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The impact of various types of steel fibres on the strength parameters and blast resistance of high – performance concrete

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Abstract. The paper describes composition proposals and subsequent optimization and testing of developed fibre-reinforced UHPC mixtures, which seem to be optimal as construction material for the blast and ballistic protective systems, such as mobile blast-resistant walls and covers, which are the expected outcomes of the presented research project. Methods of laboratory testing and optimization of developed UHPC mixtures, with the aim of achieving the best possible values of physical-mechanical parameters, are described in this paper. In connection with laboratory verification, field blast tests of UHPC board samples and consequently of the entire blast-resistant wall system were realized and resistance to dynamic stress was investigated.

1. Introduction

Presented paper summarizes the outcomes of advanced phase of research and development conducted as one of the CAMPT research centre's activities. This facility focuses on increasing safety of citizens, protection of critical infrastructure, defence and national security. It was founded in 2014 to operate for 6 years, associates 9 partners from the field of research and development and commercial sphere and it is supported by Technology Agency of the Czech Republic as one of the "Competence Centres".

Described research works were aimed at verification of the influence of various types of fibre reinforcement on resulting properties of developed fine-grained UHPC, especially the physical-mechanical characteristics - flexural strength, compressive strength, and subsequently blast resistance. Based on testing, the most suitable UHPC mixture was chosen to develop a mobile blast-resistant wall.

Research works depicted in this article build on previous phases of the research published in [1], where the same testing methodology of reinforced concrete blast resistance was used.

Fibre reinforcement is commonly used to provide enhanced toughness and ductility to brittle cementitious matrix. [2]. Owing to its dense microstructure, UHPC has both higher strength and also higher stiffness (expressed by the modulus of elasticity) when compared with normal- and high-strength concretes. It is well known that the behaviour of concrete becomes more brittle as its strength increases. This effect is particularly evident with UHPC. However, this disadvantage can be countered effectively by adding fibres, e.g. high-strength steel fibres, which bring about a considerable improvement in the post-peak behaviour in compression and tension, and that in turn means a more favourable response generally when failure is pending [3].



Fibre reinforcement in combination with high performance matrix is a way to improve blast resistance of concrete. Optimal composition with emphasis on the compatibility of the matrix and fibre is required, especially in the case of relatively thin wall elements [4] [5].

It is well known that the response of elements to dynamic loads depends on the rise time and the applied peak with respect to the natural period of vibration and the resistance of the element. The theory of the high dynamics of concrete structures and failure mechanisms of concrete elements loaded by a blast wave, including simulation methods, are described in [6] and [7]. The propagation of the compression wave during a blast creates strains in the concrete, and where the tensile strength of the concrete is exceeded, fragments are created on the rear side of the concrete element. This failure usually occurs in the surface zone, and conventional steel reinforcement is not able to help in controlling this event. On the other hand, randomly dispersed fibres are able to reinforce the concrete surface layers and thus enhance the tensile strength and prevent the concrete from fragmentation [8].

For the investigation of explosion resistance of concrete elements, the effect of concrete composition and mainly of different types of reinforcement was observed and subsequently the improved explosion resistance was evaluated.

2. Experimental works

All described works were aimed mainly on advanced optimization of developed UHPC composition so that the highest physical-mechanical values were achieved, including higher resistance to dynamic load, i.e. explosion. Such optimization lied in testing the influence of various dispersed steel fibre reinforcement combined with adjustments of water-cement ratio.

Predominantly, the physical-mechanical properties tested in new and optimized UHPC compositions were compression strength, flexural strength and bulk density. After testing, average values were calculated to choose the most suitable UHPC composition for blast tests, depicted in the latter half of this paper.

2.1. UHPC mixture composition

For evaluation and verification of physical-mechanical parameters of UHPC, total of 5 fine-grain UHPCs were proposed and verified. The testing bodies were sized $100 \times 100 \times 400$ mm and their manufacture was guided by methodology corresponding with ČSN EN 12390-2 Testing hardened concrete – Part 2: Making and curing specimens for strength tests. The compositions of individual UHPC mixtures are listed in Table 1.

Table 1. UHPC mixtures for the mechanical performance investigation.

UHPC mixture	Composition of proposed UHPC mixtures				
	S2B6%	S2B6%	S2B6%	S2B8%	S2B6%
	100	50/50	70/30	25	MIX
Cement 52.5 R	955	955	955	955	955
Sand 0-1 mm	1100	1100	1100	1100	1100
Mikrosilika Elkem 940	143	143	143	143	143
Plasticizer	25	25	25	25	25
Water	230	230	230	210	210
Water-cement ratio	0.24	0.24	0.24	0.22	0.22
Steel fibres 25/0.6	–	–	–	628	63
Steel fibres 30/0.6	–	234	312	–	–
Steel fibres 20/0.8 (corrugated)	468	234	156	–	408

Fine-grained mixture S2B with the best results in physical-mechanical and blast testing, based on the results presented in earlier stages of the research [1], was newly modified with new components - various types of steel fibre reinforcement, new plasticizer and new water-cement ratio, so that five variants of fine-grained UHPC mixture S2B were prepared. The individual variants differed mainly in type and amount of fibre reinforcement. The binder-filler ratio and also the plasticizer dose was identical in all five mixtures. The water-cement ratio was 0.22 – 0.24. The volume of fibres used for reinforcement represented 6 – 8 % of dry-mix volume. Mixtures S2B6%100 and S2B8%25 contained only one type of reinforcement while two types of fibres in different ratios were combined in the other samples.

2.2. Testing of physical-mechanical parameters

In this development stage, the tests were aimed at verification of influence of various types of dispersed steel reinforcement on UHPC mechanical parameters (see Table 1). Compression strength, flexural strength and bulk density were measured according to standards ČSN EN 12390-7 Testing hardened concrete – Part 7: Density of hardened concrete, ČSN EN 12390-5 Testing hardened concrete – Part 5: Flexural strength of test specimens, ČSN EN 12390-3 Testing hardened concrete – Part 3: Compressive strength of test specimens. The resulting average values calculated from testing six sample bodies are in Figures 1 – 3.

2.3. Blast resistance testing

Testing and subsequent evaluation of blast resistance values of designed and optimized UHPCs with various steel fibre reinforcement was conducted. Mixture compositions are listed in Table 1, their physical-mechanical properties are summarized in Table 2. The influence of various parameters of concrete mixture on blast resistance was investigated. The testing was conducted according to the following two methods:

2.3.1. *Modified method M-T0-VTUA 10/09.* Sample board is firmly attached to the test bench and loaded with a blast wave generated by initiation of the charge located at a defined distance from the test sample. After the test, the damage of the board is visually evaluated, together with determination of weight loss caused by fragmentation, and sheet metal plate for fragment capture placed under the sample. For this purpose, aluminium plates of 0.5 mm thickness were used. The charge initiated was 150 g of Semtex 10 (Eq. 180 g TNT) at a distance of 100 mm from the centre of the board sample. All samples were dried to constant weight before testing. The test configuration is in Figure 1 [9].



Figure 1. Testing bench T0B and test configuration according to modified method M-T0 VTUA 10/09.

2.3.2. The speed changes of ultrasonic wave propagation through the sample. The sample was attached to the test bench T0B and marked with 6 points, where the speed of ultrasonic wave propagation through the sample was measured before and after the blast. For the measurements, Proceq Tico device was used with 54kHz probe. The rate of increase in wave propagation time is directly dependent on the sample damage. The charge used was 100 g Sementex 10 (Eq. 120 g TNT). The charge weight was chosen in order to preserve the sample board integrity and, at the same time, to cause a measurable change in the ultrasonic wave propagation time and deflection so that individual concrete samples could be compared.

For blast test according to methods mentioned above, ten sample boards were prepared, two of each concrete mixture, sized $500 \times 500 \times 40$ mm. The results of both used testing methods are listed Table 3.

3. Results

The following figures and tables show average values of realized laboratory testing and external blast tests. The average strength and bulk density parameters of each UHPC mixture have always been calculated from measurements on at least six test specimens – beams of size $100 \times 100 \times 400$ mm. Blast tests were always carried out on two test boards from each UHPC mixture. The test board dimension was $500 \times 500 \times 40$ mm.

3.1. Bulk density after 28 days

The average bulk densities of the UHPC samples (see Figure 2) ranged $2.600 - 2.700$ kg/m³. There were no significant differences between the bulk densities of the individual UHPC samples, as the composition differed only in the type of reinforcement, dosed in the same volume of 6 %. The only mixture containing more reinforcement was S2B8%25 with 8 % fibre, therefore, the bulk density value of this sample was higher and reached $2,691$ kg/m³.

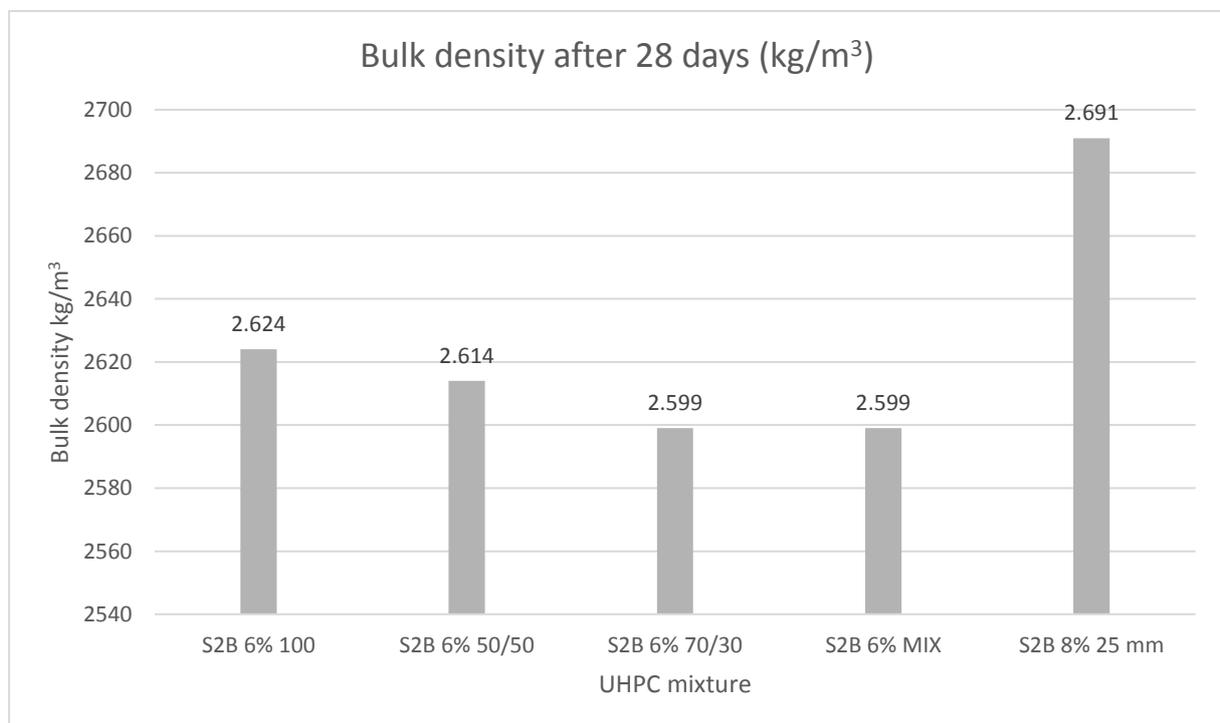


Figure 2. Average values of bulk density of the UHPC samples after 28 days of maturing.

3.2. Flexural strength after 28 days

The best results of flexural strength values were achieved with S2B8%25 UHPC mixture. Thanks to the type and amount of fibre reinforcement, the S2B8%25 mixture reached flexural strength of 28.41 MPa. The S2B6%50/50 mixture also exhibited satisfying result of 21 MPa as it contained 6 % of two types of fibre reinforcement differing in shape and length in 1:1 ratio.

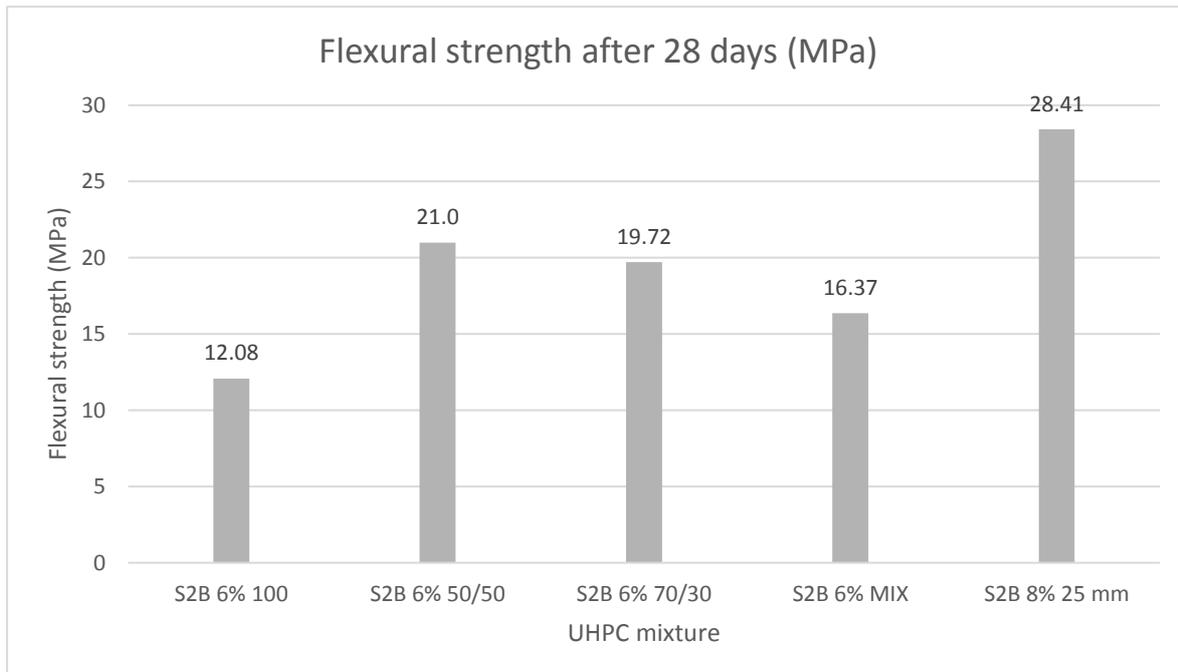


Figure 3. Average flexural strength values of the UHPC samples after 28 days of maturing.

3.3. Compressive strength after 28 days

The results of compressive strength measurements correlated with flexural strength results.

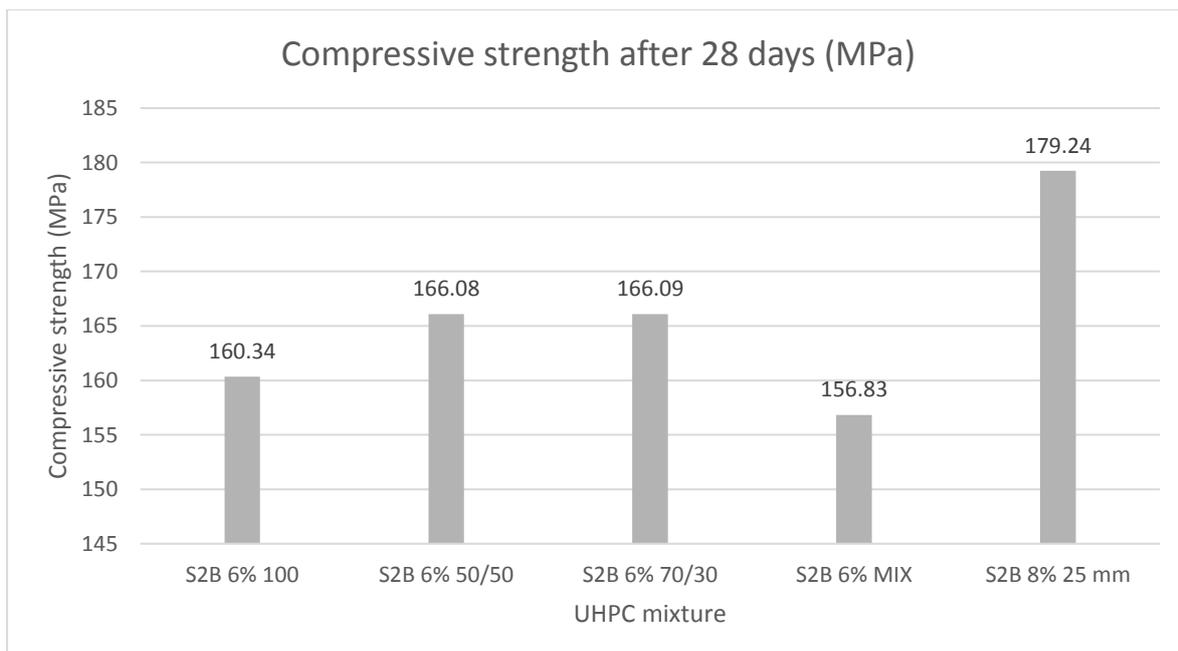


Figure 4. Average compressive strength values of the UHPC samples after 28 days of maturing.

Mixture composition S2B8%25 (containing 8 % of 25 mm fibre reinforcement) exhibiting the best flexural strength values reached also the best compressive strength values, 179.2 MPa in average. All results of physical-mechanical properties from Figures 2 – 4 are listed in Table 2.

Table 2. Summary of average physical-mechanical values of tested UHPC mixtures.

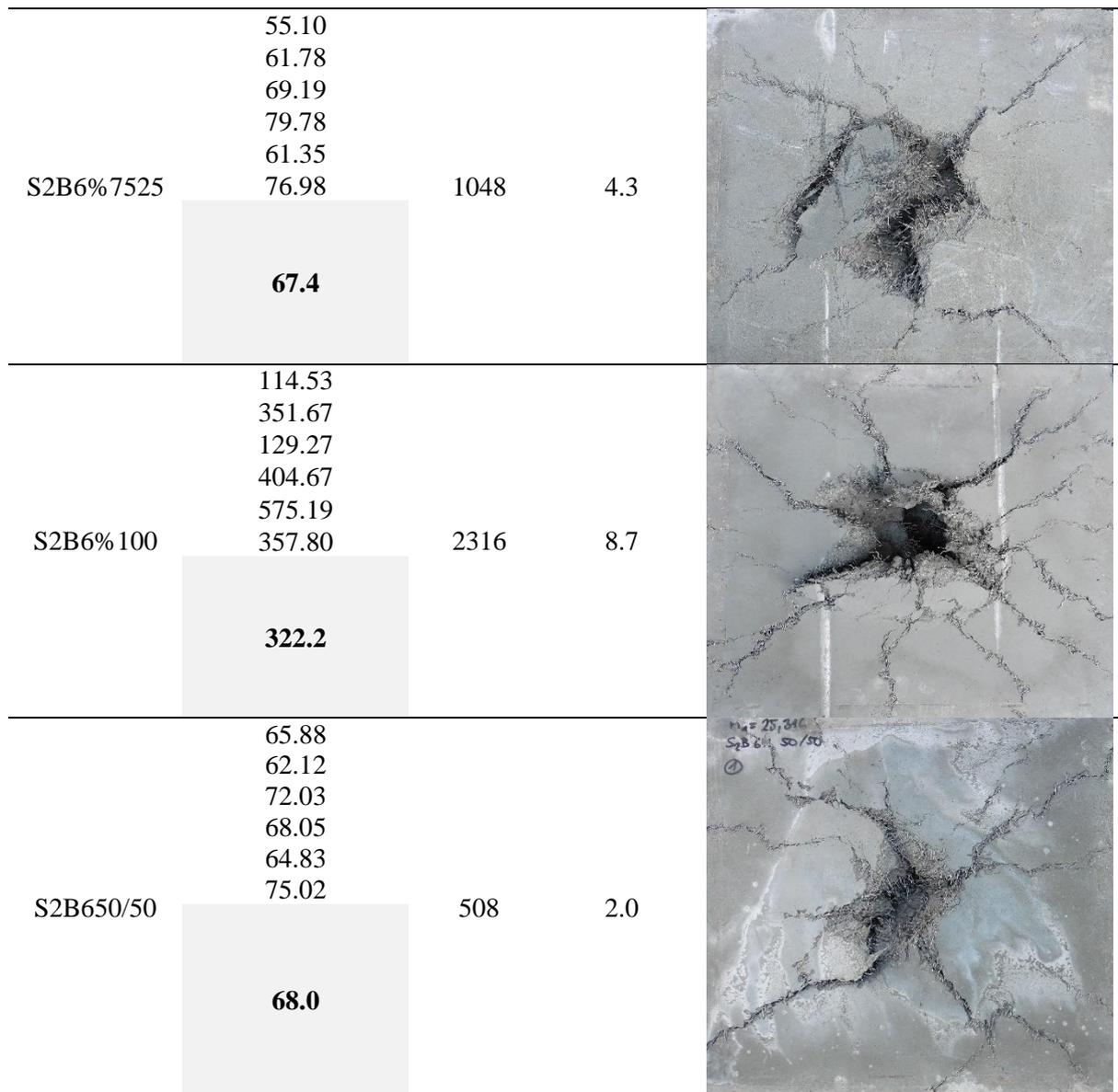
UHPC mixture	Bulk density (kg/m ³)	Flexural strength (MPa)	Compressive strength (MPa)
S2B6mix	2.599	16.40	156.80
S2B8%25	2.691	28.40	179.20
S2B6%75/25	2.599	19.70	166.10
S2B6%100	2.624	12.10	160.30
S2B650/50	2.614	21.00	166.10

3.4. Blast resistance testing

After physical-mechanical testing, blast resistance tests were conducted, according to methods depicted in 2.3. The results of both testing methods are summarized in Table 3. Measured ultrasonic wave propagation time is expressed as percentage increase after the explosion test. Absolute and relative weight loss of UHPC is also listed, together with photographs of sample board rear sides after testing according to the first method, i.e. after explosion of 150 g Semtex 10 charge. Based on results comparison, blast resistance of individual UHPC mixture compositions was evaluated.

Table 3. Summary of blast tests results.

UHPC mixture	Increase of UTS passage time [%]	Weight loss [g]	Weight loss [%]	Back of sample (150 g of Semtex 10 load)
S2B6mix	94.54	2240	8.6	
	217.66			
	96.98			
	89.09			
	86.95			
	88.83			
	112.3			
S2B8%25	49.48	498	1.9	
	42.81			
	43.82			
	31.77			
	31.89			
	3.31			
	39.5			



As seen from Table 3, from the point of view of ultrasonic wave propagation method, the best results of blast resistance of UHPC boards sized 500 × 500 × 40 mm were achieved with S2B8% 25 mixture composition. This sample showed also the best results of physical-mechanical testing thanks to the highest fibre content of all samples. Presumably due to the highest bulk density, these boards exhibited the lowest ultrasonic wave propagation increase after the blast. Subsequent weight loss (498 g, 1.9 %) caused by fragmentation was also the lowest at UHPC boards of mixture S2B8% 25. The second lowest weight loss after blast resistance test (508 g, 2 % w/w) occurred at UHPC boards of SB6% 50/50 mixture.

3.5. Application and advance testing of developed UHPC

Next advance stage was blast resistance testing of chosen UHPC mixtures in the shape of real application. The aim of this stage was to design and verify a mobile wall system resistant against highly intensive explosions. A protective wall was designed, composed of steel beams, effective anchoring and sandwich panels consisting of two UHPC layers (mixture S2B8% 25) and one absorption layer made of lightweight artificial aggregates and organic binder.

The whole developed blast protective system, its shape and dimensions were first designed in a 3D software, including the overall visualization. Subsequently, a cooperating company using LS-DYNA software, performed an explosion simulation of defined parameters in order to preliminarily determine a theoretical resistance of the designed wall and presumed deformations after the blast.

Based on the results of previous analyses, the explosion resistance of the developed protective wall system was verified. The ability of the developed protective wall to withstand the effects of a high intensity explosion was tested. The charge of the Semtex 10 plastic explosive was therefore set to the maximum possible value of 30 kg, the explosive was placed in 3 m distance from the tested wall. The course, intensity of the explosion and its effect on the tested shield system were recorded using several high-speed cameras and pressure sensors. The tested protective wall was made of steel construction and concrete panels sized $1000 \times 500 \times 40$ mm, which were made from optimized UHPC S2B8% 25 composition. Functionality and durability of the entire developed shield system against the effects of high intensity explosion of was then verified.

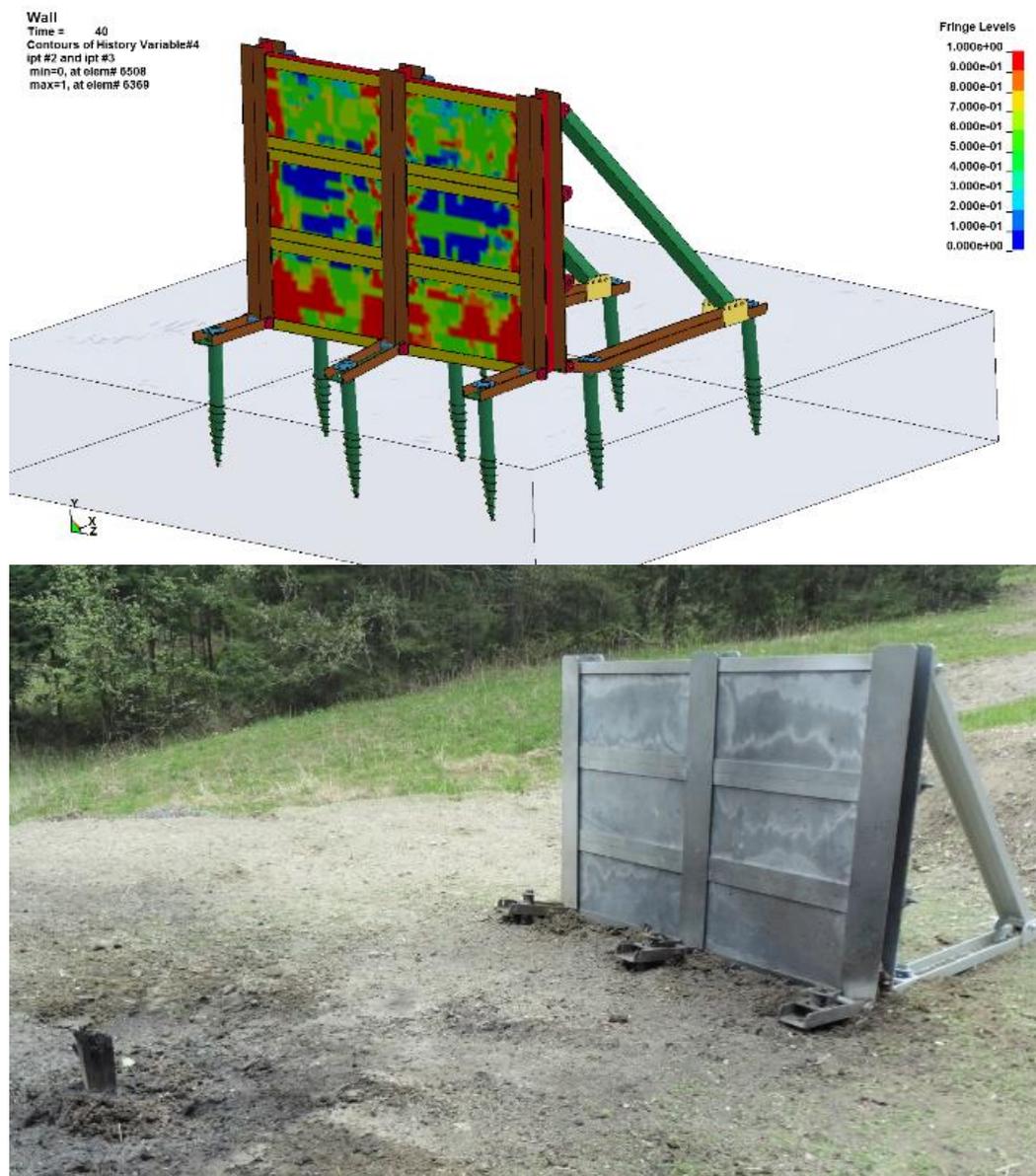


Figure 5: Comparison of results of software simulation and real explosion test.

As seen in Figure 5, the rate of damage, simulated in LS-DYNA software, was very similar to the real state of the shield system after the blast test. Panels made from UHPC mixture S2B8% 25 resisted the effects of explosion without visible damage and undesirable fragmentation. The most intensive load and slight shift were recorded only at the bottom of the shield wall as well as in the simulation, thus it can be said that the software simulations can be successfully used as an attractive alternative to the very expensive field explosive tests, in the early stages of development.

4. Conclusion

Realized research works were mainly focused on the impact of different composition of proposed UHPC mixtures on their properties. The influence of the type and amount of steel fibres content on physical-mechanical parameters and blast resistance of developed UHPC mixtures was evaluated.

On the basis of completed research works, it can be determined, that the utilization of higher volume of steel fibres content improves the strength characteristics of the UHPC samples significantly. The highest strength values demonstrated UHPC mixture marked as S2B8% 25, both in the case of flexural and compressive strength. Rather than the combination of two different types of steel fibres used, the increased dose of one type of steel fibres had significant impact on the resulting strength properties. The results of strength properties testing also demonstrated, that the use of corrugated types of steel fibres did not bring any significant UHPC strength value improvement. Despite the fact, that the corrugated fibres used improved the workability of the fresh mixture during the production of test samples, UHPC test specimens of mixture S2B6% 100 with the content of only corrugated fibres showed lowest flexural and even compressive strength values. On the other hand, if this type of corrugated fibres was used as hybrid, in combination with other type of straight steel fibres, results of developed UHPC mixtures strength parameters were higher, compare to test specimens where only the corrugated fibres were used. This theory was also confirmed in the case of the realized blast tests.

The test specimens of S2B8% 25 mixture exhibited the best integrity of all tested samples after explosion tests, which was demonstrated mainly as the lowest weight loss of tested UHPC samples. From the point of view of ultrasonic wave propagation method, the best results were achieved with UHPC boards of S2B8% 25 mixture. Second best results demonstrated specimens of S2B6% 50/50 mixture, where they hybrid content of corrugated and straight steel fibres was used. The lowest results of blast resistance of tested UHPC boards, for both methods used, demonstrated specimens of UHPC mixture S2B6% 100 with the content of only corrugated fibres. So as in the case of physical-mechanical properties tests, using the hybrid fibre type, the blast resistance parameters of the tested UHPC mixtures were improved, compared to UHPC mixture where only the type of corrugated fibre was used.

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