



AKADÉMIAI KIADÓ

The effect of recycled tyre steel fibers on the properties of concrete

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ABSTRACT

Steel fibers recovered from recycled tires were considered for use as reinforcement in concrete to improve the tensile properties of concrete as well as being an economically viable and environmentally friendly alternative. This paper investigates the effect of purified and non-purified recycled tire steel fiber in concrete with a constant fiber proportion of 30 kg m^{-3} to determine properties in fresh and hardened concrete. The results indicate that concrete with purified tire fibers have better tensile properties than those with non-purified tire fibers. Density, strength, and toughness significantly increase but workability tends to decrease when using recycled tire steel fiber as reinforcement in concrete.

KEYWORDS

steel fiber, recycled tire, steel fiber, industrial steel fiber, toughness

1. INTRODUCTION

The disposal of waste tires is considered one of the major global problems of waste management as approximately 1.5 billion tons of tires wastes are generated each year worldwide [1]. Environmental concerns about the management and treatment of the increasing amount of waste tires has made it a necessity to find possible applications for this possible resource. In Europe, the EU-funded TyGRE project [2] set out to find a use for Europe's waste tires. In 2016 [3], more than 3 million tons of waste tires remained for further treatment, about 1.9 million tons were processed for material recovery with 100,000 tons used for civil engineering, public works and backfilling using the steel fibers and granulated rubber. Using the materials recovered from tires, for example utilizing steel fibers in producing fiber reinforced concrete has the potential to decrease the amount of waste ending up in the landfill and increase the properties of concrete. Although concrete is a versatile material, it lacks certain important properties, having low tensile strength, low post cracking capacity, brittle behavior, and low ductility [4]. The main benefit of using steel fibers lies in their crack-bridging ability and after cracking, the tensile strength does not fall to zero but stabilizes at a nearly constant value [5]. In addition, the improvement in toughness was also a significant contribution of fibers to concrete. Toughness is the ability of a material to absorb energy and plastically deform without fracturing. This is particularly important for components, which may suffer from dynamic loads. ASTM C1018 [6] provided the method to evaluate the toughness or energy absorption capacity, which is defined as the area under the stress-strain or load-deflection curve up to a specific deflection level. The toughness was calculated at first crack deflection δ and at the other post crack deflection like 3δ , 5.5δ , 10.5δ , 15.5δ , 20.5δ and 25.5δ to evaluate the toughness indices. The toughness indices I5, I10, I20, I30, I40, and I50 were the ratio of area under the load-deflection of post crack deflection of 3δ , 5.5δ , 10.5δ , 15.5δ , 20.5δ and 25.5δ and the area at first crack deflection δ , respectively. To enhance the

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properties of plain concrete, steel fibers from tires can be used in producing a low-cost fiber reinforced concrete with favorable properties [7].

Over the last decade, scientific studies have investigated the usage of recovered material from industrial tires to improve the quality of concrete [8], for instance the possibility of using ground rubber extracted from tire in bitumen for road construction [9]. Certain researchers concentrated on the results of those studies to determine possible ways of using recycled steel fibers [10]. Several scientific studies indicated that using recycled steel fibers in concrete could improve the fragile matrix, toughness, and post-cracking in concrete for structural applications [11]. Aiello et al. [12] checked the mechanical behavior of concrete by adding tire steel fibers 0.13%–0.46% by volume with the result of improving flexural strength but for the same concrete mixes, the compressive strength remained unaffected. During the last two decades, the use of steel fiber reinforced concrete has steadily increased [13]. Dahake [14] found that steel fibers at a constant amount of 2.5% by weight of cement with satisfactory results; compressive strength, and flexural strength tended to increase, but there is a reduction in porosity as well as in the absorption capacity of the concrete in comparison with conventional concrete. Papakonstantinou and Tobolski [15] used the steel beads from tires in reinforced concrete with a range of fiber content 2–8% by volume, and tested uniaxial compression and splitting tension. The results showed that the compressive strength decreased, but the toughness increased and the workability was not necessarily affected. Halvax and Lubloy [16] studied the effect of embedded length, matrix strength, fiber shape, and fibers tensile strength on the bond strength. They concluded that is no clear connection between the tensile strength and the bond strength. Salunkhe [17] experimented with properties of fiber-reinforced concrete at different percentages of 1–3%, tested at 7 and 28 days by using two methods - weigh batching and volume batching in concrete. The results indicated that the workability of concrete decreased when the percentage of fibers increased in both methods. The compressive strength of concrete, when using weighs batching, is higher when compared to the volumetric batching method. Furthermore, the addition of fibers advances the ductility of concrete, split tensile strength, and post-cracking load-carrying capacity of concrete. Steel fibers from waste tires play an essential role in advancing concrete technology with many applications also suitable for waste management.

At present, there is a need to find a suitable methodology for applying steel tire fibers in concrete to effectively

improve its performance. This research focuses on the effect steel fibers from waste tires Recycled Tire Steel Fiber (RTSF) have on the mechanical properties of concrete, with the range of dimension is 0.1–2.0 mm and less than 100 mm of length. The flexural tensile strength and flexural toughness were investigated under purified and non-purified states of RTSF. The dosage of fiber content was kept at a constant 30 kg m^{-3} to avoid the balling effect due to the irregular shape of recycled tire steel fibers. It also determines a way for the utilization of recycled steel fibers in concrete by comparing its performance with conventional concrete and industrial fiber reinforced concrete.

2. EXPERIMENTAL PROCEDURE

Experimental work presented in this paper was a part of a master's thesis from the University of Pécs. The experimental investigation was achieved using beams and cubes made from conventional concrete and fiber-reinforced concrete with 2 different kinds of fiber: Industrial Steel Fiber (ISF) and Recycled Tire Steel Fiber (RTSF). In the case of RTSF, there were 2 different states: purified and non-purified. The fiber content was kept constant at the maximum allowable percentage of fiber content is 0.26% by volume, as recommended by Angelakopoulos et al. [18], while using a traditional mixer to avoid the balling effect. There were 4 groups of samples: conventional concrete, concrete with purified-RTSF, concrete with non-purified RTSF, and concrete with industrial hooked-end steel fibers. Tests were carried out to examine their influence on fresh and hardened concrete properties.

2.1. Materials and sample preparation

Four concrete mixes were prepared using Portland cement CEM II/A-M (V-LL) 42.5 N with the combination of fine aggregate 0–4 mm and coarse aggregate 4–8 mm and 8–16 mm (Table 1). Super-plasticizer Sika[®] ViscoCrete[®]-7710 was used while mixing concrete to provide workability and to improve the properties of hardened concrete. The industrial hooked-end steel fibers were used (Fig. 1a), with an aspect ratio 50 and young modulus of $200,000 \text{ N mm}^{-2}$.

RECA Kft. [19], Green Tyre Feldolgozo es Hasznosito Zrt. [20] supplied steel fiber recovered from tires RTSF (Fig. 1b and c) using a shredding process and its geometry characteristic is presented in Fig. 2. Purified steel tire fibers that were used in the concrete mixture, were further processed to remove dust, attached rubber, and corrosion by

Table 1. Aggregate properties

	Coarse aggregate	Fine aggregate
Fineness modulus	7.97	3.75
Apparent particle density	2.64	2.58
Oven-dried particle density	2.59	2.46
Saturated and surface dried particle density	2.61	2.50
The water absorption after immersion for 24 h	0.68	1.81





Fig. 1. Steel fibers, a) ISF, b) RTSF-Non-purified, c) RTSF-Purified

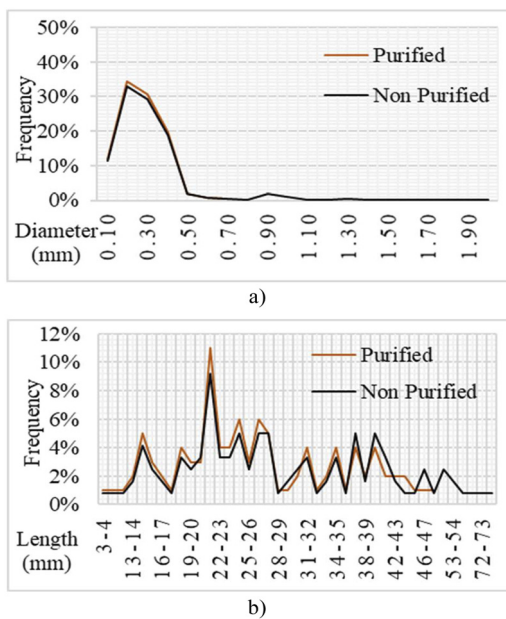


Fig. 2. Information on geometrical variability Purified and Non-purified tire steel fibers

immersion in vinegar overnight and then dried using a dryer.

The concrete mix was prepared by following the obtained mix proportion in Table 2, a total of 6 samples were prepared for each mix: 3-cubes with dimension $150 \times 150 \times 150$ mm for the compressive strength test and 3-beams with dimension $75 \times 150 \times 600$ mm specimens for the flexural strength test.

All of the tests were performed on a set of three samples for each mix, and the average value obtained from these specimens was used to evaluate the mix design. Batching should be done accurately to achieve the desired quality of the concrete mix. The fibers were carefully sprinkled while mixing the dry mix to reduce the chances of balling and to ensure a good distribution of fibers in the concrete mix. The concrete mixes were tested to determine fresh concrete properties. The concrete was placed in molds and compacted using a vibrating table. The specimens were demolded after 24 h and then placed in water with a temperature $20 \pm 2^\circ\text{C}$ for 56 days.

2.2. Testing procedure

Tests on the concrete properties were performed according to the Eurocode standard to evaluate the influence of fibers on workability and density. The cube specimens were tested for compressive strength and hardened density of concrete, Fig. 3a shows the cube specimens under the compressive strength test.

There are 2 different methods for testing flexural strength: the 3-point bending test and 4-point bending test. In this research, the flexural strength was determined using 4-point bending for each of the beam samples. Figure 3b presents beam specimens under the flexural strength test in the laboratory with the test set up, as it is shown in Fig. 3c.

The energy absorption capacity is used to define flexural toughness, which is the ability to resist crack propagation. Test configuration based on ASTM C1018 was applied to determine flexural toughness. Toughness indices were determined by dividing the area under the load-deflection curve obtained by the flexural test. Toughness indices I, I5, I10, and I30 was calculated for 4 specified deflections

Table 2. Mix proportion for four sample groups

Sample ID	W/C ratio	Cement quantity	Water	Aggregate (mm)			Steel fibers	Adm. (liter m^{-3})
				0–4	4–8 (kg m^{-3})	8–16		
Conventional concrete	0.52	350	182	732	476	622	0	0.875
Concrete with Industrial steel fibers (ISF)	0.52	350	182	732	476	622	30	0.875
Concrete with Purified RTSF	0.52	350	182	732	476	622	30	0.875
Concrete with Non-Purified RTSF	0.52	350	182	732	476	622	30	0.875

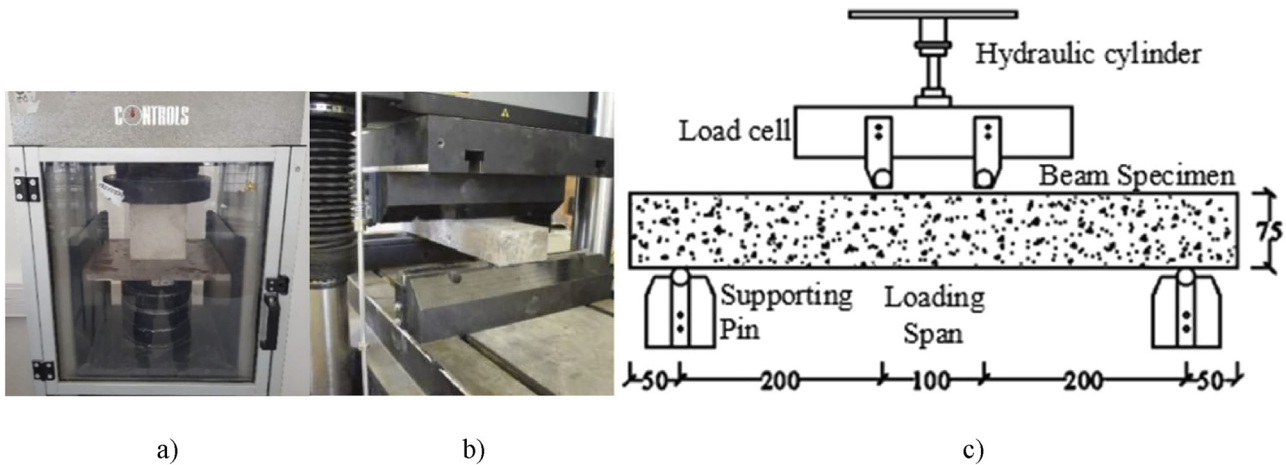


Fig. 3. a) Compressive strength test on cube specimens; b) flexural strength test on beam specimen; c) flexural strength test set up (in mm)

δ , 3δ , 5.5δ , and 15.5δ . The toughness index (I) was considered as first crack toughness, while I5, I10, and I30 were considered as post crack toughness.

2.2.1. Fresh concrete properties. The results presented in Table 3 indicate that the presence of RTSF in concrete decreases its workability, in contrast to the density that tends to increase. In particular, mixes with purified RTSF presented the lowest slump value among the other considered mixes, due to its surface that needed to be covered by cement mortar. Non-purified RTSF, which contains a small amount of attached rubber, resulted in better workability in fresh concrete. Regarding concrete with ISF, the slump decreased by 10%, which could lead to the conclusion that ISF slightly affected the workability through the addition of the recommended dosage of 30 kg m^{-3} . However, most of the mixtures were workable without any balling effect, except for non-purified RTSF, which resulted in slight balling, due to the length and irregular shape of fibers and the attached rubber which increased the tendency to interlock during

mixing. No problems were observed while compacting using the vibrating table.

2.3. Hardened concrete properties

2.3.1. Compressive strength and density of hardened concrete. Based on the design, concrete strength that was recommended from the industrial hooked-end steel fiber datasheet; the design compressive strength should be C30/37. The presence of fibers in concrete slightly increased compressive strength, and deferred failure of concrete specimens as it is shown in Table 4. Conventional concrete failed with a violent explosive failure, whereas concrete with fibers had a more ductile failure. The average 56 days compressive strength of conventional concrete and concrete with ISF had an insignificant difference of 4.98%. With the addition of RTSF, the compressive strength tended to increase by 9.05% for purified and 7.92% for non-purified mixes. The compressive strength of both states was almost identical, with a 1% difference. The purified RTSF had the most potential to improve the compressive strength among the mixes.

2.3.2. Flexural strength. The curves in Fig. 4 showed that fibers were applied in concrete to provide the plastic phase to delay sample fracture after the occurrence of the first crack. The conventional concrete suffered a sudden rapid failure without a plastic phase after reaching the first crack. The mixture with ISF presented the highest flexural

Table 3. Fresh concrete properties results

Type of specimens	Slump (mm)	Fresh concrete density (kg m^{-3})
Conventional concrete	100	2,313
Concrete with ISF	90	2,320
Concrete with Purified RTSF	50	2,360
Concrete with Non-Purified RTSF	60	2,354

Table 4. Compressive strength and hardened density results

Type of specimens	Hardened density (kg m^{-3})	Compressive strength (MPa)	Standard deviation	Relative stress index (%)
Conventional concrete	2,392	44.2	4.4	0
Concrete with ISF	2,407	46.4	1.2	4.98
Concrete with Purified RTSF	2,414	48.2	0.8	9.05
Concrete with Non-Purified RTSF	2,407	47.7	1.7	7.92



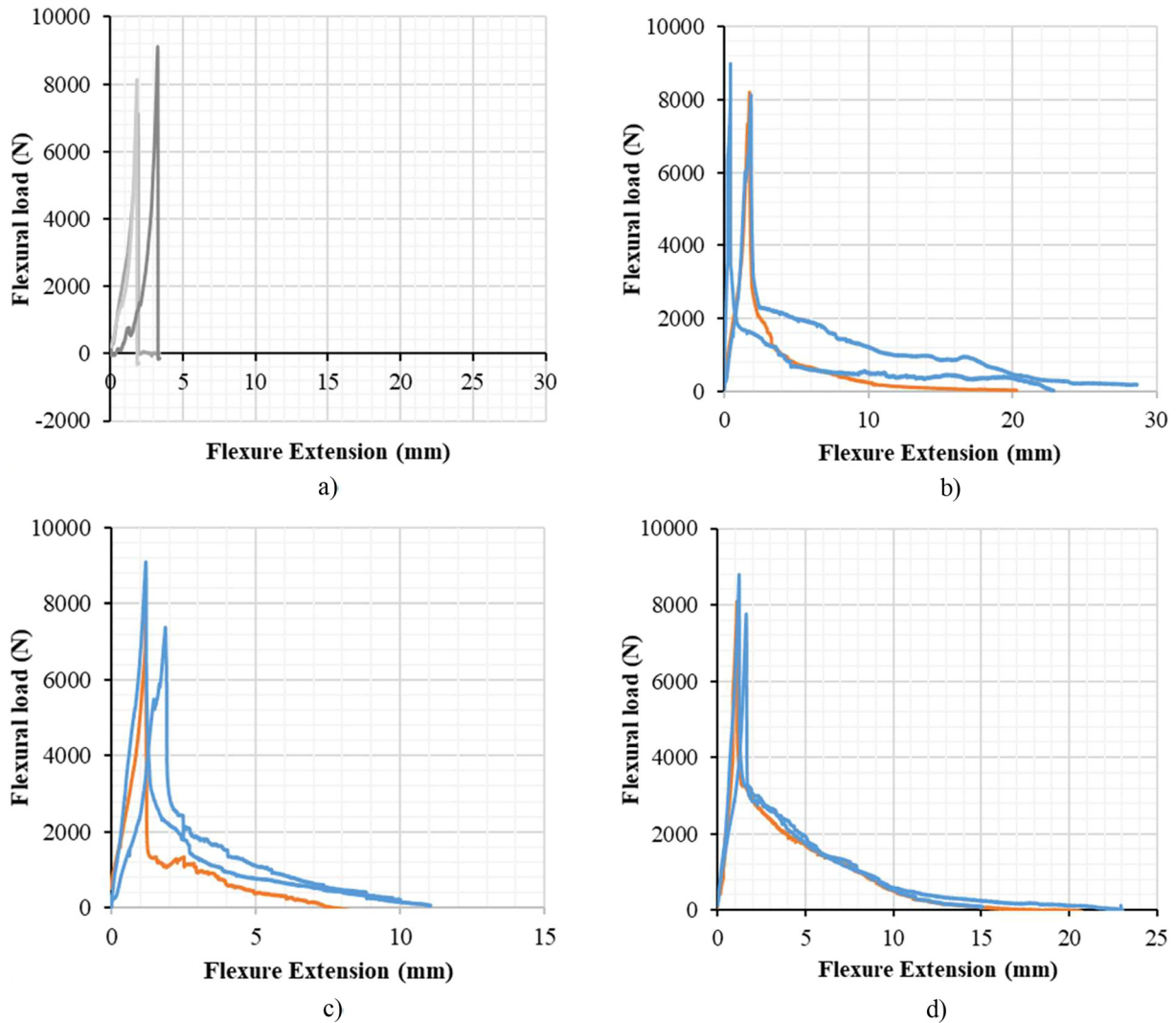


Fig. 4. Flexural load versus flexural deflection: a) conventional concrete; b) ISF-reinforced concrete; c) RTSF-non-purified reinforced concrete; d) RTSF-purified reinforced concrete

deflection with a mean value of 23.9 mm, which is 8 times more than conventional concrete. In the case of RTSF, the flexural deflection was lower than ISF but better than conventional concrete. In the non-purified samples, the mean value of flexural deflection was more than 3.5 times greater than conventional concrete but half as much as for the ISF samples. Purified RTSF performed better flexural deflection than the non-purified samples, and the mean value of flexural deflection is 19.7 mm, which is close to ISF with 2% less. Furthermore, the presence of fibers in concrete also decreased the first crack deflection of concrete, as showed in Table 5, whereas conventional concrete reached the highest crack deflection first.

The flexural strength results indicated that an improvement of flexural strength was caused by adding the fibers as reinforcement in concrete, as it is presented in Table 5. The maximum flexural strength was obtained by adding ISF, due to its properties that could provide better performance among the RTSF in flexural strength. With the addition of RTSF, the flexural tensile of both samples tended to increase.

In the purified state, results were similar to ISF, showing a difference of less than 3%. Non-purified RTSF performed the worst due to the attached rubber, dust, and corrosion that affected the strength of the fibers and provided lower tensile strength for concrete compared to other mixes.

Energy absorption and toughness index results are presented in Table 6. The toughness indices I_5 , I_{10} , and I_{30} of the conventional concrete were found to be 1.27. Nevertheless, non-purified RTSF inclusion in concrete mixtures resulted in a minimum I_5 , I_{10} , and I_{30} values of 2.01, 2.40, and 2.55 with a relative gain of 58%, 89%, and 101%, respectively. Non-purified RTSF was less effective among the others due to the corrosion which directly affected the tensile strength of fibers. In contrast, maximum I_5 , I_{10} , and I_{30} values of 2.34, 3.42, and 4.41 were observed in mixes with purified RTSF, with a relative gain of 84%, 169%, and 247% respectively.

The I_5 , I_{10} , and I_{30} of concrete with ISF were found to be 2.13, 2.92, and 4.31, with a relative gain of 68, 130, and 239%. The toughness index of purified RTSF was better than

Table 5. Flexural strength results

Type of specimens	Flexural strength (MPa)	Standard deviation	Relative strength gain or loss (%)
Conventional concrete	5.5	0.4	0.0
Concrete with ISF	6.0	0.3	9.9
Concrete with Purified RTSF	5.8	0.4	7.1
Concrete with Non-Purified RTSF	5.7	0.7	3.8

Table 6. Energy absorption and toughness index results

Name of specimens	Energy absorption in Joules				Toughness index		
	δ	3δ	5.5δ	15.5δ	I5	I10	I30
Conventional concrete	4.12	5.22	5.22	5.22	1.27	1.27	1.27
Concrete with ISF	4.48	9.74	13.37	18.81	2.13	2.92	4.31
Concrete with Purified RTSF	4.75	11.11	16.25	20.95	2.34	3.42	4.41
Concrete with Non-Purified RTSF	4.60	9.35	13.07	13.78	2.01	2.43	2.54

ISF due to the number of fibers in the concrete mix, approximately 32,000 fibers per beam, but in the case of ISF, there were about 650 fibers which were distributed in each beam, which is 50 times less than in the case of the RTSF samples.

The results indicate that the addition of fiber to the concrete extensively improved the toughness indices. Purified RTSF was more effective on the improvement of toughness than non-purified RTSF and ISF. The lowest toughness indices of the control mix are because conventional concrete beams fail immediately after the appearance of first crack.

3. CONCLUSION

The experimental program aimed to investigate the properties of fiber-reinforced concrete using recycled steel fibers from waste tires as a possible alternative to industrial fibers. The results support the potential usage of recycled fibers in producing environmentally-friendly fiber reinforced concrete. However, it has been shown that the performance can be improved further by removing the attached rubber from the recycled fibers.

The research resulted in the following main conclusions:

- The irregular geometric shape with a long length of the non-purified RTSF resulted in a higher likelihood of the balling effect occurring than in the case of purified RTSF and ISF;
- Workability was strongly affected by adding RTSF to the concrete mix due to its enhanced surface that needed to be coated with the cement paste. Concrete mixes with non-purified RTSF were found to have better workability than those with purified RTSF due to the small amount of rubber that tends to increase the slump. In case of ISF, the workability was not strongly affected because of its coat and the small amount of ISF in concrete mix;
- The presence of fibers affected the density of concrete in both fresh concrete and hardened concrete samples. In

this experiment, the amount of rubber in the state of non-purified RTSF was too small to cause a variation in concrete density;

- Fibers slightly affected compressive strength. By using RTSF in concrete, the compressive strength slightly increased. Concrete with purified RTSF had a better compressive strength than that with non-purified fibers because there was no corrosion, dust, and rubber on the surface that would weaken the bond;
- The number of RTSF was higher than ISF in concrete mix with the same weight. So, the addition of RTSF resulted in an increase in the flexural strength better than the ISF. So, the addition of RTSF resulted in an increase in the flexural strength better than the ISF. RTSF also provided a more ductile behavior after the occurrence of the first crack;
- By adding RTSF, flexural toughness tended to increase. The post cracking behavior of concrete with purified RTSF was similar to that with non-purified additions. Purified RTSF samples showed increased energy absorption capacity after the occurrence of the first crack;
- In comparison with ISF, concrete with the addition of RTSF improved the properties of concrete while being a more economical and eco-friendly solution for the construction of reinforced concrete structures in specific areas.

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