Utilization of waste steel fibres from tires in slurry infiltrated fibre concrete for blast protective elements

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Abstract
In the presented study, the possible utilization of waste steel fibres in precast concrete elements was investigated. Waste fibres coming from the recycling process of the old tires were incorporated in slurry infiltrated fibre concrete (SIFCON), which is a special type of high-performance fibre reinforced concrete with high fibre content. Test specimens were prepared with three volume fractions (5; 7,5; 10 vol. %) of waste unclassified fibres. SIFCON with industrial steel fibres (10 vol. %) and high-performance fibre concrete with industrial fibres were also cast and tested for comparison purposes. Quasi-static and dynamic drop tests were performed to obtain mechanical properties. Real blast tests of the slab specimens were performed. Damage of the slab, the change of the ultrasonic wave transit time in the slab specimen before and after the blast load in certain measurement points and the weight of fragments were evaluated and compared. The obtained results indicate, that the usage of waste fibres does not significantly reduce the values of SIFCON flexural and compressive strength at quasi-static load – the values were comparable to the specimens with industrially produced fibres. The mechanical parameters obtained from dynamic drop tests of SIFCON with waste steel fibres were about 11% lower compared to the specimens with industrial fibres. With increasing fibre content, the mechanical parameters (both quasistatic and dynamic) are increasing as well. Regarding the blast tests, using the waste fibres reduces fragmentation of SIFCON at blast load due to the fibre size parameters; the specimens with waste steel fibres showed the best resistance and outperformed also the specimens with commercial fibres.
The SIFCON material with waste fibres was used for production of the shield system for protection of critical infrastructures against blast and ballistic load; the blast resistance of the barrier against detonation of 30 kg TNT from the distance of 3 m was proven.
Using the waste fibres in SIFCON technology can reduce the price of this composite by 70% by keeping the original SIFCON extraordinary properties, which makes it very competitive material in the high-performance concrete area.

Keywords
SIFCON, waste steel fibres, barrier, quasistatic and dynamic tests, blast tests, slurry infiltrated fibre concrete

1. Introduction

It is estimated that over 4 billion used tires are generated every year [1]. Currently, scrap tires are partly recycled, but most of them are still being used as a source of energy or landfilled [2]. A typical tire consists of approximately 47% rubber, 22% carbon black, 17% steel cords, 5% fabrics, and the remaining percentage consists of some other minor additives [3]. Nowadays, mainly the rubber from waste tires is recycled in a form of rubber granulate, which is then utilized in several products, such as noise barriers, vibration dampers for train and tram tracks, outdoor sport surfaces, road furniture applications, paving blocks, playground equipment, etc. However, every passenger car tire also contains about 1.3 kg of steel fibres, which can be reused.

Although the concrete mechanical properties are often improved by addition of the steel fibres, using tire waste fibres in concrete technology is limited due to the nature of the obtained fibres – in particular the high diversity of fibre geometry, contamination and bulk nature of the product. Further processing (cutting, selecting and cleaning) of the fibres enables to prepare more suitable material for the concrete reinforcement and brings satisfactory results, but it is expensive and demanding. On the other hand, the tire fibres are made from high strength carbon steel with a tensile strength as high as 2,200 – 2,750 MPa [4]. Several studies were performed focused on mechanical properties of concrete with classified fibres [1,4,5,6] The pull-out behavior of the recovered fibers may be similar to those of the commercial fibers which may be attributed to the irregular undulations of the fibres as a result of the shredding process that can increase mechanical bonding [6] and [7]. Mechanical properties of concrete containing waste steel fibres may be improved due to the crack-bridging effect of the fibres in concrete similar to the concretes produced with commercial fibres [8], [5] and [9]. Finding the way how to reuse this type of fibres as the concrete reinforcement can save the costs connected with fibre-concrete manufacturing. As the traditional concrete technology is difficult to be adopted when using not classified waste fibres (the fibres tend to stay in bulks and the proper disintegration and homogenous dispersion is difficult to achieve in higher fibre dosage), the slurry infiltration technology was used in this study. SIFCON is prepared by infiltrating pre-placed fibres with fine grain aggregate mortar [10]. The fibre volume fraction of traditional fibre reinforced concrete is limited, because excessive amount of the fibres affects the workability of the fresh concrete in a negative way. This limits the fibre volume V_f to 1 – 5%, depending on the type of fibre used and the required workability of the mixture. SIFCON specimens can be produced with much higher V_f up to about 20% depending on the fibre geometry, length and diameter. SIFCON possesses excellent mechanical properties, extraordinary behaviour in flexure and punching shear coupled with very good energy-absorption characteristics [11,12]. Due to extraordinary ductility of SIFCON, caused by high fibre content, it seems to be very promising material mostly for applications in structures subjected to impact load. The high fibre content is connected with high production costs, so the replacement of the industrial fibres by waste fibres would significantly decrease the price of the whole composite. The main objective of the work presented herein is to provide more information about the effects of steel fibers recovered from tires on the mechanical parameters of SIFCON, both quasistatic and dynamic, with focus on its behaviour under both small and big scale blast loading.

2. Materials and methods

Waste steel fibres were obtained from recycling plant “RPG recycling”. Fibres were partly contaminated by rubber and textiles (see Fig. 1), and had variations in their geometrical properties. The geometrical characterization of the fibres was made by the measurement of their diameters and lengths on samples of randomly selected 100 fibres from three different batches. The results of the characterization are given in Table 1; about 70% of the fibres possesses the length and diameter between 20-50 mm and 0-0.2 mm respectively.

Fig. 1 Waste steel fibres from tires (left), mould with preplaced fibres (right)

Specimens with three different volume fractions of fibre reinforcement (5; 7.5; 10%) were prepared using waste fibres. The components and mix proportion (in kg.m^{-3}) of the slurry are given in Table 2. SIFCON with industrial steel fibres (10% by vol.) and high-performance fibre concrete with 4% by vol. of the fibres were also cast and tested for comparison purposes. The fibres DE 30/06N (KrampeHarex, hooked ends, length 30 mm, diameter 0.6 mm) were used as the reinforcement for the reference specimens. The manufacturing process of SIFCON involved preplacing of the steel fibres into the mould (see Fig. 1 right) with subsequent pouring of the slurry over the fibres. The reference specimen UHPFRC was prepared as follows: cement, sand and microsilica were dry-mixed, then required quantity of water with plasticizer was added. At the end of mixing, steel fibres were incorporated. The test specimens were demoulded after 24 hours and were cured for 28 days in curing water ponds.

Table 1. The results of the fibres geometrical characterization

Diameter (mm)	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.2	1.2-1.4	1.4-1.6
Amount	76	1	7	7	1	0	6	2
Length (mm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
Amount	7	14	24	27	16	9	1	2

Table 2. Composition of SIFCON and UHPFRC

Designation/component	SIFCON	UHPFRC
Cement CEM 52.5R Mokra	990	955
Fine aggregate 0-1 mm Bzenec	890	1100
Silica fume Elkem 940U	78	143
Superplasticizer Glenium ACE 446	12	16
Water	300	230

For the bulk density, compressive and flexural strength investigation the prism specimens of dimensions 400x100x100 mm were cast. The universal strength testing machine TIRAtest 2710, R58/02 was used to determine the mechanical parameters. The compressive and flexural load was applied in quasistatic conditions at speed of 3 mm/min.

For the dynamic tests, slab specimens (500x250x40 mm) were prepared and tested using the instrumented drop test machine. The test device is depicted in Fig. 2. It consists of supports and L-shape plunger with incorporated strength sensor Comforia MCF50 (see Fig. 2 right). The plunger is fixed to the rollers, drawn on the sliding rods, the impact height is adjustable. The signal from the sensor is captured and evaluated using the LeCroy WaveAce 214 100 MHz oscilloscope. The slab specimen was placed on the supports and loaded by the plunger released from the height of 500 mm. The impact velocity was ~ 3 $m.s^{-1}$. The strength-in-time courses were captured and fracturing force was evaluated for each specimen.

Fig. 2 Drop test device – general view (left), sensor (right above) and placement of the strength sensor (right down)

The blast tests were performed using modified methodology M-T0-VTU0 10/09. The methodology was upgraded to cover two tests. First test is based on observation and evaluation of the test specimen fragmentation after blast load and can be described as follows: The test specimen (500x500x40 mm) is fixed in the steel stand placed on the solid foundation. The sphere-shaped plastic high explosive Semtex 10, weighting 150 g, is used as testing charge. The weight and distance (100 mm from the test specimen) of the testing charge is adjusted to be strong enough to cause the significant visible damage of the specimens, including fragmentation. Observed and evaluated parameters are the weight of created secondary fragments. 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 connected to the damage of material. The scheme of the test rig is depicted in Fig. 3 left. The distance of the charge was the same as in the previous test – 100 mm.

The SIFCON with waste fibres was used for production of the shield system for protection of critical infrastructure against blast and ballistic load; The barrier consists of H-profile steel frame filled with SIFCON slabs in three layers, see Fig. 3 right. The resistance against blast of 30 kg TNT from the distance of 3 m of the designed system was tested. The integrity, stability and displacement of the construction as well as pressure conditions behind the barrier were the observed and evaluated parameters. The measurement of the pressure was performed using the “pencil” type pressure sensors ICP 137A23 fixed to the tripod placed 1.5 m behind the barrier at height of 1.6 m. The signal from the sensor was read using a PCB converter on the LeCroy WaveAce 214 100 oscilloscope. Voltage to pressure conversion was performed based on the calibration certificate data of the sensor.

Fig. 3 Configuration of the slab specimen blast test (left), shield system for protection of critical infrastructure (right)

3. Results and discussion

3.1 Quasi-static mechanical tests and drop tests

Quasi-static mechanical properties and bulk density of prism specimens (100x100x400 mm) were determined, the results (the average value of at least 5 specimens) are summarized in Table 3. As seen in Table 3, with increasing waste fibre content in SIFCON, the mechanical parameters at quasi-static load are increasing as well; the same trend was observed in case of SIFCON with industrial fibres [14]. The obtained results also indicate, that the usage of waste fibres does not significantly reduce the values of SIFCON flexural and compressive strength at quasi-static load – the values were comparable to the specimens with industrially produced fibres.

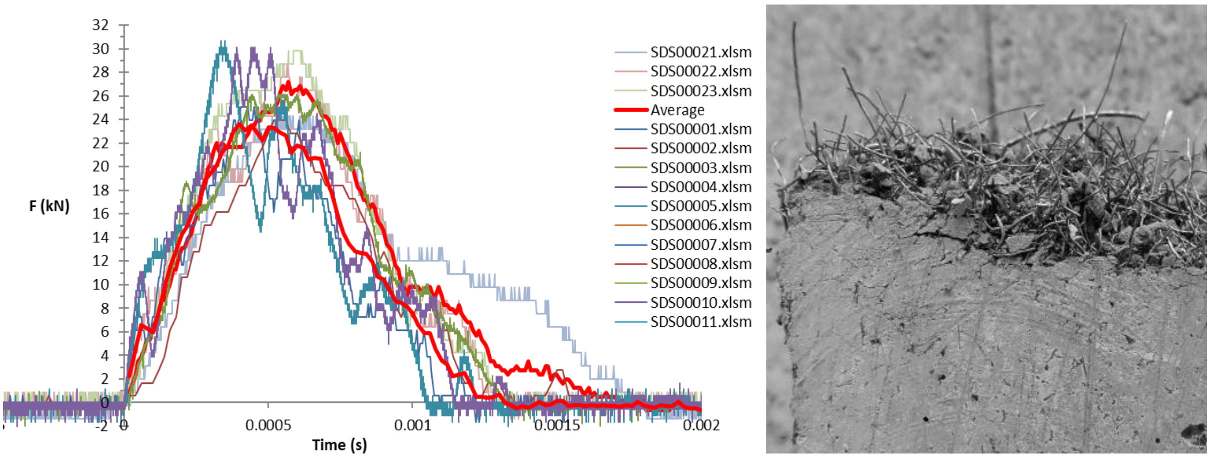

Fig. 4 Output of the drop test for specimen SIF 10.0% REF (left), fracture surface of SIF 10.0% (right)

Table 3. The results of physico-mechanical tests

Designation	Bulk density ($kg.m^{-3}$)	Compressive strength (MPa)	Flexural strength (MPa)	Fracturing force (kN)
SIF 5.0%	2,488	112.0	18.3	12.3
SIF 7.5%	2,510	115.0	20.8	20.2
SIF 10.0%	2,550	121.7	23.9	24.1
HPFRC 4%	2,220	101.2	14.2	18.5
SIF 10.0% REF	2,585	120.9	25.7	27.1

The impact behaviour was evaluated using the drop test device described in Chapter 2. The fracture surface of the specimen SIF 10.0% after the impact load shows Fig. 4 right. Typical output of the drop test (strength-in-time course) for the specimen SIF 10.0% REF is depicted in Fig 4 left. At least 10 samples were tested for each mixture. Fracturing force was evaluated for each specimen, the results are given in Tab. 3. Fracturing force is raising with increasing percentage of fibres incorporated. The same trend was reported in [17], where the impact behaviour of SIFCON slabs with 8, 10 and 12% fibre dosage was investigated and the results revealed that SIFCON containing 12% steel fibre dosage had a highest impact strength [17]. The low value measured in case of SIF 5.0% specimen (12.3 kN) can be attributed to the poorer homogeneity caused by insufficient fibre amount for creation the uniform skeleton, which corresponds with the findings published in study [10]. The best results were achieved in case of SIFCON with industrial fibres, 27.1 kN, however SIFCON with the same dosage of waste fibres possesses only 11% lower values (24.1 kN).

3.2 Blast tests of slabs

The main results of both parts of the blast tests are summarized in Table 4. The blast resistance of the specimens with waste steel fibres rises with increasing amount of incorporated fibres. The specimen with 5% of fibres showed high rate of fragmentation (see Table 4). Observed fragments were in a form of small aggregates up to 5 mm size. The increase of the ultrasonic wave transit time was in range 112.0 to 380.0% (average value 260.4%), which implies the high rate of internal damage. Specimen with 7.5% of waste fibres showed significantly lower fragmentation and ultrasonic wave transit time change, compared to the SIF 5% specimen. Ejected fragments´ size was up to 3 mm. The best results were obtained in the case of SIF 10.0% specimen. The slab´s integrity didn´t suffer, only some cracks were observed and a few flat splinters were split off from the surface layer (23.9 g). Test slab prepared from UHPFRC with 4% of commercial steel fibres showed different mode of fragmentation – only one fragment (232.0 g) was ejected. Internal damage represented by change of the ultrasonic wave transit time was higher compared to slab SIF 7.5% and SIF10.0%. Specimen SIF 10.0% REF with commercial steel fibres showed worse performance compared to the specimen with 10.0% of waste fibres, the weight of the debris was 84.0 g (compared to 23.9 g) and the increase of ultrasonic wave transit time was higher as well.

Comparing the SIFCON specimens, better performance of specimens with waste steel fibres under the blast load was observed, which is probably caused by their hybrid character. Waste fibres from tires are characterized by different shape parameters with high rate of thin shorter fibres (see the distribution in Table 1). At quasistatic load, the fracture processes of concrete loaded in tension begin by the formation of numerous fine microcracks; if the tensile load continues to increase, these microcracks connect with each other and form larger cracks, which subsequently leads to failure. Short fibres can bridge microcracks, which increases tensile strength, long fibres bridge macrocracks, so they can provide a stable post-peak response. For the blast load, as it is extremely fast phenomenon, this classical approach cannot be fully adopted, but the hybrid fibre reinforcement is still beneficial, because the same volume content of waste fibres contains more fibres than the commercial ones, so the fibres can be more homogeneously distributed within the concrete, with fewer unreinforced spaces [15, 16]. In this model, thicker and longer fibres help to keep the overall integrity of the material, whereas the shorter and thinner fibres protect the slab from the fragmentation. All the SIFCON specimens (except for SIF 5.0%) outperformed ultra-high-performance concrete, which is caused primarily by the higher fiber amount contained in SIFCON specimens.

Table 4 The blast tests results

Designation	Increase of US wave transit time (average value) [%]	Fragment weight [g]
SIF 5.0%	260.4	298.0
SIF 7.5%	105.5	42.0
SIF 10.0%	101.3	23.9
HPFRC 4%	131.0	232.0
SIF 10.0% REF	125.3	84.0

3.3 Blast test of the shield system

The explosion test verified the blast resistance of the designed shield system against the detonation of 30 kg TNT from 3 meters distance. Fig. 5 left shows the photograph of the blast test, the overall state of the shield system construction after the blast test is depicted in Fig. 5 right and Fig. 6. As can be seen, the integrity of the construction was preserved. The deflection up to 50 mm in the middle of the construction was detected, but without any negative influence on the overall stability of the construction.

Fig. 5 Photograph of the explosion test (left) and overall state of the construction after the test (right)

Regarding the SIFCON panels, the slabs adjacent to the explosion remain intact with only hair-type cracks, wider cracks (see Fig. 6 right) were observed on the rear side, but the integrity of the test object had not suffered and no fragmentation was detected.
Pressure conditions measured behind the barrier were below the limits for any health hazard, the measured value was 9 kPa at the distance of 1.5 m behind the barrier in the height of 1.6 m. The threshold value for eardrum rupture is 34 kPa.

Fig. 6 The shield system after blast test (left), detail of one SIFCON slab (right)

Conclusions

This paper summarizes the results of the research on utilization of waste steel fibres from tires into slurry infiltrated fibre concrete. Mechanical parameters of waste fibres reinforced SIFCON at quasistatic, impact and blast load were determined. Obtained results were compared to SIFCON with industrial fibres and HPFRC. The material high impact resistance was verified in the real construction intended for critical infrastructure protection.
Following conclusions can be drawn:
-Waste steel fibres have significant variations in their geometrical properties, the length varies between 0.5-80 mm, diameter between 0.03-1.6 mm. Dimension diversity and the bulk nature of the waste fibres were proven not to be obstacle in slurry infiltration technology. Bulk character of the fibres helps to create stable skeleton and fibre mix act like natural hybrid reinforcement.
-Mechanical properties (flexural strength, compressive strength and fracturing force) increases with raising waste fibre volume fraction.
-Replacement of industrial fibres by waste fibres does not significantly reduce mechanical properties of the SIFCON at quasi-static load.
-Regarding the blast load, SIFCON with waste steel fibres outperformed the SIFCON with industrial fibres, which is attributed to the hybrid nature of the waste fibres. Thicker and longer fibres help to keep the overall integrity of the material, whereas the shorter and thinner fibres protect the slab from fragmentation. Using of short low diameter fibres means less unreinforced “matrix-only” areas.
-The good performance of the waste steel fibre reinforced SIFCON under extreme impact load was verified by 30 kg TNT explosion test performed on real construction – blast resistant barrier.
-Using waste fibres in SIFCON technology can reduce the price of this composite by 70% by keeping the SIFCON extraordinary properties, which makes it very competitive material in the area of precast concrete.

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