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Influence of Variotropy on the Change in Concrete Strength under the Impact of Wet–Dry Cycles

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Abstract: One of the most dangerous types of cyclic effects, especially inherent in several regions in the world, is the alternating impact of wetting and drying on concrete and reinforced concrete structures. In the current scientific literature and practice, there is not enough fundamental and applied information about the resistance to wetting and drying of variotropic concretes obtained by centrifugal compaction methods. The purpose of the study was to investigate the effect of various technological, compositional, and other factors on the final resistance of variotropic concrete to alternating cycles of moistening and drying. For this, special methods for testing concrete samples were used in the work. It has been established that after strength gain as a result of hydration, there is a tendency for strength loss due to concrete wear. An acidic medium has the most negative effect on the strength characteristics of concretes made using various technologies, compared with neutral and alkaline media. The loss of strength of concrete when moistened in an acidic medium was greater than in alkaline and especially neutral media. The vibrocentrifuged concrete turned out to be the most resistant to the impact of an aggressive environment and the cycles of moistening and drying, compared to the centrifuged and vibrated concrete. The drop in strength was up to 7% less compared to centrifuged concrete and up to 17% less than vibrated concrete.

Keywords: concrete; wet-dry cycles; compressive strength; variotropic concrete; aggressive environment

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1. Introduction

1.1. Background

Currently, reinforced concrete structures form the basis of modern construction. Buildings and structures of various levels of responsibility are still being built from a concrete composite reinforced with metal rods, which makes such a material and such structures very susceptible to various types of aggressive influences, especially considering cyclic influences. One of the most dangerous types of cyclic impacts, especially inherent in several regions of the world, is the alternating effect of wetting and drying on concrete and reinforced concrete structures. In view of the fact that concrete in reinforced concrete structures has a protective function and provides a bearing capacity in the long term, protecting concrete from such cyclic exposure is an important task for process engineers and materials scientists [1–4]. However, it should be noted that to develop corrective measures

to improve the concrete of reinforced concrete structures operating in aggressive conditions of alternating wetting-drying, these processes should be studied in detail, identifying the fundamental processes and dependencies that occur under the destructive influence of moistening and drying cycles. These processes include corrosion of steel [5,6], diffusion of chlorides and the content of chlorides on the surface of concrete [7,8], fatigue damage to concrete caused by water [9].

Studies of various types of concrete exposed to aggressive environments during the moistening-drying cycles are presented in [10–12]. The study [10] evaluated the mechanical characteristics of concretes under conditions of combined exposure to sulfates and moistening and drying cycles. According to the results, it was found that during the cycling of moistening and drying, the compressive strength increases up to 60 cycles and then gradually decreases. As for the sulfate attack, here the dependence of the change in strength is directly proportional: with an increase in the concentration of the sodium sulfate solution, the rate of loss of compressive strength also increases. Studies [11,12] have a similar topic to [10], but the difference lies in the fact that concretes reinforced with steel fibers were studied. In general, the change in strength characteristics depends on the impact of the "moisture-drying" cycles and the degree of aggressiveness of the environment is of a similar nature. In [13], the authors studied "the effect of nano-TiO_2 additives on the corrosion characteristics of concrete". Following the results of experimental studies, it was found that the addition of a nanomodifying additive of titanium oxide increased the sulfate resistance of the composite during its alternating moistening and drying. Thus, for samples of the control composition, the maximum value of strength loss was 40%, and for modified ones, 36%. In [14,15], the authors studied the effect of fly ash additives on the durability characteristics of concrete. So, for example, in [14], for samples with 40% fly ash content, the coefficient of corrosion resistance and relative dynamic modulus of elasticity are higher than for samples of the control composition. The authors explain the higher corrosion resistance of samples with fly ash by a change in the nature of hydration processes. In [15], the authors note some negative aspects that arise when fly ash is introduced into the composition of concrete. As for the sulfate resistance of concrete, it directly depends on the percentage of ash. According to the results of the study, the best characteristics of the durability of concrete can be provided by replacing the binder with ash in an amount of 20%; however, with a replacement of 30%, a significant deterioration in these characteristics is observed. In addition to filler additives in the form of waste, chemical additives, for example, hydrophobic ones, have also been studied [16]. In [17,18], the authors studied the mechanism of concrete destruction under the conditions of "dry-wet" cycles during a sulfate attack. Based on the results of these studies, it was found that alternating wetting and drying with an increase in the number of cycles contributes to a more accelerated development of sulfate degradation in concrete. In engineering practice, concrete structures are under constant stress. Thus, in works [19–21], the effect of wetting and drying on the mechanical characteristics of concrete under load has been investigated. In general, over time, as a result of prolonged exposure to dry-wet cycles, concrete and reinforced concrete structures lose their strength characteristics.

Many works are devoted to the research of the mechanical and physical properties of various types of concrete, such as concrete of normal density [22,23], concrete on recycled aggregates [24], and self-compacting fiber-reinforced concrete [11] after exposure to dry-wet cycles and sulfate attack. All these works describe the mechanisms of degradation as well as the dependence of the deterioration of concrete properties due to the considered cyclic effects. Particular attention is paid to the mechanisms of damage to concrete under the conditions of "dry-wet" cycles and sulfate erosion in works [25–27]. The effect of crack opening width and "dry-wet" cycles on the penetration of chlorides into concrete [28] and engineering cement composite [29] is also the subject of many works. They studied and described the destructive processes occurring under these impacts and the dependence of the chloride penetration value on the "dry-wet" cycles and the crack opening width in concrete. Works [30,31] are devoted to the study of the fatigue behavior of high-strength

concrete [30] and the fatigue modeling of the wear of reinforced concrete slabs of road bridges [31] under the conditions of "moisture-drying" cycles. The influence of moisture in concrete and a humid environment on the fatigue characteristics of concrete is noted in the form of a decrease in fatigue resistance, expressed in the number of cycles to failure [30].

The influence of the pH of mixing water and various media (acidic, neutral, and alkaline) in which concrete is operated on its behavior was previously studied to assess the properties of concrete and structures made of it, such as strength [31], degradation degree [32], composition of the corroded surface of reinforcing steel [33], compressive strength and microstructure analysis, durability [34,35], loss of strength, and mass [36]. At the same time, the methods and criteria for measuring pH in the study of cement-based materials [37], as well as the main causes of concrete degradation, including mechanisms, including specific ones, designed for technically complex energy facilities [38], are important factors in this matter.

1.2. Rationale

Based on the literature review and analysis, we can identify the scientific problem that researchers face. The scientific problem lies in the lack of knowledge of the fundamental mechanisms that occur at the microlevel under the destructive effect of moistening–drying cycles on concrete. At the same time, it is important to understand not only the fundamental destructive role of these processes in concrete but also all the interrelations that ultimately lead to premature destruction and failure of reinforced concrete structures at the macro level [39–47]. It is necessary to set specific initial parameters to evaluate the influence of various factors on the final life cycle duration and operational reliability of reinforced concrete products and structures. At the same time, in view of the fact that the issue with concretes of conventional structures obtained by vibration methods is more or less studied, then, as for variotropic concretes with an improved structure and obtained by centrifugal compaction methods, a more detailed and in-depth study should be carried out on the micro and macro levels. Thus, the scientific problem is formulated by us in such a way that in modern scientific literature and practice, there is not enough fundamental and applied information about the resistance to moisture and drying of variotropic concretes obtained by centrifugal compaction methods.

Thus, the purpose of our study is to investigate the effect of various technological, compositional, and other factors on the final resistance of variotropic concrete to alternating cycles of moistening and drying. The objectives of the study are:

(1) a review and analysis of the literature evaluating the effects of alternating wetting and drying cycles on concrete in general, with a focus on vibrated plain concrete;
(2) development of an own method for determining the resistance and differentiation of the properties of concrete subjected to alternate wetting and drying, depending on the technology of its manufacture;
(3) conducting experimental studies to confirm the hypothesis put forward about the higher resistance to alternating moistening and drying of variotropic concretes and, thereby, higher efficiency for operation under cyclic impacts of variotropic reinforced concrete structures;
(4) determination of the possibility of considering the differentiation of concrete properties in the event of its variability in reinforced concrete structures made by centrifugal compaction methods;
(5) determination of further prospects for the scientific development of this theory, as well as determination of the practical applicability of the scientific results obtained during the study.

2. Materials and Methods

2.1. Materials

Portland cement CEM I 42.5N (content of Portland cement clinker 95–100%, strength class 42.5, normally hardening) was used for the preparation of concrete mixtures. The

main characteristics of Portland cement, according to the manufacturer's data sheet, are shown in Table 1.

Table 1. Portland cement properties.

Physical and mechanical properties										
Compressive strength at the age of 2 days (28 days) (MPa)				Start setting (minutes)		Uniformity of volume change (expansion) (mm)		Grinding fineness (residue on sieve No. 008 (%)		
18.9 (50.4)				135		1		3.6		
Chemical composition (%)										
SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	SO_3	TiO_3	LOI	Na_2O	K_2O	Chlorine ion Cl^-
22.65	4.13	3.96	1.29	62.2	1.68	0.05	3.69	0.12	0.22	0.01
Mineralogical composition (%)										
Tricalcium silicate				Dicalcium silicate			Tricalcium aluminate			Tetracalcium aluminoferrite
65				17			7			11

Crushed stone from sandstone with a fraction of 5–20 mm from the Potapov quarry (Azov-Donskaya Non-Metallic Company JSC, Verkhnepotapov, Russia) was used as a coarse aggregate.

The characteristics of the applied crushed stone are presented in Table 2.

Table 2. Physical and mechanical properties of crushed stone.

Crushability, (%)	The Content of Lamellar and Needle-Shaped Grains, (%)	The Content of Dust and Clay Particles, (%)	Grain Content of Weak Rocks, (%)	Bulk Density (kg/m^3)	True Density (kg/m^3)	Frost Resistance, Cycles
11.5 (type 1000)	10.5 (groop 2)	0.5	2.1	1395	2658	200 (F200)

Quartz sand from the Erofeevsky sand pit ("Legion", Erofeevka farm, Russia) was used as a fine aggregate. The main properties of the sand used in the study are shown in Table 3.

Table 3. Physical properties of sand.

Size Modulus, M_f	The Content of Dust and Clay Particles, (%)	Clay Content in Lumps, (%)	Sand Class According to GOST 8736	Bulk Density, (kg/m^3)	True Density (kg/m^3)
2.1 (medium)	1.6	0.12	I	1520	2603

To saturate concrete samples, aqueous solutions with different pH levels were prepared. Normal tap water was used as a neutral saturation medium at pH 7, a solution at pH 5 was obtained by dissolving copper sulfate, and a solution at pH 10 was prepared by dissolving sodium carbonate.

2.2. Methods

Portland cement tests were carried out according to the GOST 30744 "CEMENTS. Methods of testing with using poly fraction standard sand" [48]. The sand was tested according to GOST 8735 "Sand for construction work. Testing methods" [49], crushed stone according to GOST 8269.0 "Mountainous rock road-metal and gravel, industrial waste products for construction works methods of physical and mechanical tests" [50].

The samples of the concrete mixture were made according to three technologies: vibrating, centrifuging, and vibrocentrifuging.

The preparation of the concrete mixture using the vibrating technology was carried out in a laboratory concrete mixer BL-10 with the following order of loading the components: first water (W), then Portland cement (PC), then sand (S), and crushed stone (CrS). Prior to being loaded into the concrete mixer, each component of the concrete mixture was weighed on a VK-3000.1 scale (MASSA-K, St. Petersburg, Russia) to ensure the required dosage. The mixing of the components in the concrete mixer was carried out until a homogeneous consistency was obtained. Then, the mixture was poured into metal cube molds 2FK-50 and prism molds FB-50/200 (NPO Priborinform, Rostov-on-Don, Russia). Next, the mixture was compacted in molds on a laboratory vibration platform SMZh-739M (RNPO RusPribor, St. Petersburg, Russia) for 50 s. Next, the surface of the mixture was smoothed, leveled with the edges of the molds, and placed in a KNT-1 normal curing chamber (RNPO RusPribor, St. Petersburg, Russia). After 1 day, the samples were removed from the molds and placed back in the curing chamber for the remaining 27 days. Thus, the hardening of the samples was carried out until they reached the age of 28 days. The concrete mixture was prepared in the following proportions of components: PC:W:S:CrS = 1:0.52:1.38:3.03.

The preparation of the concrete mix according to the technologies of centrifugation and vibrocentrifugation was carried out in a laboratory vibrocentrifuge, the design and parameters of which are described in detail in [51]. The composition of the concrete mix corresponded to the following proportions of its components: PC:W:S:CrS = 1:0.44:1.67:2.89. The centrifugation parameters were set as follows: rotation speed—156 rad/s, molding time—12 min; vibration parameters: height of clamp projections—5 mm, projection length—20 mm, pitch between projections—30 mm. In general, the technology for manufacturing concrete elements of an annular section using centrifugation and vibrocentrifugation technologies included the following main technological operations: batching of concrete mixture components, mixing of the concrete mixture, determining the characteristics of the workability of the resulting mixture, loading the concrete mixture into a mold, the centrifugation process, draining the sludge, holding for 24 h in the mold, and removing the element of the annular section from the mold [52].

The concrete mixing ratios in 1 m^3 are presented in Table 4.

Table 4. Concrete mixing ratios in 1 m^3.

Technology	PC (kg/m^3)	W (L/m^3)	S (kg/m^3)	CrS (kg/m^3)
Vibration	383	199	529	1160
Centrifugation and vibrocentrifugation	409	180	683	1182

In total, 13 centrifuged and 13 vibrocentrifuged annular elements were manufactured, having an outer diameter of 210 mm, an inner diameter of 70 mm, and a height of 630 mm (Figure 1). Samples from the elements of the annular section were sawn according to the scheme shown in Figure 2.

A total of 117 cubes and 117 prisms were sawn from 13 centrifuged samples; the same number was obtained from 13 vibrocentrifuged samples. Thus, a total of 117 cubes and 117 prisms were made for each technology—vibrating, centrifuging, and vibrocentrifuging. For each technology, nine cubes and nine control prisms were made; the rest were the main samples.

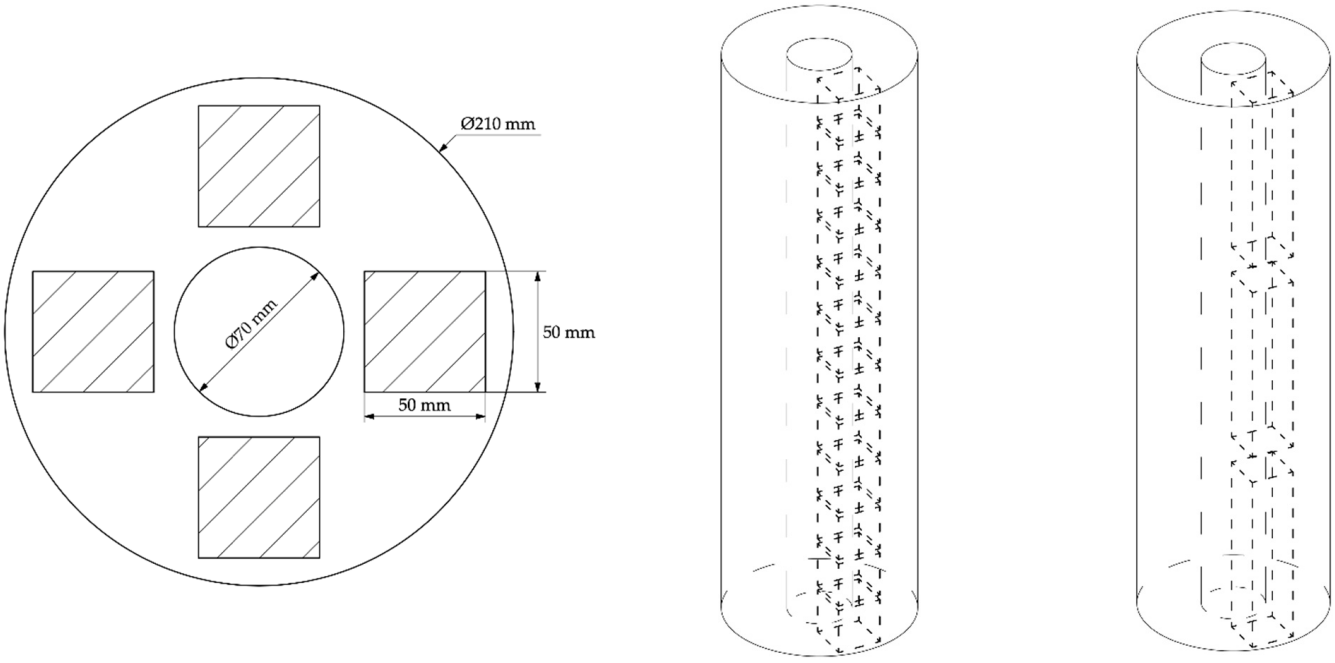
The samples were cut on a Cedima CTS-175 high-precision stone-cutting machine (CEDIMA GmbH, Celle, Germany) (Figure 3).

In the process of cyclic moistening and drying, the characteristics of the change in the strength of vibrated concrete were studied on cubes and prisms with dimensions, respectively, of 50 × 50 × 50 (mm) and 50 × 50 × 200 (mm); on centrifuged and vibrocentrifuged concrete—on cubes and prisms with dimensions, respectively, 50 × 50 × 50 (mm) and 50 × 50 × 200 (mm), sawn from elements of an annular section.



(**a**) (**b**)

Figure 1. Photograph of an annular section specimen: (**a**) in a laboratory facility during molding; (**b**) during demoulding.



(**a**) (**b**) (**c**)

Figure 2. Scheme of sawing out samples from elements of an annular section, made by centrifugation and vibrocentrifugation: (**a**) top view; (**b**) sample cubes; (**c**) prism samples.

The samples were tested for the effects of alternating wetting and drying with an intensity of about 60 cycles per month. Due to the absence of normative methods for conducting this test, the mode was as follows: drying samples at a temperature of +50–+55 °C for 5 h; humidification in water at a temperature of +15–+20 °C for 7 h. The drying temperature was assigned from the conditions of concrete heating in natural conditions with solar radiation. Saturation at the end of the wetting phase was determined empirically in the course of preliminary experiments in terms of achieving a constant mass of a saturated, that is, wetted, sample. The duration of wetting and drying, established as a result of preliminary experiments, ensured the fluctuation of humidity within 25–75% of the value of the initial water absorption after two days of wetting [53]. The scheme of experimental studies is shown in Figure 4.



(**a**) (**b**)

Figure 3. High-precision stone-cutting machine: (**a**) side view; (**b**) top view.

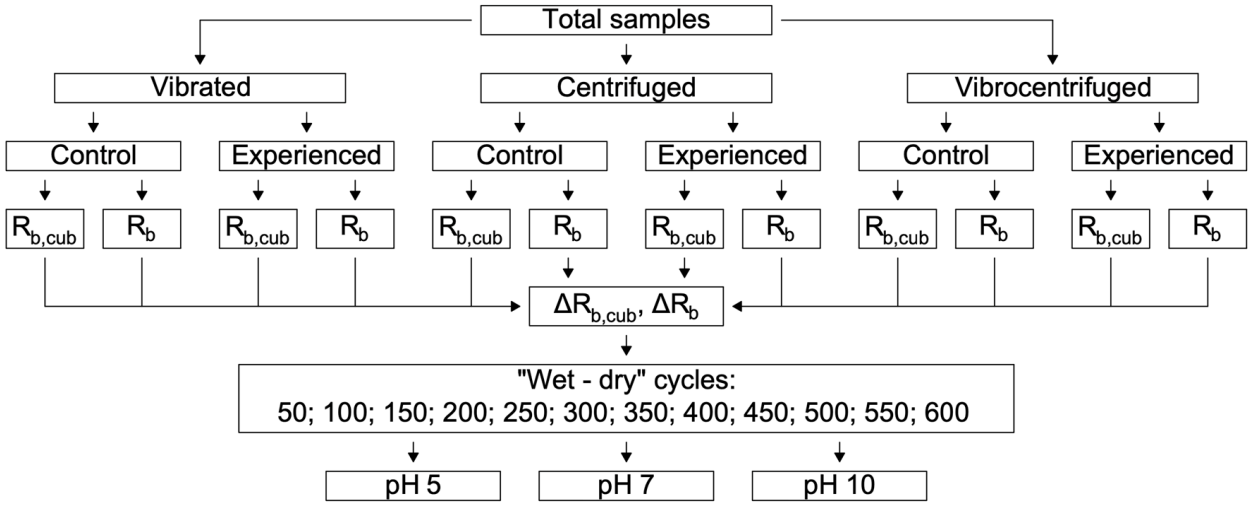


Figure 4. Block diagram of experimental studies.

Figure 5 shows photographs of the process of moistening and drying sample cubes and prism samples.

Samples were moistened in special containers with water temperature control. Samples were dried in an SNOL 67/350 oven (Umega, Ukmerge, Lithuania). The pH level was measured using a Starter 2100 digital pH meter (OHAUS SNG, Moscow, Russia). The measurement range of the device is from 0 to 14 pH, and the division value is 0.1 pH.

The technique for testing concrete samples for cubic compressive strength corresponded to the GOST 10180-2012 "Concretes. Methods for Strength Determination Using Reference Specimens" [54]. Testing of concrete samples for prismatic compressive strength was carried out according to the method of GOST 24452-80 "Concretes. Methods of prismatic, compressive strength, modulus of elasticity and Poisson's ratio determination" [55]. When determining the prism strength of concrete, the loading of samples to a load level equal to (40 ± 5)% of the expected collapse load was carried out in steps equal to 10% of

the expected collapse load at a loading rate of (0.6 ± 0.2) MPa/s. The prism strength (R_b) was calculated for each sample using the formula:

$$R_b = \frac{P_c}{F}$$

where P_c—collapse load, measured on the scale of the press force meter; F—the average value of the cross-sectional area of the sample, determined by its linear dimensions.



(**a**) (**b**)

(**c**) (**d**)

Figure 5. Testing samples for resistance to humidification and drying cycles: (**a**) humidification of sample cubes; (**b**) wetting of prism specimens; (**c**) drying of sample cubes; (**d**) drying the prism specimens.

3. Results

The experimental studies of samples' testing of vibrated, centrifuged, and vibrocentrifuged concretes subjected to alternate wetting in media with different pH levels and drying are presented in Figures 6–11 and Tables 5–7.

Figures 6 and 7 show the dependences of the change in cubic ($R_{b.cub}$) and prismatic (R_b) compressive strengths of vibrated, centrifuged, and vibrocentrifuged concretes in a moistening medium with pH 7.

According to the results of the change in the strength characteristics of vibrated, centrifuged, and vibrocentrifuged samples after a series of moistening and drying cycles, a similar trend in the change in cubic compressive strength and prism compressive strength is visible for all types of concrete. The impact of cyclic moistening and drying is characterized by an intensive initial increase in strength characteristics up to 200 cycles inclusive and their

further decrease. Starting from the 250 cycle of moistening–drying and up to the 350 cycles, the strength decreases but still has greater values compared to the control composition. Starting from the 400th cycle, the strength values begin to fall more intensively and have lower values than those of the control samples. Table 5 shows the change in strength characteristics ($\Delta R_{b.cub}$, ΔR_b) in percentage terms.

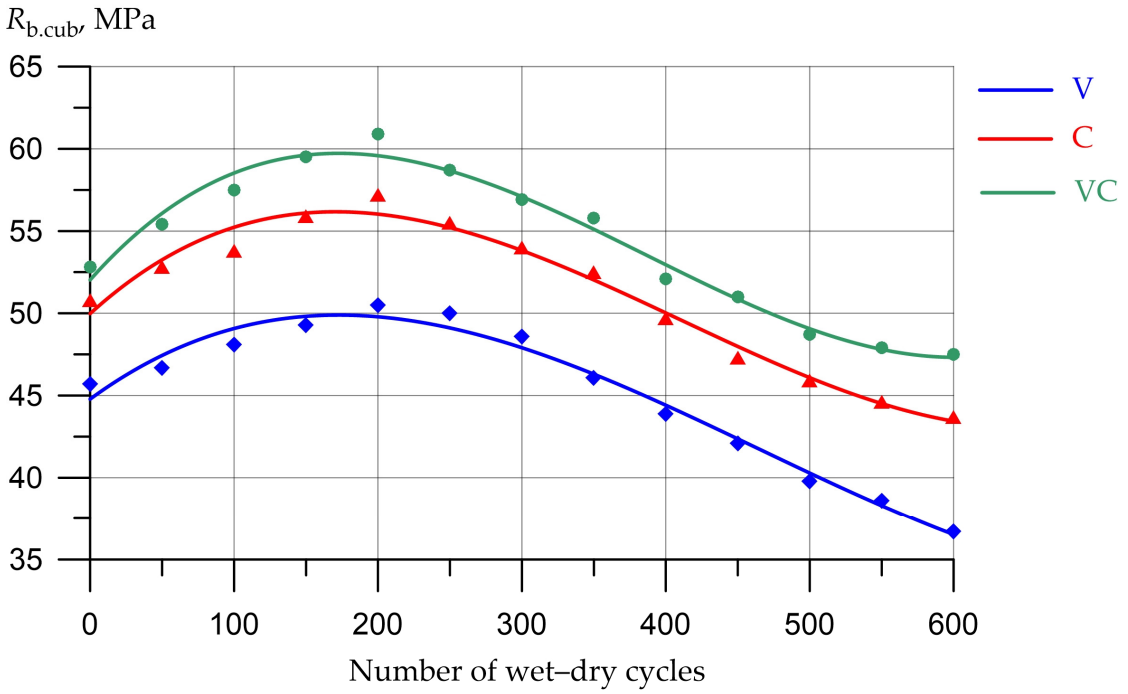


Figure 6. Dependence of the change in the cubic compressive strength of vibrated, centrifuged, and vibrocentrifuged concretes on the number of moisturizing and drying cycles at pH 7.

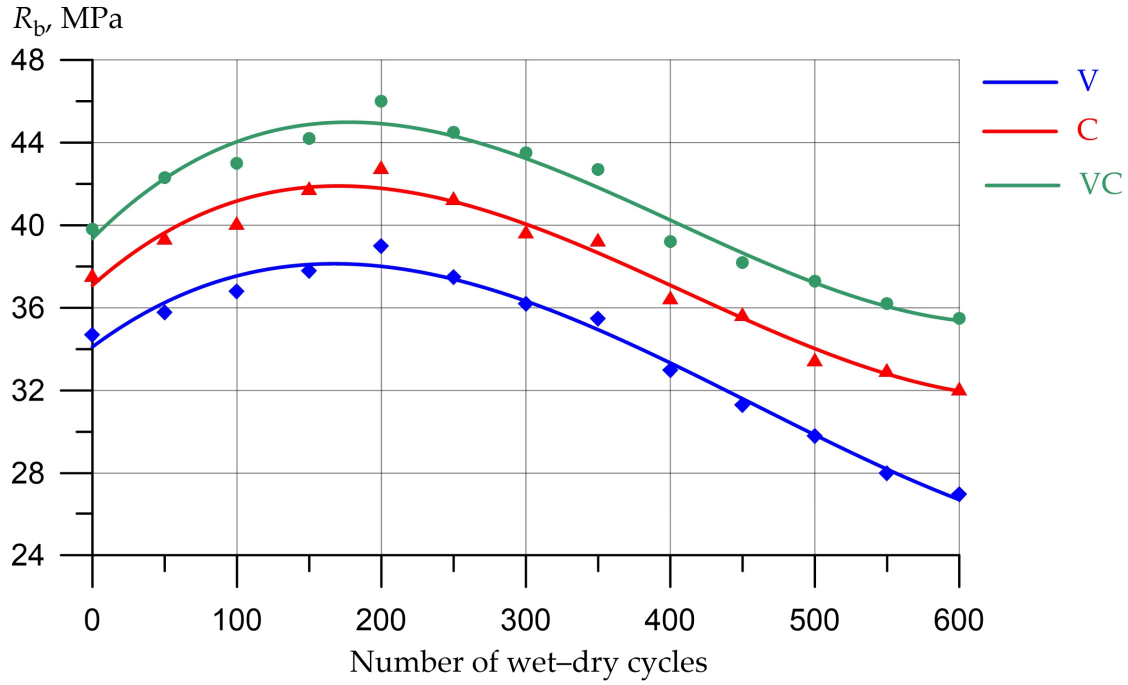


Figure 7. The dependence of the change in the prism compressive strength of vibrated, centrifuged, and vibrocentrifuged concretes on the number of "moisturizing-drying" cycles at pH 7.

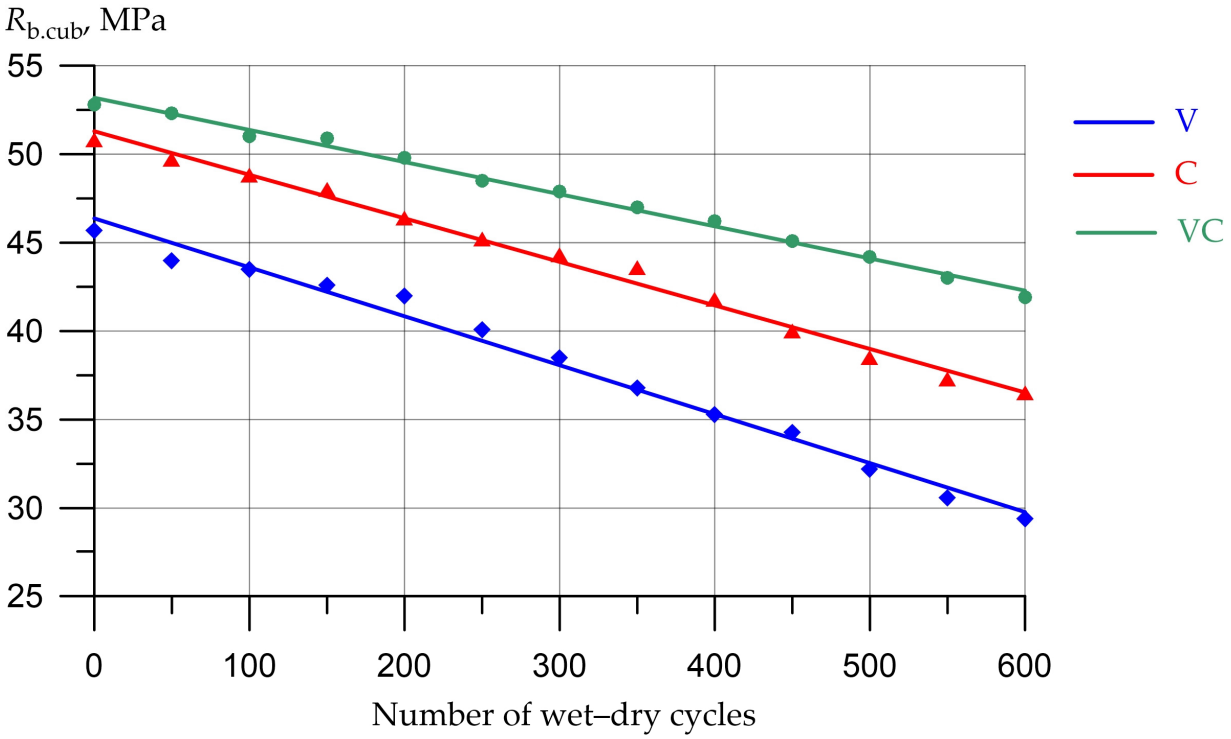


Figure 8. Dependence of the change in the cubic compressive strength of vibrated, centrifuged, and vibrocentrifuged concretes on the number of moistening and drying cycles at pH 5.

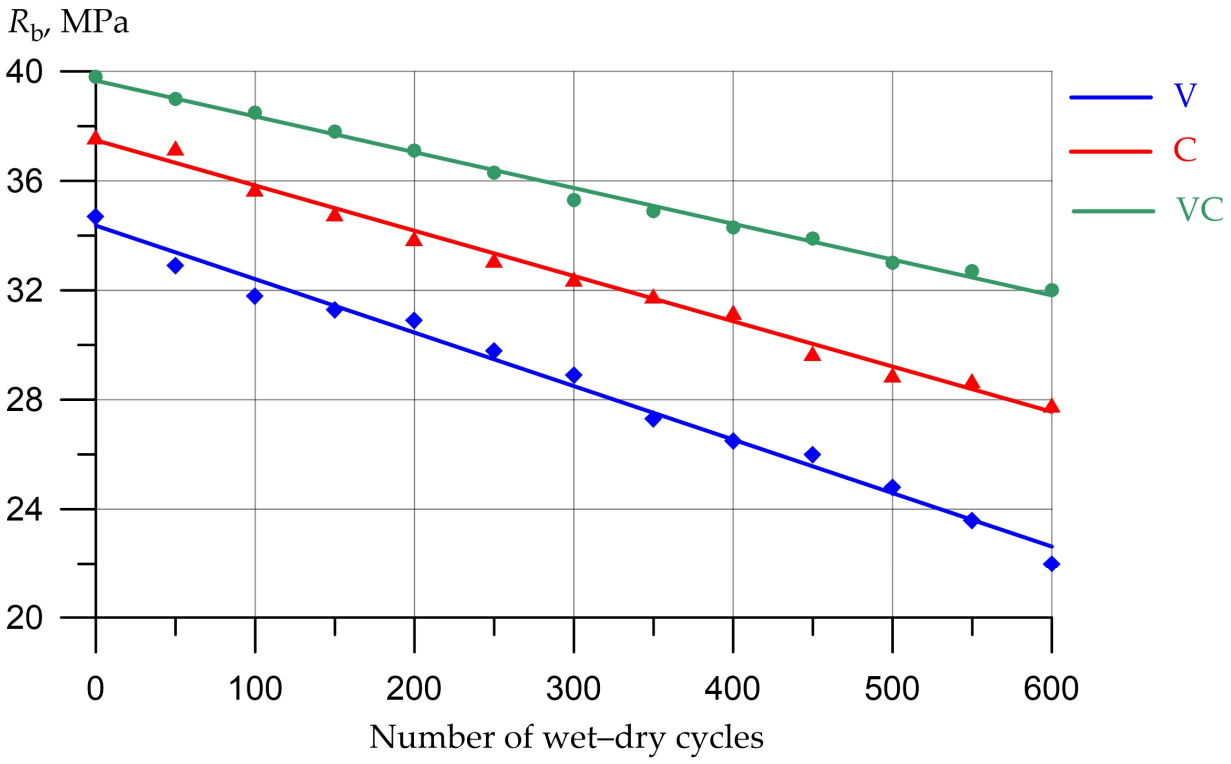


Figure 9. Dependence of the change in prism compressive strength of vibrated, centrifuged, and vibrocentrifuged concretes on the number of moistening and drying cycles at pH 5.

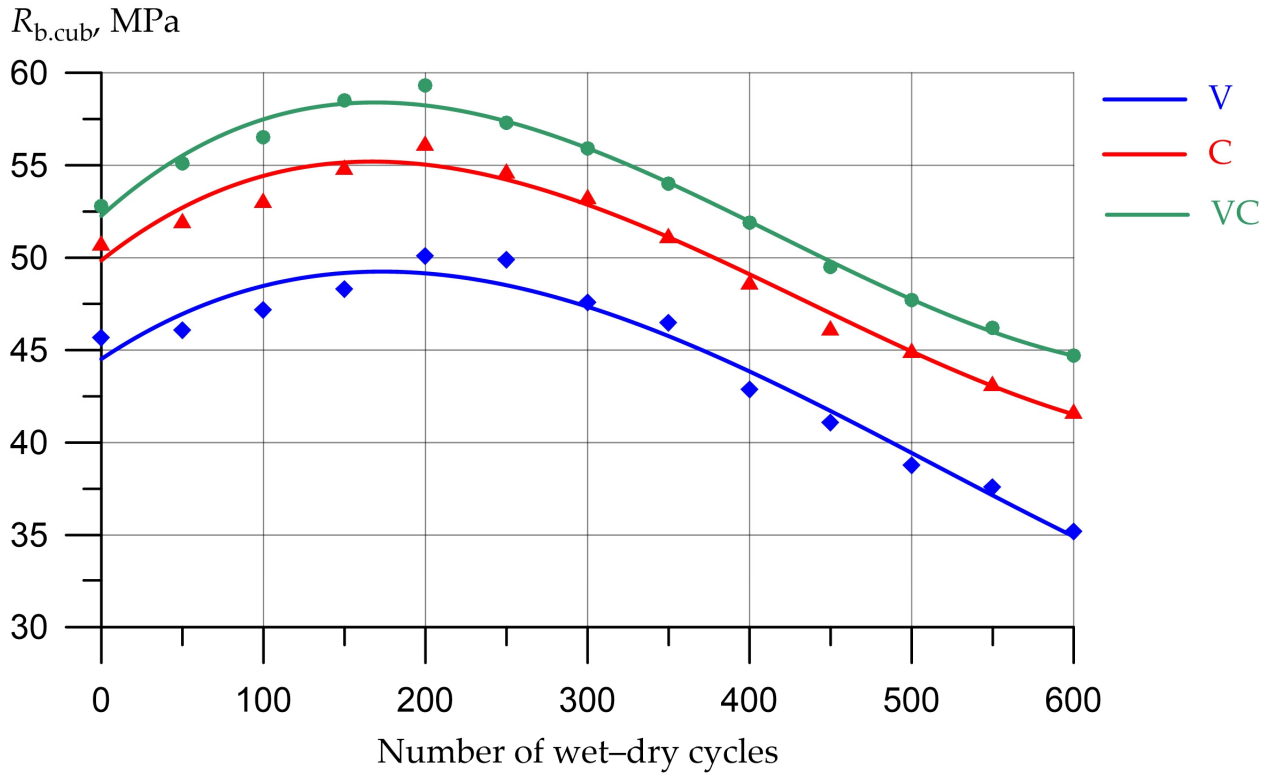


Figure 10. Dependence of the change in the cubic compressive strength of vibrated, centrifuged, and vibrocentrifuged concretes on the number of moistening and drying cycles at pH 10.

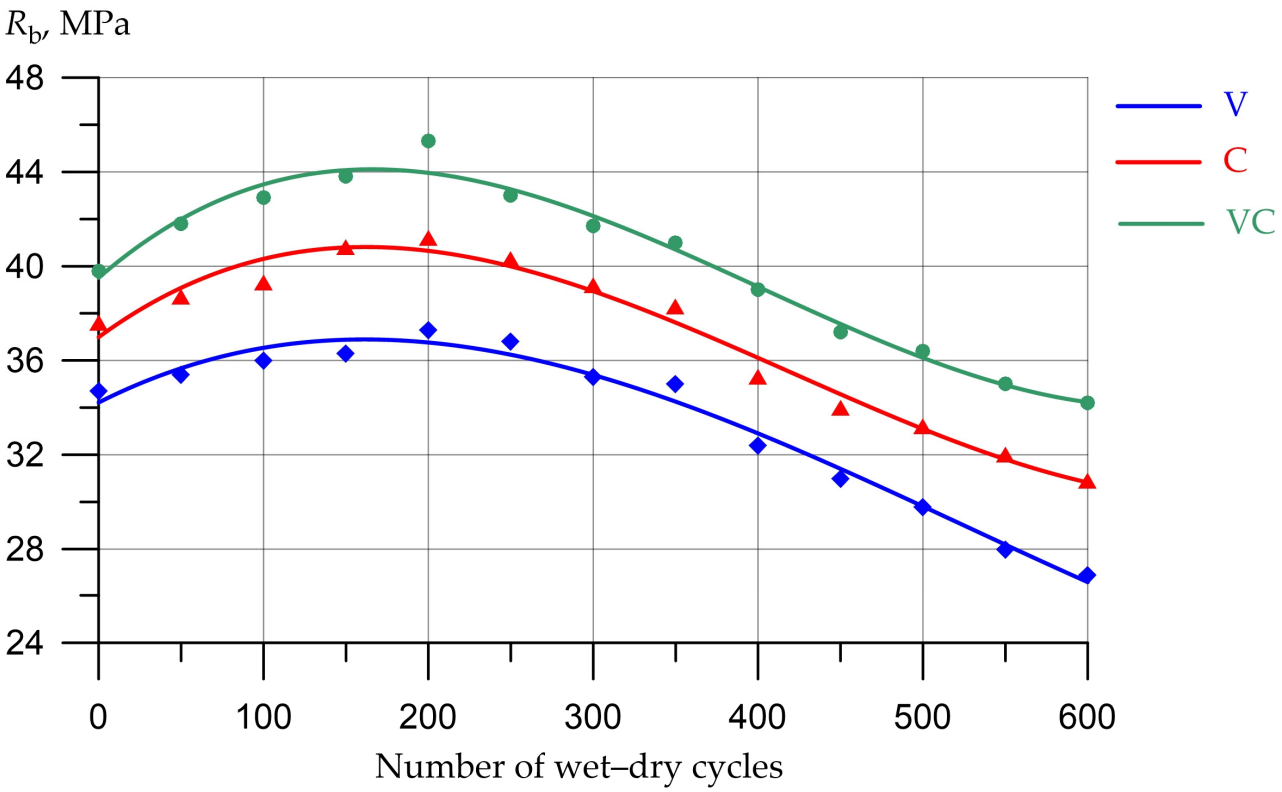


Figure 11. The dependence of the change in the prism compressive strength of vibrated, centrifuged, and vibrocentrifuged concretes on the number of moistening and drying cycles at pH 10.

Table 5. Change in the strength characteristics of vibrated, centrifuged, and vibrocentrifuged concretes after cyclic wetting and drying at pH 7.

Type of Concrete	Number of Wetting and Drying Cycles												
	0	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
Vibrated	$\Delta R_{b.cub}$, %												
	0	2	5	8	11	9	6	1	–4	–8	–13	–16	–20
	ΔR_b, %												
	0	3	6	9	12	8	4	2	–5	–10	–14	–19	–22
Centrifuged	$\Delta R_{b.cub}$, %												
	0	4	6	10	13	9	6	3	–2	–7	–10	–12	–14
	ΔR_b, %												
	0	5	7	11	14	10	6	5	–3	–5	–11	–12	–15
Vibrocentrifuged	$\Delta R_{b.cub}$, %												
	0	5	9	13	15	11	8	6	–1	–3	–8	–9	–10
	ΔR_b, %												
	0	6	8	11	16	12	9	7	–2	–4	–6	–9	–11

Table 6. Change in the strength characteristics of vibrated, centrifuged, and vibrocentrifuged concretes after cyclic wetting and drying at pH 5.

Type of Concrete	Number of Wetting and Drying Cycles												
	0	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
Vibrated	$\Delta R_{b.cub}$, %												
	0	–4	–5	–7	–8	–12	–16	–19	–23	–25	–30	–33	–36
	ΔR_b, %												
	0	–5	–8	–10	–11	–14	–17	–21	–24	–25	–29	–32	–37
Centrifuged	$\Delta R_{b.cub}$, %												
	0	–2	–4	–6	–9	–11	–13	–14	–18	–21	–24	–27	–28
	ΔR_b, %												
	0	–1	–5	–7	–10	–12	–14	–15	–17	–21	–23	–24	–26
Vibrocentrifuged	$\Delta R_{b.cub}$, %												
	0	–1	–3	–4	–6	–8	–9	–11	–13	–15	–16	–19	–21
	ΔR_b, %												
	0	–2	–3	–5	–7	–9	–11	–12	–14	–15	–17	–18	–20

Table 5 shows that the maximum loss of strength characteristics after 600 cycles of moistening and drying is observed in vibrated concrete, while the smallest loss of strength is recorded in vibrocentrifuged concrete. The maximum loss of cubic compressive strength for vibrated concrete was 20%, for centrifuged 14%, and for vibrocentrifuged 10%. A similar situation is observed for the prism strength. So, for vibrated concrete, the maximum loss of prism strength was 22%, for centrifuged concrete, 15%, and for vibrocentrifuged concrete, 11%. Attention is drawn to a slower drop in strength characteristics after prolonged exposure to moistening and drying cycles for centrifuged concretes than for vibrated ones (by 7%) and for vibrocentrifuged concretes than for centrifuged ones (by 4%). The difference in strength reduction between vibrated and vibrocentrifuged concretes was up to 11%.

Table 7. Change in the strength characteristics of vibrated, centrifuged, and vibrocentrifuged concretes after cyclic wetting and drying at pH 10.

Type of Concrete	Number of Wetting and Drying Cycles												
	0	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
Vibrated	$\Delta R_{b.cub}$, %												
	0	1	3	6	10	9	4	2	–6	–10	–15	–18	–23
	ΔR_b, %												
	0	2	4	5	7	6	2	1	–7	–11	–14	–19	–22
Centrifuged	$\Delta R_{b.cub}$, %												
	0	2	5	8	11	8	5	1	–4	–9	–11	–15	–18
	ΔR_b, %												
	0	3	5	9	10	7	4	2	–6	–10	–12	–15	–18
Vibrocentrifuged	$\Delta R_{b.cub}$, %												
	0	4	7	11	12	9	6	2	–2	–6	–10	–13	–15
	ΔR_b, %												
	0	5	8	10	14	8	5	3	–2	–7	–9	–12	–14

Figures 8 and 9 show the dependences of the change in cubic and prism compressive strengths of vibrated, centrifuged, and vibrocentrifuged concretes in a moistening medium with pH 5.

Figures 7 and 8 show that the nature of the change in the strength characteristics of vibrated, centrifuged, and vibrocentrifuged concrete is slightly different from the previous tests presented in Figures 6 and 7. These changes are directly related to the increase in the degree of aggressiveness of the saturation aqueous medium to pH 5. The drop in strength characteristics was already recorded after the first 50 cycles of moistening and drying, and up to the 250th cycle, it was not so intense. Starting from the 400th cycle, the rate of decrease in strength characteristics noticeably increases. This can be explained by the fact that, up to 400 cycles, the drop in strength is due only to the degree of aggressiveness of the medium at pH 5, and starting from 400 cycles, according to the tests already presented earlier at pH 7, the destructive effect of wetting and drying cycles is added to the aggressive medium. Thus, the resulting drop in strength characteristics in this aggressive environment after 600 cycles of wetting and drying is noticeably higher than at pH 7 (a neutral environment). Table 6 shows the changes in strength characteristics in percentage terms.

According to the data from Table 6, the maximum loss of cubic compressive strength for vibrated concrete was 36%, for centrifuged 28%, and for vibrocentrifuged 21%. As for the drop in prismatic compressive strength, it was 37% for vibrated concrete, 26% for centrifuged concrete, and 20% for vibrocentrifuged concrete. Here, as in a neutral medium, the smallest strength losses, much smaller than those of centrifuged (up to 7%) and especially vibrated (up to 17%) concretes, are observed in vibrocentrifuged concretes.

Figures 10 and 11 show the dependences of the change in cubic and prism compressive strengths of vibrated, centrifuged, and vibrocentrifuged concretes in a moistening medium with pH 10.

Figures 10 and 11 clearly show that the change in cubic and prism compressive strengths of vibrated, centrifuged, and vibrocentrifuged concretes is similar to that of the curves presented in Figures 6 and 7 (neutral medium with pH 7). Up to cycle 200 inclusive, an increase in strength characteristics is also observed, and then, starting from cycle 250, the curve goes down. Table 7 shows changes in strength characteristics in percentage terms.

Based on the data presented in Table 7, after 600 cycles of moistening and drying, the loss of cubic compressive strength for vibrated concrete was 23%, for centrifuged, 18%, and for vibrocentrifuged, 15%. The loss of prism compressive strength for vibrated

concretes was 22%, for centrifuged, 18%, and for vibrocentrifuged, 14%. The smallest losses in the strength characteristics of concretes made using three technologies are observed in vibrocentrifuged concrete in comparison with centrifuged (4%) and vibrated (8%).

After analyzing the results obtained, it can be concluded that concretes made using various technologies, when moistened in aqueous solutions with pH 7 and pH 10, have similar trends in cubic and prism compressive strengths. In all cases, the maximum strength values were recorded after 200 cycles of wetting and drying, and starting from the 250th cycle, a drop in strength was observed. As for concrete samples subjected to saturation in an aqueous medium with pH 5, the nature of the change in strength characteristics is different here. The drop in strength for vibrated, centrifuged, and vibrocentrifuged concretes was recorded after the first 50 cycles of wetting and drying and continues further. When concrete is wetted in an aggressive environment with pH 5, the effect favorable for strength described above, observed up to 200 cycles at pH 7 and pH 10, is neutralized by the degree of aggressiveness of the environment and the corresponding destructive processes occurring in the structure of the concrete due to its impact.

At the same time, different water-cement ratios are due to differences in the technology of molding and compacting the concrete mixture. For vibrated—this is a vibration seal for centrifuged and vibrocentrifuged—this is a centrifugal seal. At the same time, one of the main criteria for comparing concrete mixtures obtained using different technologies was the indicator of the workability of the mixture. For all mixtures, it was the same (grade for workability P1, that is, the draft of a standard cone was not less than 1 and not more than 4 cm) [56]. Thus, in order to obtain the same grade in terms of workability for different methods of compacting the concrete mix, a different water/cement ratio was required.

In addition, the main criterion for comparing the characteristics of concrete samples obtained by different methods of molding and compaction was not the values of cubic and prism compressive strengths, but their changes after a certain number of moistening and drying cycles, the so-called values of strength drops.

4. Discussion

The considered features of the change in the mechanical properties of concrete in the process of alternate moistening and drying according to the adopted method should be explained by the fact that in the initial period favorable conditions are created for further hydration of non-hydrated cement grains. In addition, during cyclic moisture migration, neoplasms are transferred and deposited on the walls of pores and capillaries, which leads to their narrowing and, as a result, a decrease in the permeability of concrete, which favorably affects its durability. However, a further decrease in strength occurs due to a violation of the adhesion of the cement stone with the aggregate. As is known, the contact zone is the main way of penetration and migration of moisture in concrete [53,57–59]. Subsequently, in accordance with [53,57–59], there occurs a kind of dissolution of the bonds between the cement stone and aggregate and a decrease in the strength of their mutual adhesion. Thus, it can be considered that one of the main reasons for the decrease in the strength of concrete, both during freezing and thawing and in the process of cyclic moistening and drying, is a violation of the strong bond between the cement stone and the aggregate. At the same time, the development of micro- and macrocracks in the first case occurs when the moisture in the contact zone is frozen, and in the second case, when it dries. So, when heated concrete is moistened, the alternation of cycles is similar to an impact that causes stresses of a changing sign, leading to the appearance of microcracks and then their development. The accumulation of such disturbances is accompanied by an increase in the external volume and porosity, a decrease in strength, as well as a change in other physical and mechanical properties of the material. With alternating effects of moisture and drying, they can lead to a loss of operational properties of the material of structures or elements of engineering structures.

In concrete, the negative effect of exposure to alternating cycles of moistening–drying is usually explained by a significant difference in changes in the volume of individual

components of concrete with moisture fluctuations. The structure and properties of concrete in the process of cyclic influences of the environment change. In particular, with fluctuations in humidity, the strength and deformation properties of concrete change. For example, the continued hydration of cement particles leads to an increase in the strength of concrete, while intensive and uneven dehydration of the cement stone components causes brittleness due to a decrease in the volume content of the gel-like component of the cement stone and the formation of microcracks. These cracks, for example, during long cycles of moistening and drying, can self-heal, but in other cases, with alternating short-term cycles of moistening–drying, they can be centers of destruction. As the number of moistening and drying cycles increases, the formed cracks deepen and their surfaces carbonize. One of the reasons for the predominant development of destructive processes is the aging of the gel component of the cement stone. A decrease in the volume of the gel component during its aging leads to the emergence and development of internal tensile stresses sufficient to disrupt the structure of the material. This is facilitated by the decrease in the deformability of the gel component during its aging [53,60,61].

The results obtained in this work are in good agreement with the studies presented in [2,20,62]. In [20], the authors studied the effect of the action of "dry-wet" cycles on the mechanical and seismic characteristics of reinforced concrete columns. According to the results of the experiments, the fact of the negative impact of alternate moistening and drying on the studied characteristics was recorded. In the study [2], concretes for lining tunnels with various mineral additives were considered, and their characteristics were evaluated under the influence of cycles of alternating wetting in an aggressive environment and drying, and according to the results of experimental measurements, the coefficient of resistance to the destruction of concrete during the first 20 cycles increased and then decreased. The work [62] studied the effect of wetting–drying cycles on reinforced concrete columns under eccentric loads. The results of the experiments showed that the ultimate bearing capacity of the columns first increased and then decreased with an increasing number of sulphate dry–wet cycles. Thus, the obtained dependences of the strength characteristics on the number of moistening and drying cycles and various moistening media in the current study are similar in nature to those in the studies [2,20,62] for vibrated concrete but completely differ from them by a visual comparison of the behavior of the strength of concrete made by vibration with the behavior of the strength of concrete made by centrifugal compaction methods—centrifugation and vibrocentrifugation.

Further, the mechanism for the formation of a higher resistance to alternating cycles of wetting and drying in concrete with a more perfect structure is given in detail. So, vibrated concretes, which have a simple structure and are uniform throughout the thickness of the structure, which works by resisting cycles of wetting and drying, are the least resistant. The fact is that the nature of the structure formation and porosity of such concrete, obtained by vibrating, is permeable to moisture from the outside, which thereby makes it possible to create susceptibility through the penetration of moisture and the creation of potential centers of internal stress. At the same time, centrifuged concrete, with the correct creation of a variotropic structure, has the ability to more effectively prevent the penetration of water into the concrete body. This is due to the nature of closed porosity in the outer layer of centrifuged concrete and structures made of it and the increased resistance to moisture penetration from the outside. That is, the improved variotropic structure, in comparison with the vibrated simple structure of concrete, creates a redistribution of porosity due to the escape of pores into the non-working inner layer, which, in fact, does not play a key role [63–66]. At the same time, due to this donor-acceptor mechanism of pore migration, the outer layer becomes hardened and compacted. Thus, there is an effect of preventing the penetration of moisture into the body of the structure, and, thereby, the effect of greater security of the reinforcing cage and maintaining the durability and reliability of the structure for a long time is created. As for vibrocentrifuged concrete, here we have the most effective type of structure due to an even greater redistribution of the nature of porosity, an improvement of the donor-acceptor mechanism for distributing pores in the

body of concrete, the appearance of a densely protected shell, which actually prevents the penetration of unwanted water into the body of concrete, and a reinforced concrete structure. Thus, the mechanism of water migration in concretes made using different technologies has a completely different character, and thus, experimentally and theoretically proven higher resistance and efficiency of vibrocentrifuged and centrifuged concretes compared to vibrated concretes for use in structures subject to alternating moistening cycles and drying.

5. Conclusions

Based on the results of assessing the effect of alternating wetting and drying on concretes made using various technologies—vibrating, centrifuging, and vibrocentrifuging, the following conclusions can be drawn.

(1) With an increase in the number of moistening and drying cycles, at first there is a slight increase in the strength characteristics of the samples, and then there is a decrease.
(2) The loss of cubic compressive strength after 600 wet–dry cycles for vibrating concretes was 36% at pH 5, 20% at pH 7, and 23% at pH 10; for centrifuged concretes, the cubic compressive strength decreased by 28% at pH 5, by 14% at pH 7 and by 18% at pH 10. For vibrocentrifuged concretes, the reduction in cubic strength was 21%, 10%, and 15% for pH 5, pH 7, and pH 10, respectively.
(3) The prismatic compressive strength decreased similarly to the cube strength: the losses at various levels of pH 5, pH 7 and pH 10 were 37%, 22%, and 22% for vibrated concrete, 26%, 15%, and 18% for centrifuged concrete, and for vibrocentrifuged concrete, 20%, 11%, and 14%, respectively.
(4) An acidic medium has the most negative effect on the strength characteristics of concretes made using various technologies, compared with neutral and alkaline media. The loss of strength of concrete when moistened in an acidic media was greater than in an alkaline and especially neutral media.
(5) Vibrocentrifuged concrete turned out to be more resistant to aggressive environments and moistening and drying cycles than centrifuged and vibrated concrete. The drop in strength was up to 7% less compared to centrifuged concrete and up to 17% less than vibrated concrete.
(6) Prospects for the practical application of the results obtained lie in the manufacture of real factory centrifuged and vibrocentrifuged reinforced concrete structures with a study of the possibility of using smaller grades for water resistance and lower consumption of materials, taking into account the fact that an additional protective effect will be created in the protective layer of concrete by creating variotropically improved vibrocentrifuged and centrifuged concrete structures.
(7) Prospects and directions for the development of research are seen in checking the water resistance and resistance to moisture and drying of concretes of higher classes and densities, as well as concretes with reduced density, lightened using porous aggregates, or combined aggregates.

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