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HIGH STRENGTH STEEL FIBER REINFORCED CONCRETE FOR FORTIFICATION PROTECTED STRUCTURES

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The article presents the results of research on modified steel fiber-reinforced concrete and shows the expediency of their use to increase the effectiveness of fortification protection structures against shock loads. It was established that according to the results of tests of compressive strength (f_{cm} = 79.4 MPa) and tensile strength during bending ($f_{c,\,tf}$ = 7.4 MPa), steel fiber-reinforced concrete can be classified as high-strength (strength class C 50/60) and rapid-hardening ($f_{cm2}/\ f_{cm28}$ = 0.57) in accordance with DSTU EN 206:2018. Manufacturing in factory conditions of reinforced concrete elements of structures based on high-strength steel fiber-reinforced concrete with increased resistance to various types of force effects during shelling will allow to obtain quick-assembling/quick-dismantling fortification structures that will be able to provide protection for the personnel of the units of the armed forces of Ukraine.

Key words: quick assembly/quick disassembly fortification structure, high-strength steel fiber-reinforced concrete, modifiers, steel fiber, strength, shock loads.

Introduction

Currently, in the context of martial law, research on improving the complex of fortifications that meet the tactical requirements of rapidly moving and maneuverable military action is gaining importance. At the same time, great importance is attached to the quality of the construction material, as well as to such requirements as compactness during storage and the possibility of transportation by off-road trucks. Elements manufactured by industrial methods are widely used in the construction of such structures, in particular, the coverings and walls are assembled by stacking reinforced concrete elements close together, which are interconnected by metal bolts (Danica, 2018; Kisil, 2016; Hryhorovskyi, 2022).

It is characteristic that reinforced concrete structures of fortification protective structures can be subjected to significant dynamic impacts. A characteristic feature of the impact is the development of significant forces on the surfaces of contact of bodies in a very short period of time. High loading rates can significantly affect the behavior of materials that are impacted and destroyed in this way. Therefore, the basic requirements for modern fortifications determine that the concrete of such structures must have high strength under static loads and a low modulus of deformation (Babich, 2019).

When creating fortifications, it is necessary to increase their effectiveness to protect personnel from modern attacks. Among the military fortifications, the VS-1 fire structure is known, which belongs to engineering means and is assembled from unified reinforced concrete elements (see Construction of engineering structures. Album No. 1, 2. – K.: DP MOU TsPI, 2015). At the same time, precast concrete elements of fortifications such as SP-1 and SP-2 (300 mm thick) are usually made of concrete of strength class C32/40; their elements are reinforced with meshes of reinforcing bars A 500C and A 240C in accordance with DSTU 3760:2006. This leads to an increase in the weight of the modular reinforced concrete elements of the fortification, which significantly complicates their transportation to the installation site, as well as on-site installation work. Another negative factor during shelling of fortifications with artillery and small arms is the injury of personnel by fragments of broken concrete. A highly effective way to solve this problem of concrete structures destruction and personnel protection is to use modified steel fiber concrete of a new generation (Dvorkin, 2018; Dvorkin, 2017; Marushchak, 2018; Korolko, 2018; Xiang, 2019).

To achieve high quality steel fiber concrete, it is important to choose technological parameters that ensure uniform distribution of fiber and prevent its delamination. The effectiveness of the influence of different types of fibers on concrete properties depends on the ratio of the elastic moduli of the reinforcing fibers and concrete (Trevor, 2014; Máca, 2020; Yusof, 2010; Yusof, 2013; Fediuk, 2021).

Increasing the performance of fiber-reinforced concrete for protective structures is achieved due to the combination of different types of fibers. As a result of the creation of a denser interphase transition zone between cement paste, aggregate and fibers in such concrete composites, an increase in the values of the impact viscosity coefficient by 5.5 times, the dynamic strengthening coefficient by almost 70 %, as well as the absorption of impact energy by fibers is achieved (Khan, 2021; Moein, 2022). Thus, in the conditions of martial law, the development and implementation of rapid-hardening high-strength concrete with increased resistance to various types of force influences, including shock loads, in the construction of fortifications and shelters to protect the personnel of the Armed Forces of Ukraine, as well as protecting civilians, is an urgent task.

The purpose of the work is development and research of rapid-hardening high-strength steel-reinforced concrete for the manufacture of quick-assembling/quick-dismantling fortification structures that meet modern requirements for strength, reliability and resistance to shock loads.

Materials and Methods

To produce dispersed fiber-reinforced concrete, Portland cement DSTU B EN 197-1-CEM II/A-S 42.5 R by Dyckerhoff Cement Ukraine was used. The aggregates used were quartz sand (fineness modulus of sand – 1.3), crushed granite from the Vyrivsky granite deposit, fraction 5–20 mm. Dynamon NRG 1010 polycarboxylate superplasticizer with the effect of accelerating hardening and modified lignosulfonate LS TM Mapei were used as modifiers. Steel anchor fiber 1/50 mm (Budmat) was used to improve the mechanical characteristics of fiber-reinforced concrete and increase resistance to static and dynamic loads.

Flexural tensile strength, prismatic strength, elastic modulus, and Poisson's ratio were determined on prism specimens of 100×100×400 mm in accordance with DSTU B B.2.7-217:2009. The specimen was loaded to the level of (40 ± 5) %, in steps equal to 10 % of the expected destructive load, maintaining a loading rate of (0.6 ± 0.2) MPa/s within each step. To evaluate the protective properties of steel fiber concrete, a plate measuring 400 × 400 × 100 mm was fired using an SVD rifle, a 7.62 mm bullet of a 57-N-323s rifle cartridge (7.62x54R cartridge, bullet mass – 9.6 g, initial velocity – 850 ±15 m/s), single shots from a distance of 25 m.

Results and discussion

The compositions of steel fiber concrete based on Portland cement CEM II/A-S 42.5 R with a ratio of components Cement : Sand : $Ag_{2\text{-}5\ mm}$: $Ag_{5\text{-}20\ mm}$ = 1:1.41:0.5:2.85 (C = 350 kg/m^3) using steel fiber in the amount of 20 and 40 kg/m^3, consistency class S2 were designed. As can be seen from Fig. 1, for concrete with the addition of modified LS (W/C=0.43), a somewhat slowed down kinetics of early strength growth is observed, while the compressive strength class C40/50 is achieved. The introduction of 0.3 wt. % LS and 0.7 wt. % PCE into steel fiber concrete (steel fiber content – 40 kg/m^3) ensures a 33 % reduction in W/C, while the water-reducing effect of LS reaches 20 % (for concrete without additives, W/C = 0.54). At the same time, for steel fiber concrete modified with the PCE additive, the greatest increase in compressive strength is observed after 1 day – by 33 %, after 28 days the compressive strength of concrete reaches 79.4 MPa, which allows such steel fiber concrete to be classified as high-strength and rapid-hardening (f_{cm2}/f_{cm28} = 0.57) in accordance with DSTU EN 206:2018. Modified steel fiber concrete is characterized by a compressive strength of 83.0-85.9 MPa after 56 days of hardening. At the same time, it should be noted that the introduction of steel fiber does not have a significant effect on the compressive strength during the entire hardening period. At the same time, the flexural tensile strength of steel fiber concrete increases by 31.0 % ($f_{c,\,lf}$ = 7.4 MPa) compared to concrete without steel fiber ($f_{c,\,lf}$ =5.1 MPa).

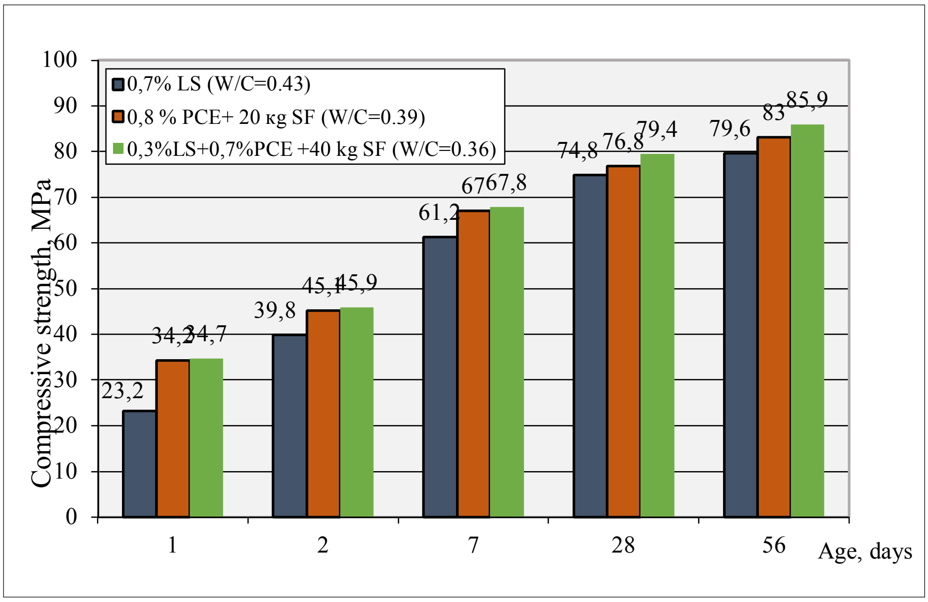

Fig. 1. Compressive strength of modified concrete reinforced with steel fiber

Studies of deformational properties have shown that the prismatic strength for concrete of compressive strength class C40/50 after 28 days is $f_{cm,prism}$=63.0 MPa, and for steel fiber concrete of compressive strength class C50/60 it corresponds to $f_{cm,prism}$=66.0 MPa. At the same time, the elastic modulus for concrete without fiber is 60 GPa, and for steel fiber concrete it decreases to 54 GPa, with Poisson's ratio of 0.20 and 0.17. The prism specimens of steel fiber concrete after testing the bending tensile strength and prism strength are shown in Fig. 2.

a *b*

Fig. 2. Prism specimens of steel fiber concrete, after testing:
a – tensile strength in bending; b – prism strength

To determine the impact resistance of steel fiber concrete, slabs with 400×400×100 mm were molded on the basis of high-strength concrete reinforced with steel fiber. After a high-speed impact of a 7.62 mm caliber bullet, holes were formed on the surface of the plates, for which the penetration depth of the bullet was 2 cm, and the diameter was 6.0–9.0 cm (Fig. 3). After shelling the samples, it was found that for a slab based on high-strength concrete, the main crack formed after the 2nd shelling, while in a slab based on high-strength steel fiber concrete, the surface of which is bonded with steel fibers, the main crack was recorded after 3 shellings.

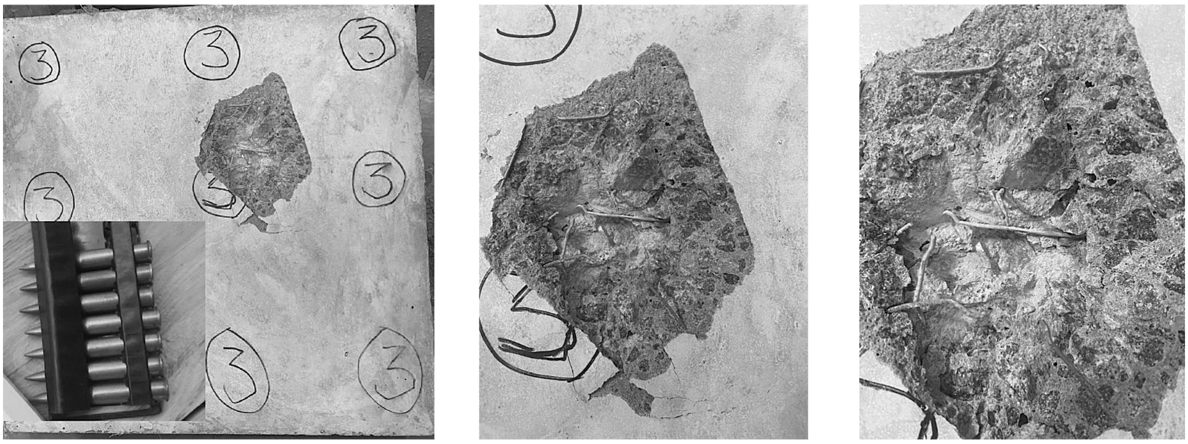

Fig. 3. The surface of a steel fiber concrete slab after being shot with a 7.62 mm bullet

Based on the results of the conducted research, a quick-assembly/quick-disassembly fire fortification structure with a plan size of 3100x3000 mm was designed; height – 2740 mm, the thickness of reinforced concrete walls – 240 mm, while the internal size of the room for conducting fire is 2400x2500 mm (Album Fire construction VS-1 VOLUME 1 Design solutions 04-22-KB). Reinforcement of the elements is provided by grids made of reinforcing steel A500S and A240S according to DSTU 3760:2006.

An experimental model of a prefabricated/quickly disassembled fortification based on modified dispersed-reinforced steel fiber concrete was manufactured. The fortification consists of unified reinforced concrete elements of full factory readiness. There are 4 loopholes in the outer walls – embrasures closed with metal doors. The total volume of fresh concrete was 11.5 m^3. Reinforced concrete elements of the quick assembly/quick disassembly construction (Fig. 4) are made of steel fiber concrete (brand of concrete mix by consistency S2) of compressive strength class C40/50.

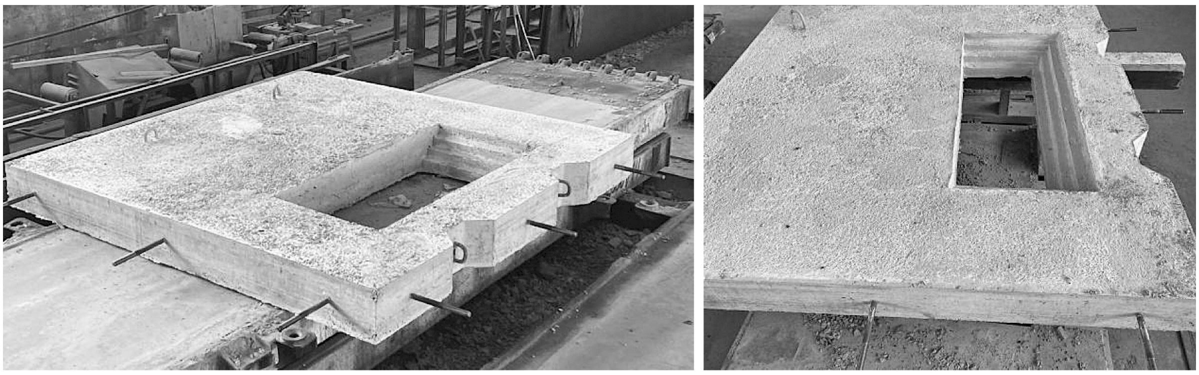

Fig. 4. Structural elements of a fortification based on high-strength steel fiber concrete

It was found that the steel fiber-reinforced concrete of modular elements (wall panel SP and PP) of the fortification structure showed rapid strength gains: SP-1 after 1 day of hardening – 22.4 MPa, SP-2 – 20.7 MPa, PP-1 – 25.2 MPa; after 28 days hardening, the compressive strength of SP-1 is 65.9 MPa, SP-2 – 67.6 MPa, PP-1 – 71.2 MPa, which corresponds to the concrete class in terms of compressive strength C40/50. At the same time, the tensile strength in bending is 6.7–7.0 MPa, the water resistance grade reaches W14–W16; the frost resistance grade is F300.

The elements of the fortifications were manufactured in the factory in compliance with all standards and regulations. The elements can be delivered and assembled using the technical means available to the troops. A prefabricated industrial structure is delivered to the construction site in the form of separate structures. The set of elements allows the structure to be assembled without the use of welding; additional protection against concrete fragments and noise insulation of the structure are provided for additional protection against damage. A quick-assembling/quick-dismantling fortification structure based on modified rapid-hardening high-strength dispersed-reinforced concrete allows to protect personnel from armor-piercing and high-explosive shells of enemy artillery to create mobile platoon strongholds. A quick-demountable/quick-demountable fortification structure based on modified fast-hardening high-strength dispersed reinforced concrete allows to protect personnel from armor-piercing and high-explosive shells of enemy artillery.

Conclusions

Rapid – hardening high-strength steel fiber-reinforced concrete with increased resistance to various types of force impacts for fortifications has been developed. By combining the physical approach, which is realized by introducing a polycarboxylate superplasticizer and dispersed steel fiber reinforcement, it is possible to obtain rapid-hardening high-strength steel fiber concrete of compressive strength class C 50/60. Dispersed steel fiber reinforcement in combination with PCE allows for a 31 % increase in flexural strength. The developed steel fiber-reinforced concrete allows for an increase in compressive strength to class C40/50-C50/60 compared to typical concrete (strength class C32/40, designed by the Defense Research Institute), which determines the reduction of the wall thickness from 300 to 240 mm.

Prospects for further research

Due to the use of high-strength steel fiber concrete, it is possible to obtain quick-assembly/quick-dismantling fortification structures with increased impact strength. In this case, a reduction in the thickness of reinforced concrete elements is achieved, which makes it possible to reduce the weight of the fortification structure and ensure its delivery and installation with the technical means available in the military. In further research, it is advisable to combine steel and basalt fibers, which will increase the protective properties of fortification structures.

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ВИСОКОМІЦНИЙ СТАЛЕФІБРОАРМОВАНИЙ БЕТОН ДЛЯ ФОРТИФІКАЦІЙНИХ СПОРУД

Представлено високоміцні сталефібробетони для швидкозбірних/швидкорозбірних фортифікаційних споруд із підвищеною стійкістю до ударних навантажень. Одержання високої міцності на розтяг при згині ($f_{c,\,lf}$ =7,4 МПа) та стиску (f_{cm} =79,4 МПа) забезпечується шляхом поєднання фізичного підходу, що реалізується введенням полікарбоксилатного суперпластифікатора та дисперсного армування бетону сталевою фіброю. Встановлено, що за результатами випробувань сталефіброармований бетон можна віднести до високоміцного (клас міцності С 50/60) та швидкотверднучого (f_{cm2}/f_{cm28} = 0,57), відповідно до ДСТУ EN 206:2018. Показано, що після дії швидкісного удару кулі калібру 7,62 мм на поверхні плит сталефіброармованого бетону магістральна тріщина фіксується після 3-х обстрілів (глибина проникнення кулі складає 2 см, а діаметр – 6,0–9,0 см).

Проведено виготовлення експериментального зразка швидкозбірної/швидкорозбірної фортифікаційної споруди на основі розробленого сталефіброармованого бетону, який характеризувався класом міцності на стиск С40/50, міцністю на розтяг при згині – 6,7–7,0 МПа, маркою за водонепроникністю W14-W16; маркою за морозостійкістю F300. Встановлено, що розроблений сталефіброармований бетон дає змогу забезпечити збільшення міцності на стиск до класу С40/50–С50/60 порівняно з типовим бетоном класу міцності С32/40 (див. Будівництво інженерних споруд. Альбом № 1, 2. К.: ДП МОУ ЦПІ, 2015), що визначає можливість зменшення товщини стіни від 300 до 240 мм. Розроблення та впровадження швидкотверднучих високоміцних сталефіброармованих бетонів із підвищеним опором до різних видів силових впливів під час обстрілів фортифікаційних споруд артилерією та стрілецькою зброєю дасть змогу забезпечити захист особового складу підрозділів Збройних сил України.

Ключові слова: швидкозбірна/швидкорозбірна фортифікаційна споруда, високоміцний сталефіброармований бетон, модифікатори, сталева фібра, міцність, ударні навантаження.