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RESTORATION THE FUNCTIONING OF ENGINEERING NETWORKS WITH REINFORCED CONCRETE STRUCTURES DAMAGED DURING SHELLING

ВІДНОВЛЕННЯ ФУНКЦІОНУВАННЯ ІНЖЕНЕРНИХ МЕРЕЖ З ПОШКОДЖЕНИМИ ПІД ЧАС ОБСТРІЛІВ ЗАЛІЗОБЕТОННИМИ КОНСТРУКЦІЯМИ

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An important component of critical infrastructure is the facilities of engineering networks, which in the current conditions of war in Ukraine are exposed to shelling from various types and calibers of conventional weapons. These include pumping stations, boiler houses, and other reinforced concrete structures of water supply, sewerage and heat supply systems. Rapid and efficient restoration of these facilities is crucial for maintaining the functioning of engineering networks. Given the limited time and resources for new construction during wartime, priority is given to reconstruction and repair based on the results of technical inspections of damage. Restoration efforts first focus on the load-bearing reinforced concrete elements, such as columns and beams, with one of the urgent measures being their strengthening. Based on an analysis of methods and technologies for reinforcing reinforced concrete structures, the use of wet shotcreting with high-strength concrete is proposed. Shotcreting continues to evolve, including its application in 3D printing of reinforced concrete structures, and offers advantages such as the absence of formwork (which accelerates concreting), the availability of concrete, and the excellent protective properties of reinforced concrete under shelling, including

high strength, rigidity, and resistance to high temperatures, fragment impacts and air shock waves. Using the example of strengthening load-bearing reinforced concrete columns, improvements to wet shotcreting technology through preliminary mechanoactivation of the binder (ordinary Portland cement + 10% microsilica + 1% SNF = 1%) have been introduced, allowing for the creation of high-strength protection (class C32/40...C70/85). This creates additional opportunities for mechanization, automation of wet shotcreting of reinforced concrete structures of engineering networks.

Військові дії супроводжуються обстрілами об'єктів інженерних мереж. Для відновлення їх функціонування пропонується посилення несучих залізобетонних конструкцій, на прикладі колон, технологією мокрого торкретування бетону класу С 32/40 ... С 70/85 розробленого складу з механоактивацією портландцементу, 10 % мікрокремнезему, 1 % СП-1.

Keywords: reconstruction, repairs, strengthening, reinforcement, high-strength concrete, technology, shotcrete, engineering networks, methodology.
реконструкція, ремонт, посилення, армування, високоміцний бетон, технологія, торкретування, інженерні мережі, методологія.

Introduction. A characteristic feature of the war in Ukraine is the damage and destruction of critical infrastructure facilities, including the buildings and structures of engineering networks. The importance of rapidly and reliably restoring the operation of these networks is linked to their economic and social significance for the country. In the extreme conditions of modern warfare in Ukraine, there is often no time for new construction to replace the buildings and structures of engineering networks damaged by shelling. Moreover, relocating facilities such as large boiler houses or pumping stations for water supply, sewerage and heating systems would require significant volumes of underground works to lay new pipeline sections. In most cases, especially in densely built urban areas, such work is technically difficult to carry out. Therefore, the most common measures currently used to restore the functionality of these engineering networks include reconstruction, restoration, and repair of buildings and structures damaged by shelling. A significant portion of the building structures of these facilities are made of concrete and monolithic reinforced concrete [1-4 et al.]. Consequently, it is crucial to explore and expand technical and technological solutions for strengthening such structures. Thus, technologies for reinforcing concrete and reinforced concrete load-bearing structures of buildings and engineering network facilities particularly reinforced concrete columns play an important role, as they make it possible to quickly restore the standard technical condition [5-7 et al.] and resume the operation of these facilities within the engineering networks.

Thus, concrete and reinforced concrete structures of engineering network facilities, which belong to critical infrastructure and have been damaged during shelling, require reliable, efficient, and rapid restoration measures to maintain the functionality of engineering networks under wartime conditions [7-11 et al.]. Among the relevant restoration methods is the use of time-tested shotcreting technologies, particularly the wet shotcreting method [12-17 et al.], employing concretes with enhanced performance characteristics.

Analysis of recent research. Numerous studies have been devoted to examining the technical and technological aspects and the reasons for applying methods to strengthen reinforced concrete structures, as well as the specific features of these methods, for example [1, 18-20 et al.]. These studies analyze the principles, designs, and materials used to create a strengthening shell around the reinforced element (such as a column or beam). Software tools have been developed for analyzing and modeling reinforced structures [21 et al.]. A noticeable trend is the reduction of shell mass through the use of new composite materials [1, 18-20, 22, 23]. However, such reinforced structures do not always meet the requirements for stiffness, resistance to high temperatures, impacts from solid objects (such as fragments from weapons or structural debris), or air shock waves characteristic of shelling [7-10]. In this regard, the use of concrete mixtures for reinforcement (jackets) that provide satisfactory performance in these aspects is relevant, though methods for reducing their weight and thickness should be studied, for example, by partially replacing Portland cement with other materials (such as microsilica) in the preparation of the concrete mixture [1, 18-20 et al.]. Analysis of many studies has shown that one of the advantages of strengthening existing structures with concrete or reinforced concrete is the minimization of changes in the design scheme and stress state of the reinforced element. The strengthening effect is achieved through the reliable bond and cooperative performance between the existing structure and the strengthening material, which depends on the correct application of technological methods, as discussed in detail in [1, 17, 23, 24].

Traditional shotcrete technologies with reinforcement are well-studied and, due to their advantages, have been successfully used for decades in repair and restoration works during the reconstruction and maintenance of buildings and structures. The scope of application of these technologies is quite broad - from strengthening structures damaged by earthquakes to the reconstruction of architecturally significant historical buildings, as well as in new shotcrete technologies used for 3D printing of reinforced concrete structures [12-16 et al.]. A drawback of strengthening load-bearing structures with reinforced concrete (for example, columns) is the considerable weight and increased dimensions of the jackets made from such materials, which create additional loads on the foundations and increase the overall size of the reinforced structures. However, the high stiffness and strength of load-bearing elements reinforced in this way can be considered an important advantage in terms of resistance to shelling.

Under the influence of modern trends in green construction, shotcrete technologies and the materials used are constantly being improved. The use of modified mixtures allows for relatively quick and efficient strengthening of load-bearing structures in buildings and facilities. In particular, an important aspect in the development of shotcrete technology is the design of the concrete mix composition and the method of its preparation. In this context, concretes containing various additives and reinforcement elements have become widespread, aimed at improving the technical and technological characteristics of concrete structures, as well as reducing the cement content, the production of which is considered energy-intensive and harmful to the environment [14, 25-29]. Additionally, the preparation of concrete is often carried out with the activation of certain processes, one of the most common being the method of mechanical activation during concrete mix preparation [26-28 et al.].

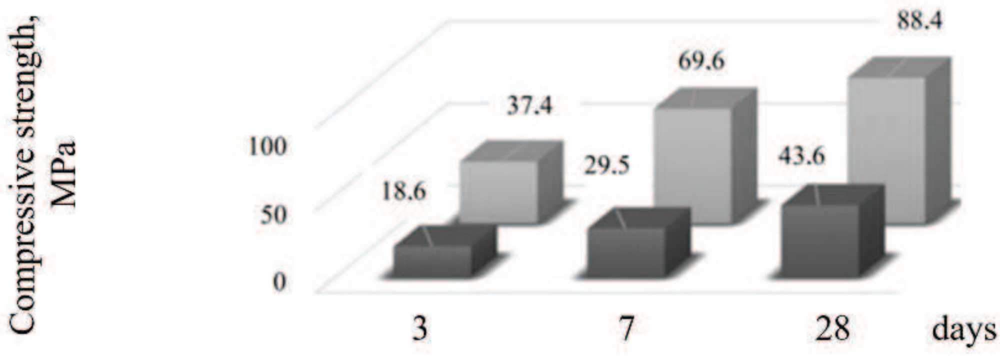
Setting the goal and objectives of research. The purpose of the research is to improve the technology for restoring load-bearing reinforced concrete structures damaged during shelling, using the example of columns in buildings and structures of engineering networks, aimed at restoring the reliability of urban water supply, sewage, and heating systems. The objectives of the research are to select the composition of a high-strength concrete based on ordinary Portland cement with the addition of microsilica (as a partial replacement) and a superplasticizer (SNF), as well as to determine the method of preparing this concrete using mechanical activation of the binder, and to improve the shotcrete technology for reinforcing reinforced concrete columns using the developed concrete mix for the installation of a reinforced concrete jacket.

Research methodology. To achieve the strength indicators (compressive strength was assessed according to [30]) required for restoring the functionality of reinforced concrete structures of utility facilities damaged during shelling, it is planned to analyze the technology of shotcreting them with high-strength concrete. For the production of such concrete, the research methodology provides for analyzing the compositions of mechanically activated concrete mixtures using: Portland cement (values of 300, 400, 500 m^2/kg specific surface are achieved by grinding clinker with gypsum); active additive – from 0 to 10 %, for which microsilica from the Nikopol Ferroalloy Plant is used; concrete mixture plasticizer in a fixed amount of 1 % of the binder mass (this value is accepted recalculated to dry matter) SNF; and filler – quartz sand (M = 2); fine-grained granite crushed stone (up to 5 mm) [29, 31].

The technology for preparing the specified concrete mixture is carried out through sequential operations by introducing water, SNF, Portland cement, and microsilica into a specially designed mechanical activator [28, 29]. The processing time in the activator is 120 seconds. After that, the components are mixed in a concrete mixer, controlling the addition of quartz sand and granite crushed stone, and then fed into a shotcrete machine for application onto the damaged element.

Research results. An analysis of the strength characteristics of high-strength concrete at the ages of 3, 7, and 28 days [29] (Fig. 1), produced according to the adopted research methodology, was carried out. The evaluation of the experimental results was performed using three variable indicators (in the table in Fig. 1: MS –

microsilica content in Portland cement by mass; binder consumption in the concrete; S_s – specific surface area of Portland cement) and one indicator with a constant value (SNF – amount of superplasticizer).



Concrete mix compositions:

Title	The value of indicators			
	variable			constant
Indicator designation	MS	BC	S_s	SNF
Unit of measurement	%	kg/m^3	m^2/kg	%
Color of histograms:				
	0	350	300	1
	10	550	500	1

Fig. 1. Strength of concrete samples according to the composition of the concrete mixture

The analysis of the results of the binder modification study [28, 29], Table 1, made it possible to establish the main directions for producing a concrete mixture with specified strength characteristics suitable for the shotcreting technology of reinforced concrete structures of engineering networks damaged during shelling.

In this case, the concrete achieves a strength of 37.4 MPa within the first 3 days when 10 % (by mass) of microsilica is added to the Portland cement (MS indicator in Fig. 1 and Fig. 2) along with 1 % superplasticizer (SNF indicator in Fig. 1 and Fig.2). This mixture composition allows the concrete to be recommended for repair purposes, given that the strength increases relatively quickly - 1.86 times by day 7 and 2.36 times by day 28, reaching 88.4 MPa.

Moreover, the preliminary mechanical activation of the binder enables the strength of concrete specimens to increase up to 120 MPa when the specified factors are applied (Table 1). The high particle dispersion achieved through mechanical activation, combined with the presence of microsilica, ensures excellent adhesion of the new repair layer to the existing surface of the reinforced concrete structure.

A concrete mixture with such strength gain characteristics during curing can be used to reinforce reinforced concrete structures of engineering networks damaged during shelling. For example, consider the shotcreting technology for a load-bearing column (Fig. 3).

The strength of the reinforcement under increased design loads for columns strengthened with monolithic high-strength concrete jackets is verified according to the condition:

$$N = N_1 + N_2 \leq \varphi\left[f_{cd1} \cdot b_1 \cdot h_1 + f_{sc1} \cdot A'_{s1} + \gamma_h \ f_{cd2} \cdot A_{c2} + f_{sc2} \cdot A'_{s2}\right], \quad (1)$$

where: φ – coefficient of longitudinal buckling; A_{b2} – cross-sectional area of the concrete jacket; γ_h – working condition factor of the clamp, taken as 0.8; b – he smallest dimension of the rectangular cross-section.

Table 1.

Strength indicators of concrete
($f^{a}_{ck.cube}$ - compressive strength of concrete on mechanically activated binder; $f^{\kappa}_{ck.cube}$ - compressive strength of concrete, the binder of which was not subject to mechanical activation)

№	Research parameters (factors)			Compressive strength indicators, MPa			
	MS, %	Binder consumption, kg/m^3	Specific surface area S_s, m^2/kg	$f^{\kappa}_{ck.cube}$ MPa [29]	$f^{a}_{ck.cube}$, MPa	$f^{\kappa}_{ck.cube}$ MPa [28, 29]	$f^{a}_{ck.cube}$, MPa [28]
				3 days		28 days	
1	0	350	300	18.6	25.1	43.6	59.7
2	10	350	300	23.8	32.2	52.3	73.2
3	0	550	300	26.9	34.9	53.9	75.5
4	10	550	300	29.5	39.8	69.5	97.3
5	0	350	500	24.8	33.5	52.7	68.5
6	10	350	500	27.6	38.6	64.3	90.0
7	0	550	500	29.14	37.9	72.8	98.3
8	10	550	500	37.4	52.4	88.4	123.8

When reinforcement is within 1%, the following are allowed:

$$A'_{s2} = 0.01A_{c2}, \quad (2)$$

$$A_{b2} = \frac{N/\varphi - f_{cd1} \cdot b_1 \cdot h_1 - f_{sc1} \cdot A'_{s1}}{\gamma_h \ f_{cd2} + 0.01 f_{sc2}}. \quad (3)$$

Design width of the jacket:

$$d = 0.25\left[\sqrt{b_1 + h_1^{\ 2} - 4A_{c2}} - b_1 + h_1\right]. \quad (4)$$

It is taken into account here that the determination of the cross-sectional area of the additional longitudinal reinforcement, A_{s2}, according to formula (1) is influenced by the values of φ, as well as A_{b2} according to formula (2).

The strength characteristics of the concrete in the damaged column are calculated based on the results of technical inspections of the columns (defects and damages) and the determination of load-bearing capacity [4, 5, 32, 33].

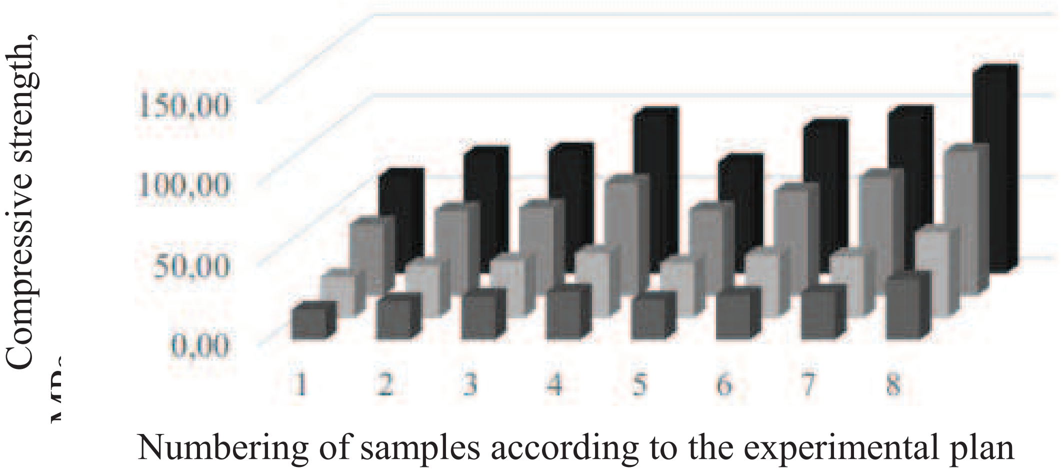


Fig. 2. The effect of mechanical activation and MS content on the strength of concrete samples (at SNF = 1 %): - without mechanoactivation $f^{к}_{ck.cube}$ (3-days); - mechanoactivation $f^{a}_{ck.cube}$ (3-days); - without mechanoactivation $f^{к}_{ck.cube}$ (28-days); - mechanoactivation $f^{a}_{ck.cube}$(28-days)

The diameter of the longitudinal reinforcement is assumed to be no less than 16 mm for compressed zones and 12 mm for tension zones, while the transverse reinforcement (with a spacing not exceeding 15 times the diameter of the longitudinal reinforcement) should be no less than 6 mm. Strengthening works are carried out based on the results of careful planning [12, 13].

The technology for reinforcing reinforced concrete columns with the installation of a concrete jacket includes the following sequence of operations (Fig. 3): cleaning the column surface, drilling holes for reinforcement elements, covering and cleaning exposed reinforcement; installing the working reinforcement and mesh; shotcreting the column surface with a high-strength concrete mixture (Fig. 3, a).

The preparation of the column surface for reinforcement includes the following operations: removal of the plaster layer (if present); chiseling recesses 3-6 mm deep into the column concrete; cleaning the exposed reinforcement to a bare metal surface, removing corrosion, oil, and other contaminants. Welding of longitudinal reinforcement bars to the existing column reinforcement is performed according to the scheme shown in Fig. 3, b, using short bars. Grinding of the welded joints of the working bars must ensure smooth transitions between surfaces, eliminating visible weld seams. A reinforcement mesh is then installed over the mounted bars, and the column is shotcreted with high-strength concrete using the mechanically activated concrete mixture proposed in this study. Two hours before the start of shotcreting, the surface is treated with compressed air and a water jet. The shotcreting process is carried out using a shotcrete machine, which feeds the concrete mixture under pressure. The concrete is sprayed onto the surface through the nozzle of the machine from a distance of 1-1.2 meters and at an angle of 15°. To improve adhesion, the shotcrete surface is primed with a polymer solution before applying the concrete.

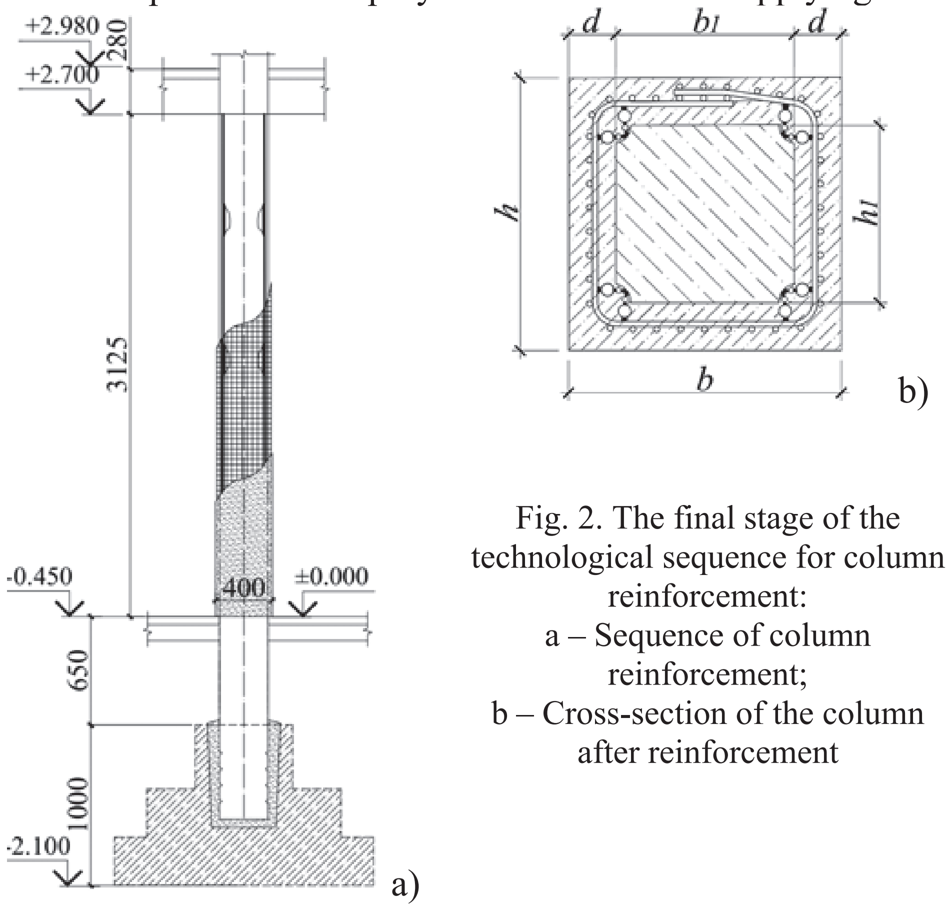


Fig. 2. The final stage of the technological sequence for column reinforcement:
a – Sequence of column reinforcement;
b – Cross-section of the column after reinforcement

Thus, it is possible to achieve full mechanization of the shotcreting technology operations and utilize automation capabilities for all processes - from developing the concrete mixture to designing and executing the construction works.

Conclusions and recommendations. To restore the reliability of urban water supply, sewerage and heating network facilities whose load-bearing reinforced concrete structures have been damaged during shelling, the use of shotcreting with a high-strength concrete mixture with enhanced properties is proposed.

As an example, a reinforced concrete column is considered, for which the possibility of strengthening by reinforcement and concreting by the wet shotcrete method is provided, carried out via full mechanization of the operations for preparing, applying, and compacting the concrete mixture. For column shotcreting, a developed concrete mixture (class C32/40 … C70/85) is proposed, produced through mechanical activation of a mixture based on ordinary Portland cement with 10% microsilica (by mass) and 1% SNF additive. Due to the higher reactivity of the components, this concrete exhibits strength gain both at early and design ages, while reduced porosity and increased microstructural density significantly improve frost resistance, impermeability, durability in aggressive environments, and resistance to repeated shelling. Thus, using such a modified mixture in shotcreting allows not only the restoration but also comprehensive strengthening of the structure, providing it with increased strength and long-term durability.

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