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DEVELOPMENT OF RAPID-HARDENING HIGH-STRENGTH FIBER-REINFORCED CONCRETE WITH INCREASED IMPACT RESISTANCE

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The article describes the development of rapid-hardening, high-strength fiber-reinforced concrete with increased impact resistance for protective structures. Fiber-reinforced concretes with the addition of Portland cement CEM II/A-LL 42.5 R (C = 390 kg/m^3) with polymer structural fiber PMS 1/60 with the addition of PCE were studied. The addition of PMS 1/60 fiber to concrete increases impact strength by 2.8–3.7 times and achieves a strength class of C 40/50. Fiber-reinforced concretes with the addition of Portland cement CEM II/A-S 52.5 R were studied. The addition of PMS 1/60 fiber provides an increase in the impact resistance of concrete at an early age by 2.7–3.1 times, and at the design age by 3.9–5.5 times. The developed fiber-reinforced concretes are classified as high-strength and rapid-hardening. The use of rapid-hardening high-strength fiber-reinforced concrete with increased impact resistance will increase resistance to mechanical loads and explosive impacts and ensure reliable protection of protective reinforced concrete structures.

Keywords: fiber-reinforced concrete, fiber, strength, impact resistance, protective structures.

Introduction

The construction of new and repair of existing protective structures is one of the main priorities for ensuring the protection of civilians and military personnel. Firearms cause a large-radius shock and explosive effect, which leads to the destruction of civilian and defensive structures and buildings (Babich, 2019; Dvorkin, 2017; Fediuk, 2021; Sanytsky, 2023).

Traditional heavy concrete is widely used for the construction of reinforced concrete structures for protective structures. According to the project of the Research Institute of the Ministry of Defense, protective reinforced concrete structures are made of heavy concrete of strength class C32/40 reinforced with steel reinforcement bars. It should be noted that such concrete is characterized by brittle fracture, and as its strength increases, its brittleness increases significantly (Zhang, 2021). Under intense loads, reinforced concrete structures are subject to various types of damage, such as multiple fragmentation, dynamic cracking, and the formation of microcracks in the concrete body (Cadoni, 2025; Shi, 2020; Korolko, 2023; Yao, 2023).

Dispersed reinforcement provides better performance characteristics for concrete structures, such as compressive strength, flexural strength, modulus of elasticity, impact resistance, crack resistance, and others. (Nia, 2012; Yi, 2024; Marushchak, 2018). According to research, fibers with a high modulus of elasticity, such as steel (200 GPa) and carbon (230–380 GPa), provide better crack bridging and stress transfer in the cement matrix of concrete. However, the use of steel fiber, particularly in industrial conditions, is accompanied by a number of technological difficulties, including: uniform addition of fiber into the concrete mixture, difficult mixing, and complications in the process of transporting and laying the mixture, which affects the quality of reinforced concrete. On the other hand, the use of fibers with low elastic modulus, such as polypropylene (3–5 GPa) and polyethylene (80–120 GPa), improves resistance to cracking and impact loads, as well as better energy absorption (Pham, 2025). At the same time, authors (Zhao, 2016; Yuan, 2021; Kropyvnytska, 2024) have found that the addition of polypropylene and polyethylene fibers leads to an increased need for water in concrete to ensure the necessary workability of the concrete mixture, as well as a longer setting time for the concrete. The addition of highly effective polycarboxylate superplasticizers makes it possible to control the course of structure formation processes at the micro-, meso-, and macrolevels (Aitcin, 2019). Therefore, the development of high-strength fiber-reinforced concrete with increased impact resistance will allow for the creation of reinforced concrete protective structures characterized by increased crack resistance, energy capacity of destruction, durability, and reliability under dynamic and impact loads, which is especially important in the construction of civil defense engineering structures.

The purpose of the work is to develop rapid-hardening high-strength fiber-reinforced concrete for protective structures, and to investigate its strength and impact resistance.

Materials and Methods

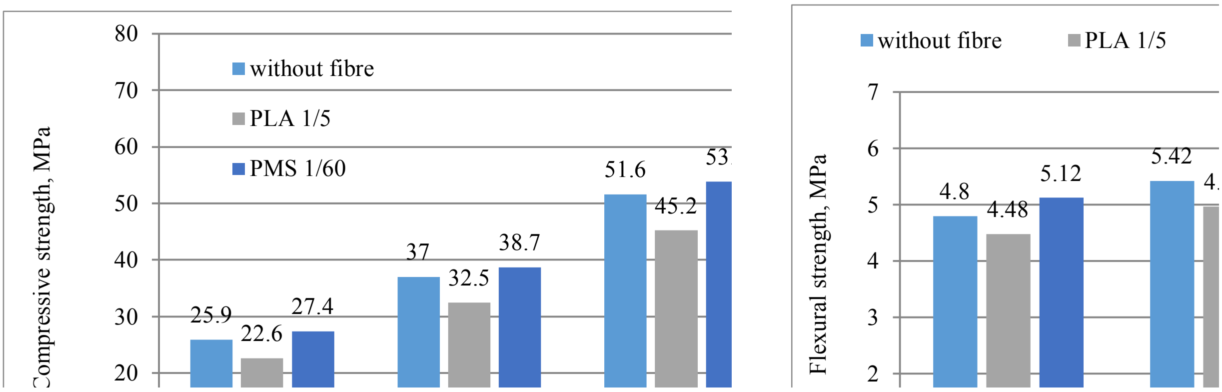
Portland cements CEM II/A-LL 42.5 R and CEM II/A-S 52.5 R from JSC "Ivano-Frankivsk Cement" were used to obtain fiber-reinforced concrete. Quartz sand from the Slavuta deposit (*Mk* = 1.95) and granite crushed stone from the Vyrivsky deposit with fractions of 2–5 mm and 5–20 mm were used as aggregates. To improve the mechanical properties of fiber-reinforced concrete, the following fibers were used: PLA l/5 polyamide fiber and PMS 1/60 structural polymer fiber. A superplasticizer based on polycarboxylate ethers (PCE) was used as a modifier.

Flexural strength was determined on prism samples measuring 100×100×400 mm in accordance with DSTU B V.2.7-214:2009. The test specimen is placed horizontally so that the plane in which tensile stresses occur during bending is parallel to the layers of the concrete mixture. The prism is mounted relative to the center on two hinged supports – one movable, the other fixed – which rest on the lower plate of the press. The distance between the hinged supports is 300 mm. Two hinges are placed on the upper edge of the prism, symmetrically relative to the center of the prism, at a distance of 100 mm from each other, with opposite placement relative to the lower hinged supports. A steel crossbar is installed on the supports relative to the center of the prism, and a spherical hinge is installed on top of it – a segment of round steel on which a dynamometer with a clock-type indicator rests. The load is transferred from the ball joint to the crossbar, and from there to the hinged supports in the form of two evenly distributed concentrated forces. In the process of "centering" the prism, it is necessary to ensure the exact perpendicular placement of the supports and the parallel placement of the crossbar. The load on the sample must be uniform, the value of tensile stresses during bending is determined as the ratio of the product of loads and the span between the lower supports to the size of the prism cross-section to the cube.

Impact resistance was tested on 70×70×70 mm samples using the repeated drop test method in accordance with ACI Committee 544-R. To determine the impact strength, a 2 kg weight was used, with a 3 cm diameter ball located in the center of the test specimen and a 70 mm diameter guide tube 1 m high. The sample, placed in a mold with a sand base, is subjected to repeated impacts until the first crack appears and complete destruction occurs. The impact energy is determined based on the number of impacts required for the first crack to appear and the sample to be completely destroyed. Impact strength indicators are determined as the ratio of impact energy to the area of the test sample.

Results and discussion

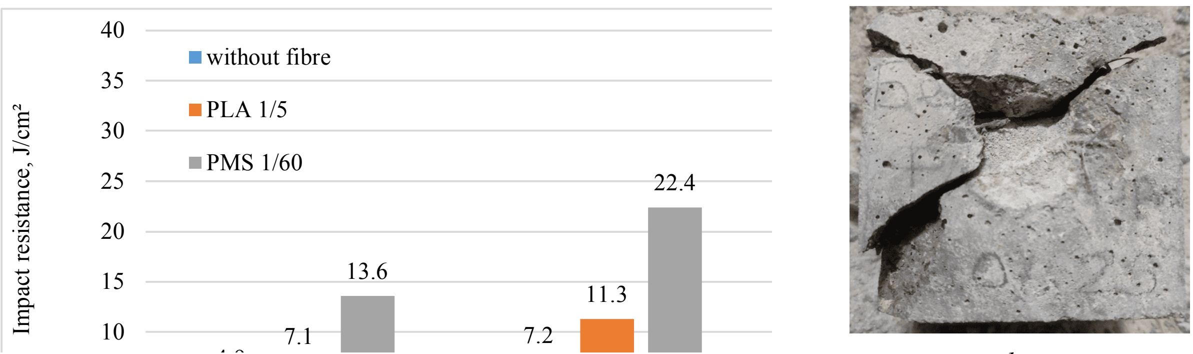
The fiber-reinforced concrete mixes were studied using Portland-limestone cement CEM II/A-LL 42.5 R (C = 390 kg/m^3), with a consistency corresponding to class S4. The influence of polyamide fiber PLA l/5 and structurally polymer fiber PMS 1/60 on the properties of modified concretes, the content of which is 1.0 kg per m^3 of concrete, was investigated. It was found that the compressive strength of fiber-reinforced concrete (W/C = 0.41, slump value 210 mm) after 1, 2, 7, and 28 days is 25.9, 37.0, 51.6, and 65.3 MPa, respectively. The flexural strength after 7 and 28 days is 4.8 and 5.5 MPa. The addition of PLA l/5 polyamide fibers leads to an increase in water demand to W/C=0.44 while maintaining a slump value of 200 mm. At the same time, there is a decrease in compressive strength by an average of 12 % and a decrease in flexural strength by 10 % throughout the entire control period of hardening. When adding PMS 1/60 polymer structural fiber to the concrete mixture to ensure slump value 210 mm, W/C was 0.41, as for concrete without fiber. Compressive strength after 1, 2, 7, and 28 days increases by 4–6 %, and flexural strength increases by 6–7 % compared to concrete without fiber (Fig. 1, *a*, *b*). At the same time, fiber-reinforced concrete achieves a compressive strength class of C 40/50.



a *b*

Fig. 1. Compressive (a) and flexural (b) strengths of the modified concrete with various types of fibers

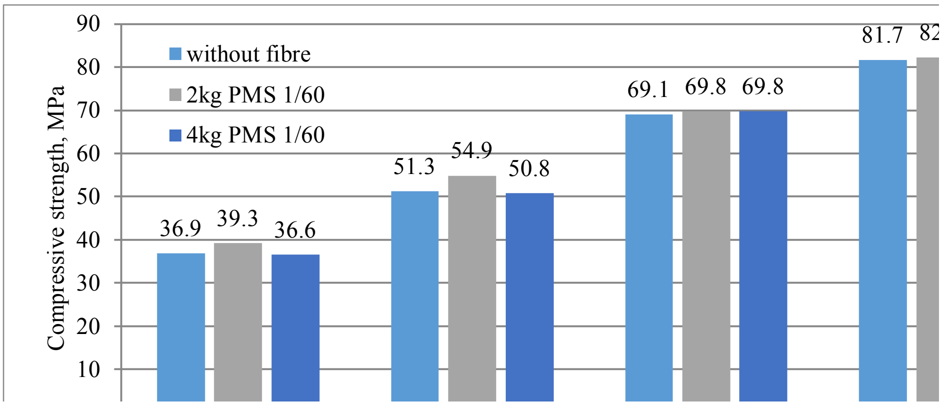
Impact testing showed that for concrete without fiber, after 2, 7, and 28 days, the impact resistance is 4.9, 7.2, and 9.6 J/cm². For modified concrete reinforced with PLA l/5, the impact resistance increases by 1.4–1.7 times and is 7.1, 11.3, and 16.5 J/cm² after 2, 7, and 28 days, respectively. Fiber-reinforced concrete with the addition of PMS 1/60 polymer structural fiber has the highest impact resistance. The impact resistance index increases by 2.8–3.7 times and amounts to 13.6, 22.4, and 35.8 J/cm² after 2, 7, and 28 days, respectively (Fig. 2, *a*). At the same time, the concrete breaks in a brittle manner, accompanied by the appearance of a main crack and rapid complete destruction of the sample after the next load drop (Fig. 2, *b*).



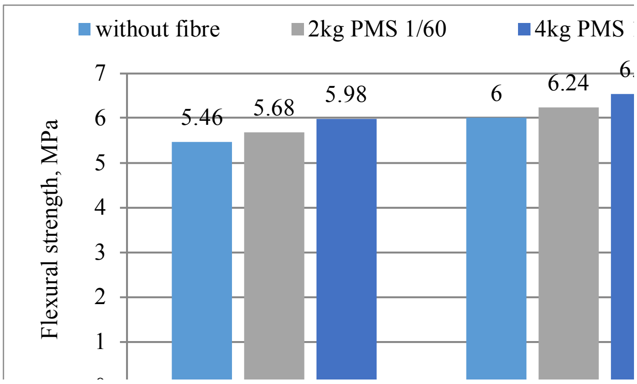
a *b*

Fig. 2. Impact resistance of the concrete with various types of fibers (a)
and concrete sample, after impact resistance testing (b)

High-strength fiber-reinforced concrete compositions were designed using high-quality Portland cement CEM II/A-S 52.5 R (C = 390 kg/m^3). In the next study, PMS 1/60 structural polymer fiber was used and its consumption was increased to 2.0 and 4.0 kg per m^3 of concrete. It was found that for a concrete mixture without fiber with the addition of 0.8 % mass. PCE, a slump value 210 mm is ensured at W/C = 0.42. At the same time, the compressive strength after 1, 2, 7, and 28 days is 36.9, 51.3, 69.1, and 81.7 MPa, respectively (Fig. 3, *a*). When 2.0 kg per m^3 of concrete of PMS 1/60 fiber is added, the compressive strength increases by 2–9 %; increasing the fiber content to 4.0 kg per m^3 of concrete leads to a slight decrease in compressive strength at all hardening times. At the same time, the addition of 2.0 and 4.0 kg per m^3 of concrete of fiber leads to an increase in flexural strength at all curing times. Thus, after 28 days of hardening at a consumption rate of 2.0 and 4.0 kg per m^3 of concrete of PMS 1/60 fiber, the flexural strength reaches $f_{c,\,lf}$ = 6.24 MPa and $f_{c,\,lf}$ = 6.54 MPa respectively (Fig. 3, *b*). According to the research results, fiber-reinforced concrete can be classified as rapid-hardening (f_{cm2}/f_{cm28} = 0.63) and high-strength (concrete class C 55/67) in accordance with DSTU EN 206:2018.



a

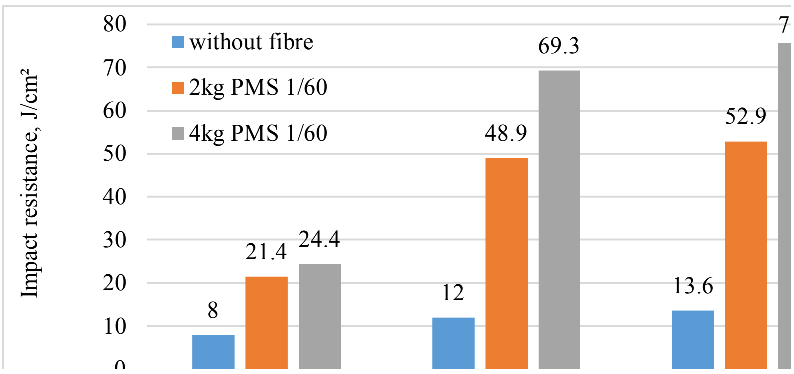


b

c

Fig. 3. Compressive (a) and flexural (b) strengths of the concrete reinforced with polymer fiber PMS 1/60 and testing of a fiber-reinforced concrete sample for flexural strength (c)

At the same time, when 2.0 and 4.0 kg of fiber per m^3 are added, the impact resistance of high-strength fiber-reinforced concrete increases significantly. It has been established that the addition of 2.0 kg per m^3 of concrete of PMS 1/60 fiber after 2, 7 and 28 days allows 21.4, 48.9 and 52.9 J/cm² to be achieved, and the addition of 4.0 kg per m^3 of concrete allows 24.4, 69.3 and 75.7 J/cm² to be achieved, respectively. Thus, the addition of 2.0 and 4.0 kg of fiber per m^3 of concrete resulted in a 2.7–3.1 and 3.9–5.5 times increase in impact resistance compared to concrete without fiber (Fig. 4, *a*).



a

b

Fig. 4. Impact resistance of fiber-reinforced concrete (a) and concrete sample after testing (b)

It has been established that after the appearance of the first crack and subsequent blows to the weight, multiple microcracks form, indicating a uniform distribution of loads by the fiber until the sample is completely destroyed (Fig. 4, *b*). This indicates that the nature of the destruction of concrete reinforced with PMS 1/60 fiber is plastic.

Conclusions

Rapid-hardening high-strength fiber-reinforced concrete with increased strength and impact resistance has been developed for protective structures. It has been established that the combination of high-quality Portland cement CEM II/A-S 52.5 R (C = 390 kg/m^3) with polymer structural fiber PMS 1/60 and highly effective PCE has resulted in rapid-hardening (f_{cm2}/f_{cm28} = 0.63) and high-strength (strength class C 55/67) concrete in accordance with DSTU EN 206:2018. When adding 2.0 and 4.0 kg per 1 m^3 of concrete of polymer structural fiber PMS 1/60, the flexural strength increases at all hardening times, and the impact resistance at an early age increases by 2.7–3.1 times, and at the design age increases by 3.9–5.5 times compared to concrete without fiber. It has been established that rapid-hardening high-strength fiber-reinforced concrete is characterized by plastic failure.

The use of rapid-hardening high-strength fiber-reinforced concrete with increased impact resistance will make it possible to counteract modern means of destruction thanks to the combination of high mechanical characteristics of the cementitious matrix based on Portland cement CEM II/A-S 52.5 R and additional energy-absorbing properties of structurally polymer fibers in concrete.

Prospects for further research

In future research, it is advisable to optimize the composition of fiber-reinforced concrete for protective structures using mathematical planning of experiments.

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РОЗРОБЛЕННЯ ШВИДКОТВЕРДНУЧИХ ВИСОКОМІЦНИХ ФІБРОАРМОВАНИХ БЕТОНІВ ІЗ ПІДВИЩЕНОЮ УДАРНОЮ В'ЯЗКІСТЮ

У статті розроблено швидкотверднучі високоміцні фіброармовані бетони з підвищеною ударною в'язкістю для захисних інженерно-технічних споруд. Спроєктовано склади фіброармованих важких бетонів із використанням портландцементів CEM II/A-LL 42,5 R та CEM II/A-S 52,5 R. Досліджено вплив поліамідних волокон та полімерних структурних волокон на міцність на розтяг при згині, міцність на стиск та ударну в'язкість фіброармованих бетонів. Введення поліамідних волокон PLA l/5 призводить до зростання водоцементного відношення бетонної суміші, зниження міцності на стискання, міцності на розтяг при згині; встановлено понижені значення ударної в'язкості. Для фіброармованого бетону на основі портландцементу CEM II/A-LL 42.5 R з фіброю PMS 1/60 досягається клас міцності на стискання С 40/50. Дисперсне армування полімерною структурною фіброю PMS 1/60 забезпечує підвищену міцність на розтяг при згині, ударна в'язкість фіброармованих бетонів збільшується в 2,8–3,7 раза порівняно із бетоном без фібри. Комплексне поєднання високоміцного портландцементу CEM II/A-S 52,5 R, полікарбоксилатного суперпластифікатора та полімерної структурної фібри PMS 1/60 забезпечує досягнення високої міцності на стискання та міцності на розтяг у разі згину. Розроблений фіброармований бетон на основі CEM II/A-S 52,5 R можна класифікувати як високоміцний та швидкотверднучий. Введення 2,0 та 4,0 кг на м^3 полімерної структурної фібри PMS 1/60 забезпечує збільшення ударної в'язкості у ранньому віці в 2,7–3,1 раза, а у проєктному – в 3,9–5,5 раза порівняно із важким бетоном без фібри. Розроблення швидкотверднучих високоміцних фіброармованих бетонів із підвищеною міцністю та ударною в'язкістю дасть змогу підвищити стійкість до механічних навантажень та вибухових впливів і забезпечить надійний захист і довговічність захисних залізобетонних конструкцій.

Ключові слова: фіброармований бетон, фібра, міцність, ударна в'язкість, захисні споруди.