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TECHNICAL PAPER

Reuse of elevator wire rope waste to improve the tensile strength of plain concrete

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Abstract
The present study aims to explore ways of reusing elevator wire rope waste (EWRW) produced by elevator manufacturers. This investigation focused on the ultimate tensile strength and flexural toughness of the improved samples. The primary types of EWRW used in sample preparation are those with a fiber core (EWRW-F) or a polypropylene core (EWRW-P). The results indicated that the ultimate tensile strength of the improved EWRW-F samples outperformed the results of the EWRW-P. The results also revealed that an increase in the ultimate tensile strength of 2–15% can be achieved using EWRW. The results also showed that the flexural toughness of the improved samples increased significantly (up to 32-fold) with the use of 3% EWRW-F compared to the plain concrete. The present work establishes that the inclusion of EWRW-F can improve the tensile behavior of plain concrete.

Keywords Elevator wire rope waste · Tensile strength · Flexural toughness

Introduction

The lack of tensile strength in concrete, which makes it fragile and subject to rupture under force, is the main weakness of concrete. Reinforcement or fibers have been used to eliminate these defects. Accumulated industrial waste requires recycling, which is a costly process. If such waste can be reused at a low cost, it can be a good alternative to more expensive products or the use of natural resources. The use of waste materials to address civil engineering problems can help prevent their accumulation in the environment. It is known that the concrete is weak under tension and the solutions have been proposed by researchers in order to improve its mechanical properties. Environmentally friendly materials such as polypropylene fiber, PET, steel fiber, steel wool, natural filler, ferrochrome slag, palm and jute fibers, glass, natural volcanic powders, rice straw ash, steel-glass hybrid fiber, and other types of slag and waste have been used in concrete for environmental purposes and to increase its compressive and tensile strength [1–14].

Nedeljković et al. [15] evaluated the effects of ductile alkali-activated fly ash and ground granulated blast furnace slag, mixed with plastic fiberglass mesh as an environmentally friendly material for improving the engineering properties of plain concrete, such as its workability and compressive strength. Their results recorded an increase in the workability and durability of the improved concrete. The compressive strength and toughness indices of crumb rubber (CR) alkali-activated mortar reinforced with recycled steel fiber (SF) were determined and evaluated by Zhong et al. [16]. They reported a 4.7–26.7% improvement in workability with the inclusion of CR. The optimal mixture (5% CR and 1.0% vol. of SF) recorded the highest strength and toughness properties compared to the reference mixture.

Several studies have shown that steel fibers are being used as reinforcements to improve the tensile strength and flexibility of concrete [17, 18]. For example, Aydın and Baradan [19] used steel fibers of 6 and 13 mm at volume fractions of 0.5%, 1.0%, 1.5%, and 2.0% in alkali-activated slag/silica fume mortar. The addition of steel fiber improved the compressive, flexural strength and toughness of the mixes. On

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Table 1 Chemical specifications of cement

Chemical parameters	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Cl (%)	SO_3 (%)	LOI (%)	I.R (%)	C_3A (%)
Sepahan cement	21.1	4.90	4.00	64.20	2.20	0.025	2.20	1.00	0.35	6.00
Iranian standard	> 20.00	< 6.00	< 6.00	–	< 5.00	–	< 3.00	< 3.00	< 0.75	< 8.00
European standard	–	–	–	–	–	< 0.100	< 3.50	< 5.00	< 5.00	–

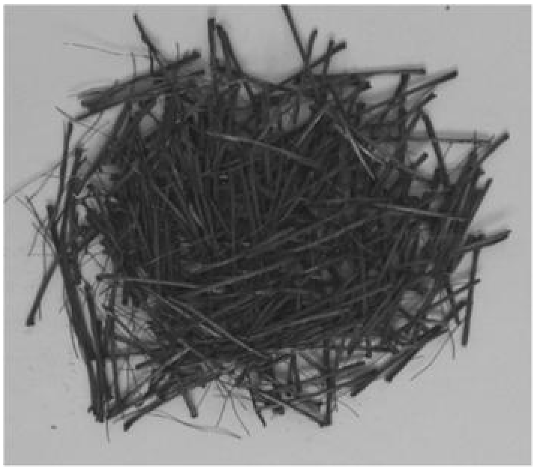


Fig. 1 Wire rope waste with fiber core (EWRW-F)

Fig. 2 Wire rope waste with polyethylene core (EWRW-P)

the other hand, a decrease in workability was a drawback noted in this research. An increase in toughness and flexural strength of concrete was improved by steel fibers and were also reported by Keshavarz and Mostofinejad [20]. They used steel chips and porcelain ceramic waste as replacements for coarse aggregate. The results showed that a 64.7% increase in flexural strength was achieved using the optimum amount of steel chips.

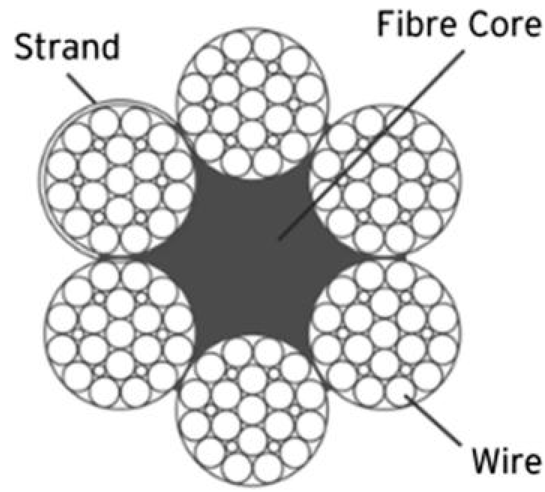


Fig. 3 Fiber with six strands, each with 19 spun wires

Table 2 Specifications of wire rope waste

Parameters	EWRW-P	EWRW-F
Weight (kg/m)	0.21	0.22
Tensile strength (N/mm^2)	1690	1770
Minimum breaking load (kN)	33.2	34.8

Quadir et al. [21] used granulated steel as a partial replacement for fine aggregate. Their results indicated that the flexural strength and toughness of the mixes at steel weight ratios of 11%, 31%, and 38% increased from 10 to 60%, respectively. Iqbal [22] also used steel fibers in a closed format. Their results indicated that the workability of the fiber-reinforced concrete decreased with the addition of the fiber, and no significant improvement in the concrete compressive strength and modulus of elasticity were observed. On the other hand, the flexural strength and tensile strength of the concrete increased 36% and 46%, respectively.

Hassanpour et al. [23] determined the mechanical properties, such as the splitting tensile strength and compressive strength of structural lightweight concrete improved with low volumes of steel fiber (≤ 1%). Their results demonstrated that the use of 0.25%, 0.5%, 0.75%, and 1% steel fiber increased the 28-day compressive strength 14–32%. In addition, the splitting tensile strength of the samples

Table 3 Concrete mix design

S/G	S (fine coarse)	G (natural coarse)	C (kg)	W (kg)	W/C	Unit weight (kg/m^3)	F_c (MPa)	Reference mixture
0.5	625	1250	350	175	0.5	2400	25	I
0.63	678	1077	400	190	0.47	2345	35	II
0.68	730	1074	336	205	0.61	2345	25	III

W/C, water to cement; *C*, cement; *G*, gravel; *S*, sand

Table 4 Details of concrete mixes

Mix code	EWRW core	Concrete specimen composition	Curing period (days)	Reference mixture
TS-1	–	C	28	I
TS-2	–	C	28	I
TS-3	EWRW-P	C + 1.5% P	28	I
TS-4	EWRW-F	C + 1.5% F	28	I
TS-5	EWRW-P	C + 2% P	28	I
TS-6	EWRW-F	C + 2% F	28	I
TS-7	EWRW-P	C + 2.5% P	28	I
TS-8	EWRW-F	C + 2.5% F	28	I
TS-9	–	C	28	II
TS-10	EWRW-P	C + 1.5% P	28	II
TS-11	EWRW-F	C + 1.5% F	28	II
TS-12	EWRW-P	C + 2% P	28	II
TS-13	EWRW-F	C + 2% F	28	II
TS-14	EWRW-P	C + 2.5% P	28	II
TS-15	EWRW-F	C + 3% F	28	II
TS-16	EWRW-F	C + 2.5% F	28	II
*TS-17	EWRW-P	C + 3% P	28	II
*TS-18	EWRW-F	C + 3% F	28	II
*TS-19	EWRW-F	C + 3% F	28	II
TS-20	–	C	28	III
TS-21	EWRW-F	C + 2% F	28	III
TS-22	EWRW-F	C + 2.5% F	28	III
TS-23	EWRW-F	C + 3% F	28	III
TS-24	–	C	42	III
*TS-25	EWRW-F	C + 2% F	42	III
*TS-26	EWRW-F	C + 2% F	42	III
*TS-27	EWRW-F	C + 2.5% F	42	III
*TS-28	EWRW-F	C + 2.5% F	42	III
*TS-29	EWRW-F	C + 3% F	42	III
*TS-30	EWRW-F	C + 3% F	42	III

EWRW-F, EWRW with fiber core; *EWRW-P*, EWRW with polyethylene core; *C*, Plain concrete;

* tests were repeated

increased up to 69%. Syamsir et al. [24] investigated the combined effect of the addition of 0.2% drink can and different percentages of steel fiber on the flexural strength and indirect tensile strength of concrete. Their results revealed that a combination of 2% steel fiber and 0.2% drink can aluminum was the optimum combination which significantly increased the flexural strength and indirect tensile strength of the concrete. Similar improvements in the use of steel fiber have also been reported by Leone et al. [25] and Abbass et al. [26].

Fig. 4 Concrete samples during curing

The use of polypropylene fiber and steel fibers on the quasi-static and dynamic splitting tensile properties of high-strength concrete were investigated by Guo et al. [27]. Their results indicated that an increase in steel fiber increased the tensile strength accordingly. However, when polypropylene fiber was added to the steel fiber, the risk of brittle failure of the concrete decreased. Marar et al. [28] investigated the effects of steel fiber-reinforced concrete on the direct shear behavior of plain (C30 and C50) and improved concrete beams of 100 × 100 × 300 mm in size. Aspect ratios (*l/d*) of 65 and 80 for the steel hooked-end fibers and fibers contents of 0.5%, 1.0%, and 1.5% by volume of concrete were utilized in sample preparation. Their results showed that when the steel fibers content increased to 1.5%, the shear strength increased about 2.46-fold compared to plain concrete. In a similar study, Qureshi and Muhammad [29] examined the effects of steel and glass fibers on the shear behavior of

Fig. 5 **a** Laboratory testing of concrete specimens; **b** data recording system

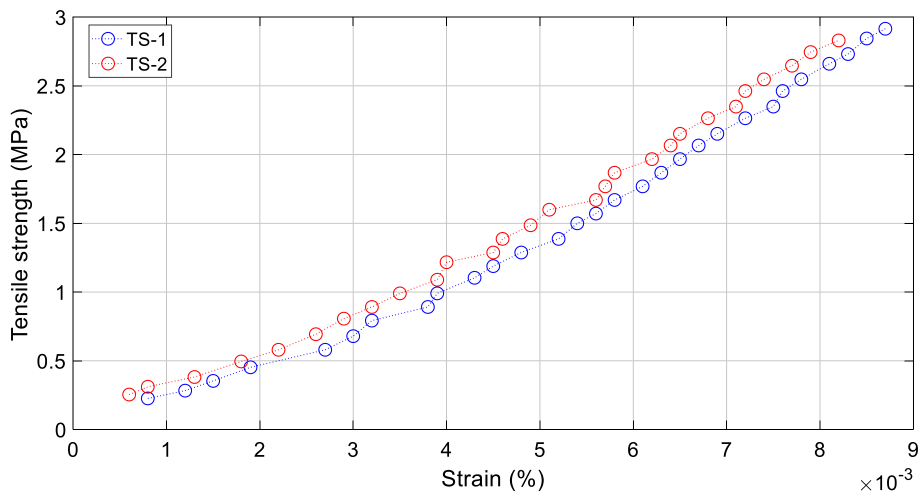


Fig. 6 Tensile strength of plain concrete (reference mixture I; 28-day)

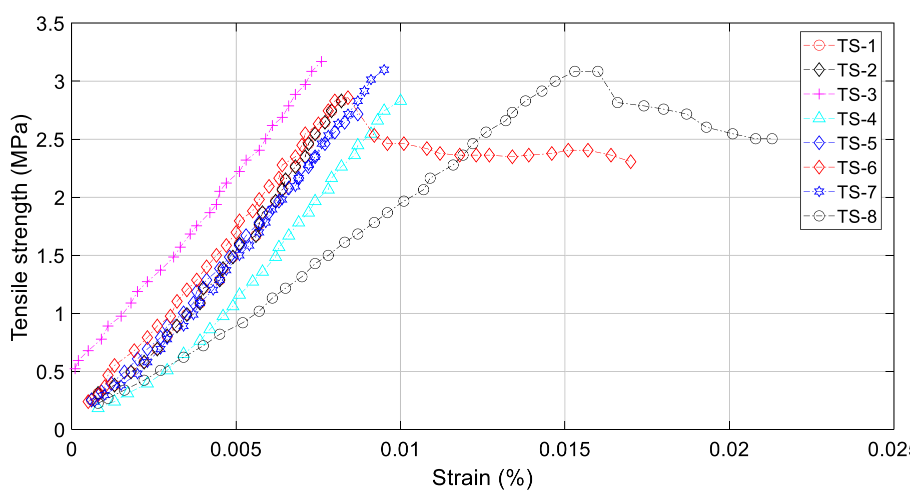


Fig. 7 Tensile strength of improved samples (reference mixture I; 28-day)

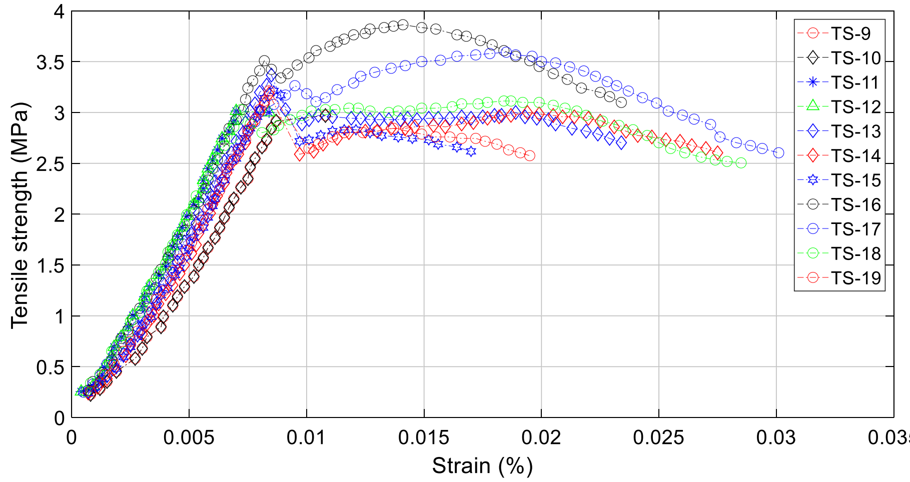


Fig. 8 Tensile strength of improved samples (reference mixture II; 28-day)

concrete column-beam joints. The results revealed that the addition of a mixture of these fibers improved the stiffness, ductility and strength. In a similar study on the behavior of concrete beams, resistance under bending was improved when a combination of steel fibers and longitudinal rebars was utilized [30].

Significance of study

The accumulation of industrial waste from steel wires has increased worldwide and has caused serious environmental problems. This type of waste is generally covered with grease and can pollute the soil, water, and air. Therefore, there is a need to overcome these environmental problems. For this matter, in the present study, two types of elevator wire rope waste (EWRW) were tested for their effects on the tensile behavior and toughness of plain concrete. EWRW is quite different from conventional steel fibers [31–34] and, to the author's knowledge, this type of waste material has not previously been used in this format as fiber.

Experimental design

Cement and waste wire rope

Ordinary Portland cement ASTM type II (Sepahan) was used in all samples. Table 1 shows the physical and chemical specifications of the cement. Gravel with diameters ranging from 5 to 10 mm and sand with diameters ranging from 0 to 5 mm and a fineness modulus of 2.66 were used in accordance with ASTM C33 (ASTMC33; [35]). No superplasticizer was used in this study.

EWRW with a fiber core (EWRW-F) and EWRW with a polyethylene core (EWRW-P) were the two types of waste product used (Figs. 1, 2). Ropes with fiber cores (EWRW-F) are resistant to contact pressure and exhibit low deformability. EWRW-P is popular for use as crane and cable car ropes and is also used for elevator ropes. All the EWRW used in this study had six strands with 19 spun wires, as shown in

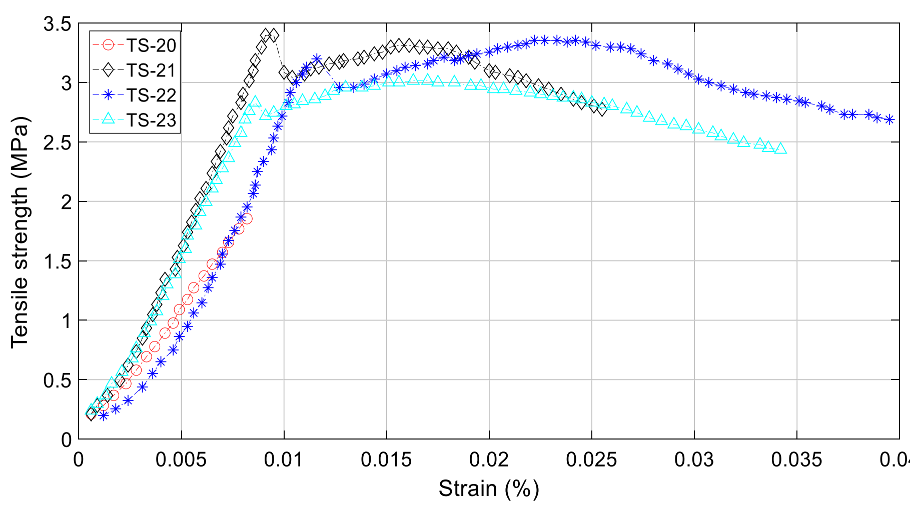


Fig. 9 Tensile strength of improved samples (reference mixture III; 28-day)

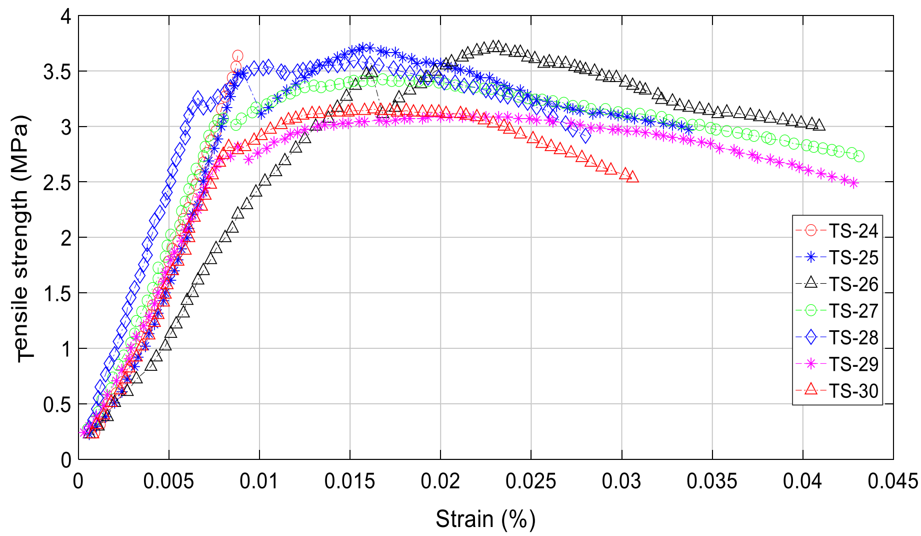


Fig. 10 Tensile strength of improved samples (reference mixture III; 42-day)

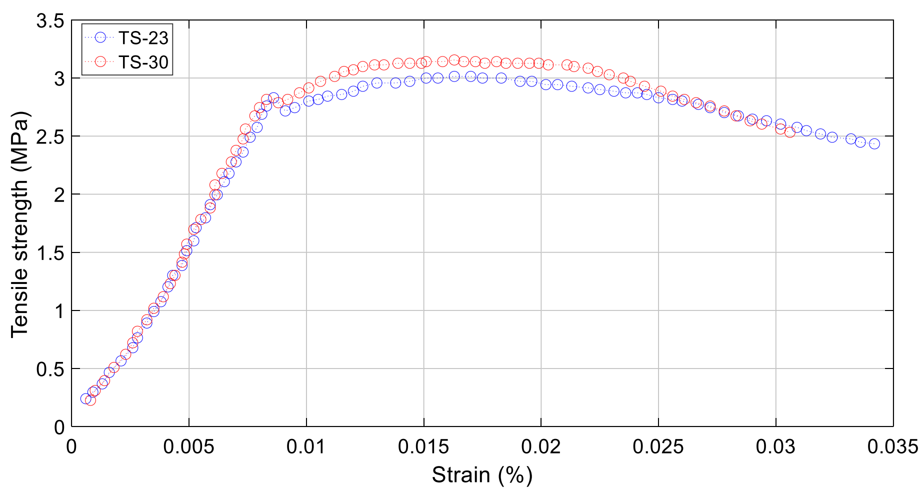


Fig. 11 Effect of curing time on tensile strength

Fig. 3. Table 2 shows the specifications of used wire rope waste.

Mix proportions

In the sample preparations, because the EWRW waste was gathered from a local elevator construction company, the materials were coated with grease; thus, they first were thoroughly washed and dried and then were cut manually in the lab to obtain straight steel fibers that were 60 mm in length. Three series of concrete mix designs were prepared at compressive strengths of 25 and 35 MPa. The details of the concrete mix designs are shown in Table 3. Three reference mixtures were considered for the concrete. The differences between the mixtures are shown in Table 4. Thirty splitting tensile tests were performed. As can be seen in Table 3, tests TS-1, TS-2, TS-9, TS-20, and TS-24 were the reference tests carried out on plain concrete. The percentage of EWRW in the mixed samples was 1.5%, 2% and 2.5% for reference mixture I, 1.5%, 2%, 2.5% and 3% for reference mixture II, and 1.5%, 2%, 2.5%, and 3% for reference mixture III. The samples were cured for 28 and 42 days. In order to control and evaluate the homogeneity of the sample preparations, some tests were repeated with large amounts of EWRW.

Tensile strength tests

Splitting tensile strength tests were carried out to determine the ultimate tensile strength of the samples. The samples were cylinders of 15 cm in diameter with a height of 30 cm. The metal molds had a mean internal diameter of 15 cm ± 0.2 mm and a height of 30 ± 0.1 cm. The test specimens were stored at a temperature of 27C° for 24 h. Then they were removed from the molds and submerged in clean fresh water for curing for 28 or 42 days, as shown in Fig. 4. During testing, the samples were placed horizontally

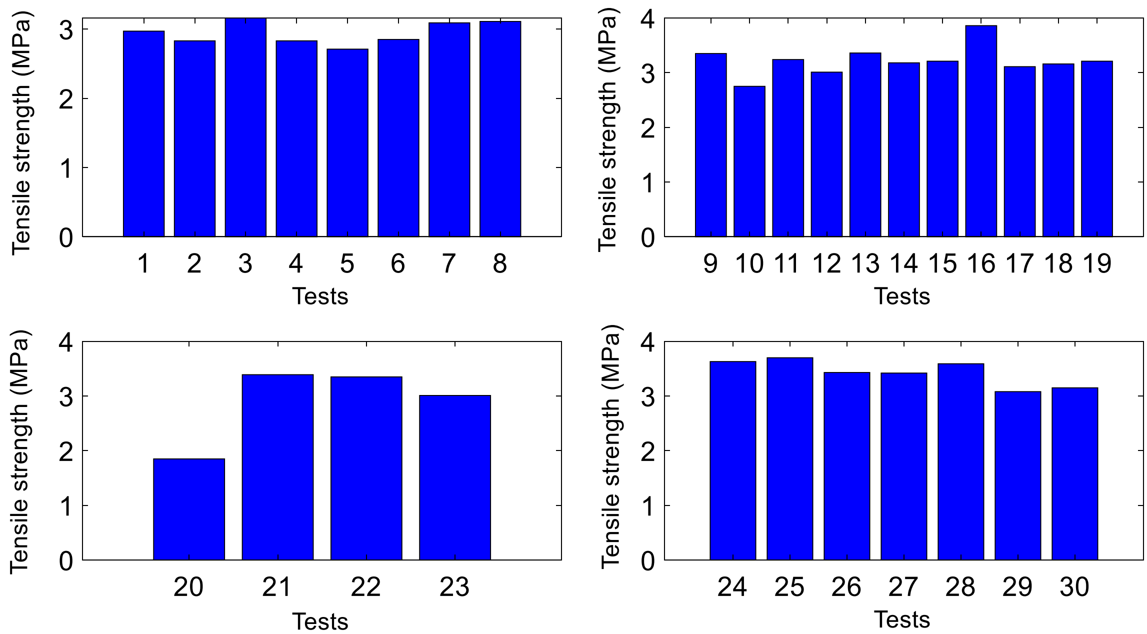


Fig. 12 Tensile strength of improved samples (all tests)

Fig. 13 TIR for tests TS-9 to TS-19 (reference mixture II)

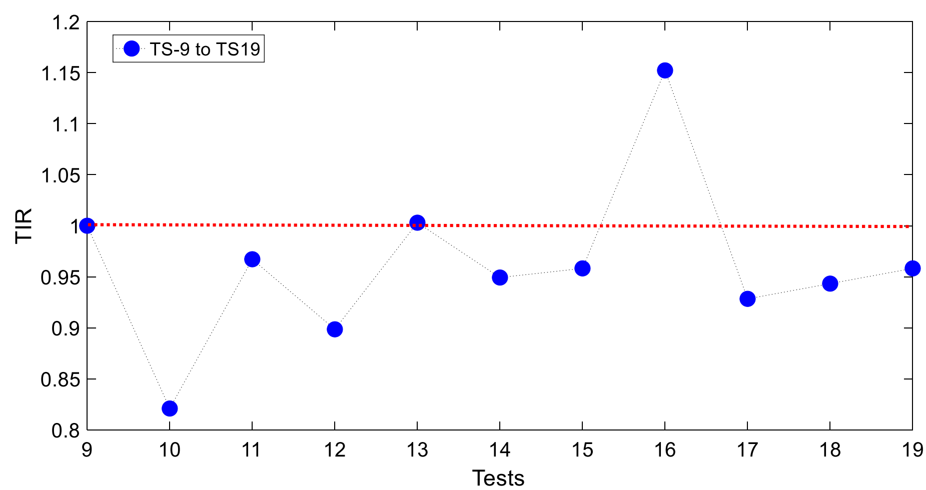
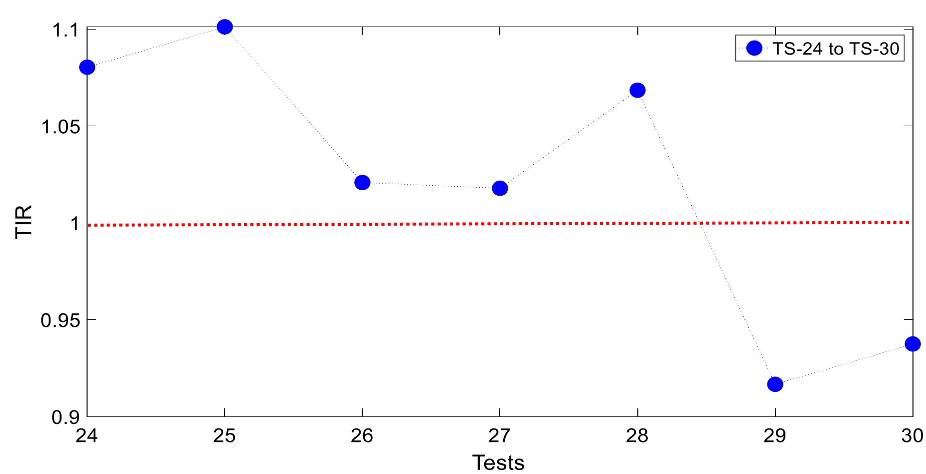


Fig. 14 TIR for tests TS-24 to TS-30 (reference mixture III)



between the loading surfaces of the compression testing machine as shown in Fig. 5a. The compression stress was applied uniformly and diametrically along the length of the cylinder at a rate of 1 MPa/min. A data recording system was employed to automatically calculate the stress-displacement trends and the final splitting tensile strength in each test. All data were recorded per second. Figure 5b shows a sample calculation where the *T* is the ultimate tensile strength.

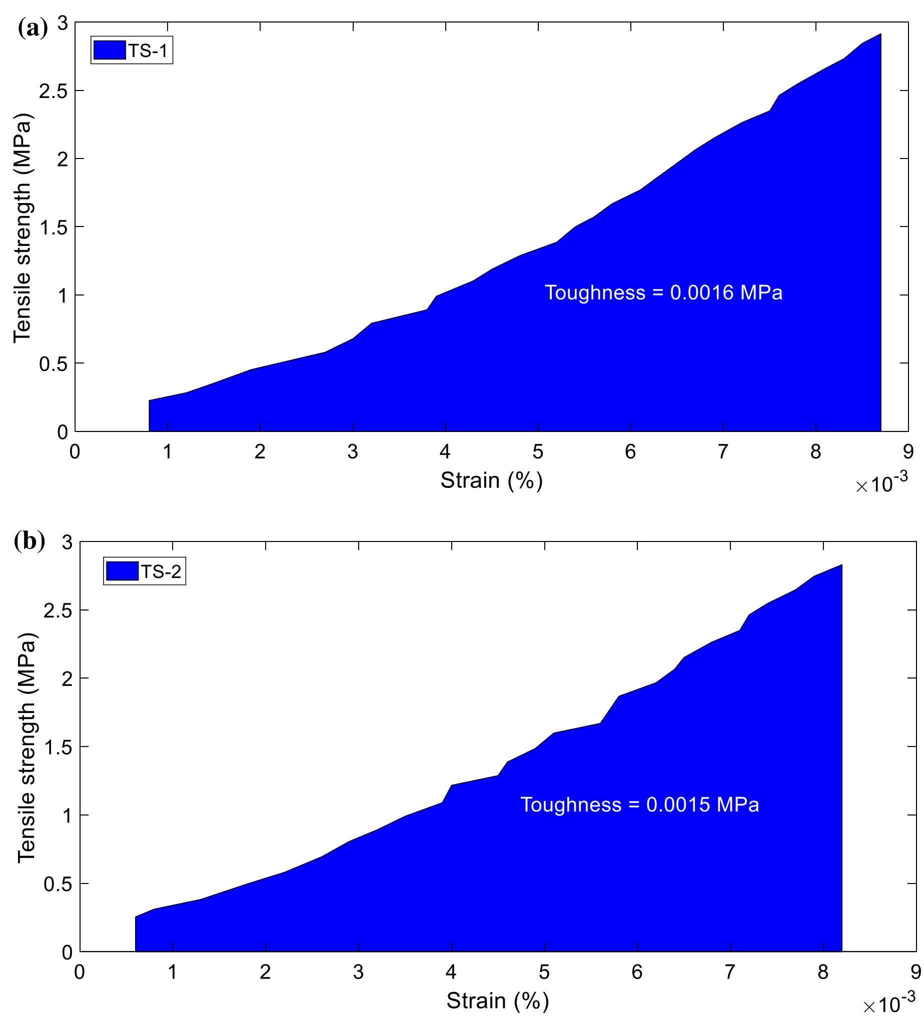
Results and discussion

Stress–strain behavior of improved samples

Figure 6 shows the tensile strength behavior of tests on samples TS-1 and TS-2, which were created with the same concrete mix design. Clearly, both samples performed similarly. The results showed that TS-1 and TS-2 failed at 2.97 and 2.83 MPa, respectively. Figure 7 compares the tensile strength of improved samples TS-3 to TS-9 with plain concrete samples. These samples were created with reference mixture I. The tests compared the effect of core types EWRW-F and EWRW-P. Comparison of TS-5 (C + 2% EWRW-P) with TS-6 (C + 2% EWRW-F) and TS-7 (2.5% EWRW-P) with TS-8 (2.5% EWRW-F) confirmed that, in reference mixture I, the EWRW with a fiber core had higher tensile strength than the one with a polyethylene core.

Figure 8 shows the tensile strength of improved samples TS-9 to TS-19 using reference mixture II. Plain concrete TS-9 showed an ultimate tensile strength of 3.35 MPa, which was 12% higher than TS-1 using reference mixture I. Test TS-16 (2.5% EWRW-F) with an ultimate tensile strength of 3.86 MPa showed the best performance, followed by TS-13 (2.5% EWRW-F) with an ultimate tensile strength of 3.36 MPa. The remaining tests followed a similar trend.

Fig. 15 Toughness of plain concrete: **a** TS-1; **b** TS-2



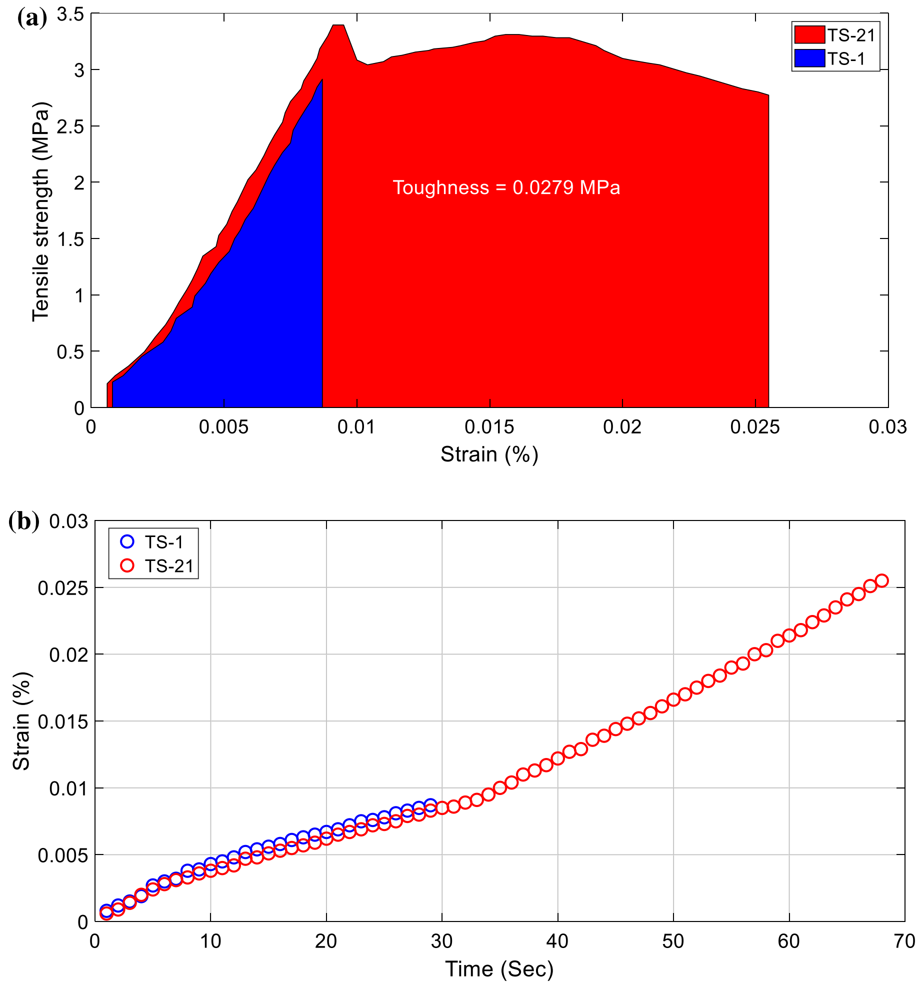


Fig. 16 Toughness of plain concrete and TS-21: **a** toughness; **b** failure time

Tests TS-1 to TS-8 and TS-9 to TS-9 were constructed and tested after a 28-day curing time. Their results indicated that the EWRW-F performed better than EWRW-P; therefore, it was decided to run the remaining tests only on the EWRW-F samples. Samples with a polyethylene core were removed from the testing program.

Figure 9 compares the behavior of TS-20 to TS-23. These samples were cured for 28 days. TS-20 is the plain concrete for reference mixture III. It showed a lower tensile strength value than the other plain concrete tests because of its higher W/C value. TS-21 (2% EWRW-F), TS-22 (2.5% EWRW-F), and TS-23 (3% EWRW-F) recorded ultimate tensile strengths of 3.39, 3.35, and 3.01 MPa, respectively. The stress–strain trends shown in Fig. 9 (reference mixture III) are similar to those shown in Fig. 8 (reference mixture II).

Figure 10 depicts the results of the splitting tensile strength tests on the improved samples for reference mixture III and compares tests TS-24 to TS-30. It can be seen that the stress–strain behavior in these samples was approximately the same, but the peak points differed. TS-25 with 2% EWRW showed the highest tensile strength of 3.7 MPa.

Figure 11 shows the effects of curing time (28 and 42 days). The behavior of TS-23 and TS-30, which had the same combination (3% EWRW-F) for reference mixture III, were compared. It can be seen that the stress–strain behavior in both tests was similar, with TS-30 recording only a 5% higher ultimate tensile strength result than TS-23. Figure 12 provides bar charts of the maximum values in all ultimate tensile strength tests.

Tensile improvement ratio

In order to evaluate the effects of EWRW on the ultimate tensile strength of the improved samples, the parameter of the tensile improvement ratio (TIR) is defined in Eq. (1). When calculating TIR, the ultimate tensile strength of each test is divided by that of the plain concrete.

$$\text{TIR} = \frac{\text{Ultimate tensile strength of improved samples}}{\text{Ultimate tensile strength of plain concrete}} \quad (1)$$

Figure 13 shows the TIR values of samples TS-9 to TS-19 (reference mixture II). It is evident that samples with 1.5%

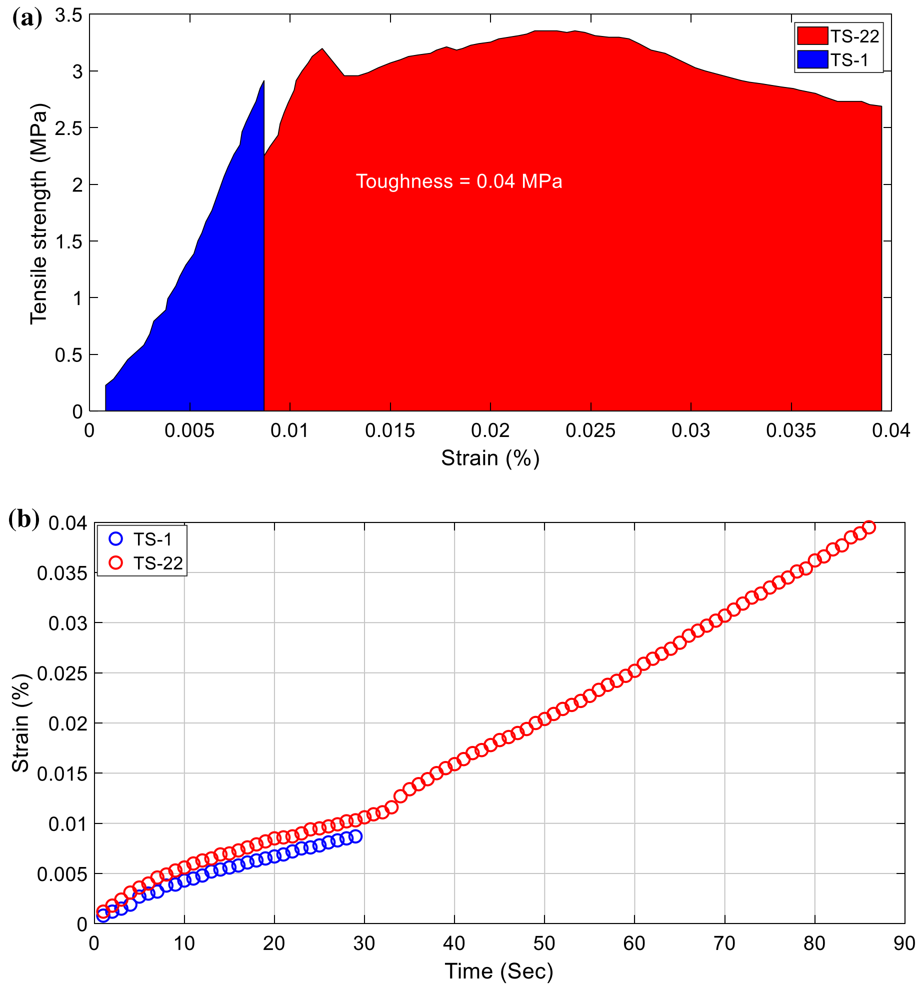


Fig. 17 Toughness of plain concrete and TS-22: **a** toughness; **b** failure time

EWRW-P, 1.5% EWRW-F, 2% EWRW-P, and 2% EWRW-F showed an increase in TIR and a decrease in ultimate tensile strength. In Fig. 13, TS-16, with 2.5% EWRW-F, recorded the highest TIR, which indicates that there was no improvement in the tensile behavior for low percentages of EWRW.

Samples with EWRW percentages greater than 2.5% showed greater decreases in the ultimate tensile strength because all EWRW values beyond this level caused a decrease in concrete cohesion. This behavior was also observed by Keshavarz and Mostofinejad [20]. They reported that both the compressive strength and tensile strength of plain concrete improved with the inclusion of steel chips and porcelain ceramic waste, but the addition of more than 1% steel chips had little effect. This suggests that, for reference mixture II, the concrete tensile strength varied as the EWRW content varied, and the inclusion of 2.5% EWRW-F yielded the highest tensile strength.

Figure 14 displays the TIR for tests TS-24 to TS-30 (reference mixture III) using EWRW-F. Clearly, the tensile strength values in this figure differ from those in Fig. 13. In these tests, the addition of EWRW increased the TIR, except in TS-29 and TS-30. It can be observed that the calculated TIR values were significantly lower than those in Fig. 13. It was also again observed that, at high EWRW contents, TIR declined because of a decrease in concrete cohesion. Test TS-25 with 2% EWRW showed the best performance (TIR = 1.1).

Comparison of Figs. 13 and 14 reveals that the addition of 2–2.5% EWRW-F improved the tensile strength of the samples. In previous studies [19, 20, 23], it was observed that the TIR values of samples containing steel fibers were significantly higher than those in the present study. This difference may relate to the type of steel fibers used. In the present study, the fibers were not commercially produced for the purpose of adding to concrete, but were gathered as waste from a local elevator construction company. The average tensile strength for normal-strength steel fibers is 1100 MPa [22], while the EWRW-F had a lower tensile strength of 200 MPa. Thus, it was expected that the results of the present study would be lower than those of similar studies.

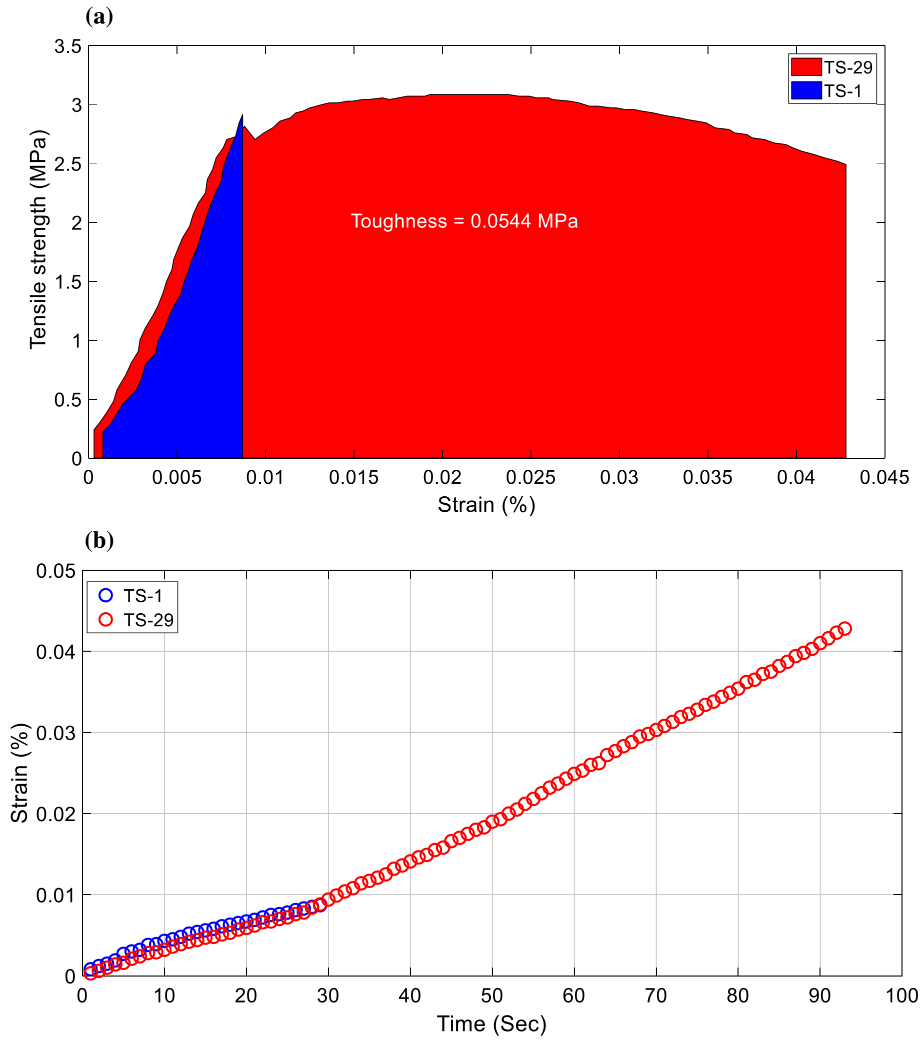


Fig. 18 Toughness of plain concrete and TS-29: **a** toughness; **b** failure time

Flexural toughness of improved samples

Generally, the toughness of a material is defined as its ability to absorb energy and plastically deform without fracturing. In this study, the stress–strain curves obtained for the concrete specimens were used to compute the flexural toughness. Hence, the calculated area of stress–strain curves was considered as toughness of each sample as:

$$\text{Flexural toughness} = \frac{energy}{volume} = \int_0^{\varepsilon_f} \sigma . d_\varepsilon \quad (2)$$

where σ denotes the applied stress and ε_f denotes the strain upon failure.

Figures 15a, b show the toughness of plain concrete in TS-1 and TS-2. It is apparent from the results that both tests showed approximately the same toughness of 0.0016 and 0.0018 MPa. In this regard, Figs. 16a, b compare the toughness of TS-21 to TS-1. Clearly, with a toughness of 0.0279 MPa, the inclusion of 2% EWRW-F significantly increased the toughness of the plain concrete. As shown in Fig. 16b, the failure of the plain concrete took about 30 s. The addition of 2% EWRW increased this failure time to roughly 70 s.

Figures 17a, b compare the toughness of plain concrete (TS-1 and TS-22). The addition of 2.5% EWRW improved the toughness of the concrete to 0.04 MPa. At failure, TS-22 was able to resist the applied stress for roughly 85 s before it failed. Such a trend of increase in the toughness of the concrete samples improved with steel fibers has been observed in previous studies. For example, Syamsir et al. [24] reported that the flexural strength increased to 32% compared to their control sample. Similarly, Keshavarz and Mostofinejad [20] reported an increase in the flexural strength of plain concrete to 64%. In these studies, differences in sample size and loading conditions created differences in the range of flexural strength. Figures 18a, b depict the effects of 3% EWRW on the flexural strength of plain concrete. This amount of EWRW increased the failure time up to 97%, resulting in flexural strength of 0.054 MPa. It is evident that the combination of plain concrete and 3% EWRW yielded the highest

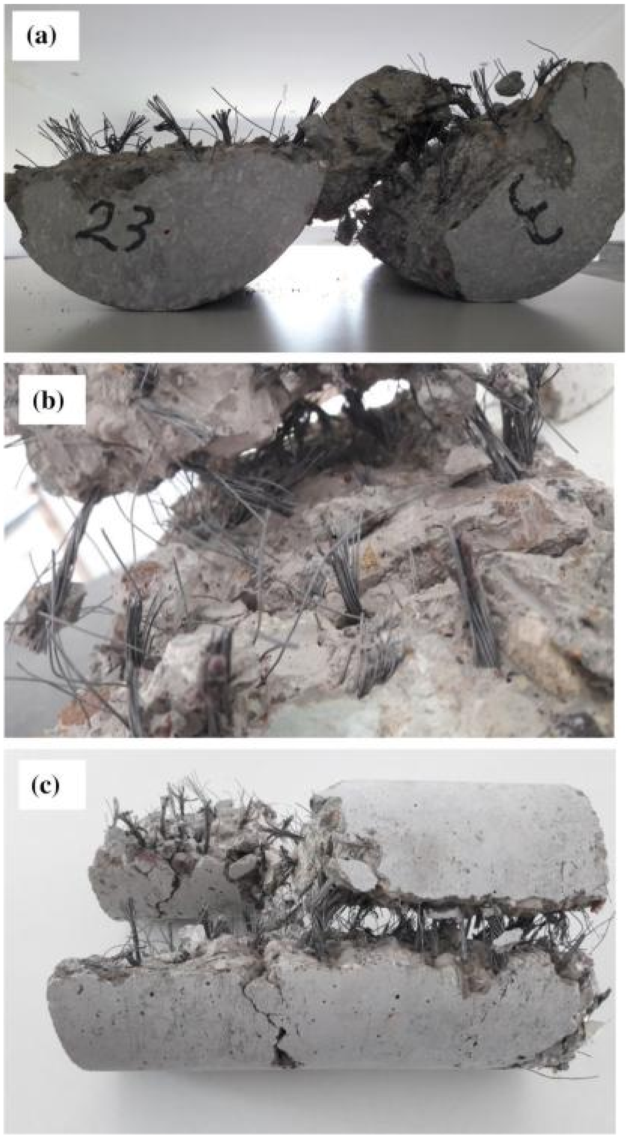


Fig. 19 Failed samples: **a** TS-23; **b** TS-26; **c** TS-30

flexural strength of all samples. Figures 19a, c show the failed samples.

Conclusions

The present experimental work aimed to recycle the waste products to improve concrete using elevator wire rope waste (EWRW). The main objective was to examine the possibility of reusing these types of waste materials. For this purpose, the EWRW was gathered locally from elevator manufacturing companies. Two types of EWRW were available as waste: those with a fiber core (F) and those with a polypropylene core (P). The tensile strength of these waste materials was significantly lower than for conventional steel fibers. In addition to the improvement of the tensile strength and flexural toughness of the improved samples, this study was undertaken to eliminate these waste materials from the environment. Three reference mixtures were chosen for the control concrete. The following conclusions were drawn:

- Regardless of EWRW core type, the tensile strength of improved samples increased when 2–3% waste was used in reference mixture I (F_c = 25 MPa, W/C = 0.5, and S/G = 0.5). However, the performance of EWRW-F was better than EWRW-P.
- In reference mixture II (F_c = 35 MPa, W/C = 0.47, and S/G = 0.63), the inclusion of EWRW-F and EWRW-P had no significant effects on the ultimate tensile strength of improved samples.
- In tests TS-10 to TS-19 (except TS-16), the inclusion of EWRW in reference mixture II decreased the ultimate tensile strength of the samples.
- The results showed that the optimum amount of 2.5% EWRW-F in reference mixture II after 28 days of curing produced the highest ultimate tensile strength value of 3.86 MPa.
- The sample with 3% EWRW-F in reference mixture III after 42 days ranked second and recorded an ultimate tensile strength of 3.15 MPa.
- The flexural strength of concrete increased up to 32-fold that of plain concrete with the addition of 3% EWRW-F after 42 days of curing. In general, it was found that the effect of these types of waste enhanced the flexural strength more than the ultimate tensile strength. A complementary study has to be conducted also for a higher percentage of EWRW.

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Availability of data and material The data of this research is available.

Declarations

Conflict of interest The authors declare that there is no conflict of interest in presenting this manuscript.

Code availability There is no code in this study.

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