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# THE USE OF HIGH-PERFORMANCE CONCRETES, ULTRA HIGH-PERFORMANCE CONCRETES, AND ADDITIVE MANUFACTURING TECHNOLOGY IN INCREASING THE BALLISTIC PROTECTION LEVEL OF FIELD FORTIFICATIONS

**ABSTRACT:** High-Performance Concretes (HPC) and Ultra High-Performance Concretes (UHPC) allow for the production of extremely durable construction elements when compared to those same elements made of C35/45 concrete. Increased compressive- and flexural strength markedly contribute to ballistic resistance reducing the area and depth of the "crater" which results from a potential impact of a projectile or a fragment.

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Additionally, the presence of dispersed fibres in these mixtures eliminates the need of using reinforcement bars, which, in turn, reduces the time expenditure and labour. The article compares the results of various ballistic tests of elements made of high-performance concrete mixtures to determine the viability of applying such elements in the defence sector. Furthermore, the authors present the possibility of adapting additive technologies for the performance of field fortification tasks by the military, as part of which the HPCs and UHPCs are used as working mixtures. The authors also show the possibility of fabricating construction elements without the use of formworks, as well as printing construction elements directly at the site of future operation of the buildings.

**KEYWORDS:** high-performance concrete, additive manufacturing, fortification, ballistic protection

## INTRODUCTION

Field fortification is a vital area of the military engineering force support tasks, one which has accompanied warfare from the very beginning. The first defensive formations included embankments and wooden structures, such as palisades. However, with the development of technology and material capabilities, the nature of field fortifications has shelters and trenches.

After the collapse of the Soviet Union, the type of threats changed, and with it the needs relative to fortification. The spectre of armed conflict on a scale comparable to World War 1 and 2 has been pushed aside, and the threats of terrorism and asymmetric conflicts have come to the fore. This resulted in significant inhibition of efforts on the development of new fortification techniques. Currently, to develop defensive positions, most of the armies in the world use tried and true solutions known for many decades, such as:

- constructions of wood and earth (earthworks), where the easy availability of materials makes them the main, go-to way of fortifying the area, especially in temporary defence and observation posts;
- typical fortification equipment, such as gabions ("Hasco bastions") or sheet metal shelters, characterized by a level of protection higher than that of temporary structures but requiring specialized equipment to set up;
- various types of shelters and trenches of precast concrete providing the highest levels of protection while requiring the greatest labour intensity and heavy equipment to be constructed.

In contrast to the slowed development of defence technologies, offensive warfare technologies and reconnaissance systems have been gradually improving, adapting state-of-the-art technological developments for the most effective impact and undermining the significance of field fortifications. A breakthrough moment in these activities was the mass use of unmanned aerial vehicles (UGVs) with integrated firing systems. Their effectiveness was confirmed, among others, in the Nagorno-Karabakh region in 2021, where observers from abroad recognized that with the current offensive measures, locating and pin-pointing a single soldier on the battlefield is much easier, while a shelter or other type of hiding spot does provide adequate safety level for the soldier. Therefore, it can be concluded that the solutions currently utilised as field fortifications are inadequate, incapable of handling the threats of the modern battlefield and require development.

In order to protect key buildings, facilities and resources, the armed forces must have military engineering units at their disposal capable of producing effective and varied ballistic and blast protection products capable of keeping up with the ever-increasing pace of operations. To achieve this, the following aspects need to be improved:

- increased endurance and ballistic resistance/performance;
- reduction of the labour intensity of fortification development;
- limiting the use of heavy equipment in the construction of fortifications;
- reduction of the logistic burden involved with the transport of prefabricated elements.

As a result of the search for a material that would ensure adequate strength and durability of the planned fortifications, concrete is often pointed to. Due to its characteristics, useful for a specific purpose, i.e. for the construction of emplacements and defensive fighting positions, concrete should be used in a wide range of applications in the development of various field fortification systems.

HPC and UHPC are more durable than conventional concrete due to the use of a low water-to-binder (concrete) ratio (W/C) of around 0.2 and a large number of fine particles in their formula. It is considered an innovative composite material that can be used in structures exposed to aggressive environments. Despite many studies to date, no comprehensive evaluation of the properties of UHPCs and HPCs in ballistic applications has been conducted.\

## HIGH-PERFORMANCE CONCRETES – GENERAL PROPERTIES AND COMPARATIVE CHARACTERISTICS

Despite its drawbacks, such as inadequate flexural strength and low ductility[1], concrete is a popular material in civil construction. Large-scale military use of concrete can be dated back to the early years of the 20th century, when it was used to build fortified districts, providing protection against artillery fire[2]. Currently, concrete is often used in the high-quality blast and

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[1] Shaikh, F. (2013). Review of mechanical properties of short fibre reinforced geopolymer composites. Construction and Building Materials, 43, pp. 37-49.

[2] Krauthammer, T. (2014). Foreword: Challenges for advancing the performance of military concrete. Magazine of Concrete Research, 66, pp. 3-5.

fallout shelters, which are made of prefabricated elements delivered to the construction site. C35/45 concrete or its equivalent is most often used for this purpose. However, the problem in such cases is the substantial mass of such prefabricated elements, which generates the need for specialized equipment and increased labour consumption. In addition, such elements have to be delivered directly to the area of final installation for the structure, which limits the possibility of future development in hard-to-reach locations. However, since the use of concrete as a construction material has been established, scientists all around the world have been striving to improve its performance parameters by changing the composition of the mixture. The result of their efforts was the development of concrete with dispersed reinforcement, using silica fume and fly ash[3,4] among others. Due to its characteristic features, concrete with such a composition was called High-Performance Concrete (HPC) or Ultra High-Performance Concrete (UPHC), if its minimum specified compressive strength exceeds 120 MPa[5,6]. The basic properties that have been improved in concrete include increased mechanical strength, in particular, compressive strength[7,8], hardness[9], or the ability to obtain concrete self-healing effects in the reconstructive process[10]. There are several studies dedicated to the

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[3] Richard, P., & Cheyrezy, M. (1994). Reactive Powder Concretes With High Ductility and 200 - 800 Mpa Compressive Strength.

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change in the proportion of the mixture[11,12], its workability[13,14], or specific additives, the comparison of which is presented in Table 1.

Table 1. Comparison of basic strength parameters of various HPCs and UHPCs.

| Concrete type | Density [kg/m$^3$] | Compressive strength [MPa] | Flexural strength [MPa] |
|---|---|---|---|
| C35/45 concrete | 2200.00 – 2600.00 | 35/45 | 2.20 |
| Basalt fibre-reinforced concrete[15] | 2500.56 | 110.00 | 10.00 |
| Steel fibre reinforced concrete[16] | 2487.00 | 56.00 | 16.80 |
| Concrete with 10 wt.% of copper slag content[17] | 2530.00 | 99.80 | 5.20 |
| Ultra-high-performance fibre-reinforced concrete (UHP-FRG)[18] | 2650.00 | 162.40 | 19.20 |
| Ultra-high-performance fibre-reinforced concrete type T (T-UHPFRC)[19] | 2670.00 | 200.00 | 14.90 |

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[11] Yu, R., Spiesz, P.P., & Brouwers, H.J. (2014). Mix design and properties assessment of Ultra-High-Performance Fibre Reinforced Concrete (UHPFRC). Cement and Concrete Research, 56, pp. 29-39.

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Based on the comparative analysis of the concrete parameters presented in Table 1, it can be concluded that the compressive and flexural strength of the high-strength UHP-FRGs and T-UHPFRCs substantially exceeds the corresponding parameters of ordinary concretes. This is due to the modification of the composition of the typical, ordinary concrete mix, in terms of quality and quantity, to use the properties of new generation concretes in the most optimal manner.

## BALLISTIC RESISTANCE OF ULTRA-HIGH-PERFORMANCE CONCRETES

The currently produced concrete mixes allow for a more than 6-fold increase in strength parameters, compared to the concrete of class C35/45, while maintaining similar density[20,21,22.] In addition, it is possible to increase the flexural strength by about 9 times, which, based on the available publications, considerably impacts the ballistic resistance.

Ballistic tests are mainly based on the measurement of the following parameters:

- the surface of the crater formed after the impact of the projectile;
- projectile penetration depth;
- the difference in the projectile velocity before and after striking the test object.

Unfortunately, it is very challenging to compare test results, as different test procedures are being used along with different types of ammunition or even different standards are followed. These standards include national standards[23], American NIJ standards[24] or NATO

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[20] Mára, M., Sovják, R., & Fornůsek, J. (2020). USING TEXTILE ARAMID FABRICS TO INCREASE THE BALLISTIC RESISTANCE OF ULTRA-HIGH-PERFORMANCE STEEL-FIBRE REINFORCED CONCRETE. Acta Polytechnica.

[21] 23. Kristoffersen, M.M., Toreskås, O.L., Dey, S., & Børvik, T. (2021). Ballistic impact on concrete slabs: An experimental and numerical study. EPJ Web of Conferences.

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[23] Kristoffersen, M.M., Toreskås, O.L., Dey, S., & Børvik, T. (2021). Ballistic impact on concrete slabs: An experimental and numerical study. EPJ Web of Conferences.

[24] Mára, M., Kheml, P., Carrera, K., Fornůsek, J., & Sovják, R. (2021). Effect of Corundum and Basalt Aggregates on the Ballistic Resistance of UHP-SFRC. Crystals.

standardisation agreements (STANAGs)[25,26] among others. An additional, frequently occurring issue relative to comparing studies by different authors is the lack of complete information on the test conditions, such as the projectile/cartridge velocity or its components, as well as the lack of information on the test sample size or its curing, as in the case of concretes. The list of tests whose test conditions were similar and thus the results could be compared is included in Table 2.

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[25] STANAG 2280 – MC ENGR (Edition 1) (Ratification draft 1) – Design Threat Levels and Handover Procedures for Temporary Protective Structures. NATO Standardization Agency, June 2007.

[26] Štoller, J., & Dvořák, P. (2016). Field Tests of Cementitious Composites Suitable for Protective Structures and Critical Infrastructure. Key Engineering Materials, 722, pp. 11 - 3.

Table 2. Comparison of ballistic parameters of selected high-performance concretes.

| Concrete name | Reinforcement or additives used | Compressive strength [MPa] | Flexural strength [MPa] | Projectile energy, [J] | Projectile type and velocity, [m/s] | Crater surface, [mm2] | Crater depth, [mm] | Difference in velocity after sample penetration, [m/s] |
|---|---|---|---|---|---|---|---|---|
| C35/45 concrete [34] | none | 41.0 | 2.2 | 56 000 | ONSP*<br>152x25.3<br>540 | 63 700 | 300 | 231 |
| C35/45 concrete [34] | Steel reinforcement | No data | No data | 56 000 | ONSP*<br>152x25.3<br>540 | 32 600 | 300 | 243 |
| UHP-SFRC [25] | Corundum | 170.4 | 26.4 | 2 000 | 7.62x39<br>710±10 | 5200 | 20 | NP** |
| UHP-SFRC [25] | Basalt aggregate | 110.7 | 19.8 | 2 000 | 7.62x39<br>710±10 | 12000 | 11 | NP** |
| HPC [35] | Steel and polypropylene fibres | 102.9 | 16.3 | 7 420 | 7.62x51<br>838 ± 15 | 15000 | 36.2 | NP** |
| HCP [36] | Dolomite aggregate, dispersed steel reinforcement | 115 | 22 | 51 000 | 199x49<br>292±10 | 28 300 | 130 | NP** |

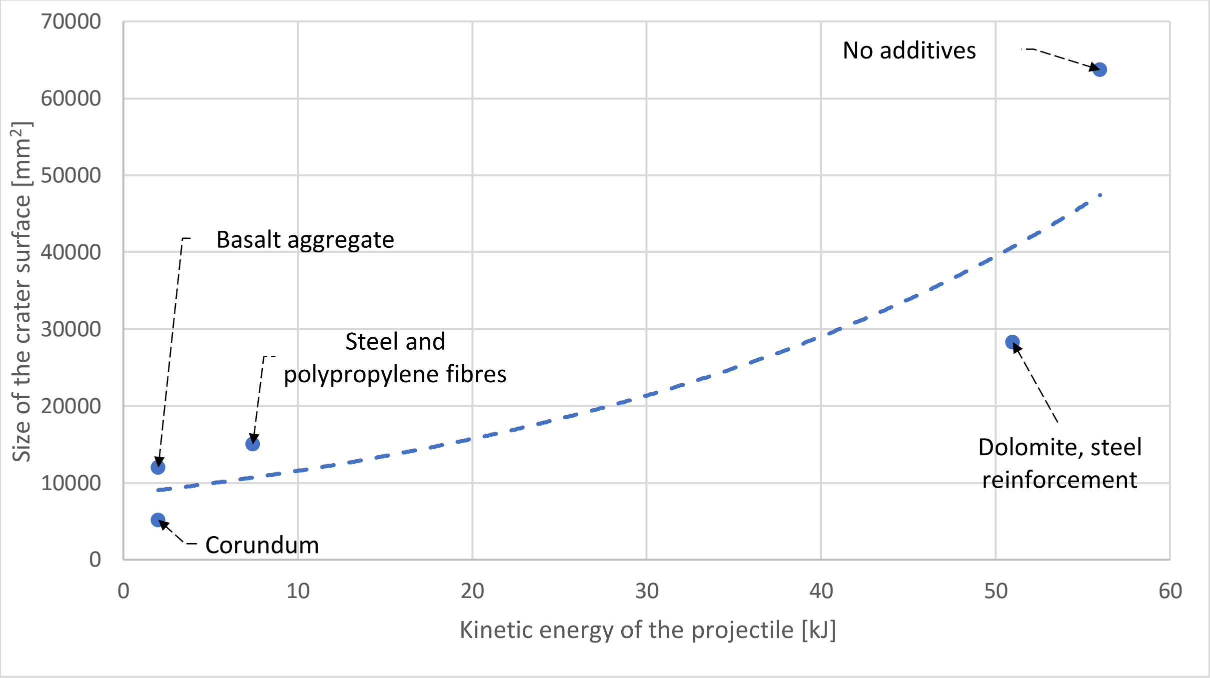
* Ogive-nosed steel projectile (LxD)

** No penetration

When comparing the above-mentioned studies, the ratio of the kinetic energy of the test projectile to the surface of the crater formed as a result of the impact should be taken as the primary parameter to be assessed. Nonetheless, this is an obvious generalisation, as due to the different shapes and materials used to produce the test projectiles, the only constant parameter in all of those tests is their kinetic energy. However, even assuming this simplification, we can draw a graph in which the relationship of damage done to the projectile kinetic energy is evident, the trend line of which is clearly exponential.

Fig. 1.

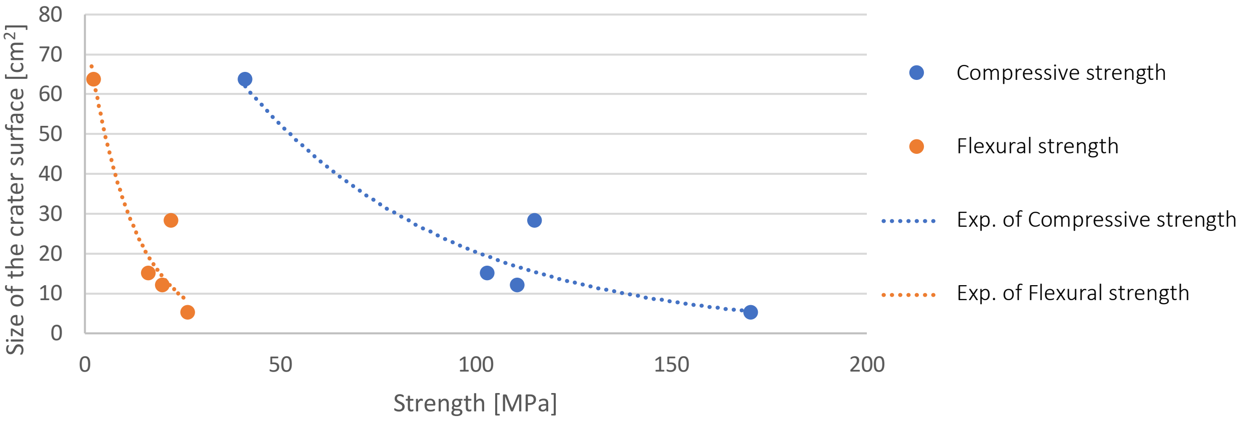
Comparison of the test projectile kinetic energy and the size of the crater surface



Another factor worth analysing is the impact of the parameters of the concrete element itself, in particular the compressive- and flexural strength, on the size of the crater surface. Figure 2 shows the relationship between these parameters.

Fig. 2

Comparison of the strength of the concrete elements and the size of the crater surface



When analysing the graph above, it should be noted that the optimal values for concrete in terms of ballistic protection will range from 80 to 100 MPa for compressive strength, and from 8 to 15 MPa for flexural strength. Creating mixtures that would be characterised by superior parameters will not be profitable due to the material- and technological costs disproportionate to the possible profit in the form of increased ballistic resistance.

A vital aspect when considering high-performance concrete as a material for the development of fortifications is to use dispersed reinforcements in the form of distinct types of fibres/aggregates. On account of these additives, elements made of HCP and UHCP can be produced both in a traditional way and through additive manufacturing.

## ADDITIVE MANUFACTURING OF CONCRETE ELEMENTS

Additive manufacturing of concrete elements is not a newly-developed process. The first attempts at this technology can be traced back to the 1990s[27]. However, this field has not developed as dynamically as other branches of 3D printing. This may even be evidenced by the

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[27] Buswell R, Soar RC, Gibb A, Thorpe T (2007) Freeform construction: mega-scale rapid manufacturing for construction. Autom Constr 16, pp. 224–231

use of non-uniform nomenclature, as the following terms describing the same process are currently in use:

- Freeform Construction (FFC)[28];
- Additive Manufacturing of Concrete (AMoC)[29];
- 3D Concrete Printing (3DCP)[30].

According to the current technology, additive manufacturing of concrete elements is based on pumping the concrete mix via a pump from the tank to the extrusion nozzle, which moves around the working area constructing the desired element layer by layer, in a manner similar to the Fused Deposition Modelling (FDM) technology. Based on the available scientific literature[31,32], it is known that concrete elements produced from HCP mixes by printing technology have a compressive strength of 80-90 MPa and a flexural strength of 6-9 MPa, which makes them apt for fortification purposes. What is more, printers can create complex shapes, even employing inner empty volume, and using several extrusion nozzles, they can produce an element with varying parameters, such as a dam that has a hard shell and is filled with a lighter mixture to reduce weight. This approach to the production of concrete elements means

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[28] Buswell R, Soar RC, Gibb A, Thorpe T (2007) Freeform construction: mega-scale rapid manufacturing for construction. Autom Constr 16, pp. 224–231

[29] Bos, FP Freek, et al. "Additive Manufacturing of Concrete in Construction: Potentials and Challenges of 3D Concrete Printing." Virtual and Physical Prototyping, vol. 11, no. 3, 2016, pp. 209–225.

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[31] Anton, A., Reiter, L., Wangler, T., Frangež, V., Flatt, R.J., & Dillenburger, B. (2021). A 3D concrete printing prefabrication platform for bespoke columns. Automation in Construction, 122, 103467.

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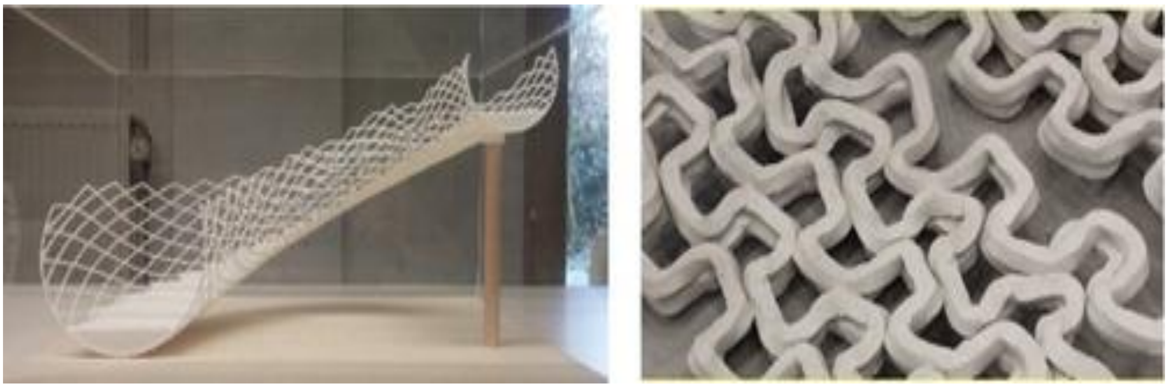
discarding the use of forms or formwork altogether, which translates into a reduction in production time.

Fig. 3

Concrete element printed with inner empty spaces[33]

Fig. 4

Elaborate shapes of 3D printed concrete elements[34]



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[33] Suiker, A.S., Wolfs, R., Lucas, S., & Salet, T.A. (2020). Elastic buckling and plastic collapse during 3D concrete printing. Cement and Concrete Research, 135, 106016.

[34] Freek Bos, Rob Wolfs, Zeeshan Ahmed & Theo Salet (2016) Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing, Virtual and Physical Prototyping, 11:3, pp. 209-225, DOI: 10.1080/17452759.2016.1209867.

An important advantage of using the technology in the case of concrete elements is the possibility of producing those elements directly on-site, where they are to be installed or at a short distance away, thus the amount of transport equipment, which would be necessary, if we were to transport prefabricated elements from the production facility with traditional manufacturing methods, can be limited. This concept of fortification development will reduce the logistics involved and the necessity to utilize heavy construction equipment.

The disadvantages of such a solution include the presence of layer connections, which constitute weak points within the structure. The phenomenon responsible for these points is adhesion between the layers, where the semi-solid top is applied onto the lower, pre-hardened layer, which makes their connection weaker than the properties of the working mix. This problem can, nonetheless, be solved with the appropriate design of the fortification elements.

The concept of using additive manufacturing would include two ways to use it:

direct development, where the objects would be built on-site;

indirect development, where the objects would be printed in the rear zone and transported to their final location.

The construction of field munitions warehouses, where individual ammunition stacks would be separated by barriers preventing the propagation of detonation to adjacent ammunition chambers, thanks to which only a direct hit would be able to destroy the ammunition stack can serve as an example of a direct fortification development. Another proposal for the use of 3D printers involves the expansion of supplementary battle positions along an avenue of approach that is not the primary avenue where the enemy is expected to attack and where engineering units would not be exposed. In such a system, concrete elements will be produced directly on-site, saving time and reducing the number of means of transport and construction machinery involved.

Indirect development is based on the currently used practice of land development, i.e. transporting prefabricated elements from the production plant to the place where they would be used, the difference being that by using the mobility of 3D printers and their ability to work under field conditions, the distance travelled is reduced significantly. Military units responsible for the production of concrete elements form a part of a group conducting a given operation, which means that a single means of transport would be capable of moving a greater number of elements than in the case of using existing production plants.

## CONCLUSION

Based on the review of the state of knowledge and preliminary research conducted by the authors, the following can be stated:

[1]. High-performance concretes and ultra-high-performance concretes have properties that drastically increase the ballistic resistance of concrete elements, without meaningfully increasing their weight.

[2]. The use of additive manufacturing technologies for the development of fortifications will make it possible to reduce the share of heavy equipment involved in fortification building and lessen the need for means of transport.

[3]. Printing of concrete elements has the potential to optimize the structure (shape, filling, working mixture composition) thus maintaining a high level of ballistic protection while minimizing the weight of individual elements.

[4]. Ballistic tests of concrete elements require greater standardization, which would allow a comparison of the obtained test results to be performed, in particular the impact of various types of admixtures on the level of ballistic protection.

The authors have already started work on the technology of printing concrete elements, and the results of their studies will be presented in future publications.

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