The Static and Dynamic Properties of Slurry Infiltrated Fibre Concrete with Waste Steel Fibres from Tires

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***Abstract*—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. The technological feasibility (i.e. suitability of the waste fibres for SIFCON technology) was assessed using infiltration test and homogeneity test. Test specimens were prepared with three volume fractions (5; 7,5 and 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 mechanical properties were determined. The impact test was carried out by using an in-house manufactured impact testing machine based on drop test principle. Realized tests confirmed the possibility of using the waste fibres for SIFCON technology. 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 and energy absorption at dynamic load, the values were comparable to the specimens with industrially produced fibres.**

***Index Terms*— Waste steel fibres, sifcon, slurry infiltrated fibre concrete, drop test, flexural strength, compressive strength**

I. Introduction

It is estimated that over approximately 4 billion used tires are generated each year [1]. 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 [2]. Every passenger car tire thus contains approximately 1,3 kg of steel fibres, which can be reused. Fibre obtaining process basically starts with cutting the tires into 50-mm pieces using a preliminary shredder. The tire chips then enter a granulator, where the chips are reduced, while liberating most of the steel and textile fibre from the rubber granules. Upon leaving the granulator, steel is removed magnetically, and the fibre fraction is removed by a combination of shaking screens and wind sifters. The obtained fibre contains about 3-5 % of rubber and textile fibres. Specific machinery exists to separate clean fibre from contaminated one, allowing the processor to obtain higher revenues for the uncontaminated material.

Recycled iron and steel scrap is mostly used as a vital feedstock in the production of new steel and cast iron products. 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 form of the product. Further processing (cutting, selecting and cleaning) of the fibres to prepare more feasible material for the concrete reinforcement brings satisfactory results, but is expensive and demanding. On the other hand, the tyre fibres are made from high strength carbon steel with a nominal tensile strength of 2 200 – 2 750 MPa [3], so they seem to be promising reinforcing material. 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 fibers as a result of the shredding process that can increase mechanical bonding [6] and [7]. Mechanical properties of concrete containing waste steel fibers may be improved due to the crack-bridging effect of the fibers in concrete similar to the concrete produced with commercial fibers [8], [5] and [9]. Finding the way how to reuse waste fibres (in particular without any further classification after recycling process) as the concrete reinforcement can save the natural resources and costs connected with fibreconcrete production. As the traditional concrete technology (with adding the fibres at the end of the mixing process) is impossible to be adopted when using not classified waste fibres (or allows to incorporate only little amount of the fibre with almost negligible positive results on mechanical properties), the slurry infiltration technology was tested in this study. Slurry infiltrated fibre concrete - SIFCON was first developed in 1979 by Lankard Materials Laboratory, Columbus, Ohio, USA, by incorporating large amounts of steel fibres in fibre reinforced cement-based composites [10]. SIFCON is prepared by infiltrating pre/placed fibres with fine grain aggregate mortar. 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

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can be produced with V_f between 5% and 30% [10], the fibre volume depends on the fibre geometry, length and diameter and vibration of the fibres during their placement process. SIFCON possesses extraordinary mechanical properties-excellent behaviour in flexure and punching shear coupled with very good energy-absorption characteristics [11,12]. Due to high ductility of SIFCON, caused by high fibre content, it seems to be very promising material mostly for applications in structures subjected to dynamic 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 technological feasibility of using the unclassified waste fibres recovered from scrap tires in SIFCON and effects of these steel fibers on the mechanical parameters of SIFCON at both quasi-static and dynamic loading. According to the author knowledge, there is no study dealing with this topic currently available. Presented results of executed experimental investigation can bring significant contribution to the current knowledge in the field.

II. Experimental

A. Raw Materials and Preparation of Specimens

Waste steel fibers recovered from scrap tires were obtained from recycling plant “RPG recycling” situated in Czech Republic. Fibers were partly contaminated by rubber and textiles (see Fig. 1), In addition, steel fibers had significant variations in their size properties. The size characterization of the fibers was made by the measurement of their diameter and length on samples of randomly selected 100 fibers from three different batches. The distribution of fibre length and diameter is displayed in Fig. 2. Specimens with different volume fractions of dispersed fibre reinforcement were prepared using waste fibre. Fine SiO_2 sand with grain size of 0-1 mm, cement CEM 52.5R and water were the main components of the slurry mixture. Superplasticizer Glenium 422 (produced by BASF) was added to achieve good workability with low water/binder ratio. High dosage of silica fume Elkem 940U (produced by Elkem), was used to create an optimized particle packing density and also for its pozzolanic properties. The mix proportion of the slurry is given in Table 1. SIFCON with industrial steel fibres (10 Vol. %,) and high performance fibre concrete with 4 Vol. % of the same fibres were also cast and tested for comparison purposes.

TABLE I. Mix Proportion of Concrete Mixture (Kg/M^3)

Designation	Cement	Fine aggregate	Silica fume	Plasticizer	Water
SIFCON	990	670	78	10	320
HPFRC	929	701	51	9.4	303

Figure 1. Unclassified waste fibres from recycling process of the tires

The fibres with hooked ends DE 30/06 N (producer KrampeHarex, length 30 mm, diameter 0.6 mm) were selected, as previous studies revealed their best performance in the composite in term of production technology [10]. The production process of SIFCON involved pre-placing of the steel fibres into the mould with subsequent pouring of the slurry over the pre-placed fibres. The mixing procedure of the reference specimen HPFRC was as follows: steel fibres were first mixed into the dry mixture of cement, sand and microsilica, then required quantity of water with plasticizer was added. The composition of the mixture is given in Table 1. The test specimens were demoulded after 24 hours and were cured for 28 days in curing water ponds. For technological feasibility test, the specimens with 5-12,5 Vol. % with 2,5 % step were prepared (100x100x400 mm) and infiltrated with the slurry. After demoulding and maturing, the ultrasonic test was adopted to assess the homogeneity of the specimens, using the Proceq Tico device with 54 kHz probe. The velocity of ultrasonic wave was measured at 10 determined spots.

After a travel distance “L” and a propagation time “t” in the material, the wave reaches the second transducer. Thus, it is possible to determine the propagation velocity of sound wave in the material: $V = L/t$. [13]. The results of ultrasonic pulse velocity can be used to check the concrete homogeneity by evaluation of the velocity variation. After this non-destructive test, specimens were cut transversally

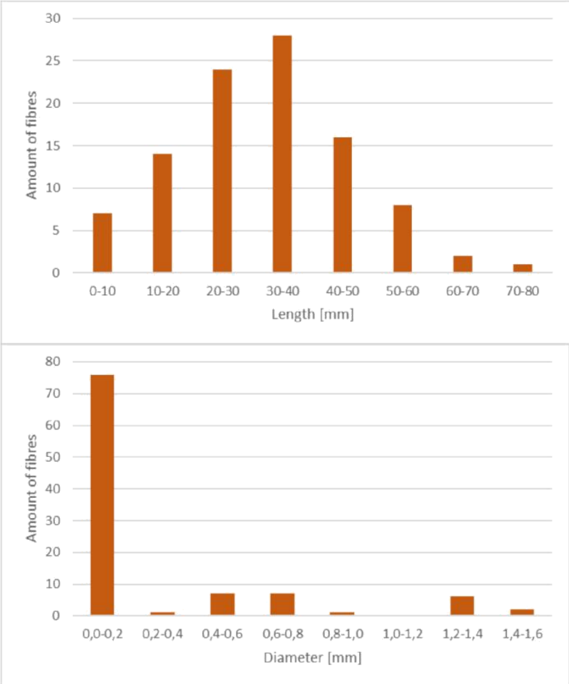

Figure 2. The distribution of fibre length and diameter

in the middle and the level of infiltration was observed visually. For the bulk density, compressive and flexural strength investigation, the prism specimens (400x100x100 mm) were cast with three different amounts of fibres – 5.0, 7.5 and 10.0 Vol. %. The mechanical parameters were obtained using universal strength testing machine TIRAtest 2710, R58/02. The compressive and flexural load was applied in quasi-static conditions at speed of 5 mm/min. For dynamic tests, the slab specimens (400x400x40 mm) were cast. The impact test has been carried out by using an in-house manufactured impact testing machine. The detail of test setup used for conducting impact test on slabs is described in author´s previous work [14]. During the test, the weight is hitting the centre of the slab specimen. The test has been adjusted as follows: height of drop 700 mm, weight 25 kg, repeating of the process up to reaching the ultimate failure stage. The total absorbed energy is obtained using the following formula: $E = m.a_g.h.x$, where: E…Total absorbed energy [J], m…Weight of the impactor [g], a_g…Gravity acceleration [$m.s^{-2}$], h…Height of drop [m], x…Number of the drops [-].

B. Results and discussion

Technological feasibility: Moulds were filled with 5 – 12.5 Vol. % of fibres. 5 and 12.5 Vol. % of the fibers were the threshold values for efficient filling of the moulds – under 5 %, the mould was not fully filled, over 12.5 %, the structure was so dense, that no more fibres were possible to be placed in the mould even the vibration was adopted. Up to 10 %, the fibres can be placed without vibration, crossing this amount, the vibration was a necessity for whole amount fibre placement.

The results of ultrasonic velocity measurements are summarized in Table 2. The velocity variation coefficient was calculated according to the following formula: $\Delta = ((v_{max}-v_{min})*100)/v_{min}$, where v_{max}/v_{min} are maximal/minimal values of ultrasonic velocity obtained.

For high performance concrete,   must not exceed 7.5 % for the tested specimen to be evaluated as homogenous. According ultrasonic measurement results, the specimen with 5.0 Vol. % of fibres did not achieve satisfactory homogeneity (Δ = 8.4 %), due to insufficient fibre amount for creation the uniform skeleton, which corresponds with the findings published in study [10]. All the other specimens showed very good homogeneity-regardless of the measuring point, the ultrasonic velocities of these specimens remain almost constant, with lower than 5 %. As the second step, the specimens were cut and the quality of infiltration was assessed by visual observation. The quality of infiltration of the SIF 5-10.0 specimens was found excellent, no cavities and voids in the structure were observed. In the case of specimen SIF 12.5, two small caverns (7 mm diameter) at the bottom surface of the specimen were identified.

Quasi-static mechanical tests and bulk density: The overall results of the quasi-static mechanical test are presented in Table 3, the average value of five specimens is presented. As seen in the Table 3, raising of the fibre volume fraction causes increase of the compressive and most noticeable flexural strength - similarly to the SIFCONs with industrial fibres [14]. The strengths values obtained in the case of specimen SIF 10.0 % are very closed to the SIF 10.0 % REF with industrial fibres. Considering the deviations, it can be concluded that both specimens perform similarly. Parameters of waste fibres from tires are suitable for SIFCON technology as they are able to prepare uniform dense skeleton with all benefits of hybrid fibre reinforcement. Also, the irregular deformation of the fibre surface caused by shredding during recycling process is beneficial, as it improves anchoring of the fibres in the matrix.

Dynamic Drop test: A comparison of total energy-absorption capacities of different slab specimens at ultimate impact strength stages is presented in Table 4. All the SIFCON slabs overcame the HPFRC reference specimen with total absorbed energy 95.2 J. The best value of total absorbed energy 18,536.2 J was achieved in the case of SIF 10.0 % REF specimen.

TABLE II. SONIC AUSCULTATION – CALCULATED ULTRASONIC VELOCITY

Measurement No./Specimen	SIF 5.0 %	SIF 7.5 %	SIF 10.0 %	SIF 12.5 %
1	3,520	3,820	4,020	4,310
2	3,760	3,950	4,020	4,360
3	3,800	3,990	4,060	4,320
4	3,520	3,840	3,980	4,480
5	3,790	3,910	4,110	4,440
6	3,490	3,810	4,100	4,370
7	3,630	4,000	4,030	4,410
8	3,620	3,890	3,990	4,380
9	3,630	3,960	4,030	4,440
10	3,610	3,890	4,100	4,430
Velocity variation coefficient [%]	8.4	4.8	4.4	3.1

TABLE III. PROPERTIES OF THE SPECIMENS AT QUASI-STATIC LOAD

Designation	Flexural strength	Compressive strength
	[MPa]	[MPa]
SIF 5.0 %	18.3	112.0
SIF 7.5 %	20.8	115.0
SIF 10.0 %	23.9	121.7
HPFRC 4 %	14.2	101.2
SIF 10.0 % REF	25.7	120.9

TABLE IV. ENERGY ABSORPTION CAPACITY OF THE SPECIMENS

Designation	Bulk density	Total absorbed energy
	[kg.m-3]	[J]
SIF 5.0 %	2,488	5,369.4
SIF 7.5 %	2,510	12,235.3
SIF 10.0 %	2,550	16,862.3
HPFRC 4 %	2,200	95.2
SIF 10.0 % REF	2,585	18,536.5

The specimen SIF 10.0 % with incorporated waste fibres (the same amount as SIF 10.0 % REF) performed great as well – the achieved value of total absorbed energy was 16,862.3 J, which is lower value than the of REF specimen, but very competitive. Different failure modes were identified, comparing SIF 10.0 % and SIF 10.0 % REF specimens with the same fibre volume fraction: the waste fibre specimen showed small cracks and only insignificant surface damage around the impact area; the specimen with industrial fibres exhibited no visible cracks, but dent accompanied by fragmentation in surrounding of the point of impact was observed. This fact is caused by better reinforcing effect of the waste fibres – the fibre mix contains substantial portion of low diameter fibres (see Fig. 1), thus the same volume contains more fibres, so they are more homogeneously distributed within the matrix. Less areas between the fibres remain unreinforced and thus brittle, which is connected with lower fragmentation of the matrix.

Evaluating the effect of the fibre amount, the slab with 10. 0 % fibre volume shows least damage and the highest energy absorption capacity compared to the other two, i.e., slabs with 7.5 and 5 % fibre volume; the higher content of fibres, the higher total absorbed energy and less damage – the same (only less steep) trend was also observed for SIFCONs with industrial fibres [14].

III. CONCLUSIONS

This paper summarizes the results of research on slurry infiltrated fibre concrete reinforced with waste steel fibres from tires. Technological feasibility was assessed and mechanical parameters both at quasi-static and dynamic load were determined. Obtained results were compared to SIFCON with industrial fibres and HPFRC. Following conclusions can be drawn:

-Using of unclassified waste steel fibres from tyres in SIFCON is feasible from technological point of view. 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 may cause technological problems in traditional concrete, but was proved 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. Excellent infiltration level and homogeneity of the specimens can be achieved.

-The optimal fibre amount for SIFCON technology was determined between 7.5 and 10.0 Vol. %. Lower amount of fibres does not fully fill the mould; higher amount of fibres is very difficult to place in the mould and the created skeleton is too dense to be properly infiltrated.

-The higher the amount of fibres, the better homogeneity is achieved (in the tested volume fraction range). -Mechanical properties (flexural strength, compressive strength and total absorbed energy) increases with raising waste fibre volume fraction.

-Replacement of industrial fibres by waste fibres did not reduce mechanical properties of the SIFCON at quasi-static load and slightly decreases the total absorbed energy at dynamic load. On the other hand, using of the waste fibres reduces fragmentation of SIFCON at dynamic load due to the fibre size parameters. Using of low diameter fibres means more fibres in the matrix and thus better homogeneity of the whole composite with less unreinforced areas.

-Using of 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 concrete area.

As SIFCON with its ductility is very promising material for several impact applications, the following research will be focused on behaviour of this material under blast and ballistic load.

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