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Blast resistance of hybrid fibre reinforced concrete containing polyvinyl alcohol, polypropylene and steel fibres with various shape parameters

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Abstract. This paper experimentally investigates the blast resistance of hybrid-fibre high performance concrete reinforced with various combinations of polyvinyl alcohol (PVA), polypropylene (PP) and steel fibres. The binary reinforcement systems were designed using combinations of steel/PP and steel/PVA fibres with various fibre geometries. Eleven different batches were examined to determine the influence of the parameters of the hybrid reinforcement (the material, shape parameters of the fibre, combinations of fibres) on the blast resistance of the concrete. Mechanical parameters under quasistatic load (flexural strength, compressive strength) were determined and load-displacement curves were captured. Real blast tests were performed on slab specimens (500 × 500 × 40 mm) according to the modified methodology M-T0-VTU0 10/09. The damage to the slab, the change in the ultrasound wave velocity propagation in the slab specimens before and after blast loading in certain measurement points, the weight of fragments and their damage potential were evaluated and compared. The results indicate that hybrid fibre reinforcement, when properly designed, can significantly enhance the overall blast resistance of concrete and can reduce spalling. Steel/PVA combinations provided higher blast resistance compared to steel-PP fibre mixes. The specimen containing a combination of 50 mm steel fibres and 12 mm PVA fibres showed the best performance under blast load.

1 Introduction

High performance concrete (HPC) itself as a quasi-brittle material does not conform to blast resistance requirements. The propagation of a compression wave during a blast creates tensile strain in concrete, which can cause the concrete element to exceed a spall threshold and fragments to be ejected from the reverse side of the concrete

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element. As this failure usually occurs in the surface zone, the presence of conventional steel reinforcement is not helpful in limiting this phenomenon.

Fibre reinforcement is commonly used to provide enhanced toughness and ductility to brittle cementitious matrix. The addition of steel fibres to conventional concrete allows the impact strength value to be increased 2–15 times depending on the amount used [1]. Research on the use of fibres to increase both the blast and impact resistance of concrete has typically been focused mainly on steel fibres, with less of an emphasis on polypropylene (PP) fibres [2–4]. Some studies have been found that deal with glass, nylon, ceramic and carbon fibre reinforced concrete (FRC) related to the blast or impact resistance of the material [5–8]. These studies confirm the better performance of FRC under impact load compared to plain concrete without reinforcement. Reference [9] focused on the blast performance of concrete elements used as vehicle barriers. Four concrete samples representing different FRCs were examined. Two types of synthetic FRC and two steel-synthetic blend FRCs with different fibre volumes were tested. A sample of traditional reinforced concrete served as the control specimen.

Each of the FRCs exhibited less material loss and surface damage compared to the control. The two steel-synthetic blended concretes exhibited the least amount of damage of all barriers, with no visible difference in performance between the two fibre volumes. The control barrier suffered widespread spalling and only a limited amount of concrete in the core of the specimen remained intact [9]. Reference [10] is a comparative study of concretes with a wide spectrum of different kinds of fibres (PP, glass, basalt, steel) and fibre blends in the same matrix, and their resulting performance when subjected to 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 fibre may improve the desired properties to a limited level, whereas a combination of two or more types of fibres, if incorporated optimally in concrete, achieves better engineering properties due to the consequent positive synergetic effect [11]. Generally, the inclusion of fibres in concrete to create hybrid forms improves many of the material's engineering properties such as toughness, ductility, energy absorption capacity and durability performance in comparison with mono fibre reinforcement [12]. The various methods of hybridization include combining the different lengths, diameters, moduli and tensile strengths of fibres [13,14]. Maalej et al. [15] found that hybrid FRC offered increased shatter resistance with reduced scabbing, spalling and fragmentation and exhibits higher energy absorption at the same time. Also, concrete back face spalling can be reduced through the use of dispersed fibre reinforcement, as the fibres ensure the bridging of tensile cracks and thus additional tensile capacity is achieved. As fibres either pull out or yield, energy is absorbed and the fracture energy of the matrix is increased [15]. Therefore, hybrid-fibre reinforcement, with a proper volume of high and low modulus fibres, is expected to show an improvement in both tensile strength, which is important for penetration resistance, and strain capacity, which is important for energy absorption [16].

So far, most existing experimental studies on the impact behaviour of hybrid reinforced cement-based composites have focused on an impact velocity of up to $700\,\mathrm{m/s^{-1}}$ [15,17–19], and it was found that hybrid fibres improved shatter resistance and strain capacity with reduced scabbing, spalling, fragmentation and zone of damage [19]. Zhang et al. [16] evaluated the effects of the content, type and length of fibres on the impact resistance of concrete struck by a projectile at a velocity of 610–$710\,\mathrm{m/s^{-1}}$. Their experimental results showed that concrete containing 1% of steel fibres and a combination of 0.75% steel fibres and 0.25% PP fibres was more promising in resisting the projectile impact than concrete containing only 1% polyethylene

Table 1. Properties of the investigated fibres.

Designation	Tensile strength (MPa)	Fibre diameter (μm)	Length (mm)	Modulus of elasticity (GPa)	Elongation at break (%)	Density ($kg\,m^{-3}$)
Krampe Harex DE50/08N	1200	800	50	210	0.5–3.5*	7800
Krampe Harex DE30/06N	1200	600	30	210	0.5–3.5*	7800
Krampe Fibrin PM12/18	300	18	12	1.5–4.2*	50–80	910
Krampe Fibrin PM6/18	300	18	6	1.5–4.2*	50–80	910
Kuralon RESC15	1600	40	6	41	6	1300
Kuralon RESC100L	1200	100	12	38	12	1300

* The data was obtained from [21].

(PE) or 1% PP fibres. In addition to the aforementioned experimental studies on the impact behavior of cementitious materials, the high velocity impact process affecting hybrid-fibre cement-based panels with 1.5% PE and 0.5% steel fibres subjected to hard projectile impact was simulated by Li and Zhang [19]. These investigations demonstrated that hybrid fibres could indeed improve the impact resistance of cementitious materials. The impact resistance of hybrid FRC was also studied by Khin et al. [20] A combination of polyvinyl alcohol (PVA) fibre and steel fibre was used (1.75% PVA fibre and 0.58% steel fibre). It was concluded that this material exhibited increased impact resistance and energy absorption capability compared to both plain concrete and a hybrid-fibre reinforced reference specimen with 1.5% PVA and 0.5% steel fibres. However, the body of research into the high velocity impact behavior of hybrid-fibre concrete is still rather limited in scope, particularly with regard to structural behaviour under blast load. The presented research aims to fill this gap, as it is focused on research on the behaviour of HPC reinforced with various combinations of PVA, PP and steel fibres under blast load.

2 Experimental

2.1 Materials

Concrete mixtures containing various binary hybrid reinforcement systems were prepared. Steel, PP and PVA fibres were used. The properties of the fibres are summarized in Table 1.

Fine-aggregate HPC was selected as a standard. This type of concrete is compatible with all of the fibres selected; owing to the limited grain size and excellent workability of the material due to additives, good dispersion of the fibres can be achieved. Fine SiO_2 sand with 0–1 mm grains, CEM 52.5R cement and water were the main components of the concrete mix. Glenium422 super-plasticizer (produced by BASF) was added to achieve good workability with a low water/binder ratio. Elkem 940U silica fume (also produced by BASF), with a typical particle size of 100–500 nm, was used to create an optimized particle packing density, and also for its pozzolanic properties. The mix proportions of the concrete are described in Table 2. A fine-grained matrix containing a high amount of cement and microsilica was reported by other researchers to be the optimal material for use in structures that are the potential targets of terrorist attacks [22,23]. The fibres were selected so as to cover the variety of properties under consideration, and the mixes were designed to enable data to be obtained on the influence of the parameters of the tested hybrid reinforcements on

Table 2. Mix proportion of concrete matrix in kg m^{-3}.

Cement CEM 52.5R	Fine aggregate	Silica fume	Superplasticizer	Water
955	1050	115	15	229.2

Table 3. Mix proportion of fibres incorporated in specimens in vol.%.

Designation	Krampe Harex DE50/08N	Krampe Harex DE30/06N	Krampe Fibrin PM12/18	Krampe Fibrin PM6/18	Kuralon RESC15	Kuralon RESC100L
30/06PP12	0	70	30	0	0	0
30/06PP6	0	70	0	30	0	0
50/08PP12	70	0	30	0	0	0
50/08PP6	70	0	0	30	0	0
30/06PVA12	0	70	0	0	0	30
30/06PVA6	0	70	0	0	30	0
50/08PVA12	70	0	0	0	0	30
50/08PVA6	70	0	0	0	30	0
30/06 ref I	0	100	0	0	0	0
50/08 ref II	100	0	0	0	0	0
Ref III	0	0	0	0	0	0

the blast resistance of the concrete. Steel fibre was selected as the high modulus fibre to ensure the high tensile strength of the materials. For the middle modulus fibre, PVA fibres were selected.

PP fibres were selected as a representative of low modulus fibres because the properties of the other fibres in this group were less favourable than those of PP fibres. E.g. low-density PE and polyolefine (PO) fibre exhibit lower tensile strength than PP fibre, and the smooth surfaces of PO fibres lead to more difficult bonding with the cement paste than steel fibres and would thus require surface treatments to improve the bond strength [24]. Also, PP fibres are easily accessible and have a low manufacturing price compared to other polymeric fibres [21]. Eleven mixes (including three reference samples) were prepared; the volume fraction of the fibres (3%) was kept constant for all the mixes except for the Ref III specimen, which did not contain any fibre reinforcement. According to [5], the higher the amount of incorporated fibres, the higher the blast resistance of the concrete. The selection of a 3% fibre content was based on the results of initial technology tests which found that this was the maximal amount that can be easily incorporated while preserving good workability. The mix proportions of the fibres incorporated in each batch are presented in Table 3. According to the literature, the reported optimal ratio of polymer to steel for the best impact resistance ranges between 50–75:50–25 [20,25], but this fact is not completely valid for the impact caused by detonation. It was thus decided that a fibre mix ratio of polymer to steel of 30:70 would be used according to the results of previous research [10]. The fibres used are depicted in Figures 1 and 2.

2.2 Specimens and procedures

Prism specimens of 100 × 100 × 400 mm in size were prepared for the mechanical performance investigation. The mixing procedure was as follows: first, the dry components (cement, sand and microsilica) were mixed together using a concrete mixer, and then the required quantity of water with plasticizer was added and mixed for 3 min. The fibres were incorporated at the end of the mixing process, steel fibres at first,

Fig. 1. The polypropylene (left) and polyvinylalcohol (right) fibres used.

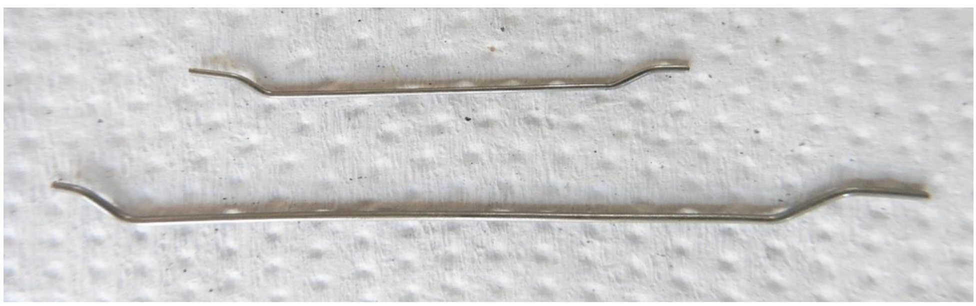


Fig. 2. The steel fibres used (30 and 50 mm).

followed by polymeric fibres, and the mixture was stirred for another 2 min to achieve good dispersion of the polymeric fibres. Selected appropriate mixing procedures were used after 30 s so that the fibres were well dispersed without any visible agglomerations. The mixes were placed in moulds treated with releasing agent and a vibration table was employed for better compaction of the mixture. The test specimens were demoulded after 24 h and cured for 28 days in water-filled curing ponds. The bulk density was measured according to CSN ISO 6275, and the compressive and flexural strengths were ascertained after 28 days in accordance with CSN EN 12390-3 and CSN EN 12390-5. At least five specimens of each mix were tested and the average values computed. The load-displacement curves were captured during flexural tests.

For the explosion tests, 40 × 500 × 500 mm concrete panels were produced and a test procedure was applied according to the certified methodology M-T0-B VTÚO 10/09, which was 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. A concrete specimen is fixed in the steel frame of a stand and clamped around its whole perimeter; the stand is placed on a solid foundation. During the first test, 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 significant visible damage to the specimens, including fragmentation. A witness panel consisting of a hardboard-polystyrene-aluminium plate sandwich was placed under the stand. The observed and evaluated parameters are the weight of ejected secondary fragments and their destructive power expressed as the degree of damage to the witness panel. The second test was designed by the authors and covers the loading of the specimen fixed in the stand with a 100.0 g charge of Semtex 10. The weight for this test was

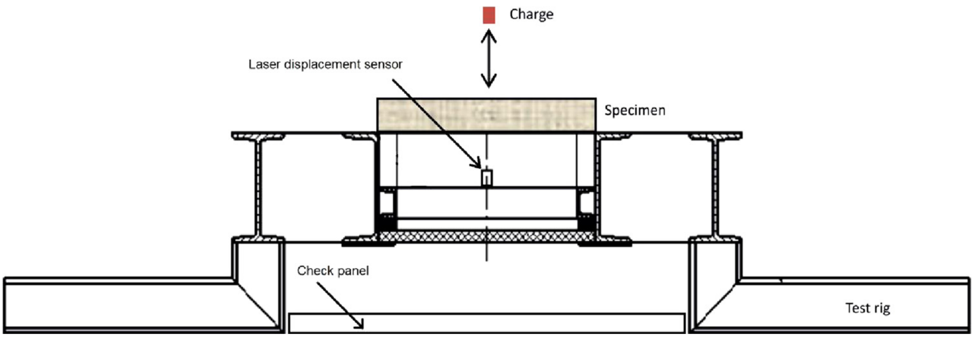


Fig. 3. Scheme of the test rig.

adjusted to cause low-level damage (small cracks; the slab should retain structural integrity). The change in the ultrasonic wave transit time at four measuring points before and after the test was evaluated. The measuring points were fixed for all panels. The rate of the change in this parameter is directly connected to the damage to the material. The scheme of the test rig is depicted in Figure 3. The distance of the charge was the same as in the previous test – 100 mm. Additionally, the residual (permanent) deflection of the centre of the test slab is measured by an optoNCDT ILD2300 laser sensor. This was fixed in a wooden holder filled with absorbent foam, covered by a transparent shield and placed under the test specimen. The position of the sensor is depicted in Figure 3 – the distance between the sensor and the centre of the slab was 200 mm. The sensor was only used during the second test, when the lower load was applied and the test slab retained its integrity. The lower the measured value of residual deflection, the better the performance of the material under the blast load that can be expected. The data obtained from both tests correspond well and give enough information to create a good overview of how the particular material performs under blast load; also, materials can be compared easily.

A numerical simulation was performed on specimens REF I, REF II, 50/08PVA12 and 50/08PP12 in the LS-Dyna solver. The Constrained Lagrange in Solid model was used for the simulations. The damage to the specimen was evaluated and maximal residual deflection was calculated. The slab specimens were fixed around the whole perimeter and loaded with a 100.0 g charge of Semtex 10 from a distance of 100 mm. A model of the steel fibre reinforcement was created (see Fig. 4) and combined with three different kinds of matrix – a plain cementitious matrix, a matrix reinforced with 12 mm PP fibres and a matrix reinforced with 12 mm PVA fibres (represented by their mechanical properties). The explosive wave was modelled as a blast in Euler mesh. The described load was simulated as an interaction between the Euler mesh of the air and blast mixture and the solid Lagrange mesh of the specimen. The residual deflection of the centre of the slab and the damage to the rear face of the slab was calculated.

2.3 Test results and discussion

2.3.1 Effect of various hybrid fibre mixes on mechanical properties under quasi-static load

The flexural and compressive strengths after 28 days are shown in Table 4; the given data is the average values of 5 specimens. The specimens were tested under quasi-static conditions according to the aforementioned standards at a loading rate

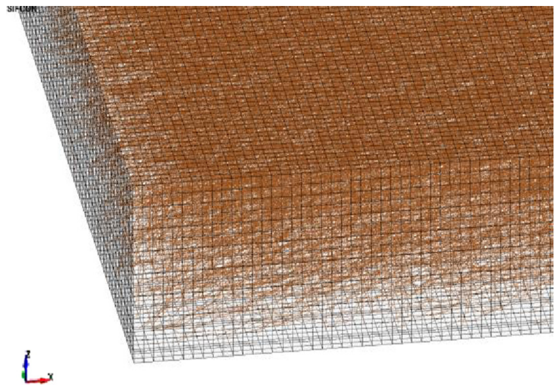


Fig. 4. Created model of fibre reinforcement.

of 5 mm/s^{-1}. Prism specimens (100 × 100 × 400 mm) were used to determine the flexural strength values, while the compressive strength was determined on the free edges of the specimens subjected to flexural loading. Direct compression tests were conducted in which the loading area was 100 × 100 mm. All the specimens exhibit low coefficients of variation of up to 0.15, which indicates the good dispersion of the fibres and thus the good homogeneity of the prepared materials. The fibre distribution was also checked visually on the fracture surface after flexural testing. No bundles of fibres were observed. As seen in Table 4, the addition of any type of fibre or fibre blend enhances the flexural strength of the HPC. The fibres form a network that bridges the cracks that appear during flexural loading. In general, the individual fibres may be subdivided into two groups: discrete monofilaments separated from one another, e.g. steel; and fibre assemblies in the form of filaments, e.g. PP, glass or PVA. The combination of both types is reported to enhance the flexural strength of FRC, as the thin short fibres limit microcracking and the long thicker fibres limit macrocracking, which leads to a higher flexural loadbearing capacity [10]. Load-deflection curves (Figs. 5 and 6) were captured for all specimens in order to better understand the influence of several hybrid fibre combinations on the energy absorption and bending load bearing capacity of the HPC. The mixtures with added PP fibres show lower flexural strength values compared to the mixtures containing PVA fibres. The values were even lower than in the case of mixtures containing steel fibres only, which corresponds with the findings of the study [26], where the partial replacement of steel fibres with PP fibres leads to a decrease in mechanical properties. Other findings were reported in studies [27,28], in which the authors concluded that the replacement of a small proportion of the steel fibres with PP fibres does not negatively influence the mechanical properties of the composite. The lower flexural strength of the composite with steel-PP fibres in our study could be connected to the larger amount of air entrapped in the specimens as a consequence of the process of mixing very low diameter (18 μm) staple PP fibres into the material. This could be inferred from the reduced bulk density of the steel-PP specimens, which is only partly caused by the lower specific gravity of the PP fibres.

The mixtures containing PVA showed better performance under flexural load compared to both PP-steel and mono-steel systems, which is in agreement with results published by Lawler [29,30]. In particular, in the case of the addition of 12 mm long PVA fibres, the hybridization enhances the flexural strength and energy absorption capacity of the composite. This can be mainly attributed to the inherent affinity of PVA to water (due to the presence of OH– groups), which leads to efficient dispersion and strong bonds in the hardened HPC. The high tensile strength and modulus of the

Table 4. Quasi-static mechanical tests and bulk density.

Designation	Bulk density [kg m^{-3}]	Compressive strength [MPa]	Flexural strength [MPa]	Coefficient of variation [–]
30/06PP12	2294	108.08	11.60	0.090
30/06PP6	2279	103.30	13.89	0.100
50/08PP12	2248	109.90	16.57	0.105
50/08PP6	2273	99.93	18.40	0.130
30/06PVA12	2345	120.73	19.09	0.140
30/06PVA6	2354	116.74	16.60	0.140
50/08PVA12	2377	123.88	24.28	0.080
50/08PVA6	2372	118.63	21.59	0.013
30/06 ref I	2380	116.45	16.62	0.15
50/08 ref II	2388	123.53	21.65	0.14
Ref III	2277	110.78	6.70	0.12

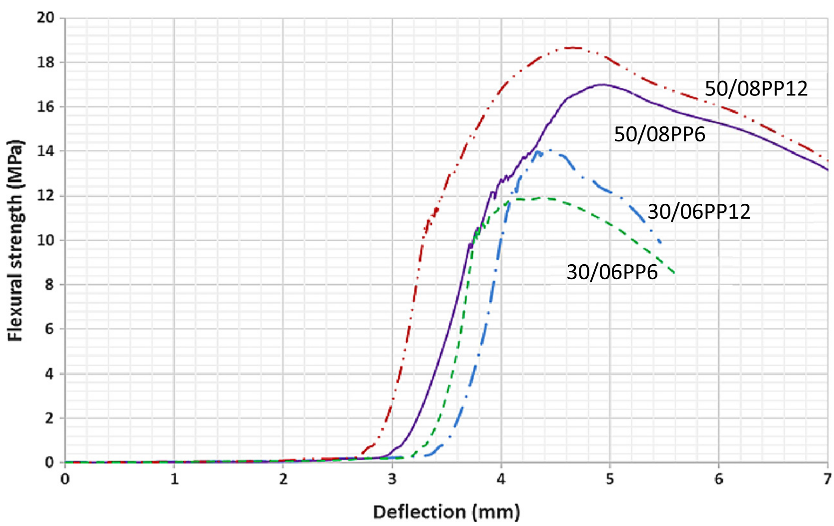


Fig. 5. Load-deflection curves of specimens with steel-PP reinforcement.

fibres is also an important factor. As seen in Figures 5 and 6, steel fibre parameters have a dominant influence on mechanical performance. Longer fibres provide higher flexural strength. The post-peak behaviour and energy absorption does not seem to be highly affected by the introduction of the second type of fibre. The best performance, as regards flexural strength, was shown by specimen 50/08PVA12, which had 2 vol.% of 50 mm long fibres and 1 vol.% of 12 mm long PVA fibres.

2.3.2 Effect of various hybrid fibre mixes on mechanical properties under blast load

The experiments focused on the effect of different hybrid fibre mixes on the blast performance of concrete were carried out. Two slabs were prepared from each mix. The first slab from each mix was subjected to the detonation of a 100.0 g charge of Semtex 10 (11 blast tests), while the second slab was subjected to the detonation of a 150.0 g charge of Semtex 10 (11 blast tests). This was carried out according to the

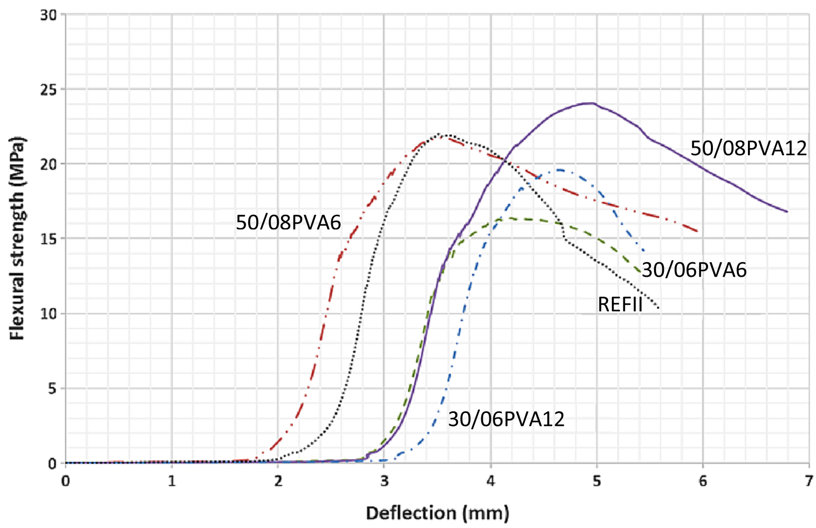


Fig. 6. Load-deflection curves of specimens with steel-PVA reinforcement.

Table 5. Blast test results.

Designation	Residual (permanent) deflection [mm] (charge 100.0 g)	Increase of US wave transit time in four points [%] (charge 100.0 g)	Fragment weight [g]/[%] (charge 150.0 g)	Witness panel perforation/ quantity of perforation (charge 150.0 g)
30/06PP12	6.0	847.0/207.4/287.12/147.69	454/2.01	Yes/1
30/06PP6	5.3	625.1/201.4/286.1/270.2	350.4/1.6	Yes/1
50/08PP12	4.6	572.64/123.6/184.4/269.7	166/0.7	No
50/08PP6	5.9	598.14/197.1/224.4/239.3	334/1.5	No
30/06PVA12	5.9	545.67/168.81/125.99/54.37	42/0.19	No
30/06PVA6	3.2	1.57/45.96/97.20/47.55	32/0.15	No
50/08PVA12	2.9	0/54.07/47.05/44.82	8/0.03	No
50/08PVA6	2.9	78.29/55.69/46.97/55.93	16/0.07	No
30/06 ref I	5.5	520.51/197.4/268.12/162.8	625/2.7	Yes/2
50/08 ref II	5.7	726.01/233.4/289.12/247.3	680/2.8	Yes/2
Ref III	–	–	Completely destroyed	Completely destroyed

methodology M-T0-B VTÚO 10/09 described in Section 2.2. In total, 22 blast tests were performed. The results of both tests are presented in Table 5.

When evaluating the behaviour of concrete under blast load, special attention must be paid to secondary debris. To study trends in the size and speed of fragments ejected from specimens is of great importance, as both small and large fragments can threaten bystanders during a blast. Flying concrete fragments are more dangerous if they are large and have high velocities. Large fragments are more likely to cause injuries and fatalities than smaller fragments, though small fragments can still seriously threaten bystanders. Though the actual velocities of the fragments were not measured, the destructive power of the debris was expressed as the degree of damage to the witness panel.

None of the specimens exhibited a complete breach (except for the control specimen, Ref III), but their damage varied significantly. The control specimen (Ref III) without fibres sustained the greatest amount of damage, see Figure 7. A 300 mm crater was created in the slab, and after being removed from the test rig, the slab collapsed and lost its integrity. This failure was anticipated, and despite the fact that the inclusion of this slab cannot provide a quantitative comparison with fibre-reinforced slabs, its performance can qualitatively demonstrate the effectiveness of FRC against blast load. Specimens 30/06 Ref I and 50/08 Ref II with mono – steel fibre reinforcement showed better performance (compared to Ref III), confirming the well-known positive effect of fibre reinforcement on the blast resistance of concrete reported by other authors [31,32]. However, fragments were still created and ejected from the reverse side of the specimens, perforating the aluminium witness panels (50/08 Ref II: 5 fragments of total weight 680 g, 2 perforations; 30/06 Ref I 4 fragments of total weight 625 g, 2 perforations). Under blast load, the specimen with 30 mm steel fibres outperformed the specimen with 50 mm fibres, whereas under quasi-static load (in particular flexural strength), the specimens performed in an opposite fashion. This indicates that higher flexural strength parameters under quasistatic load do not necessarily provide higher overall blast resistance. Specimens with PP and PVA mono-fibre reinforcement have not been covered in the presented research as their blast resistance has been reported to be insufficient [10]. The hybrid reinforcement used in all tested specimens provided an improvement in blast resistance, though its contribution differed significantly depending on the type and size parameters of the fibres used in the hybrid mixes. Regarding the steel-PP hybrid fibre reinforcement, secondary fragmentation was observed in the case of all specimens. However, the extent of the damage was in all cases a little less than the damage to the 30/06 Ref I and 50/08 Ref II specimens, and varied depending on the shape parameters of the incorporated fibres. The combination of 50 mm steel fibres and 12 mm PP fibres leads to the best performance within the PP-steel group (see Tabs. 5 and 6): only one small 166 g fragment was created, no perforation of the witness panel occurred, and the measured permanent deflection of the slab was 4.6 mm. A typical output of the deflection-time measurements is depicted in Figure 8. From this group, the lowest resistance against blast load was shown by the specimen with 30 mm steel and 12 mm PP fibres – three fragments with a total weight of 454 g were ejected from the reverse side, perforating the check panel at 1 point. Also, the internal damage to the slab expressed as a percentage increase in the ultrasonic wave transit time was close to that of the Ref I and II specimens.

The addition of PVA fibres had an unambiguously positive influence on the response of the slabs to the blast load. As seen from Table 5 and Fig. 7, the best results were obtained from the combination of 50 mm steel fibres and 12 mm PVA fibres. No fragmentation and thus zero damage to the witness panel occurred, and only narrow cracks on the test slab were observed. The increase in the US wave transit time in four measuring points was in the range of 0–44% (123–573% in the case of 50/08PP12 specimen with PP fibres), while the maximal permanent deflection reached 2.9 mm. Similar results and behaviour were observed in the case of the specimen with 50 mm steel and 6 mm PVA fibres: only 1 very small flat fragment weighing 16 g was created with no visible indication of damage to the witness panel; the permanent deflection measured was 2.9 mm. Both specimens with 30 mm steel fibres showed higher deflection – 3.2 and 5.9 respectively – and higher internal damage, but retained their integrity almost without fragmentation.

The results indicate that long steel hook-ended fibres with high modulus and tensile strength in combination with higher modulus polymer fibre with higher length and high surface area can provide good overall blast resistance. Steel fibres with higher length ensure better overall integrity when used as the main load bearing element, while fragmentation can be greatly reduced by using higher modulus bundle type polymeric fibre. The proper selection of the polymer fibre type is important, as its

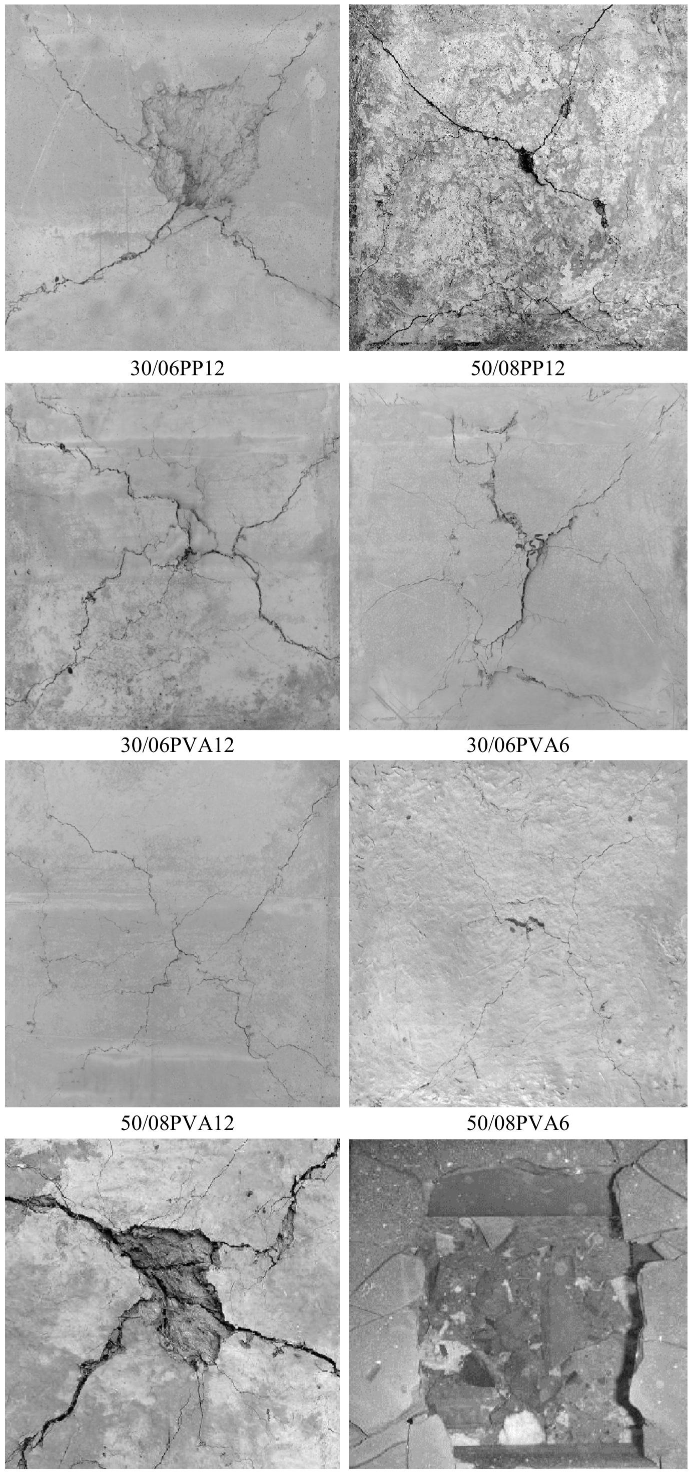


Fig. 7. The damage to the reverse side of the slab specimens after blast testing (150.0 g of Semtex 10).

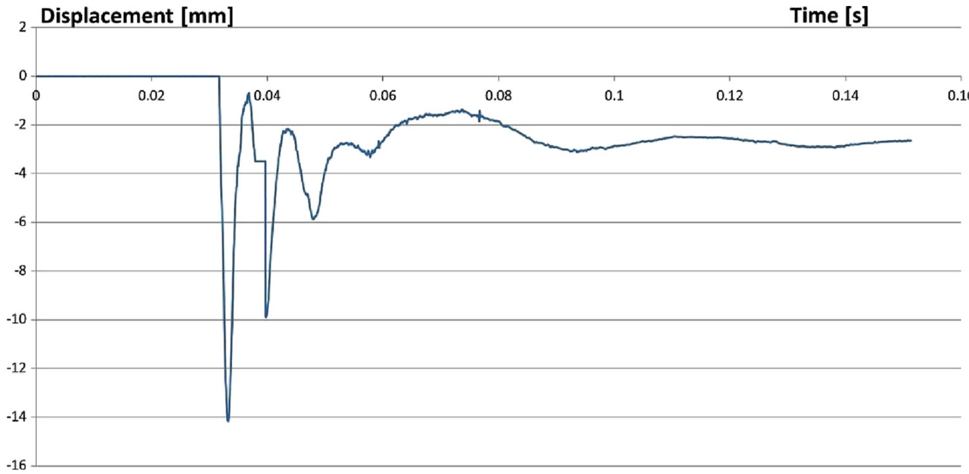


Fig. 8. Deflection-time history of hybrid FRC – an example of the measurement output (specimen 50/08PVA12, load 100.0 g of Semtex 10).

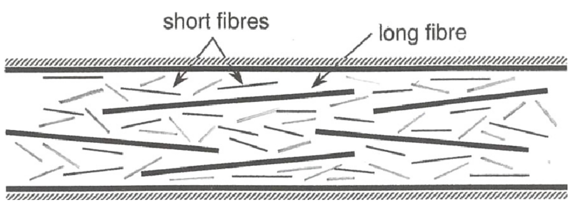


Fig. 9. Scheme showing an effective hybrid fibre distribution [34].

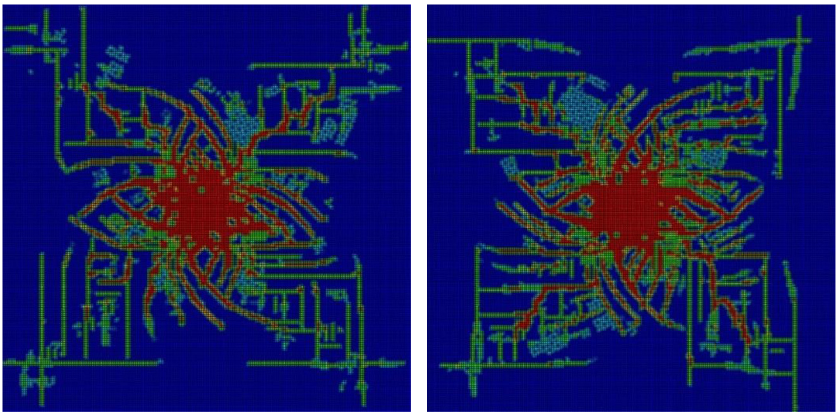
properties seem to be the crucial factor in improving the survivability of concrete structures during a blast event. PVA fibres with higher length (here about 12 mm) seem to be very suitable for enhancing the blast resistance of concrete. Good results can be achieved by fibres with high tensile strength and relatively high modulus (40 GPa) and good anchoring due to both the length and the bundled character of the fibres – the same volume content of bundled fibres contains many more fibres than that of monofilament ones, so the bonding area is much larger. The fibres are more homogeneously distributed within the concrete, with fewer unreinforced spaces, which can highly reduce fragmentation [10]. With regard to resistance to cracking and spalling, long fibres performed better than short fibres, which corresponds with the findings published by Lan et al. [33]. PP fibres were proved to be less suitable for enhancing the blast resistance of HPC due to their lower mechanical characteristics. Another reason can be the weaker bond between the fibre and matrix.

The lengths of the fibres in hybrid fibre mixes should be adjusted to be proportional in order to achieve good homogeneity and a maximal reinforcement effect, which provides the best blast resistance of the whole composite. The matrix composition (in particular the maximum grain size), the dimensions of the structure and the workability of the fresh mix must also be taken into account.

The long fibres form a kind of a barrier for the short fibres (see Fig. 9 [34]), and thus the fibre length ratio (the length of the long fibres : the length of the short fibres) must be properly adjusted to enable the spaces between the long fibres to be effectively and homogenously filled while maintaining the longest possible anchoring length. The most effective fibre length ratio (from the point of view of blast resistance) in the range of investigated fibres in the presented study is about 4.2.

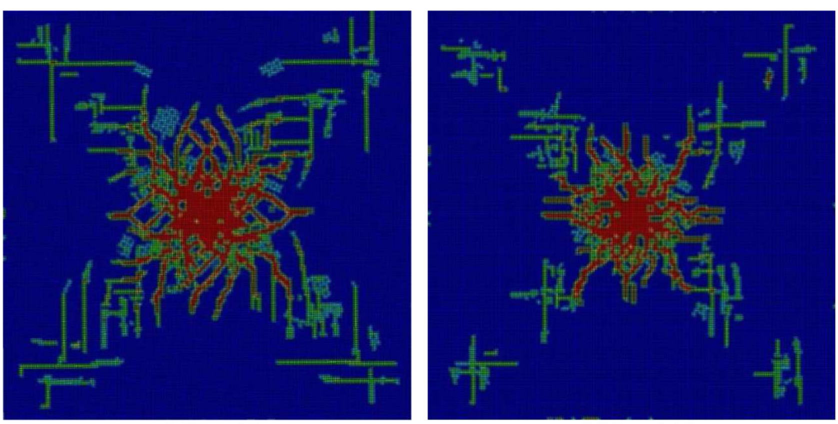
Table 6. Numerical simulations and real test results for residual deflection after the detonation of 100.0 g of Semtex 10.

Specimen	Residual deflection calculated/real	Specimen	Residual deflection calculated/real
REFI	5.1/5.5	50/08PVA12	2.3/2.9
REFII	5.3/5.7	50/08PP12	4.4/4.6



REFI REFII

Fig. 10. Numerical simulation of the damage to specimens REFI and REFII after blast loading.



50/08PP12 50/08PVA12

Fig. 11. Numerical simulation of the damage to the selected hybrid fibre reinforced specimens after blast loading.

The results of the numerical simulations performed according to the methodology described in Section 2.2 are summarized in Table 6 and Figures 10 and 11, which depict the damage to the rear side of the test slab.

The damage observed after blast testing corresponds to the results of the numerical simulations. The calculated residual deflection was lower (for all tested specimens) than the values measured after real blast testing, but the deviation was only up to 20%. The approach based on the creation of automatic scripts designed to generate FE networks of fibre elements (using Constrained Lagrange in Solid) was found promising for the accurate modelling of hybrid FRC. The proposed approach enables the creation of an FE model with various shape types and amounts of fibres. It will be used as a support for further investigation focused on the blast resistance of concrete with fibre reinforcement with various size parameters and volume contents.

3 Conclusions

Research on the behaviour of HPC reinforced with various combinations of PVA, PP and steel fibres under blast load was carried out. The following conclusions can be drawn:

- Fibre reinforcement limits the extent of damage and keeps damaged concrete more compact than plain concrete which has been exposed to a detonation. The improved spall and cratering resistance of slabs was evident even with mono-fibre reinforcement.
- Steel-PVA hybrid fibre reinforcement was shown to provide a great improvement in performance under blast load in comparison with mono-fibre (steel only) reinforced concrete specimens in terms of the reduction in mass lost, the destructive power of created secondary fragments, and internal and superficial damage. The higher fibre surface area of added PVA fibres was found to increase the prevalence of large fragments in the debris field by holding debris together. Long steel fibres ensure overall integrity, but due to their shape parameters (monofilament character, high diameter), the amount of such fibres in the matrix is limited and the interspace between the fibres remains unreinforced and thus brittle, with the tendency to create fragments. The addition of fibres with a bundled character and different shape parameters (of low diameter) can increase the fibre availability in the matrix (while the volume content of the fibres is kept constant), which reduces fragmentation. Due to the extraordinary fibre-matrix bond strength, high tensile strength and modulus of elasticity of PVA fibres, the steel-PVA combination provides excellent blast resistance.
- The steel-PP fibre combination was proved to be less useful in blast resistance enhancement, which is the result of their low tensile strength, modulus of elasticity and weaker matrix-fibre bond. Still, the blast resistance of all steel-PP specimens was better than that of the specimens reinforced only with steel fibres.
- Steel fibres in concrete could be partly replaced (1/3 in presented research) with polymeric (both PP and PVA) fibres without any reduction in the blast resistance of the concrete. The overall blast resistance was found to be higher for all PP-steel and PVA-steel hybrid systems compared to the mono-reinforced specimens. The replacement of steel fibres with polymeric fibres can be very beneficial, as the steel fibres are highly corrodible, which can lead to structural corrosion failure. The use of polymer fibres to replace part of the steel fibres in concrete can thus extend the durability of the structure and also reduce its weight.
- The length of the fibres in hybrid fibre mixes and the length ratio plays an important role in the blast resistance of FRC. In the case of hybrid systems, specimens with 50 mm steel fibres performed generally better than specimens with 30 mm fibres. The best blast resistance was shown by specimen 50/08PVA12, which was with 12 mm polymeric fibres. Combined with 50 mm steel fibres, 12 mm fibre is long enough to provide sufficient bonding (anchoring)

area yet short enough to homogenously fill the matrix spaces between the steel fibres.

- Regarding the numerical simulations, the proposed approach based on the creation of automatic scripts designed to generate FE networks of fibre elements (using Constrained Lagrange in Solid) was found to be promising for the accurate modelling of steel FRC.
- The proposed modified methodology was found suitable for use in the comparison of test specimens' blast resistance. The data obtained from both tests correspond well and give enough information to create a necessary overview of how a particular material performs under blast load. Thus, the measurement of the ultrasonic wave transit time changes can be confirmed as a simple, quick and effective method of assessing the blast resistance of specimens more accurately than just visually assessing the damage level of specimens and witness desks. In addition, a lower amount of explosive charge is needed for this test, which reduces the requirements on the testing site and therefore also the costs connected with the testing.

The results of the presented research were used in the formulation of an HPC with high resistance to blast load. This new material was subsequently used in the production of elements for critical infrastructure protection, such as blast resistant litter bins, barriers, urban furniture, etc.

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Authors contribution statement

M. Drdlová is the leader of the presented research. She is the author of the research methodology and all mixture and fibre reinforcement designs, and she conducted the described quasi-static mechanical testing and processed all of the obtained test data. She also drafted and finalised the manuscript. O. Koutný developed a modified methodology for the blast tests and performed all the blast tests in cooperation with M. Drdlová and M. Popovič. M. Popovič was responsible for the deflection measurements during the blast tests and is the author of the numerical simulations used.

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