

DEFORMATION OF REINFORCED HIGH-STRENGTH LIGHTWEIGHT CONCRETE ELEMENTS UNDER COMBINED ECCENTRIC COMPRESSION AND TORSION

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Abstract: This paper presents the results of an experimental study on the deformation and failure of reinforced high-strength lightweight concrete elements under combined eccentric compression and torsion. The physical patterns and characteristics of deformation for such elements under the specified stress state have been established. The investigated parameters include concrete and reinforcement strains, crack patterns and crack widths, as well as deflections and angles of twist for the elements under consideration. The study demonstrates that crack formation in high-strength lightweight reinforced concrete structures has its own specificities: under loading with an eccentrically applied compressive force and a torque, one or several spatial cracks develop. As the load increases, one dominant crack emerges, leading to failure along this crack. A further characteristic of the deformation behavior is that after crack initiation, the deformation stage range leading to failure is more than two times shorter compared to structures made of conventional normal-weight concrete. A comparison of the obtained experimental data with the results of calculations based on the proposed analytical model confirms its reliability and potential for practical application.

Keywords: High-strength lightweight concrete, complex stress state, torsion, eccentric compression, experimental studies

ДЕФОРМИРОВАНИЕ АРМИРОВАННЫХ ЭЛЕМЕНТОВ ИЗ ЛЕГКОГО БЕТОНА ПОВЫШЕННОЙ ПРОЧНОСТИ ПРИ ВНЕЦЕНТРОМ СЖАТИИ С КРУЧЕНИЕМ

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Аннотация: Приведены результаты экспериментальных исследований деформирования и разрушения железобетонных элементов из легкого высокопрочного бетона при внецентренном сжатии с кручением. Установлены физические закономерности и особенности деформирования таких элементов при рассматриваемом напряженном состоянии, определены деформации бетона и арматура, картины и ширина раскрытия трещин, а также прогибы и углы закручивания для рассматриваемых элементов. Показано, что трещинообразование в конструкциях из легкого высокопрочного железобетона имеют свою специфику: при нагружении к элементу внецентренно приложенной сжимающей силы и крутящего момента в нём образуются одна или несколько пространственных трещин из которых, по мере нагружения выделяется одна и по ней происходит разрушение. Особенностью деформирования является и то, что после образования трещин в рассматриваемом элементе диапазон стадии деформирования до

разрушения более чем в два раза меньший, чем в конструкциях из обычного тяжелого бетона. Сопоставлением полученных опытных данных с результатами расчета по предложенной аналитической модели подтверждена ее достоверность и возможность практического использования.

Ключевые слова: легкий бетон повышенной прочности, сложное напряженное состояние, кручение, внецентренное сжатие, экспериментальные исследования

INTRODUCTION

Currently, both domestically and internationally, intensive research is being conducted aimed at the development and application of high-strength structural lightweight concrete. In current Russian [11] and foreign codes for the design of reinforced concrete structures [12, 13], the class of structural lightweight concretes is limited. Consequently, these documents lack the physico-mechanical characteristics of high-strength lightweight concrete. At the same time, in Russia, an experimental self-compacting high-strength lightweight concrete with density grades below D2000 and strength classes B50-B65 [1-3] has been developed, which appears to be a highly promising material for lightweight load-bearing walls, columns, and floors of high-rise buildings [2,7]. This direction, associated with the use of a new generation of lightweight concretes in the construction industry aimed at reducing building mass, is gaining new relevance, especially for construction in seismically active regions and for the design of buildings and structures considering special impacts [2,5,6,14]. However, due to the low initial modulus of elasticity of lightweight concretes and other physico-mechanical peculiarities of the material, a problem arises in ensuring the stiffness of floors and other flexural and eccentrically loaded compression members.

An analysis of Russian [1-6] and foreign [8-10] publications on lightweight concrete research shows that lightweight concrete as a material in reinforced concrete structures can possess good performance characteristics in construction due to its expectedly lower contribution to the structure's self-weight.

However, as noted in the publications, despite some experience in using such concrete for load-bearing elements of buildings, existing research on this material in Russia and abroad is limited to the study of mixes [2] and some physico-mechanical properties. Recently completed studies on the strength and deformation characteristics of self-compacting high-strength expanded clay concrete of classes B50–B65 [1-3], as well as the long-term deformation of such concretes with different structures [4], can be noted here.

Foreign research is increasingly focusing on the study of the physico-mechanical properties of lightweight concrete with various types of fiber reinforcement. For example, study [8] experimentally investigated the mechanical properties and the complete stress-strain diagram of lightweight concrete reinforced with steel and carbon fibers. The research was conducted on cylindrical specimens with strength classes from LC40 to LC60 and a fiber volume fraction from 0% to 0.9%. The results of these tests showed that steel fiber can significantly increase flexural strength and split tensile strength.

Publication [9] presents a series of tests on cylinders made of steel fiber-reinforced lightweight aggregate concrete (SFRLWAC) aimed at developing a physical deformation model for this material (SFRLWAC) under monotonic compressive loading. Experiments established that adding steel fiber to lightweight concrete has an insignificant effect on the ascending branch of the stress-strain curve but has a noticeable effect on the descending (post-peak) branch of deformation. The publication also includes some analysis results for beam structures (1200mm span, 200×150 mm cross-section) made of steel fiber-reinforced

lightweight concrete. It is shown that adding steel fiber changes the pattern of crack propagation in the structures. In conventional lightweight concrete, cracks propagate parallel to the load direction (normal cracks), whereas in steel fiber-reinforced lightweight concrete structures, the direction of crack development under load changes, and the cracks gradually incline and become perpendicular to the load direction.

Research on the physico-mechanical properties of lightweight concrete with a strength of 50-70 MPa, reinforced with carbon and polypropylene fibers both individually and in hybrid form, is presented in publication [10]. As a result, these studies obtained parameters such as slump cone flow, density, segregation resistance, compressive strength, split tensile strength, flexural strength, compressive stress-strain diagrams, and other characteristics of the fiber-reinforced lightweight concrete.

Research works on the stress-strain behavior of structures made from the new generation of high-strength lightweight concretes are practically absent in open sources. Apart from the mentioned publication [9], which studied beam structures made of high-strength lightweight concrete and steel fiber-reinforced lightweight concrete under a complex stress state—bending from a concentrated force—a few other publications dedicated to studying the stress-strain state of beam structures made of high-strength lightweight concretes under simple stress states are known, such as works [15-18]. Separate recent studies conducted for structures made of high-strength normal-weight concrete under various stress states [19-21] have shown a number of specific features of their deformation, cracking, and failure compared to structures made of normal-strength concrete.

In this regard, the goal of this research was to conduct experimental studies of the deformation and failure of reinforced concrete elements made of high-strength lightweight concrete under eccentric compression with torsion, and to

establish the features, physical nature, and parameters of their load-bearing capacity in comparison with calculated values obtained using a developed analytical model [22].

METHODS

To achieve the goal and objectives of the research, a program of experimental studies was developed accordingly. This program included the design and fabrication of test specimens, a methodology for measuring test parameters, and methods and equipment for loading the test specimens. Three series of test specimens were designed and manufactured (Figure 1):

Series 1K-1 (1K-1.1, 1K-1.2, 1K-1.3) — Reinforced concrete columns, 3 units, each 2000 mm long with a cross-section of 100x50 mm. Longitudinal reinforcement: 8 mm diameter (4 bars) and 6 mm diameter (2 bars). Transverse reinforcement: 2 mm diameter with a spacing of $s=120\text{ mm}$ (Figure 1a).

Series 1K-2 (1K-2.1, 1K-2.2, 1K-2.3) — Reinforced concrete columns, 3 units, each 2000 mm long with a cross-section of 100x50 mm. Longitudinal reinforcement: 8 mm diameter (4 bars). Transverse reinforcement: 2 mm diameter with a spacing of $s=120\text{ mm}$ (Figure 1b).

Series 1K-3 (1K-3.1, 1K-3.2, 1K-3.3) — Reinforced concrete columns, 3 units, each 2000 mm long with a cross-section of 100x50 mm. Longitudinal reinforcement: 6 mm diameter (4 bars). Transverse reinforcement: 2 mm diameter with a spacing of $s=120\text{ mm}$ (Figure 1c).

Materials used for manufacturing the test specimens: High-strength lightweight concrete B40. The structural reinforcement was of class A500C, and the transverse reinforcement was made from wire with characteristics equivalent to class A240 reinforcement.

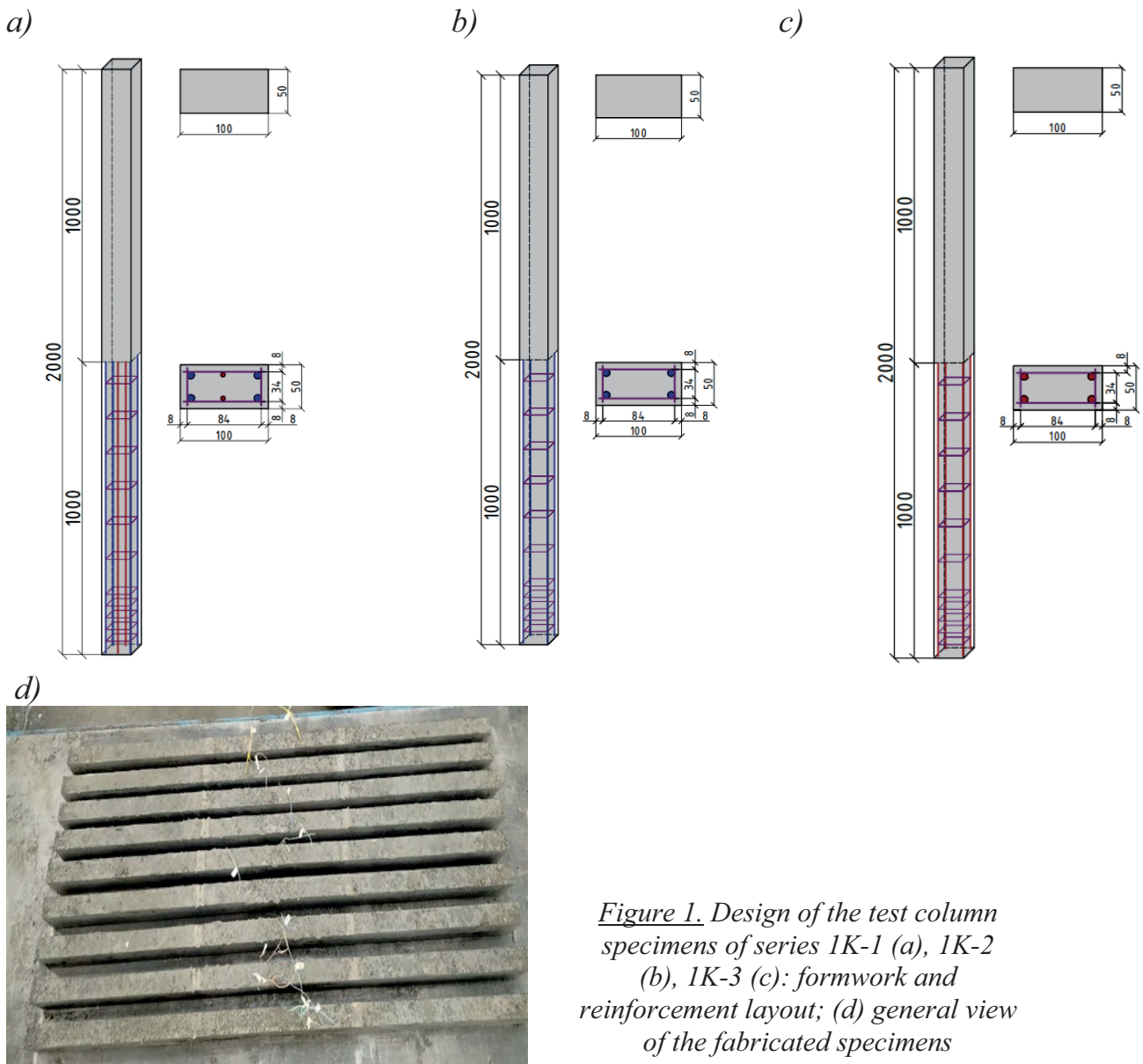


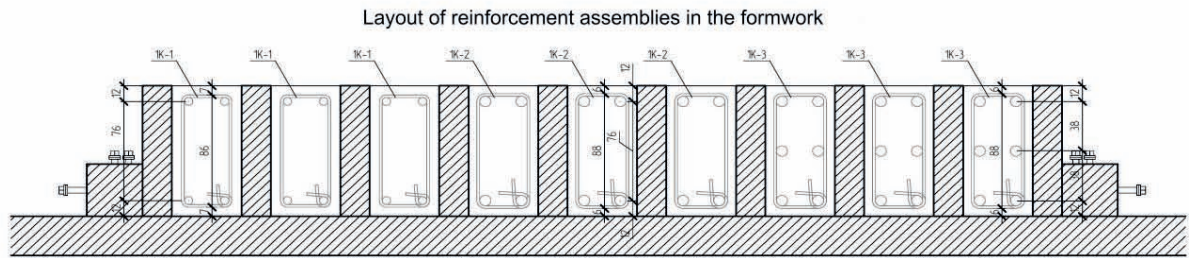
Figure 1. Design of the test column specimens of series 1K-1 (a), 1K-2 (b), 1K-3 (c): formwork and reinforcement layout; (d) general view of the fabricated specimens

Manufacturing of the test specimens for all series was carried out in specially designed and manufactured formwork made of waterproof plywood (Figure 2a). The concreting of the test specimens was performed at the "MonArkh Group of Companies" construction materials plant (Figures 2b, 2c). The experimental research was conducted in the laboratory of the Mytishchi branch of the National Research

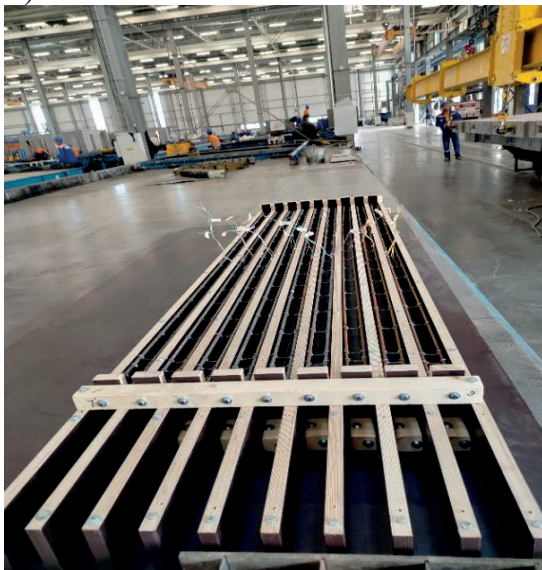
Moscow State University of Civil Engineering (MGSU).

Concurrently with the main structural specimens, auxiliary prism and cube specimens were fabricated and tested using concrete from the same batch as that used for the main test specimens. The characteristics of the tested cubes and prisms are presented in Table 1.

a)



b)



c)

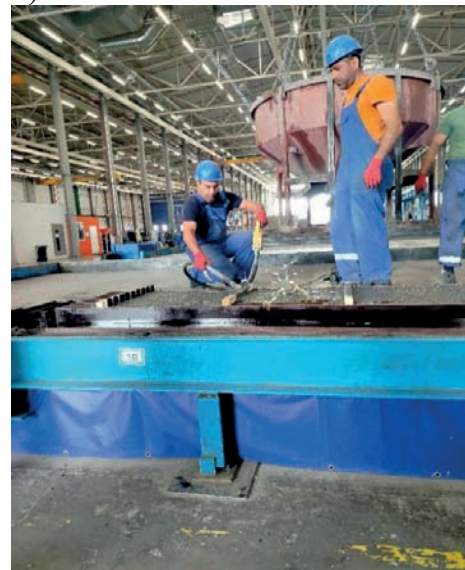


Figure 2. Formwork layout with installed rebar cages (a, b) and a general view of the test structures during concreting (c)

Table 1. Key Properties of Cube and Prism Specimens

Series / Specimen ID	Dimensions, mm	Mass, g	Average Mass, g	Density, kg/m ³	Avg. Density, kg/m ³	Failure Load, kN	Avg. Failure Load, kN
Series 1K / Cube 1	104x100x99	1815	1826,6	1762,62	1762,05	375	381,6
Series 1K / Cube 2	104x100x100	1860		1788,46		420	
Series 1K / Cube 3	101x100x103	1805		1735,07		350	
№	Specimen Series*	Failure Load (kN)*	Modulus of Elasticity (MPa)*	Poisson's Ratio*	R, MPa	R _b , MPa	
1	1K-1	200	22 · 10 ³	0,24	40	30,77	

2	1K-2	200	$21,7 \cdot 10^3$	0,28	40	30,77
3	1K-3	200	$20 \cdot 10^3$	0,29	40	30,77
	Average 1K	200	$21,3 \cdot 10^3$	0,27	40	30,77

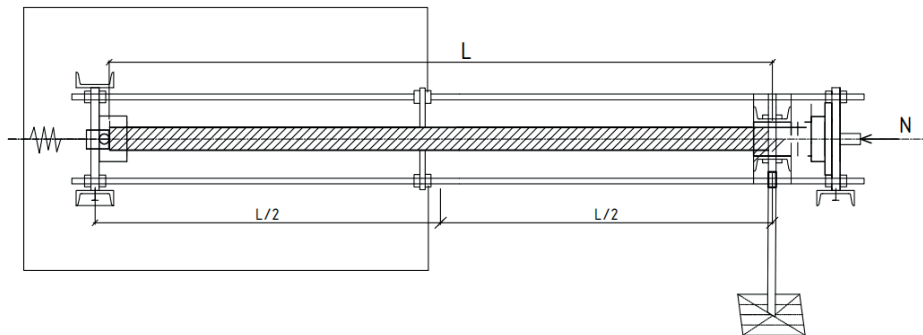
* Average Value for Each Specimen Series

RESULTS AND DISCUSSION

To test the experimental specimens, special non-standard equipment was designed and manufactured in the form of a rigid frame with tie rods, fixed support, and rotational devices (Figure 3). One end of the test specimen was rigidly fixed in the crosshead. A compressive force with a specified eccentricity was applied to the other end using a jack. Simultaneously, a torque was applied to the specimen via a lever rigidly connected to it through a roller assembly.

The applied compressive force and the torque acting on the specimen were measured. During the experiment, mechanical instruments were used to measure deflections in two planes of the specimen and at several sections along its length, as well as the angles of twist due to the torque, longitudinal strains, and shear strains. A digital video camera was used to record the crack formation pattern and measure the crack width at different stages of loading the structure.

a)



b)



Figure 3. Experimental test setup: (a) schematic diagram; (b) general view

Based on the experimentally measured strains in the investigated sections of the columns, "load-strain" dependencies were constructed for the test columns 1K-1, 1K-2, and 1K-3. The experimental values of the cracking load for the test specimens were determined from the principal strain values. For specimen 1K-1 made of B40 concrete, the cracking load $(Ne)_{crc} + T_{crc}$ was 0.544 kN·m. For specimen 1K-2, it was 0.429 kN·m, and for specimen 1K-3, it was 0.413 kN·m. Comparing the experimental values of the principal concrete strains (curves 2, 3) with the calculated ones (curves 1, 4) obtained from the

strain data of strain gauges oriented at 0°, 45°, and 90° to the longitudinal axis of the specimen (see Figure 3), it can be observed that the proposed computational model satisfactorily describes the deformation in complexly stressed sections of the structures at different loading levels. A similar conclusion can be drawn from the analysis of the tensile reinforcement strains. The obtained strain graphs (Figure 5) show that after crack formation in the reinforcement, a sharp increase in strain occurs, and yielding is reached relatively quickly.

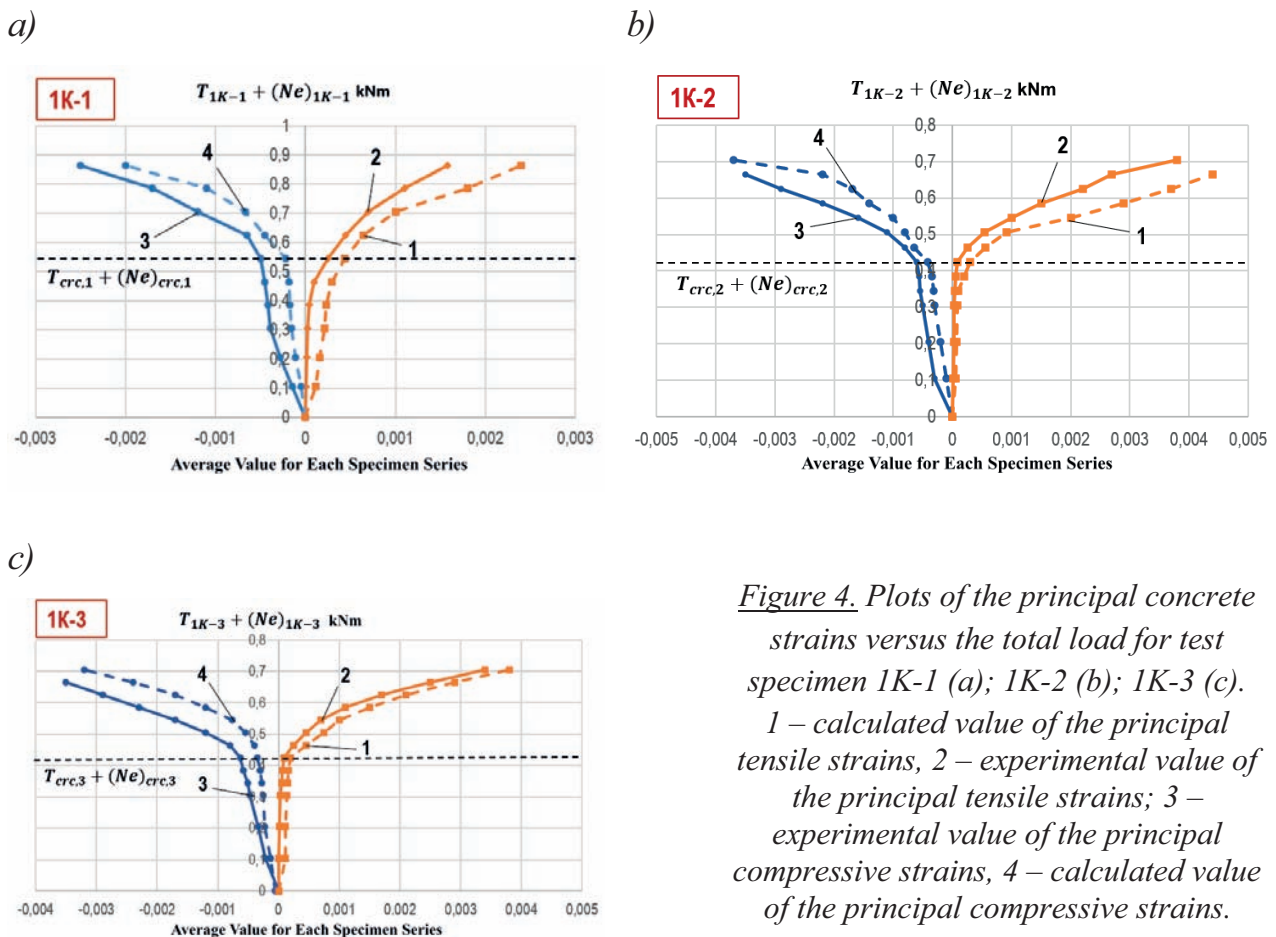


Figure 4. Plots of the principal concrete strains versus the total load for test specimen 1K-1 (a); 1K-2 (b); 1K-3 (c). 1 – calculated value of the principal tensile strains, 2 – experimental value of the principal tensile strains; 3 – experimental value of the principal compressive strains, 4 – calculated value of the principal compressive strains.

For lightweight expanded clay concrete, within the load range (up to 40-50% of the ultimate load), the relationship between stresses and strains, both compressive and tensile, can be

considered with sufficient accuracy as close to linear. An increase in load causes a non-linear growth of deformations in both compressed and tensile concrete.

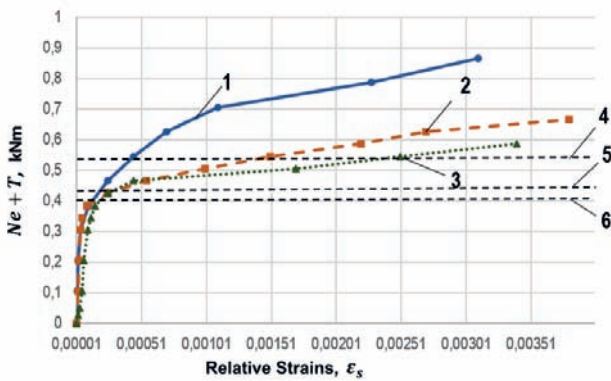


Figure 5. Plots of tensile reinforcement strain versus load: 1 – strain values for 1K-1, 2 – for 1K-2, 3 – for 1K-3, 4 – crack formation load $(Ne)_{crc} + T_{crc}$ for specimen 1K-1, 5 – same for specimen 1K-2, 6 – same for specimen 1K-3

Analyzing the experimental "load-deflection" and "load-angle of twist" graphs (Figures 6, 7), the following can be noted. The deformation range of the structures, from the moment a spatial crack forms until the failure of the test specimen, constitutes 15–20%. It is pertinent to note that for high-strength heavyweight concrete, the formation of the first crack also occurs at a relatively high load level, typically in the range of 70-90% of the failure load [23,24]. This indicates significant differences in the physical phenomena governing the resistance of such structures compared to structures made of conventional concrete.

The crack pattern (Figure 8a) obtained for specimen 1K-1 appeared at load stage VIII under a load of 0.544 kN·m. Subsequently, with a slight increase in load, a brittle failure of the test specimen occurred along the section of one of the initially formed spatial cracks and through the compressed concrete.

A similar process of crack formation was observed for the test specimens of series 1K-2 (Figure 8b) and 1K-3. Cracks appeared at load stage IX under a load of 0.429 kN·m and at load stage VII under a load of 0.413 kN·m, respectively.

A similar crack pattern was also obtained during the testing of structures made of high-strength heavyweight concrete [23, 24].

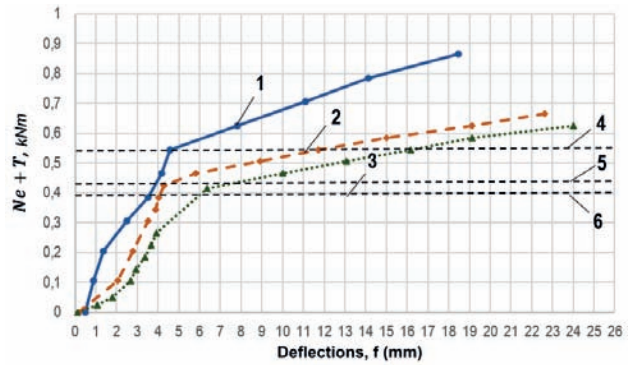


Figure 6. Load-deflection curves for the specimens: 1 – 1K-1, 2 – 1K-2, 3 – 1K-3; 4 – crack formation $(Ne)_{crc} + T_{crc}$ for specimen 1K-1, 5 – same for specimen 1K-2, 6 – same for specimen 1K-3

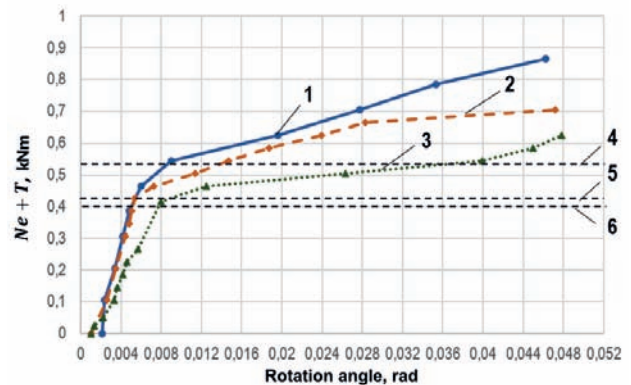
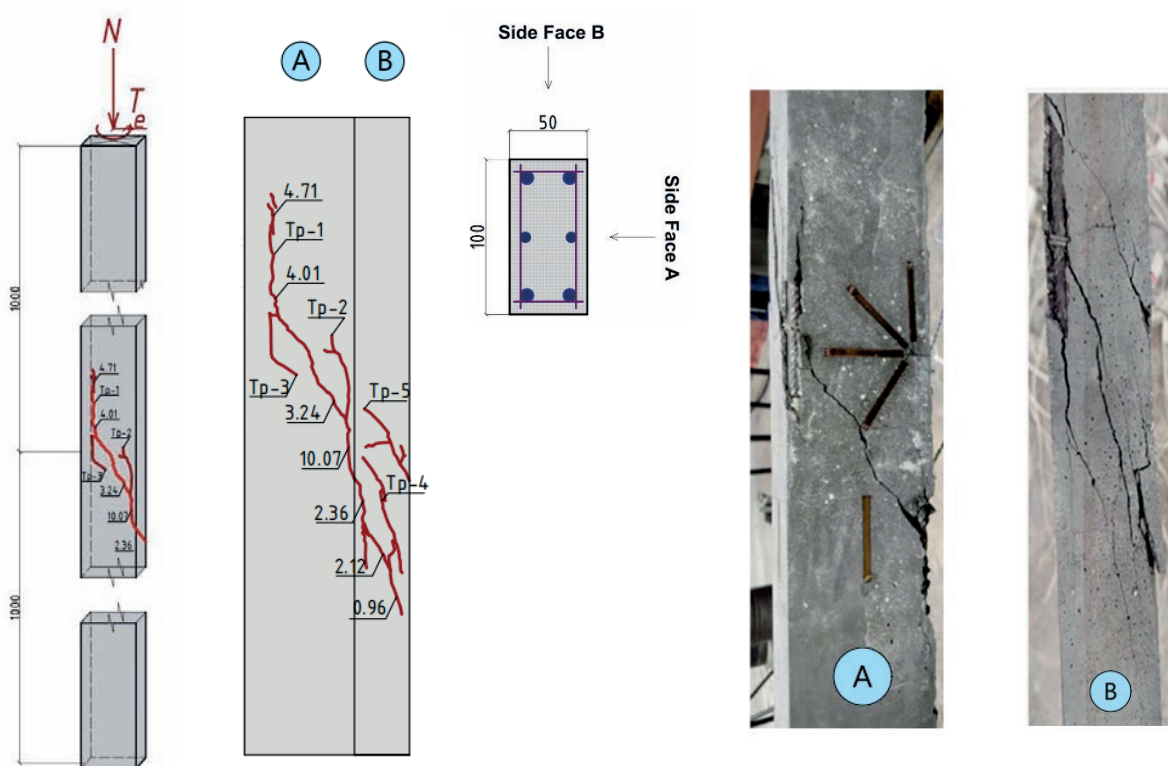


Figure 7. Load-rotation angle curves for the specimens: 1 – 1K-1, 2 – 1K-2, 3 – 1K-3; 4 – crack formation $(Ne)_{crc} + T_{crc}$ for specimen 1K-1, 5 – same for specimen 1K-2, 6 – same for specimen 1K-3

a)



b)

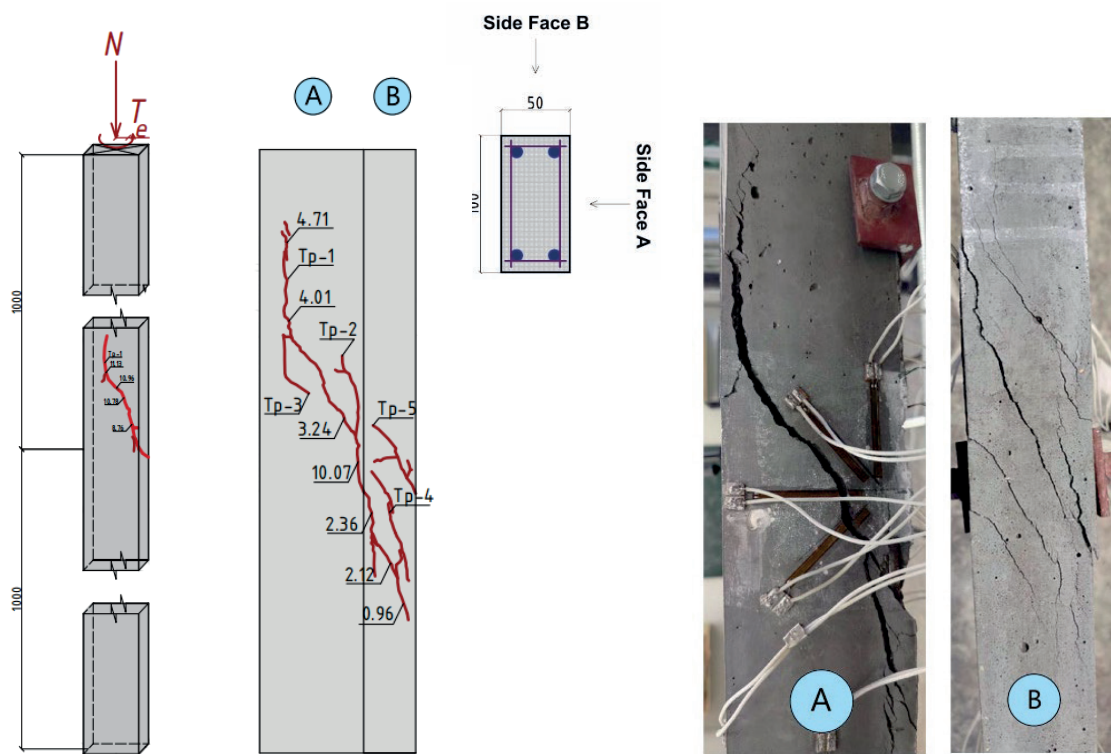


Figure 8. Experimental crack pattern for specimen 1K-1 (a) and specimen 1K-2 (b)

CONCLUSION

1. Experimental studies of three series of test column specimens made of high-strength lightweight concrete B40 under eccentric compression with torsion revealed the specific characteristics of their load-bearing resistance at all loading levels, including up to the point of ultimate capacity exhaustion.
2. It was established that under the considered complex stress state—eccentric compression with torsion—several spatial cracks form in the reinforced concrete structures made of high-strength lightweight concrete. The width of one of these cracks increases intensively as the load increases, and the ultimate load-bearing capacity is exhausted along a spatial section passing through this crack and the compressed concrete.
3. The obtained experimental data on the deformation of concrete and reinforcement, deflections, and rotation angles for the test specimens, both before and after crack formation, made it possible to identify the physical specifics of the load-bearing resistance of structures made from high-strength lightweight reinforced concrete. Crack formation in such structures occurs at a relatively high load level, constituting 80-85% of the failure load. After crack formation, the relative range of their deformation until failure constitutes 15-20% of the structure's load-bearing capacity. This indicates significant differences in the physical phenomena governing the resistance of such structures compared to structures made of conventional concrete.

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