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Blast resistance of slurry infiltrated fibre concrete with hybrid fibre reinforcement

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Abstract. This paper investigates experimentally the blast resistance of slurry infiltrated fibre concrete (SIFCON) with hybrid fibre reinforcement realized by various combinations of polypropylene (PP), aramid, carbon, glass, wollastonite and steel fibers. The binary reinforcement systems were designed using the combinations of steel/PP, steel/aramid, steel/glass, steel/wollastonite and steel/carbon fibres with various fibre geometry. Six different batches (including one reference specimen) were examined with aim to determine the influence of the parameters of hybrid reinforcement on blast resistance of the concrete. Mechanical parameters at quasistatic load (flexural strength, compressive strength) were determined and load-deflection curves were captured. Real blast tests were performed on the slab specimens (500 x 500 x 40 mm) according to the modified methodology M-T0-VTU0 10/09. The change of the ultrasonic wave transit time before and after the blast load in certain measurement points, damage of the slab, the weight of fragments and their damage potential were evaluated and compared. The results indicate, that hybrid fibre reinforcement, when properly designed, can highly enhance overall blast resistance of SIFCON and can significantly reduce the spalling. Steel-aramid combination brought the best blast resistance.

1. Introduction
High performance concrete itself as a quasi-brittle material does not conform to the blast resistance requirements. Fiber reinforcement is often used to provide enhanced toughness and ductility to brittle cementitious matrix. By the addition of steel fibres to conventional concrete, the impact strength value can be increased 2–15 times depending on the amount of the fibres [1]. Research on the use of fibres to increase both the blast and impact resistance of concrete has typically been focused to steel fibres and, less, on polypropylene fibres. [2–4] Some studies have been found dealing with glass, nylon, ceramic and carbon fibres reinforced concrete related to blast or impact resistance of the material [5–9]. These studies confirm better performance of fibre reinforced concrete (FRC) under impact load compared to plain concrete without reinforcement. Ref. [10] is comparative study of concrete with high spectra of different kind of fibres (PP, glass, basalt, steel) and fibre blends in the same matrix and their performance while subjected to the blast load. According to this study, the blast resistance of the concrete is connected with the tensile strength of the incorporated fibre. Fibres with a low tensile strength are not able to resist the high shear and flexural strains generated by blast loads. [10]

The reinforcement of concrete with a single type of fiber may improve the desired properties to a limited level, whereas combination of two or more types of fibres, if used in optimal way in concrete, achieves better engineering properties due to positive synergetic effect. [11] Generally, inclusion of fibers in concrete in hybrid forms improves many of its engineering properties such as toughness,
ductility, energy absorption capacity and durability performance in comparison with mono fiber reinforcement. [12] The different methods of hybridization include combining different lengths, diameters, modulus and tensile strengths of fibers [13, 14]. Maalej et al. [15] found that hybrid fibre-reinforced concrete offered increased shatter resistance with reduced scabbing, spalling and fragmentation, whilst exhibiting better energy absorption.

Special type of high performance concrete with high steel fibre reinforcement is slurry infiltrated fibre concrete (SIFCON). This composite is prepared by infiltrating of the preplaced fibres by the mortar slurry. This production technology enables to incorporate large amounts of steel fibres (typically 8–10%, but in general up to about 15%) in cement-based composites [16]. Compared to ordinary high performance fiber-reinforced concrete, SIFCON exhibits enhanced ductility, energy absorption capacity and overall integrity under dynamic load [17], and thus has potential for applications in protective structures. Excellent blast resistance of SIFCON in terms of overall integrity and internal damage was concluded in [18], but some fragmentation of the matrix was admitted. This can be prevented by using small amount of micro-fiber reinforcement in the mortar, but more information in this field must be provided, as the studies comparing the dynamic properties of hybrid fibre reinforced SIFCON composites are very limited [19] and focus only on low strain rates.

The presented research is part of the development process of cement-based materials with enhanced blast resistance, which will be used in the elements for critical infrastructure protection, such as barriers and sandwich structures. The main objective of the work presented herein is thus to provide more information about the effects of various hybrid-fibre reinforcement on mechanical properties and blast resistance of SIFCON.

2. Experimental program

2.1. Materials and specimen preparation

Fine SiO₂ sand (670 kg/m³) with grain size of 0–1 mm, cement CEM 52.5R (990 kg/m³) and water (320 kg/m³) were the main components of the slurry mixture. Superplasticizer Glenium 422 (10 kg/m³), produced by BASF, was added to achieve good workability. Silica fume Elkem 940U (78 kg/m³), produced by BASF, with a typical particle size 100–500 nm, was used to achieve an optimized particle packing density and for pozzolanic properties. As the main reinforcement, the steel fibres KrampeHarex 50/0.8DE fibres (length 50 mm, diameter 0.8 mm) with hooked ends were selected, the dosage in each specimen was 9 vol. %. As secondary reinforcement, microfibres were used; their properties and volume fraction are summarized in Table 1. The particular micro-fibres were selected to cover the high spectra of properties. The amount of the fibres varied slightly to achieve similar workability of the slurry.

| Designation | Fibre content (Vol. %) | Fibre material | Density of the fibre (kg.m⁻³) | Length/diameter of the fibre (mm/μm) |
|-------------|------------------------|----------------|-------------------------------|-------------------------------------|
| ST50AR0.5   | 0.5                    | Aramid         | 1,400                         | 1.0/12                              |
| ST50GL0.7   | 0.7                    | AR glass       | 2,680                         | 1.3/12                              |
| ST50PP0.5   | 0.5                    | Polypropylene  | 910                           | 2.2/15                              |
| ST50CP0.5   | 0.5                    | Carbon PAN     | 1,760                         | 2.0/12                              |
| ST50WO2.0   | 2.0                    | Wollastonite   | 2,800                         | 0.3/9                               |

Steel moulds were used to cast the specimens. Moulds were treated with releasing agent and sealed at the edges by using silicone to prevent any leakage of cement–sand slurry from the mould. The mixing procedure of the slurry was as follows: 2/3 of the required water amount with whole dosage of superplasticiser was poured into the Power-sprays GRC 125 mixer; sand, cement and microsilica were added and stirred together for 60 seconds, to achieve homogenous paste without any bulks. As the next
step, the micro-fibres were added and mixed for another 60 seconds. At the end of the mixing process, the rest of the water was added and mixed for another 30 seconds. Prepared mortar was poured over the pre-placed steel fibres. Prepared slurry was workable enough and the infiltration was possible for all tested mixes, but the length of PP fibre (2.2 mm) was determined as limit value to keep good infiltration level. The test specimens were demoulded after 24 hours and were cured for 28 days in curing water ponds. For quasistatic mechanical tests, prism specimens of dimensions 100 × 100 × 400 mm were cast, for blast tests, slabs of dimensions 500 × 500 × 40 mm were prepared.

2.2. Quasistatic mechanical tests and bulk density

The mechanical parameters were obtained using universal strength testing machine TIRAtest 2710, R58/02. The compressive and flexural load (four-point flexural test) was applied at quasi-static conditions (speed of 5 mm/min). The stress-deflection curves were captured to compare the post peak behaviour of the materials.

2.3. Blast tests

Prepared slabs were subjected to the test procedure according to the certified methodology M-T0-B VTUO 10/09 modified to cover two tests. The methodology was developed by the Military Research Institute of the Czech Republic and is used for assessing the blast resistance of several materials. The concrete specimen is fixed in the steel frame of the stand and the stand is placed on a solid foundation. During the first test, the spheres of Semtex 10 plastic high explosive weighing 150.0 g are used as testing charges. The weight and distance (100 mm from the test specimen) of the testing charge was adjusted to be strong enough to cause the significant visible damage of the specimens, including fragmentation. Under the stand, the check panel consisting of hardboard-polystyrene-aluminium plate sandwich is placed. Aluminium plate creates the front face adjacent to the test specimen and its thickness is 0.5 mm. Observed and evaluated parameters are the weight of created secondary fragments and their destructive power expressed as the degree of damage of the check panel (without damage/indentation/perforation). Second test covers the loading of the specimen fixed in the stand with the charge 100 g of Semtex 10. The weight for this test was adjusted to cause the low-level damage (small cracks, the slab should remain integral). The change of the ultrasonic wave transit time at four measuring points before and after test was evaluated. The rate of the change of this parameter is directly connected to the internal damage of material. The scheme of the test rig is depicted in Figure 1. The distance of the charge was same as in the previous test – 100 mm. The data obtained from both tests corresponds well and give enough information to create good overview about how the particular material performs under blast load; and materials can be compared easily.

![Figure 1. Scheme of the test rig.](image)
3. Results and discussion

3.1. Physico-mechanical properties

The results of determined physico-mechanical properties are summarized in Table 2. The compressive strength was positively affected by addition of secondary micro-reinforcement. On contrary, the flexural peak strength was almost not affected by secondary fibre incorporation, the values were similar - between 32–35 MPa, except for specimen with aramid fibres (42 MPa). Stress-deflection curves (see Figure 2, 3 and 4) showed different post peak behaviour for specimens with secondary reinforcement. The ascending part of the curve is similar for all specimen. All specimens with secondary reinforcement, except for specimen with wollastonite, showed no sharp flexural peak stress with plateau region and less steep shape of the decreasing part of the curve (= the post peak stress was higher at a given strain), which indicates higher load bearing capacity of the specimens. The highest post-peak load bearing capacity showed the specimen with aramid fibre reinforcement.

Table 2. Physico-mechanical properties of specimens with various hybrid reinforcement.

| Designation | Bulk density (kg·m⁻³) | Compressive strength (MPa) | Flexural strength (MPa) |
|-------------|-----------------------|----------------------------|------------------------|
| ST50AR0.5   | 2,679                 | 136.0                      | 42.1                   |
| ST50GL0.7   | 2,680                 | 132.0                      | 33.3                   |
| ST50PP0.5   | 2,686                 | 143.1                      | 32.1                   |
| ST50CP0.5   | 2,697                 | 150.2                      | 35.1                   |
| ST50WO2.0   | 2,693                 | 128.1                      | 33.2                   |
| ST50REF     | 2,681                 | 122.4                      | 34.1                   |

Figure 2. Stress-deflection curves for specimen ST50CP0.5 (left) and ST50PP0.5 (right).

Figure 3. Stress-deflection curves for specimen ST50GL0.7 (left) and ST50WO2.0 (right).
3.2. Blast test results

The experiments focused on the effect of different hybrid fibre mixes on the blast performance of SIFCON were carried out. Performance was determined according to the methodology described above, and the results are presented in Table 3. Two slabs were prepared with each mix. When evaluating the behaviour of the concrete under blast load, the special attention must be paid to secondary debris creation, as the bystanders can be injured by them during a blast. The destructive power of the debris was expressed as the degree of damage of the check panel.

None of the specimens exhibited a complete loss of integrity. The REF specimen with only primary reinforcement sustained the greatest amount of damage, see Table 3 and Figure 5b. Surface crater was created in the centre of the rear side of the slab. Using the polypropylene and wollastonite secondary reinforcement, the overall blast resistance of the specimens increased, the internal damage of the slab expressed as increase of US wave transit time in % was lower compared to the ST50REF specimen, but fragmentation of the slab still occurred, see Figure 5a and 5c, and created fragments caused perforation of the check panels. The low performance of specimen ST50PP0.5 with polypropylene fibres is probably caused by their low mechanical properties – the tensile strength of the PP fibre is 0.3 GPa, which is almost the order of magnitude lower than of the other used fibres. Another reason can be the weaker bond of the fibre in the hardened concrete. Observed low effectivity of PP fibres in enhancement of blast resistance of hybrid fibre reinforced concrete corresponds with findings published in [10]. In the case of ST50WO2.0 (wollastonite reinforced specimen), the low enhancement of the blast resistance was probably caused by unsuitable geometry of the used fibres – the length of the fibre was only 0.3 mm, which was not sufficient for effective strain transfer. The results of blast test were consistent with results of quasistatic tests, where the low reinforcing effect of wollastonite fibres was also observed – the flexural peak stress and post peak behaviour was almost the same as in case of REF specimen, without any enhancement.

![Figure 4. Stress-deflection curves for specimen ST50AR0.5 (left) and ST50REF (right).](image)

| Designation | Increase of US wave transit time at four points (%) | Fragment weight (g) (%) | Check panel damage/quantity of perforation |
|-------------|---------------------------------------------------|-------------------------|------------------------------------------|
| ST50AR0.5   | 23/90/134/96                                      | 20/0.08                 | Indentation/0                             |
| ST50GL0.7   | 40/24/80/75                                       | 50/0.21                 | Indentation/0                             |
| ST50PP0.5   | 436/1200/75/97                                    | 166/0.69                | Perforation/2                             |
| ST50CP0.5   | 90/98/114/102                                     | 30/0.13                 | Indentation/0                             |
| ST50WO2.0   | 423/968/86/88                                     | 126/0.49                | Perforation/5                             |
| ST50REF     | 230/2284/90/74                                    | 192/0.44                | Perforation/5                             |
Figure 5. Slabs after blast test a) ST50PP0.5, b) ST50REF, c) ST50WO2.0.

Figure 6. Slabs after blast test d) ST50GL0.7 e) ST50AR0.5 f) ST50CP0.5

Specimen ST50GL0.7 with glass fibre reinforcement performed well under the blast load – only very few splinters of total weight 50 g were created, without perforation of the check panel. The addition of aramid fibre as secondary reinforcement had unambiguous positive influence on the response of the slab to the blast load. Very low internal damage and almost no fragmentation (see Figure 6e) were observed in the case of specimens ST50AR0.5. The slab remained integral with only 20 g weight loss, with no visible cracks or crater creation. Similar results were achieved in the case of the specimen ST50CP0.5 with carbon fibre, just some surface splinters of total weight 30 g were created without perforation of the check panel. High enhancement of the overall blast resistance of the specimens ST50AR0.5 and ST50CP0.5 can be attributed to the mechanical properties of the fibres (high tensile strength and modulus) coupled with their shape parameters, in particular the length sufficient for good anchoring and high aspect ratio (L/d). With the same fibre length, the higher aspect ratio means higher amount of fibres included in the matrix for the same volume content of fibres, thus the matrix is more homogenously reinforced. Less areas between the fibres remain unreinforced and thus brittle, which prevents the slab from fragmentation.

4. Conclusions

Research on behaviour of SIFCON with various hybrid fibre reinforcement under blast load was carried out in order to obtain new knowledge necessary for designing the SIFCON type materials for protective structures. The following conclusions can be drawn:

- At quasistatic load, the addition of secondary reinforcement improves the post peak behaviour of SIFCON, except for specimen with wollastonite fibre. The hybrid fibre reinforced specimens (except for ST50WO2.0) showed plateau region around the flexural peak strength and less steep shape of
the decreasing part of the curve (= the post peak stress was higher at a given strain). Both
the aforementioned statements indicate higher load bearing capacity compared to REF specimen.
- The addition of secondary micro-fibre reinforcement brought improvement of blast resistance of all
specimens, as the micro-fibres reinforced and thus strengthened the matrix between the steel fibres.
The contribution differed significantly depending on the type of fibre.
- The aramid fibre and PAN carbon fibre secondary reinforcement was proved to give great improvement
in performance under blast load over mono-fibre reinforced specimen, in terms of reduction of mass
lost, fragmentation and internal damage. This can be attributed to the high tensile strength of the fibres
and suitable shape parameters (length and high L/d aspect ratio) connected with high anchoring length
and high amount of fibres in the specimen.
- PP micro-fibres were proved to be less suitable for enhancement of the blast resistance, probably due
to their lower mechanical parameters. Another reason can be the weaker bond of the fibre in the hardened
concrete.
- Wollastonite micro-fibre inclusion was not very effective for improvement of blast resistance of
the SIFCON composite, the main reason are unsuitable shape parameters – the length of the fibers is too
short for effective transfer of the strain.
- The fibre length must not exceed 2.2 mm to achieve good infiltration of primary reinforcement and
thus homogeneity of the specimen.

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References
[1] Schrader E K 1981 ACI Journal 78 p 141
[2] Wu C, Oehlers D J, Rebentrost M, Leach J and Whittaker A S 2009 Eng. Struct. 31 p 2060
[3] Luo X, Sun W and Chan S Y N 2000 Cement Concrete Res. 30 p 907
[4] Masuya H, Yamamoto M, Toyama M and Kajikawa Y 2000 Structural Mater. 8 p 205
[5] Tabatabaei Z S, Volz, J S, Baird J, Gliha, B P and Keener D I 2013 Int. J. Impact Eng 57 p 70
[6] Su H and Xu J 2013 Constr. Build. Mater. 45 pp 306–313
[7] Musselman E 2007 Blast and impact resistance of carbon fibre reinforced concrete Ph. D
dissertation (Pennsylvania, USA: The Pennsylvania State University. University park)
[8] Ginter V T, Baeza F J, Ivorra S et al 2012 Materials and Des. 34 p 332
[9] Coughlin A M, Musselman E S, Shokkerb A J and Linzell D G 2010 Int. J. Impact Eng 37 p 521
[10] Drdlová M, Buchar J, Ridký R et al 2015 Blast resistance characteristics of concrete with
different types of fibre reinforcement Struct Concrete 16 p 508
[11] Singh S K, Chourasia A, Dalbehera, M M et al 2013 Hybrid fibre reinforced concrete – A review
New Building Material & Construction World
[12] Pakravan H R, Latifi M and Jamshidi M 2017 Constr. Build. Mater. 142 p 280
[13] Silva E R, Coelho J F J and Bordado J C 2013 Constr. Build. Mater. 40 p 473
[14] Ahmed S F U and Maalej M 2009 Constr. Build. Mater. 23 p 96
[15] Maalej M, Qeck S T and Zhang, J 2005 J. Mater. Civil Eng. 17 p 143
[16] Zhang M H, Sharif M S H and Lu G 2007 Mag. Concrr. Res. 59 p. 199
[17] Drdlová M, Řídký R and Čechmánek R 2016 Mater. Sci. Forum 865 p 135
[18] Drdlová M, Sviták O and Prachař V 2017 Mater. Sci. Forum 908 p 72
[19] Azoom K T and Pannem R M R 2017 Int. J. Civil. Eng. Technol. 8 p 1123