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L. R. Mailyan¹, S. A. Stel'makh², E. M. Shcherban³

CALCULATION AND DESIGN OF BUILDING STRUCTURES CONSIDERING THE VARIATION OF THE STRUCTURE, SECTIONS AND DIFFERENTIATION OF THE CONSTRUCTION CHARACTERISTICS OF MATERIALS*

Don State Technical University^{1, 2, 3}
Russia, Rostov-on-Don

¹ *D. Sc. in Engineering, Prof. of the Dept. of Department of Roads*

² *PhD in Engineering, Assoc. Prof of the Dept. of Engineering Geology, Bases and Foundations,*
e-mail: sergej.stelmax@mail.ru

³ *PhD in Engineering, Assoc. Prof of the Dept. of Engineering Geology, Bases and Foundations,*
e-mail: au-geen@mail.ru

Statement of the problem. The increasing volumes of construction require new technological, structural and design solutions for reinforced concrete elements. Centrifugation, being a promising production technology, leads to variatropic - differing in their characteristics (density, strength, deformability, etc.) in the section of concretes and structures made of them. In many cases, this must be taken into account in the calculation and design, but such studies have practically not been carried out. Therefore, when calculating and designing building structures of a variatropic structure, an unreasonably large margin of safety is usually laid, which leads to their strong rise in price. In the design standards and scientific literature, there are no theoretical and practical methods for calculating centrifuged reinforced concrete building structures, taking into account the variability of the structure and characteristics of concrete over the section. Separate data have confirmed the efficiency of centrifugation, but it is not yet possible to fully use its advantages due to the lack of accounting for structure variability in existing calculation methods.

Results and conclusions. As a result of the review and analysis, the vectors of development and directions of future research have been identified, which consist in studying the work of steel-reinforced concrete centrifuged and vibro-centrifuged compressed elements using fiber-reinforcing fibers. It is proposed to improve the manufacturing technology and calculation methods for a complete and comprehensive study of such an undoubtedly interesting and unique phenomenon as the variatropy of the structure of concrete of building structures.

Keywords: variatropic structure, vibro-centrifuged concrete, reinforced concrete structures, structural characteristics, design, calculation, compressed element, centrifuged concrete.

Introduction. An overwhelmingly large amount of funds is being allocated into the construction of centrifuged structures, as variatropia which takes place during centrifugation in regulatory and scientific sources is thought of as a negative property.

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However, it is believed that variatropia can be utilized as a positive property, if properly considered in the calculations in the design and construction of structures, as well as its prescription and technological factors well managed. Thus the use of centrifugal structures is a promising and common solution. Additionally, vibrocentrifuged structures are being focused on, which are even more promising, but call for a more nuanced approach in calculations considering all of the factors emerging in the process of their creation, calculation and design. In such constructions variatropia is reinforced. Therefore this article explores the technological, construction and design aspects of the issue as well as the introduction of such structures in the practice of design and construction. The major research papers, dissertations, monographs of scholars studying the issues of centrifugation and vibrocentrifugation as well as the phenomenon of variatropicity in building structures produced both domestically and overseas have been analyzed.

The working hypothesis of the research relies on the following premises: 1) improvement of manufacturing technology by means of transiting to vibrocentrifugation; 2) updating constructive solutions using vibrocentrifuged reinforced concrete elements; 3) modernizing calculation and design considering variatropy and characteristics of concrete differing in section, 4) use of previously hidden reserves of resource savings. The objective of the study is to design technology of vibrocentrifugation, production of concretes of variatropic structure and vibrocentrifuged designs differing in section by characteristics of concrete using them; development of recommendations for the evaluation of the characteristics of concrete and the operation of reinforced concrete structures at all the stages. The objectives of the study are 1) to evaluate the influence of technological factors on the properties of centrifuged and vibrocentrifuged concrete; 2) identify rational combinations of their values; 3) to investigate the integral (typical in cross section) and differential (different in cross section) structural characteristics of variatropic centrifuged and vibrocentrifuged concrete; 4) to propose calculation recommendations for identifying the design characteristics of centrifuged and vibrocentrifuged concrete depending on the values of technological factors and age; 5) to develop methods for calculating centrifuged and vibrocentrifuged reinforced concrete columns taking into account the variatropia of concrete; 6) to identify and evaluate neglected and hidden strength reserves of centrifuged and vibrocentrifuged reinforced concrete columns. The object of the study are centrifuged and vibrocentrifuged concretes of variatropic structure and compressed elements based on them. The subject of the study are technologies for obtaining concretes of variatropic structure, structural characteristics of variatropic concretes and considering variatropicity in the calculation and design of reinforced concrete elements.

1. The influence of technological factors on the properties of centrifuged and vibro-centrifuged concrete, rational combinations of their values. There are multiple technological methods of controlling the properties of centrifuged concrete [1-8, 10, 21, 23, 24, 27, 29, 30, 34—50, 52—55, 57—60]. Hence in [9, 21, 23, 24] the possibility of obtaining high-strength centrifuged concrete with increased crack resistance using conventional raw materials by adding to the concrete mixture of mineral porous and fibrous substances that specifically modify the structure of concrete. Based on this, a physical model of the motion of concrete mixture components during centrifugal molding is set forth which allows one to predict the direction of motion of aggregate particles in a concrete ring depending on its size, density, particle density ratio, cement test and centrifugation parameters. This model contributed to the sensible choice of modifying additives.

In [24], the influence of the type, size and amount of mineral fiber on the properties of vibrated and centrifuged concrete was examined. It is noted that due to its directed redistribution during centrifugation towards the inner layer, the structure and properties of the concrete ring change considerably. This causes a significant increase in the bending and tensile strength of concrete during cracking, which has a dramatic effect on the crack resistance of the material. The efficiency of the technique was most evident in the addition of loose asbestos, waste asbestos-cement production and mineral wool fiber (0.05... 0.07 % by weight of cement).

The positive effect of the addition of porous aggregate on the nature of the distribution of mineral fiber has been recorded - with their joint introduction high-strength concretes of classes B50...B60 with moderate cement consumption for conventional raw materials can be produced. Concretes have not only the required compressive strength, but also the increased tensile one, which causes an increase in the levels of the boundaries of microcracking [24]. High-strength centrifugal concretes with combined aggregate and fibrous component have the increased modulus of elasticity, Poisson's ratio and reduced creep. The favorable outline of the descending branch of the " $\sigma - \varepsilon$ " diagram indicates that the use of such concretes in reinforced concrete structures allows the consumption of reinforcing steel to be reduced [24].

The authors [21] analyzed the work of enterprises manufacturing centrifugal racks. The analysis revealed that most products have a heterogeneous layered structure of concrete. This generates the appearance of longitudinal cracks and reduces the durability of structures during operation. A physical model of the mechanism of separation of components during centrifugation is set forth which enables the evaluation of the likelihood of aggregate distribution in the process of compaction and formation of a concrete structure uniform in a cross section of the product [21].

Also, in [21] the dependence of the major characteristics of centrifuged concrete on the type, size and amount of porous aggregate instead of dense. The analysis of the results showed that the compressive strength of concrete in this case increases by an average of 40 %, and frost resistance reaches the brand F300 [21].

In [21], the modes of centrifugation of concrete mixes with a combined aggregate were selected and it was found that the duration of compaction could be reduced by 30 % without a considerable reduction in the strength, density and frost resistance. The influence of surface-active additives on the properties of centrifuged concrete with combined aggregate was also examined. It was found that the most effective for such concretes were hydrophilic-plasticizing additives with a dosage of 0.25 % of cement consumption.

In addition, in [21] a method for selecting the composition of centrifuged concrete with a combined aggregate was developed. The introduction of a porous aggregate reduced the shrinkage of concrete by an average of 25% compared to concrete based on a dense aggregate [21].

The experiments conducted in [23] revealed the inhomogeneity of the properties of concrete along the wall thickness of the annular section of the products compared to the vibrated one. The authors argue that the segregation of the concrete mixture during centrifugal compaction accounts for this. In [23], the difference in the properties of the layers of concrete of annular cross section was studied. There is a fundamental difference between the compressive strength and porosity of the inner and outer layers. The influence of the relative wall thickness of the annular section of the products and various empirical coefficients on the strength of centrifuged concrete is discussed [23].

The authors [23, 33] note the total reinforcement coefficient corresponding to the boundary between I and II cases of destruction. Under the conditions of the maximum width of crack opening and deflection, the design strength of the supports of transmission line supports (TL) increases as does the total reinforcement factor and the amount of prestressed reinforcement. However, under the condition of the limiting width of crack opening, the strength of the struts is higher than that observed under deformability [23].

The authors conclude that a rise in the flexibility of the racks of the transmission line towers causes a decrease in the design strength under the conditions of the maximum crack opening width and the maximum deformability. At the same time, an increase in the content of prestressed reinforcement and the total reinforcement coefficient causes that in the moment of formation of cracks in the struts. In the case of cylindrical struts, the overall reinforcement coefficient has almost no effect on the degree of crack formation [23].

In [10], the authors obtained a denser and stronger concrete in the cross section of the pipes and a smoother inner surface due to the application of the mode of smooth acceleration of the centrifuge. The dependence of the sealing quality of pressureless reinforced concrete centrifuged pipes on the dispersal intensity of the centrifuge is theoretically justified and confirmed experimentally. The list of equations used for calculating the optimal centrifugation parameters is presented. The authors set a rational time interval when it is necessary to accelerate the centrifuge smoothly. The design of the laboratory centrifuge and forms to it by which enables the exposure of any mode of centrifugation is created. According to the authors, the mode of smooth dispersal of the centrifuge allows up to 10 % of cement to be saved during molding and consolidation of rigid concrete mixes. The analysis of the results of the experimental study showed that together with the use of steel fiber the suggested technology allows pressureless pipes with the characteristics of low pressure to be obtained [10].

In [29], the analysis of centrifuges employed in practice was performed and based on it an experimental setup was developed and constructed allowing concrete products to be obtained both by centrifugation and vibrocentrifugation. Its detailed description is presented, the parameters of the operation are calculated, and the results of trial experiments confirming the correctness of the assumptions and postulates are provided [29].

Also, the authors [13—18, 25, 26, 29, 32, 51, 56] compiled a list of raw materials for concrete preparation, established the fundamental compositions needed for the production of centrifuged and vibrocentrifuged elements of annular cross section with a variatropic structure. The methods and instrumentation for estimating actual variatropy of the structure of concrete products of annular cross-section obtained by means of centrifugation and vibrocentrifugation methods were also selected for the study [29].

2. Integral and differential design characteristics of variatropic centrifuged and vibrocentrifuged concretes. During centrifugation, large grains of aggregate move to the outer surface of the product, and small ones to the inner. The concrete structure of the cross section of the centrifuged product has a distinct variatropy, i.e., considerable differences in the thickness characteristics. This is clearly shown in Fig. 1 and 2.

The following raw materials were used: Portland cement grade 500, granite crushed stone fraction 5—20 and quartz sand with a modulus of size 2.0 [29].

The correctness of the direction of the study was confirmed by the choice of equipment and tools that allowed the researchers to evaluate actual variatropy of the concrete structure [29].

In [29] the effect of the type of manufacturing technology (vibration, centrifugation, vibrocentrifugation) on the integral (common in cross section) and differential (different in cross

section) characteristics of concrete, i.e., density, compressive strength (on cubes and prisms) and tensile (axial and bending) one, ultimate deformations during compression and tension, modulus of elasticity as well as diagrams of «stress — strain».

Fig. 1. Variatropy of the properties of centrifuged product of a ring section

Fig. 2. Variatropy of the properties of vibrocentrifuged product of a ring section

In the laboratory on three technologies (vibration, centrifugation and vibrocentrifugation) samples with the following values of the diameter were formed: the external one — 450 mm, the internal one — 150 mm and the height of 1200 mm. Each of these was used in several types of tests (in order to calculate the integral and differential characteristics) at different times of concrete hardening, i.e., 7, 28 and 180 days. Also, for the completeness of the study data with the help of the device „Pulsar 2.2“ the strength of the outer, middle and inner conditional layers of concrete, the formation of which was ultrasonically controlled by means of centrifugation and vibrocentrifugation [29].

In [29], the authors experimentally confirmed the justification of the three-layer variotropic structure of centrifuged and vibrocentrifuged concrete.

It was found that the manufacturing technology had almost no effect on the density of concrete in all of the studied curing times. Vibrocentrifuged concrete at any time of hardening had the highest strength compared to vibrated and centrifuged one (compression — up to 22 %, tensile — up to 27 %). The ultimate deformations during axial compression and tension at any time of hardening when compared between the three technologies of concrete compaction were minimal in vibrocentrifugation (the difference of up to 6 %). The differences in compressive and tensile modulus at any age were up to 8 % between vibrocentrifuged concrete and that based on the other two technologies. The diagrams of «stress — strain» in compression and tension in concrete following the vibrocentrifugation compared with vibration and centrifugation in all of the studied curing periods had the following characteristics: the maximum shifted up and to the left (an increase in the strength with reduced deformation) the diagrams have increased slopeness of the ascending branches and flatness of the descending ones [29].

A comparative analysis of the properties of the layers of centrifuged concrete showed that the outer layer has the highest strength (around 49 % more than the inner one and 23 % higher than the middle layers), then the middle layer (around 21.5 % higher than the inner layer) and the lowest strength of the inner layer whose properties are minimally affected by the manufacturing technology [29].

The strength of the layers of vibrocentrifuged concrete was distributed in the following way: the outer layer — 13 % more than the middle one, and 55 % more than the inner one; in the middle layer — 37 % more than in the inner one. Thus the tendency of the distribution of strength in the two technologies was identical, but the differently qualitatively expressed curves of the dependence of the strength of the layers during centrifugation had a downward convexity down and during vibrocentrifugation an upward one.

The ultimate deformations in both compression and tension are minimal in the outer layer, maximum in the inner one and approximately intermediate ones between them — in the middle layer: slightly more — in centrifuged concrete and less — in vibrocentrifuged one.

It makes sense that the cross sections turned out to be different diagrams of «stress-strain». In centrifuged concretes, the diagram of the outer layer with the highest strength and the elasticity modulus and the smallest deformations is characterized by the movement of the maximum up and to the left with a greater lift in the ascending branch and a sharper slope in the descending branch. In the inner layer with the lowest strength and the elasticity modulus and the

largest deformations, the diagram was the lowest and flattest. The deformation diagram of the middle layer had an intermediate position compared to the other two. The deformation diagrams of vibrocentrifuged concrete layers show the same pattern but with a larger difference [29].

The authors conclude that the variability of concrete elements of annular cross-section and the different characteristics of concrete should be considered while calculating the structures.

3. Calculation recommendations for identifying the design characteristics of centrifuged and vibrocentrifuged concrete depending on the values of technological factors and age.

In [29], according to the results of statistical processing of experimental data with a reliability of 0.95, the values of normative and calculated resistances for limit states of groups I and II, limit deformations and initial modulus of elasticity in compression and tension of centrifuged and vibrocentrifuged concrete are proposed.

The authors provide variants of calculating the integral structural characteristics of concrete at the age of 28 days, obtained by centrifugation and vibrocentrifugation. This being the case, the indicators of vibrated concrete were taken as a unit, and for the other two types of concrete the coefficient $K_{i,28}$ was used in addition to the indicators of vibrated concrete [29].

The calculated definition of the integral characteristics of centrifuged and vibrocentrifuged concretes depending on the type of molding and compaction technology was expressed in the introduction of coefficients to find each of the characteristics of compression ($K_{Rb,28}R_b$; $K_{\epsilon bR,28}\epsilon_{bR}$; $K_{Eb,28}E_b$) and tensile; ($K_{Rbt,28}R_{bt}$; $K_{\epsilon btR,28}\epsilon_{btR}$; $K_{Ebt,28}E_{bt}$), where $K_{i,28}$ are correction coefficients equalling its base value for vibrated concrete at the age of 28 days [29].

Integral characteristics of concrete depending on the curing time are proposed to be calculated using the dependences where the coefficients are defined by means of statistical methods. A calculated estimate is proposed to be made based on analytical dependences to identify the coefficients $K_{i,t}$ introduced for each of the strength and deformation characteristics, equal to the ratio of a characteristic to its basic value at the age of 28 days [29]:

$$K_{i,t} = f_{i,t}(t/28), \quad (1)$$

where $f_{i,t}$ are the corresponding functions of one type; t is the age of concrete, days.

For a single function $f_{i,t}(t)$ in equation (1) for uniformity, the formula of P. Sarzhin (ECB-FIP) was employed to describe the diagrams of deformation of concrete:

$$K_{i,t} = \frac{K_o \left(\frac{t}{28} \right) - \left(\frac{t}{28} \right)^2}{1 + (K_o - 2) \left(\frac{t}{28} \right)}, \quad (2)$$

where $K_{i,t}$ are the ratios of the original value of the current characteristics of concrete at age t to its value at the age of 28 days; K_o is the control parameter for each characteristic [29].

Therefore considering the dependence of changes in the characteristics of concrete on their age, it is essential to multiply the values of their characteristics at the age of 28 days by the corresponding coefficients $K_{i,t}$ whose the values are found for all the characteristics of concrete at any age. All the structural characteristics of the investigated concretes were given by dependences (2) [29].

Experimentally and analytically, the deformation diagrams of compression and tension of all of the investigated concretes at any time of hardening were obtained, their similarity was proved and recommendations for their construction were provided based on to the dependence by P. Sarzhin, recommended by EKB-FIP:

$$\frac{\sigma}{R} = \frac{K \left(\frac{\varepsilon}{\varepsilon_R} \right) - \left(\frac{\varepsilon}{\varepsilon_R} \right)^2}{1 + (K - 2) \left(\frac{\varepsilon}{\varepsilon_R} \right)}, \quad (3)$$

where R and ε_R are the compressive or tensile strength and deformation of the dependence of P ; $K = \varepsilon_R E / R$ is a numerical parameter equalling the ratio of the original E (tangential) elasticity modulus to the specific (cutting) elasticity modulus at the moment of achieving the maximum of function (3) with the coordinates R and ε_R [29].

The analysis revealed the similarity of the stress-strain diagrams in compression and tension for centrifuged and vibrocentrifuged concrete as well as the location of the maxima of these diagrams on one line passing through the origin; it has also been proved that the similarity of the « $\sigma_b - \varepsilon_b$ » and « $\sigma_{bt} - \varepsilon_{bt}$ » diagrams is also characteristic of the increments of these diagrams after their maxima for the investigated concretes at any curing time [29].

For the uniformity of the calculated dependences, the same functions were used for three purposes: to evaluate the change in strength and deformation characteristics during compression and tension; to describe the diagrams of deformation and their increments during compression and tension; to evaluate the dependence of changes in strength and deformation characteristics and deformation diagrams and their increments during compression and tension [12, 19, 20, 22, 28, 29].

The authors identified three stages of defining the design characteristics and diagrams of «stress — strain» of all the investigated types of concrete at any time of hardening. The first stage involves the analysis of change of strength and deformable characteristics of the

vibrocentrifuged and centrifuged concretes in relation to the vibrated after 28 days of hardening: at compression — $K_{Rb,28}R_b$; $K_{\varepsilon bR,28}\varepsilon_{bR}$; and in tension — $K_{Eb,28}E_b$. The second stage involves researching the dependence of characteristics of concrete on its age using coefficients: at compression — $K_{Rb,t}K_{Rb,28}R_b$; $K_{\varepsilon bR,t}K_{\varepsilon bR,28}\varepsilon_{bR}$; $K_{Eb,t}K_{Eb,28}E_b$ and at stretching — $K_{Rbt,t}K_{Rbt,28}R_{bt}$; $K_{\varepsilon btr,t}K_{\varepsilon btr,28}\varepsilon_{btr}$; $K_{Ebt,t}K_{Ebt,28}E_{bt}$. The third stage includes the interpretation of diagrams of «stress — strain» of concrete during compression and tension at any age using the following parameters: at compression — $K_{Rb,t}K_{Rb,28}R_b$; $K_{\varepsilon bR,t}K_{\varepsilon bR,28}\varepsilon_{bR}$; $K_{Eb,t}K_{Eb,28}E_b$ and at stretching — $K_{Rbt,t}K_{Rbt,28}R_{bt}$; $K_{\varepsilon btr,t}K_{\varepsilon btr,28}\varepsilon_{btr}$; $K_{Ebt,t}K_{Ebt,28}E_{bt}$ [29].

The authors identified three stages of defining the design characteristics and diagrams of «stress — strain» of all the investigated types of concrete at any time of hardening. The first stage involves the analysis of change of strength and deformable characteristics of vibrocentrifuged and centrifuged concretes in relation to vibrated following 28 days of hardening: at compression — and at stretching — The second stage involves researching the dependence of characteristics of concrete on its age by means of coefficients: at compression — and at tensile — The third stage involves the interpretation of diagrams of «stress — strain» of concrete during compression and tension at any age, using the following parameters: during compression — and during tension — [29].

It is suggested that the differential characteristics of centrifuged and vibrocentrifuged concrete are evaluated using universal dependences where the functions are strength (Y_i), and the arguments are the distances from the center of rotation and angular velocities (X_i):

$$Y(X_1, X_2) = B_0 + B_1 \cdot X_1 + B_2 \cdot X_2 + B_3 \cdot X_1 \cdot X_2 + B_4 \cdot X_1^2 + B_5 \cdot X_2^2. \quad (4)$$

The dependences developed by the authors [29] for the differential characteristics of concretes obtained by centrifugation and vibrocentrifugation contributed to a fuller use of reserves [29].

4. Methods of calculation of centrifuged and vibrocentrifuged reinforced concrete columns considering the variatropia of concrete. The authors of [30] conducted a large-scale study in order to develop a refined method for calculating reinforced concrete centrifugal racks of technological trestle working on torsion and compression with torsion. This technique is designed to account for the features of changes in the strength and deformation properties of centrifuged concrete in a flat stress state «stretching — compression».

The authors [30] also suggested that the strength of centrifuged concrete at a flat stress state "tensile — compression" is evaluated by means of formula (5), and the ultimate deformations in the direction of the main compressive axis — by equation (6) based on the ratio of principal stresses:

$$\sigma_1 = R_p \left(1 + \frac{\sigma_2}{R_k} \right) = R_p k_{p.c.}, \quad (5)$$

where R_k is the prismatic strength of centrifuged concrete; R_p is the tensile strength of centrifuged concrete; $k_{r.s.}$ is the coefficient considering the effect of stresses on the reduction of concrete strength under compressive and tensile loads.

$$\varepsilon_2^* = \frac{R_n^*}{R_k} \varepsilon_{2np}, \quad (6)$$

where ε_{2np} are the ultimate relative deformations of centrifuged concrete during central compression; R_n^* is the ultimate compressive stress depending on the stress state and determined by condition (7) for the known $\sigma_1/\sigma_2 = \beta$ (the ratio of the tensile (σ_1) and compressive (σ_2) stresses). I.e.,

$$R_n^* = \frac{R_k R_p}{\beta R_k - R_p}. \quad (7)$$

Also in [30], the authors were able to expand the range of experimental data and proceed to a uniform assessment of the operation of centrifuged elements of the annular cross section due to experiments performed on pure torsion and compression with torsion up to axial compression.

Numerous experiments on concrete and reinforced concrete centrifuged elements enabled the authors [30] to accept the condition of strength corresponding to the destruction of concrete samples as a condition for the formation of cracks in reinforced concrete elements.

The ratio of the main stresses in concrete has the greatest effect on the strength of centrifuged reinforced concrete elements working on torsional compression [30]. It is found that the fracture moment takes place when the values of average stresses in concrete for centrifuged concrete re-enter the strength line [11, 30].

The increase in the angles of twist and the width of the opening of cracks takes place largely following their formation. This being the case, the reduction of the twisting angles takes place in the case of an increase in the proportion of normal force. Also, the reduction of the axial deformations of compression from the normal force, passing at certain stress ratios into elongations, takes place due to the torque. The author's experimental values of the crack opening width and torsion angles coincide with the theoretical values obtained by means of the method of N. I. Karpenko [11, 30].

The numerous experimental data of rack tests [30] and data of other authors confirmed the reliability of the proposed calculation method.

The study [2] presents the results of experiments of centrifuged concrete of non-reinforced and reinforced elements of annular cross-section under conditions of short-term axial and eccentric compression in terms of mechanical characteristics. The analysis is performed and the suggestion as to how the dependence of structure formation should be evaluated and the basic mechanical characteristics at compression of the centrifuged concrete on longitudinal reinforcement are provided [2].

Given the complete deformation diagram of compressed concrete, a technique for controlling the strength for short-term axial and eccentric compression of short elements with the annular cross section and longitudinal high-strength reinforcement has been developed. The methods of a recommendatory nature are also formulated to define the characteristics of both the stress-strain of concrete and reinforcement, and the degree of their use. Proof of the effectiveness of the suggested methods is the similarity of experimental and calculated results [2].

The result of the analysis of the study is the suggested dependences of the compressive strength of both reinforced and non-reinforced short columns with the annular cross section obtained by means of centrifugation. Note that the authors presented an algorithm for evaluating the calculated resistance to compression of longitudinal high-strength reinforcement considering the factors of mechanical characteristics of compressed concrete, their variability and reinforcement rates [2].

The research of the previously presented dependences needed to calculate the strength of products with the annular cross section confirmed the possibility of their use to calculate the strength of both normal sections and inclined. But it is worth noting that these dependencies do not cover some factors that directly influence the performance of products and structures with the annular cross section, i.e., the span of the cut, the area and pitch of the spiral reinforcement, the loading scheme [1].

The authors [1] noted that while calculating the strength of elements that were obtained by means of centrifugation, should consider the solutions obtained by calculating the strength of normal sections of bending elements having a rectangular profile. The length of the longitudinal section should be taken as a variable and account for the effect of the span of the cut and the location of the support.

In all of these studies, the calculation of structures was conducted without considering the variability of the properties of centrifuged concrete. In [29], the variatropy of the structure of centrifuged and vibrocentrifuged concrete columns was taken into consideration. It is suggested that the normative approach to the calculation of the strength of centrifuged and

vibrocentrifuged reinforced concrete columns is improved considering the general cross-sectional (integral) and different in cross-sectional (differential) design characteristics.

Based on the norms, the identification of the load-bearing capacity (N) of concrete and reinforced concrete short elements that have a different cross-section or with a small eccentricity is possible in the presence of stresses in these elements as well as in the case of normative parameters of concrete:

$$N = R_b \cdot A_b; N = R_b \cdot A_b + R_{sc} \cdot A_s, \quad (8)$$

where R_b is the compressive strength (design resistance); A_b is the area of compressed concrete; R_{sc} is the calculated value of the resistance of the reinforcement to compression; A_s is the cross-sectional area of the compressed reinforcement.

If compressed products obtained by centrifugation or vibrocentrifugation are compared to the elements obtained by vibration, the strength limit of concrete products and elements will be different: $R_{b,red} = K_{rb}R_b$, which in the case of application of integral characteristics of concrete yields the following equations:

$$N = R_{b,red} \cdot A_b; N = R_{b,red} \cdot A_b + R_{sc} \cdot A_s, \quad (9)$$

where $R_{b,red}$ is the ultimate compressive strength of the centrifuged and vibrocentrifuged element.

In case of application of differential characteristics of concrete the following dependences are deduced:

$$N = \sum R_{b,red,i} \cdot A_{bi}; N = \sum R_{b,red,i} \cdot A_{bi} + R_{sc} \cdot A_s. \quad (10)$$

In the formulas, it is now viable to employ the obtained strengths considering their differences in the layers $R_{b,red}$ and their area A_{bi} [29].

For the diagram approach, complete diagrams « $\sigma - \epsilon$ » with descending branches were used, and in such cases the dependences took the following form:

$$N = N_b = \int_0^h \sigma(\epsilon) A_b dx, \quad (11)$$

where N_b is the load-bearing capacity of concrete; $\sigma(\epsilon)$ is the compressive stress in concrete depending on the relative deformation; dx is the height of the compressed area; h is the height of the section.

$$N = N_b + N_s = \int_0^h \sigma(\epsilon) A_b dx + \sigma_{sc} A_s, \quad (12)$$

where N_s is the load-bearing capacity of the reinforcement; σ_{sc} is the design resistance of the reinforcement during compression.

Iterative calculation of norms or general cross-sectional characteristics involved the use of stress-strain diagrams of concrete with R_b ; ε_{bR} ; E_b and $K_{Rb,28}R_b$; $K_{\varepsilon bR,28}\varepsilon_{bR}$; $K_{Eb,28}E_b$. Instead of integration there is the final summation by the sections:

$$N = N_b = \sum \int_0^h \sigma(\varepsilon) A_b dx, \quad (13)$$

$$N = N_b + N_s = \sum \int_0^h \sigma(\varepsilon) A_b dx + \sigma_{sc} A_s. \quad (14)$$

In the iterative calculation of the cross-sectional characteristics of the investigated columns, the equations take another form:

$$N = N_b = \sum \sum \sum \int_0^h \int_{\omega_1}^{\omega_2} \int_d^D \sigma(\varepsilon) A_{bi} dx d\omega dl, \quad (15)$$

$$N = N_b + N_s = \sum \sum \sum \int_0^h \int_{\omega_1}^{\omega_2} \int_d^D \sigma(\varepsilon) A_{bi} dx d\omega dl + \sigma_{sc} A_s, \quad (16)$$

where ω_1 is the internal angular rotation speed; ω_2 is the external angular rotation speed; d is the internal diameter of the column; D is the external diameter of the column; A_{bi} is the area of the layer of the compressed concrete; $d\omega$ is the angular rotation speed; dl is the distance from the rotation centre to the grain centre.

The iterative approach in the calculation involved specifying ε_b at each iteration with a certain interval of concrete deformations [12, 29]. The authors noted a difference in iterative and normative calculations: the first allows one to evaluate the performance of compressed elements even in the supercritical stage in contrast to the second, including when the decrease in stresses and forces in concrete on the descending branch of the diagram is compensated for and even overlapped by the rising stresses $\Delta N_s \geq \Delta N_b$ [29]. At the same time it is justified that only high-strength fittings without a flowing site are appropriate. If this condition is not satisfied, the column will exhaust its load-bearing capacity after the maximum strength of concrete has been reached [29].

The following data are needed for the iterative calculation: diagrams of «stress — strain» and the area of concrete and reinforcement; the geometric parameters and cross-sectional shape. At the same time the condition of equality of deformations of concrete and armature at all the stages of its work is accepted:

$$\varepsilon_b = \varepsilon_s = \varepsilon, \quad (17)$$

where ε_b is the concrete deformation; ε_s is the reinforcement deformation.

The longitudinal force, which perceives the cross section of the compressed element, at all the stages of work is calculated as:

$$N = N_b + N_s = \sigma_b(\varepsilon_b) A_b + \sigma_s(\varepsilon_s) A_s = \sigma_b(\varepsilon) A_b + \sigma_s(\varepsilon) A_s, \quad (18)$$

where σ_b are the stresses in the concrete; σ_s are the stresses in the reinforcement.

The load-bearing capacity of a compressed element is characterized by the maximum of the function «longitudinal force N — longitudinal deformation ε »:

$$\frac{dN}{d\varepsilon} = 0. \quad (19)$$

Equations (18) and (19) enable us to calculate the load-bearing capacity of the concrete element using the found deformations of concrete and reinforcement [29].

In the calculation, the values of deformations of concrete and reinforcement were assumed to equal $\varepsilon_b = \varepsilon$ and $\varepsilon_s = \varepsilon$, respectively, and the amount of deformation of concrete was close to the maximum of the stress-strain diagram of concrete. The stresses in concrete and reinforcement were identified using the analytical diagrams “ $\sigma - \varepsilon$ ”. Then the forces N_b and N_s and the total load-bearing capacity of the cross section of the element $N = N_b + N_s$ were calculated. Then the calculation started again, but with a new value of concrete deformation $\varepsilon_b = \varepsilon + \Delta\varepsilon$. These calculations were conducted until the value of N reached a maximum and started decreasing. The value of the maximum N was taken as the load-bearing capacity of the column [29].

The authors [13—17, 29] explained the condition for reaching the maximum value of N at the amount of strain ε_{cr} . When all the layers of concrete had the same strength (vibrated columns) deformation ε_{cr} following the exhaustion of the load-bearing capacity of the columns could be not less than the ultimate deformations of concrete ε_{bR} , corresponding to R_b . Thus when the load-bearing capacity of the columns was exhausted, the entire cross section had stresses in the concrete either less than or equal to R_b .

The case when the stresses in the concrete were less than R_b was due to insufficient reinforcement of the columns, the rise in the forces in the reinforcement which did not compensate for the decrease in the forces in the concrete while reaching the maximum of its deformation diagram R_b ; ε_{bR} .

The second case, when the stresses in concrete equal R_b , was characterized by strong reinforcement or even re-reinforcement of columns, the rise in reinforcement forces which not only compensated for, but also overshadowed the drop in the stress in concrete when columns exhausted it during the deformation of concrete already on the descending branch of its diagram [29].

When the concrete layers had different values of strengths and deformations (centrifuged and vibrocentrifuged reinforced concrete columns), the deformations of concrete ε_{cr} after the load-bearing capacity of the columns remained the same for all the layers, but could be greater than or equal to the deformations of concrete of one of the corresponding layers, R_{bi} [29]. In this case, this is accounted for not only by the amount of reinforcement of the columns, but also

by different values of the strength and deformability of concrete layers, each of which following the depletion of the load-bearing capacity of the column can be deformed on both ascending and descending branches of its deformation diagram [29].

Therefore the column at the same deformations for all the concrete layers exhausts the load-bearing capacity while deforming the inner layer on the ascending branch, the middle layer — at the maximum, and the outer layer — on the descending branch of its deformation diagrams « $\sigma_b - \varepsilon_b$ ». As a result, during the transition from vibrated to centrifuged and vibrocentrifuged columns, the calculation formulas with one term are transformed into equations with three terms (based on the number of conditional layers) [29].

The reduction in the load-bearing capacity of the columns considerably exacerbates the process of force distribution both in the layers and in the reinforcement. Hence even with the insignificant reinforcement, the drop in the force in the concrete of the inner layer, based on the maximum of its deformation pattern, is compensated for by the rise in resistance of concrete to loads in the outer layer or in the outer and middle layers together, rather than in the reinforcement. Such features are more typical of vibrocentrifuged columns [29].

The authors of [29] noted that ordinary cross sections of building structures are considerably less active in the processes of stress and force redistribution compared to variatropic ones.

In order to simplify the calculations manually and to abandon numerous iterations, an approximate method is looked at [29]. The authors consider the decrease in the strength of reinforced concrete columns based on its ε_{cr} deformations which fluctuate in the range of $0.85 \dots 1.15 \varepsilon_{bR}$. According to the method used, the strength calculation was conducted only in three iterations, although the deformations ε_{cr} at each iteration are equal to 0.9; 1; $1.1 \varepsilon_{bR}$, and the value of ε_{bR} of the middle layer was taken as ε_{bR} [29].

Note that in the case of high-strength reinforcement, which operates considering the exhausted load-bearing capacity of the column in the elastic stage can be said to be accepted:

$$\sigma_s = E_s \varepsilon_s, \quad (20)$$

where E_s is the elasticity modulus of the reinforcement.

Therefore the dependence for calculating the strength takes the form:

$$N = N_b + N_s = \sigma_b(\varepsilon_{cr}) A_b + \varepsilon_{cr} E_s A_s, \quad (21)$$

where ε_{cr} are the longitudinal deformations of concrete at exhaustion of the load-bearing capacity of columns.

Using an approximate calculation to calculate the strength of the columns, the authors chose the maximum value of the three results.

In order to simplify the calculation as much as possible, the authors recommended two simplified methods. According to the first method, it is suggested that a diagram of the operation of high-strength valves according to (20) is presented; based on this, formula (19) following the substitution (12) and (20) and differentiation will take the form:

$$a\varepsilon^2 + b\varepsilon + c = 0, \quad (22)$$

the variables a, b, c are transformed to be:

$$\begin{aligned} a &= E_b^2 (K - 2) [\mu \alpha K (K - 2) - 1], \\ b &= -2E_b K R_b [\mu \alpha K (K - 2) - 1], \\ c &= K^3 R_b^2 (1 + \mu \alpha), \end{aligned} \quad (23)$$

where $\mu = A_s/A_b$ is the relative reinforcement of the element; $\alpha = E_s/E_b$ is the ratio of the elasticity moduli of the reinforcement and concrete; K is the correction coefficient equalling the ratio of this or that constructive characteristics to its basic value.

Using dependence (22), the value of the limit deformations was obtained where it became possible to achieve the maximum longitudinal force [29].

The second method involves a few simplifying rules [29], i.e., the reduction of the strength of short reinforced concrete columns obtained by means of vibration is performed under the condition of achieving deformations ε_{cr} equal to ε_{bR} , which corresponds to the stresses in concrete of the total cross section R_b and the stresses in the reinforcement $\sigma_s = E_{sR}$. These changes enabled the load-bearing capacity in the calculation to be expressed as follows:

$$N = N_b + N_s = R_b A_b + E_s \varepsilon_{bR} A_s, \quad (24)$$

where ε_{bR} are the ultimate deformations of concrete corresponding to its maximum durability. The reduction in the strength of short reinforced concrete columns obtained by means of centrifugation and vibrocentrifugation to values where the load-bearing capacity is depleted is possible on the condition that ε_{cr} deformations equal to the ε_{bR} deformations of the middle layer are achieved.

Therefore if we consider each layer of a concrete product, we get: the middle layer — $\varepsilon_{b, cpe\partial} = \varepsilon_{bR, cpe\partial}$; $\sigma_{b, cpe\partial} = R_{b, cpe\partial}$; the internal layer — $\varepsilon_{b, внут} = \varepsilon_{bR, cpe\partial} < \varepsilon_{bR, внут}$; $\sigma_{b, внут} < R_{b, внут}$; the external layer — $\varepsilon_{b, вней} = \varepsilon_{bR, cpe\partial} > \varepsilon_{bR, вней}$; $\sigma_{b, вней} < R_{b, вней}$. As for the stresses in the reinforcement, they will be equal to: $\sigma_s = E_s \varepsilon_{bR, cpe\partial}$ [29] where $\varepsilon_{b, cpe\partial}$ are the deformations of concrete of the middle layer; $\varepsilon_{bR, cpe\partial}$ are the specific deformations of concrete of the middle layer; $\sigma_{b, cpe\partial}$ are the stresses in concrete of the middle layer; $R_{b, cpe\partial}$ is the specific compressive strength (design resistance) of concrete of the middle layer; $\varepsilon_{b, внут}$ are the deformations of

concrete of the internal layer; $R_{b,внут}$ is the specific compressive strength of concrete of the internal layer; $\varepsilon_{b,внеш}$ are the deformations of concrete of the external layer; $\varepsilon_{bR,внут}$ are the specific deformations of concrete of the internal layer; $\sigma_{b,внут}$ are the stresses in concrete of the internal layer; $R_{b,внеш}$ is the specific compressive strength (design resistance) of concrete of the external layer; $\varepsilon_{bR,внеш}$ are the specific deformations of concrete of the external layer.

It is also accepted that the drop in strength occurs during the deformation of the middle layer at the maximum point of its diagram « σ_b , medium — ε_b , medium», the inner layer — at the distance from the beginning of the ascending branch to the maximum point of the diagram « σ_b , внут — ε_b , внут», but as for the outer layer, the decrease in its strength takes place at a distance from the beginning of the descending branch to its end according to the diagram « σ_b , external — ε_b , external» [29]. Hence the dependence for the calculation of the load-bearing capacity takes the form:

$$\begin{aligned} N &= N_{b,внут} + N_{b,сред} + N_{b,внеш} + N_s = \\ &= \sigma_{b,внут} (\varepsilon_{bR,сред}) A_{b,внут} + R_{b,сред} A_{b,сред} + \\ &+ \sigma_{b,внеш} (\varepsilon_{bR,сред}) A_{b,внеш} + E_s \varepsilon_{bR,сред} A_s, \end{aligned} \quad (25)$$

where $N_{b,внут}$ is the load-bearing capacity of the internal layer; $N_{b,сред}$ is the load-bearing capacity of concrete of the middle layer; $N_{b,внеш}$ is the load-bearing capacity of concrete of the external layer; $A_{b,внут}$ is the area of the section of concrete of the external layer; $A_{b,сред}$ is the area of the section of concrete of the middle layer; $A_{b,внеш}$ is the area of the section of concrete of the external layer.

As part of the laboratory experiments, 9 concrete and reinforced concrete columns of annular cross-section were manufactured. Every 3 samples were produced by means of vibration, centrifugation and vibrocentrifugation technologies, respectively. The geometric parameters of the columns are the height is 120 cm; the outer diameter 45 cm, the inner one 30 cm. Concrete ordinary heavy class B30, reinforcement 6 A10 A400 и 6 A10A600 [29].

Hence in each technology, one sample without reinforcement, one sample with an inner diameter of 6 cm, an outer diameter of 10 cm and A400 and one sample with diameters of 6 cm and 10 cm, but A600, were produced and tested. Concrete compositions, equipment, modes and technologies for the manufacturing the experimental columns were accepted in compliance with the proposals developed in studies [13—17, 29]. The samples were exposed to central compression tests at the age of 30...35 days. The IPG-500 press was used as a test equipment, the load was changed in 10—12 stages, with the same increments of longitudinal deformations enabling us to analyze the operation of the columns when the load increased to

maximum, and then when it dropped on the descending branch. Tensometric and oscillographic equipment was used in the experiments. In order to determine the actual characteristics of concrete products, both cube samples and prisms, which serve as reference samples, were tested [29].

According to the results of the laboratory experiments, the analysis of the load-bearing capacity and deformability of the columns was conducted, and the way they are affected by the manufacturing technology and the class of reinforcement was also investigated. The indices of vibrated columns were taken as a reference point, so deviations were recorded relative to them [29].

It was found that the manufacturing technology also has an effect on the load-bearing capacity of the columns. Hence it was recorded that the greatest influence was exerted on the samples obtained by means of vibrocentrifugation; slightly less - on centrifuged relative to the vibrated samples [29].

The authors noted that the load-bearing capacity rises with increasing class of reinforcement. Hence in the samples obtained by means of vibration with the reinforcement of class A400 and A600, the load-bearing capacity rose by 7.5 % and 13.1 %, respectively, relative to non-reinforced samples. Similar figures were obtained in the study of samples produced by means of centrifugation and vibrocentrifugation, and were 2.6 % and 6.8 %, 6.1 % and 9.2 %, respectively [29].

As for the influence of manufacturing technology on the deformability, in this case the deformations of the products relative to the reinforced vibrated samples were in all the cases invariably less — this applies to both centrifuged and vibrocentrifuged samples [29].

The authors also noted the effect of reinforcement on the deformability. Therefore as the reinforcement class increases, the deformability index drops. Thus, in the samples obtained by the method of vibration with the reinforcement class A400 and A600, the deformations dropped by 22.7 % and 27.3 %, respectively, relative to non-reinforced samples. As for the columns produced by means of centrifugation and vibrocentrifugation methods — 25 % and 30 %, 11.8 % and 29.4 %, respectively [29].

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For the sake of performing an extended analysis, a numerical experiment was also employed — conditional columns were calculated considering the rise in the range of variation of element reinforcement. Hence the following conditions were added: reinforcement class — A500; A800; the amount of reinforcement — 6Æ14; 6Æ18. According to the results of the analysis, it is clear that the tendencies revealed in the course of the physical experiment are significantly strengthened.

The authors found that the strength and deformation of columns produced by means of different technologies, identified using the approach of norms based on the normative, integral and differential characteristics of concrete, differ greatly both with the experimental data [29] and among one another.

The difference in the experimental values of the strengths and norms calculated according to the method using the normative characteristics of concrete for all of the investigated types of columns ranged from 20 % to 30 %. In the case of employing the integral characteristics of concrete, the deviations of the strength values equalled 8—12 %. The differences in the strength of columns while using the differential characteristics of concrete for the centrifuged and vibrocentrifuged columns ranged from 4 % to 6 %.

Hence the authors concluded that the best results were obtained while calculating the strength of short centrally compressed reinforced concrete columns based on the approach of norms using the differential characteristics of concrete [29].

While calculating in compliance with the diagrammatic approach by the three methods set forth by the authors (iterative, approximate and simplified), even more indicative results were obtained. Two noteworthy points have been noted. First, all of the suggested methods showed better convergence of results than the calculation of the norm approach. Secondly, the use of differential characteristics for the centrifuged and vibrocentrifuged columns in a diagrammatic approach in any of the suggested implementations yields better results than the use of integrated characteristics. The same tendencies in the deviations of the calculated values from the experimental ones were observed in the deformations of the columns [29].

The large differentiation of concrete characteristics considered in the calculations calls for the adjustment of the calculation for the two groups of limit states.

The authors [13—17, 29] employed analytical methods to identify hidden, previously unaccounted for reserves of short reinforced concrete centrifuged and vibrocentrifuged columns of varatropic structure.

It is concluded that the strength and deformation characteristics of the vibrated, centrifuged and vibrocentrifuged columns are satisfactorily estimated by the suggested iterative, approximate and simplified methods using the diagrammatic approach [29].

5. Hidden strength reserves of centrifuged and vibrocentrifuged reinforced concrete columns. The authors of [29] identified the hidden strength reserves of industrial centrifuged and vibrocentrifuged columns of varatropic structure. The major advantages of vibrocentrifuged reinforced concrete columns over centrifuged ones are identified and detailed.

Also in [29], the serial type of reinforced concrete column obtained by means of centrifugation was redesigned to vibrocentrifuged with a higher load-bearing capacity (by 35 %). In this case, in order to achieve the operation on a similar regulatory load, the reinforcement process is reduced and the same values of the structural parameters of the column as in the standard one are observed [29].

Conclusions. Theoretical and practical aspects devoted to the problem of estimating the influence of technological factors and their significance on the properties of centrifuged and vibrocentrifuged concretes of reinforced concrete structures of annular cross-section are explored, and rational combinations of values of these factors are identified.

A review and analysis of the existing studies of centrifuged and vibrocentrifuged concrete of reinforced concrete structures of the annular cross-section is provided considering the variability of the structure of their cross-sections, their integral and differential structural characteristics. The developed suggestions and recommendations for calculating constructive characteristics of the centrifuged and vibrocentrifuged concretes and designing structures using them taking into consideration the technological and time factors, ways of calculating the centrifuged and vibrocentrifuged reinforced concrete designs of the annular section considering their variatropy of their concrete are provided.

The estimated hidden strength reserves and unused resources of centrifuged and vibrocentrifuged reinforced concrete columns are evaluated.

As a result of the review and analysis, the vectors of development and directions of future research which involve studying the operation of reinforced concrete centrifuged and vibrocentrifuged compressed elements using fiber-reinforcing fibers are outlined. There are plans being made to improve the manufacturing technology and calculation methods for a more

complete and in-depth study of such an indisputably fascinating and unique phenomenon as variatropia of the concrete structure of building structures.

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