST 25192-2012) over time is described by the equation 3.2 EN 1992-1-1:

$$\frac{f_{c,\tau}}{f_{c,28}} = \exp\left(s \cdot \left(1 - \sqrt{\frac{28}{\tau}}\right)\right),\ \tau > 1. \tag{4}$$

As is known, the compressive strength of concrete depends on the porosity of concrete and the hardening temperature, in connection with which the concepts “reduced age” or “degree of maturity” are used [22, 23]:

$$f_c = f\left(P\right), \quad \text{or} \quad \frac{f_c}{f_{P=0}} = \exp\left(k \cdot P\right), \tag{5}$$

and the porosity of concrete depends on the degree of hydration of the cement:

$$P = f\left(\alpha\right) = k\left(\frac{1}{\rho_c} + \frac{W}{C}\right) - \left(\frac{\left(1+n\right)\alpha}{\rho_{cs}} + \frac{1-\alpha}{\rho_c}\right), \tag{6}$$

therefore, the tensile strength of concrete f_{cm} at time τ depends on the relative heat dissipation at this moment and there is a relationship of the form [24]:

$$\frac{f_{cm,\tau}}{f_{cm,28}} = b \cdot \left(\frac{Q_\tau}{Q_{28}}\right)^x. \tag{7}$$

To take into account the influence of temperature conditions other than normal, the dependence of the ultimate strength of concrete from the “reduced age” (“degree of maturity”) [20, 23], similar to (2), in which the value τ_r is defined as:

$$\tau_r = \frac{\sum Q_i \tau_i}{T_a} - \tau_s, \tag{8}$$

where Q_i is the amount of heat dissipation per period τ_i; T_a is an average concrete temperature over a controlled hardening period; τ_s is the duration of the induction period (a parameter adjusted to take into account different setting times due to different mix temperatures caused by the use of retarding/ accelerating admixtures).

The value of autogenous shrinkage $\varepsilon_{ca}(\infty)$ according to EN 1992-1-1 is determined by the formulas:

$$\varepsilon_{ca}(\infty) = 2.5(f_{ck} - 10)10^{-6}; \tag{9}$$

$$\varepsilon_{ca}(t) = \beta_{as}(t)\varepsilon_{ca}(\infty); \tag{10}$$

$$\beta_{as}(t) = 1 - \exp\left(-0.2t^{0.5}\right). \tag{11}$$

Using (3) and taking $f_{ck} = f_{c,\tau}$, and instead of 10 taking $10 f_{c,\tau} / f_{c,28}$, after some transformations, we obtain a function connecting the kinetics of autogenous shrinkage and the kinetics of compressive strength of the form:

$$\frac{\varepsilon_{ca,\tau}}{\varepsilon_{ca,5}} = f\left(\frac{f_{c,\tau}}{f_{c,5}}\right) = f\left(\frac{R_\tau}{R_{28}}\right). \tag{12}$$

These dependencies make it possible to consider the kinetics of heat dissipation, strength, and autogenous shrinkage in relation to each other.

Experimental studies of temperature fields and deformations of concrete of a massive monolithic structure in the early period of hardening were carried out by the authors using temperature and deformation sensors [25]. The ultimate axial tensile strength of concrete f_{ctm} (R_{bt} in the Russian Code of Regulations 63.13330.2018*)*, the modulus of elasticity of concrete E_0, the creep coefficient of concrete φ at any time were calculated as a function of the ultimate compressive strength f_{cm} (R_b in the Russian Code of Regulations 63.13330.2018*)*, taking into account the degree of concrete maturity, according to (7) time [20, 24]:

$$f_{ctm} = 0.29 \cdot f_{cm}^{0.6}; \tag{13}$$

$$E_0 = 1000 \cdot \frac{0.05 \cdot f_{cm} + 57}{1 + \dfrac{29}{3.8 + f_{cm}}}; \tag{14}$$

$$\varphi(\tau) = \frac{8000}{\left(E_0(\tau)\right)^{0.785}}. \tag{15}$$

Tensile stresses from temperature deformations ε_T at any time were calculated using the formula [9]:

$$\sigma_T = \frac{k_r \cdot E_0 \cdot \alpha \cdot \Delta T}{(1+\varphi)} = \frac{k_r \cdot E_0 \cdot \varepsilon_T}{(1+\varphi)} \tag{16}$$

and taking into account the deformations of autogenous shrinkage ε_{ca} according to the formula:

$$\sigma_T = \frac{k_r \cdot E_0 \cdot (\varepsilon_T + \varepsilon_{ca})}{(1+\varphi)}. \tag{17}$$

3. Results and Discussion

The kinetics of heat dissipation, compressive strength of concrete and autogenic shrinkage are described by the equation:

$$Y_\tau = Y_{[\tau]} \cdot \exp\left(k \cdot \left(1 - \left(\frac{[\tau]}{\tau}\right)^d\right)\right), \quad (18)$$

the coefficients k, d of which for concrete based on cements with different hardening kinetics (with different hydration rates) are presented in Table 1.

Table 1. Coefficient values in (18) for concretes with different hardening kinetics.

Properties of concrete, Y	Coefficient	$f_{c,2}/f_{c,28}$ according to EN 206.1			
		Rapid > 0.5	Medium 0.3–0.5	Slow 0.15–0.3	Very slow < 0.15
Compressive strength, $R(f_{c,\tau})$	$k\ (s)$	< 0.25	0.25–0.43	0.43–0.7	≥ 0.7
	d	0.5			
	$[\tau]$	28			
Heat dissipation, Q_τ	k	$\lesssim$ 0.15	0.16–0.2	0.21–0.24	> 0.24
	d	$\lesssim$ 0.45	0.46–0.51	0.52–0.62	> 0.62
	$[\tau]$	28			
Autogenous shrinkage, $\varepsilon_{CA,\tau}$	k	$\lesssim$ 0.33	0.3–0.4	> 0.4	–
	d	$\lesssim$ 0.65	0.66–0.9	> 0.9	–
	$[\tau]$	5			–

Fig. 1 shows the calculated values according to (18) kinetics of heat dissipation under normal hardening conditions.

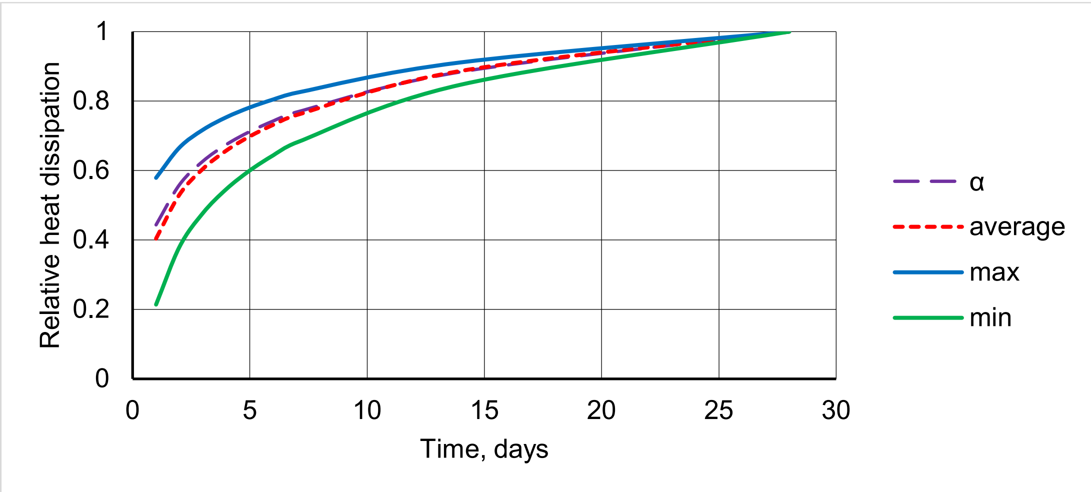

Figure 1. Relationship between relative heat dissipation and age of concrete under normal conditions. α – average statistical values for hydration kinetics for normally hardening concrete; max, min – according to (18) for quickly and slowly hardening concrete according to Table 1; average – average between max and min.

As is known, the value of autogenous shrinkage depends on the properties of cement, the presence of additives and can differ significantly (Table 2, 3) from the values according to (9). Autogenous shrinkage develops most intensively under normal conditions during the first 5–7 days [10].

Table 2. Values of autogenous shrinkage of concrete of various classes.

Concrete class	Autogenous shrinkage, (10^{6})	
	EN 1992-1-1	Data of the authors with different admixtures and additives
C20/25	25	17…72 (0.68…2.88)
C60/75	125	110…360 (0.88…2.88)

Table 3. Autogenous shrinkage values.

Data	Autogenous shrinkage, (10^{6})			
	Cement paste		Concrete or mortar[1]	
	72 h	120 h	72 h	120 h
[11]	1200	1470	(120–240)*	(147–295)*
[26]	600	750	(60–120)*	(75–150)*
	300	390	(30–60)*	(39–78)*
[13]			2000[1] (800–1000)*	
			1100[1] (440–550)*	
			950[1] (238–475)*	
			450[1] (180–225)*	
[27]	250	275	(25–50)*	(27.5–55)*

* according to our forecast

It is obvious that autogenous shrinkage deformations can vary over a very wide range. In this study, values at the age of 28 days were taken from $20 \cdot 10^{-6}$ for C20/25 to $80 \cdot 10^{-6}$ (ε) and $160 \cdot 10^{-6}$ (2ε) for B40 (by the Russian Code of Regulations 63.13330.2018).

Fig. 2 shows the measured values of autogenous shrinkage of concrete according to Table 2 in the first 5 days of hardening. It is obvious that the kinetics of autogenous shrinkage, especially in the first two days of hardening, varies significantly depending on the individual characteristics of cements and additives.

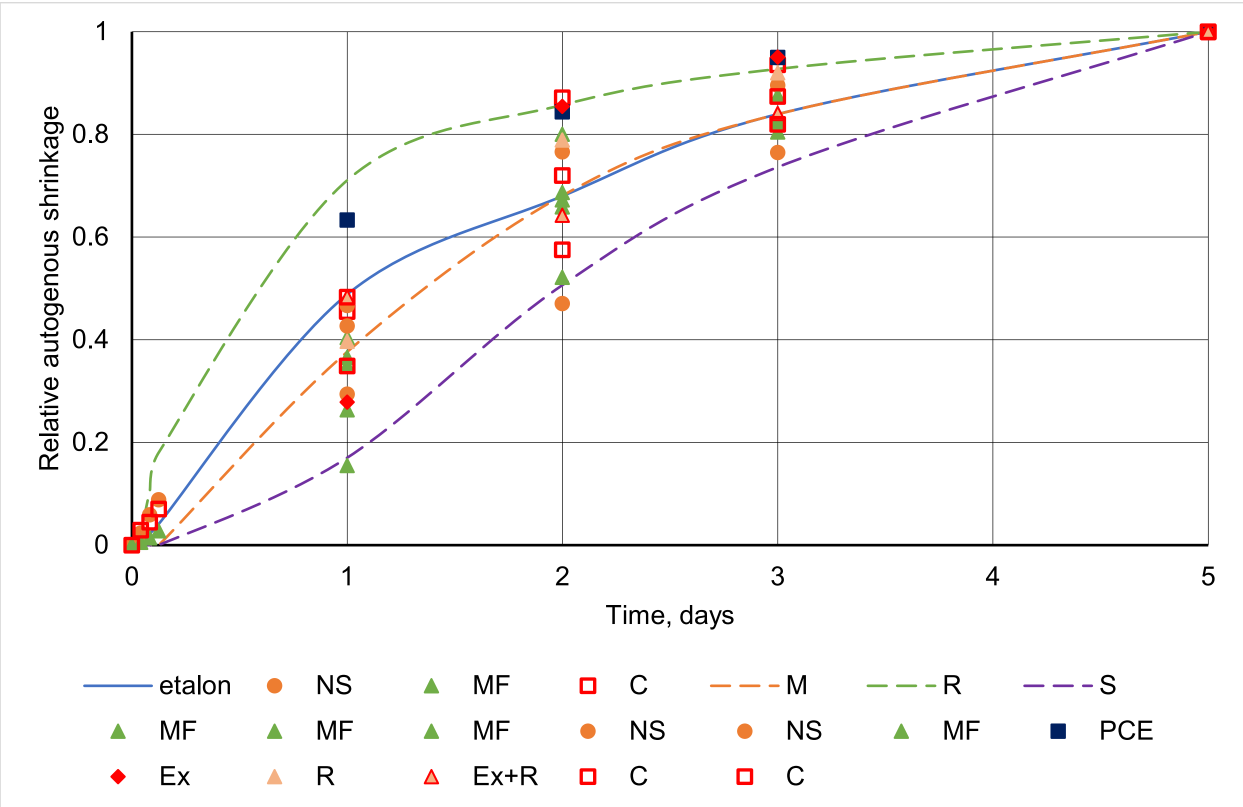

Figure 2. Kinetics of autogenous shrinkage. Etalon – without admixture, 1–15 with different PCE, MF, NS superplasticizers; Ex; R; C – expansion additive, hardening accelerator, complex additive; R – rapid; M – medium; S – slow according to Table 1.

Fig. 3 shows a comparison of the kinetics of the calculated values of autogenous shrinkage according to Table 1 with the values according to (9–11). A good compliance for type "M" concrete according to Table 1 with values according to EN 1992-1-1 for $\tau > 2$ is obvious.

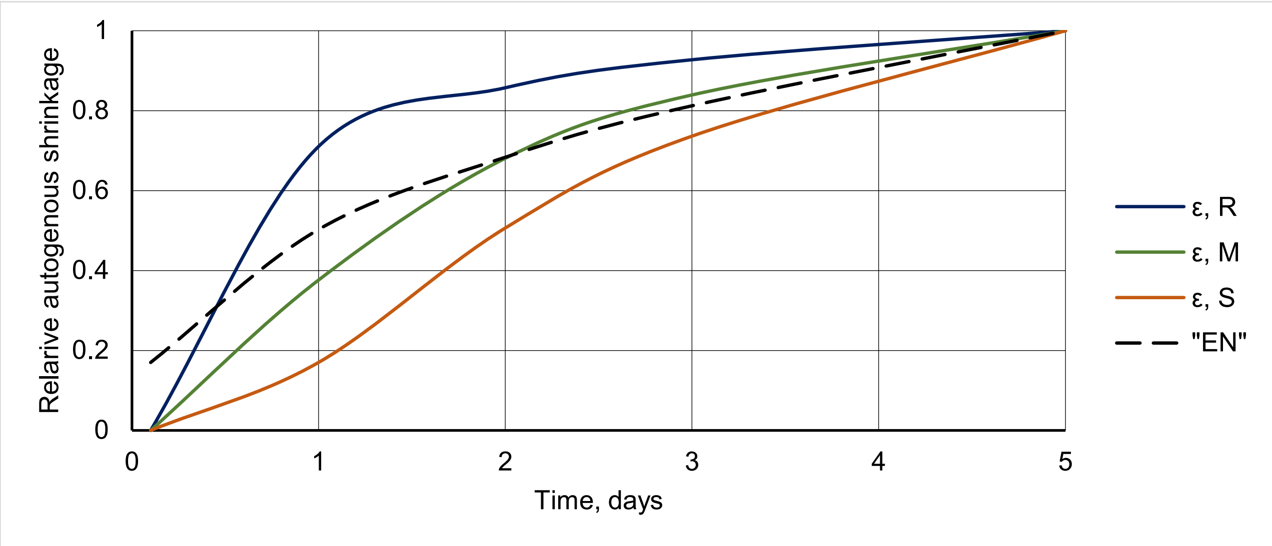

Figure 3. Kinetics of autogenous shrinkage. ε, R; ε, M; ε, S – according to (16); "EN" – according to EN 1992-1-1.

Fig. 4 shows the calculated "center-top" temperature difference of foundation slabs 0.7 and 1.5 m thick made of fast-hardening concrete of classes C20/25 (B25) – B40 and the "center-top" temperature difference measured during the construction of a real foundation slab 1.5 m thick made of class B40 concrete. According to data, for example, [28], a temperature difference between "center-top" of up to 28.7 °C was noted, while deformations on the surface reached values of 126–137 µs.

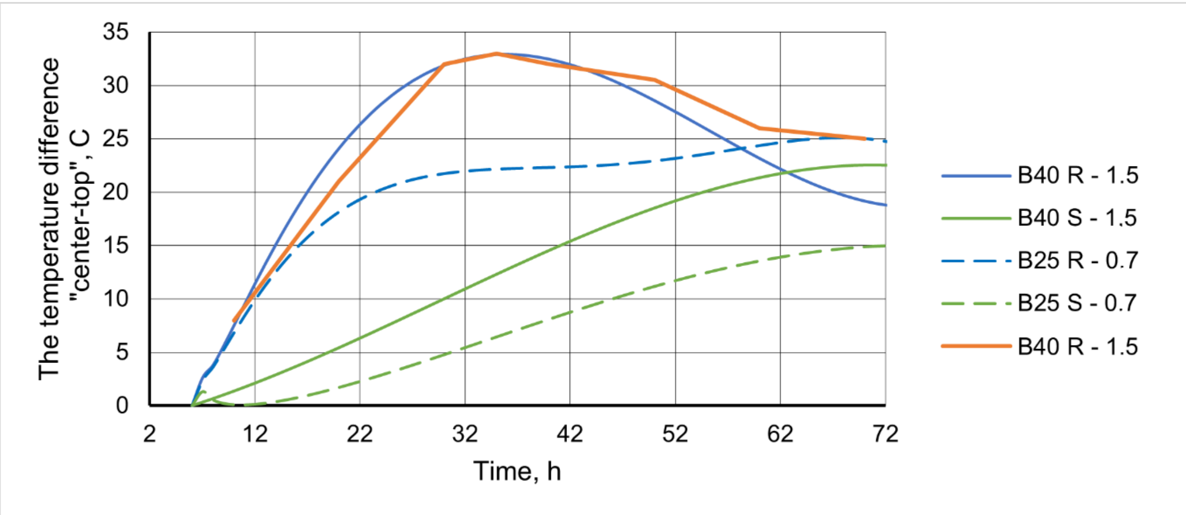

Figure 4. Relationship between "center-top" temperature difference of foundation slabs 1.5 m and 0.7 m thick. B25…B40 – 1.5 (0.7) – design values for concrete of the corresponding classes; B40 R – 1.5 Э – measured values; R, S – rapid and slow hardening concrete.

3.1. Theoretical Prerequisites for Constructing a Calculation Methodology

Calculation of the kinetics of the stress level from temperature-shrinkage deformations in the early period of hardening of massive monolithic structures can be implemented using the following algorithm:

- depending on the class and hardening kinetics of cement (concrete) according to (18), the kinetics of heat dissipation is determined;
- according to the method, for example, [29], temperature fields are calculated with the determination of the temperature in the center and on the surface of the structure and the temperature difference "center-top" at any time of the analyzed period τ;
- average temperature for the analyzed hardening period T_a is determined;

– according to (8), the degree of concrete maturity is determined at any time during the analyzed period τ;
– reduced hardening time τ_a is determined for the analyzed period;
– compressive strength of concrete is determined at any time of the analyzed period τ according to (4) with $\tau = \tau_r$;
– determined by (13–15) concrete tensile strength, elastic modulus, and creep coefficient at any time τ are calculated;
– according to (18), the magnitude of autogenous shrinkage deformations at any time τ is calculated;
– according to (16) or (17), the magnitude of stress and the level of stress at any time τ are calculated.

Fig. 5 shows the calculated and measured values of the stress level in the first 5 days of hardening during the early period of hardening of a foundation slab 1.5 m thick. The value τ_s = 0 in (8) is accepted. The ratio of the stress level without taking into account autogenous shrinkage to the stress level taking into account autogenous shrinkage according to EN 1992-1-1 is 1.36 for concrete of class B40 and 1.09 for concrete of class B25. If the autogenous shrinkage deformation exceeds 2.5 times relative to the data in EN 1992-1-1 (Table 2), for class B40 concrete, the ratio of stress levels is 2.15. Comparison of the influence of autogenous shrinkage increased relative to (9) for concrete classes C20/25 and B40 clearly shows the increase in influence with increasing autogenous shrinkage, which increases with increasing class of concrete.

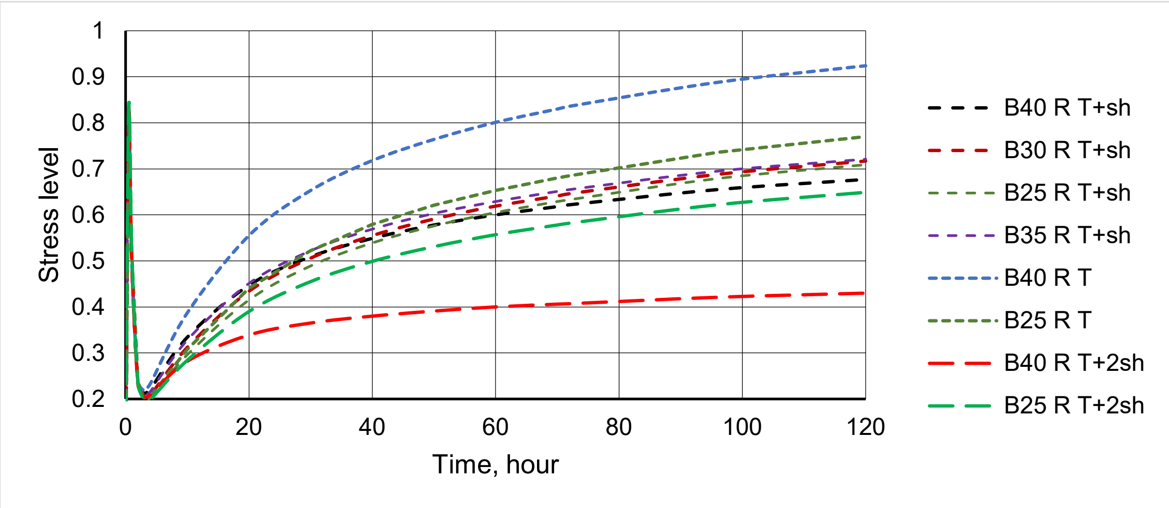

Figure 5. Dependence of the calculated values of the stress level in the early period of hardening of a foundation slab 1.5 m thick. B25…40 R T+sh, T+2sh – calculated values taking into account the influence of autogenous shrinkage for concrete of the corresponding classes; B25…40 R T – without taking into account the influence of autogenous shrinkage.

Fig. 6 shows the dependence of the stress level on the temperature difference “center-top” according to calculated and measured [25] results. The dependence of the stress level on the temperature difference “center-top” is described by the equation:

$$U(\sigma) = k\Delta T, \quad (19)$$

with k = 0.029 for calculated values without taking into account autogenous shrinkage and k = 0.033 for measured values.

It is in good agreement with the values measured in a real structure [20]. Taking the value $[u]$ = 1/1.5 = 0.67 for the calculated value of the permissible level of tensile stresses, we obtain for the permissible temperature difference “center-top” according to experimental data and the model the value ΔT = 20–23 °C, at $[u]$ = 0.85 we get ΔT = 26–28 °C. According to modeling data [30], at a temperature difference of 29 °C, the stress level was approximately 0.55, which is lower than the values according to our data. This once again confirms the relevance of research in this area. In [28], very different results, when modeling using five different techniques, were also obtained.

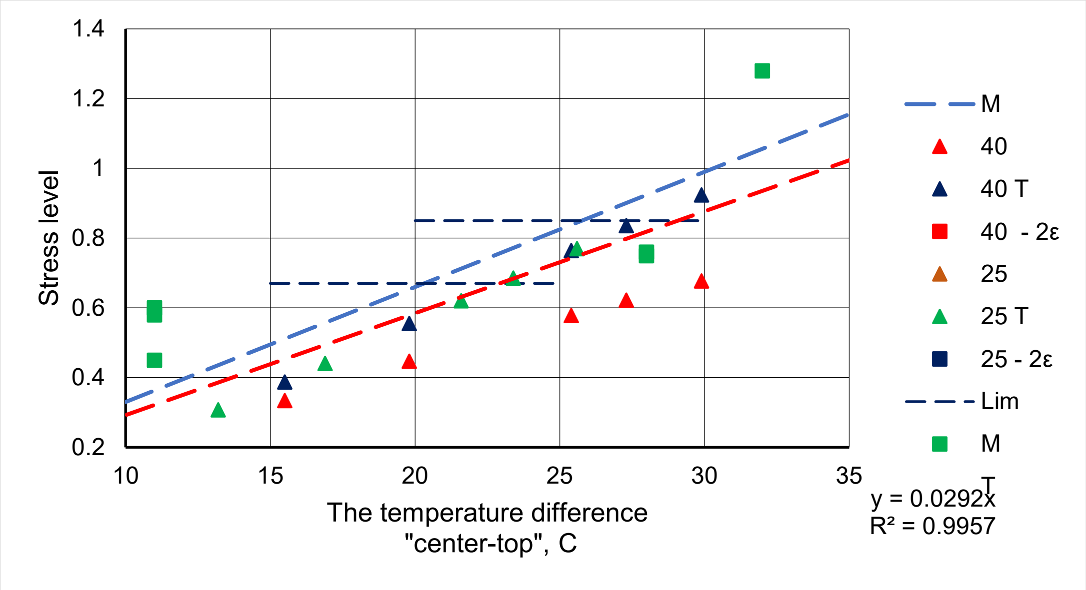

Figure 6. Dependence of the stress level on the temperature difference "center-top". 25…40 – calculated values for the corresponding class of quick-hardening concrete; T – excluding autogenous shrinkage; 2ε – with autogenous shrinkage doubled relative to (8); M – measured values; Lim – limit values.

4. Conclusions

1. The relationship between the kinetics of heat dissipation, strength, and autogenous shrinkage is shown and the corresponding calculation equations are presented. A classification of concretes based on the kinetics of the above properties is proposed.
2. The effect of some superplasticizing and mineral additives on the kinetics of autogenous shrinkage is shown.
3. An algorithm is proposed for calculating the stress level in the early (up to 5 days) period of hardening of massive monolithic slab foundations, taking into account autogenous shrinkage and the degree of maturity of concrete at any time. It is shown that failure to take autogenous shrinkage into account, when determining temperature-shrinkage deformations and stresses, can lead to an overestimation of the tensile stress level, depending on the concrete class and the value of autogenous shrinkage by up to 30 % or more.
4. An equation is obtained for the dependence of the tensile stress level on the "center-top" temperature difference for the structures under consideration. Comparison of the calculated values based on the simulation results and the values measured on the real structure showed a difference within 15 %.
5. A conclusion was made about the advisability of limiting the temperature difference "center-top" depending on the required reliability in the range from 20…23 °C to 26…28 °C.

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Received: 07.06.2024. Approved after reviewing: 16.09.2024. Accepted: 17.09.2024.