Experimental Research of Biaxially Bended Reinforced Concrete Columns Manufactured on Granite Sifting

Olha Harkava, Andrii Pavlikov

Educational and Research Institute of Architecture, Civil Engineering and Land Management, National University «Yuri Kondratyuk Poltava Polytechnic», 24, Pershotravneva Avenue, 36011 Poltava, Ukraine

Summary

The production by-product, specifically granite sifting, can constitute up to 10 – 15% of the primary product in stone crushing plants during the production of crushed stone. Granite sifting possesses properties comparable to crushed stone from the same source, yet its cost per cubic meter is considerably lower. In view of this, the use of grain sifting in the production of reinforced concrete columns is considered as a promising direction. The reinforced concrete columns typically experience biaxial bending conditions. This is attributed not only to the uniaxial application of external loads but also to random eccentricities arising from various factors such as inaccuracies in reinforcement installation, assembly discrepancies, and local damages. To validate the developed strength calculation method, which consider the effects of biaxial bending, explore column behavior under load, and acquire experimental values for parameters characterizing the stress-strain state during failure, experimental tests on 10 biaxially bended columns were conducted. The columns were loaded with an axial force applied with two eccentricities in such a way that the forms of the compressed concrete area in the cross-section of the columns were different. An analysis of strength and deformation characteristics of fine-grained concrete in composition of biaxially bended reinforced concrete columns was carried out and the possibility of using granite sifting for their production is confirmed.

1 INTRODUCTION

The amount of production by-product, namely: granite screening, can reach 15% of the main product at stone crushing plants during the manufacture of crushed stone. Since in terms of its properties, granite sifting is not inferior to crushed stone from the same stone, but its cost per cubic meter is significantly lower, therefore granite crumb is a common raw material. In view of this, the use of grain screening in the production of various reinforced concrete structures is a promising direction.

The wide range of applications of reinforced concrete columns is explained by the positive qualities of these structures, in which concrete and reinforcement are used most effectively. Moreover, unlike beams, concrete in columns plays a much greater role in terms of their bearing capacity. Quite often, the reinforcement of columns is carried out structurally due to the significant compressive strength of concrete. Therefore, with small loads on reinforced concrete columns, it is possible to use fine-grained concrete to ensure equal strength between the concrete and the reinforcing cage. At the same time, attention may be paid to other design features of this material, giving preference to ease of manufacture, minimization of external equipment, cost and the possibility of effective use of production waste.

The advantages of fine-grained concrete, among others, are the high quality of the surface of finished structures, which practically does not require additional equipment, the convenience of manufacturing and casting the concrete mixture, the cost of concrete. The use of granite sifting as both coarse and fine aggregates additionally eliminates the need for sand mining, thereby conserving land resources. With a rational selection of the composition, fine-grained concrete is not inferior in strength to ordinary heavy concrete, and it is characterized by increased tensile strength during bending. Such concretes are distinguished by increased homogeneity, and therefore higher values of frost resistance and waterproofing, although they require some excess consumption of cement. The amount of cement in fine-grained concrete is usually 20...40% higher than in concrete with crushed stone of the same strength. The reason for this is the increased voids of fine aggregate compared to the total voids of coarse and fine aggregates for ordinary concrete. Higher specific surface area of the aggregate and, accordingly, higher water absorption of concrete mixtures also contribute to increased consumption of cement in fine-grained concrete [1] – [2].

In many sources [3] – [9], it is noted that reinforced concrete columns, as a rule, work in conditions of biaxial bending, caused in addition to the uniaxial application of the external load by random eccentricities arising from various factors, such as inaccuracies in the installation of reinforcement, inaccuracies in assembling, local damage and others. When designing a column, the effect of eccentricities in mutually orthogonal planes is usually calculated separately. More accurate calculation results can be achieved by performing the calculation on the action of biaxial bending. At the same time, there are certain difficulties due to the variety of forms of the compressed zone of concrete, for each of which the calculation will have its own characteristics [9]. Experimental data on the strength and the process of forming the compressed zone of concrete of biaxially bended columns made of fine-grained concrete are scarce. Therefore, to test the developed calculation method [9] and to study the operation of columns under load, as well as to obtain experimental values of parameters characterizing the stress-strain state of the column during failure, experimental tests of biaxially bended columns were conducted.

2 METHOD OF EXPERIMENTAL RESEARCH

During the manufacture of experimental columns, it was taken into account that the strength and stress-strain state of the element primarily depend on such factors as: the number and placement of principal reinforcement in compressed and tesile zones, physical and mechanical properties of materials, and eccentricity of load application. The main tasks in conducting experimental research were: determination of the position of the neutral axis in the cross-section of the column at each stage of loading; establishment of the form of the compressed area in the cross-section of the column at the time of failure; investigation of the nature of the destruction of test samples with different forms of the compressed area of concrete; determination of deformations in the most compressed fiber of concrete of normal cross-section at different levels and patterns of loading; determination of the bearing capacity of the columns during their biaxial bending.

10 samples of reinforced concrete columns of rectangular profile from fine-grained concrete were produced. All experimental columns had a length of 1 m and design cross-sectional dimensions of 125x125 mm. The design of the experimental samples is shown in Fig. 1. The characteristics of concrete and reinforcement used for the manufacture of experimental columns are listed in table 1.

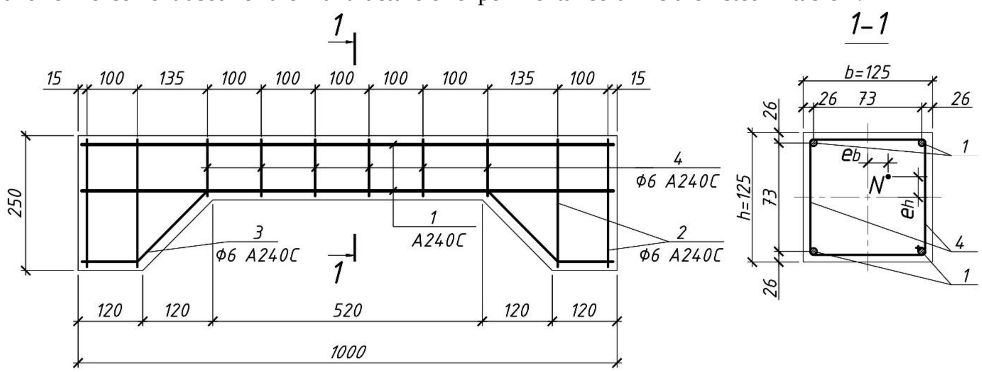

Fig. 1 Design and reinforcing scheme of experimental column samples

The test columns are divided into three series depending on the diameter of the longitudinal principal reinforcement (Fig. 1, position 1). Reinforcement of the A240C class with diameters of 8,10 and 12 mm was used as principal longitudinal reinforcement and reinforcement with diameter of 6 mm was used as structural (Fig. 1, positions 2, 3, 4). The principal and structural reinforcement of the samples were connected to each other with the help of a tie wire into spatial cages.

The electrical resistance strain gauges with a base of 20 mm were glued to the principal longitudinal reinforcing bars in their middle part from diametrically opposite sides after the manufacture of the cages. After the sensors were soldered to the switching wires, they were covered with epoxy resin, which ensured reliable hydraulic and electrical insulation.

Concreting of the columns was carried out in laboratory conditions. 10 columns and 3 prisms measuring 150x150x600 mm were made of one batch. The fine-grained concrete mix for the columns was produced manually by using a concrete mixer. M400 Portland cement produced at a factory in Ivano-

Frankivsk was used as a binder. Granite screening with a fraction of 0-5 mm was used as a coarse and fine aggregate. The following ratio of cement: granite screening: water components was selected – 1:3:0.5 and then used for columns manufacture. After placing the concrete mixture in the metal formwork, it was compacted with a deep vibrator.

Table 1 Characteristics of experimental column samples

Sample code	Eccentricities		Concrete characteristic	Reinforcement A240C characteristics					
	e_b, mm	e_h, mm	f_{cm}, MPa	Ø, mm	σ_y, MPa	E_s, MPa	Ø, mm	σ_y, MPa	E_s, MPa
C-1-1	15	30	15.7	8	285	210000	6	256	210000
C-1-2	10	20	15.7	8	285	210000	6	256	210000
C-1-3	30	15	15.7	8	285	210000	6	256	210000
C-2-1	10	30	15.7	10	278	210000	6	256	210000
C-2-2	30	40	15.7	10	278	210000	6	256	210000
C-2-3	0	20	15.7	10	278	210000	6	256	210000
C-2-4	0	50	15,7	10	278	210000	6	256	210000
C-3-1	15	30	15,7	12	328	210000	6	256	210000
C-3-2	10	20	15,7	12	328	210000	6	256	210000
C-3-3	10	30	15,7	12	328	210000	6	256	210000

Concreted samples were kept for 28 days in a metal formwork under conditions of natural hardening in a wet state. Columns that reached the age of 30-40 days were prepared for testing.

After drying the samples of the columns on the concrete in the zone of possible destruction, along the entire perimeter of the cross-section of the columns, tensor resistors with a base of 50 mm were glued. Previously, the concrete surface was polished, degreased with a solvent and primed with BF-2 glue. The layout of strain gauges on concrete and reinforcement is shown in Fig. 2. It should be noted that the outer surface of the columns due to the use of fine-grained concrete and its careful compaction was uniform with a minimum number of pores and caverns. Therefore, the use of such concrete in structures minimizes the costs of their equipment.

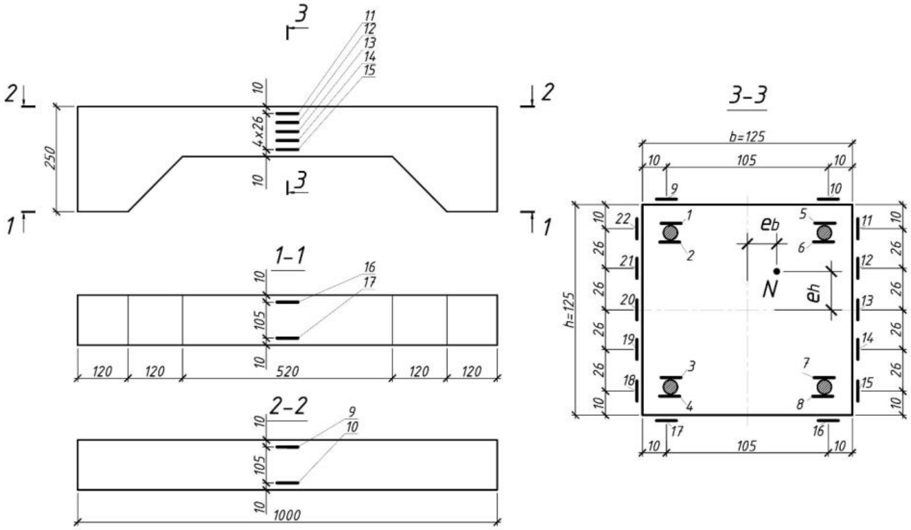

Fig. 2 Diagram of the strain gauges location

To determine the physical and mechanical characteristics of reinforcing steel, previously prepared samples of 600 mm length, cut from each working and structural longitudinal bar, were used. Tensile testing of reinforcement samples was carried out on a certified HMS-50 press, force meter scale 100 kN. As a result of the tests, the yield strength of reinforcing steel was determined. The spread of values was small, because the reinforcing bars were cut from the same batch. Average data based on the test results of three samples are shown in Tab. 1.

To determine the properties of concrete, concrete prisms were tested before testing the columns. Research was carried out on a 2PG-125 hydraulic press. The scale of the force meter is 490 kN. Mean value of compressive concrete strength of during the prism test is determined by the actual values of the experimental data at the time of sample destruction. The test results are shown in Tab. 1.

Testing of experimental samples of columns for the effect of biaxial bending was carried out on a PG-125 hydraulic press. Before conducting the tests, the column was installed on the working plate of the press, centred along the geometric axis, and a hinge was installed in the upper part of the column, which transmitted the force with two eccentricities relative to the axes of inertia of the column section.

Before starting, the scale of the press was calibrated by supplying oil to the piston of the working plate, until the arrow on the scale of the press took the zero position. The load on the sample was transferred using the upper movable plate of the press. Provision of load application with accepted eccentricities is shown in Fig. 3. The load was applied in increments of no more than 10% of the calculated destructive load. The total test time of one column was 1.5 – 2 hours.

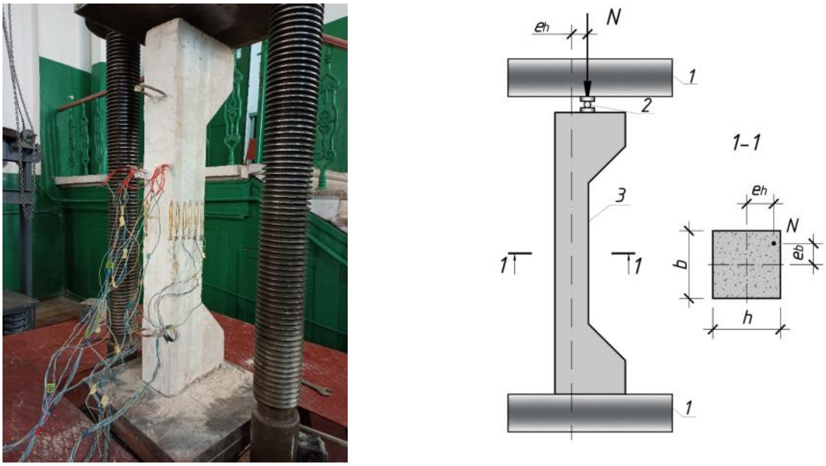

Fig. 3 General view of the installation during the test (a) and sample loading scheme (b): 1 – press plates; 2 – hinge; 3 – experimental sample

The columns were brought to destruction, i.e. the exhaustion of the bearing capacity, which character was changed depending on the eccentricity. The destruction of the concrete in the compressed area with a slight opening of cracks in the tensile area was observed at smaller values of eccentricities, the development and opening of cracks in the tensile concrete with the formation of a winch in the compression area was detected at maximal eccentricities. After the maximum load was reached, followed by gradual decrease in pressure on the scale of the press.

3 RESULTS AND DISCUSSION

As it is known, during biaxial bending of reinforced concrete members, depending on the change in the eccentricity of the application of longitudinal force, the compressed concrete area can take on different geometric forms, which are clearly determined by the location of the neutral axis in the section. When studying biaxially bended columns, special attention was paid to finding out the position of the neutral axis, since it is an important criterion for the stress-strain state of such members.

In general, all cases of the position of the neutral axis in the rectangular cross-section of the columns during biaxial bending are reduced to the formation of three forms of the compressed concrete area: triangular, trapezoidal and pentagonal.

The location of the neutral axis in the section is uniquely determined by two parameters, namely: the angle θ of the neutral axis inclination and the neutral axis depth x. The position of the neutral axis in the cross-section of the test columns at each stage of loading was determined using the graphs of the relative strains of the reinforcement and concrete, plotted according to the readings of the strain gauges. According to the results of the tests, it was noted that a trapezoidal compressed area of concrete was mainly formed in the test columns (Fig. 4). At the same time, the formation of a trapezoid was realized with bases both on the longitudinal (Fig. 4, C-2-3) and on the transverse faces of the section (Fig. 4, C-2-2). The triangular form of the compressed area was not realized during the tests of the experimental samples, and the pentagonal one was realized at the smallest eccentricities values. At the same time, in the absence of eccentricity in one direction, plain uniaxial bending was not realized, as evidenced by the rotation of the neutral axis from its horizontal position (Fig. 4, C-2-3). Which additionally confirms the statement that the implementation of plain deformation in reinforced concrete structures is impossible.

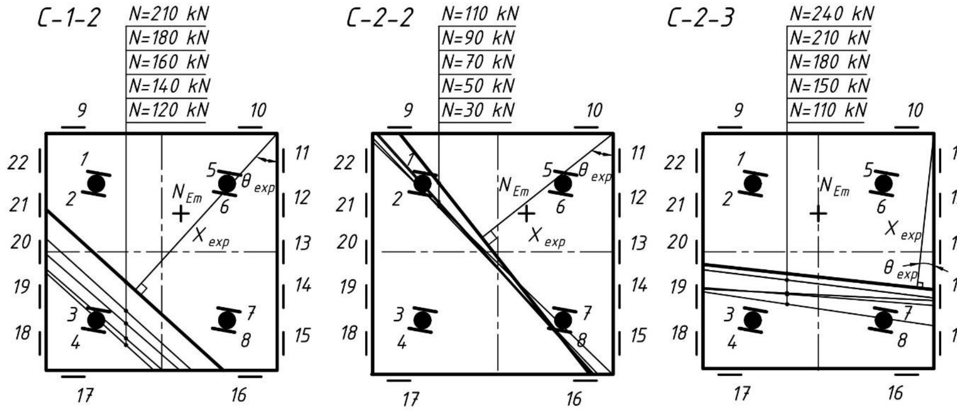

Fig. 4 Changing the position of neutral axis and forms of the compressed concrete area in the cross-section of test columns

Based on the analysis of the formation of the compressed concrete area in the cross-section of the experimental columns, it was established that biaxial deformation, which can be caused by random factors, that is, with eccentricities, one of which (incidental) is significantly smaller than the other (design), as a rule, is realized with the formation of a trapezoidal form compressed area or pentagonal with a relatively small value of the design eccentricity. The implementation of the triangular form of the compressed area is most likely in structures subjected to longitudinal force with design eccentricities in two planes.

It can be seen from Fig. 4 that in the columns during the entire loading, the movement of the neutral axis in the direction of the most compressed rib occurred almost parallel with small deviations. Exceptions were noted when transitioning from one form to another in the form of jump-like turns of the neutral axis. The direction of rotation was ambiguous in each specific case, and also changed when the neutral axis passed through the rib. This is probably explained by the balancing of internal and external moments of forces in the cross-section of the column when the form of the compressed area changes.

During experimental tests of the columns, attention was paid to determining the ultimate fiber strains of fine-grained concrete in the compressed area. The method of conducting experimental studies made it possible to determine the longitudinal strains of both concrete and reinforcement at all levels of loading. From the very beginning of loading, the maximum deformations of concrete were observed in the most compressed edge of the biaxially bended columns, and at the moment of failure, they reached the maximum values of ε_{cm} (Fig. 5).

Analysis of the given graphs (Fig. 5) shows that the ultimate strains of fine-grained concrete in the experimental columns depend on the area As of the principal longitudinal reinforcement. Thus, in the columns of the C-1 series, which have a smaller diameter of the principal reinforcement (A_s = 201 mm^2), the ultimate strains of concrete reach smaller values compared to the concrete deformations of the C-2 columns (A_s = 314 mm^2). Considering the nature of the N-ε_{cm} dependences, it is possible to note the following nature of the influence of the area of longitudinal work on the curvature of the graphs: with an increase in the amount of reinforcement, the deformation of the concrete of the most compressed edge occurs less intensively, as indicated by the curvature of the N-ε_{cm} graphs for columns C-2 compared to C-1. The reason for this is that the reinforcement absorbs a significant part of the compressive force, thereby relieving the concrete.

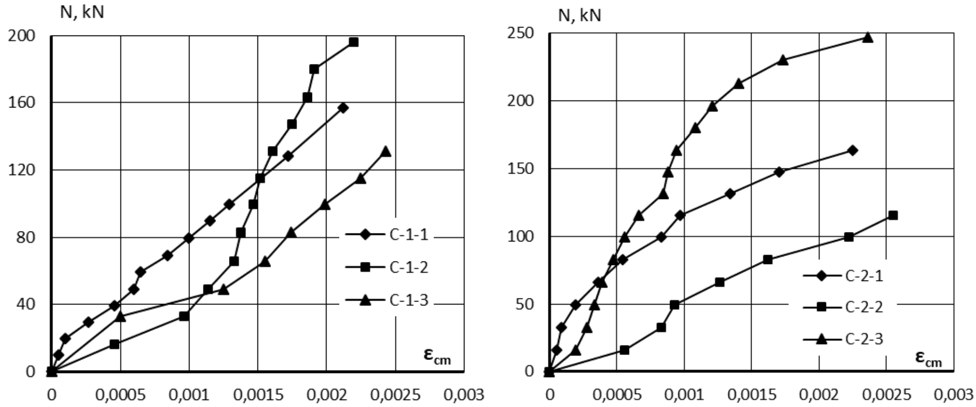

Fig. 5 N-ε_{cm} diagrams for experimental columns

According to the results of the analysis of the ultimate strains of fine-grained concrete, it was noted that with the same reinforcement, they increase during the transition from a pentagonal to a trapezoidal form of the compressed area and when it further approaches a triangular one, and therefore change according to the patterns that were noted for heavy concrete [10]. Values of ultimate fiber strains of fine-grained concrete vary from 0,00212 to 0,00392.

The analysis of the strains of the principal longitudinal reinforcement at all stages of loading provided an opportunity to find out the nature of the work of each reinforcing bar and to reveal its influence on the stress-strain state and bearing capacity of the columns. Fig. 6 presents the most characteristic graphs of the dependence of the strains εs of the reinforcing bars on the action of the external longitudinal force *N*.

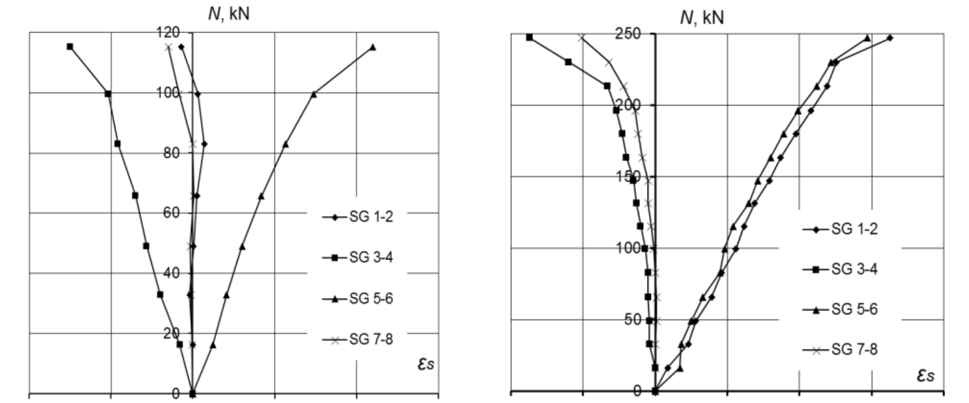

Fig. 6 Graphs of dependence of N-ε_s for experimental columns: (left) column C 2-2; (right) column C-2-3; SG … – strain gage number (Fig. 2).

Considering the change in the relative strains of reinforcing bars with sensors 1-2 and 7-8 (Fig. 6, left), which are located on the border of the compressed and tensile cross-sectional areas of the C-2-2 column, the graphs show the rotation of the neutral axis in the process of loading. The indicated reinforcing bars at the first stages of loading undergo tension, then compression, and at the last stages they again perceive tensile forces. Similar changes in reinforcement strains are noted in columns C-2-1 and C-1-3. For the deformations of the bars of column C-2-3 (Fig. 6, right) and other columns, in which no change in the form of the compressed area occurred from the beginning of loading, a similar variation of the reinforcement deformations was not observed.

The strains of the tensile and compressed bars farthest from the neutral axis occurred more intensively compared to others. At loading levels of 0.85 – 0.90N, strains in the most tensile bars of columns C-1-3 and C-2-2 reached values corresponding to the yield point, as a result of which the nature of their destruction was plastic. In other columns, strains characterizing the yield point of the reinforcement were determined only in the most compressed bars at load levels of 0.9 –1.0N, while the strains of the most tensile bars were 65 – 80% of the strains corresponding to the yield point. As a result, the nature of the failure of these columns was brittle.

The data of experimental tests of columns made of fine-grained concrete on a granite screening were compared with the results of calculating the strength of columns in biaxial bending according to the method developed in [9] for structures made of heavy concrete. In the calculation, generally accepted prerequisites according to Eurocode 2 were applied. As can be seen from the analysis of these comparisons (Tab. 2), the calculation method for biaxial bending according to [9] allows to obtain quite accurate values of the strength of columns made of fine-grained concrete. The coefficient of variation in the values of the destructive longitudinal force *N* is 8.37%.

Table 2 Comparison of the results of theoretical strength calculations of biaxially bended reinforced concrete columns with experimental data

Sample code	Neutral axis inclin. angle θ^o			Neutral axis depth *x*, mm			Destructive force *N*, kN		
	Theor.	Exp.	Theor./Exp.	Theor.	Exp.	Theor./Exp.	Theor.	Exp.	Theor./Exp.
C-1-1	15	30	33,63	32,01	1,05	108,65	97,45	1,11	142,90
C-1-2	10	20	34,34	42,24	0,81	119,50	109,86	1,09	172,60
C-1-3	30	15	53,17	52,56	1,01	105,74	99,44	1,06	131,10
C-2-1	10	30	26,06	26,09	1,00	110,88	100,35	1,10	171,00
C-2-2	30	40	39,53	52,00	0,76	99,70	87,02	1,15	115,30
C-2-3	0	20	0,00	6,00	-	104,01	80,60	1,29	209,30
C-2-4	0	50	0,00	6,00	-	70,51	62,02	1,14	108,20
C-3-1	15	30	33,45	24,00	1,39	115,50	100,87	1,15	195,40
C-3-2	10	20	34,47	35,00	0,98	126,53	108,82	1,16	235,20
C-3-3	10	30	26,05	25,35	1,03	113,29	103,40	1,10	205,60
Expectation			1,0051			1,1347			0,9254
Arithmetical mean deviation			0,0359			0,0039			0,0060
Dispersion			0,1895			0,0624			0,0775
Root mean square deviation			0,1885			0,0550			0,0837
Variation coefficient			1,0051			1,1347			0,9254

It should also be noted a certain overestimation of the theoretical values of the neutral axis depth x, which is due to the simplifications adopted in the calculation, namely the use of a rectangular distribution of stresses in the concrete of the compressed area. The overestimation of the value of the depth *x* was 13.47%. The most variable values of discrepancies were observed for the values of the angle θ of the neutral axis inclination, the coefficient of variation for which was 18.85%, which is explained by a set of random factors that could affect this sensitive parameter during the test, since the values of the angle θ differ significantly with the smallest changes in strains of concrete or reinforcement. Nevertheless, the general tendency of the change of this parameter depending on the change in the eccentricity of the application of the external load of the experimental columns corresponds to the calculated one.

4 CONCLUSIONS

As a result of testing samples of fine-grained concrete columns for biaxial bending, the following was established:

1. The compressed concrete area of experimental biaxially bended columns acquired two geometric forms: trapezoidal and pentagonal.

2. The neutral axis in the normal cross-section of the columns during the entire loading moved in parallel towards the most compressed edge at a constant form of the compressed concrete area. When the form changes, i.e. when the neutral axis passes through the edge of the section, a rotation of the neutral axis was observed during the loading process.

3. Ultimate fiber strains of fine-grained concrete in the composition of biaxially bended reinforced concrete columns increase with an increasing in the area of the longitudinal reinforcement of the columns, as well as with the transition from a pentagonal to a trapezoidal form of the compressed area, approaching a triangular form. The values of the ultimate fiber strains of the fine-grained concrete of the columns varied from 0,00212 to 0,00392.

4. The conducted comparative analysis of the results of calculating the parameters of the stress-strain state of experimental columns at the time of failure confirms the possibility and feasibility of applying the developed method of strength analysis when determining the bearing capacity of biaxially bended columns made of fine-grained concrete.

5. The possibility of using waste from stone crushing plants, in particular granite screening, for the production of fine-grained concrete for biaxially bended reinforced concrete columns has been experimentally confirmed. Since, during the study of the strength and deformability of fine-grained concrete, no features were found that would prevent its use as a material for reinforced concrete structures.

References

[1] Aruova, L.B., Ospanova, Z.N., Gordienko, B.S., Alibekova, N.T., Kalieva, Zh.E., Urkinbaeva, Z.I. and Nurbaeva, M.N. 2020. “Properties of fine-grained concrete mixtures during the construction of monolithic structures”. *IOP Conf. Series: Mater. Science and Eng.* 829(1): 012018. doi:10.1088/1757-899X/829/1/012018

[2] Bochmann, J., Jesse, F., Curbach, M. 2017. “Experimental Determination of the Stress-Strain Relation of Fine Grained Concrete under Compression”. Paper presented at Eleventh High Performance Concrete (11th HPC) and the Second Concrete Innovation Conference (2nd CIC), Oslo: Norsk Betongforening, 6: 10-19

[3] Bousias, S.N., Verzeletti, G., Fardis, M.N, and Gutierrez, E. 1995. “Load-Path Effects in Column Biaxial Bending with Axial Force”. *Journal of Engineering Mechanics* 121(5) doi:10.1061/(ASCE)0733-9399(1995)121:5(596)

[4] Fafitis, A. 2001. “Interaction Surfaces of Reinforced-Concrete Sections in Biaxial Bending”. *Journal of Structural Engineering* 127(7) doi:10.1061/(ASCE)0733-9445(2001)127:7(840)

[5] Chen, S.F., Teng, J.G., and Chan, S.L. 2001. “Design of biaxially loaded short composite columns of arbitrary section”. *Journal of Structural Engineering* 127(6) 678 doi:10.1061/(ASCE)0733-9445(2001)127:6(678)

[6] Furlong, Richard W., Hsu, Ch-T.Tomas, and Mirza, S.Ali 2004. “Analysis and Design of Concrete Columns for Biaxial Bending-Overview”. *ACI Structural Journal* 101(3): 413-423.

[7] Bouzid, T. and Demagh, K. 2011. “Practical method for analysis and design of slender reinforced concrete columns subjected to biaxial bending and axial loads”. *Slovak Journal of Civil Engineering* 1(24). doi:10.2478/v10189-011-0004-1

[8] Pavlikov, Andrii, Harkava, Olha, Prykhodko Yulia, and Baryliak, Bohdan. 2019. “Highly constructed precast flat slab frame structural system of buildings and research of its slabs”. Proceedings of the International fib Symposium on Conceptual Design of Structures, Madrid, Torroja Institute: 493-500

[9] Baryliak, Bohdan, Pavlikov, Andrii, and Harkava, Olha. 2020. “General Method of Structural Analysis of Reinforced Concrete Columns under Axial Load and Biaxial Bending”. Proceedings of the 2020 session of the 13th fib International PhD Symposium in Civil Engineering, Paris, Fédération Internationale du Béton: 179-186

[10] Pavlikov, Andrii, Kochkarov, Dmytro, and Harkava, Olha. 2020. “Structural deformability of concrete”. Proceedings of the fib Symp. 2020 Concrete Structures for Resilient Society, Shanghai, International Federation for Structural Concrete: 519-525