

STUDY OF THE DEFORMATION CHARACTERISTICS AND CREEP COEFFICIENT OF HIGH-STRENGTH SELF-COMPACTING HEAVY-WEIGHT AND LIGHT-WEIGHT CONCRETES AT VARIOUS RELATIVE HUMIDITY OF THE ENVIRONMENT

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Abstract: The paper presents the results of an experimental study of the characteristics of high-strength self-compacting heavyweight and lightweight concretes of strength classes B60–B100 at different ambient relative humidity levels. The aim of the study was to evaluate the effect of environmental humidity on strength, elastic modulus, shrinkage and creep strains, creep compliance, and creep coefficient of high-strength self-compacting modified concretes. The tests were carried out in accordance with GOST 24452 and GOST 24544 in climatic chambers at relative air humidity levels of 20, 60, and 90% for 240 days. A formula for the numerical determination of the creep coefficient is proposed and recommended for inclusion in GOST 24544. It was found that a decrease in ambient relative humidity may lead to an increase in creep strains by more than 1.7 times. It is shown that the calculation procedure specified in GOST 24544 may, in some cases, overestimate ultimate creep strains, with the overestimation becoming more pronounced as the concrete strength class increases and the ambient humidity decreases. The creep coefficient values of high-strength heavyweight and lightweight concretes do not exceed 1 and are more than two times lower than the standard values specified in SP 63.13330.2018 and EN 12390. The obtained results demonstrate that experimental determination of creep coefficients can significantly improve the efficiency of using modern modified concretes in the construction of unique buildings and structures.

Keywords: high-strength concrete; self-compacting concrete; lightweight concrete; heavyweight concrete relative humidity; shrinkage; creep; creep coefficient; elastic modulus; long-term deformations

ИССЛЕДОВАНИЕ ДЕФОРМАЦИОННЫХ ХАРАКТЕРИСТИК И КОЭФФИЦИЕНТА ПОЛЗУЧЕСТИ ВЫСОКОПРОЧНЫХ САМОУПЛОТНЯЮЩИХСЯ ТЯЖЕЛЫХ И ЛЕГКИХ БЕТОНОВ ПРИ РАЗНОЙ ОТНОСИТЕЛЬНОЙ ВЛАЖНОСТИ ОКРУЖАЮЩЕЙ СРЕДЫ

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Аннотация: В статье представлены результаты экспериментального исследования характеристик высокопрочных самоуплотняющихся тяжелых и легких бетонов классов В60–В100 при различной относительной влажности окружающей среды. Цель работы заключалась в оценке влияния влажности среды на прочность,

модуль упругости, деформации усадки и ползучести, меру ползучести и коэффициент ползучести высокопрочных самоуплотняющихся модифицированных бетонов. Испытания выполнялись по ГОСТ 24452 и ГОСТ 24544 в климатических камерах при относительной влажности воздуха 20, 60 и 90 % в течение 240 суток. Предложена формула для численного определения коэффициента ползучести, которую рекомендуется внести в ГОСТ 24544. Установлено, что снижение относительной влажности среды может приводить к увеличению деформаций ползучести более чем в 1,7 раза. Показано, что расчетная методика ГОСТ 24544 в ряде случаев завышает предельные деформации ползучести, причем в большей степени при повышении класса бетона и снижении влажности среды. Значения коэффициентов ползучести высокопрочных тяжелых и легких бетонов не превышают 1 и более чем в 2 раза ниже нормативных значений по СП 63.13330.2018 и EN 12390. Полученные результаты показали, что экспериментальное определение коэффициентов ползучести, позволит значительно повысить эффективность использования современных модифицированных бетонов при строительстве уникальных зданий и сооружений.

Ключевые слова: высокопрочный бетон; самоуплотняющийся бетон; легкий бетон; тяжелый бетон; относительная влажность; усадка; ползучесть; коэффициент ползучести; модуль упругости; длительные деформации

INTRODUCTION

High-strength concretes based on highly fluid and self-compacting concrete mixes are currently widely used in civil, industrial, and transportation construction, both in reinforced concrete and steel-reinforced concrete structures [1–3]. However, while the influence of various technological factors on the structure, strength, and corrosion characteristics of these concretes has been sufficiently studied [4–7], the influence of service conditions—primarily relative humidity—on long-term deformation characteristics still requires further investigation [8–10].

The consideration of the long-term deformation characteristics of concrete in the design of reinforced concrete structures according to SP 63.13330.2018 is achieved by reducing the initial modulus of elasticity of concrete according to Equation (1) using a creep coefficient that depends on the concrete's compressive strength class and the relative humidity of the ambient air.

$$E_{b,\tau} = \frac{E_b}{1 + \varphi_{b,cr}} \quad (1)$$

where:

E_b is the modulus of elasticity of concrete, MPa
 $E_{b,\tau}$ is the effective deformation modulus of concrete under long-term loading, MPa;

$\varphi_{b,cr}$ is the creep coefficient

The creep coefficient $\varphi_{b,cr}$ is a parameter that reflects the ratio of ultimate plastic strains to elastic

strains. It should be noted that no regulatory document in the Russian Federation contains a formula that expresses the physical meaning of the creep coefficient ($\varphi_{b,cr}$). However, in [11], it is derived by substituting the ratios of stresses to strains (2) for the initial modulus of elasticity and the modulus of deformation under sustained loading, provided that the concrete specimens are subjected to the same loading level during testing in accordance with GOST 24452 and GOST 24544.

$$E_b = \frac{\sigma}{\varepsilon_{el}}, \quad E_{b,\tau} = \frac{\sigma}{\varepsilon_{cr} + \varepsilon_{el}}, \quad (2)$$

where:

σ is the stress in a concrete specimen during short-term tests for elastic modulus and long-term tests for concrete creep, MPa;

ε_{el} is the elastic component of strains when loading a concrete specimen to a constant stress σ in accordance with GOST 24452, when setting it up for long-term tests to determine concrete creep;

ε_{cr} - ultimate creep strains of concrete obtained under long-term stresses σ in the specimen according to GOST 24544.

Then, the formula for determining the creep coefficient is expressed as in (3), confirming its physical meaning, which lies in the ratio of the ultimate creep strains to the elastic strains of the concrete.

$$\varphi_{b,cr} = \frac{\varepsilon_{cr}}{\varepsilon_{el}}, \quad (3)$$

The method for determining the ultimate creep strains of concrete is specified in GOST 24544 and is based on probabilistic prediction of the behavior of the decay curve of creep obtained from tests lasting 180 days, assuming an infinitely long time. For this purpose, this function is linearized from the $\varepsilon-t$ coordinates to the $t/\varepsilon-t$ coordinates. After constructing a regression line in these coordinates, the ultimate value of the creep strains is determined as the cotangent of the angle of inclination of this line to the x-axis (t). This method of extrapolating deformation curves over time is not new. It was actively used by O. Ya. Berg [8] in the 1970s, but was first proposed as early as the 1950s [12]. This approach first appeared in GOST 24544 in 1981, as at that time it yielded satisfactory results that, on the whole, did not contradict physical concepts regarding the nature of concrete creep. It has remained unchanged since then. However, the values of the ultimate creep strains of modified high-strength concretes obtained using this approach do not always correspond to experimental data for longer test durations, as will be shown below.

Consider the evolution of the creep coefficient values for concrete, including high-strength concrete, in the regulatory documents of the USSR and Russia.

In 2002–2003, at the A.A. Gvozdev Research Institute of Civil Engineering Structures, A.S. Zalesov, V.A. Klevtsov, and V.V. Shugaev conducted a review of foreign literature, based on which the creep coefficient $\varphi_{b,cr}$ for high-strength concrete of class B60 was adopted at the following relative humidity levels: over 75%—1.0, at 40–75%—1.4, and at less than 40%—2.0. These values were included in the subsequently published SP 52-01-2003 for B60-class concrete. As a precaution, the authors recommended extending these values to higher concrete classes up to B100 [13].

As the Russian construction industry was already producing high-strength concretes of classes B60–B100 in the early 2000s, and these were in demand for the construction of reinforced concrete structures for unique buildings, and there were no large-scale experimental studies of the long-term deformation characteristics of such concretes, based on the above review, the creep coefficient values for

B60 concrete were extended in SP 63.13330.2012 to high-strength concretes of classes B70–B100. Since then, the creep coefficients $\varphi_{b,cr}$ for high-strength concretes of classes B60 to B100, as specified in the currently valid standard SP 63.13330.2018, have remained unchanged.

Over the past 20 years, Russian researchers have published data on the long-term deformation characteristics of high-strength heavy concretes of classes up to B80 [9, 10, 13], which are not fully reflected in regulatory documents. However, that the standards of the European Committee on Concrete, as well as the regulatory documents of Norway, Finland, the Netherlands, and Sweden already contained extensive information on heavy-duty concrete of classes B90–B100; German standards already included information on concrete up to class B115; and the Model Code 2010 already included characteristics for concrete up to class B120.

The importance of differentiating the creep coefficient has already been noted by many experts [14, 15], since the constant values of creep coefficients adopted in current codes which are overestimated for classes B70–B100 on the one hand, assume an insufficiently justified increased deformability of building frame elements. To compensate for this, an increase in the cross-sections of the elements is required. On the other hand, the actual redistribution of forces changes in rigid joints, which will already lead to a distortion of the calculation results relative to the actual stress-strain state (SSS) of the building. As high-strength, self-compacting lightweight structural concretes of classes B60–B70 with an average density grade of D1800–D2000 were developed in Russia in 2023 [4, 16, 17, 18], evaluating the deformation characteristics of such concretes in comparison with those of heavy concretes will provide a more complete view of the behavior of high-strength modified concretes under long-term loading.

This is relevant because, as noted in publications [18–21], concretes of equal strength may differ significantly in their deformation characteristics (modulus of elasticity, ultimate strains, shrinkage and creep strains, etc.) depending on technological factors. At the same time, it should be admitted that publications containing data on the influence of ambient relative

humidity on the long-term characteristics of high-strength concretes are few in number [22].

Therefore, the objective of this study was to conduct comparative long-term tests in accordance with GOST 24452 and GOST 24544 on high-strength, self-compacting modified heavy and lightweight concretes of classes B60–B100, determining their strength, initial modulus of elasticity, shrinkage and creep deformations, as well as the creep coefficient, using various methods for calculating ultimate creep deformations at different relative ambient humidity levels (20, 60, and 90% in accordance with the classification in SP 63.13330.2018).

2. MATERIALS AND TEST METHODS

To produce high-strength self-compacting concrete, materials (Portland cement, organomineral modifier, microfiller, aggregates) were used that are mass-produced in the Russian Federation and are employed in the production of concrete mixes for various construction projects, including:

- Portland cement CEM I 42.5 ZHI, compliant with the requirements of GOST R 55224;
- MB10-50S A-II-2 organomineral concrete modifier, comprising microsilica (45%), fly ash (45%), and superplasticizer (10%), complying with the requirements of GOST R 56178;
- Microfiller – non-activated mineral powder (ground limestone) grade MP-1, 0–1.25 mm fraction, complying with the requirements of GOST R 52129 and GOST R 56592;

- Class I quartz sand with a particle size modulus of $M_{kr} = 2.42$, meeting the requirements of GOST 8736;

- Granite crushed stone, 5–10 mm fraction, meeting the requirements of GOST 8267;

- expanded clay gravel, 5–10 mm fraction, bulk density grade M500, strength grade P125, average density 910 kg/m³, complying with the requirements of GOST 32496;

- water, complying with the requirements of GOST 23732.

Under laboratory conditions, self-compacting concrete mixtures were prepared from the above materials, including three heavy concrete mixes of classes B70, B80, and B100, and one lightweight concrete mix of class B60, with a cement content of 349–495 kg/m³, with the addition of the organomineral modifier MB10-50S in an amount ranging from 14 to 26% of the cement mass and a water-to-cement ratio ($W/(C+MB)$) ranging from 0.23 to 0.39.

It is worth noting that B60 lightweight concrete has approximately the same composition and volume of cement paste as B100 heavy concrete, and the reduction in average density is achieved by replacing 0.254 m³ of heavy granite crushed stone with a density of 2,700 kg/m³ with lightweight expanded clay gravel with an average density of 910 kg/m³ [23]. At the same time, the true water-cement ratio will also be approximately the same, due to the higher water demand of porous expanded clay gravel, whose water absorption is 14.5% by mass.

The compositions and properties of self-compacting concrete mixtures are presented in Table 1.

Table 1. Compositions and Properties of Self-Compacting Concrete Mixes

Composition No.	Compositions and Properties of Self-Compacting Concrete Mixes, kg/m ³							Properties of Self-Compacting Concrete Mixes			
	C	MB	MP	S	CS	GEC	W	SF, cm	ρ , kg/m ³	V_{cs} , m ³ /m ³	$W/(C+MB)$
1	349	50	150	818	868	-	155	63	2390	0.351	0.39
2	444	99	0	809	808	-	146	60	2405	0.334	0.27
3	497	129	0	745	914	-	144	62	2430	0.363	0.23
4	495	105	0	743	229	218	160	57	1950	0.355	0.27

Notes: C – Portland cement; MB – organo-mineral modifier; MP – microfiller; S – sand; CS – granite crushed stone; GEC – expanded clay gravel; W – water; SF – standard cone slump; ρ – average density of the concrete mix; V_{cs} – volume of cement paste; $W/(C+MB)$ – water-cement ratio.

The mixtures were prepared in a 0.050 m³ forced-action mixer and mixed for 5 minutes.

The test results for the mixtures showed (Table 1) that the average density of the heavy concrete mixtures falls within a narrow range of 2390–2430 kg/m³ and meets the requirements of GOST 26633 (2000–2600 kg/m³), while the average density of the lightweight concrete mixture is 1950 kg/m³ and meets the requirements of GOST 25820 (no more than 2000 kg/m³).

The slump of all mixtures, determined by the spread of a standard cone according to GOST R 59715, ranges from 57 to 63 cm. This allows them to be classified as self-compacting, taking into account the absence of signs of bleeding and segregation of the mixtures, in accordance with GOST R 59714.

Specimens were cast from the prepared concrete mixtures and stored under standard conditions (at a temperature of 20±2 °C and relative humidity of 95±5%):

- 12 cubes measuring 100×100×100 mm for determining average density and cube compressive strength in accordance with GOST 27005, GOST 10180, and GOST 31914;

- 21 prisms measuring 100×100×400 mm for determining prismatic compressive strength and modulus of elasticity in accordance with GOST 24452, as well as shrinkage and creep deformations in accordance with GOST 24544.

To better align the results of long-term tests with the actual performance of structures using various concrete classes and the design age typically specified for them in the working documentation, the specimens were tested at ages ranging from 28 to 90 days.

The modulus of elasticity was determined at a load level of 30% of the prismatic strength (R_b). The prisms were loaded in increments of 0.1 R_b , with a 5-minute dwell time at each increment.

Tests of the specimens for shrinkage and creep were conducted in standard spring-loaded test rigs for one and two specimens in automated climatic chambers at a constant temperature of 20±2 °C, but with different relative humidity levels of 20, 60, and 90% (±5%) over a period of

240 days [11]. During long-term testing, the deformation readings of the samples were determined using a portable deformometer, the operating principle of which is described in [25].

Moisture loss in concrete was determined by the difference in the average density of the same cubic specimens after curing under normal conditions and after additional curing for 240 days at various relative humidity levels [11].

The residual water content of high-strength concretes was determined by drying the cube specimens to a constant mass at a temperature of +105 °C after they had been cured at various relative humidity levels for 240 days [11].

The water absorption of high-strength concretes was determined in accordance with GOST 12730.3 on cube specimens after they had been cured at various relative humidity levels for 240 days [11].

The ultimate creep strains of high-strength concretes, required for calculating the creep coefficient, were determined using two methods for comparison:

- using the calculation method specified in GOST 24544, with a regression line;

- based on experimental data obtained when the creep strains reached a plateau.

The duration of exposing the samples to load during the experimental determination of the ultimate creep strains of concrete was carried out until their attenuation—for 240 days, which exceeds the duration of tests according to GOST 24544 (180 days) by 33%. It was assumed that the data from the experimental studies are the most reliable results, since the use of a computational method for prediction can lead to significant errors in the estimation of ultimate creep strain values.

3. RESULTS AND DISCUSSION

Test results for heavy and lightweight modified high-strength self-compacting concretes in terms of: cube strength (R) and actual compressive strength class (B_f), prism strength (R_b) and mod-

ulus of elasticity (E_b), moisture loss (Δ_{ml}), residual moisture content (Δ_{rwc}), and water absorption (Δ_{wa}) of the concretes before and after testing at different ambient relative humidity levels (W) are presented in Tables 2 and 3.

Table 2. Strength and deformation characteristics of high-strength concretes under short-term loading and at various relative humidity levels

Composition No	W, %	Properties of high-strength concrete before and after 240 days of testing, MPa							
		R		B _f		R _b		E _b · 10 ⁻³	
		prior to testing	after 240 days	prior to testing	after 240 days	prior to testing	after 240 days	prior to testing	after 240 days
1	20	-	-	-	-	-	74,4	-	41,3
	60	-	-	-	-	-	76,7	-	41,7
	90	81,2	88,4	71	77	76,8	82,0	40,5	42,8
2	20	-	-	-	-	-	85,7	-	42,8
	60	-	-	-	-	-	88,3	-	44,2
	90	92,3	104,2	81	91	88,7	99,2	42,4	45,0
3	20	-	-	-	-	-	107,1	-	44,9
	60	-	-	-	-	-	110,0	-	46,4
	90	114,3	116,8	100	100	104,6	112,2	44,6	47,2
4	20	-	-	-	-	-	66,4	-	35,0
	60	-	-	-	-	-	65,3	-	34,6
	90	69,5	70,2	61	61	64,5	64,6	33,3	34,5

Notes: W – relative humidity; R – cube compressive strength; B_f – actual compressive strength class; R_b – prism compressive strength; E_b – initial modulus of elasticity; “-” – value not determined.

Table 3. Moisture characteristics of high-strength concrete after curing for 240 days under varying relative humidity conditions

Composition No.	W, %	Properties of high-strength concrete after 240 days of testing			
		B _f	Δ_{ml} , mass. %	Δ_{rwc} , mass. %	Δ_{wa} , mass. %
1	20	-	0,67	2,99	0,85
	60	-	0,47	3,24	0,50
	90	77	0,18	3,98	0,25
2	20	-	0,46	2,38	0,46
	60	-	0,33	2,72	0,28
	90	91	0,15	3,10	0,12
3	20	-	0,33	2,04	0,33
	60	-	0,25	2,24	0,16
	90	100	0,01	2,80	0,08
4	20	-	1,00	4,91	1,21
	60	-	0,62	5,32	1,05
	90	61	0,00	5,98	0,97

Notes: W – relative humidity; B_f – actual compressive strength class; Δ_{ml} – moisture loss; Δ_{rwc} – residual moisture; Δ_{wa} – water absorption.

As shown in Tables 2 and 3, the curing of heavy-weight concrete at the same temperature but under different relative humidity conditions over a 240-day period results in a significant increase in the concrete’s strength and initial modulus of

elasticity. As the concrete class and relative humidity increase, moisture loss and water absorption decrease, while the residual moisture content, compressive strength, and initial modulus of elasticity of the concrete increase. Thus, at an

ambient relative humidity of 90%, the increase in prism strength of heavy-duty concrete ranges from 7% to 12%, and the initial modulus of elasticity increases by 6%. When the ambient relative humidity decreases from 60% to 20%, the increase decreases and amounts to no more than 5% for prismatic strength and no more than 4% for the modulus of elasticity.

The curing of lightweight concrete at a constant temperature but under varying relative humidity conditions over a period of 240 days results in a slight increase in strength of up to 3% and in the initial modulus of elasticity of up to 5% as shown in Table 3. As relative humidity increases, moisture loss and water absorption in lightweight concrete decrease, while residual water content increases as shown in Table 4. At the same time, unlike heavy concrete, when relative humidity decreases from 90% to 20%, the prismatic

strength and initial modulus of elasticity of lightweight concrete increase by 2–3%.

These results can be explained by the structural characteristics of the cement paste in high-strength modified concretes. Previous studies of the structure of high-strength cement paste [5, 9, 25] have shown that it is characterized by a 30–50% increase in the volume of gel pores at the supramolecular level of dispersion with diameters of $1 \cdot 10^{-3} \dots 5 \times 10^{-3} \mu\text{m}$, which are insensitive to changes in the relative humidity of the environment. The formation of such pores is associated with a 1.5–2.5-fold increase in the content of highly dispersed CSH(I)-type calcium hydro-silicates, which constitute an ultradisperse solid structure of a lamellar (“scaly”) form with a size, in one direction, of no more than $2.5 \times 10^{-3} \mu\text{m}$ (2.5 nm), with the interlayer space filled with water as shown in Figure 1.

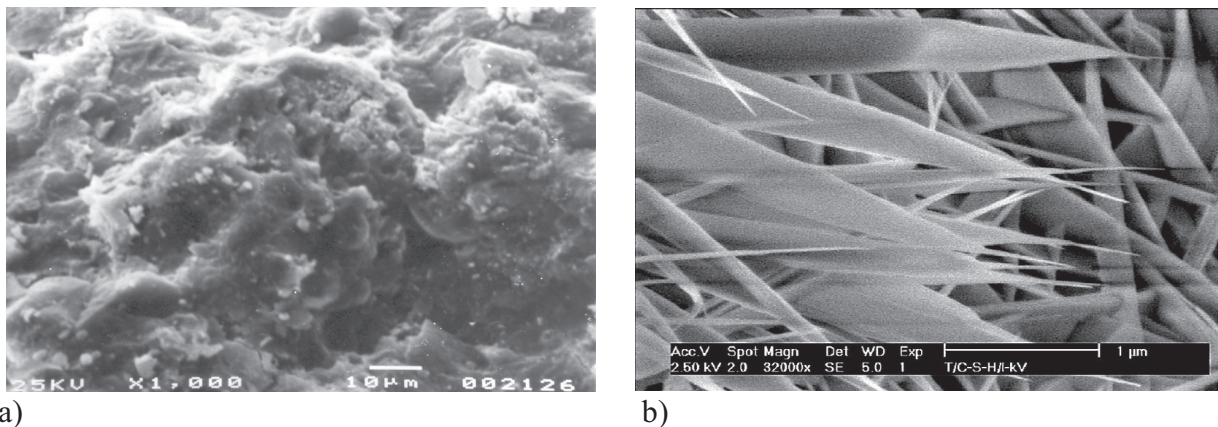


Figure 1. Structure of high-strength cement stone (a) and low-alkali calcium silicate hydrates¹ of the CSH(I) type (b)

¹The photograph of low-base calcium hydrosilicates was taken by B. Möser at the Finger Institute for Building Materials

The interlayer water, or hydration shell, has a density of 1200–1350 kg/m³, which contributes to the system’s stiffness and increases its modulus of elasticity [26–29]. Taken together, this forms a high-density, strong, and rigid gel-like tobermorite mass. The structural feature described above determines the ultra-low water absorption and permeability to water and gases of modified cement stone and concretes, as noted by N.K. Rosental et al. [6–7].

The minimal (3–5%) increase in the compressive strength and initial modulus of elasticity of lightweight concrete over time can be explained by

the fact that a significant volume of lightweight, porous expanded clay gravel (0.240 m³/m³), which has low strength and deformation characteristics, reduces their increase due to the compaction of the cement paste.

The summary results of relative shrinkage and creep deformations, as well as the creep modulus and coefficient, obtained during long-term tests of high-strength self-compacting heavy and lightweight concretes at different relative air humidity levels are presented in Table 4.

Based on the results of long-term tests of heavy and lightweight high-strength concretes, kinetics curves were plotted showing the increase in their relative shrinkage and creep deformations at various relative air humidity levels.

Table 4. Deformation characteristics of high-strength concrete under a load applied for 240 days at different relative humidity levels

Composition No.	W, %	$\varepsilon_{sh} \cdot 10^5$	Stress and creep strains					Creep coefficient, $\varphi_{b,cr}^1 / \varphi_{b,cr}^2$	
			σ , MPa	$\varepsilon_{el} \cdot 10^5$	$\varepsilon_{cr}^1 \cdot 10^5$	$\varepsilon_{cr}^2 \cdot 10^5$	$\varepsilon_{cr}^1 / \varepsilon_{cr}^2$		$C \cdot 10^5, \text{MPa}^{-1}$
1	20	38.0	24.5	57.0	50.6	40.5	1.25	1.65	0.89 / 0.71
	60	28.5	24.5	55.0	28.6	27.5	1.04	1.12	0.52 / 0.50
	90	4.5	24.5	54.0	18.1	17.3	1.05	0.71	0.33 / 0.32
2	20	36.1	28.0	62.0	55.6	39.7	1.40	1.42	0.89 / 0.64
	60	25.2	28.0	61.0	35.4	27.5	1.29	0.98	0.58 / 0.45
	90	2.2	28.0	63.0	29.0	23.9	1.21	0.85	0.46 / 0.38
3	20	33.3	32.0	63.8	63.2	39.2	1.61	1.23	0.99 / 0.61
	60	22.5	32.0	62.1	37.0	25.5	1.41	0.80	0.59 / 0.41
	90	2.0	32.0	62.1	26.6	20.5	1.30	0.64	0.43 / 0.33
4	20	27.5	19.4	59.3	28.2	25.8	1.09	1.33	0.48 / 0.44
	60	21.1	19.4	60.2	24.4	19.0	1.28	0.98	0.41 / 0.32
	90	5.5	19.4	62.7	13.3	10.1	1.32	0.52	0.21 / 0.16

Notes: W is the relative humidity; σ is the stress in concrete specimens under long-term loading; ε_{sh} is the shrinkage strains; ε_{el} is the elastic component of relative strains when loading a concrete specimen to a constant stress σ ; ε_{cr}^1 is the ultimate relative creep strains calculated according to GOST 24544; ε_{cr}^2 is the ultimate relative creep strains obtained experimentally after 240 days of testing; $\varphi_{b,cr}^1$ and $\varphi_{b,cr}^2$ are the creep coefficients obtained using formula (1) at different ultimate relative creep strains, calculated according to GOST 24544 and obtained experimentally; C is a measure of creep, determined by the formula $C = \varepsilon_{cr}^2 / \sigma$.

Figures 2 and 3 show approximate graphs of the relative shrinkage and creep deformations of high-strength self-compacting heavy concrete of class B100 and lightweight concrete of class B60 under long-term loading at various relative air

humidity levels. The kinetics of shrinkage and creep in heavy concrete of classes B70 and B80 do not differ qualitatively from those of heavy concrete of class B100.

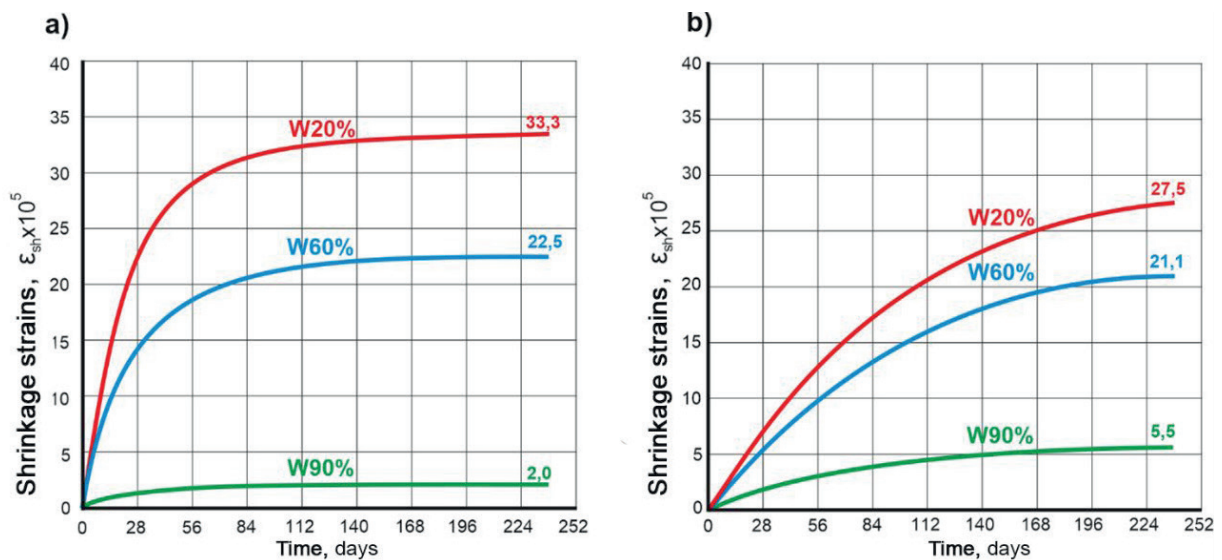


Figure 2. Shrinkage strains of high-strength self-compacting heavy concrete of class B100 (a) and lightweight concrete of class B60 (b) over time at different relative air humidity levels

As shown in Table 5, relative humidity has a significant effect on the shrinkage strains ε_{sh} of both heavy and lightweight concretes, which is con-

sistent with the results of determining the moisture characteristics of high-strength concretes after curing for 240 days under various relative humidity conditions as can be seen from Table 4.

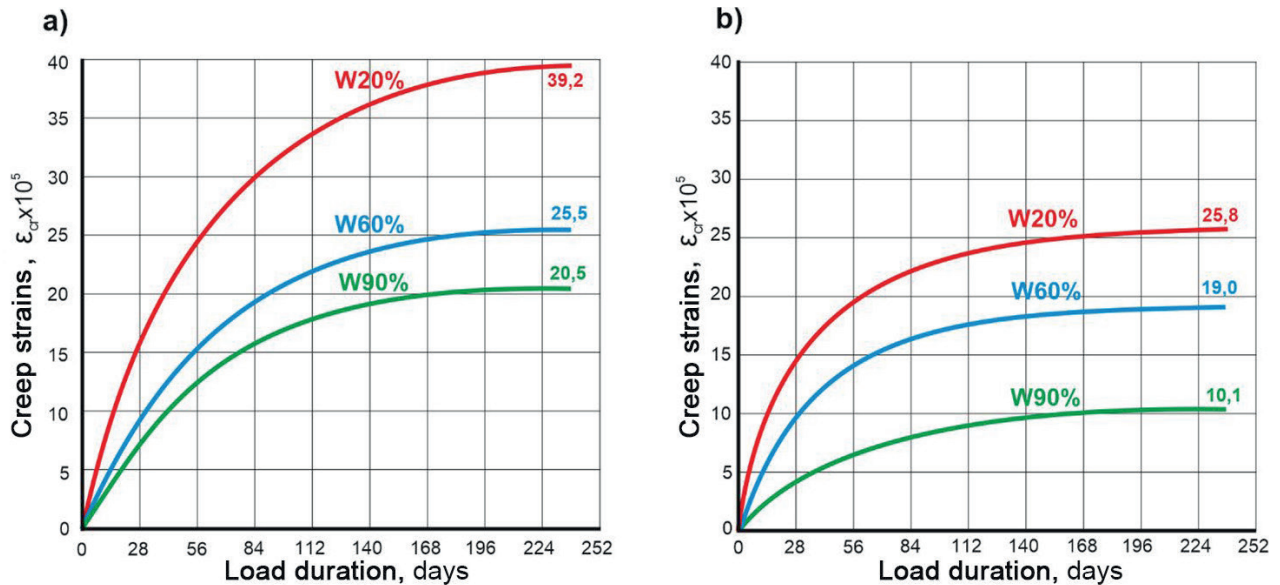


Figure 3. Creep strains of high-strength self-compacting heavy concrete of class B100 (a) and lightweight concrete of class B60 (b) under long-term loading at different relative air humidity levels

s relative humidity decreases, the shrinkage deformation of high-strength concrete increases significantly, ranging from $2.0\text{--}5.5 \times 10^{-5}$ at 90% humidity, $21.1\text{--}28.5 \times 10^{-5}$ at 60% humidity, and $27.5\text{--}38.0 \times 10^{-5}$ at 20% humidity, but do not exceed the value of 43.0×10^{-5} recommended in [30] for B60-grade concrete. At the same time, the strength and type of concrete have a significantly smaller effect on the shrinkage deformations of concrete as can be seen from Table 5 and Figure 3. However, while the shrinkage strains of heavy concretes of classes B70–B100 decay rapidly and stabilize at 120–140 days, lightweight concrete of class B60 is characterized by relatively linear shrinkage deformation curves up to 150–170 days of observation. This is likely due to the fact that, in the presence of porous aggregate in the composition of lightweight concrete, in a partially water-saturated state, two mass-moisture transfer processes overlap. On the one hand, there is moisture loss from the cement paste due to evaporation at low relative air humidity. On the other hand, there is moisture influx into the cement paste from the

porous aggregate, which acts as a reserve water volume uniformly distributed throughout the volume of the lightweight concrete.

An analysis of the results of determining the creep strains of high-strength self-compacting heavy and lightweight concretes under long-term loading (over a period of 240 days) revealed the following patterns:

- the time-dependent growth of creep strains follows a decaying exponential function, which for high-strength self-compacting heavy and lightweight concretes stabilizes at 180–200 days, depends on relative air humidity and does not contradict known physical laws (see Figure 3);
- The values of elastic strain ε_{el} for all four concrete mixtures fall within a fairly narrow range of $54.0\text{--}63.8 \times 10^{-5}$. Despite a significant difference in prismatic strength from 64.6 to 112.2 MPa and elastic modulus from 34.5 to 47.2 GPa, they differ by no more than 18%. This circumstance is a consequence of the wide range of specimen loading levels, from 19.4 to 32.0 MPa, regulated by GOST 24452 and GOST 24544 at 0.3 times the prismatic strength as can be seen from Table 5;

- As relative humidity decreases, the ultimate creep strains ε_{cr}^2 of high-strength heavy and light-weight concretes, obtained experimentally at 240 days of age, increase and range from $10.1\text{--}23.9 \times 10^{-5}$ at 90% humidity, $19.0\text{--}27.5 \times 10^{-5}$ at 60% humidity, and $25.8\text{--}40.5 \times 10^{-5}$ at 20% humidity. At the same time, the strength of heavy concrete has virtually no effect on the ultimate relative creep strains, which for concrete grades B70–B100 fall within a narrow range: at 90% humidity— $39.2\text{--}40.5 \times 10^{-5}$, at 60% humidity— $25.5\text{--}27.5 \times 10^{-5}$, and at 20% humidity— $17.3\text{--}23.9 \times 10^{-5}$ as shown in Table 5;

- The ultimate creep strains ε_{cr}^1 of high-strength heavy and lightweight concretes, determined using the method specified in GOST 24544 with a regression line, exceed the experimental values by 4–9% to 21–61% as shown in Table 5. Considering that the duration of the long-term load was 240 days and exceeded the 180-day duration specified in GOST 24544 by 33%, as well as the stabilization of creep strains after 180–200 days of testing, it can be concluded that the values of ultimate creep strains calculated according to GOST 24544 are, in some cases, overestimated. At the same time, the accuracy of the standard method for calculating ultimate creep strains decreases with an increase in concrete class and a decrease in relative air humidity. This is clearly evident in a comparison of the values of ultimate creep strains in Table 5 and Figure 3a. Accordingly, the creep coefficients calculated using Equation (3) will also be overestimated;

- The creep strains of lightweight high-strength concrete of class B60 are lower than those of heavy concrete of classes B70–B100 (see Figure 3 and Table 5). This result can be explained by the fact that the composition and volume of the cement paste, which characterizes creep strains under long-term loading, were practically identical for heavy concrete of class B100 and light-weight concrete of class B60, while the loading levels applied to the specimens, taken as 0.3 times the prismatic strength of the concrete, differed by 65% and ranged from 32.0 to 19.4 MPa. This is confirmed by the results of determining the creep modulus of high-strength concretes,

which are practically identical for heavy concrete of class B100 and lightweight concrete of class B60 as shown in Table 5 and Figure 4;

- the creep modulus of high-strength self-compacting heavy and lightweight concretes of classes B60–B100 ranges from 0.52 to $1.65 \times 10^{-5} \text{ MPa}^{-1}$ and does not exceed the value of $3.9 \times 10^{-5} \text{ MPa}^{-1}$ recommended in [30] for B60 concrete in the absence of data on the characteristics of the concrete mix composition. As relative air humidity decreases, the creep modulus of high-strength concretes increases and amounts to: $0.52\text{--}0.85 \times 10^{-5} \text{ MPa}^{-1}$ at 90% humidity, $0.80\text{--}1.12 \times 10^{-5} \text{ MPa}^{-1}$ at 60% humidity, and $1.23\text{--}1.65 \times 10^{-5} \text{ MPa}^{-1}$ at 20% humidity as can be seen from Figure 4.

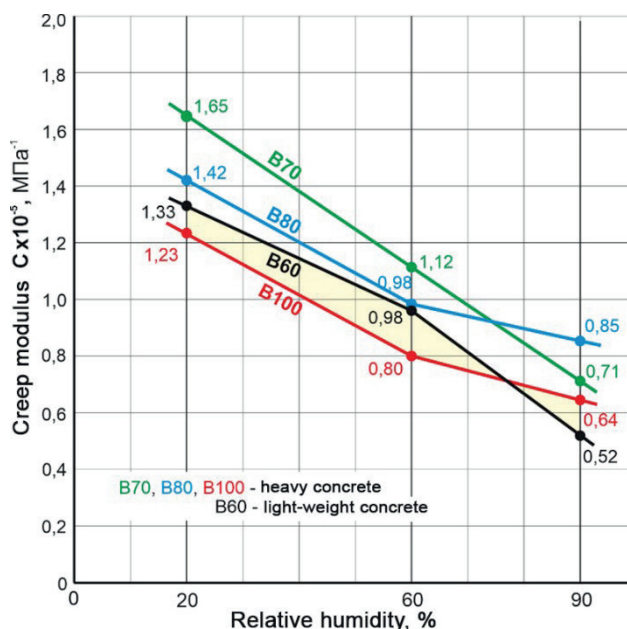


Figure 4. Creep modulus of high-strength self-compacting heavy and lightweight concretes under prolonged (240-day) loading at various relative air humidity

Based on the obtained results for elastic and ultimate relative creep strains, the creep coefficients for high-strength self-compacting heavy and lightweight concretes of classes B60–B100 were determined using Equation (3), used for the design of reinforced concrete structures under long-term loading, and a comparison was made with the values given in SP 63.13330.2018 and EN

12390. In this case, the values of the creep coefficients were determined taking into account the ultimate relative creep strains calculated according to the GOST 24544 method (ε_{cr}^1) and obtained from experimental data (ε_{cr}^2) as shown in Table 5.

Analysis of the results of determining the creep coefficients of high-strength self-compacting heavy and lightweight concretes under long-term loading revealed the following patterns:

- As relative humidity decreases, the creep coefficients ($\varphi_{b,cr}^1$ and $\varphi_{b,cr}^2$) of high-strength heavy and lightweight concretes of classes B60–B100, obtained by calculation and experiment, increase and range from 0.16 to 0.46 at 90% humidity, 0.32–0.59 at 60% humidity, and 0.44–0.99 at 20% humidity as can be seen from Table 5;
- The creep coefficients of high-strength heavy concretes of classes B70–B100 depend to a lesser extent on the compressive strength grade than on the relative humidity of the air, which can be explained by the similar quality of the cement paste, determined by the use of the organomineral modifier MB10 -50S in an amount of 14–24% of the cement mass, and the identical volume of cement paste (334–363 m³/m³) in the composition of self-compacting concretes;

- The creep coefficients of lightweight concrete are 30–100% lower than those of heavy concrete, which is clearly due to the lower loading on lightweight concrete specimens during long-term tests, while the quality, and the amount of cement paste (MB10-50S dosage of 21% of cement mass and true cement paste volume of 355 m³/m³);
- The creep coefficients determined by calculation exceed the experimentally obtained values by 4 to 62%. At the same time, the differences in creep coefficient values for heavy concrete increase with a decrease in relative air humidity and an increase in strength, while for lightweight concrete, they decrease with an increase in relative air humidity. These results show that the determination of ultimate relative strains at low relative air humidity values using the calculation method specified in GOST 24544 requires adjustment.

Table 5 and Figure 5 present a comparison of experimentally determined creep coefficients for high-strength self-compacting heavy and lightweight concretes at various air humidity levels (20, 60, and 90%) and their standard values, referenced to the classification adopted in the code of rules SP 63.13330.2018 and Eurocode EN 12390.

Table 5. Experimental and standard values of the creep coefficients for high-strength concrete at different relative air humidity levels

W, %	Creep coefficient $\varphi_{b,cr}$ for high-strength concrete of B60-B100 grades							
	experimental data				According to CII 63.13330.2018		According to EN 12390	
	B60 ¹⁾	B70 ²⁾	B80 ²⁾	B100 ²⁾	B60-100	Δ , %	C60-C100	Δ , %
> 75	0.16	0.32	0.38	0.33	1.0	-(62...84)	0.97-0.71	-(54...83)
40-75	0.32	0.50	0.45	0.41	1.4	-(64...77)	1.41-0.98	-(58...77)
< 40	0.44	0.71	0.64	0.61	2.0	-(65...78)	-	-

Notes: W – relative humidity; 1) – lightweight concrete; 2) – heavyweight concrete; Δ – difference between experimental data and standard values.

A comparison of the creep coefficients of high-strength self-compacting heavy and lightweight concretes of classes B60–B100, obtained experimentally, with their standard values according to SP 63.13330.2018 and EN 12390 showed that:

- The standard values of creep coefficients for concrete classes B60–B70 according to SP

63.13330.2018 generally correspond to the values in EN 12390. However, for higher-grade concretes (B80–B100), the standard values in EN 12390 are 30% lower than those in SP 63.13330.2018 (see Table 5);

- values of the creep coefficients ($\varphi_{b,cr}^1$ and $\varphi_{b,cr}^2$) for high-strength heavy concretes of classes

B70–B100, obtained by calculation and experiment at various relative air humidity levels (from 20% to 90%), do not exceed 1.0 and are more than two times lower than the standard values specified in SP 63. 13330.2018 and EN 12390 (see Figure 5);

- the insignificant difference in creep coefficients for heavy concretes of different classes B70, B80, and B100 indicates that a single value can be used for them at the same relative air humidity;

- The values of the creep coefficients ($\varphi_{b,cr}^1$ and $\varphi_{b,cr}^2$) for high-strength lightweight concrete of class B60, obtained through calculation and experimentation at various relative air humidity (from 20% to 90%), do not exceed 0.5 and are four times lower than the standard values specified in SP 63.13330.2018 and EN 12390 (see Figure 5).

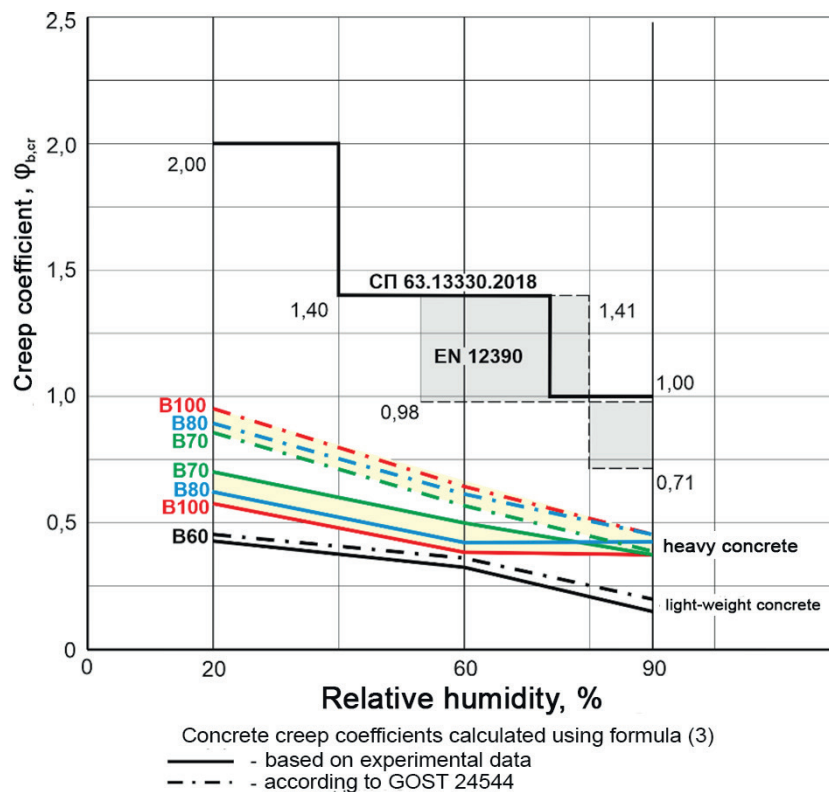


Figure 5. Comparison of experimental creep coefficients for high-strength heavy and lightweight concretes of classes B60–B100 at different relative air humidity levels with their standard values according to SP 63.13330.2018 and Eurocode EN 12390

The results obtained are determined both by the structural characteristics of the modified cement paste and by its content in the concrete mixture, which determines the concrete’s strength and deformation properties. It can be assumed that in low-cement concretes of classes below B60, prepared using organomineral modifiers of the MB type or individual components included in its composition (microsilica and fly ash), the values of the creep coefficients ($\varphi_{b,cr}$) at various relative

air humidity levels will be lower than those specified in the SP 63.13330.2018 code.

4. CONCLUSIONS

1. Comparative tests have been carried out on high-strength self-compacting heavy and light-weight concretes of classes B60–B100 with a Portland cement content of 350–500 kg/m³ and an organo-mineral modifier MB10-50S added at

a rate of 14–26% of the cement mass. The strength (cubic and prismatic compressive strength) and deformation (initial modulus of elasticity, shrinkage and creep strains, measure and coefficient of creep) characteristics of the concretes during their curing before and after prolonged (240 days) loading at various relative ambient humidity levels of 20, 60, and 90% in accordance with GOST 10180, GOST 31914, GOST 24452, and GOST 24544.

2. A decrease in ambient relative humidity from 90% to 20% slows down, but does not halt, the hardening processes of high-strength heavy and lightweight concretes over a period of 240 days. The increase in compressive strength and modulus of elasticity of heavy concretes at minimum humidity decreases from 7–12% to 4–5%, while for lightweight concrete, it even increases slightly by 1–3%, which is consistent with previous studies of the structure of high-strength cement stone with organo-mineral modifiers of the MB type.

One of the main features of the pore structure of modified cement stone is a shift in the balance between the volumes of capillary pores at the macro-level of dispersion, responsible for the migration (mass transfer) of moisture, and the so-called gel pores at the supramolecular level of dispersion with a diameter of 1–5 nm—toward the latter. Thus, the 30–50% increase in the volume of more dispersed and less permeable to water and gases gel pores in the cement stone structure makes high-strength concretes less sensitive to changes in the relative humidity of the environment.

3. The shrinkage strains of high-strength self-compacting heavy and lightweight concretes of classes B60–B100 increase significantly by a factor of 7–13 as the relative humidity of the air decreases from 90% to 20%, ranging from $2.0\text{--}5.5 \times 10^{-5}$ to $27.5\text{--}38.0 \times 10^{-5}$. At the same time, the strength and type of concrete have a significantly smaller effect on the shrinkage strains of concrete. The shrinkage strains of heavy concretes of classes B70–B100 decay rapidly and stabilize at 120–140 days. For lightweight concrete of class B60, the shrinkage deformation

curves exhibit relative linearity up to 150–170 days of observation. This is likely due to the superposition of two moisture-mass transfer processes: moisture loss by the cement pastes due to evaporation at low relative air humidity, and moisture influx into the cement paste from the porous aggregate, which acts as a reserve of water uniformly distributed throughout the volume of lightweight concrete.

4. The elastic strains of high-strength self-compacting heavy and lightweight concretes fall within a narrow range of $54.0\text{--}63.8 \times 10^{-5}$, and despite a significant difference in prismatic strength (from 64.6 to 112.2 MPa) and modulus of elasticity (from 34.5 to 47.2 GPa), they differ by no more than 18%, which is a consequence of the wide range of specimen loading levels (from 19.4 to 32.0 MPa), regulated by GOST 24452 and GOST 24544 at a uniform value of 0.3 times the prismatic strength.

5. The ultimate creep strains of high-strength heavy and lightweight concretes, obtained experimentally at 240 days of age, increase with decreasing relative air humidity and range from $10.1\text{--}23.9 \times 10^{-5}$ at 90% humidity, $19.0\text{--}27.5 \times 10^{-5}$ at 60% humidity, and $25.8\text{--}40.5 \times 10^{-5}$ at 20% humidity.

The ultimate creep strains, determined using the method specified in GOST 24544, exceed the experimental values by 4 to 61 percent. At the same time, the accuracy of the standard calculation method decreases as the concrete class increases and relative air humidity decreases, which necessitates revisions to the method.

6. The creep modulus of high-strength self-compacting heavy and lightweight concretes of classes B60–B100 increases as relative air humidity decreases and is as follows: $0.52\text{--}0.85 \times 10^{-5}$ MPa⁻¹ at 90% humidity, $0.80\text{--}1.12 \times 10^{-5}$ MPa⁻¹ at 60% humidity, and $1.23\text{--}1.65 \times 10^{-5}$ MPa⁻¹ at 20% humidity.

7. The creep coefficients of high-strength self-compacting heavy concretes of classes B70–B100, obtained by calculation and experiment, increase with decreasing relative air humidity and amount to 0.32–0.46 at 90% humidity, 0.41–

0.59 at 60% humidity, and 0.61–0.99 at 20% humidity, which is two times or more lower than the standard values specified in Eurocode EN 12390 and the code of rules SP 63.13330.2018.

The creep coefficients of high-strength, self-compacting lightweight concrete of class B60, obtained through calculation and experimentation, increase as relative air humidity decreases, ranging from 0.16 to 0.21 at 90% humidity, 0.32–0.41 at 60% humidity, and 0.44–0.48 at 20% humidity, which is four times lower than the standard values specified in Eurocode EN 12390 and the design code SP 63.13330.2018.

8. Based on the results obtained, it is recommended that GOST 24544 include a direct formula for determining the creep coefficient of concrete, extend the duration of long-term tests on high-strength concretes to 270 days, and amend the procedure for determining the ultimate creep strains of concrete in Appendix G, and to include in SP 63.13330.2018 a provision regarding the possibility of experimentally determining the concrete creep coefficient, which will significantly improve the efficiency of using modern modified concretes in the construction of unique buildings and structures.

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