Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 12, No. 01, January, 2026

Drying Shrinkage of Cement Stone with Superplasticizers of Various Chemical Bases

Ta Van Phan [1], G. V. Nesvetaev [2], Yu. I. Koryanova [2*], V. V. Shut [3]

[1] *Faculty of Civil Engineering, Thuyloi University, Hanoi, Vietnam.*

[2] *Don State Technical University, Rostov-on-Don, Russia.*

[3] *IE «Shut Vladimir Valeryevich», v. Vopopadny, Russia.*

Received 15 September 2025; Revised 16 December 2025; Accepted 21 December 2025; Published 01 January 2026

Abstract

The crack resistance of reinforced concrete structures also depends on concrete shrinkage. Therefore, assessing the influence of mix design factors and operating conditions on concrete shrinkage is essential to determine the relationships between shrinkage magnitude and kinetics and variables such as ambient humidity, cement properties, and admixture characteristics. These relationships are important for calculating shrinkage crack resistance and, consequently, the durability of reinforced concrete structures. The widespread use of superplasticizers and other mineral additives in concreting, including new complex modifiers, highlights the need to clarify known relationships and identify new dependencies involving the material and mineralogical composition of cements, the properties of admixtures, concrete mix formulation, and environmental humidity on both the magnitude and kinetics of shrinkage deformations. The purpose of this study is to identify patterns in the development of shrinkage deformations of cement paste depending on the type of cement and superplasticizer, including the influence of dehydration degree, and to propose equations that can be used to calculate the shrinkage crack resistance of reinforced concrete structures. The study includes an analysis of established approaches for evaluating changes in drying shrinkage of cement paste as ambient humidity varies. Experimental investigations were conducted on the drying shrinkage of cement paste as a function of evaporable water content and the chemical basis of superplasticizers. The influence of superplasticizers on both the kinetics and magnitude of the basic shrinkage of cement paste is demonstrated, considering evaporable water content under standard conditions as well as after drying to constant mass at 105 °C. The effect of relative air humidity on the basic shrinkage of cement stone has also been clarified. Furthermore, an equation describing the kinetics of shrinkage of cement pastes and a classification of cements based on shrinkage kinetics are proposed. Finally, the dependence of shrinkage for the studied cements with different superplasticizers on relative air humidity is established.

Keywords: Drying Shrinkage; Relative Shrinkage; Total Shrinkage; Relative Humidity; Degree of Dehydration; Water/Cement Ratio.

1. Introduction

As is known from the works of Holt (2001) [1], Nesvetaev & Davidyuk (2009) [2], and Aksharamol et al. (2020) [3], shrinkage is a decrease in the volume of hardening cement paste (stone) and concrete over time. Shrinkage includes early-age shrinkage (plastic, autogenous, thermal) and long-term shrinkage (drying, autogenous, carbonation, thermal). Due to the negative impact of shrinkage on the durability of reinforced concrete structures, the works of Bornstein et al. (2013) [4] presented the results of large-scale studies of the effect of prescription factors and

* Corresponding author: koryanova.yi@mail.ru

https://doi.org/10.28991/CEJ-2026-012-01-01

environmental conditions on concrete shrinkage, primarily drying shrinkage (in conjunction with carbonation shrinkage), including over a long period. Studies by Reichard (1964) [5] showed an increase in drying shrinkage by more than 20% at the age of 1 year compared to 90 days, and by 1.5 times or more at the age of 2 years. The effect of the e-modulus of concrete on drying shrinkage has been established. Brue et al. (2017) [6] note several phases in the development of drying shrinkage depending on changes in ambient humidity. In studies by Kucharczykova et al. (2017) [7] for up to 300 days, it was noted that "the measured progress of shrinkage corresponded well to the progress of mass loss." According to Zhang et al. (2025) [8], "there is an almost linear relationship between drying shrinkage and evaporable water content". The development of drying shrinkage over time, depending on environmental conditions, prescription factors, and mass loss, is analyzed in Wallah (2009) [9], Vikan et al. (2010) [10], Hansen (1987) [11], and Zhang (2025) [12]. Among the prescription factors determining shrinkage, Nesvetaev & Davidyuk (2009) [2], CCAA (2002) [13], Karimov (2010) [14], and Skazlić et al. (2025) [15] highlight, in particular, the value of the *W/C* ratio, the properties of cement, and the concentration of aggregate (or the concentration of cement stone) in concrete. According to research by Nesvetaev & Davidyuk (2009) [2] concrete shrinkage depends on the properties of the aggregate ($k_{SH,CA}$), the volume concentration of the aggregate V_A, *W/C* ratio and the value of basic shrinkage of cement paste $\varepsilon_{SH,CP}$ and can be calculated by Equation 1.

$$\varepsilon_{SH,C} = k_{SH,CA}(1 - V_A)^X(2W/C + 0.18)\varepsilon_{SH,CP} = k_{SH,CA}k\varepsilon_{SH,CP} \tag{1}$$

The value of k in Equation 1 depending on the class of concrete and the slump of the concrete mix according to Nesvetaev & Davidyuk (2009) [2] changes from 0.13 to 0.33. The value of X in Equation 1 according to Nesvetaev & Davidyuk (2009) [2], Karimov (2010) [14] changes from 1.2 to 1.8.

Chepurnenko et al. (2024) [16] showed that when calculating the stress-strain state of a reinforced concrete structure based on the hypothesis of flat sections, the stress increments can be determined by Equation 2:

$$\Delta\sigma(z) = \frac{E_0(z,t)}{1-\nu}\cdot\left(\Delta\varepsilon - \alpha\cdot\Delta T(z) - \Delta\varepsilon_{sh}(z) - \Delta\varepsilon_{cr}(z)\right) \tag{2}$$

where: $E_0(z,t)$ is the e-modulus of concrete, $\Delta\varepsilon$ is the average increment of total deformation over the thickness of the plate, α is a coefficient of thermal expansion, $\Delta T(z)$ is the difference between the temperature at the point in the current and previous time step, $\Delta\varepsilon_{sh}(z)$ is the increment of shrinkage deformation, $\Delta\varepsilon_{cr}(z)$ is the creep strain increment, ν is the Poisson's ratio of concrete. The multiplier $(1-\nu)$ in the denominator in Equation 2 takes into account the work of concrete under conditions of biaxial tension (compression) $\sigma_x = \sigma_y = \sigma$. Therefore, to calculate time-varying temperature and shrinkage stresses, the dependence of the change in concrete shrinkage over time is necessary.

Numerous dependencies are well-known to describe the development of drying shrinkage over time, presented, for example, in the studies of Wallah (2009) [9], Kassimi et al. (2010) [17], Teranishi (2010) [18], Tai et al. (2018) [19], Deng et al. (2025) [20], Gedam (2024) [21]. Most of the well-known dependencies, in principle, are reduced to the form $\varepsilon_{sh,\tau} = f(\tau)$ or $\varepsilon_{sh,\tau} = \varepsilon_{sh,u}f(\tau)$. The disadvantage of such type of equations is the uncertainty of the value $\varepsilon_{sh,u}$. According to Nesvetaev & Davidyuk (2009) [2] the development of concrete shrinkage over time is described by Equation 3:

$$\varepsilon_{SH,\tau} = \varepsilon_{SH,120}\,exp\left(k\left(1 - (\tfrac{120}{\tau})^{0.545}\right)\right) \tag{3}$$

in which 120 is the duration, day, of determining the basic shrinkage of concrete (cement paste) in accordance with Russian standards, the value of k depends on the kinetics of shrinkage, i.e. it is determined by the properties of cement, the presence of chemical admixtures and mineral additives, and the value of *W/C* ratio. A similar dependence was used to describe autogenic shrinkage at early age in studies by Phan et al. (2024) [22].

Superplasticizer with different chemical base are widely used in modern concrete. Polycarboxylate superplasticizer (PCE) and shrinkage-reducing polycarboxylate superplasticizer (SRP) admixtures are widely used. Studies by Barabanshchikov et al. (2014) [23], Zhu et al. (2025) [24], Wan et al. (2024) [25], Yoon et al. (2024) [26] have shown that these chemical admixtures can influence, among other things, the kinetics of shrinkage deformations. Qian et al. (2022) [27] showed that "the addition of three types of SPs leads to a significant increase in the early-age drying shrinkage of cement paste, and drying shrinkage increases with the dosage of SPs." Li et al. (2022) [28] showed that drying shrinkage of cement paste with *W/C* = 0.29 containing 0.2 % (SRP) at the age of 28 days can be reduced to 15 % relative to shrinkage of cement paste with *W/C* = 0.29 containing 0.2 % (PCE).

This paper presents the results of studies of the effect on the kinetics and basic shrinkage of six cements presented in Table 1, three types of superplasticizer with different chemical base presented in Table 2 (PCE, NF, NFA) The effect of the relative humidity of air on the amount of the basic shrinkage of the cement paste is shown. The results obtained are compared with some well-known data.

2. Materials and Methods

Experimental studies were performed using six cements from five manufacturers and three superplasticizing admixtures, presented in Table 1.

Table 1. Cements

№	PC, Admixture	Properties of cements: Strength, MPa, at age: 2 days	28 days	ND, %	NA, min.	Clinker: C_3S	C_2S	C_3A	C_4AF	Cement: SO_3
1	CEM I 42.5H[1,6]	4.59/22.4*	7.81/51.5	22.75	115	66.5±0.2	12.1±0.3	6.8±0.2	12.1±0.2	2.37±0.2
2	CEM II/A-Sh 42.5H[1,6] cinder	4.84/23.4	8.58/55.3	25.0	150	66.7±0.3	11.9±0.3	6.9±0.3	12.3±0.2	2.11±0.2
3	CEM I 42.5H[2,6]	5.04/28.5	8.55/50.9	26.5	150	64.9±0.4	12.1±0.3	5.3±0.3	15.1±0.2	2.84±0.2
5	CEM I 42.5H[3,6]	5.82/30.1	8.96/55.6	26.25	170	68.4±0.4	10.7±0.3	4.96±0.2	13.1±0.3	2.78±0.2
6	CEM II/A-P 42.5H CC[4,7]	5.09/23.5	9.95/54.6	27.25	150	63.8±0.3	16.1±0.3	4.4±0.2	14.2±0.2	2.82±0.2
7	CEM I 42.5 H[5,6] opoka (flask)	6.49/32.3	8.79/63.1	27.75	140	58.3±0.3	15.3±0.4	7.7±0.2	12.3±0.2	3.06±0.3

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

All the studied cements are fast-hardening according to GOST 31108-2020. Information on the admixtures is presented in Table 2. The dosage of all admixtures was 0.5% of the cement mass for the commercial product.

Table 2. Admixtures

№	Admixture	Standard	
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)

Manufacturing of specimens in accordance with the Russian Standard included the preparation of cement paste with a *W/C* value of 0.27 without admixtures (reference) and with admixtures, molding of 40x40x160 mm specimens with admixtures by casting, without admixtures with vibration compaction, keeping of specimens under film for 20 hours, removing specimens from the mold, keeping of specimens for 7 days under normal conditions at a temperature of 20±2 °C and a relative humidity of at least 95 %. During specimen molding, benchmarks were installed in the ends of the prisms to measure changes in the linear dimensions of the specimens in order to determine shrinkage. The molds for specimen preparation complied with EN 196-1, clause 4.5. After 7 days, initial measurements of the dimensions and weight of the specimens were taken. Then, for 120 days, during shrinkage determination, the specimens were kept at a temperature of 20±2 °C and a relative humidity of 60±5 %. Cement shrinkage strains were determined using the GOST 24544-2020 method (Figure 1). During testing, changes in the linear dimensions and mass of the samples were recorded at set time intervals of 1, 2, 3, 4, 5, 6, and 7 days, then after 7 days up to 60 days, and then after 14 days.

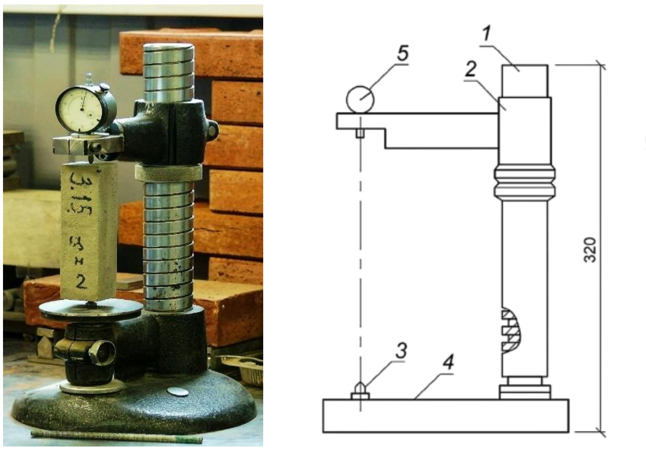


Figure 1. Determining drying shrinkage, Left – diagram according to GOST 24544-2020, right – photo

The samples were then dried to constant weight at 105±3 °C and their total drying shrinkage was determined.

Cement activity (Figure 2) was determined in accordance with GOST 30744-2001 (EN 196-1, clauses 4.7 and 4.8).

Figure 2. Determination of cement activity, Left – in flexural, right – in compression

3. Results

Table 3 presents the values of shrinkage deformations of the studied cements.

Table 3. Shrinkage of the cements, mm/m

Shrinkage	Admixtures	Cements					
		C1	C2	C3	C5	C6	C7
Drying shrinkage 120 days age	no	1.64	1.88	1.62	2.07	2.01	1.33
	1	1.52	1.73	1.60	1.49	1.86	1.62
	2	1.78	2.08	1.86	2.09	2.17	1.88
	3	1.81	2.07	1.83	1.81	2.31	1.82
Total shrinkage after 105 °C	no	3.96	4.12	3.58	4.37	4.51	3.59
	1	3.82	3.74	3.49	3.82	3.99	3.40
	2	3.87	4.17	3.90	4.68	4.43	3.51
	3	3.62	4.02	3.03	4.72	4.57	3.56

Figure 3 shows the shrinkage of the cements with admixtures relative to the standard without admixtures.

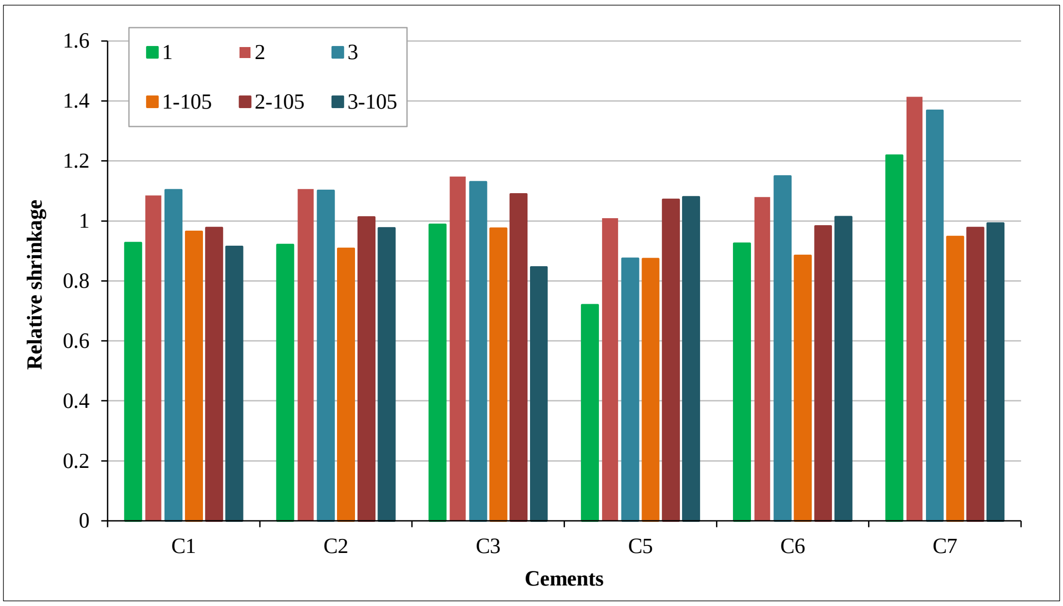
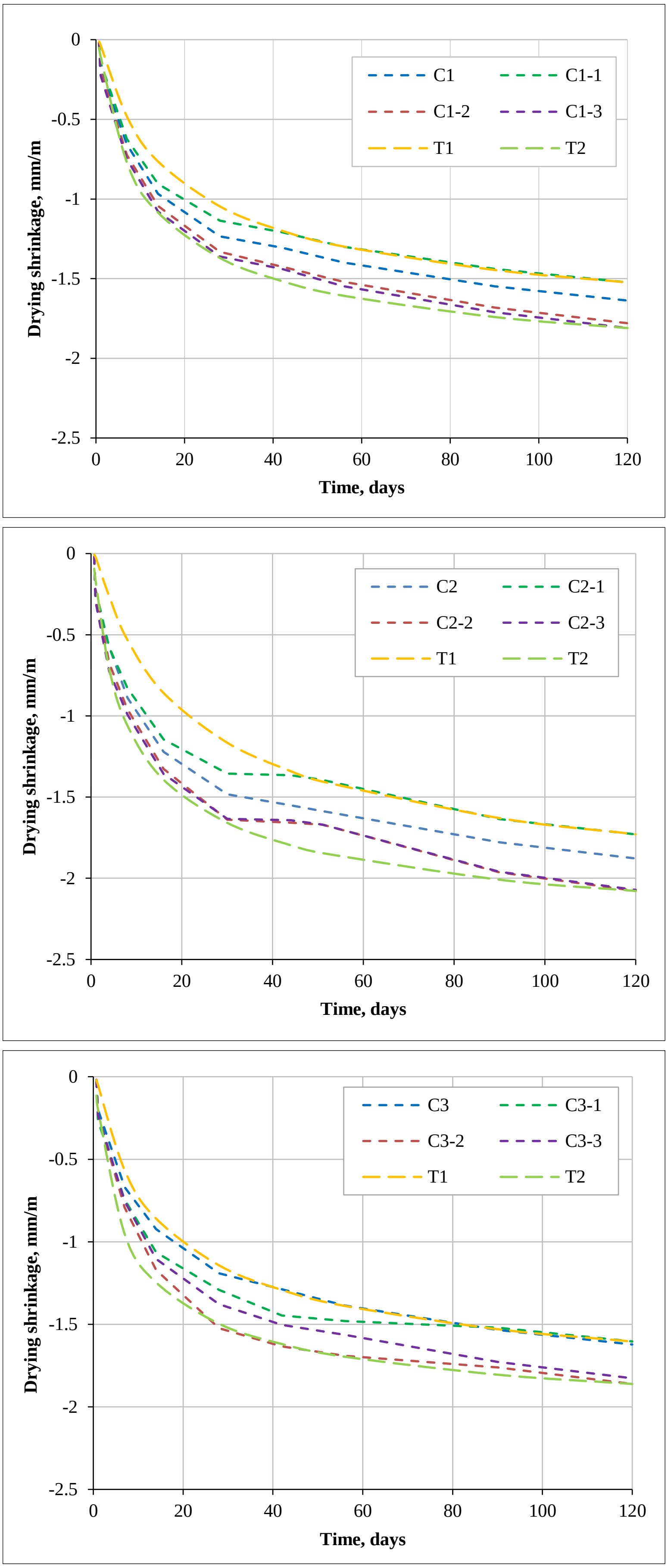


Figure 3. Relative drying and total shrinkage, 1, 2, 3 – admixtures according to Table 2; 105 – after drying at 105 °C

Figure 4 shows the results of measurements of shrinkage over 120 days at a temperature of 20±2 °C and a relative humidity of 60±5 %.



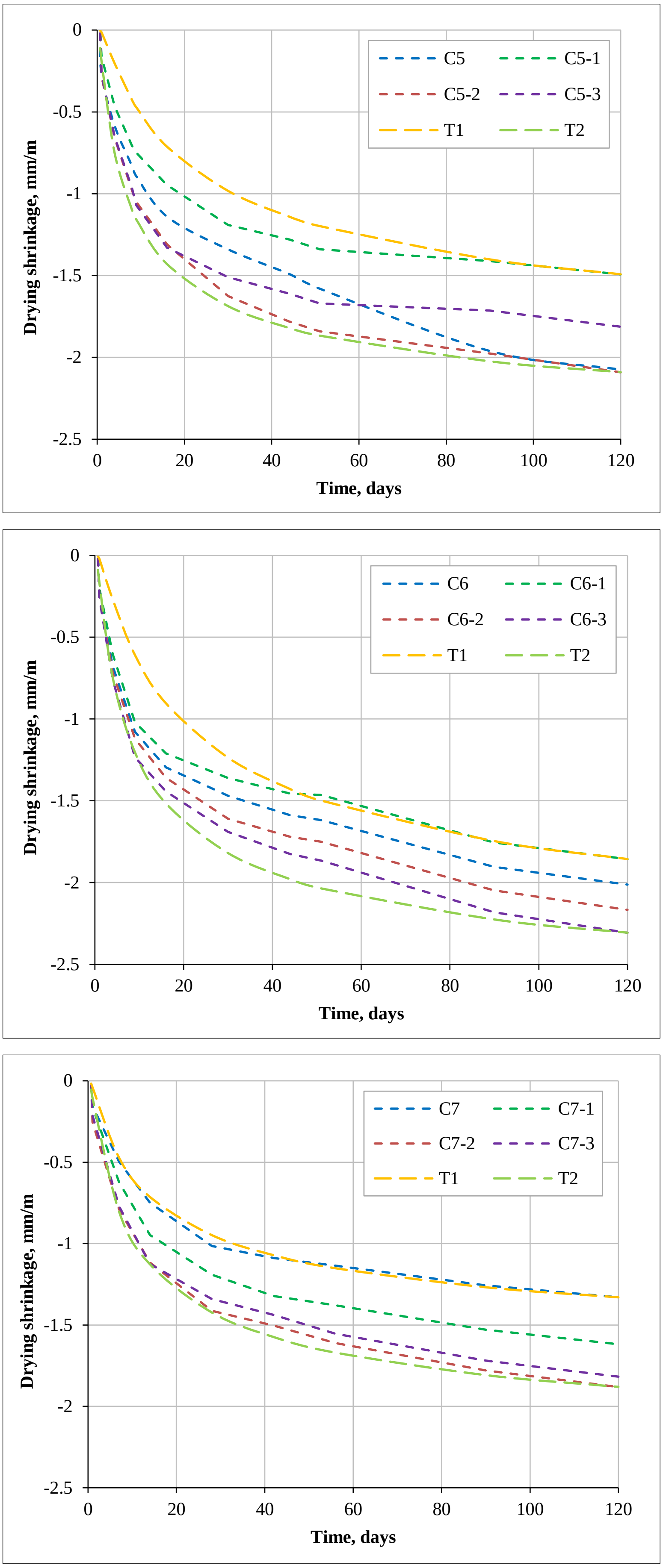
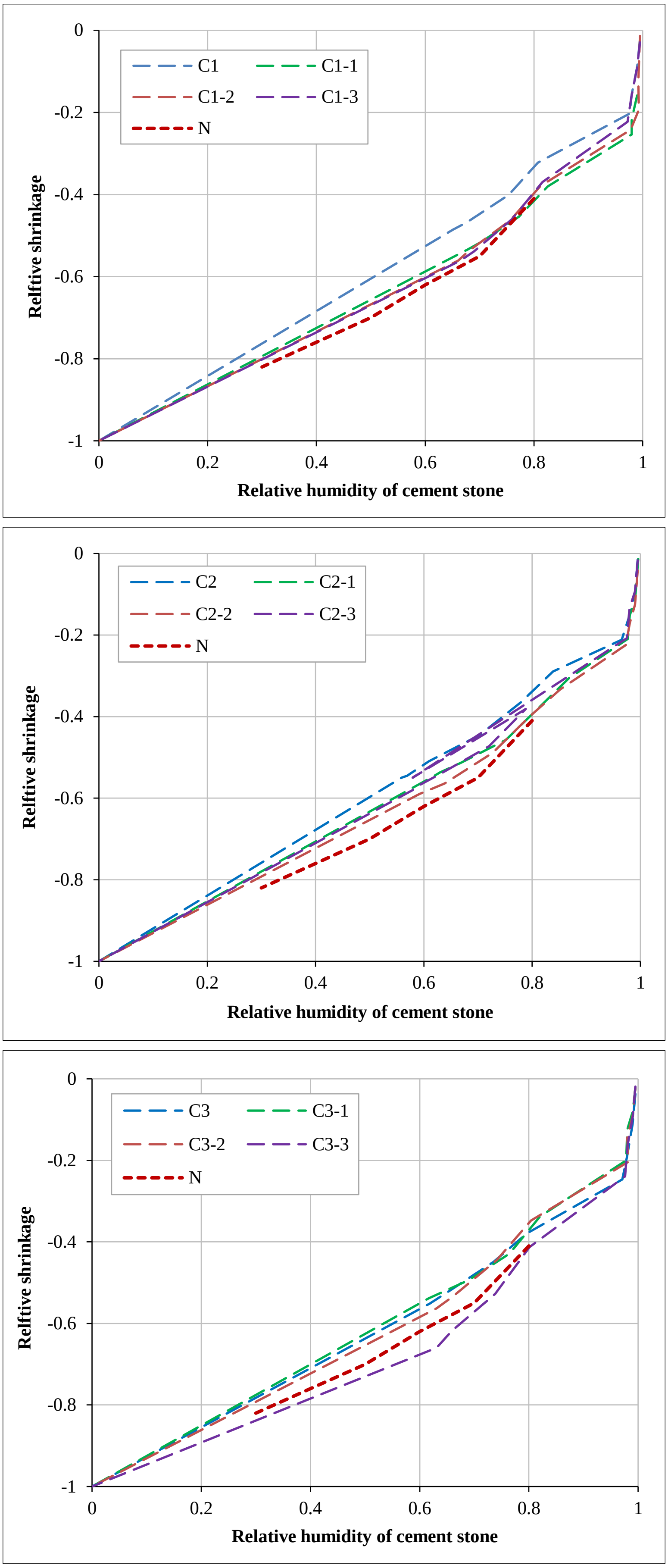


Figure 4. Relationship between drying shrinkage and degree of dehydration, C1-C7 – cements according to Table 1; 1-3 – admixtures according to Table 2

Figure 5 shows the dependence of the change in total shrinkage deformations of the studied cements with admixtures on the degree of dehydration.



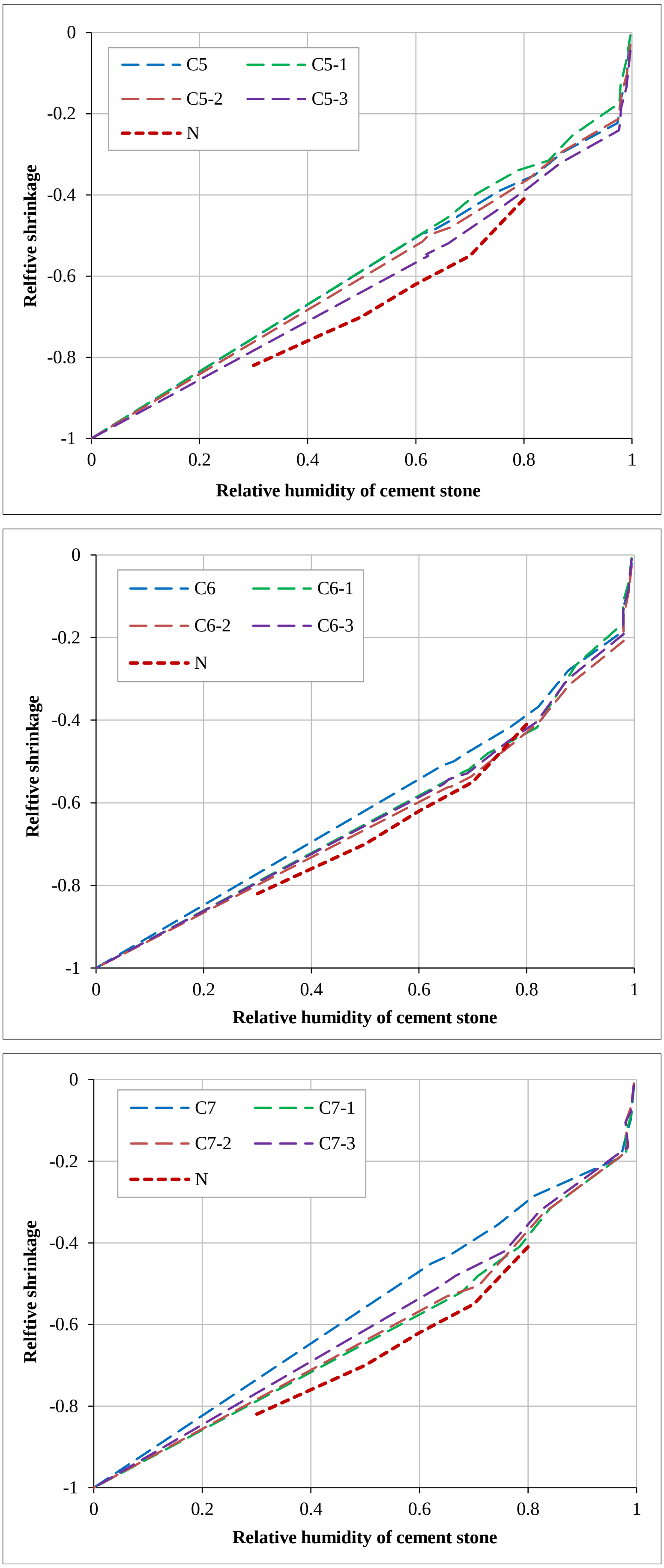


Figure 5. Relationship between total shrinkage and degree of dehydration, C1-C7 – cements according to Table 1; 1-3 – admixtures according to Table 2; N – according to data Nesvetaev et al. (2015) [29]

4. Discussion

The effect of the admixture on the amount of shrinkage deformations depends on both the type of superplasticizer and the type of cement (Table 4).

Table 4. Relative shrinkage deformation $\varepsilon_{sh,a}$ with superplasticizer relative to the admixture-free standard $\varepsilon_{sh,0}$

Cement according to Table 1	The value of $\varepsilon_{sh,a}/\varepsilon_{sh,0}$ of cements with superplasticizer relative according to Table 2		
	1	2	3
C1	0.93/0.96**	1.09/0.98	1.10/0.91
C2	0.92/0.91	1.11/1.01	1.10/0.98
C3	0.99/0.97	1.15/1.09	1.13/0.85
C5	0.72/0.87	1.00/1.08	0.87/1.08
C6	0.93/0.88	1.08/0.98	1.15/1.01
C7	1.22/0.95	1.41/0.98	1.37/0.99

Note: ** - in the numerator after 120 days in standard tests, in the denominator - after drying at 105 °C.

Superplasticizer 1 (NF) did not increase drying shrinkage in all cements, except for C7, which had a 22 % drying shrinkage increase. For the rest of the cements studied, see Table 1, there is a decrease in drying shrinkage deformations from 7 to 28 % in combination with superplasticizer 1 according to Table 2. Superplasticizer 2 (PCE) increased the shrinkage of all cements from 8 to 41 % (C7), except for C5, in which the shrinkage with superplasticizer 2 did not change. Superplasticizer 3 (NFA) increased shrinkage in all cements from 10 to 37 %, except for C5, which recorded a decrease in shrinkage by 13 %. C7 cement, which contains as an active mineral additive opoka (flask) with pozzolan activity, with all superplasticizer, shown an increase in shrinkage deformations from 22 to 41 %.

The total shrinkage after drying at 105 °C for almost all cements with superplasticizer ranged from 0.85 to 1.09 % of the shrinkage of the reference. The shrinkage deformation at 20±2 °C and relative air humidity of 60±3 % relative to the total shrinkage after drying at 105±3 °C ranged from 0.37 for C7 without superplasticizer to 0.60 for C3 with superplasticizer 3 according to Table 2.

The kinetics of shrinkage deformations insignificant depends on the type of cement and the superplasticizer (Figure 6).

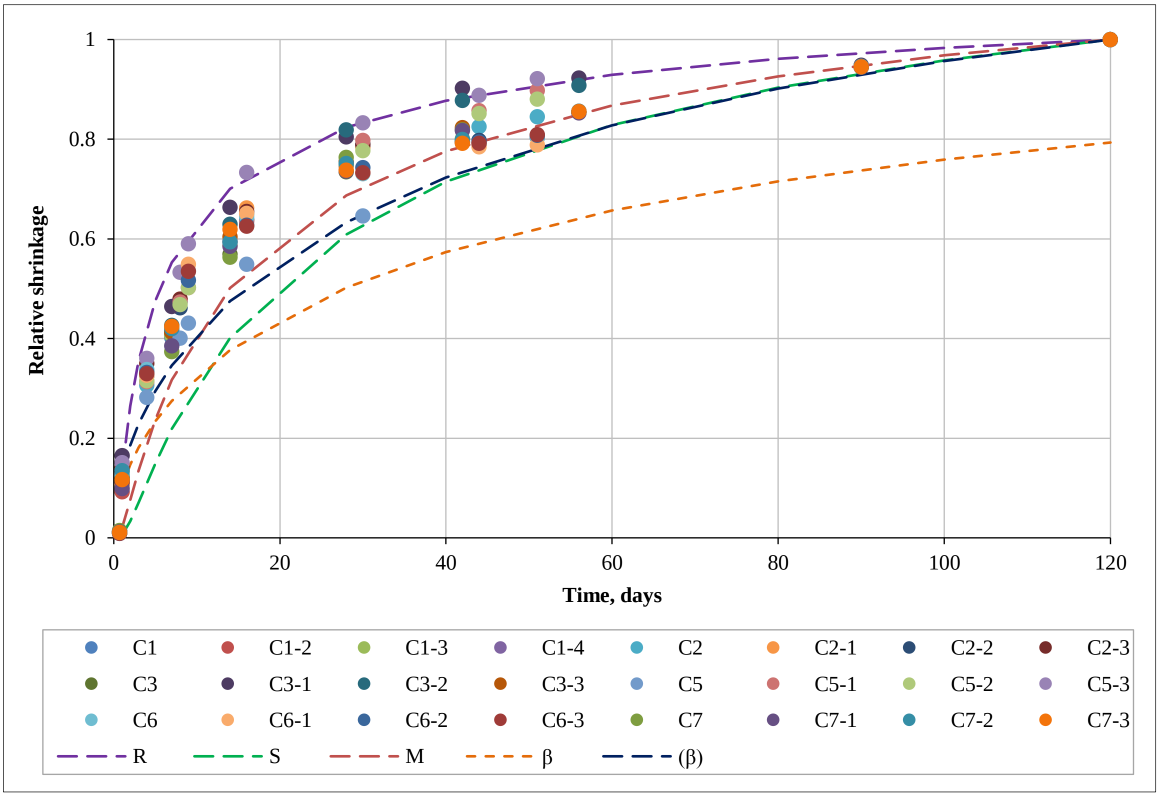


Figure 6. Relationship between relative shrinkage and time under standard conditions, C1-C7 – cements according to Table 1; 1-3 – admixtures according to Table 2; R, M, S – according to equation (2); *β* – according to equation Sakata (1993) [30], (*β*) – according to equation Sakata (1993) [30] at $\varepsilon_{sh,\infty} = \varepsilon_{sh,120}$.

In Figure 6, the β line is obtained according to Equation 4 presented in the studies of Sakata (1993) [30].

$$\beta = \frac{\varepsilon_{sh,\tau}}{\varepsilon_{sh,\infty}} = 1 - \exp(-0.108(\tau - \tau_c)^{0.56} \quad (4)$$

The disadvantage of Equation 4 is the uncertainty of the value $\varepsilon_{sh,\infty}$ - "shrinkage at a time tending to infinity". The values according to Equation 4 approach 1 for a time τ of more than 1000 days. If we conditionally accept in accordance with the Russian standard $\varepsilon_{sh,\infty} = \varepsilon_{sh,120}$, then Equation 4 Sakata (1993) [30] will be describing the curve (β) shown in Figure 6, which occupies a position between curves M and S (Figure 6).

The drying shrinkage of cement stone when tested under standard conditions at any time can be calculated by Equation 3, the parameters of which are presented in the Table 5. If, for the classification of cements by shrinkage kinetics, the ratio of shrinkage deformations after 14 days to the values after 120 days $\varepsilon_{sh,14}/\varepsilon_{sh,120}$ is used as a criterion, equal respectively more than 70 % for group "R", 50-70 % for group "M" and less than 50 % for group "S", then the corresponding values of the coefficient k in Equation 3 are given in Table 5. According to the proposed classification, almost all the studied cements with superplasticizers in terms of the kinetics of shrinkage deformations can be classified as group "M" (average).

Table 5. Parameters of Equation 3

Parameters	**Kinetics of shrinkage**		
	R rapid $\varepsilon_{sh,14}/\varepsilon_{sh,120}$>0.7 $\varepsilon_{sh,14}/\varepsilon_{sh,120}$ = 0.7	**M normal** 0.5<$\varepsilon_{sh,14}/\varepsilon_{sh,120}$<0.7 $\varepsilon_{sh,14}/\varepsilon_{sh,120}$ = 0.6	**S slow** 0.4<$\varepsilon_{sh,14}/\varepsilon_{sh,120}$<0.5 $\varepsilon_{sh,14}/\varepsilon_{sh,120}$ = 0.5
k	0.16	0.31	0.41
x		0.545	

Figure 7 shows data on the relative shrinkage $\varepsilon_{sh,\tau}/\varepsilon_{sh,120}$ according to the classification proposed by the authors and according to ACI 209.2R-08 and EN 1992-1-1. Values according to ACI 209.2R-08 and EN 1992-1-1 are taken as 1 at τ = 120+τ_c, where τ_c, where τ_c is the start of drying.

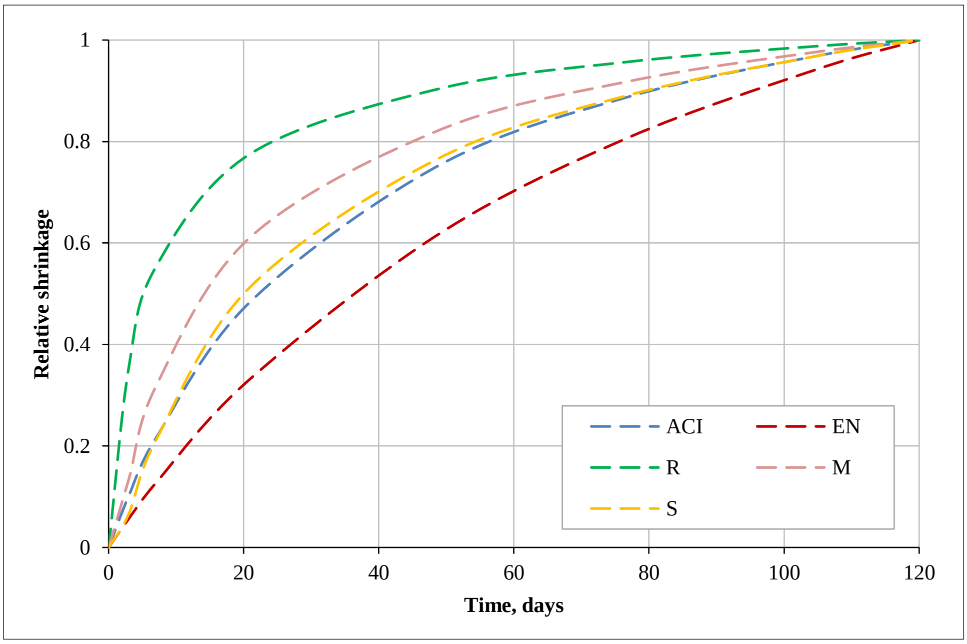


Figure 7. Relative shrinkage, R, M, S – according to Equation 3 with coefficients according to Table 5

There is an almost complete overlap of dependencies for the "S" group and ACI.2R-08.

The nature of the dependence of shrinkage deformations on the evaporable water content depends on the type of cement and admixtures. The change in shrinkage of the tested cements with superplasticizers and with an equal value of evaporable water content in almost all cases occurs more intensively relative to the superplasticizer-free standard. There is some exception for cements C3 and C5.

The drying shrinkage of concrete $\varepsilon_{C,\tau}$ tested with standard conditions at any time can be calculated using equations (1, 3), which for a specific concrete composition can be reduced to Equation 5:

$$\varepsilon_{C,\tau} = k\varepsilon_{CP,\tau} \tag{5}$$

in which the coefficient k depends on the volume concentration of cement paste V_{CS}, the shrinkage of cement concrete (paste) $\varepsilon_{CP,\tau}$ and the value of *W/C* of concrete. It is well-known that there are many dependencies that establish a relationship between the shrinkage of cement paste and concrete in the form of Equation 6:

$$\varepsilon_{sh,C} = k\varepsilon_{sh,CS} \tag{6}$$

in which the concentration of aggregate is V_a = 1 - V_{CS}, V_{CS} - concentration of cement stone, and the function k is set either by a specific value, for example, 0.1, or has the form of Equations (7 to 9):

$$k = 1 + \beta\frac{V_a}{V_{CS}}, \beta = 1.5\ldots3.1; \tag{7}$$

$$k = \exp(-bV_a), b = 1.88\ldots2; \tag{8}$$

$$k = (V_{CS})^{\alpha}, \alpha = 1.2\ldots1.8. \tag{9}$$

Figure 8 shows the dependence of the relative drying shrinkage (RS) of cement paste on the W/C ratio. The shrinkage at *W/C* = 0.4 is assumed to be a single value.

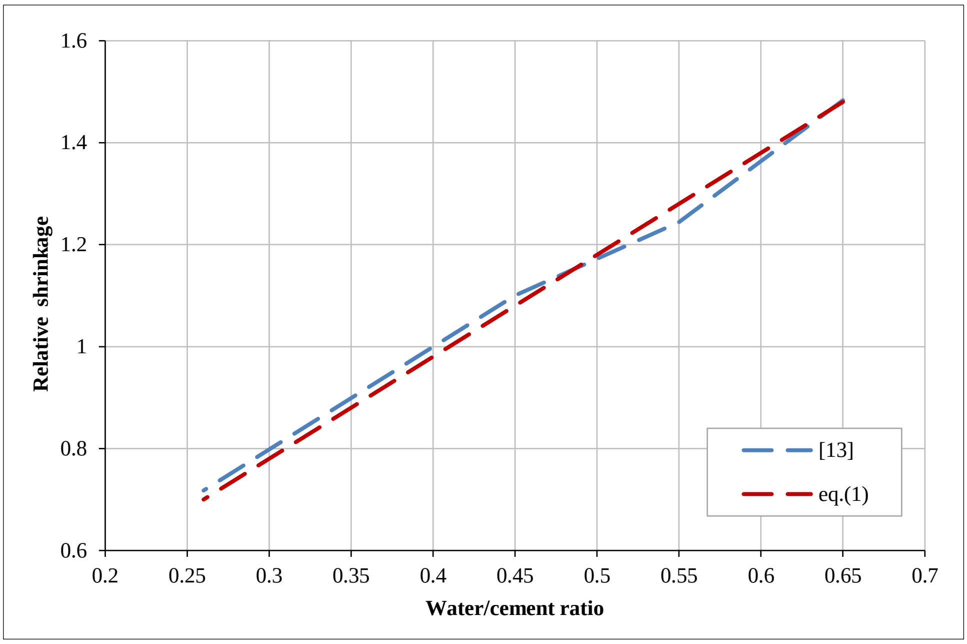


Figure 8. Relationship between relative shrinkage and W/C ratio, Equation 1: $RS = 2W/C + 0,18$; [13] – according to data Sheet (2002) [13]

The dependence of the relative drying shrinkage (RS) on the *W/C* ratio according to Sheet (2002) [13] is described by Equation 10:

$$RS = 1.92W/C + 0.22 \tag{10}$$

practically coinciding with the dependence of relative drying shrinkage (RS) on the *W/C* ratio in Equation 1.

Taking into account the influence of the value of *W/C*, the slump of the concrete mixture and using Equations 7 to 9, we obtain the values of the coefficient k in equation (5) in the approximate range of 0.1 ...0.3.

Another important factor determining concrete shrinkage is the relative humidity of the operating environment. According to Table 3.2 EN 1992-1-1 set by the dependence of concrete shrinkage of various classes on the humidity of the operating environment. If we take shrinkage at a relative humidity of air φ = 60 % as 1, then Figure 9 shows in relative coordinates the dependence of shrinkage on the humidity of the operating environment according to our and some other experimental data, as well as according to EN 1992-1-1. The relative shrinkage according to EN 1992-1-1 is practically independent of the concrete class. For data processing, the dependence of cement stone moisture on ambient humidity was used by Sakata (1993) [30]. Data from Hansen (1987) [11], containing information on the dependence of cement stone shrinkage on ambient humidity of 75, 50, and 11 %, and data from Zhang et al. (2025) [12] were also used to obtain the dependence of shrinkage change on ambient humidity shown in Figure 9.

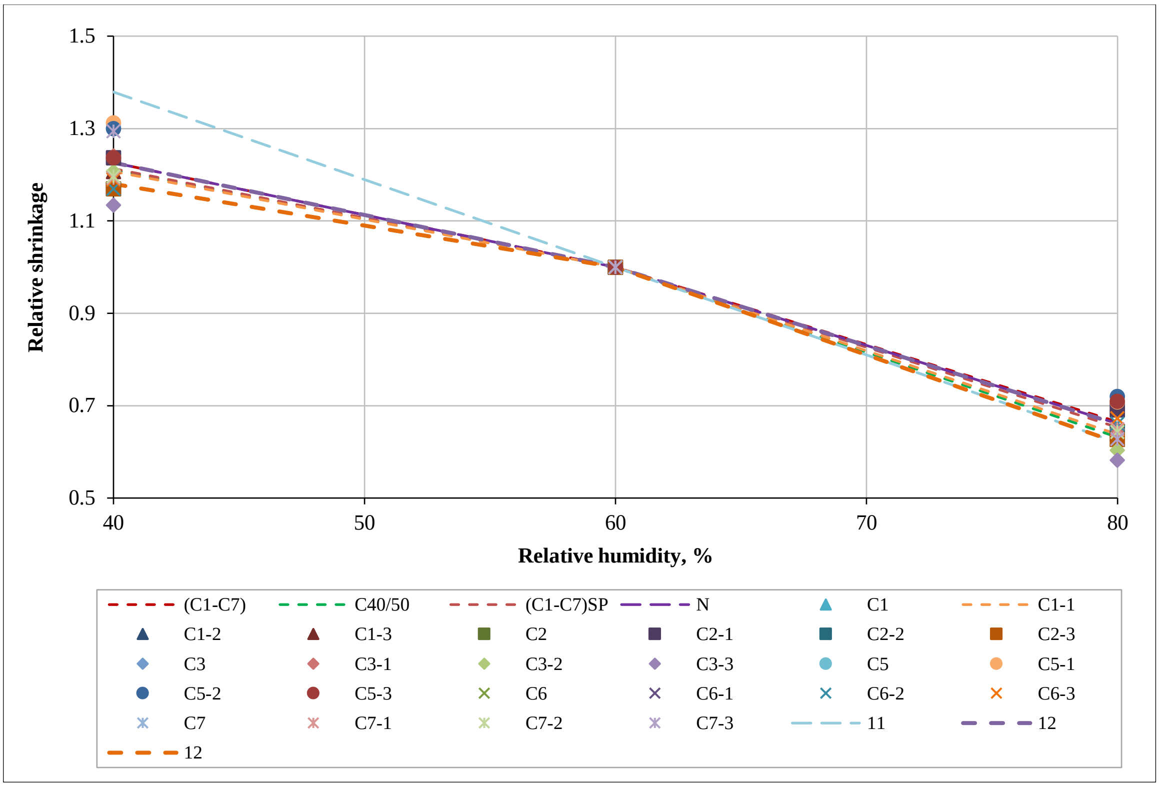


Figure 9. Relationship between the relative shrinkage of cement stone and the relative humidity of the environment, C1-C7 – cements according to Table 1; 1-3 – admixtures according to Table 2; (C1-C7), (C1-C7)SP – respectively, average data for standards without admixture and the studied cements with admixtures; N – according to data Nesvetaev et al. (2015) [29]; 11 – according to data Hansen (1987) [11]; 12 – according to data Zhang et al. (2025) [12].

The dependence of drying shrinkage $\varepsilon_{sh,\varphi}$ on ambient humidity φ can be described by the Equation 11:

$$\varepsilon_{sh,\varphi} = \varepsilon_{sh,60}(a + b\varphi + c\varphi^2), \tag{11}$$

where $\varepsilon_{sh,60}$ is the basic shrinkage under standard tests (φ = 60 %), the coefficients are for the studied cements, respectively *a* = 0.552...2.035, *b* = -0.0197…0.029, *c* = -0.0004...0.00004 depending on the combination of cement + superplasticizer. At φ = 40 %, the increase in shrinkage of cement paste relative to φ = 60 % was 1.09...1.3 with an average value of 1.226 for the superplasticizer-free etalon and 1.13...1.38 with an average value of 1.213 for the studied cements with superplasticizer. According to Table 3.2 EN 1992-1-1, at φ = 40 %, the increase in shrinkage of concrete relative to φ = 60 % is 1.184 for concrete C20/25 and 1.2 for concrete C60/75.

At a relative humidity of φ = 80 %, the values of drying shrinkage deformations for the superplasticizer-free etalon were 0.62...0.72 with an average value of 0.665, for the studied cements with superplasticizer 0.58...0.72 with an average value of 0.653 of the values for standard tests.

With the value of the function *k* = 0.2 in equation (5), the predicted shrinkage deformations of concrete C40/50 on the studied cements at a relative humidity of φ = 80 % are 0.18...0.3 mm/m (0.24 mm/m according to EN 1992-1-1), at a relative humidity of φ = 40 % are 0.32...0.56 mm/m (0.46 mm/m according to EN 1992-1-1). Taking into account the data presented in Figure 9, in principle, using equation (1), it is possible to obtain the values of concrete shrinkage at a relative humidity of the operating environment from 40 to 80 %.

5. Conclusion

The results of the study examine the effect of three types of superplasticizers with different chemical bases (PCE, NF, and NFA) on the kinetics and magnitude of drying shrinkage of six different cements, depending on the evaporable water content under standard testing conditions as well as after drying to full mass loss at 105 °C. Cement containing opoka (flask) with pozzolanic properties as a mineral additive, combined with a superplasticizer, showed an increase in shrinkage deformations by 22–41 % compared with the reference sample. The remaining cements with superplasticizer exhibited a decrease in shrinkage deformations ranging from 7 % to 28 %.

The basic shrinkage values of the studied cements without admixtures, after 120 days of curing at a temperature of 20 ± 2 °C and relative humidity φ = 60 ± 3 %, ranged from 1.33 to 2.07 mm/m. The minimum drying shrinkage was observed for cement C7 containing opoka (flask). With the addition of NF, the basic shrinkage values after 120 days ranged from 1.52 to 1.86 mm/m. With PCE superplasticizer, the values ranged from 1.78 to 2.17 mm/m, while with NFA they ranged from 1.81 to 2.31 mm/m under the same conditions. In all cases, among cements without mineral additives (C1, C3, C5, C6), the minimum shrinkage was observed for cement C1, which had the maximum C_3A/SO_3 ratio, whereas the maximum shrinkage was observed for cement C6, which had the minimum C_3A/SO_3 ratio.

The influence of relative air humidity on the basic shrinkage of cement paste was also demonstrated. Shrinkage measured under standard conditions ranged from 0.37 to 0.60 of the total shrinkage after drying at 105 °C. The presence of superplasticizers altered the shrinkage after drying within the range of 0.85–1.09 relative to the reference. Equations describing the dependence of basic shrinkage on the water–cement ratio (W/C) and on relative air humidity are proposed, enabling prediction of concrete shrinkage based on cement paste shrinkage, concrete class, and ambient humidity. At φ = 40 %, shrinkage increased by 1.07–1.38 times compared with standard tests at φ = 60 %. According to EN 1992-1-1, the corresponding increase at φ = 40 % is 1.184 for concrete C20/25 and 1.2 for concrete C60/75. At φ = 80 %, shrinkage decreased to 0.58–0.72 of the values at φ = 60 %. EN 1992-1-1 gives corresponding ratios of 0.61 for concrete C20/25 and 0.63 for concrete C60/75. The predicted shrinkage deformations of C40/50 concrete made with the studied cements are 0.18–0.30 mm/m at 80 % relative humidity (0.24 mm/m according to EN 1992-1-1) and 0.32–0.56 mm/m at 40 % relative humidity (0.46 mm/m according to EN 1992-1-1).

An equation of the kinetics of shrinkage and a classification of cements according to the kinetics of shrinkage are proposed. For classification by shrinkage kinetics, it is proposed to use the ratio $\varepsilon_{sh,14}/\varepsilon_{sh,120}$ of shrinkage deformations after 14 days to the values after 120 days as a criterion. Depending on the groups for the rate of development of shrinkage deformations "R", "M" and "S", criterion values of more than 0.7 for "R", from 0.5 to 0.7 for "M" and less than 0.5 for "S" are proposed, respectively. At the same time, there is an almost complete coincidence of the kinetics of shrinkage deformations for the "S" group with the data on the kinetics of ACI. 2R-08. The effect of superplasticizer on the kinetics of the studied cements is insignificant, in all cases the value $\varepsilon_{sh,14}/\varepsilon_{sh,120}$ changes from 0.53 to 0.7, which according to the proposed classification belongs to the "M" group.

6. Declarations

6.1. Author Contributions

Conceptualization, G.V.N.; methodology, G.V.N.; software, Y.I.K., V.V.S., and T.V.P.; validation, G.V.N., Y.I.K., V.V.S., and T.V.P.; formal analysis, Y.I.K.; investigation, G.V.N.; resources, Y.I.K., V.V.S., and T.V.P.; data curation, Y.I.K.; writing—original draft preparation, G.V.N.; writing—review and editing, Y.I.K.; visualization, G.V.N. and Y.I.K.; supervision, G.V.N.; project administration, Y.I.K.; funding acquisition, G.V.N. and Y.I.K. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The study was supported by the grant of the Russian Science Foundation No. 25-19-00164, https://rscf.ru/project/25-19-00164/.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Holt, E. E. (2001). Early age autogenous shrinkage of concrete. Ph.D. Thesis, University of Washington, Seattle, United States.

[2] Nesvetaev G. V., & Davidyuk A. N. (2009). Self-Compacting Concrete: shrinkage. Building Materials, (8), 52-54.

[3] Raj, A. G., James, J. S., & John, E. (2020). Drying Shrinkage of Concrete Containing Shrinkage Reducing Admixtures With and Without Supplementary Cementitious Materials. International Research Journal of Engineering and Technology, 7(7), 1600–1608.

[4] Bornstein, B., Song, T., & Mukhin, V. (2013). Laboratory Assessment of Drying Shrinkage of Concretes Containing Shrinkage Reducing Agents Compared with a new low Shrinkage Concrete. Proceedings of the 26th Biennial Conference of the Concrete Institute of Australia, 16-18 October, 2013, Gold Coast, Australia.

[5] Reichard, T. W. (1964). Creep and drying shrinkage of lightweight and normal-weight concretes (No. 74). National Bureau of Standards, US Department of Commerce, Washington, United States.

[6] Brue, F. N. G., Davy, C. A., Burlion, N., Skoczylas, F., & Bourbon, X. (2017). Five year drying of high performance concretes: Effect of temperature and cement-type on shrinkage. Cement and Concrete Research, 99, 70–85. doi:10.1016/j.cemconres.2017.04.017.

[7] Kucharczyková, B., Daněk, P., Kocáb, D., & Misák, P. (2017). Experimental Analysis on Shrinkage and Swelling in Ordinary Concrete. Advances in Materials Science and Engineering, 2017(1), 3027301. doi:10.1155/2017/3027301.

[8] Zhang, J., Kang, S., Shen, Y., Song, C., Lei, H., Xie, W., Chen, X., Wang, J., Wu, W., & Wang, X. (2025). Effects of Sand Type and Alkali Equivalent on Drying Shrinkage and Microstructure of Seawater–Sea Sand Alkali-Activated Slag Concrete. Materials, 18(5), 1005. doi:10.3390/ma18051005.

[9] Wallah, S. E. (2009). Drying Shrinkage of Heat-Cured Fly Ash-Based Geopolymer Concrete. Modern Applied Science, 3(12), 14. doi:10.5539/mas.v3n12p14.

[10] Vikan, H., Hammer, T. A., & Kjellsen, K. O. (2010). Drying Shrinkage of SCC – Influence of the Composition of Ternary Composite Cements. Design, Production and Placement of Self-Consolidating Concrete, RILEM Bookseries, Springer, Dordrecht, Netherlands. doi:10.1007/978-90-481-9664-7_23.

[11] Hansen, W. (1987). Drying Shrinkage Mechanisms in Portland Cement Paste. Journal of the American Ceramic Society, 70(5), 323–328. doi:10.1111/j.1151-2916.1987.tb05002.x.

[12] Zhang, M., Lu, C., Min, Q., Wang, X., He, Y., Deng, G., & Wang, Y. (2025). Evaluation of Concrete Structural Cracking Behavior Induced by Early Drying Shrinkage. Materials, 18(2), 395. doi:10.3390/ma18020395.

[13] CCAA. (2002). Drying shrinkage of cement and concrete. Cement Concrete & Aggregates Australia, 1-6.

[14] Karimov, I. Sh. (2010). The mechanism of shrinkage deformations of concrete and factors influencing them (review). Part 2. Concrete Technologies, (7-8), 20-23.

[15] Skazlić, M., Mešić, H., & Gabrijel, I. (2025). Experimental Analysis of Creep and Shrinkage of Self-Compacting Concrete with Recycled Concrete Aggregates. Applied Sciences (Switzerland), 15(8), 4309. doi:10.3390/app15084309.

[16] Chepurnenko, A., Turina, V., & Akopyan, V. (2024). Artificial Neural Network Models for Predicting the Early Cracking Risk in Massive Monolithic Foundation Slabs. The Open Civil Engineering Journal, 18(1), 1-13. doi:10.2174/0118741495358647241024110350.

[17] Kassimi, F., & Khayat, K. H. (2010). Drying shrinkage model for fiber reinforced SCC. Design, Production and Placement of Self-Consolidating Concrete, Proceedings of SCC2010, 26-29 September, 2010, Montreal, Canada.

[18] Eguchi, K., & Teranishi, K. (2005). Prediction equation of drying shrinkage of concrete based on composite model. Cement and Concrete Research, 35(3), 483–493. doi:10.1016/j.cemconres.2004.08.002.

[19] Wan, K. T., Zhu, H., Yuen, T. Y. P., Chen, B., Hu, C., Leung, C. K. Y., & Kuang, J. S. (2018). Development of low drying shrinkage foamed concrete and hygro-mechanical finite element model for prefabricated building fasçade applications. Construction and Building Materials, 165, 939–957. doi:10.1016/j.conbuildmat.2018.01.024.

[20] Deng, P., Wang, X., Guo, J., Liu, Y., & Zheng, Q. (2025). Experimental Investigation of the Drying Shrinkage Performance of a Modified Ceramsite Geopolymer Concrete. Materials, 18(4), 915. doi:10.3390/ma18040915.

[21] Gedam, B. A. (2024). ANN-Powered Models for Predicting Shrinkage and Creep Properties of High-Performance Concrete Using Supplementary Cementitious Materials. Journal of Computing in Civil Engineering, 38(6), 04024033. doi:10.1061/jccee5.cpeng-6029.

[22] Van Phan, T., Nesvetaev, G. V., & Koryanova, Y. I. (2024). Suggestions for Describing the Kinetics of Autogenous Shrinkage of Concrete in the Early Hardening Period. AIP Conference Proceedings, 3243(1), 20070. doi:10.1063/5.0247355.

[23] Barabanshchikov, Y. G., Arkharova, A. A., & Ternovskii, M. V. (2014). On the influence on the efficiency of anti-shrinkage additives superplasticizer. Magazine of Civil Engineering, 51(7), 23–30. doi:10.5862/MCE.51.3.

[24] Zhu, Y., Wu, Y., Wan, L., & Zhou, X. (2025). Effect of Different Mineral Admixtures on the Dry Shrinkage and Mechanical Properties of Mortar. Journal of Architectural Research and Development, 9(2), 52–59. doi:10.26689/jard.v9i2.9917.

[25] Wan, Z., He, T., Yang, R., & Ma, X. (2024). The effect of shrinkage-reducing agents on autogenous shrinkage and drying shrinkage of cement mortar with accelerator. Mechanics of Time-Dependent Materials, 28(4), 2121–2150. doi:10.1007/s11043-023-09614-y.

[26] Yoon, S. H., Oh, S. R., Kim, J. Y., & Choi, S. (2024). Early-Age Shrinkage Stress of Alkali-Activated Cement-Free Mortar Using Shrinkage Reducing Agent and Expansive Additive. Buildings, 14(6), 1852. doi:10.3390/buildings14061852.

[27] Qian, X., Yu, C., Zhang, L., Qian, K., Fang, M., & Lai, J. (2020). Influence of Superplasticizer Type and Dosage on Early-age Drying Shrinkage of Cement Paste with Consideration of Pore Size Distribution and Water Loss. Journal Wuhan University of Technology, Materials Science Edition, 35(4), 758–767. doi:10.1007/s11595-020-2318-1.

[28] Li, S., Liu, X., Xu, Y., Lai, G., Ding, Y., Chen, Y., Xia, C., Wang, Z., & Cui, S. (2022). Synthesis and Performances of Shrinkage-Reducing Polycarboxylate Superplasticizer in Cement-Based Materials. Materials, 15(19), 7002. doi:10.3390/ma15197002.

[29] Nesvetaev, G.V., & Shcherbinina, T. A. (2015). On the issue of standardization of shrinkage of cement concrete. Bulletin of Eurasian Science, 7(5(30)), 145.

[30] Sakata, K. (1993). Prediction of Concrete Creep and Shrinkage of concrete. Proceedings of the 5th International RILEM Symposium on Self-Compacting Concrete, SCC 2007, 3-5 September, 2003, Ghent, Belgium.