APPLICATION OF FIBERS FROM END-OF-LIFE TIRES AS A SELF-COMPACTING CONCRETE REINFORCEMENT – AN EXPERIMENTAL STUDY

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Abstract
Concrete reinforced with various types of fibers is increasingly used construction material. The currently applied steel fibers are characterized by various geometrical parameters and are produced specially for this purpose. The paper deals with application of steel fibers coming from end-of-life tires (RSF) in self-compacting concrete. The geometry of RSF with small diameter, variable length and their curved longitudinal shape causes doubts in their effectiveness in the concrete mix in comparison to industrial fibers. To clarify the real influence of RSF on mechanical properties of self-compacting concrete (SCC) the compression and flexural tests were evaluated. The high amounts of RSF equal to 1% and 1.5% were choosen. As expected, RSF slightly influenced the compressive strength of SCC. The results from the four-point flexural tensile tests demonstrate that the RSF fibers were not only a material that improves the ductility of brittle SCC matrix but also were uniformly distributed in the matrix. The high amounts of RSF truly decreased the rheological parameters of SCC, what was tested in slump flow and L-box test, however, did not have a negative influence on the homogeneity of the mix. Concluding, the fibers from end-of-life tires were fibers that can be successfully used as a randomly distributed reinforcement of self-compacting concrete.

Streszczenie
Beton zbrojony różnego rodzaju włóknami jest coraz chętniej stosowanym materiałem konstrukcyjnym. Obecnie stosowane stalowe zbrojenie rozproszone stanowią specjalnie w tym celu wytwarzane włókna o przeróżnej geometrii. Artykuł dotyczy możliwości zastosowania włókien stalowych pochodzących ze zużytych opon (RSF) do zbrojenia betonu samozagęszczalnego. Geometria RSF z ich małą średnią, zmienią długością i zakrzywionym podłużnym kształtem powoduje powątpiewanie w ich skuteczność w mieszanice betonowej w porównaniu z włóknami przemysłowymi. W celu określenia prawdziwego wpływu RSF na właściwości mechaniczne SCC wykonano testy ściskania i zginania. Zastosowano duże zawartości objętościowe RSF wynoszące 1.0% i 1.5%. Zgodnie z oczekiwaniami, odnotowano niewielki wpływ RSF na wytrzymałość betonu samozagęszczalnego na ściskanie. Wyniki uzyskane w badaniach czteropunktowego zginania wskazywały, że włókna RSF są nie tylko materiałem, który poprawia plastyczność kruchej matrycy SCC, ale również są równomiernie rozmieszczone w matrycy. Zaaplikowanie wysokich zawartości objętościowych włókien istotnie zredukowały parametry reologiczne SCC, które były badane w teście rozpływ i L-box, jednakże nie spowodowały negatywnego wpływu na homogeniczność mieszanki. Podsumowując można stwierdzić, że włókna pochodzące z recyklingu opon są materiałem, który z powodzeniem może być stosowany jako zbrojenie rozproszone w betonie samozagęszczalnym.

Keywords: Fibers from end-of-life tyres; Self-compacting concrete; Flexural tensile strength.

1. INTRODUCTION
The EU citizens used 3.6 millions of tires in 2013 based on ETRMA report from 2015 [1]. The 96% of them were recovered or recycled creating new materials. According to this report one of the material obtained in the recycling process is a steel cord, which can be further used as a concrete reinforcement. However, the data indicating for using the steel fibers reclaimed from the end-of-life tires in concrete ele-
ments are limited. The problem is connected with the fact, that even though the recycled steel fibers were analysed by some researchers e.g. [2-8] there is still a deficiency of knowledge considering the real influence of that kind of fibers on the mechanical properties of concrete matrix.

Immensity of studies has proved the effectiveness of the randomly distributed fibers in enhancing the tensile mechanical properties, fracture energy and behaviour under impact of brittle concrete matrix [9,10]. The fiber reinforced concrete (FRC) has found a wide range of practical application e.g. in slabs, floors, tunnels or precast elements [11,12]. Most of the fibers that are used as a concrete reinforcement are manufactured especially to that purpose and even new types of fibers are being discovered to satisfy the requirements of market [12]. Meanwhile, the waste could be used.

The reason of lack of interest of application of recycled steel fibers (RSF) as a concrete reinforcement is connected with their geometrical parameters. They are considerably different from all other fibers available in the market recognized as effective (e.g. hooked) [13]. As they are received from the useless tires, their parameters are dependent on the technological process of their reclamation. It is nearly impossible to design their length and longitudinal shape, just like in case of all other manufactures fibers. It is well known, that the factors that mostly influence the effectiveness of the fibers in the concrete matrix are precisely the geometrical parameters, like: length, diameter, longitudinal shape, aspect ratio, etc. [14].

Referring to the statistical analysis of the dimensions of RSF they are stochastic depending on the original source and the procedure adopted for the recycling process [2-5]. The length can vary from 5 mm to even 70 mm and its diameter can be in a range of 0.1 mm÷0.4 mm. Considering different lengths of fibers, mixing the straight fibers of different lengths (hybrid mix) can be more promising than using only one type of fibers [15, 16] what was also noted in case of mixing different types of fibers [17, 18]. In case of RSF with various lengths of separated fibers the hybrid mix is actually observed. The diameter of RSF is in the range of the smallest typical steel fibers. The aspect ratio (λ - length to diameter ratio) can achieve the value of even 300 [4], what is much higher in comparison with ordinary fibers of λ =40-80 [19]. Taking into account the longitudinal irregular shape of RSF with curls and twists it also diversifies from standard forms of manufactured fibers (hooked, curved, etc.). Further, in case of concrete reinforced with typical fibers the post-peak behavior is strongly dependent on their orientation in the matrix due to direction of concreting, elements’ size etc. [20]. This feature is a great disadvantage as it discriminates typical fibers in many fields of application. Referring to the rheological parameters of concrete, which are highly influenced by any kind of fibers, the increase of amount of fibers concurrently significantly decreases the workability and passing ability of concrete [21].

Concluding, all described geometrical features of RSF diverging from the norms designed by standard fibers can have a positive influence on mechanical properties and rheological parameters of concrete. The fibers from the end-of-life tires are hybrid fibers with a curved longitudinal shape and much higher aspect ratio than typically used fibers. It should result in increasing mechanical parameters as the fibers with higher aspect ratio are more effective in concrete matrix than the one with lower λ [22]. The orientation of the fibers that plays the crucial role regarding mechanical properties of FRC is eliminated in case of RSF. Moreover, the better distribution of fibers with a comparatively small diameter in the concrete matrix was reaffirmed by many researchers [23]. The negative influence of fibers on workability could also be minimized in case of application of fibers with untypical geometrical characteristic.

Due to discussed characteristic of RSF they have a huge potential in creating a more homogenous (repeatable) material in combination with concrete matrix, than in case of manufactured fibers. The paper deals with determining the rheological parameters and main mechanical properties of recycled steel fibers reinforced self-compacting concrete (RSF-SCC). The high amount of RSF was investigated to evaluate its influence on the mechanical response and the same show no obstacles to be used for engineering purpose.

2. EXPERIMENTAL INVESTIGATIONS

2.1. Materials, mix design and specimen preparation

The composition of the self-compacting concrete (SCC), which was used as a matrix was shown in the Table 1. The Portland cement, locally available sand and coarse aggregate were used. To decrease the amount of cement the silica fume was used in the amount of cement equal to 10%. In order to achieve a proper workability of SCC the superplasticizer and stabilizer were applied in the mix in the amount of respectively: 3.5%, 0.4% of the mass of cement.

The fibers from the end-of-life tires, further called as
recycled steel fibers (RSF), which are available at European market, were used as a self-compacting concrete reinforcement. The length of the RSF varied in a range of 2÷30 mm and the diameter was equal to around 0.15 mm (Table 2). The shape of the fibers couldn’t be uniquely determined because they are twisted and curved in all directions. The fibers used in the investigation are presented in the Fig. 1., where the variation of their length and diversity of the longitudinal shape could be clearly seen. Among the fibers few small amounts of rubber and bigger fibers remaining from recycled process could be found. The fibers were added to SCC matrix with the high volume fraction (Vf) equal to 1.0% and 1.5% which is the dosage weight of 80 kg/m³ and 120 kg/m³, respectively. The aim of the research was to determine the effectiveness of high volume content of RSF in concrete, paying attention to their impact on rheological parameters of concrete.

The self-compacting concrete was prepared according to the methodology presented in [24]. Oven dry aggregates and cement were added to the ordinary drum mixer where they were mixed for about 2 minutes. Than the fibers were added and all components were mixed for next minute. In the next stage, the half of amount of water with superplasticizer were poured to the mixer to be mixed for two minutes. The third stage of mixing lasted about 2 minutes followed by adding the second part of water with stabilizer. After preparation of the specimens they were kept in moulds under polyethylene sheet for one day and after that time they were cured in 20°C water till the time of the test.

### Table 1. Composition of RSF-SCC mix

| Material                      | Description         | Amount (kg/m³) |
|-------------------------------|---------------------|----------------|
| Cement                        | CEM I 42.5R         | 485            |
| Natural sand (0–2 mm)         |                     | 749            |
| Coarse aggregate (2–8 mm)     |                     | 936            |
| Superplasticizer              |                     | 17             |
| Stabilizer                    |                     | 1.6            |
| Silica fume                   |                     | 48.5           |
| Water                         |                     | 203            |
| Steel fibres by volume (%)    |                     | 1.0; 1.5       |
| dosage (kg/m³)                |                     | 80; 120        |
| W/B                           |                     | 0.38           |

### Table 2. Properties of fibers from end-of-life tires

| Property                        | Value                |
|---------------------------------|----------------------|
| Length [mm]                     | 2÷30                 |
| Diameter [mm]                   | 0.15 ± 5%            |
| Tensile strength [MPa]          | ≥ 2850               |
| Aspect ratio (length/diameter)  | 13 ÷ 200             |
| Longitudinal shape              | irregular (curved, twisted) |

Figure 1. Fibers from end-of-life tires – recycled steel fibers (RSF)
2.2. Tests
The workability of recycled steel fibers self-compacting concrete was investigated in slump flow test, while the ability of the mix to pass through the ordinary reinforcement was tested in L-box test. The laboratory investigations which covers the compression and flexural tensile tests were carried out to evaluate the mechanical properties of RSF-SCC. The compressive strength of RSF-SCC was assigned on the cylinders with the dimension of 150 x 300 mm according to PN-EN 12390-3 [25].

The four-point flexural tensile tests were performed according to ASTM C1609 [26] on the beams with the dimension of 100 x 100 x 400 mm. The geometry of the tested beams is depicted in (Fig. 2). The span of the beam was equal to 0.3 m. All the tests were performed in the servo-hydraulic testing machine MATEST (C109N) with the rate of mid-span deflection equal to 0.2 mm/min. The tests were conducted until the deflection reached 2 mm.

The mechanical compression and flexural tests were performed after 28-days of curing of RSF-SCC specimens. For each test the four specimen were analysed.

3. TEST RESULTS AND DISCUSSION
3.1. The rheological parameters
The results from rheological tests were summarized in Table 3. Generally, the addition of fibers coming from end-of-life tires considerably decreased the workability and passing ability of the matrix (Fig. 3). The reduction in slump flow diameter due to application of RSF was 5% and 25% of the value obtained on plain SCC for amount of fibers equal to 1% and 1.5%, respectively. However, the diameter equal to 740 mm and 550 mm satisfied the requirements for self-compacting concrete. Meanwhile, the passing ability of mix containing 1.5% of RSF was lower than 0.75, what discriminate this mix to be used in structures with congested reinforcement. Referring to Figure 3, the ideal distribution of RSF in case of all tested amounts of fibers was noted.

Behaviour of the self-compacting concrete reinforced with high amount of waste fibers was also investigated in [5,8]. For the amounts equal to 0.75% [8] and 1.0% [5] a very good homogeneity of the mix with no balling was noted. In the present investigation even the addition of 1.5% of RSF indeed decreased the rheological parameters, but do not caused negative influence on the homogeneity of the self-compacting concrete (Fig. 3c).

Some researchers observed problems during the mixing process of the waste fibers in ordinary concrete, what limited the maximum amount of RSF that could be applied to achieve a homogenous mix [2, 6]. In [2] the planetary mixer was used to prevent from tangle of the fibers and the same increase the amount of the fibers. The final applied amount of fibers was equal to 0.46%. The maximum dosage weight of fibers that could be applied to concrete in [6] was very small and equal to only 15 kg/m³, which is the amount of about 0.19%. The problem of tangling of fibers observed in ordinary concrete was solved in [3], where it was recommended to use a high amount of superplasticizer.

Thought, it could be concluded that there are no obstacles to use even a high amount of RSF in SCC. Meanwhile, the geometric characteristic of RSF may cause some impediments during preparation of conventional concrete.

3.2. Compressive strength
The compressive strength of plain self-compacting concrete was equal to 59.62 MPa. The variation in $f_c$ due to the use of RSF were presented in Table 3, where in parenthesis the coefficient of variation was shown. As expected, the RSF exhibit minor influence on the compressive strength of SCC what can be also
observed in case of manufactured fibers. The variation of $fc$ can be attributed to the fact that the fibers start to act in concrete matrix mainly after cracking and generally are a kind of perturbation in the concrete matrix.

3.3. Flexural performance
To evaluate the influence of RSF on post-peak parameters of SCC the four-point flexural tensile tests were performed according to ASTM C1609 [26], what was described in the point 2.2.

The Figure 4 presents the example of the RSF-SCC beam before and after the tests. The failure pattern, with one main crack, in case of all tested beams was noted. The load-deflection curves obtained in the flexural tests were graphically presented in the Fig. 5. Regarding the results, the steel fibers from end-of-life tires pronouncedly improved the post-peak mechanical properties of the self-compacting concrete. It is worth noting that the proceeding of the load-deflection curves were comparable in case of all four beams tested in series (Fig. 5a, Fig. 5b). The scatters were a little bit bigger in case of beams containing 1.5% of RSF. The repeatability of the results indicate that the fibers were distributed homogeneously in the SCC matrix, what could also be seen in
Figure 3. It seems, that the occurrence of pollutions and bigger fibers (Fig. 1) did not have any negative effect on flexural behaviour of SCC.

The repeatability of the results were also observed in [3]. Besides, the scatter of the experimental results of flexural tests of beams were smaller when the concrete was reinforced with RSF than the industrial fibers.

The comparison of flexural behavior of the plain SCC and SCC containing 1.0% and 1.5% of RSF were depicted in Fig. 6, where the average curves were shown. Figure 6 indicates that the flexural performance of SCC increased proportionally with the amount of RSF.

According to the recommendation [26] the following parameters can be calculated from load-deflection curve using formulas:

- flexural tensile strength (maximum or residual):

\[ f_i = \frac{P_i L}{bh^2} \]  

(1)

where: \( P_i \) – load recorded at variable deflection; \( L \) – span (300 mm); \( b, h \) – width and high of the beam (100 mm);

- toughness (the area under the load-deflection curve up to the deflection equal to 2.0 mm (L/150)):

\[ T_\delta = \int_0^\delta P(\delta) d\delta \]  

(2)

where: \( P \) – load; \( \delta \) – deflection.

The determination of flexural tensile strength \( (f_p) \) and the residual flexural tensile strength at the deflection equal to 0.5 mm \( (f_{100,0.5}) \) and 2.0 mm \( (f_{100,2}) \) was shown in the Fig. 7.

In the paper the flexural toughness factor (FT) [27] known also as equivalent flexural tensile strength \( (f_{eq}) \) [28] was also assigned:

\[ f_{eq} = \frac{T_\delta}{\delta_{L/150}} \cdot \frac{L}{b \cdot h^2} \]  

(3)

where: \( \delta_{L/150} \) – deflection of 1/150 of span.

The \( f_{eq} \) was used to specify the amount of energy needed to bring the sample to the deflection equal to L/150 of the span.
The flexural strengths, toughness and equivalent flexural tensile strengths were calculated from the average load-deflection curves according to (1), (2) and (3), respectively. The results were summarized in the Table 4, where in parenthesis the coefficient of variation was shown. The flexural tensile strength and residual flexural tensile strength of RSF-SCC increased with the increase of the amount of RSF due to the fiber bridging effect. The residual flexural tensile strengths calculated for all the beams according to (1) at the net deflection equal to 0.5 mm and 2 mm were depicted in the Fig. 8. The formulas to predict the residual flexural tensile strengths were proposed in the Fig. 8. The formulas to predict the residual flexural tensile strengths were proposed in the Fig. 8.

The f_{100,2} was equal to 47% and 58% of f_{100,0.5} for V_f = 1.0% and V_f = 1.5%, respectively. In the other words, after the appearance of the crack, when the deflection was equal to 2 mm the beams still possessed about half of their residual flexural tensile strength noted at the deflection equal to 0.5 mm. Thus, the RSF significantly improved the ductility of the brittle self-compacting concrete matrix. Further, the repeatability of the results had its reflection in low values of coefficient of variation (<17%) obtained for residual flexural tensile strengths (Table 4). The inclusion of RSF in self-compacting concrete pronouncedly enhanced the toughness, calculated to the net deflection equal to L/150 (2 mm).

The previous studies indicated that the flexural performance of concrete was improved due to application of RSF [2-8]. Moreover, the increase in toughness noted in work [3] caused by the RSF was comparable to the industrial fibers.

It can be inferred that RSF fibers when added to SCC not only create a homogeneous mix but also enhanced the brittle nature of SCC. In works [2-6] the RSF were considered as promising material for reinforcement of concrete. Even though, it was proved in [5] that the RSF are highly effective in improving crack control of beams reinforced with steel bars, there is still a need of experimental investigation of full-scale structural elements [3]. Further, although the small diameter of the fibers allows for their uniform distribution in the concrete matrix, it can be disastrous in aggressive environments [4]. For this reason, there is still a necessity of testing the durability properties of concrete reinforced with RSF.

### Table 4.

| Mix  | Peak load P_p (kN) | Net deflection δ_p (mm) | Flexural tensile strength f_p (MPa) | Toughness T_{100,2} (Nm) | Residual flexural tensile strength at L/600 f_{100,0.5} (MPa) | Residual flexural tensile strength at L/150 f_{100,2} (MPa) | Equivalent flexural tensile strength f_{eq} [MPa] |
|------|------------------|------------------------|-------------------------------|-------------------|--------------------------------|-------------------------------|---------------------------|
| 0    | 16.87 (8%)       | 0.02 (70%)             | 5.06 (8)                      | -                 | -                              | -                              | -                         |
| 1%   | 19.61 (1%)       | 0.07 (84%)             | 5.88 (1.4%)                  | 23.78 (6.4%)      | 4.13 (9.9%)                    | 1.95 (9.6%)                    | 3.57 (6.45%)              |
| 1.5% | 21.71 (5%)       | 0.17 (85%)             | 6.51 (4.9%)                  | 29.58 (10.1%)     | 5.57 (10.6%)                   | 3.24 (17%)                     | 4.44 (10.6%)             |
4. CONCLUSIONS

Based on the compressive and flexural tests conducted on the self-compacting concrete reinforced with steel fibers from end-of-life tires – recycled steel fibers (RSF) - with the dosage weight of 80 kg/m³ and 120 kg/m³ it can be concluded that:

- The geometrical characteristic of RSF diverging from observed in case of manufactured fibers was not an obstacle for the fibers to be applied as the self-compacting concrete reinforcement. The geometry of fibers enabled for their uniform distribution in the SCC matrix creating a homogeneous material in case of both tested amounts of fibers;
- The workability of SCC was significantly decreased due to addition of RSF. However, even the SCC with the 1.5% of RSF could be classified as self-compacting concrete considering the slump flow diameter. Only the passing ability was reduced to the value that discriminate this mix to be used in the structures with congested reinforcement;
- As expected, the RSF did not affect considerably the compressive strength of the self-compacting concrete. The small variation of fc was noted;
- The fibers from end-of-life tires improved the brittleness of SCC what had its reflection in enhancing the flexural post-peak properties of SCC. The flexural tensile strength, the residual flexural tensile strength, the equivalent flexural tensile strength and toughness of SCC increased proportionally to the amount of fibers. The comparability of the proceedings of the load-deflection curves in each series affirmed the uniform distribution of RSF in the matrix observed in rheological tests;
- The presented research demonstrated the potential in fibers for concrete reinforcement. However, the further wider laboratory research are needed as well as numerical simulations which will confirm the suitability of fibers for practical applications.

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