doi: 10.18720/MCE.75.4

Spun concrete properties of power transmission line supports

Свойства центрифугированного бетона опор линий электропередач

D.A. Dedukh,
V.L. Schsuzkiy,
A.A. Kuzmenko,
Don State Technical University, Rostov-on-Don, Russia

старший преподаватель Д.А. Дедух,
канд. техн. наук, профессор В.Л. Щуцкий,
студент А.А. Кузьменко,
Донской Государственный Технический Университет, Ростов-на-Дону, Россия

Key words: spun concrete; physical and mechanical properties of the fresh concrete, mechanical properties, hardened concrete, power transmission tower

Ключевые слова: центрифугированный бетон, физико-механические свойства свежеуложенного бетона, прочностные характеристики бетона, опоры линий электропередач

Abstract. The article presents results of investigation study of physical and mechanical properties of spun and vibrated samples. Heterogeneity of freshly placed concrete was assessed for change in water to cement proportion, residual water content, density throughout the spun sample height, as well as changes in mechanical properties of hardened concrete. Analysis of experimental data showed a significant change (up to 4%) in the average density of concrete throughout the spun sample, while the overall voids content in the sludge layer increased by almost 10%, and strength of concrete changes by 18-25% along the lift height. By using the method of least squares, a consistent change in the strength of concrete along the lift height of samples was observed. An experiment, assessing the bearing capacity of spun pylons, accounting for the resulting changes in strength of concrete along the wall height, was carried out.

Аннотация. В статье приведены результаты экспериментальных исследований физико-механических свойств центрифугированных и вибрированных образцов. Проведена оценка неоднородности свойств свежеуложенной бетонной смеси для определения изменения водоцементного отношения (В/Ц), остаточного водосодержания и плотности по толщине центрифугированного образца, а также изменение прочностных свойств затвердевшего бетона. Анализ экспериментальных данных показал, что наблюдается значительное изменение средней плотности бетона по толщине центрифугированного образца (до 4%), при этом общая пористость в шламовом слое увеличивается почти на 18%, а прочность бетона изменяется по толщине на 18-25%. Используя метод наименьших квадратов, получена закономерность изменения прочности бетона по толщине образцов. Проведен численный эксперимент по исследованию несущей способности центрифугированных опор линий электропередач с учётом полученной зависимости изменения прочности бетона по толщине стенки изделия.

Introduction

Reinforced concrete structures of annular cross section attract researchers' attention in the beginning of the last century. Prof. Schule F [1] conducted one of the first studies in the Swiss laboratory; results of which were published in 1908.

Interest in such structures especially increased with introduction of spun manufacturing products. In 1933–1935, engineer P.A. Abeles [2, 3] conducted experiments on bends of reinforced concrete elements of annular cross section of different diameter, under varying value of reinforcement percentage. At the same period prof. V.V. Mikhailov [4] and prof. S.A. Dmitriev conducted research of different spun structures and offered calculation methods as well as means of prestressing in laboratory and semi-industrial conditions.

Spun reinforced-concrete poles and masts [5, 6] were widely used in 50–70th of the last century in Russia for high-voltage power transmission line (PTL) supports, due to the rapid development of power construction America and the European countries.

Дедух Д.А., Щуцкий В.Л., Кузьменко А.А. Свойства центрифугированного бетона опор линий электропередач // Инженерно-строительный журнал. 2017. № 7(75). С. 37–51.

I.N. Akhverdov [7, 8], S.A. Dmitriev [9], V.M. Batashev[10, 11], R.R. Valduga [12–14], A.P. Kudzis [15–22], R. Kliukas [23], V. Sh. Kalandadze [24], E.E. Mikhelson [25], V.I. Soroker [26–28] and other scholars studied strength, crack resistance and deformability of PTL supports as well as physical and mechanical properties of the spun concrete in different years.

Methods of vibrated concrete strength measurement are well studied and rated. Physical and mechanical properties of the spun concrete are less studied, and there is no standard method of strength measurement in normative documents.

Offers of different studiers relating to spun concrete strength measurement can be divided into following groups:

- according to the results of vibrated samples with initial water to cement proportion $(W/C)_{init}$ having regard to conversion factor testing [13, 14];

- according to the results of vibrated samples with residual water to cement proportion $(W/C)_{res}$ testing [27, 28];

- according to the results of spun cubes testing [11, 17, 27];

- according to the results of annular cross section spun samples testing[12–14, 17, 26];

- according to the results of cubes (samples) cut out from spun hollow circles testing [24].

Each of the listed methods has special features and reflects the actual strength of spun concrete in manufactured item with various reliability. For example, determining the strength of spun concrete from the test results of vibrated cubes of concrete mixture with initial water/cement ratio, can result in significant error, because it does not account for the influence of the structure of the spun concrete wall along the height, the mode of centrifugation and some other factors.

I.N. Akhverdov has conducted the most extensive research in the field of spun concrete structure in the Russian Federation. He notes that the pressing pressure changes during the manufacturing of the product, and has the greatest value at the surface. Therefore, water is pressed optimally from an outer layer of a wall. Besides, a large number of filtration channels are found along the wall height, section and quantity of these channels increases in wall inner surface direction. It leads to concrete density and strength change along the manufactured item height.

When assessing the strength of spun concrete from the results of vibrated cubes of concrete with water/cement residual ratio [27], the actual structure of concrete wall is not considered, and the process of concrete mix selection is very time consuming.

Annular cross section samples testing provides the most exact data about spun concrete strength in the manufactured item, but samples are unwieldy, tests are time consuming and demand pressure equipment of high power [10, 11].

The results of sample (cubes, prisms, hollow circles) cut out from natural structures testing can provide the actual spun concrete strength with adequate accuracy. But all the preparatory works before testing are highly time consuming and demand special equipment.

The strength of spun concrete is most frequently determined by taking into account the conversion factors. But these factors considerably differ in works of different authors. R.R. Valduga and A.P. Kudzis [12, 14] suggest conversion factor value equal to 1.18, V.I. Soroker [27, 28] – 1.5–1.7, V.Sh. Kalandadze [24] – 1.37, E.E. Mikhelson [25] – 1.35.

Taking into account the data indicated below we can assume, that methods of spun concrete mechanical properties measuring require further research. And the regularity of concrete mechanical properties change throughout the manufactured item wall is almost not studied.

Methodology of the research

Methodology of the material and concrete research

Rationale for the raw materials for the experiment

Normative documents for the manufacturing of centrifuged reinforced concrete structures define main requirements for quality of raw materials for concrete mixing.

Use of Portland cement without additives or with mineral additives of cement grade 400 and higher as the binding agent is acceptable; and granulated blast-furnace sludge can be used as a mineral admixture in an amount no greater than 20 % of the cement mass. Use of Portland sulfate-resisting cement and Portland cement that is meant for concrete surfacing of roads is acceptable.

These requirements to the cement are associated with the fact that the material composition of the used Portland cement changes in the centrifugation process, since light floured additives are pressed to the inner cavity of the product and go to the sludge.

It is noted that cement paste normal consistency (CPNC) is one of the main factors, which influences the strength and uniformity of centrifuged concrete. It should not be more than 28 %.It is specified in the studies of different authors [8, 14, 26], that changing of CPNC from 24 to 28 % increases centrifugation durability by 1.3 times. Increasing the strength of spun concrete by increasing the consumption of cement over its optimal content does not produce a proportional effect. Besides, it was determined that increasing spending of cement over 500 kg/m3 doubles heat-shrinking deformation.

According to normative documents, the use of coarse- and average-grained natural and crushed sands as the fine aggregate is acceptable. In the case when fine sand is used, it is necessary to increase centrifugation durability [28]. Increased water requirement of fine sand mixes leads to increment of initial water /cement ratio $(W/C)_{init}$ and demands extra cement to warranted concrete strength. For example, increasing of the initial water /cement ratio $(W/C)_{init}$ from 0.35 to 0.41 leads to concrete strength reduction on the average by 28 %, in such case transition coefficient value changes from vibrated samples strength to centrifuged samples strength.

Use of gravel or crushed gravel of hard rock and freeze-proof rock is acceptable as the coarse aggregate. Gravel strength should be as much as twice the concrete strength. Coarse aggregate size regulations are especially specified. It is recommended to perform gauging of two fractions of size 5–10 mm and 10–20 mm separately by proportion of 1:1.5 between them and at maximum allowable voids ratio of mix as much as 40 %.

In our research [29, 30] we used fine-grained mixes a model concrete mix, consisting of stone screening dust of fractions size 2.5–5 mm, refined glass sand of fractions size 0.14–2.5 mm and Portland cement without admixtures made by Novorossisk cement plant “Oktyabr”. The choice of raw materials completely corresponded to the requirements of centrifuged concrete normative documents described above.

Fine-grained concrete mix segregation in the process of centrifugal consolidation will surely be less expressive than segregation of ordinary concrete mix, but we were limited by the size of the formed sample and the necessity of sample fragmentation for physical and mechanical properties measurement of the centrifuged concrete.

For this very reason all the mentioned tests were conducted on fine-grained concrete mixes.

Quality evaluation of the used raw materials.

Properties measurement of the used Portland cement was conducted according to the Russian State Standard GOST procedure 310.1…310.3-76 “Concretes: Test methods. General requirements. Methods of grind fineness, normal consistency, setting up time and soundness measurement.” And quality evaluation was conducted as per Russian State Standard GOST 10178-85 “Portland cement and Portland blast-furnace sludge cement. Technical regulations.”

Properties measurement of glass sand of fractions size 0.14–2.5 mm and stone screening dust of fractions size 2.5–5 mm was conducted according to the Russian State Standard GOST procedure 8735-88 “Sand for construction activity. Test methods.” And their quality evaluation was conducted as per Russian State Standard GOST 26633-2015 “Heavy concrete. Aggregates technical requirements.” Potable mains water, which complies with the requirements of Russian State Standard GOST 23732-2011 “Water for concrete and mortar. Technical regulations.” was used as mixing water.

Basic properties of the used raw materials (concrete, glass sand and stone screening dust) as well as their quality evaluation are presented in Table 1.

By these means fine-grained concrete mix components, which are used in tests, comply requirements of the normative documents and can be used for centrifuged concrete mixing.

Table 1. Properties of the initial raw materials

Name of the component	Basic properties	Compliance with the requirements of normative documents
Portland cement without admixtures made by Novorossisk cement plant "Oktyabr"	Cement fineness (rest on a sieve 008) – 9 %. Setting up time: - initial set 2h. 10 min. - final set 3 h. 50 min. Soundness – bears the activity of Rц = 43.5 MPa Flexural strength of 28 days – 5.65 MPa	Complies GOST Standard 10178-85*and has M400 grade
Refined glass sand of the Volzhsky occurrence	Average bulk density 1510 kg/m^3 Density – 2.66 g/cm^3 Void ratio – 43.2 % Fineness modulus = 1.8 Content of flour and clay particles – are absent Content of organic impurities – are absent	Complies GOST Standard 8736-93* "Sand for construction activity. Technical regulations."
Granit crushing riddlings Pavlovsky quarry (fractions size 2.5–5 mm)	Average bulk density 1300 kg/m^3 Density – 2.67 g/cm^3 Void ratio – 51% Content of flour and clay particles – are absent Content of organic impurities – are absent	Complies GOST Standard 8736-93* "Sand for construction activity. Technical regulations."

Investigation of centrifuged concrete mix properties

The analysis of the experimental studies [29, 30] of heterogeneity and centrifuged concrete strength along the product wall was conducted. The experiments were conducted on test cylinders with a diameter of 6.5 cm and height of 8 cm in laboratory condition with compliance with GOST Standard 18105-2010. The possibility of the laboratory setup, Centrifuge, to form the samples is responsible for the choice of the former. Measurement assurance of the experimental results validity was reached by means of parallel tests on 5 set of vibrated and centrifuged samples with 5 twin samples in each. Low-slump fine-grained concrete mix (Cone Slump = 3-4sm) was used for investigations as well as for production of the actual centrifuged reinforced concrete supports. Initial concrete mix composition per 1 m^3: cement – 500 kg, water – 225 l, sand – 745 kg, stone screening dust – 915 kg for an average density of the concrete mix – 2385 kg/m^3.

The evaluation of centrifuged concrete heterogeneity was conducted in two stages. The freshly-placed concrete mix properties were studied at the first stage, the properties of the hardened concrete - at the second one.

The production of the cylinder samples was made in special individual forms with removing bottom plate and the sample consolidation was made by using laboratory Centrifuge.

Before centrifugation the weighted concrete mix was placed into a mold in two layers with 15 times rodding of each layer. Then the next centrifugal consolidation mode for the experimental samples according to the GOST Standard 22687.0-85 and GOST Standard 22687.3-85 [6] was set on.

- accelerating to the 300 r/min rotation speed – 2 min;

- cure by n=300 r/min – 1 min;

- accelerating to the 500 r/min speed - 2 min;

- cure by n= 500 r/min – 15 min;

TOTAL: 20 min.

As-formed samples were weighted once again to measure pressed sludge quantity, the molds were removed, and as-formed samples were divided into three parts along their height.

Thereupon, each piece was divided into two portions. The first portion was to measure residual water of mixing. The second one was washed off through the 0.071 mm sieve and dried to fixed-mass. The measurement of cement paste content in each layer of the formed sample became possible after dry mineral components were weighted. The quantity of mixing water ΔB, that passed to sludge by centrifugal consolidation of the experimental samples, determines from the formula:

$$\Delta B = \frac{(M_H - M_K)}{V}; \quad (1)$$

where $M_н$ – concrete mix mass before consolidation, g;

$M_к$ – concrete mix mass after consolidation, g;

V – sample volume, cm^3.

To determine sample volume, we measured its height with caliper with an accuracy of 0.1 mm straight after pressing-out.

To determine the quantity of retained mixing water we used the following dependence:

$$B_{ост} = \frac{M_{vl} - M_c}{M_{vl}} \cdot \rho_{bc}^{c}; \quad (2)$$

where M_{vl} – mass of the wet concrete mix portion, g;

M_c – mass of the dry concrete mix portion, g;

ρ_{bc}^{c} – an average density of the concrete mix after the centrifugal consolidation, g/cm^3.

To determine ρ_{bc}^{c} we measured as-formed sample mass and volume.

Investigation of the hardened concrete strength

Solidification of the formed samples was performed in two stages: curing in the laboratory curing room and supplementary standard curing.

Molded samples in forms after 2–3 hours of air storage were placed in the laboratory curing room with automatic control of the cycle mode and were steam cured according to the regime:

– temperature rise up to 80° C – 2 hours;

– isothermal warming at a temperature of 80° C – 10 hours;

– cooling in natural conditions.

Demolding operation and marking of the cured samples was carried out after cooling. Then they were placed in special capacities and matured up to the age of 28 days in wet scrubs (relative humidity of the atmosphere 90–100 %) at the temperature of 20 ± 5° C.

When reaching the age of 28 days the samples were deplaned out from curing room and dried to fixed-mass. Then they were placed in special plastic bags and were kept there until the test.

Samples preparation constituted of dimension measurement, then they were weighted and scanned by ultrasonic device. The samples of each set were divided into two parts. The first part that consisted of three centrifuged cylinders, was tested on compression.

The second part that consisted of two centrifuged cylinders, was exposed to layer-by-layer cutting into three pieces along height.

Then the edges of each piece were trimmed extensively. After dimension measuring, weighting and scanning by ultrasonic device the pieces were tested on compression.

The special test for the purpose of showing “Concrete strength to ultrasonic sound propagation velocity” calibration curve was conducted for actual control of concrete strength by ultrasonic sound propagation velocity. The test procedure and its elaboration corresponded to GOST Standard 17624-2012 “Concretes. Ultrasonic method of strength measurement.” Instrument inverters were placed against the samples sides due to the fact that in order to measure ultrasonic travel time in the samples we used through-scanning method.

3 sets of cube-samples, 10 cm on edge (6 samples in each set), were produced for the purpose of this test. Planned concrete grades in each set were M400; M500 and M600. The samples had been dried for 28 days after concrete hardening, then the ultrasonic travel time in each sample was measured.

The ultrasonic travel time in each sample was measured at least three times. The measurement result of the ultrasonic travel time in the sample was ignored in the calculation of the ultrasonic travel time in a given sample set, if there was a departure of more than 5 % of measurement result of the single ultrasonic travel time measurement in each sample from the mean arithmetical value of the measurement results for a particular sample.

The concrete samples strength was determined by compression testing, by applying the compression apparatus according to the GOST Standard 18105-2010 "Concretes. Strength testing rules". Then we made the results equal to standard sample strength value by multiplying the obtained result by scaling factor, that is equal to 0.91.

The primary investigation of the obtained results has shown a little data spread within each set; this has made it possible to start data computing.

The obtained results with their statistical analysis are represented in Table 2.

The arithmetical average of strength, speed and ultrasonic travel time in set samples were taken as a unit value of these properties in determining the "Concrete strength to ultrasonic sound propagation velocity" calibration curve.

The abnormal results processing of the testing of single samples in a set followed the rule: the test result of the single sample will be considered to be abnormal and will be ignored in calculating of the average result in the set, if "T" value, which is determined from the formula (3), is a subject to the condition:

Table 2. Main results of the test

Set and number of samples	Ultrasonic travel time, us					Breaking strength, kg-f	
	At the top of a sample	In the middle part of a sample	At the bottom of a sample	Average in a sample	Average in a set	A single sample	Average in a set
1-1	26.66	25.7	25.6	25.9	25.52	48300	48250
1-2	25.9	25.5	25.5	25.7		46625	
1-3	25.5	25.0	25.2	25.2		49625	
1-4	25.8	25.5	25.4	25.7		48250	
1-5	25.8	25.6	25.6	25.7		48875	
1-6	25.0	25.5	25.0	25.2		47850	
2-1	24.3	24.0	23.9	24.1	24.18	64250	66810
2-2	24.1	24.2	24.0	24.1		64250	
2-3	24.8	24.4	24.3	24.5		67125	
2-4	24.4	24.1	24.0	24.2		68750	
2-5	24.0	24.3	23.8	24.0		68500	
2-6	24.3	24.4	24.1	24.3		68000	
3-1	23.6	23.5	23.4	23.5	23.73	72250	70810
3-2	23.3	23.3	23.2	23.3		74625	
3-3	24.0	23.9	24.0	24.0		71250	
3-4	24.0	24.0	23.9	24.0		67500	
3-5	24.2	24.0	23.7	24.0		71000	
3-6	23.6	24.0	23.5	23.7		68250	

$$T = \frac{(X_1 - X_J)}{S} \geq 1.74, \quad (3)$$

where X_J is an average strength or ultrasonic sound propagation velocity (travel time) of the set of samples;

S – mean root square deviation of strength or sound propagation velocity (travel time);

$$S = \frac{\sum_{J=1}^{N}(X1_{max} - X1_{min})}{1.69N}, \quad (4)$$

where $X1_{max}$ and $X1_{min}$ – maximal and minimal test results of samples in a set;

N – number of sample sets used in the test.

Average concrete density, concrete voids content, ultrasonic sound propagation velocity; compression strength determined from “Concrete strength to ultrasonic sound propagation velocity” calibration curve, actual compression strength were evaluated as outcome parameters.

Concrete voids content calculation was determined from the formula:

$$\Pi_o = \left(1 - \frac{\rho_0^c}{\rho^c}\right) \cdot 100; \quad (5)$$

where ρ_0^c – average concrete density, g/cm^3;

ρ^c – actual concrete density, g/cm^3;

Results and Discussion

Results of investigation of concrete mix

Comparative data on heterogeneity of the properties of fresh concrete are shown in Table 3

Table 3. Average density and water/cement ratio of concrete mix

Layer of concrete mix in a sample	**Average density**		**Actual residual flow of water in mix**		**Actual residual content of cement in mix**		**Residual water/cement ratio**
	kg/m^3	variation,%	l/m^3	variation,%	kg/m^3	variation,%	
top	2282	1.48	223	2.06	477	0.96	0.47
middle	2295	0.44	218	3.03	485	1.16	0.45
bottom	2296	0.58	219	2.01	488	1.19	0.45
whole sample	2291	1.07	220	1.41	484	0.871	0.46
inner	2290	2.92	142	8.6	495	0.47	0.287
middle	2338	2.10	133	5.5	478	0.50	0.277
outer	2375	1.51	123	5.3	466	1.23	0.263
whole sample	2334	1.07	133	5.0	480	0.99	0.275

Experimental graphs of variance of compacted concrete physical properties along a sample height are represented in Figure 1.

Analysis of the received experimental dependence represents a significant difference in quantity of residual mixing water and cement in each layer of the compacted concrete sample. The average density of the inner layer decreased by 6-7%, but consumption of residual water and cement increased. In such manner the conducted test provides not only an illustration of concrete mix segregation along samples depth by centrifugal consolidation, but allows to quantify this heterogeneity of properties as well. Different values of $(W/C)_{res}$ in each sample layer are critically important conditions in determination of physical and mechanical properties of hardened concrete. $(W/C)_{res}$ value of compacted concrete mix in the inner layer (towards centrifuge axis) of concrete is 10-12% greater than in the outer layer.

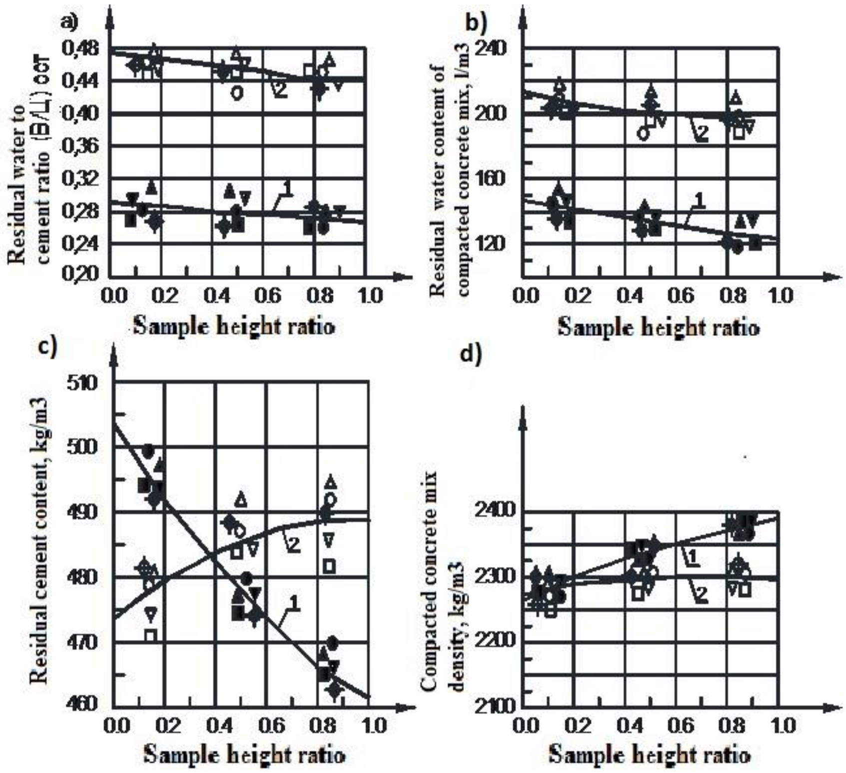

Figure 1. Variance of compacted concrete physical properties along a sample height (a – residual water/cement ratio; b – residual content of water; c – residual cement content; d – average density).

1 – centrifuged samples

2 – vibrated samples

▲ △ - the 1st set
● ○ - the 2nd set
■ □ - the 3rd set
▼ ▽ - the 4th set
⊕ - the 5th set

Results of investigation of concrete strength along a wall height

Comparative data on evaluation of structural heterogeneity of hardened concrete is represented in Table 4.

Table 4. Average density, porosity and strength of concrete

Layer	Average concrete density		Concrete porosity		Compressive strength		
	kg/m³	variation,%	%	variation,%	Determined from the calibration curve, MPa	actual	
						MPa	variation, %
a) vibrated samples							
top	2260	0.96	16.72	4.7	50.66	51.28	4.03
middle	2268	1.28	16.42	6.4	52.06	52.08	4.84
bottom	2268	1.08	16.42	5.9	51.20	51.72	3.02
whole sample	2265	1.40	16.52	4.9	51.31	51.69	0.80
b) centrifuged samples							
inner	2270	0.51	16.23	2.10	59.22	60.26	3.51
middle	2317	0.31	14.40	1.62	64.93	65.04	2.64
outer	2356	0.33	13.30	2.78	72.78	73.89	4.40
whole sample	2314	0.20	14.64	1.62	65.64	66.39	1.91

Experimental graphs of variance of average concrete strength and compressive strength through sample height are represented in Figure 2.

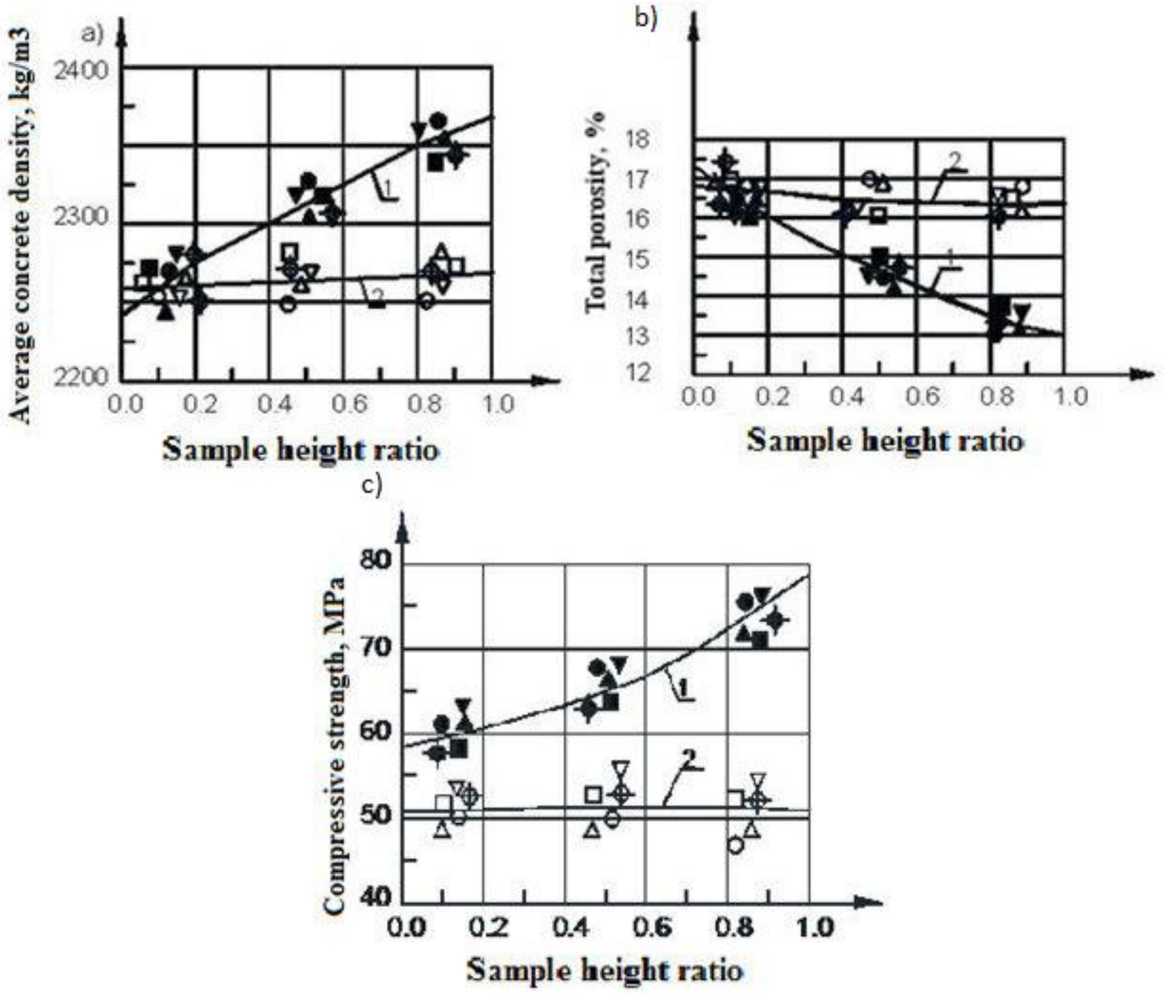

Figure 2. Variance of physical and mechanical properties of concrete along a sample height.
(a – average concrete density; b – total porosity; c – compressive strength)

1 – centrifuged samples

2 – vibrated samples

▲ △ - the 1st set
● ○ - the 2nd set
■ □ - the 3rd set
▼ ▽ - the 4th set
⊕ ⊕ - the 5th set

Analysis of the received data revealed that centrifuged concrete properties in samples sawn by layers (fragments) change considerably. The average concrete density change is observed along the height (up to 4 %), the total porosity in sludge layer is up almost by 18 %, and concrete strength in the outer layer is up by 18–25 %. Gross data of property distribution along a sample height conforms fully to analysis results of fresh-placed concrete mix properties.

A mathematical treatment of the received experimental data was conducted to determine a dependence of centrifuged concrete strength change along a product wall. Parabolic, hyperbolic and linear relations were taken as approximating functions.

Different regression equations describing the concrete strength change dependence along the height were obtained by the least square method (Fig. 3).

Particularly for parabolic function the following regression equations is provided:

$$R_b = R_{b1} + 2{,}064 \cdot \delta_x + 18{,}382 \cdot \delta_x^2; \quad (6)$$

where R_{b1} – concrete strength on the inner surface of a centrifuged product (MPa);

δ_x – wall height ratio

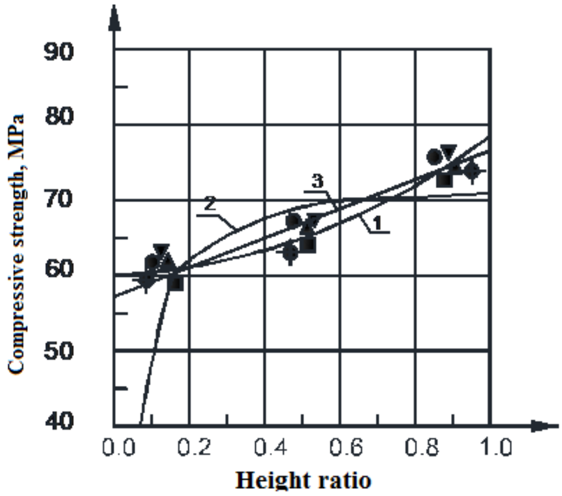

Figure 3. Comparison of mathematical relationships describing the patterns of change in the strength of centrifuged concrete

1 – parabolic relation
2 – hyperbolic relation
3 – linear relation

▲ - the 1st set
● - the 2nd set
■ - the 3rd set
▼ - the 4th set
◆ - the 5th set

Analysis of the experimental data revealed that the relationship of centrifuged concrete strength on the inner surface R_{b1} to the average strength along the height $R_{bк}$ was changing within the following limits $R_{b1}/R_{bк}$=0.87-0.94.

To assess the reliability of the obtained dependence (6) of concrete strength change a numerical experiment, investigating the bearing capacity of power transmission line supports was conducted [31–34].

Tower bodies of high-voltage power transmission lines were taken as study samples according to the GOST Standard 22687.0-85, 22687.3-85. The recommendations and directions presented in design codes Eurocode 2 and ACI 318-05 are not perfect and not fully formulated. This can lead to groundless overestimation or underestimation of reliability of designed and executed spun and vibrated concrete tubular structures [21, 23].

General constant and variable parameters of cylindrical tower bodies are represented in Table 5:

Table 5. General constant and variable parameters of cylindrical tower bodies

Parametrs of tower bodies (unit of measurement)	Code number and height of tower bodies (m)		
	CC20.0	CC22.2	CC26.4
Constant			
- outer diameter (m)	0.80	0.56	0.56
- inner diameter (m)	0.63	0.43	0.44
- flexibility	37.5	60.7	75
- grade of concrete	B45	B40	B40
- reinforcement grade	A600	A600	A600
-pretensioning level of reinforcement (σ_{sp}/R_{sk})	0.7	0.7	0.9
Variable Total reinforcement ratio, $\mu_{s,tot}$,%	2.5 3.5 4.5	2.7 3.7 4.7	2.7 3.7 4.7
The ratio of prestressing reinforcement to the whole area, ($A_{sp}/A_{s,tot}$),%	0;25; 50;75; 100	0;25; 50;75; 100	0;25; 50;75; 100
The ratio of vertical load moment to the	0;	0;	0;

full moment, (M_v/M),%	20; 40	20; 40	20; 40

In the numerical experiment total reinforcement ratio coefficient $\mu_{s,tot}$% for all types of tower bodies was changing withing the limits: 2.5÷4.5% (for CC=20.0 m), 2.7÷4.7% (for CC= 22.2), 2.7÷4.7% (for CC=26.4).

The ratio of prestressing reinforcement area to the whole area ($A_{sp}/A_{s,tot}$) and the ratio of vertical load moment to the full moment (M_v/M) was changing in each samples set. Bearing capacity for each tower bodies was determined in accordance with three conditions:

1 – according to strength conditions (V);

2 – according to target crack width (M_{acrc});

3 – according to limit deflection (M_f).

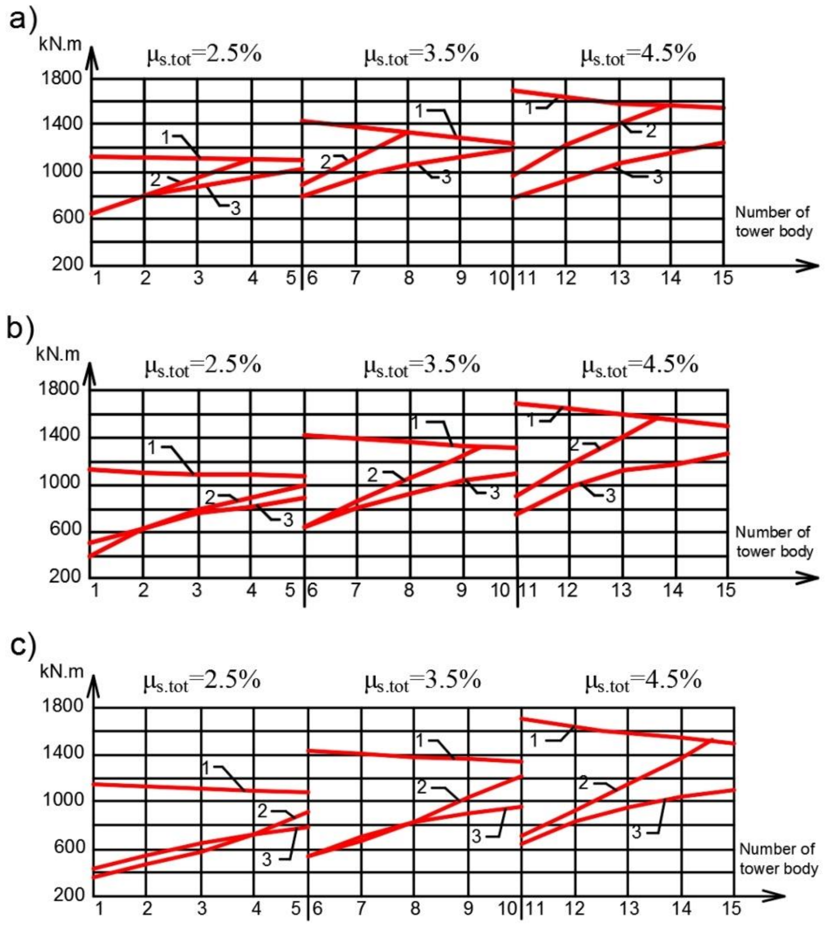

Figure 4. Changing of bearing capacity of CC20 tower bodies when
a) MV/M=0; b) MV/M=0.2; c) MV/M=0.4
1 – according to strength conditions (V); 2 – according to target crack width (Macrc);
3 – according to limit deflection (Mf).

Graphs of changing of bearing capacity of 45 CC20 tower bodies are depicted in Figure 4. Similar dependence is observed for other series of tower bodies (CC22, CC25).

Analysis of the received results demonstrates, that bearing capacity of tower bodies by uniform cross-section of concrete increases when total reinforcement ratio $\mu_{s,tot}$ increases. However, by constant $\mu_{s,tot}$, when ratio of prestressing reinforcement area A_{sp} to the whole area $A_{s,tot}$ increases, a modulated (close to linear) reduction of bearing capacity (Fig. 4) appears. This value goes up when percentage of reinforcement increases.

Similar changing of bearing capacity is observed in others series of tower bodies (CC22, CC25). The reason for this is connected with a symmetrical distribution of prestressing reinforcement according to the parameter of the annular cross section and can be explained by the earlier destruction of a compression area as a result of increasing prestressing reinforcement content.

It is interesting to compare the carrying capacity of tower bodies on the procedure adopted in the standards and methodology. The numeral comparison by different procedures is demonstrated in the Table 6.

Analysis of these results revealed, that standards inflate the bearing capacity for all the cylindrical series of tower bodies, besides the more reinforcement ratio is, the more the overestimation is.

Analysis of the graphs (Fig. 4) of changing of calculated strength of tower bodies according to crack width condition and limit deflection shows, that strength according to crack width condition for all types of tower bodies, as a rule, is higher than strength according to limit deflection.

Table 6. The numeral comparison of bearing capacity of tower bodies by different procedures

Type of tower body	Total reinforcement ratio $\mu_{s,tot}$	Bearing capacity, kN/M				(V3-V1)/V3*100,%	(V4-V2)/V4*100,%
		Author's procedure		Standards procedure			
		Asp/As.tot=0 V1	Asp/As.tot=1 V2	Asp/As.tot=0 V3	Asp/As.tot=1 V4		
CC20	2.5	1129.8	1066.1	1179.5	1115.4	4.2	4.4
	3.5	1409.9	1289.0	1555.9	1406.8	9.4	8.4
	4.5	1651.7	1468.9	1899.1	1632.1	12.8	10
CC22	2.7	416.9	388.3	456.5	429.0	8.6	9.5
	3.7	510.7	458.6	589.5	528.8	13.4	13.2
	4.7	594.2	516.2	710.4	605.7	16.3	14.7
CC26	2.7	390.7	357.7	428.0	401.2	8.7	10.8
	3.7	478.3	415.2	552.4	492.6	13.4	15.7
	4.7	556.2	463.1	665.2	561.8	16.3	17.5

Conclusion

1. Investigation of fresh-placed concrete mix properties determined a substantial segregation of its components by centrifugal consolidation. Density of the inner layer of the as-formed concrete is by 6–8 % less, but increased content of water and cement. Besides, a residual water content $(W/C)_{res}$ in the inner layer was 10–12 % greater, than in the outer layer.

2. Centrifuged concrete has a considerable heterogeneity of physical and mechanical properties along the wall of a formed product. The difference in average density of the outer and inner layer in our test varies within the limits of 4–6 %, and porosity of the inner layers was higher than porosity of the outer layers by over 18 %.

3. Actual compressive resistance varies within wide limits. In the analyzed tests on the inner surface the actual compressive resistance was 60.3 MPa in average and on the outer surface it was 74 MPa.

4. Parabolic dependence of change of centrifuged concrete strength from the wall height ratio of the product annular cross section was provided. Values of empirical coefficient were also determined.

5. Investigation of the bearing capacity of cylindrical power transmission line supports by using the provided dependence of concrete strength changing along the wall height (6) showed a satisfactory repeatability with calculation of tower bodies by standard procedure. Besides, bearing capacity of tower bodies, according to standard procedure, has an inflated value by 4.4–10 % for CC20 tower bodies with flexibility – 53.5, and for CC26 tower bodies with flexibility 75 by 10.8–15.7 %in comparison with the procedure provided by the author.

The authors are planning to continue the investigation of crack resistance and deformability of power transmission line supports with running values of the total reinforcement ratio, the relation between prestressing and nonprestressed reinforcement and different flexibility.

References

1. Schule F. Versuche und Berechnung von Eisenbetonmasten mit ringformigen Quersehnitt. *Beton und Eisen.* 1908. No. 4. Pp. 41–44.
2. Abeles P. Schleuderbetonmaste fur Bahn-Fahrleitungen. *Beton und Eisen*. 1935. No. 15. Pp. 27–30.
3. Abeles P. Mast und Mastfusse aus Schleuder beton. *Zeitschrift O.J.A.V.* 1961. No. 25/26. Pp. 13–17.
4. Mikhailov V.V. *Teoriya i praktika centrifugirovannogo napryazhenno armirovannogo betona* [Theory and practice of centrifugated prestressed reinforced concrete]. Moscow: JSC "Publishing house GosStroiizdat". 1939. (rus)
5. Korner C. Universell verwedbare Spannbetonmaste. Entwicklung eines neuen sortimentes. *Schriftenreihen der Bauforschung, Reihe stahlbeton.* 1967. №6. Pp. 108–112.
6. *Russian State Standard GOST 22687.0-85, GOST 22687.3-85.* Stojki zhelezobetonnye centrifugirovannye dlya opor vysokovoltnyx linij elektroperedach [Reinforced concrete centrifugated power bodies for high-voltage power transmission line supports]. (rus)
7. Akhvedov I.N. *Vysokoprochnyj beton* [High-strength concrete]. Moscow: GosStroiizdat 1961. 162 p. (rus)
8. Akhvedov I.N. *Zhelezobetonnye napornye centrifugirovannye truby* [Reinforced concrete pressure centrifuged pipes]. Moscow: JSC "Publishing house GosStroiizdat", 1967. (rus)
9. Dmitriev S.A. Raschet zhelezobetonnyx elementov kolcevogo secheniya [Salculation of reinforced concreteelements of annular cross section]. Construction industry. 1940. № 2. Pp. 72–74. (rus)
10. Dmitriev S.A., Batashev V.M. Prochnost i treshhinostojkost zhelezobetonnyx elementov kolcevogo secheniya [Strength and crack resistance of reinforced concreteelements of annular cross section]. *Treshchinostojkost i deformativnost obychnyh i predvaritelno napryazhennyh zhelezobetonnyh konstrukcij*. 1965. (rus)
11. Dmitriev S.A., Batashev V.M. Issledovanie zhelezobetonnyx elementov s mnogoryadnym raspolozheniem armatury [Investigation of reinforced concrete elements with multilanearrangement of reinforcement]. *Beton i zhelezobeton.* 1966. No. 5. Pp. 55–57. (rus)
12. Valduga R.R. Issledovanie raboty trubchatyx obrazcov iz centrifugirovannogo vysokoprochnogo betona pri centralnom ili vnecentrennom szhatii [Investigation of behavior of high-strength concrete pipe samples by direct and eccentrical compression]. *Issledovaniya po zhelezobetonnym konstrukciyam.* 1969. (rus)
13. Valduga R.R., Kudzys A.P. Issledovanie predelnoj szhimaemosti betona izgibaemyx prednapryazhennyx elementov kolcevogo secheniya [Investigation of maximum concrete compressibility of flexural prestressing elements of annular cross section]. *Zhelezobetonnye konstrukcii.* 1967. (rus)
14. Valduga R.R., Kudzys A.P. O prochnosti centrifugirovannogo zhelezobetona pri szhatii [On centrifugated reinforced concrete compression strength]. *Issledovaniya po zhelezobetonnym konstrukciyam.* 1966. No. 1. (rus)
15. Kudzys A.P. K voprosu opredeleniya prochnosti centrifugirovannogo betona [On the question of determination of centrifugated concrete strength]. *Stroitelstvo i arhitektura.* 1964. Vol. IV. No. 1. Pp. 28–31. (rus)
16. Kudzys A.P., Valduga R.R. O prochnosti centrifugirovannogo betona na szhatie pri izgibe [On

Литература

1. Schule F. Versuche und Berechnung von Eisenbetonmasten mit ringformigen Quersehnitt // Beton und Eisen. 1908. № 4. Pp. 41–44.
2. Abeles P. Schleuderbetonmaste fur Bahn-Fahrleitungen // Beton und Eisen. 1935. № 15. Pp. 27–30.
3. Abeles P. Mast und Mastfusse aus Schleuder beton // Zeitschrift O.J.A.V. 1961. No. 25/26. Pp. 13-17.
4. Михайлов В.В. Теория и практика центрифугированного бетона. // М. Гостройиздат. 1939.
5. Korner C. Universell verwedbare Spannbetonmaste. Entwicklung eines neuen sortimentes. // Schriftenreihen der Bauforschung, Reihe stahlbeton. 1967. №6. Pp. 108-112.
6. ГОСТ 22687.0-85, ГОСТ 22687.3-85. Стойки железобетонные центрифугированные для опор высоковольтных линий электропередач.
7. Ахвердов И.Н. Высокопрочный бетон. М.: Госстройиздат. 1961. 162 с.
8. Ахвердов И.Н. Железобетонные напорные центрифугированные трубы. М.: Госстройиздат, 1967.
9. Дмитриев С.А. Расчет железобетонных элементов кольцевого сечения. // Строительная промышленность, 1940. № 2. С. 72-74.
10. Дмитриев С.А., Баташев, В.М. Прочность и трещиностойкость железобетонных элементов кольцевого сечения // Трещиностойкость и деформативность обычных и предварительно напряженных железобетонных конструкций. 1965.
11. Дмитриев С.А., Баташев В.М. Исследование железобетонных элементов с многорядным расположением арматуры // Бетон и железобетон. 1966. №5. С. 55-57.
12. Валдуга, Р.Р. Исследование работы трубчатых образцов из центрифугированного высокопрочного бетона при центральном или внецентренном сжатии // Исследования по железобетонным конструкциям. 1969.
13. Валдуга, Р.Р., Кудзис, А.П. Исследование предельной сжимаемости бетона изгибаемых преднапряженных элементов кольцевого сечения // Железобетонные конструкции. 1967.
14. Валдуга, Р.Р., Кудзис, А.П. О прочности центрифугированного железобетона при сжатии // Исследования по железобетонным конструкциям. 1966. №. 1.
15. Кудзис А.П. К вопросу определения прочности чентрифугированного бетона // Строительство и архитектура. 1964. Вып. 4. № 1. С. 28-31.
16. Кудзис А.П., Валдуга Р.Р. О прочности центрифугированного бетона на сжатие при изгибе // Строительная механика и конструкции. Вильнюс. 1964. № 7. С. 58-60.
17. Кудзис А.П., Новиков Ю.Н. Изготоваление преднапряженных железобетонных опор ЛЭП-35 // Бетон и железобетон. 1960. № 11. С. 22-25.
18. Kudzys A., Kliukas R. Reliability index design in reinforced concrete structures of annular cross sections // The 10th International Conference “Modern Building Materials, Structures and Techniques”: Selected papers. Vol. 2. Lithuania. Vilnius: Technika, 2010. Pp. 948–956.
19. Kliukas R., Kudzys A., Vadlūga R. The quasi-ductile resistance of compressed spun concrete beam-columns // Civil Engineering and Management. 2010. Vol. 16. № 2. Pp. 189–196.
20. Kudzys A., Kliukas R. Probability-based design of spun

centrifugated concrete compression strength under bending]. *Stroitelnaya mekhanika i konstrukcii.* 1964. No. 7. Pp. 58–60. (rus)

17. Kudzys A.P., Novikov Y.N. Izgotovalenie prednapryazhennyx zhelezobetonnyx opor LEP-35 [Production of prestressed reinforced concrete power transmission line supports – 35]. *Beton i zhelezobeton. 1960.* No. 11. Pp. 22–25. (rus)
18. Kudzys A., Kliukas R. Reliability index design in reinforced concrete structures of annular cross sections. *The 10th International Conference "Modern Building Materials, Structures and Techniques": Selected papers.* Vol. 2. Lithuania. Vilnius: Technika, 2010. Pp. 948–956.
19. Kliukas R., Kudzys A., Vadlūga R. The quasi-ductile resistance of compressed spun concrete beam-columns. *Civil Engineering and Management*. 2010. Vol. 16. No. 2. Pp. 189–196.
20. Kudzys A., Kliukas R. Probability-based design of spun concrete beam-columns. *Journal of Civil Engineering and Management.* 2013. Vol. 16. Pp. 451–461.
21. Kudzys A., Kliukas R. The limit state design of spun concrete columns using load combinations recommended by EN 1990 and ASCE/SEI 7–05. *Journal of Civil Engineering and Management.* 2015. Vol. 15. Pp. 289–297.
22. Kudzys A., Kliukas R. The resistance of compressed spun concrete members reinforced by high-strength steel bars. *Materials and Structures.* 2008. Vol. 41. No. 2. Pp. 419-430.
23. Kliukas R. *Design of spun concrete columns reinforced by high strength steelbars.* Vilnius: Vilnius Gediminas Technical University, 2017.
24. Kalanadze V.S. Opredelenie prochnosti centrifugirovannogo betona [Determination of centrifugated concrete strength]. *Beton i zhelezobeton.* 1962. No. 8. Pp. 54–59. (rus)
25. Mikhelson E.E. *Opory iz centrifugirovannogo zhelezobetona elektricheskix vozdushnyx linij* [Electrical aerial circuit support from centrifugated reinforced concrete]. Tbilisi: Publishing house Tsodna, 1938. (rus)
26. Liberman M.Y., Soroker V.M. Dannye poluzavodskix opytov po centrifugirovannomu betonu [Data of semi-scale tests on centrifugated concrete]. *Stroitelnaya promyshlennost.* 1935. No. 2. Pp. 38–39. (rus)
27. Soroker V.I. Kontrol prochnosti betona v centrobezhnyx trubax [Concrete strength control in centrifugal pipes] *Construction and Architecture.* 1998. No. 3. Pp. 37–38. (rus)
28. Soroker V.I., Kozyuk M.F. Issledovanie deformativnyx i prochnostnyx svojstv centrifugirovannogo betona [Investigation of stress-related and strength properties of centrifugated concrete]. *Energy Construction.* 1998. No. 9, Pp. 67–69. (rus)
29. Suval R., Shchutsky V.L. Vliyanie strukturnoj neodnorodnosti centrifugirovannogo betona na ego prochnost v izdelii [Influence of centrifugated concrete structure heterogeneity on its strength in a product]. Rostov-on-Don. *Sbornik SEVKAVNIPIAGROPROM.* 1995. Pp. 60–65. (rus)
30. Suval R., Shchutsky V.L., Tkachenko G.A. Eksperementalnye issledovaniya neodnorodnosti centrifugirovannogo betona po tolshhine stenki kolcevogo secheniya [Experimental investigation of centrifugated concrete heterogeneity along annular cross section wall height]. *Rostov-on-Don: Sbornik SEVKAVNIPIAGROPROM.* 1995. Pp. 65–70. (rus)
31. Shchutsky V.L., Tolipova T.D. Issledovanie nesushhej sposobnosti cilindricheskix opor LEP/ID [Investigation of bearing capacity of cylindrical power transmission line supports]. *Scientific overview.* 2014. No. 10. Pp. 654–658. (rus)

concrete beam-columns // Journal of Civil Engineering and Management. 2013. Vol. 16. Pp. 451–461.

21. Kudzys A., Kliukas R. The limit state design of spun concrete columns using load combinations recommended by EN 1990 and ASCE/SEI 7–05 // Journal of Civil Engineering and Management. 2015. Vol. 15. Pp. 289–297.
22. Kudzys A., Kliukas R. The resistance of compressed spun concrete members reinforced by high-strength steel bars // Materials and Structures. 2008. Vol. 41. No. 2. Pp. 419-430.
23. Kliukas R. Design of spun concrete columns reinforced by high strength steelbars. Vilnius: Vilnius Gediminas Technical University, 2017.
24. Каланадзе В.С. Определение прочности центрефугированного бетона // Бетон и железобетон. 1962. No. 8. С. 54-59.
25. Михельсон Е.Э. Опоры из центрифугированного железобетона электрических воздушных линий // Тбилиси. Издательство Цодна. 1938.
26. Либерман М.Я., Сорокер В.М. Данные полузаводских опытов по центрифугированному бетону // Строительная промышленность. 1935. №2. С. 38-39.
27. Сороккер В.И. Контроль прочности бетона в центробежных трубах // Строительство и архитектура. 1958. №3. С. 37-38.
28. Сороккер В.И. Козюк М.Ф. Исследование деформативных и прочностных свойств центрифугированного бетона // Энергетическое строительство. 1968. № 9. С. 67–69.
29. Сувал Р., Щуцкий В.Л. Влияние структурной неоднородности центрифугированного бетона на его прочность в изделии. // Ростов-на-Дону. Сборник СЕВКАВНИПИАГРОПРОМ. 1995. С. 60–65.
30. Сувал Р., Щуцкий В.Л., Ткаченко, Г.А. Эксперементальные исследования неоднородности центрифугированного бетона по толщине стенки кольцевого сечения. // Ростов-на-Дону. Сборник СЕВКАВНИПИАГРОПРОМ. 1995. С. 65–70.
31. Щуцкий В.Л., Толипова Т.Д. Исследование несущей способности цилиндрических опор ЛЭП/ИД // Научное обозрение. 2014. № 10. С. 654–658.
32. Fouad H., Detwiler R. High-strength materials for spun concrete poles // Pci Journal. 2012. Pp. 27–32.
33. Volgyi I., Farkas G., Nehme S.G. Concrete strength tendency in the wall of cylindrical spun-cast concrete elements // Periodica Polytechnica: Civil Engineering. 2010. Vol. 54. № 1. Pp. 23–30.
34. Irawan C.E.A. A review of prestressed concrete pile with circular hollow section (Spun pile) // Jurnal Teknologi. 2015. Vol. 72. № 5. Pp. 115–123.

Dedukh D.A., Schsuzkiy V.L., Kuzmenko A.A. Spun concrete properties of power transmission line supports. *Magazine of Civil Engineering.* 2017. No. 7. Pp. 37–51. doi: 10.18720/MCE.75.4.

32. Fouad H., Detwiler R. High-strength materials for spun concrete poles. *Pci Journal*. 2012. Pp. 27–32. (rus)
33. Volgyi I., Farkas G., Nehme S.G. Concrete strength tendency in the wall of cylindrical spun-cast concrete elements. *Periodica Polytechnica: Civil Engineering.* 2010 Vol. 54. No. 1. Pp. 23–30. (rus)
34. Irawan C.E.A. A review of prestressed concrete pile with circular hollow section (Spun pile). *Jurnal Teknologi*. 2015. Vol. 72. No.. 5. Pp. 115–123. (rus)

Dmitriy Dedukh,
+79185373033; hasturd@gmail.com

Viktor Schsuzkiy,
vikluk00@mail.ru

Anna Kuzmenko,
+79896363258; akuzmenk2009@yandex.ru

Дмитрий Андреевич Дедух,
+79185373033; эл. почта: hasturd@gmail.com

Виктор Лукьянович Щуцкий,
эл. почта: vikluk00@mail.ru

Анна Алексеевна Кузьменко,
+79896363258;
эл. почта: akuzmenk2009@yandex.ru

Дедух Д.А., Щуцкий В.Л., Кузьменко А.А. Свойства центрифугированного бетона опор линий электропередач // Инженерно-строительный журнал. 2017. № 7(75). С. 37–51.