UHPC for Blast and Ballistic Protection, Explosion Testing and Composition Optimization

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Abstract. The realization of high performance concrete resistant to detonation is the aim and expected outcome of the presented project, which is oriented to development of construction materials for larger objects as protective walls and bunkers. Use of high-strength concrete (HSC / HPC - "high strength / performance concrete") and high-fiber reinforced concrete (UHPC / UHPFC - "Ultra High Performance Fiber Reinforced Concrete ") seems to be optimal for this purpose of research. The paper describes the research phase of the project, in which we focused on the selection of specific raw materials and chemical additives, including determining the most suitable type and amount of distributed fiber reinforcement. Composition of UHPC was optimized during laboratory manufacture of test specimens to obtain the best desired physical-mechanical properties of developed high performance concretes. In connection with laboratory testing, explosion field tests of UHPC specimens were performed and explosion resistance of laboratory produced UHPC testing boards was investigated.

1. Introduction
The paper refers to the experimental works being carried out within the research of ultra high performance concrete (UHPC) mixtures for special applications such as concrete precast elements, which exhibit improved mechanical performance when exposed to the explosion. For lower explosion load levels the UHPC seems to be a good and mainly inexpensive solution compared to other systems. The concrete itself as a quasi-brittle material does not conform to the resistance requirements, as at the explosion many secondary fragments are formed while the concrete breaks. The additional reinforcement (planar or randomly dispersed) provides the support within the concrete structure and thus increases the performance significantly [1]. Adding steel fibers to conventional concrete increases the impact strength by 2 to 15 times depending on the amount of fibers [2].

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 [3] and [4]. 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 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, the random dispersed fibers are able to reinforce the concrete surface layers and thus enhance the tensile strength and prevent the concrete from fragmentation [5].
For the investigation of explosion resistance of concrete elements the effect of concrete composition and mainly of different types of binder, filler and reinforcement was observed and further the improved explosion resistance was evaluated.

2. Used testing methods and UHPC mixture composition

2.1. UHPC mixture composition

Concrete mixtures of various compositions and reinforcement (see Table 1) were designed. The laboratory specimens for the mechanical performance investigation were prepared and the bulk density, compressive strength and flexural strength at 28 days of age were measured.

Table 1. Selected UHPC mixtures for the mechanical performance investigation.

| Designation of the mixture: | S2b   | S3    | S4    |
|----------------------------|-------|-------|-------|
| Weight unit                | kg/m³ | kg/m³ | kg/m³ |
| CEM I 52.5 R               | 955   | 650   | 650   |
| Water                      | 229   | 161   | 145   |
| w/c                        | 0.24  | 0.25  | 0.22  |
| Aggregate 0-2 mm           | 1,100 | 244   | -     |
| Aggregate 2-4 mm           | -     | 278   | 950   |
| Aggregate 4-8 mm           | -     | 425   | 416   |
| Aggregate 8-16 mm          | -     | -     | 230   |
| Superplasticizer           | 15    | 38    | 25    |
| Microsilica                | 143   | 177   | 100   |
| Micro - Dorsilit 405       | -     | 325   | -     |
| Micro - Dorsilit 2500      | -     | 131   | -     |
| Steel Fibers 30 mm, 600 N/mm² | 628   | 471   | 160   |

The exact composition of optimized recipes used for the test specimens preparation is given in Table 1. The UHPC recipes were designed to encompass the widest possible range of aggregates fractions. S2b recipe contains only fine aggregate, recipes S3 and S4 are representing UHPC recipes using a coarser aggregate fractions of maximal particle size 8 mm and 16 mm. Portland cement of strength class 52.5 was used as a binder in all cases. Steel fibers of length 30 mm had an important role in the formulation of UHPC composition, especially in terms of flexural strength. Steel fibers were dosed into the mixture in an appropriate amount depending on the type of the selected recipe. Our intention in UHPC recipes designation was to achieve the highest flexural strength values of prepared UHPC specimens and subsequently demonstrate the association of these values with explosion resistance of UHPC samples of the same composition.

2.2. Laboratory manufacture of test specimens

Test specimens - prisms of size 100x100x400 mm were made in order to optimize the composition of proposed UHPC recipes and verify their physical-mechanical characteristics. Test specimens - boards with dimensions 500x500x40 mm were manufactured for testing within explosion tests. Production of UHPC test specimens took place according to a predetermined methodology, corresponding to the requirements of EN 12390-2 Testing hardened concrete - Part 2: Preparation and treatment of test specimens for strength tests and EN 12390-1 Testing hardened concrete - Part 1: Shape, dimensions and other requirements for test specimens and molds.

All the dry input materials in the form of cement, aggregates and additives were weighed first on a laboratory weighing equipment. Likewise, the necessary amount of steel fibers was weighed.
The necessary amount of water and liquid superplasticizer was then added. Subsequently, all the dry input materials were homogenized and added to the mixer. The exact time of the fresh mixture mixing was established. Finally, measured amount of water and superplasticizer was added during the mixing. Adequate mixing of the individual components of the moist mixture was monitored and consistency of the ready fresh mixture was measured before the final addition of steel fibers. Consistency was determined by visual assessment using a slump test according to EN 12350-2 Testing fresh concrete - Part 2: Slump test. Thanks to the low water/cement ratio, the consistency class was determined as S0 (very stiff) or S1 (solid). Laboratory produced fresh UHPC mixture was dosed into the steel molds to produce test specimens. Homogenization of fresh mixture was carried out using a laboratory vibrating table. Laboratory-made test specimens were removed from the molds next day and stored for 7 to 28 days in water tank at a constant temperature of 20 °C. After 28 days of wet storage the specimens were tested for the desired physical-mechanical characteristics.

2.3. Determination of physical-mechanical characteristics

Testing of physical and mechanical properties of selected UHPC recipes and their subsequent optimization of the composition, based on the obtained results, were carried out according to the procedures specified in the relevant standards for concrete testing. Bulk density, compressive and flexural strength of the hardened concrete specimens were tested. Testing of physical and mechanical properties of selected UHPC recipes was done according to the following standards:

- Bulk density - test was carried out according to EN 12390-7 Testing hardened concrete - Part 7: Bulk density of hardened concrete.
- Flexural strength – test was carried out according to EN 12390-5 Testing hardened concrete - Part 5: Flexural strength of test specimens
- Compressive strength - test was carried out according to EN 12390-3 Testing hardened concrete - Part 3: Compressive strength of test specimens.

Realized experimental works on the laboratory manufactured test specimens were made to optimize the UHPC recipes in relation to achievement of the best values of physical-mechanical characteristics of UHPC specimens. Thus the influence of UHPC composition on flexural and compressive strength values of laboratory manufactured specimens was verified.

Figure 1 shows course of flexural strength values determination of laboratory manufactured UHPC test specimens. On figure 2 we can see UHPC test specimens after the determination of flexural strength properties. The symmetrical distribution of aggregate and wire reinforcement is clearly visible on the cross sections of the test specimens.

Figure 1. UHPC specimens tested on flexural strength – 4 point bending.
2.4. **UHPC structure analysis using polarizing microscope**

Hardened test specimens were also used for UHPC structural analysis using a polarizing microscope. Verification of even distribution of aggregate and binder in the structure of specimens was the main purpose of this analysis. We could also get a clear idea of the distribution, quantity and size of the air pores in the specimen structure.

Measurements were performed on polished uncovered samples of thickness 25 µm. Samples were cured with resin, in which fluorescein was mixed. Polarizing microscope operates in the following modes:

- **PPL** – Mode with one polarizer. We observe the color and pleochroism.
- **XPL** – Mode with a polarizer and analyzer. We observe interference colors and extinction.
- **XPL + gypsum plate** – Mode with a polarizer and analyzer and with inserted gypsum plate (adds λ / 2 wavelength of used light) extinct, black turns into purple.
- **FL** – Fluorescent mode.

The results of the analysis revealed the following facts: Aggregates were uniformly distributed and cementitious adhesive evenly filled the space between the grains of aggregate. Most specimens were found without signs of degradation of the test sections and without any segregation of aggregate. Air pores occurred in a completely normal quantity and of appropriate size. For some specimens presence of air pores was observed in the lines. It was found that the weakened zones are linked to the movement of the steel fiber reinforcement in the structure of the fresh mixtures and to the larger air voids. The occurrence of these weakened zones can be caused by too intensive or inappropriate method of vibration during homogenization of a fresh mixture or by insufficient tightness or defect of molds for specimen production. Therefore it is necessary to avoid of these technological errors.

Figure 3 shows a detail of the UHPC test specimen of recipe S2b. The picture was taken under the PPL mode with one polarizer. Black spherical object at the center of the image shows a cross section of the wire reinforcement. UHPC specimen had a very homogeneous structure with a minimal amount of air pores, which was positively reflected in the achieved strength characteristics. Slight spread out of aggregate particles can be noticed around the wire reinforcement. That was caused by the movement of the wire reinforcement before the hardening of fresh concrete mixture.
Figure 3. Detail of polished uncovered UHPC sample, recipe S2b.

Figure 4. Detail of polished uncovered UHPC sample, recipe S2b.

Figure 4 shows detail of another test specimen of UHPC recipe marked S2b, sample thin section was 42x23 mm and figure is 20x magnified. Vertical fissure shows the cavity after the fiber reinforcement, which was released during preparation of the test sample. The presence of two large air pores and connection between these pores in the form of tiny crack can be seen in the left part of the picture (marked with red circle). It is important to avoid occurrence of large pores in order to preclude weakening of homogeneous structure of UHPC, which can be subsequently reflected as a decrease in the values of the strength characteristics.

2.5. Explosion testing
Research works in the form of explosive testing of developed UHPC specimens were realized in order to verify the explosion resistance of developed UHPC recipes. Explosion tests were carried out according to two proposed methods – Modified methodology M-T0-VTÚO 10/09 [6]. Concrete board
was firmly attached to the test bench, explosive hung at a defined distance from the test sample and explosive resistance of UHPC samples was tested. Damage of UHPC boards was assessed visually after the test, and then the weight loss of UHPC boards was measured. Metal plates 1 mm thick, which were placed under the testing bench and used to capture potential fragments, were also visually assessed. The used explosive charge was Semtex 10, the charge quantity and the distance were set by primary tests on 150 g of Semtex 10 (Eq. 180 g of TNT) at a distance of 100 mm from the center of the charge.

Described test bench T0B for modified explosive testing methodology M-T0-VTÚO 10/09, developed by cooperating Military Research Institute in Brno, Czech Republic is shown on figure 5.

Figure 5. Test bench T0B for modified methodology M-T0-VTÚO 10/09 explosive testing.

The second testing methodology was based on monitoring of changes in the speed of transmission of ultrasonic waves thru the sample before and after exploding load. The samples were tested again on the test bench T0B (figure 5). Each sample was designated with a network of 12 measuring points and transit time of ultrasonic waves before and after the blast was measured. It has been proven that the rate of increase in time of transit of the wave thru the sample is in direct connection with the breach of the sample. The dynamic deviation of tested concrete boards with laser displacement sensor was also monitored.

Sensor placement is evident from figure 6. Sensor was placed in a wooden base, covered with an absorbent foam for mitigating shocks and covered with a plexiglas plate for maximum protection. 100 g of Semtex 10 (eq. 120 g of TNT) was used as a load.
Explosion tests carried out according to a modified methodology M-T0-VTÚO 10/09 were aimed at determining of the optimal mass of charge and its distance from the test sample, in order to achieve sufficient breach of sample with respect to the evaluation methodology. Weight losses of concrete samples, breach of concrete samples and steel plates were monitored. The tests were carried out using 150 g of Semtex 10 explosive.

3. Results

As the graph in Figure 7 shows, the highest average values of flexural and compressive strength reached specimens of fine grained UHPC recipe labeled as S2b. The decrease in strength values, due to the used coarse aggregate in composition and lower binder content, can be seen at recipes labeled as S3 and S4. Nevertheless the values of flexural and compressive strength still fully reflected the category of high-strength concrete.

![Figure 7. Average strength values of optimized UHPC recipes.](image-url)

Additional values of tension, deformation and stress were monitored during the strength testing. The results of these tests were then used for analytical methods and computational simulation in ANSYS.
LS-DYNA software. This program allows simulation of the explosion and its effects on an element of a predetermined size. One of the objectives of these numerical simulations is design and optimization of test components and determination of the extent of their supposed resistance before the start of the field explosion tests. So it can be used as an attractive alternative to the very expensive field explosive tests.

Due to the high cost of field explosion tests, four test specimens maximum from each UHPC recipe were tested. The following figures shows some examples of tested UHPC test specimens and their ability to withstand the effects of a test explosion. Figure 8 shows front side of the same UHPC test specimen of size 500 x 500 x 40 mm (recipe S2b) before and after explosion testing.

![Figure 8. UHPC test sample (recipe S2b) before and after explosive test.](image)

Figure 9 shows front and back side of UHPC specimen, recipe S3, after explosion test. As can be seen, back side of the sample is always more damaged due to an explosion effect. Some weight loss can be observed due to the concrete fragmentation. The extent of fragmentation was monitored using sheet metal plates, which were placed under the UHPC specimen. Achievement of total fragmentation avoidance is necessary for successful test of the UHPC explosion resistance.

![Figure 9. UHPC test sample (recipe S3) after explosive testing – front and back side of the board.](image)

Figure 10 shows front and back side of UHPC specimen, recipe S4, after explosion test. As can be seen, UHPC specimens of the S4 recipe showed higher resistance to explosion in the form of lower weight loss and fragmentation.
Other explosion tests were carried out according to the second selected test methodology based on measurement of changes in the structure of the test samples with the use of non-destructive testing. For this case, measuring of the changes of ultrasonic waves passing through the test specimen was used. Semtex 10 explosive charge of weight 100 g was chosen for this test purposes. Weight of Semtex 10 explosive was chosen to maintain the integrity of the test sample, and further to enable measurement of the changes of ultrasonic wave transit times through the UHPC test samples before and after explosion tests. Device Proceq Tico with the 54 kHz probe was used for this purpose. The progress of dynamic variations in time were recorded using graphs.

Dynamic variation means the non permanent deflection of the UHPC test sample during an explosion. An example of a dynamic variation graph is shown in Figure 11. As shown in the figure 11, the largest deflection of the UHPC test specimen was recorded at 0.1565 ms from the beginning of this explosion test and its value was 3.5 mm.

Summary of results with the inclusion of the parameters of both used methods is shown in Table 2. The table summarizes only the samples that were tested with 150 g of Semtex 10. The table does not include the samples tested at a lower load value. Only two UHPC recipes with best values - fine grained...
S2b recipe and coarse grained S4 recipe were used for final summary. Instead of S3 recipe, S4 recipe was chosen as a representative of coarse grained UHPC recipes because of better values of physical-mechanical parameters and better results of previous explosive tests. All the monitored parameters showed appreciable differences between samples. Measuring of the dynamic variations provides valuable results, but it is necessary to use a more accurate sensor with a higher sampling frequency in the future. The transit time of ultrasonic waves through the UHPC samples has increased significantly after explosion tests due to disruption of the internal structure of samples. Increase was also evident at samples without significant external damage. Transit time, expressed in percentage, corresponds to a visual assessment of UHPC samples (sample weight loss and disruption).

**Table 2.** A summary of the results of both implemented methodologies for two best UHPC recipes S2b (fine aggregate) and S4 (coarse aggregate).

| Sample | Dynamic deflection [mm] | Dynamic deflection [mm] | Increase of UTS wave transit times in selected points [%] | Weight loss [g] | Back side of samples after explosion testing (150 g of Semtex 10) |
|--------|-------------------------|-------------------------|---------------------------------------------------------|----------------|---------------------------------------------------------------|
| S4     | 8.37                    |                         | 140.6                                                   | 538            | ![Image of S4 sample](image) |
|        |                         |                         | 197.3                                                   |                |                                                               |
|        |                         |                         | 164.0                                                   |                |                                                               |
|        |                         |                         | 220.3                                                   |                |                                                               |
| S2b    | 3.97                    |                         | 6.5                                                     | 28             | ![Image of S2b sample](image) |
|        |                         |                         | 31.5                                                    |                |                                                               |
|        |                         |                         | 26.9                                                    |                |                                                               |
|        |                         |                         | 28.5                                                    |                |                                                               |

**4. Conclusion**

Based on previous research, three best UHPC recipes were selected for research works of year 2016. The recipes were selected to encompass the widest possible range of fractions of used aggregates. UHPC recipe S2b contained only fine aggregate, recipes S3 and S4 contained aggregate of coarser fractions. Maximal grain size was 8 mm and 16 mm. These UHPC recipes were used for laboratory production of concrete samples. Subsequent research has mainly dealt with the evaluation of explosive resistance of designed concrete mixtures. The influence of various parameters on explosive resistance of designed concrete samples was evaluated. Realized research works were mainly focused on the impact verification of different composition of proposed UHPC recipes and on verification of the appropriateness of the proposed test methodologies.
The following conclusions can be drawn:

- A relation between the flexural strength of the UHPC samples and the overall explosive resistance evaluated according to the methodology M-T0-B VTÚO 10/09 was found. The higher was the flexural value the better was the explosive resistance of the concrete. This relation enables prediction of UHPC explosive resistance using the simple quasi-static test procedure.
- The utilization of fine grained aggregates in combination with higher binder and steel fibers content enhanced the blast resistance of the UHPC samples.
- The highest resistance to explosion load demonstrated a fine-grained UHPC recipe marked as S2b. Test specimens of S2b recipe exhibited best integrity of tested samples after realized explosion tests. This was reflected mainly in the form of the lowest weight loss of tested UHPC samples. Also, the values of dynamic displacements of S2b recipe reached the best (lowest) values.
- Coarse grained UHPC recipes labeled as S3 and S4 also reached satisfactory results in the form of sufficient explosion resistance, despite the higher weight loss of the test specimens compared to the specimens of fine grained UHPC recipe S2b and good physical-mechanical parameters in the form of high values of flexural and compressive strength characteristics.
- Based on carried out research, adequacy of developed methodologies for assessment of explosive resistance of samples can be concluded as sufficient. The results of both methods correspond to each other. However it is counted with minor modifications of these methodologies for future testing.

Described UHPC recipes will be used for the manufacture and testing of developed shield systems - protective walls in 2017. These shield systems will have to withstand considerable loads. Expected mass of plastic explosive for these explosive tests is equal to 30 kg of Semtex 10.

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