



Autogenous shrinkage of cement and concrete with superplasticizers of various chemical bases

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Abstract. Introduction. The stress-strain state of massive monolithic reinforced concrete structures during the early stages can cause cracks due to temperature deformation and autogenous shrinkage of concrete. Ignoring the deformations caused by autogenous shrinkage in calculations of the stress-strain state is often an unjustified simplification. This emphasizes the importance of studying the influence of formulations and technological factors on the amount and rate of autogenous shrinkage in concretes. The kinetics of autogenous shrinkage, especially during the first two days of hardening, can vary significantly depending on the specific characteristics of the cement and superplasticizer used. The aim of the study. To investigate the influence of the type of cement and superplasticizers with different chemical basis on the magnitude and kinetics of autogenous shrinkage and to obtain the necessary equations for calculations of thermally stressed states in the early stages. Methods. Analysis of existing approaches to assessing autogenous shrinkage in cement paste and concrete. Experimental study of autogenous shrinkage of cement pastes. Comparison results with published data and EN and JSCE standards. Results. Based on the proposed equation a classification of autogenous shrinkage kinetic of cements is proposed. The kinetics of autogenous shrinkage was varied: at the age of one day, the amount of autogenous shrinkage relative to seven days can vary up to six times, at the age of three days up to two times. An equation of the dependence of autogenous shrinkage on concrete strength is proposed for calculating the thermally stressed state of massive monolithic structures in the early period.

Keywords: massive monolithic structures, risk of early cracking, heat dissipation, superplasticizers, autogenous shrinkage, compressive strength of concrete

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1. INTRODUCTION

When forming the stress-strain state of massive monolithic reinforced concrete structures due to temperature and shrinkage deformations, there is a risk of early cracking [1, 2]. Shrinkage deformations are not usually the dominant factor in the risk of early cracking [3], and when assessing the level of tensile stresses, they can either be taken into account [2], including by introducing a temperature strain equivalent to shrinkage deformations [4], or not [2, 5]. However, their consideration provides a more reliable assessment of the stress level [6, 7], especially with a significant overlap time of layers and supply of concrete mix from different concrete mixing plants. This is due to the different shrinkage deformations of concrete, even from the same class, during the initial hardening period. This is because different manufacturers of concrete mixes can use different cements and chemical admixtures. When calculating the stress-strain state based on the hypothesis of planar sections, stress increments are defined as [2]:

$$\Delta\sigma(z) = \frac{E_0(z,t)}{1-\nu} \cdot (\Delta\varepsilon - \alpha \cdot \Delta T(z) - \Delta\varepsilon_{sh}(z) - \Delta\varepsilon_{cr}(z)), \quad (1)$$

where $E_0(z,t)$ is the E-modulus of concrete, $\Delta\varepsilon$ is the average increase in total deformation over the thickness of the slab, α is a coefficient of thermal expansion, $\Delta T(z)$ is the difference in temperature between the point at the current time step and the previous time step, $\Delta\varepsilon_{sh}(z)$ is the increase in shrinkage deformation, and $\Delta\varepsilon_{cr}(z)$ is the increase in creep deformation, ν is the Poisson ratio of concrete, and $(1 - \nu)$ takes into account the behavior of concrete under biaxial tension or compression conditions $\sigma_x = \sigma_y = \sigma$, and the value of $\Delta\varepsilon$ is defined as follows [2]:

$$\Delta\varepsilon = \frac{\int_0^h E_0(z) \cdot (\alpha \cdot \Delta T(z) + \Delta\varepsilon_{sh}(z) + \Delta\varepsilon_{cr}(z)) dz}{\int_0^h E_0(z) dz}, \quad (2)$$

where h is the thickness of the foundation plate.

When predicting the risk of early cracking using computer modeling methods, the algorithm for calculating temperature stresses usually includes [2, 4, 6]:

- calculation of temperature fields taking into account the conditions of heat exchange, ambient temperature and kinetics of heat generation of concrete;
- calculation of the degree of maturity of concrete based on the results of the assessment of temperature fields;
- calculation taking into account the degree of maturity of concrete, the tensile strength and the modulus of deformation;
- stress calculation with or without considering drying and autogenic shrinkage (AS) of concrete (ACS), despite the fact that shrinkage can partially compensate for temperature deformations during the temperature rise stage and, most importantly, increase the negative effect of shrinkage during the cooling stage. The possibility of early cracking due to the occurrence of ACS itself cannot be excluded [6, 8, 9].

Calculation of temperature fields is based on solving the differential equation of thermal conductivity [2]:

$$\lambda \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q = \rho \cdot c \cdot \frac{\partial T}{\partial t}, \quad (3)$$

where λ is the thermal conductivity coefficient, T is the temperature, Q is the internal heat source density, ρ is the material density, c is specific heat of concrete, and t is time.

The boundary conditions for convective heat transfer with the environment are given by [2]:

$$\lambda \cdot \frac{\partial T}{\partial n} + h \cdot (T - T_{\infty}) = 0, \quad (4)$$

where n is the normal vector to the surface, h is the heat transfer coefficient, and T_{∞} is the ambient temperature. Because the temperature distribution over the cross-section of the foundation plate is one-dimensional, therefore, instead of using equation (3), equation (5) can be used to give the result which is more accurate for this case [2]:

$$\lambda(z, t) \cdot \frac{\partial^2 T}{\partial z^2} + Q = \rho \cdot c \cdot \frac{\partial T}{\partial t}. \quad (5)$$

Ignoring shrinkage deformation in many cases may seem like an unreasonable simplification. According to our forecasts, it is possible, depending on design parameters, heat generation, magnitude, kinetics of ACS, to reduce or increase the risk of early cracking. This determines the relevance of studying the influence of formulation and technological factors on the magnitude and kinetics of ACS.

Shrinkage is a decrease in the volume of hardening concrete over time and is caused by physical and chemical processes. It includes [10, 11]:

- shrinkage due to evaporation of water (drying shrinkage) [12];
- shrinkage caused by a decrease in the volume of neoplasms relative to the volume of the reacting substances [6, 7, 10, 12, 13].

The latter is historically known as "contracting" or "general contracting" (from Latin - la contradizione), hereinafter - chemical shrinkage (CS) and consists of contractual porosity (CP) and AS [10, 13]. Well known that CP has a positive effect on frost resistance of concrete [13]. ACS creates a risk of early cracking of structures [2]. Well known that ACS increases with decreasing W/C ratio [10, 14-18]. It depends on the properties of cement [5, 19], the presence of chemical admixtures [20-24], for example, superplasticizers [25], and develops most intensively in the first 5-7 days of hardening [26-28].

There is relatively little data on the effect of superplasticizers on the magnitude and especially the kinetics of ACS. The CP/ACS ratio depends on the mineralogy of cement, the presence of chemical admixtures and mineral additives [22-24], W/C ratio [14-16], the timing of the formation of the crystalline framework [13, 28, 29].

Even an incomplete review shows that ACS can vary over a very wide range (Table 1). In addition, the kinetics of AS and ACS, especially during the first two days of hardening, can vary significantly depending on the individual characteristics of the cements and admixtures.

Table 1. Some literary data on the magnitude of ACS.

Data	AS, ACS, mm/m								
	cement paste (stone)				concrete or cement mortar				
	72 h	120 h	168 h	no data	24-48 h	72 h	120 h	168 h	no data
Soliman A.M. et al. (2011)	1.2	1.47				0.12–0.24	0.147–0.295		
Saje D. (2015)	0.6 0.3	0.75 0.39				0.060– 0.120 0.030– 0.060	0.075–0.15 0.039– 0.078		
Soliman A.M. (2011)						0.8–1.0 0.44–0.55 0.238– 0.475 0.18–0.225			

Continuation of Table 1

[30]	0.25	0.27 5				0.025– 0.050	0.0275– 0.055		
[31]									0.1–0.5
Lee N.K. et al. (2014)				0.75– 1.2					
Esping O. et al. (2005)									0.4–1.05
Holt E.E. (2001)									0.35– 1.25
Jonasson J.E. et al. (2000)						0.071– 0.817			
Saje D. (2015)					0.203– 0.235				
[32]					0.02				
Gowripala n N. (2019)					0.055– 0.18				
Khairallah R.S. (2009)			1.0						
Koenders E.A.B. et al. (1997)			0.9					0.03– 0.1	
[33]								0.15	
[34]								0.3–0.6	
[35]			0.2						

In 2016 Marušić E. et al. was shown that at the daily age, the ACS of concretes with a W/C of 0.318–0.625, with a cement consumption of 360–440 kg/m³ with a mobility of the concrete mixture of at least S4 was 0.08–0.23 mm/m, and up to 0.33 mm/m in 7 days. According to Soliman A.M. (2011), at the age of 96 hours, the ACS was 0.35 – 0.65 mm/m. According to the data Jonasson J.E. et al. (2000) concretes with a strength of 37.3 – 70.3 MPa at the age of 72 hours had ACS values of 0.74 – 0.83 mm/m, and at the age of 120 hours up to 0.9 mm/m. According to the above data, the ACS value of concrete at 72 hours is between $(25 \text{ and } 1000) \times 10^{-6}$, and at an older age, it is between $(27.5 \text{ and } 1250) \times 10^{-6}$. Obviously, these values can vary by up to a factor of 40. According to Delsaute B. et al. [36], the ACS values greatly exceed the predicted values according to the formulas ACI, CEB-FIP, JTC D 62-2004. Significant differences in ACS values are due to the influence of the type of cement and admixtures, the composition of concrete, and differences in measurement methods, according to, for example, Weng J. [11, 37]. The differences are not only in the experimental data. According to the equations of EN 1992-1-1 for concrete grades from C20/25 to C60/75, ACS is approximately $(25 \dots 125) \cdot 10^{-6}$, and according to JSCE No. 15, the values are approximately $(40 \dots 350) \cdot 10^{-6}$, i.e. according to JSCE No. 15, the ACS increases more intensively with an increase in the concrete grade (decrease in water consumption), which is well known.

An important point for taking into account the influence of ACS when calculating the stress-strain state of massive monolithic structures in the initial period is the presence of equations describing the kinetics of ACS. The dependence of ACS on time is generally represented as (for example, EN 1992-1-1):

$$\varepsilon_{ca}(t) = \beta_{as}(t) \varepsilon_{ca}(\infty), \quad (6)$$

where:

$$\beta_{as}(t) = 1 - \exp(-0,2t^{0,5}). \quad (7)$$

Equation (7) is used with coefficient variation quite often, for example, Ghanem H. et al. [19], Lee N.K. et al. (2014). The disadvantage of equations (6) and (7) is the uncertainty of the value $\varepsilon_{ca}(\infty)$. In equation (7), the value of $\beta_{as}(t) \approx 1$ at $t \approx 3000$ days, which does not imply the use of real experimental data, especially since it is not uncommon for significant ACS attenuation to occur as early as day 6, for example, according to Wen C. et al. [38]. Type of equations (8), such as proposed, for example, by, Lee N.K. et al. (2014) and Jonasson J.E. et al. (2000), are preferable:

$$\beta_{as}(t) = k \cdot \exp(a(c - (\frac{[t]}{\tau - \tau_s})^b)). \quad (8)$$

Equation (8) allows us to describe the kinetics of ACS at a known value of ε_{ca} at a specific time $[t]$, for example, 7 or 28 days.

In this work, we use authors equations of the type (9) to describe the change in properties such as heat dissipation (Q), compressive and tensile strength (R and R_t), and ACS (ε_{ca}), which depend on the degree of cement hydration [39]. These properties are interrelated and are important for evaluating the stress-strain state of concrete.

$$(Q, R, \varepsilon_{ca})_{\tau} = (Q, R, \varepsilon_{ca})_{[t]} \cdot \exp(k \cdot (1 - (\frac{[t]}{\tau - \tau_s})^d)). \quad (9)$$

The coefficients of equation (9), as proposed by the authors, are presented in Table 2, depending on the kinetics of the process, that is, on the actual kinetics of cement hydration.

Table 2. Coefficient in equation (9).

Properties of concrete	Coefficient in equation (9)	$f_{c,2}/f_{c,28}$ according to EN 206.1			
		Rapid > 0.5 «R»	Medium 0.3 – 0.5 «M»	Slow 0.15 – 0.3 «S»	Very slow < 0.15 «VS»
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	≤ 0.15	0.16-0.2	0.21-0.24	> 0.24
	d	≤ 0.45	0.46-0.51	0.52-0.62	> 0.62
	$[\tau]$	28			
Autogenous shrinkage, $\varepsilon_{CA,\tau}$	k	≤ 0.25	≤ 0.35	≤ 0.45	≤ 0.6
	d	0.5	0.6	0.75	0.9
	$[\tau]$	7			

Due to the fact that highly mobile and self-sealing concrete mixtures, commonly used in the construction of massive monolithic structures, contain various admixtures, primarily superplasticizers based on different chemical bases, which can affect the hydration kinetics and, consequently, the heat dissipation, strength, and autogenous shrinkage, the aim of this work is to investigate the effects of different types of cement and superplasticizers on the magnitude and kinetics of autogenous shrinkage, as well as to obtain dependences of autogenous shrinkage kinetics for use in calculations of the thermally stressed state during the early period of hardening of massive monolithic structures.

2. METHODS AND MATERIALS

Experimental studies were conducted using six different types of cement from five different manufacturers, as well as three different superplasticizers with various chemical compositions. Information about the cements used in the study is presented in Table 3. All of the cements were classified as fast-hardening, according to the Russian standard GOST 31108-2020 ($f_{c,2}/f_{c,28} > 0.4$). Details about the admixtures used can be found in Table 4.

Table 3. Studied cements.

Cement properties	Cements					
	1	2	3	5	6	7
	CEM I 42.5H ^{1,6}	CEM II/A- III 42.5H ^{1,6} slag	CEM I 42.5H ^{2,6}	CEM I 42.5H ^{3,6}	CEM II/A- II 42.5H CC ^{4,7}	CEM I 42.5 H ^{5,6}
Flexural/ Compressive strength, N/mm ² , 2 days age	4.59/22.4*	4.84/23.4	5.04/28.5	5.82/30.1	5.09/23.5	6.49/32.3
Flexural/ Compressive strength, N/mm ² , 28 days age	7.81/51.5	8.58/55.3	8.55/50.9	8.96/55.6	9.95/54.6	8.79/63.1
Normal consistency of cement paste, %	22.75	25.0	26.5	26.25	27.25	27.75
Setting time, min	115	150	150	170	150	140
C ₃ S	66.5±0.2	66.7±0.3	64.9±0.4	68.4±0.4	63.8±0.3	58.3±0.3
C ₂ S	12.1±0.3	11.9±0.3	12.1±0.3	10.7±0.3	16.1±0.3	15.3±0.4
C ₃ A	6.8±0.2	6.9±0.3	5.3±0.3	4.96±0.2	4.4±0.2	7.7±0.2
C ₄ AF	12.1±0.2	12.3±0.2	15.1±0.2	13.1±0.3	14.2±0.2	12.3±0.2
SO ₃	2.37±0.2	2.11±0.2	2.84±0.2	2.78±0.2	2.82±0.2	3.06±0.3
ε _{sh, 120 d} , mm/m	1.64	1.88	1.62	2.07	2.01	1.33
ε _{sh, 105 C} , mm/m	3.96	4.12	3.58	4.37	4.51	3.59

Notes: 1-5 – manufacturers; 6 – GOST 31108-2020; 7 – GOST 22266-2013; * – flexural/compressive strength.

Table 4. Admixtures.

№	Admixture	Standard	Chemical basis
1	"POLIPLAST SP-4"	TS 5745-026-58042865-2007	sopolymers based on naphthalene sulfonic acid (NF)
2	"LINAMIX PC" type 2	TS 5745-033-58042865-2008	polyoxyethylene derivatives of polycarboxylic acids and polyethylene glycol (PCE)
3	PFM-NLK	TS 5745-022-58042865-2007	mixture of sodium salts of polymethylene naphthalene sulfonic acids, hydrophobizing and air-entraining component (NFA)

The dosage of all superplasticizers used was 0.5% of the commercial product. The properties of the cements were determined in accordance with Russian standard GOST 30744-2001. Shrinkage deformations of the cements were measured using the method described in Russian standard GOST 24544-2020. Samples measuring 40x40x160 mm were prepared from cement paste with a water-cement ratio of 0.27. After being kept in molds for 22 hours under isolation, the samples were removed from the molds and protected from water evaporation. The first measurements of the dimensions of samples were taken 24 hours after the molding process. Next, ACS was measured for 7 days at a temperature of 20 ± 2 °C. During the tests, changes in the linear dimensions of the samples

were recorded with an accuracy of 0.005 mm. In parallel, the volumetric deformations of the second series of samples were measured using the method of measuring volumetric autogenous shrinkage described, for example, by Lee N.K. et al. (2014). The ACS results for the samples from the first series were then recalculated based on the initial point of 12 hours, using data on the volume change for the samples in the second series from 12 to 24 hours.

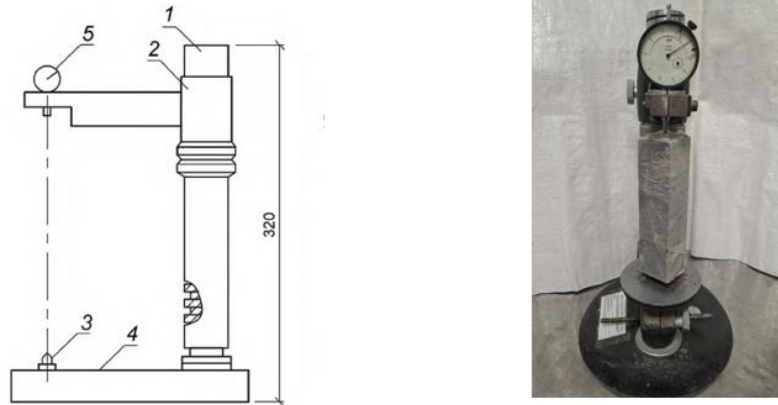


Fig. 1. Determining drying shrinkage. Left – diagram according to GOST 24544-2020, right – photo.

To estimate the ACS values of concrete, we used a relationship similar to the one that describes the drying shrinkage of concrete as a function of the volume concentration of cement in the concrete by Pickett and Sheikin A.E.:

$$\varepsilon_{AS,C} = \varepsilon_{AS,CS} \cdot V_{CS}^{\alpha}, \quad (10)$$

where $\varepsilon_{AS,C}$ is the ACS of concrete; $\varepsilon_{AS,CS}$ is the ACS of cement stone; V_{CS} is the volume concentration of cement stone. The value of the α indicator is assumed to be 1.6.

3. RESULTS AND DISCUSSION

The values of the ACS deformation for the studied cements are presented in Table 5.

Table 5. ACS studied cements, mm/m.

Shrinkage	Superplasticizer	Cements, Table 3					
		C1	C2	C3	C5	C6	C7
ACS 7 days age	no	0.619	0.618	0.685	0.706	0.578	0.527
	1	0.828	0.566	0.434	0.50	0.459	0.446
	2	0.748	0.713	0.561	0.712	0.70	0.361
	3	0.586	0.541	0.495	0.864	0.617	0.372

The values of ACS deformations at the age of 7 days relative to drying shrinkage (DS) deformations at the age of 120 days are presented in Table 6.

Table 6. Relative ACS studied cements.

Relative shrinkage	Admixture	Cements, Table 3					
		C1	C2	C3	C5	C6	C7
<u>ACS, 7 days</u> DS, 120 days	no	0.43	0.34	0.55	0.38	0.31	0.41
	1	0.66	0.35	0.32	0.34	0.26	0.29
	2	0.45	0.38	0.34	0.41	0.45	0.20
	3	0.44	0.36	0.29	0.51	0.34	0.31

Autogenous shrinkage deformation of cement C1, according to Table 3, with superplasticizers 1-3, according to Table 4, relative to the admixture-free reference sample, were plotted in Fig. 2.

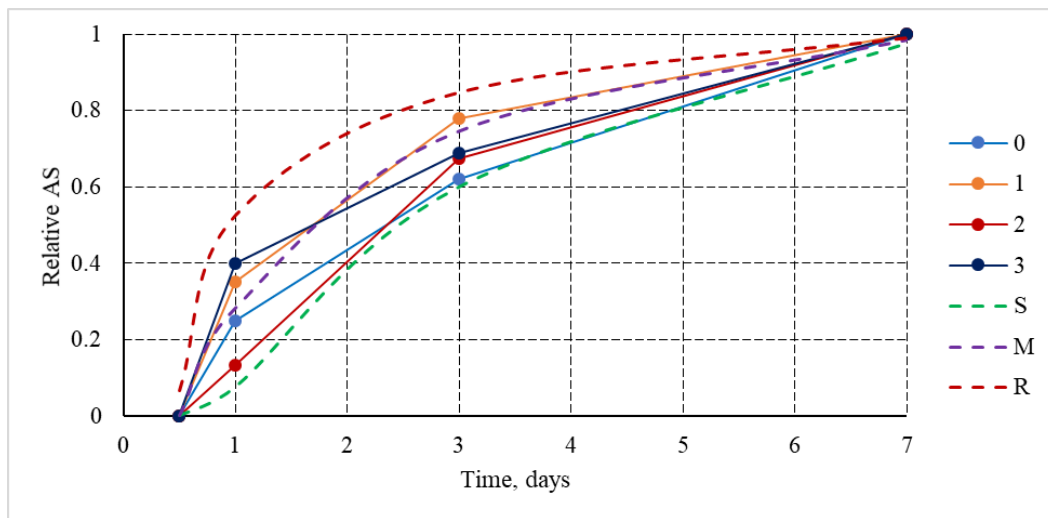


Fig. 2. Time variation of AS deformations of C1 cement with superplasticizers 1-3 relative to the admixture-free reference sample. S, M, R – according to equation (9).

AS deformation of cement C2, according to Table 3, with superplasticizers 1-3, according to Table 4, relative to the admixture-free reference sample, were plotted in Fig. 3.

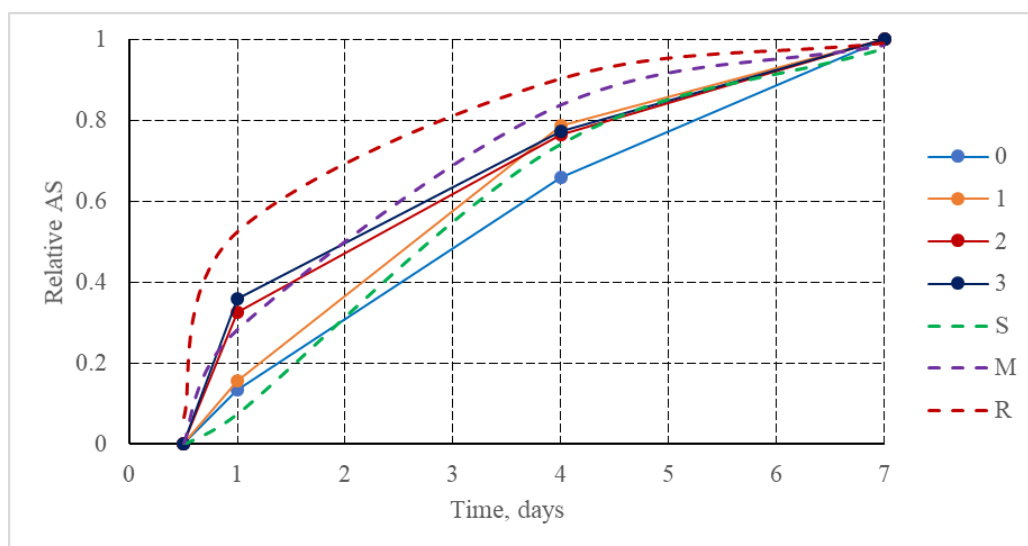


Fig. 3. Time variation of AS deformations of C2 cement with superplasticizers 1-3 relative to the admixture-free reference sample. S, M, R – according to equation (9).

AS deformation of cement C3, according to Table 3, with superplasticizers 1-3, according to Table 4, relative to the admixture-free reference sample, were plotted in Fig. 4.

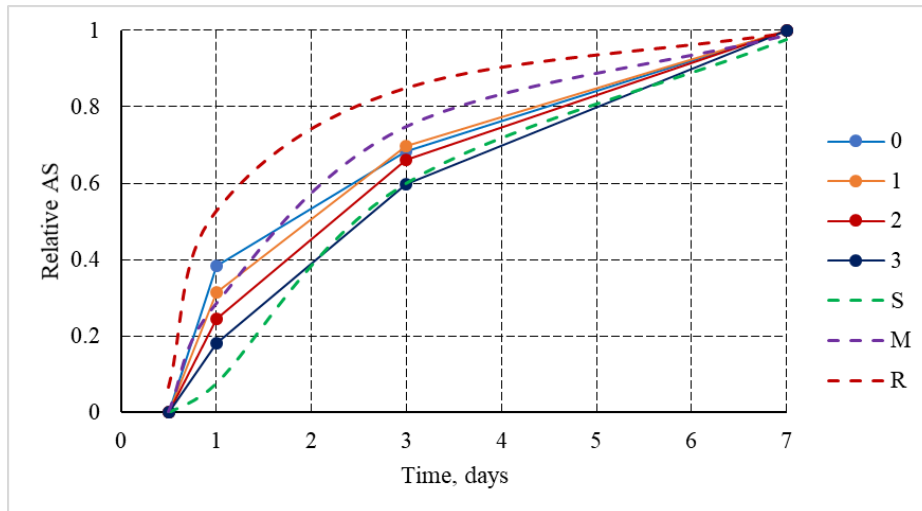


Fig. 4. Time variation of AS deformations of C3 cement with superplasticizers 1-3 relative to the admixture-free reference sample. S, M, R – according to equation (9).

AS deformation of cement C5, according to Table 3, with superplasticizers 1-3, according to Table 4, relative to the admixture-free reference sample, were plotted in Fig. 5.

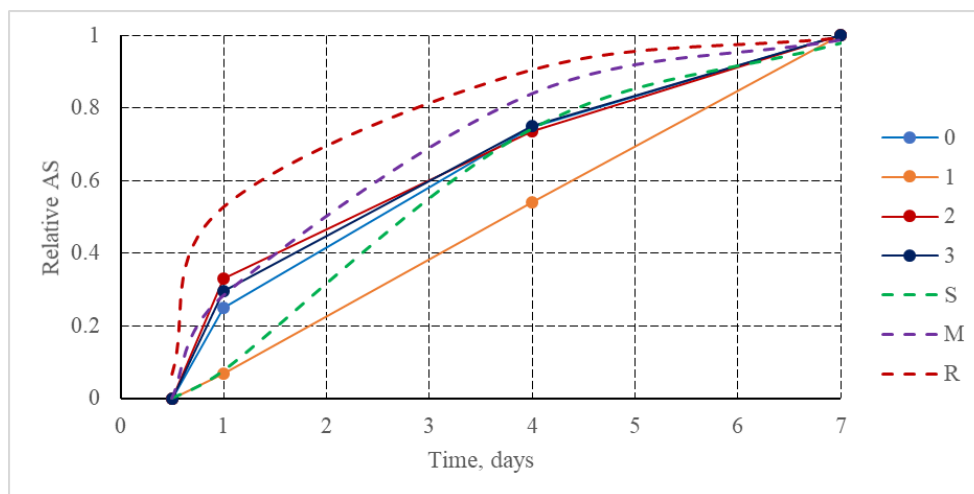


Fig. 5. Time variation of AS deformations of C5 cement with superplasticizers 1-3 relative to the admixture-free reference sample. S, M, R – according to equation (9).

AS deformation of cement C6, according to Table 3, with superplasticizers 1-3, according to Table 4, relative to the admixture-free reference sample, were plotted in Fig. 6.

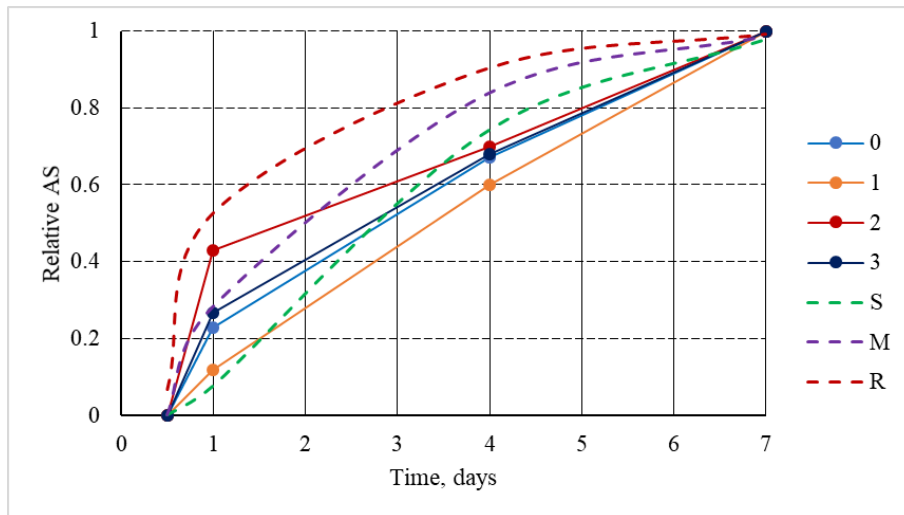


Fig. 6. Time variation of AS deformations of C6 cement with superplasticizers 1-3 relative to the admixture-free reference sample. S, M, R – according to equation (9).

AS deformation of cement C7, according to Table 3, with superplasticizers 1-3, according to Table 4, relative to the admixture-free reference sample, were plotted in Fig. 7.

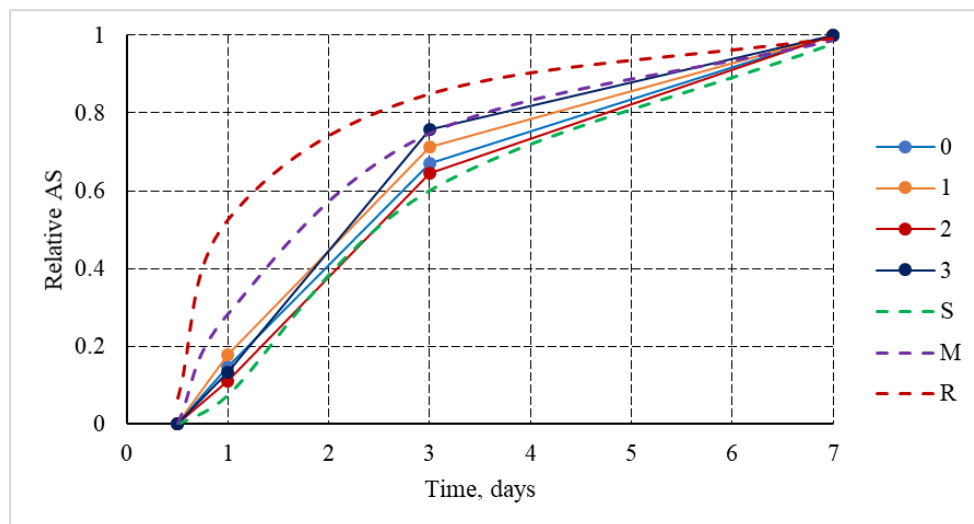


Fig. 7. Time variation of AS deformations of C7 cement with superplasticizers 1-3 relative to the admixture-free reference sample. S, M, R – according to equation (9).

The value of AS for the studied cements, including those with superplasticizers, was 0.2-0.66 DS at the age of 7 days. The kinetics of AS in the studied cements without and with superplasticizers can be mainly attributed to the "VS" and "S" groups in accordance with Table 2. In some cases, take place transitioning to the "M" group in accordance with Table 2 at an age of less than 24 hours. After 3 days, a significant portion of the results can be attributed to the "VS" group. For concreting massive monolithic structures, preference should be given to the "cement + admixture" combination, which provides the maximum AS value at the age of about 1-2 days, since it is during this period that massive monolithic structures often experience a rapid increase in temperature to a maximum and, naturally, an increase in temperature deformations to a maximum. The type of cement and admixture have a significant effect on the kinetics of AS. At the age of 1 day, the relative AS of the studied cements was 0.07...0.43 of the value at the age of 7 days, at the age of 3 days 0.38...0.78, and at the age of 4 days 0.54...0.85 (Fig. 8). For the concreting of massive monolithic structures, it is

recommended to use the "cement + superplasticizer" combination, which provides the maximum early AS value at about 1-2 days after casting. This is because during this time period, massive monolithic structures often experience a rapid temperature increase to a maximum, which naturally leads to a maximum increase in thermal deformation. The type of cement and superplasticizers has a significant impact on the kinetics of early AS development. At 1 day after casting, the relative early AS of the studied cements ranged from 0.07 to 0.43 of its value at 7 days. At 3 days, it ranged from 0.38 to 0.78, and at 4 days, it was between 0.54 and 0.85 (see Fig. 8).

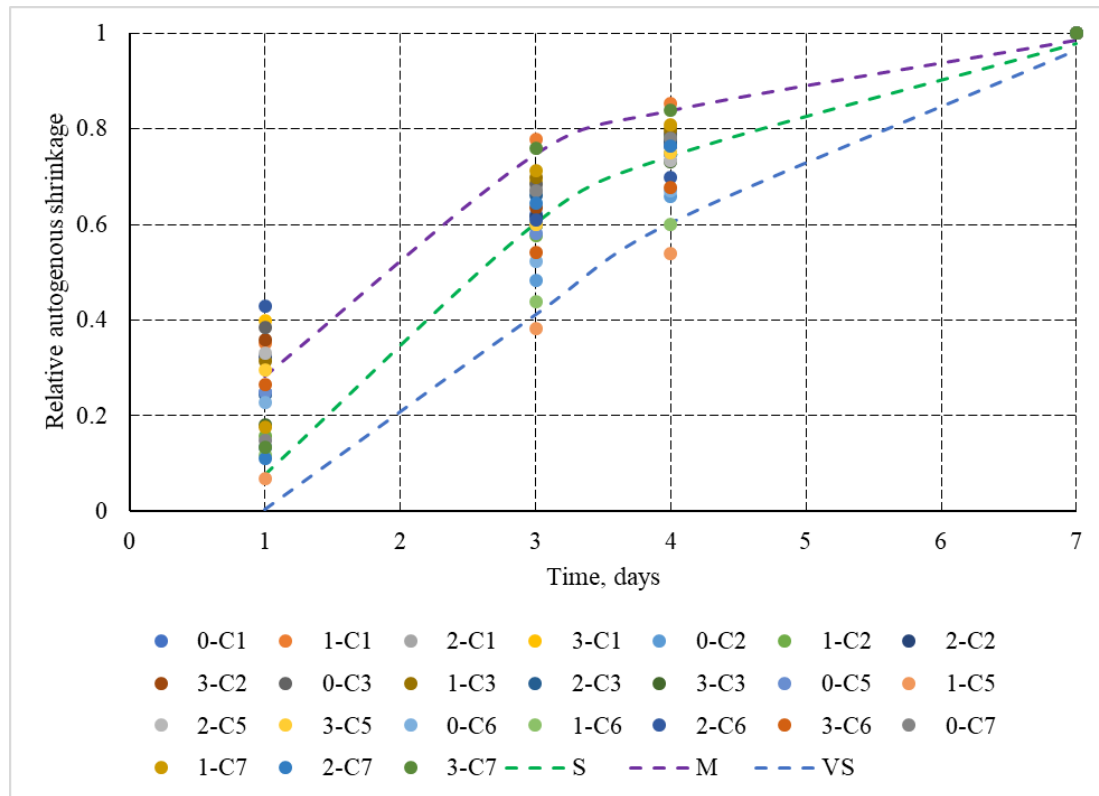


Fig. 8. Autogenous shrinkage of the studied cements. 1, 2, 3 – superplasticizers according to Table 2; 0 – standard without superplasticizer; C1 – C7 – cements according to Table 3; S, M, VS – according to Table 2 and equation (9).

A clear dependence of the effect of the type of superplasticizer on the kinetics of AS was not observed (Table 7).

Table 7. The effect of different types of superplasticizers on the kinetics of AS after 24 hours.

Superplasticizer	Cement in accordance to Table 3					
	C1	C2	C3	C5	C6	C7
1	speeds up*	speeds up	slows	slows	slows	speeds up
2	slows	speeds up	slows	speeds up	speeds up	slows
3	speeds up	speeds up	slows	speeds up	speeds up	slows

Note – * relative to the reference without superplasticizer.

The dependence of AS kinetics at the age of 7 days according to the experimental data obtained in comparison with kinetics according to EN 1992-1-1, JSCE, and Lee N.K. et al. (2014), transformed to $[t] = 7$ days are plotted in Fig. 9. At the first stage of the procedure of transformation according to equations (7, 8), the values $\beta_{as,i3000}$ from 0 to 1 at $[t] = 3000$ were obtained. Further, it was assumed that $[t] = 7$ and the values $\beta_{as,7} = Z$ were calculated. Further, the values $\beta_{as,i7}$ from 0 to 1 were calculated at $[t] = 7$.

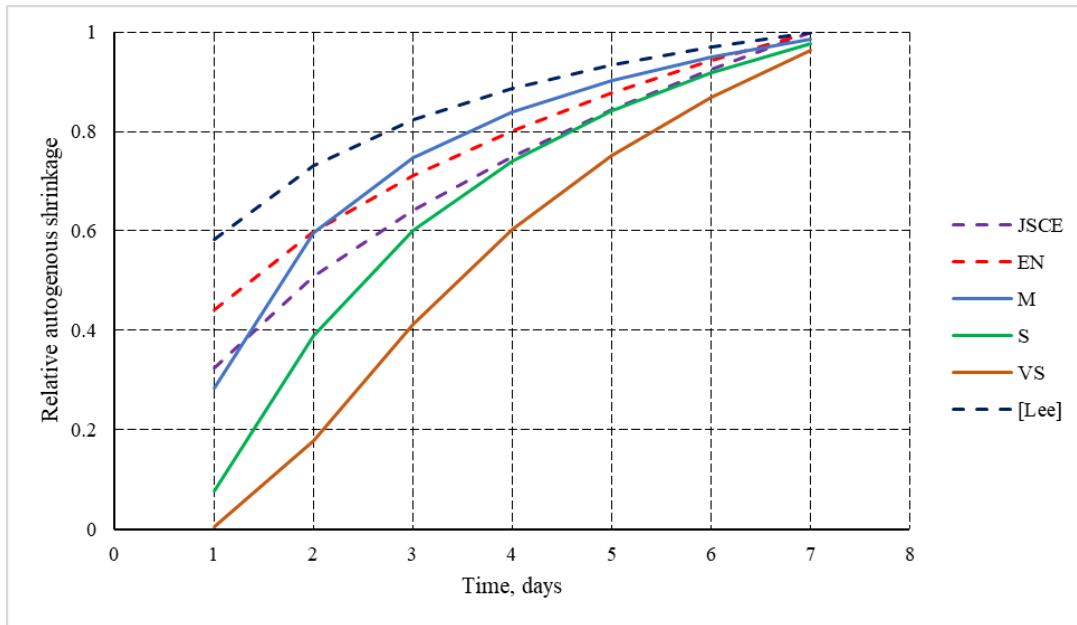


Fig. 9. Autogenous shrinkage according to experimental data (M, S, VS), equation (9), EN 1992-1-1, JSCE, [Lee] – by Lee N.K. et al. (2014).

It is clear that, at an age of up to 7 days, the cements studied with superplasticizers assigned to the "M" group correlate more closely with EN 1992-1-1 and, to a lesser extent, with JSCE, in terms of the kinetics of AS deformation. Up to 7 days the cements with superplasticizers from groups "S" and "VS", show significantly slower increase of AS deformation, which is not sufficient to compensate for temperature stresses.

The type of cement and superplasticizer has a significant impact on the amount of AS deformation, especially at an early age (Fig. 10).

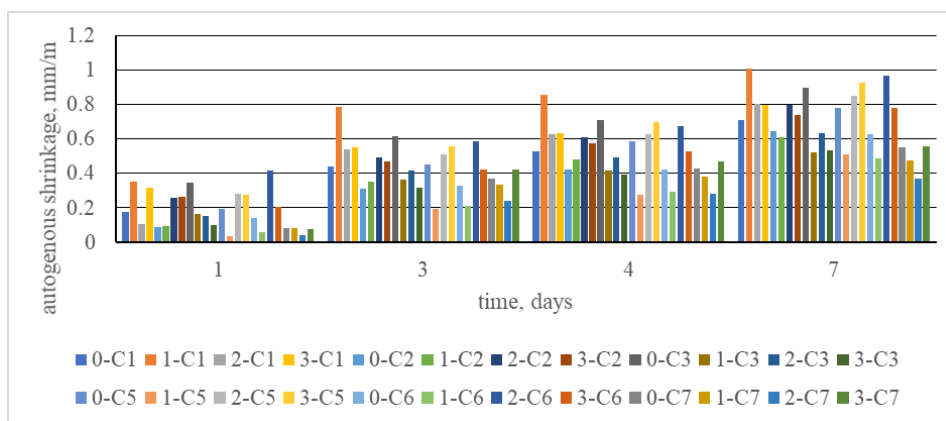


Fig. 10. Autogenic shrinkage of the studied cements. 1, 2, 3 – superplasticizers according to the Table 4; 0 – standard without superplasticizer; C1 – C7 – cements according to Table 3.

At the age of one day, the AS value relative to the reference without a superplasticizer for the studied cement was between 0.18 and 3.09. At the age of 3 days relative AS was changed from 0.43 till 1.79, and at the age of 7 days from 0.58 till 1.54. With increasing age, the influence of the type of cement and the superplasticizer on the change in the AS value relative to the etalon without superplasticizer decreases (Fig. 11).

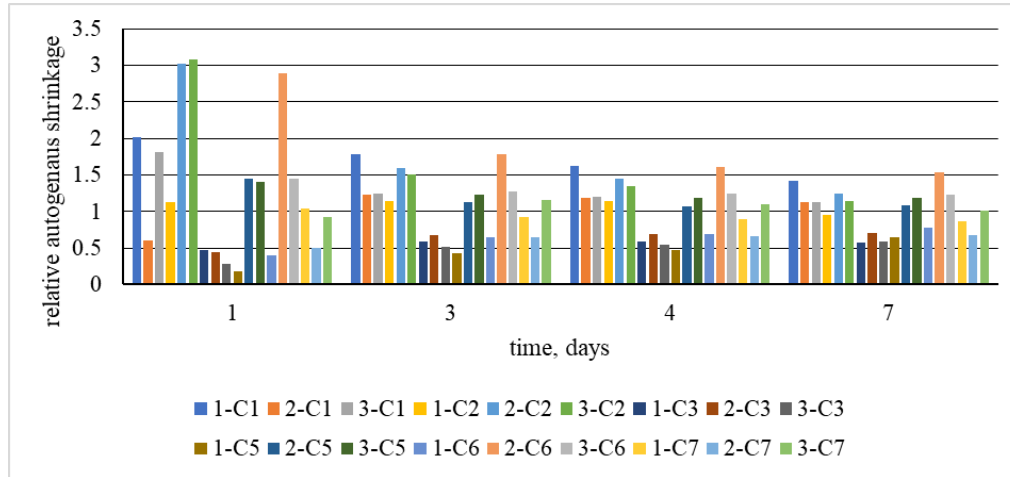


Fig. 11. Autogenic shrinkage of the studied cements relative to the reference without superplasticizer. 1, 2, 3 – superplasticizers according to Table 4; C1 – C7 – cements according to Table 3.

A clear relationship between the type of superplasticizer and the value of AS after one day was not observed (Table 8). Cement C2 demonstrated an increase in AS deformations with the use of all superplasticizers. Cement C3 showed a decrease in AS deformations when using all superplasticizers. The behavior of cements C5 and C6 was similar.

Table 8. The effect of the type of superplasticizer on the value of AS at the age of 24 hours.

Superplasticizer	Cement in accordance to Table 3					
	C1	C2	C3	C5	C6	C7
1	more*	more	less	less	less	more
2	less	more	less	more	more	less
3	more	more	less	more	more	less

Note – * relative to the reference without superplasticizer.

The AS magnitude predicted by equation (10) for concretes with a cement content of 260 kg/m³ ($W/C = 0.65, f_c \approx 30 \text{ N/mm}^2$) and 420 kg/m³ ($W/C = 0.4, f_c \approx 57 \text{ N/mm}^2$) on the studied cements in age 1, 3 and 7 days relative to the etalon without superplasticizer were plotted in Fig. 12. The influence of the W/C ratio on the AS of concrete were taken into account in accordance with JSCE.

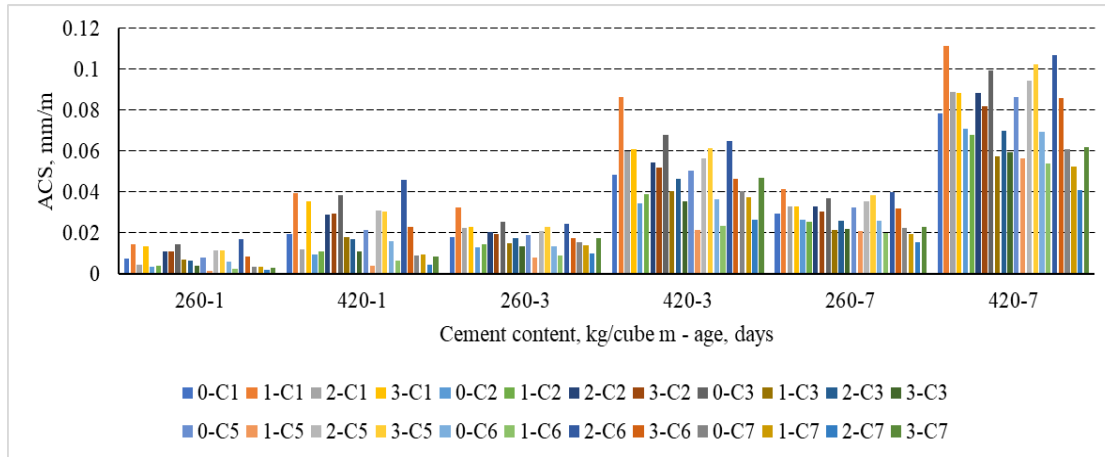


Fig. 12. Predicted values of autogenous shrinkage of concretes on the studied cements. 1, 2, 3 – superplasticizers according to Table 4; C1 – C7 – cements according to Table 3; 260, 420 - cement content; 1, 3, 7 – age, days.

At the age of 3 days, the predicted magnitude of the ACS for concrete with a cement content of 260 kg/m³ were between 0.008 and 0.032 mm/m, and for concrete with 420 kg/m³, they were between 0.021 and 0.087 mm/m. At the age of 7 days, these magnitudes increased to 0.015 and 0.42 mm/m for concrete with 260 kg/m³ and 0.041 and 1.11 mm/m for concrete with 420 kg/m³. The ACS magnitude for C 35/45 concrete at 7 days is approximately 0.047 mm/m according to JSCE and approximately 0.034 mm/m according to EN. These results do not conflict with the data in Table 1 or the conclusions of Delsaute B. et al. [36], and although the obtained quantitative values may not be suitable for practical use, they provide an insight into the effect of superplasticizers on the magnitude and rate of ACS.

A relationship has been established between the relative ACS $\varepsilon_{AS,\tau}/\varepsilon_{AS,7}$ and the relative compressive strength of concrete $f_{C,\tau}/f_{C,28}$. This relationship is rational for calculating the thermally stressed state of massive monolithic structures during the early period.

$$\frac{\varepsilon_{AS,\tau}}{\varepsilon_{AS,7}} = a \frac{f_{C,\tau}}{f_{C,28}} + b \left(\frac{f_{C,\tau}}{f_{C,28}} \right)^2. \quad (11)$$

The values of coefficients a and b in equation (11) are respectively minus 0.64 and 2.48 for the "VS" group, 0.24 and 1.4 for the "S" group, 1.4 and minus 0.12 for the "M" group in accordance with Table 2. The presence of dependence by equation (11) with $R^2 > 0.99$ makes it possible to take into account the influence of ACS depending on the strength kinetics when calculating stresses according to equations (1, 2). The values of the coefficients a and b in equation (11) are $a = -0.64$ and $b = 2.48$ for the group "VS", $a = 0.24$ and $b = 1.4$ for the group "S", and $a = 1.4$ and $b = -0.12$ for the group "M" in accordance with Table 2. The high value of $R^2 = 0.99$ in equation (11) indicates a strong relationship between the variables, allowing us to account for the influence of ACS on stress when calculations using equations 1 and 2.

4. CONCLUSIONS

The results of studies on the effect of three types of superplasticizers (PCE, NF, and NFA) on the kinetics and magnitude of autogenous shrinkage for six different cements up to 7 days old are presented. Without the use of superplasticizers, C5 cement with a class of 52.5 showed the maximum increase in autogenous shrinkage from 1 day to 7 days, which was 0.706 mm/m. The values of autogenous shrinkage for other cements ranged from 0.527 mm/m to 0.685 mm/m, indicating a difference of up to 30% between them. When the NF type superplasticizer was used, C1 cement of class 42.5 showed a maximum increase in autogenous shrinkage from 1 to 7 days of 0.828 mm/m. The

values of autogenous shrinkage for other cements ranged from 0.434 to 0.566 mm/m, which is a difference of up to 30%. For all the cements, except C1 with an NF-type superplasticizer, the autogenous shrinkage at the age of 7 days was between 0.63 and 0.91 compared to cement without a superplasticizer. When a superplasticizer of the PCE-type was used, C1 cement with a class of 42.5 showed the maximum increase in autogenous shrinkage of 0.748 mm/m between 1 and 7 days. The magnitude of autogenous shrinkage ranged from 0.361 to 0.713 mm/m, which is an almost doubled difference. In C1, C2, and C6 cements with a PCE-type superplasticizer, the autogenous shrinkage at 7 days was between 1.15 and 1.21 compared to cement without a superplasticizer. C3 and C7 cements with a PCE-type superplasticizer, had magnitude of relative autogenous shrinkages at 7 days between 0.69 and 0.82 compared to cement without the superplasticizer. However, for C5 cement, the autogenous shrinkage remained unchanged with the addition of a PCE-type superplasticizer. When the NFA-type superplasticizer was used, C5 cement with a class of 52.5 showed the maximum increase in autogenous shrinkage from 1 to 7 days, which was 0.864 mm/m. The magnitude of autogenous shrinkage ranged from 0.372 to 0.617 mm/m, meaning there was a difference of more than 1.6 times between the highest and lowest values. For C5 and C6 cements containing NFA-type superplasticizers, the autogenous shrinkage at 7 days was between 1.07 and 1.22 times that of cement without a superplasticizer. For all other cements containing an NFA-type superplasticizer, relative autogenous shrinkage was equal on 0.7 and 0.95 of autogenous shrinkage of plain cement.

The magnitude of autogenous shrinkage of the studied cements, including those with superplasticizers, at the age of 7 days was equal 0.2...0.66 of the magnitude of drying shrinkage at the age of 120 days. The type of cement and the chemical base of the superplasticizer have a significant effect on the kinetics of autogenous shrinkage. At the age of 1 day, the relative autogenous shrinkage in the studied cements was equal 0.07...0.43 of the magnitude at the age of 7 days. At the age of 3 days, this magnitude was equal 0.38...0.78, and at the age of 4 days was equal 0.54...0.85. At the age of 7 days, the predicted magnitude of autogenous shrinkage of concrete for concretes with a cement content of 260 kg/m³ were 0.015...0.042 mm/m, and with a cement content of 420 kg/m³ was equal 0.041...0.111 mm/m. The magnitude of autogenous shrinkage of concrete class 35/45 aged up to 7 days according to JSCE is equal $t_0 \approx 0.047$ mm/m, and according to EN is equal $t_0 \approx 0.034$ mm/m. A classification of the kinetics of autogenous shrinkage and an equation of the kinetics of autogenous shrinkage of concrete are proposed. The classification related to the kinetics of heat dissipation and compressive strength of concrete. To calculate the thermally stressed state of massive monolithic structures in the early period, an equation of dependence of relative autogenous shrinkage on relative compressive strength was proposed.

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