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RESEARCH OF DEFORMATION AND STRENGTH CHARACTERISTICS OF CONCRETE COLUMNS WITH COMPOSITE REINFORCEMENT

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Abstract. The article presents the results of experimental studies on the load-bearing capacity of concrete specimens reinforced with a fiberglass shell under axial loading. Cylindrical concrete specimens were reinforced with strip fiberglass reinforcement (SFRP) using a developed winding technology and layer-by-layer bonding with a polymer binder.

The main focus is on studying the influence of lateral pressure, created by the fiberglass shell, on the strength and deformation characteristics of concrete. The experiments demonstrated that the use of a fiberglass shell significantly increases the failure load. For concrete of class C16/20, the failure load increased from 100 kN (without the shell) to 980 kN (with a 4 mm thick shell), which is 9.8 times higher. A similar increase in strength was observed for concretes of other classes (C25/30, C32/40, C50), with the failure load for C50 concrete increasing by a factor of 5.2.

It has been established that the intensity of strength gain depends on the concrete class; however, at high levels of lateral pressure (above 80 MPa), the strengthening coefficient (α) becomes nearly identical for all concrete classes (α ≈ 1.85). This indicates the similarity of concrete behavior in a fiberglass jacket to its behavior in steel jackets, with the added advantage of fiberglass's high corrosion resistance.

The deformation characteristics of the specimens were also studied. It was shown that the fiberglass jacket not only enhances strength but also improves the deformation properties of concrete, making it more resistant to longitudinal and transverse deformations.

The obtained results confirm that glass fiber-reinforced concrete can be considered a promising structural material for the construction of highly loaded structures. The developed technology for strengthening concrete with a fiberglass jacket opens new possibilities for creating lightweight, durable, and long-lasting structures with low metal consumption and high corrosion resistance.

Keywords: fiberglass jacket, concrete specimens, load-bearing capacity, lateral pressure, deformation characteristics, strengthening coefficient, corrosion resistance.

Introduction. The relevance of research on strengthening concrete structures with fiberglass jackets is driven by the need for modern, lightweight, strong, and durable materials capable of withstanding high loads and operating in extreme conditions. The advancement of technologies and the implementation of composite materials open new opportunities for creating innovative and reliable structures.

The behavior of fiberglass in concrete structures requires detailed study. Experimental data on the influence of fiberglass jackets on the load-bearing capacity and deformation characteristics of concrete will help develop recommendations for design and construction.

Analysis of Recent Research and Publications. The works of Müller H.S. and Haist M. [1-2] are dedicated to studying the behavior of concrete under triaxial compression using composite materials. The researchers confirmed that fiberglass jackets significantly enhance the strength of concrete, especially under high levels of lateral pressure.

Schmidt-Döhl F. and Rostásy F.S. [3] investigated the durability of concrete structures strengthened with composites in aggressive environments. Their results demonstrated that fiberglass provides high corrosion resistance, which is particularly important for bridges and coastal structures.

Teng J.G. and Chen J.F. [4] developed a methodology for calculating the strength of concrete columns confined with composite jackets, considering different types of loads.

Fukuyama H. and Matsuzaki Y. [5] designed new types of fiberglass jackets with improved mechanical properties, allowing an increase in concrete strength by 50-70%.

The studies conducted by Shui Liu and Xin Wang [6] describe the behavior of concrete columns with combined reinforcement.

The research by Ruitian Xu [7] and Duc Q. Tran, S.M.ASCE [8] demonstrates that the use of CFRP-PVC tubes and steel elements significantly improves the mechanical properties of columns, including their load-bearing capacity and deformation resistance. The advantages of such a design, including lightweight properties, corrosion resistance, and high strength, are also highlighted.

The studies by Chen Chen and Hai Fang [9] show that the use of spiral FRP mesh ties significantly enhances the mechanical properties of concrete columns, including their strength and ductility. The advantages of FRP materials, such as high strength, corrosion resistance, and lightweight properties, are discussed, making them an attractive option for construction applications.

The research conducted by Mostafa Habibpour [10] demonstrates that an increase in the number of FRP layers and their elongation degree significantly improves the mechanical properties of columns, including their strength and deformation resistance. The benefits of using FRP materials for reinforcing reinforced concrete columns, such as high strength, corrosion resistance, and lightweight properties, are also discussed.

The works [11, 12] indicate that hybrid reinforcement (steel-GFRP) combines the advantages of both steel and GFRP reinforcement, providing high strength, ductility, and corrosion resistance. Columns reinforced solely with GFRP exhibit high corrosion resistance but may have limited ductility. Traditional steel-reinforced columns demonstrate high strength and ductility but are susceptible to corrosion.

The conducted review and analysis of both domestic [14, 15] and foreign [1-13] scientific publications have shown that the crack formation process in solid bodies can be controlled. The physical laws governing crack propagation suggest that it is possible to slow down and even stop a rapidly growing crack. The process of crack deceleration should be associated with the energy consumption of fracture. It is known that at low crack propagation speeds, the energy required for plastic deformation at the crack tip is significantly high, while as the speed increases, this energy decreases in inverse proportion to the square of the speed. This makes it possible to control the crack development process. If the crack is slowed down, the forces required for its further propagation increase, and additional energy is needed to accelerate it to the level required for the relaxation of the elastic impulse. If plasticity reaches a certain threshold level, which depends on stress and crack length, fracture ceases.

Overall, the properties of concrete with indirect reinforcement in the form of spirals or solid steel jackets have been significantly studied. However, the mechanism of concrete failure under triaxial compression has not been fully explored. Therefore, the task of determining the load-bearing capacity of a concrete core reinforced with a spiral or a solid steel jacket remains relevant. Solving this problem should contribute to the development of new structural solutions, particularly fiberglass columns.

Purpose of the study. To study the effect of a fiberglass jacket on the load-bearing capacity and deformation characteristics of concrete specimens under axial loading, as well as to assess the effectiveness of using fiberglass strip reinforcement (FSR) for strengthening concrete structures.

The tasks of the research:

To conduct tests on concrete specimens reinforced with a fiberglass jacket to determine their load-bearing capacity under axial load.

To investigate the relationship between the ultimate load and the intensity of lateral pressure created by the fiberglass jacket.

To compare the strength of concrete specimens of different strength classes (C16/20, C25/30, C32/40, C50) with and without a fiberglass jacket.

To analyze longitudinal and transverse deformations of the specimens depending on the magnitude of axial stress and lateral pressure.

To determine the dependence of the reinforcement coefficient (α) on the concrete class and the jacket thickness.

Materials and Research Methods. A column design was proposed, consisting of a concrete core and a pre-stressed fiberglass jacket. This column design is characterized by its relatively low weight, low metal consumption, and high corrosion resistance.

The column is a concrete cylinder, around which fiberglass strip reinforcement (FSR) is wound using the spiral-cross winding method at a specific angle. The winding process follows the previously described technology, ensuring optimal structural performance.

To determine the load-bearing capacity of concrete specimens encased in a fiberglass jacket under axial compressive loading, experimental studies were conducted. The reinforcement of concrete cylinder specimens was carried out by wrapping them with fiberglass strip reinforcement (FSR) on specially designed winding machines, with each layer bonded using a polymer adhesive (ED-20 resin).

A total of 10 test series were conducted, in which the concrete class (ranging from C16/20 to C50) and the thickness of the fiberglass jacket (reinforcement percentage) were varied $\mu = A_{sp}^{CT} / A \cdot 100\%)$ δ_{CT} = 1,0; 2,0; 3,0; 4,0 mm, diameters of concrete cores D=80; 120 mm, length of samples l=130; 400; 1200 mm.

Application of Axial Compressive Load and Experimental Procedure. The axial compressive load was applied stepwise using a hydraulic press P-125. Most specimens were tested until failure. Longitudinal and transverse deformations were measured using dial indicators and resistance strain gauges. The failure of short elements encased in a fiberglass jacket was primarily caused by the rupture of the fiberglass in the circumferential direction.

Experiments aimed at determining the effect of the fiberglass jacket thickness on the failure load of concrete cylinders were conducted using specimens with a diameter of 60 mm and heights of 400 mm and 130 mm. These specimens were wrapped with fiberglass strip reinforcement with a tensile strength of 800 MPa. A total of 60 specimens were manufactured using four different concrete classes: C16/20, C25/30, C32/40, and C50.

The specimens were cast in vertical metal formwork, and the concrete mix was prepared using cement grade 500. To facilitate fixation in the winding machine, a 2 cm diameter central channel was incorporated into the specimens. After winding the fiberglass reinforcement, these internal channels were filled with mortar of the same composition.

The loading process was conducted in 50 N increments, and at each loading stage, boundary and transverse deformations of the specimen were measured.

The stress-strain state of the concrete core confined in a continuous fiberglass jacket formed by winding fiberglass strip reinforcement is illustrated in Figure 1.

The stress-strain state of the concrete core will be fully determined if the contact pressure (p_k) is found. The value of p_k is determined based on the compatibility condition between the deformation of the jacket and the concrete core. The jacket layer is assumed to be unidirectional.

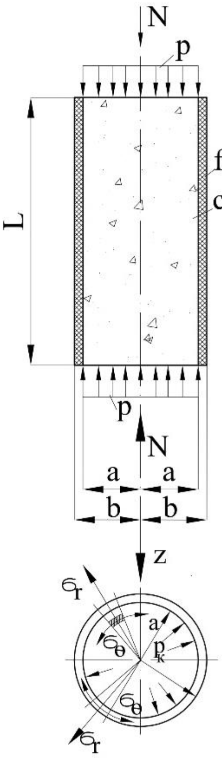

Fig. 1. Stress-Strain State of the Concrete Core Confined in a Continuous Fiberglass Jacket

Figure 2 illustrates the stress-strain state in the jacket layer, where axis 1 coincides with the fiber direction. The orientation angle of the reinforcement tape winding is shown in the rotated axes, and the reinforced layer exhibits anisotropic properties.

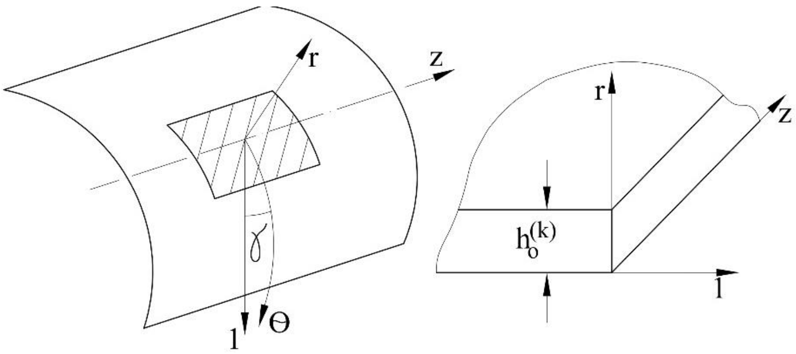

Fig. 2. Stress-Strain State in the Jacket Layer

Research Results. Tests conducted on 400 mm-high specimens showed that when the diameter-to-height ratio was 1:5, it was not possible to determine the full load-bearing capacity of the concrete confined in the fiberglass jacket. The specimens failed due to longitudinal bending. The heterogeneity of the concrete in the specimens likely caused eccentric loading effects as they approached failure load. Consequently, in subsequent tests, the specimen height was reduced to 130 mm.

The graphs in Figure 3 illustrate the dependence of failure load on lateral pressure intensity (fiberglass jacket thickness). The graphs indicate that lateral pressure created in the concrete core by the fiberglass jacket significantly increases the failure load for all tested specimens.

For C16/20 concrete specimens without fiberglass jackets, the failure load under axial compression was F = 100 kN. However, for similar concrete specimens with a 4 mm-thick fiberglass jacket (lateral pressure p = 80 MPa), the failure load increased to 980 kN, meaning a 9.8-fold strength increase.

A similar strength enhancement was observed for concrete specimens of other classes. For example, for C50 concrete specimens, within a lateral pressure range of p = 0 to 80 MPa, the failure load increased by a factor of 5.2.

These test results highlight an important conclusion: Encasing the concrete core in a fiberglass jacket reinforced with fiberglass tape significantly enhances the axial compressive strength of the specimens.

The rate of strength increase depends on the concrete class. In this regard, concrete specimens confined in a fiberglass jacket share similarities with steel-reinforced concrete specimens.

In addition to high mechanical strength, the fiberglass jacket exhibits excellent corrosion resistance, making it superior to steel jackets in terms of durability.

During the testing of all specimens, longitudinal and transverse deformations were measured. These measurements served two main objectives:

To study the effect of lateral pressure intensity on the deformation of the specimens.

To analyze the mechanical properties of concrete under confinement.

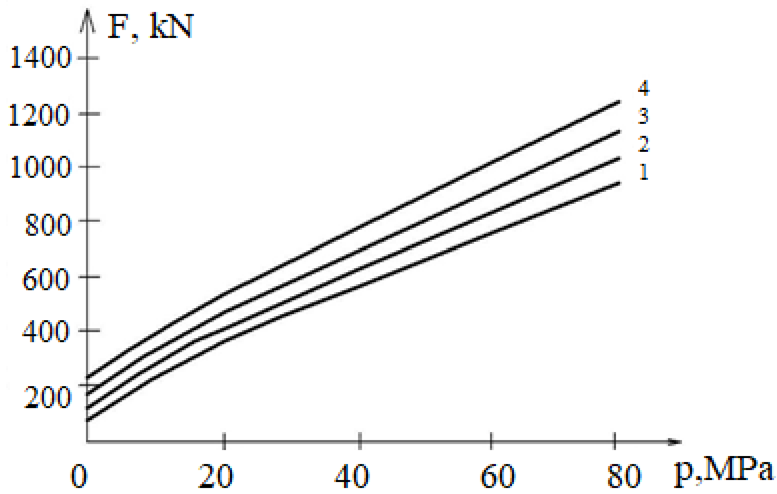

Fig. 3. Dependence of the ultimate load p on the intensity of lateral pressure at the ultimate state: 1 – Concrete class C16/20; 2 – C20/25; 3 – C32/40; 4 – C50

The dependence of longitudinal ε_z and transverse ε_r deformations of centrally compressed concrete cylindrical elements on the magnitude of axial compressive stress was studied using specimens with a diameter of 8 cm, made from concrete classes C16/20, C25/30, C32/40, and C50. Fig. 4 presents the typical deformation graphs obtained from tests on C16/20 concrete specimens.

The efficiency of a steel jacket is commonly evaluated using a coefficient, which, according to different authors, varies. Some researchers suggest that this coefficient is not a constant value, with its range fluctuating between 1 and 5.

The coefficient for fiberglass-reinforced concrete specimens was determined using the following formula:

$$\alpha = \frac{F_p - F_0}{A_T \cdot \sigma_0},$$

where:

F_p – ultimate load of the specimen with the jacket;

$F_0 = A_0 \cdot f_{ck}$ – ultimate load of the concrete core (without the jacket);

$F_p - F_0$ – force carried by the specimen in the ultimate state due to the effect of the jacket;

A_T – cross-sectional area of the jacket;

f_{ck} – strength of the reference concrete without the jacket;

σ_0 – ultimate tensile strength of the jacket material.

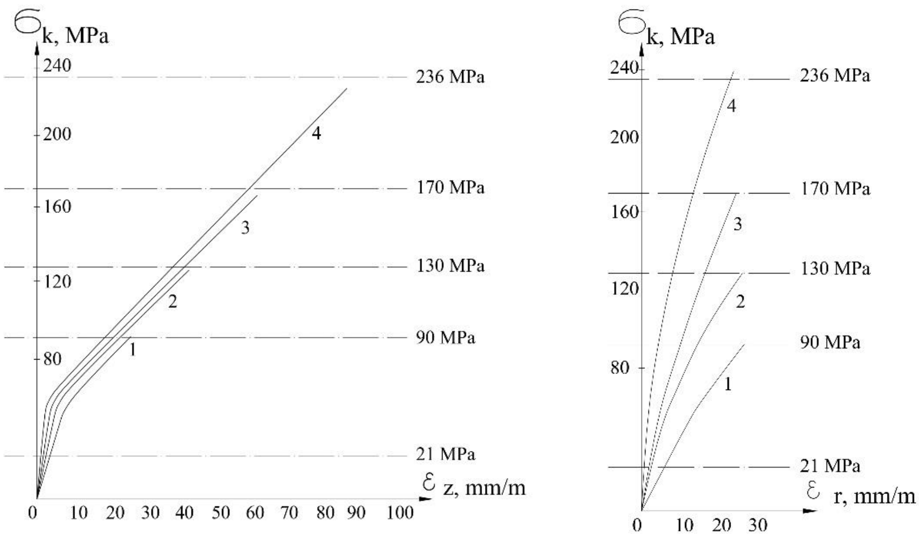

Fig. 4. Graphs of longitudinal ε_z and transverse ε_r deformations of centrally compressed concrete cylindrical elements with a fiberglass jacket:
1 – 5 layers of LSPA; 2 – 10 layers; 3 – 15 layers; 4 – 20 layers

Based on the research results, it was established that the coefficient α depends on two main factors:

The lateral pressure *p*, exerted on the concrete by the fiberglass jacket. The class of concrete.

The strength of the jacket is determined by the magnitude of lateral pressure ppp exerted by the jacket in the ultimate state, which was calculated using the formula:

$$p = \sigma_0 \frac{\delta}{r},$$

where:

$\sigma_0 -$ ultimate tensile strength of the fiberglass reinforcement;

$r -$ radius of the specimen cross-section;

$\delta -$ wall thickness of the fictitious tube.

The dependence of the coefficient α on lateral pressure was determined based on test results of specimens with a diameter of 8 cm. The magnitude of the lateral pressure exerted by the jacket was varied by adjusting the number of layers of fiberglass tape. The coefficient α was determined for specimens made of four concrete classes: C16/20, C25/30, C32/40, and C50.

The dependence of coefficient α on lateral pressure p is shown in Fig. 5.

The dependence of coefficient α on the concrete class is observed only in jackets of low strength, where α ranges from 1.8 to 2.7 (Figure 5). As the jacket strength increases, this dependence almost disappears, and the coefficient α stabilizes at approximately 1.85 for all tested specimens.

The theoretical dependence of the strength enhancement coefficient (α) on the level of lateral pressure, which aligns with experimental results and allows for the prediction of the behavior of concrete confined in a fiberglass jacket under various load types, is calculated using the following formula:

$$\alpha = 8{,}91 p^{-0.358} - \frac{F_0}{A_T \cdot \sigma_T}.$$

From the graph (Figure 5), it is evident that at high levels of triaxial compression, different materials tend to exhibit a similar failure pattern, whereas at low compression levels, their failure characteristics can vary significantly.

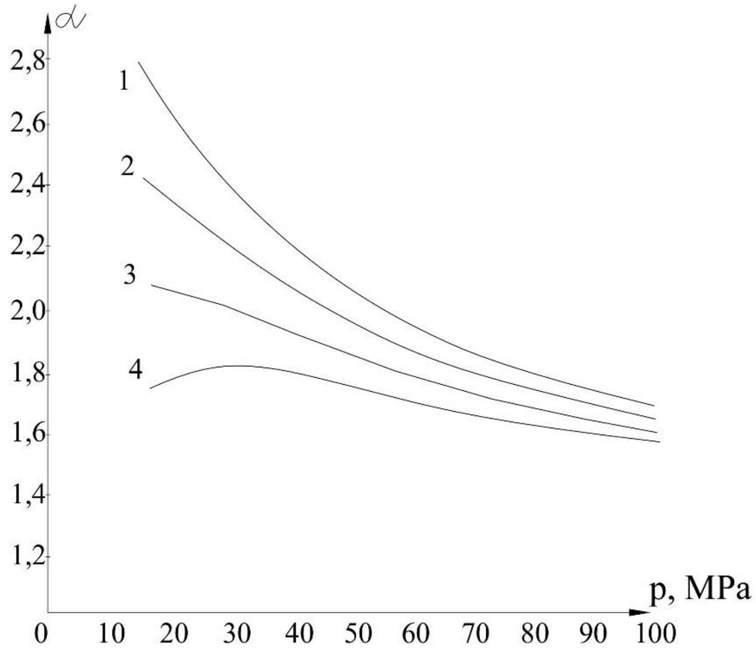

Fig. 5. Dependence of the effectiveness coefficient (α) of the fiberglass jacket on lateral pressure (p): 1 – Concrete class C16/20; 2 – C20/25; 3 – C32/40; 4 – C50

Conclusions:

1. It has been established that the use of a fiberglass jacket significantly increases the load-bearing capacity of concrete specimens. For example, for C16/20 concrete, the failure load increased from 100 kN to 980 kN (by a factor of 9.8) when a 4 mm-thick jacket was applied.

2. The rate of strength increase depends on the concrete class. At low levels of lateral pressure, the strength enhancement coefficient (α) varies from 1.8 to 2.7, depending on the concrete class. However, at high pressure levels (above 80 MPa), this coefficient becomes nearly identical for all concrete classes (α ≈ 1.85).

3. Deformation studies have shown that the fiberglass jacket not only enhances strength but also improves the deformation properties of concrete specimens, making them more resistant to both longitudinal and transverse deformations.

4. The fiberglass jacket demonstrates high mechanical strength and corrosion resistance, making it more advantageous compared to traditional steel jackets.

5. A theoretical relationship between the strength enhancement coefficient (α) and lateral pressure has been derived, confirming the experimental data and allowing for predicting the behavior of concrete confined in a fiberglass jacket under various loads.

6. The research results confirm that fiberglass-reinforced concrete (GFRP-confined concrete) can be considered a promising structural material for highly loaded structures, due to its high strength, low weight, and corrosion resistance.

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ДОСЛІДЖЕННЯ ДЕФОРМАЦІЙНИХ І МІЦНІСНИХ ХАРАКТЕРИСТИК БЕТОННИХ КОЛОН ПРИ КОМПОЗИТНОМУ ПОСИЛЕННІ

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Анотація. У статті представлені результати експериментальних досліджень несучої здатності бетонних зразків, посилених склопластиковою обоймою, при дії осьового навантаження. Бетонні зразки-циліндри були армовані стрічковою склопластиковою арматурою (ЛСПА) з використанням розробленої технології намотування та пошарового обклеювання полімерним сполучним.

Основну увагу приділено вивченню впливу бокового тиску, що створюється склопластиковою обоймою, на міцність та деформаційні характеристики бетону. Експерименти показали, що застосування склопластикової обойми значно підвищує руйнівне навантаження. Для бетону класу С16/20 руйнівне навантаження збільшилося зі 100 кН (без обойми) до 980 кН (з обоймою товщиною 4 мм), що у 9,8 рази вище. Аналогічне зростання міцності спостерігалося для бетонів інших класів (С25/30, С32/40, С50), при цьому для бетону класу С50 руйнівне навантаження зросло в 5,2 рази.

Встановлено, що інтенсивність наростання міцності залежить від класу бетону, проте при високих рівнях бічного тиску (понад 80 МПа) коефіцієнт посилення (α) стає практично однаковим для всіх класів бетону ($\alpha \approx 1{,}85$). Це свідчить про схожість поведінки бетону в склопластиковій обоймі з його поведінкою в сталевих обоймах, але з перевагою у вигляді високої стійкості корозійної склопластику.

Також досліджено деформаційні характеристики зразків. Показано, що склопластикова обойма не тільки підвищує міцність, але й покращує деформаційні властивості бетону, роблячи його більш стійким до поздовжніх та поперечних деформацій.

Отримані результати підтверджують, що склопластбетон може розглядатися як перспективний матеріал для будівництва високонавантажених споруд. Розроблена технологія посилення бетону склопластиковою обоймою відкриває нові можливості для створення легких, міцних та довговічних конструкцій з низькою металоємністю та високою корозійною стійкістю.

Ключові слова: склопластикова обойма, бетонні зразки, несуча здатність, бічне тиск, деформаційні характеристики, коефіцієнт посилення, корозійна стійкість.

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