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Research Article

Experimental investigation on mechanical properties of HSSCC containing waste steel fibers obtained from end-of-life tires

Kutalmış Recep Akça [1*], **Metin İpek** [2], **Sevgi Çelenk** [3], **Aykut Karabulak** [4]

[1] University of Applied Sciences, Sakarya (Türkiye); akca@subu.edu.tr
[2] University of Applied Sciences, Sakarya (Türkiye); metini@subu.edu.tr
[3] University of Applied Sciences, Sakarya (Türkiye); sevgicelenk41@gmail.com
[4] University of Applied Sciences, Sakarya (Türkiye); aykut.karabulak@ogr.sakarya.edu.tr
*Correspondence: akca@subu.edu.tr

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Abstract: In this study, use of end-of-life tires (ELTs) in self-consolidating concretes (SCC), which enable higher rates of fiber use than conventional concrete due to its superior flow properties, for the elimination of the environmental negative impacts and recycling of them were aimed. Besides, it is aimed to investigate the behavior of waste steel wires with different aspect ratio obtained from different types of tires, contrary to what is mostly researched in the literature. Therefore, bead, cord and base wires, obtained from tires, were used in high-strength self-consolidating concrete (HSSCC) production as fiber reinforcement. Fresh and hardened state properties of the waste wire-reinforced (1-2-3%) samples of different sizes that were produced, were compared with industrial steel-reinforced and non-fibrous samples. In this regard, slump flow and T_{50} durations were determined, compression and bending tests were performed. Significant improvements in the mechanical properties of conventional concretes were observed with the use of waste wire. Using the optimum ratio of waste wire, an increase of approximately 102% in flexural strength and 14% in compressive strength was observed compared to the reference specimen. Aspect ratio was recognized as one of the most effective factor on optimum fiber content. Moreover, experimental results were analyzed with "paired sample t-test", and it was seen that there were no considerable differences in the mechanical properties of the samples in which industrial fiber and waste-wire had been used. Besides, cost analysis was carried out to assess the economic benefits of the use of waste tire wires in the concrete industry.

Keywords: End-of-life tires, recycle, fiber reinforced concrete, self-consolidating, t-test.

1. Introduction

Waste management, when economic and environmental reasons are taken into consideration, has recently come into more prominence. In this regard, studies on the use of recycled materials in concrete have become increasingly widespread (Akça *et al*., 2015; Çelik *et al*., 2022a; Karalar *et al*., 2022a; Karalar et al., 2022b; Qaidi *et al*., 2022; Sarıbıyık and Gurbuz, 2021; Zeybek *et al*., 2022a). The increase in the need for a vehicle in transportation has led to an increase in tire production, and therefore waste tire amount has been increased. Thus, keeping the end-of-life waste tires under control has become an important problem worldwide. Average 200-300 thousand tons of waste tires/year from approximately 14 million vehicles in Turkey come to the recycling companies (Marmore Green Engineering 2016). The annual waste tire amount worldwide, on the other hand, reaches 1.2 billion (Sahajwalla et al., 2011). In 2017, yearly tire production exceeded 2.9 billion worldwide (Raffoul *et al.* 2017). Since the amount of waste is quite a lot, lots of disposal and utilization by recycling methods have been used and developed. Being in a large amount and environmental damages as a result of their burning, have put these wastes into hazardous waste class. In waste management and waste removal/disposal approach, having an opinion for the transformation of the waste into a re-utilizable form will provide such trouble-making wastes to be transformed into comfortable materials. Owing to becoming a significant environmental problem, it has been forbidden to store the waste tires in Europe and in the United States of America with new regulations (European Commission 1999; New York State 2003). Recycling ratio of the waste tires has reached 85% in the USA, Europe, and Japan with such strict regulations put in force, with also the realization of economic return as well as increasing of the environmental consciousness. Thus, waste tires have become one of the most recycled products (JATMA 2015; WBCSD 2015). The burning of ELTs also in Turkey is forbidden for any reason whatsoever (The law on ELT, 2006).

Tires made of materials of which approximately 95% are recyclable; are composed of average 47% rubber, 22% carbon black, 17% steel wire, 5% fabric, and a little amount of various additive agents as a content (Evans and Evans 2006). Primary side products obtained from waste tires that can be recycled in various dimensions from whole to powder, are bead wires, cord wires, base wires and rubber parts that are shaped into piece, shredded, chips, granule or powder. Whole waste tires are used in playgrounds, motorsports fields, areas used for mooring vessels at seacoast, vehicle parking lots, chamfer and road stabilization; shredded and powdered waste tires, on the other hand, are used in the automotive industry, on playfield surfaces, asphalt and groundwork applications (Snelson 2009). Besides, only 8% of the tire wastes are recycled for civil engineering applications, in the USA (U.S. Tire Manufacturers Association 2019). The use of tire wastes in concrete production in the literature, on the other hand, is generally in way of using shredded and granule rubber pieces as aggregate (Alwesabi *et al.* 2020; Si *et al.* 2018, Siddique and Naik 2004, Skariah and Gupta 2016). Besides, many studies showing that steel fibers have numerious positive contributions to the mechanical properties of concrete (such as tensile, flexural and impact strengths, toughness and ductility) are existing in the literature (Akça and İpek, 2022; Brandt, 2008; Çelik *et al*., 2022b; Li *et al.*, 2018; Özkılıç *et al*., 2021; Soufeiani *et al.,* 2016). However, steel fiber is a very costly material and significantly increases the unit cost of concrete. Thus, although it offers many advantages, its use in engineering applications has not become as widespread as expected (Kong *et al.*, 2023).

In this context, investigations on the use of recycled steel fibers obtained from ELT in concrete production, are also gaining popularity day by day (Aiello *et al.* 2009; Domski *et al*. 2017; Frazão *et al.* 2019; Grzymski *et al.* 2019; Zamanzadeh *et al.* 2015; Zeybek *et al.* 2022b), in order to find an effective and sustainable alternative to high-cost material such as industrial steel fibers (ISF). On the other hand, Zhong and Zhang (2020) investigated the usability of constant recycled steel fiber amount (i.e. 1%) with various amounts of polypropylene fibers (i.e. 0.1% to 0.5%). It is reported that approximately 117% greater flexural tensile strength was obtained through the use of recycled steel fibers while the compressive strength was slightly enhanced (Zhong and Zhang 2020). Köroğlu and Ashour (2020) investigated the properties of SCC with waste steel bead wires with diameters in the range of 0.22-0.27 and reported that the optimum fiber content for the bead wire was 4% for their study. While Ahmadi *et al.* (2017) investigated the combination of recycled aggregates derived from construction and demolition waste and recycled steel fibers obtained from ELT, Mastali *et al.* (2018) compared the effect of ISF, recycled steel fiber and PP fiber on the mechanical performance of concrete. As the result of the study, it is reported that significant improvements were observed on both compressive and tensile properties of the plain concrete when using 1.5% recycled steel fiber.

Moreover, although PP fibers did not affect mechanical performance as much as steel fibers, the contribution of recycled steel fibers was found comparable to that of ISF. However, studies regarding the use of steel wires produced from end-of-life waste tires by recycling in concrete are ever-increasingly attracting attention in the literature. Since it has an irregular form (Frazão *et al.* 2019), its heterogeneous structure depends on the tire obtained from, and it may contain rubber pieces attached on the surface (Ahmadi *et al.* 2017), more investigations may be needed to encourage the use of this material in concrete manufacture. Besides, Liew and Akbar (2020) stated that mostly investigated steel fibers in the literature are the wires obtained from passenger vehicle tires (within the diameter range 0.15 to 0.26), rather than truck or heavy vehicle tires that contain thick wires. More studies in this field were also recommended to entirely understand the behavior of recycled steel fiber reinforced concretes, since the effect of the waste material having various geometric characteristic on various concrete types and mixtures is still not clear.

Therefore, in this study, opening a new usage area for the end-of-life tires (ELT) and recycling for the elimination of the environmental negative impacts have been aimed. When optimizing the cost, strength might be maximized by using these wastes in concretes within an Eco mentalist perspective. In other words, improvement of the tensile properties of the concrete, which is a construction material having low tensile strength, has been aimed at opening a new usage area to a material that is called as waste, by contributing to the waste management. In addition to this, contrary to what is mostly researched in the literature, it is aimed to present a more comprehensive study by investigating the behavior of waste wires obtained from truck and heavy vehicle tires in addition to passenger vehicles. Hence, although the average length is the same as industrial fiber, the bead, cord and base wires obtained from ELT, which have various aspect ratios, have been used as fiber reinforcement in high-strength self-consolidating concrete (HSSCC) production as a type of concrete that attracts attention in construction processes with its ability of self-compacting.

2. Materials and methods

ISF and 3 types of fiber obtained from ELT, were used in 1-2-3% ratios (by volume) within the scope of the experimental study. Fresh and hardened concrete properties of fibrous samples were compared with that of non-fibrous SCC samples ("Reference"). In the coding of experimental series; I represent industrial fiber; W represents waste fiber; A, B, and C represent fiber type according to their geometrical properties; 1,2 and 3 numbers represent fiber % by volume.

2.1. *Materials*

In the experimental study, CEM II A-M (P-L) 42.5 R type (which contributes to concrete workability) cement and uncondensed silica fume were used. The chemical content of these binder materials has been shown in Table 1, and physical and mechanical properties have been shown in Table 2. Crushed stone Type 1 (4/12) and crushed stone Type 2 (12/24) as a coarse aggregate; natural sand (0/4) as fine aggregate were added into mixtures in the ratio of 25%, 25% and 50%, respectively. Particle size distribution of aggregates used in SCC series is shown in Fig. 1.

Table 1. Chemical composition of the cement and silica fume (%).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss of ignition	Na_2O	K_2O	Cl^-	Lime-stone	Pozzo-lana	Total addtv.	C
Cement	18.4	4.70	2.70	62.13	1.78	2.53	6.60	0.35	0.66	0.01	15	5	20	-
Silica Fume	96.0	0.70	0.25	0.50	0.60	3.03	1.50	0.25	0.85	0.10	-	-	-	1.50

Table 2. Physical and mechanical properties of the cement and silica fume.

	Density (g/cm^3)	Setting time (minutes)		Specific Surface (cm^2/g)	Compressive Strength (MPa)	
		Initial	Final		2 days	28 days
Cement	3.10	150	190	3600	25.0	46.2
Silica Fume	2.26	-	-	200000	-	-

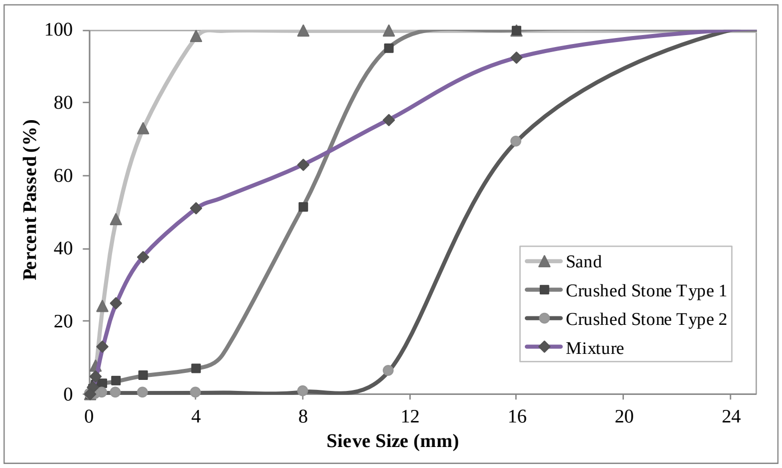

Figure 1. Aggregates grading.

Details about the fibers used in the study are given in Fig. 2. End-of-life waste tire was obtained as a mix (Fig. 2a) and the steel was separated from the rubber in the laboratory. After this process, steel fibers were classified according to their dimensional characteristics. Classified ELT wires (named as A, B and C according to their geometric characteristics in this study) that were obtained from recycling facilities, and commercially available hooked-end ISFs have been shown in Fig. 2b. After classification, tensile test was carried out for each type of the fiber and their tensile strengths were determined on Shimadzu AG-IC universal test machine with the capacity of 50 kN (Fig. 2c). Average length values obtained from the statistical analysis of minimum 150 fiber samples for each waste fiber type and technical properties of the steel fibers have been given in Table 3. Unlike the mostly used recycled fiber diameters (i.e. between 0.15-0.26 mm) in the literature, which were recycled from passenger vehicle tires, as stated by Liew and Akbar (2020); much thicker and lower aspect ratio (type A and B) fibers were also investigated in this study, as seen on Table 3. In addition to these, new generation superplasticizer developed for prefabricated concrete production and reactive powder concrete that is highly water reducer, strengthener, has long workability duration; which can be used in self-consolidating and hardening concrete production dependent on the usage dosage was used.

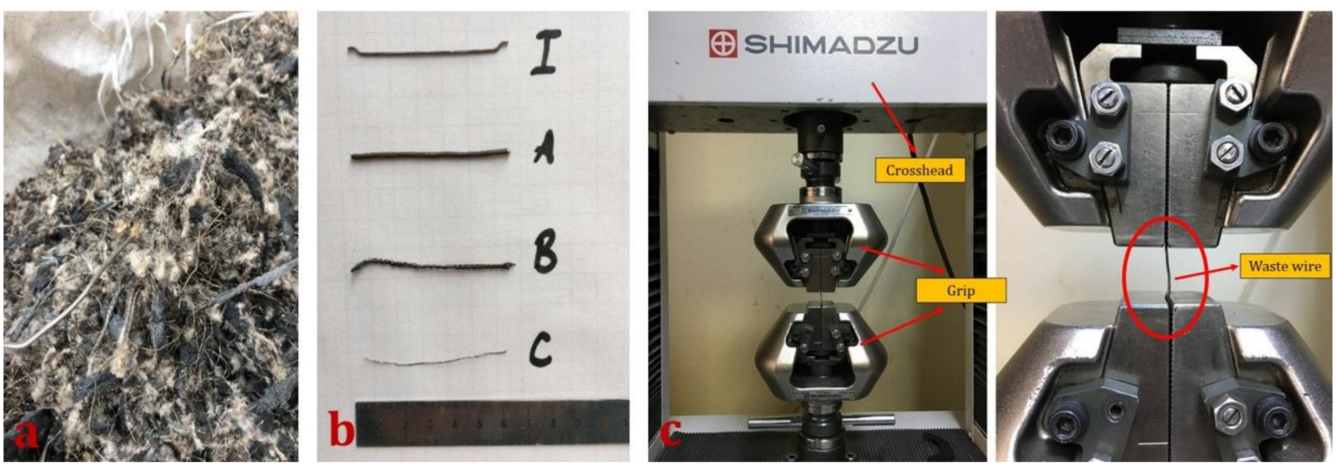

Figure 2. Fibers a) unsorted ELT waste b) types of fibers c) tensile test setup of waste fibers.

Table 3. Fiber types and technical properties.

Type of Fiber	Length (mm)	Diameter (mm)	Average Slenderness Ratio	Tensile Strength (MPa)	Specific Gravity (kg/dm^3)	Cross Section
Industrial (I)	60	1	60	1115	7.81	Circle
Waste (Type A)	~60	1.80	33	1581	7.20	Circle
Waste (Type B)	~60	1.15	52	1256	7.20	Circle
Waste (Type C)	~60	0.3	200	1050	7.20	Circle

2.2. *Method*

In the first stage, pre-productions of SCC were made. As a result of the preliminary productions, SCC mix was obtained in accordance with EFNARC (2005) in terms of fresh concrete properties and thus the final SCC mix was decided. In the next stage, different types of fibers (industrial and waste) were added to the final SCC mix at different ratios and thus test series were generated. Experimental series and mixing amounts required for 1 m^3 concrete production have been given in Table 4.

Table 4. Mix proportions (for 1 m^3).

Concrete Type	Ref.	I-1	I-2	I-3	WA-1	WA-2	WA-3	WB-1	WB-2	WB-3	WC-1	WC-2	WC-3
Cement (kg)	400	400	400	400	400	400	400	400	400	400	400	400	400
Silica Fume (kg)	100	100	100	100	100	100	100	100	100	100	100	100	100
Water (kg)	162	162	162	162	162	162	162	162	162	162	162	162	162
Superplast. (%)	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Fiber (vol. %)	0	1	2	3	1	2	3	1	2	3	1	2	3
Industrial Fiber (kg)	-	78	156	234	-	-	-	-	-	-	-	-	-
Waste Fiber-A (kg)	-	-	-	-	72	144	215	-	-	-	-	-	-
Waste Fiber-B (kg)	-	-	-	-	-	-	-	72	144	215	-	-	-
Waste Fiber-C (kg)	-	-	-	-	-	-	-	-	-	-	72	144	215
Sand (kg)	840	827	814	801	827	814	801	827	814	801	827	814	801
Crushed Stone Type 1	404	398	391	385	398	391	385	398	391	385	398	391	385
Crushed Stone Type 2	404	398	391	385	398	391	385	398	391	385	398	391	385

At first, workability tests on non-fibrous SCC mixture were made. Chemical additives ratio was adjusted to bring the workability to the desired level, then fiber was added into fresh SCC mixture and was mixed till it becomes homogeneous in a pan type concrete mixer. Non-fibrous, SCC samples having 1-2-3% ratios of industrial wire and 1-2-3% ratios of different geometrical properties of ELT wire, were produced. Slump flow values and T_{50} times in fresh state to determine the properties of fresh concrete of the produced samples were determined by using the slump cone in accordance with ASTM C1611 (2014). Compression and 3-point bending test were performed in accordance with EN 12390-3 (2009) and EN 14651 (2005), with the purpose of determining the mechanical properties.

Bending tests were performed on Shimadzu AG-IC universal test machine with a capacity of 50 kN. Toughness values of the samples were calculated with the aid of the area under the load-deflection curves that had been obtained as a result of 3-point bending test. Cubic samples in the dimension of 15×15×15 cm were produced to determine compressive strengths of the reference and fiber reinforced SCC mixtures, for determining flexural tensile strengths, on the other hand, prism samples in the dimension of 7.5×7.5×50 cm were produced. The samples were removed from the mold 24 h after production and cured in lime-saturated water at 20±2 °C temperature until the experiment day, in accordance with (EN 12390-2 2009). Hardened concrete tests were performed with three specimens of each concrete series on the 28th day. Sizes and numbers of the tested specimens are given in Table 5.

Table 5. Design of experiment.

Type of experiment	Size of specimens (mm)	Number of specimens	Age of concrete (day)	Test procedure
Compression	150×150×150	3 for each series	28	EN 12390-3
3-point bending and Toughness	75×75×500	3 for each series	28	EN 14651

3. Experimental results and analysis

3.1. *Properties of fresh concrete*

Fresh concrete test results of the SCC samples that are expected to fulfill the opposite two conditions such as high workability and having a resistance to segregation; slump flow (mm), T_{50} (s) values and fiber inclusion factors (FIF) of specimens (calculated by the authors as: aspect ratio multiplied by the volume of fiber) have been given in Table 6. In case of fiber content increase which is known to have a negative effect on fluidity (Alsaif *et al.* 2018; Zhong and Zhang 2020), slump flow values decreased. Besides, it is well-known that matrix workability may be effected negatively due to the fact that the heterogeneity of the concrete increases with the increase of fiber content. Decreases are clearly be seen especially after the fiber amount exceeds 2% in all fiber types (industrial fiber and ELT wire). Non-fibrous reference specimen, all series having 1% and 2% fiber and WA series having 3% fiber content provided 600 mm slump flow value which is the minimum requirement (EFNARC, 2005). When the fiber content reached to 3%, the desired workability could not be obtained (except for WA-3). When T_{50} results are taken into consideration, it can be seen that all series except the samples having 3% fiber (I-3 and WB-3) are present in between 2 and 5 which are the limits stated in EFNARC (2005). Correspondingly, it's possible to state that all samples containing 1% and 2% fiber together with the reference sample have the desired viscosity. Although WA-3 have desired workability, could not meet the viscosity criteria of SCC.

Table 6. Fresh concrete properties.

	Ref.	I-1	I-2	I-3	WA-1	WA-2	WA-3	WB-1	WB-2	WB-3	WC-1	WC-2	WC-3
Slump-flow (mm)	800	790	720	590	780	690	600	750	630	550	650	-	-
T_{50} (s)	2.7	3.2	4.0	6.4	3.0	4.6	6.3	4.0	4.5	8.5	3.8	-	-
"FIF" =	0	60	120	180	33	66	99	52	104	156	200	400	600

High aspect ratio would lead to the balling effect during mixing (Fig. 3b). As fiber content and aspect ratio increased together, mixing problems emerged. Agglomeration in the mixture was observed in the mixer, and therefore a homogeneous mixture could not be obtained with the fiber having the greatest aspect ratio (i.e. type C fiber with an aspect ratio of 200), when the fiber content exceeds 1% (i.e. this means the FIF exceeds 200, as seen on Table 6). In other words, WC-2 and WC-3 samples (FIFs equal to 400 and 600, respectively) could not be produced. The number of fiber varies depending on the diameter of the fiber in the samples having the same fiber content.

The increase of the "number of fibers" due to the increasing aspect ratio is also thought to be effective in this circumstance. Besides, it is known that the suitable fiber content is related to the slenderness ratio of the fiber. Due to the fact that SCC, with its superior flow properties, enables higher rates of fiber use than conventional concrete (Liew and Akbar, 2020; Najim *et al.*, 2018) and due to fibers' quite low slenderness ratios (See Table 3); it was thought that samples could be produced even in high fiber ratios (i.e. 2% and 3%) in I, WA and WB series. Similarly, as a special kind of SCC type, it is known that frequently used fiber content is 2-3% in Ultra-High Performance Concretes (UHPFRC) (Wu *et al.* 2018). Moreover, satisfactory results were obtained especially from mechanical properties of I and WA series having 2% fiber content.

Figure 3. (a) Homogeneous mixture and, (b) glomeration.

3.2. Properties of hardened concrete

28-day compressive strength test results and the standard deviation values of the concrete series have been given in Fig. 4. Compressive strengths of the concrete series generally increased with uniformly dispersed industrial fiber and A-type waste fiber reinforcement. Compared to non-fibrous reference concrete series having 70.3 MPa compressive strength; while in industrial wire-reinforced I-1 and I-2, 17% and 16% increase have been observed, respectively, in the A-type ELT-reinforced samples in 1% and 2% ratios on the other hand, 4% and 14% increase have been observed, respectively. Similar enhancement was also found by Zhong and Zhang (2020), in the research that investigates 1% of recycled steel fiber addition. However, although 30% greater compressive strength was obtained with the use of only 40 kg/m^3 recycled steel fiber by Alsaif *et al.* (2018); it is reported only slight enhancements with more fiber inclusion in another research (Najim *et al.* 2018). These increases, that vary by the properties of concretes (i.e. type of concrete and mix proportions) and fibers (i.e. geometric characteristics such as aspect ratio), in the compressive strength can be explained by the fact that the steel wires contribute to the concrete behavior as a durable aggregate and slow down the cracks to spread in the concrete (İpek *et al.* 2011). Moreover, during the compression test, it has been thought that the fibers' resistance of the tensile stress arisen from the axis towards out in the concrete, contribute to the increase of the compressive strength. However, the increase of compressive strength when using ISF is greater than that of ELT wire. Considering that the ISF is hooked-end providing extra mechanical anchorage (see Fig. 2b), matrix/fiber interface properties are thought to be effective in this circumstance.

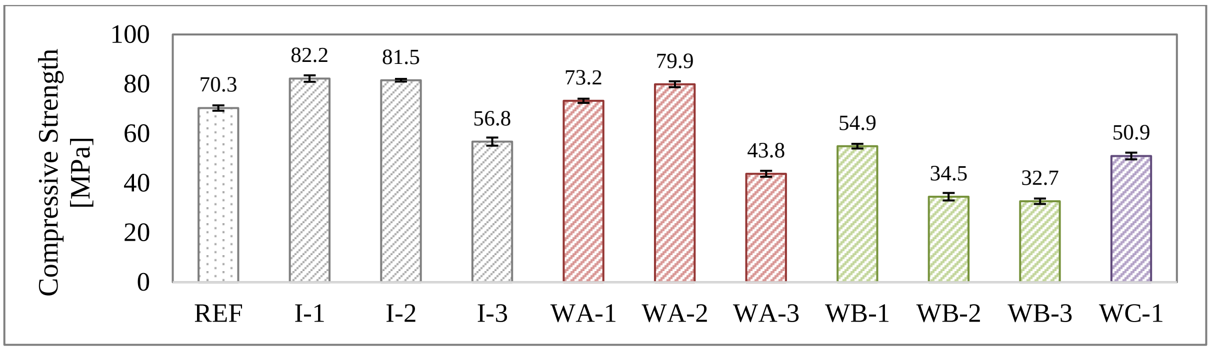

Figure 4. Compressive test results.

In I-3 and WA-3 on the other hand, some decrease in the compressive strength was observed. This situation can be explained by the fact that the fibers influence the aggregate granulometry negatively in the concrete samples having a high amount of fiber and lead to placement problems. Zhong and Zhang (2020) referred to the fiber agglomeration that is caused by poor fiber dispersion of the fibers when the critical fiber content is exceeded, for a similar circumstance. Besides, the use of fiber can cause both an increase and a decrease in compressive strength due to the effect of the fibers such as crack arresting and increased air voids (Mastali *et al.* 2018). It can be stated that the crack arresting effect of the fibers was dominated by the latter effect, in the case of fiber inclusion beyond 2%. Besides, similar to critical fiber content mentioned by Zhong and Zhang (2020); Caggiano *et al.* (2017) mentioned a certain threshold for the suitable fiber content, which mainly depends on the aggregates and matrix quality. Additionally, it is difficult to draw a reliable conclusion from the literature about the optimum fiber content which varies on the concrete and recycled steel fiber types or quality, because of the variability of the results. Considering the defined term of "threshold", it is possible to state that the critical threshold value for this concrete mixture used in this study is 2%.

In addition to this, the influence of the fiber diameter or aspect ratio on the compressive strength can clearly be seen on the graph (Fig. 4). Compressive strength values on B and C-type waste fiber reinforcement, are under those of the samples having both industrial and A-type fiber. This finding seems to differ from the study conducted by Zeybek *et al.* (2022b). However, due to the fact that waste fibers in WB and WC series have small diameter and high aspect ratio, the current number of fiber was increased. While the increase of the number of the fibers complicates to obtain a homogeneous mixture as mentioned in the fresh concrete results section, it also affects the aggregate grain distribution negatively. The highest compressive strength (i.e., 54.9) in B-type fiber content (having a higher aspect ratio than A-type), was reached with the lowest fiber content (1%). The compressive strength of WB mixture in higher fiber ratios decreased to some extent due to the number of fibers and mixture homogeneity. This situation that was also mentioned in the fresh concrete results did also directly affect the mechanical properties (Fig. 5). Low correlation coefficients (i.e. 0.414 and 0.697), especially obtained from concrete series having waste steel fibers, could be related to the fluctuation of compressive strength values with the increase of steel fiber content. Reasons for irregular fluctuations were explained before, as confirmed by Mastali *et al.* (2018) and Zhong and Zhang (2020). In another study (Ahmadi *et al.* 2017), that observed similar increase (at the first stage of the increase of recycled steel fiber content) and decrease (with further increase of recycled steel fiber content) of compressive strength, this circumstance was explained with the inconsiderable effect of fibers on compressive strength. It was also pointed out that the efficient factors on compressive strength are the aggregate and cement paste strengths and their interfacial transition zone (Ahmadi *et al.* 2017), as confirmed by Akça *et al.* (2015) as well.

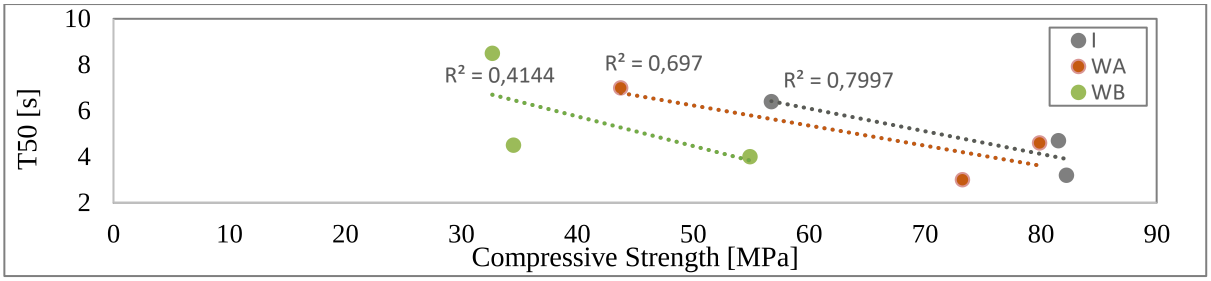

Figure 5. Correlation of compressive strength and T50.

I-1 has the highest compressive strength (i.e., 82.2 MPa) among the experiment series. The highest compressive strength in the samples having ELT wire, on the other hand, has been reached in WA-2 having 2% fiber. This value and the compressive strength of WA-2 has shown slight decreases (3% and 2%) compared to I-1 and I-2 having the same fiber content by ratio. Differences interpreted as slight changes have also been confirmed statistically. Compressive strength averages of the series having ISF and waste wire-reinforced series (A-type) which has the closest strength to the former one, were compared. Whether the difference between the averages is statistically significant or not, was examined by paired sample t-test (Table 7). As a result of statistical analysis, in p=1% significance level, it has been determined that there is no significant difference between the average of two groups (0.142>0.01).

Table 7. T-test results for compressive strength.

Group	N	Mean Value [MPa]	Std. Deviation [MPa]	t	Degrees of freedom (d_f)	p
ISF reinforced specimens	9	73.49	14.50	2.361	8	0.142
ELT wire reinforced specimens	9	65.63	19.23			

28-day flexural tensile strength test results and standard deviations of the strength values of the concrete series have been given in Fig. 6. Unlike the fluctuations in compressive strength results, as both industrial steel fiber and ELT wire content increase, the flexural tensile strengths of the concrete series steadily increase. All fiber-reinforced samples have higher flexural tensile strength than reference non-fibrous sample (i.e. 6.3 MPa). Steel fiber reinforcement provides a significant contribution to the flexural tensile strength with compensating the tensile stress by making crack bridging after cracking of the concrete of lower strength under the flexural tensile. In addition to this, in case of increasing the fineness of the fiber used, flexural tensile strengths decreased to some extent. While the average strength of the WB series is 8.6 MPa, the average strength of the WA series is 12.1 MPa. In the WC series on the other hand, due to mixing problems owing to intense fiber content, the production could be made and tests could be performed only in WC-1. As can be seen on the fresh concrete results, the homogeneity of the mixture has been effective on the flexural tensile strength test results as one of the hardened concrete properties (Fig. 7). Considerably high correlation coefficients (i.e. greater than 0.90) obtained from all series show that there is a strong relationship between the flexural tensile strength and T_{50}.

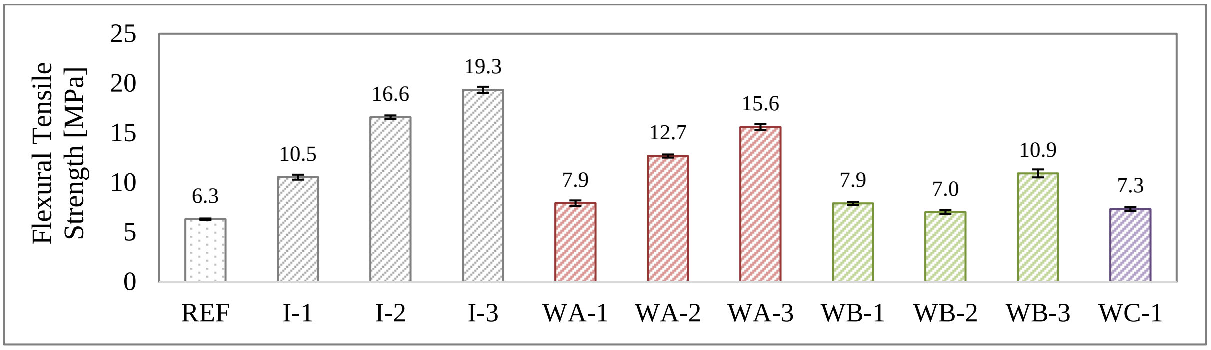

Figure 6. Flexural strength results.

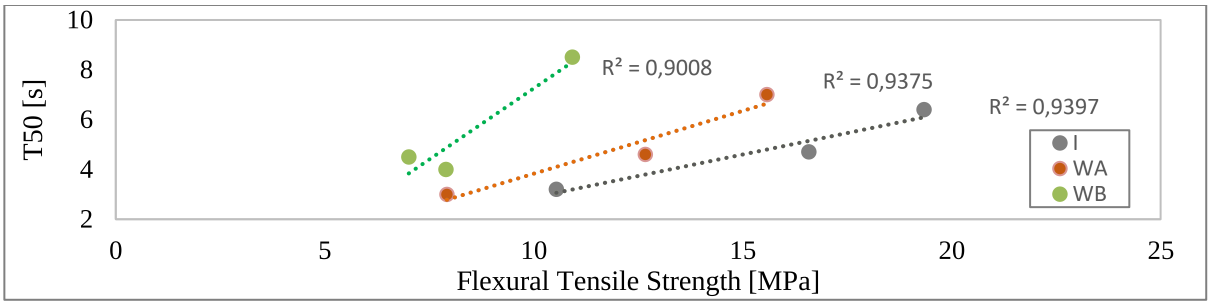

Figure 7. Correlation of flexural tensile strength and T50.

Compared to reference plain concrete series, in case of using the industrial steel in the ratios of 1%, 2%, and 3%; 67%, 163%, and 206% increases have been observed, respectively. Although it wasn't possible to reach to the flexural tensile strength of the industrial steel-reinforced samples in any sample having the same fiber content, remarkable increases have been observed also in ELT wire-reinforced mixtures compared to the reference non-fibrous series. In case of including the waste tire wires (A-type fiber) having low fineness ratio, into the mixtures in 1%, 2%, and 3% ratios, 25%, 102%, and 148% increases have been observed in the flexural tensile strengths, respectively compared to the reference non-fibrous sample. However, ELT wire-reinforced samples were not able to reach to the flexural tensile strength values of the samples having industrial steel fiber. This circumstance can be explained with the previous research findings (Frazão *et al.* 2019, Liew and Akbar 2020) which are also given below;

- adherence couldn't be provided in between the fiber and the concrete due to residual rubber coating on the outer surface of the waste rubber wires,
- the wires have a heterogeneous structure because they are obtained from the different type of tires,
- possible partial damage of fibers caused by the recycling process
- and irregularity of the fiber geometry.

In addition to the reasons given above, considering that industrial steel fibers are hooked-end, geometrical properties of fiber is also thought to have an effect on achieving high mechanical properties. Besides, flexural tensile strength averages of the series having industrial steel wire (I) and waste wire-reinforced series which has the closest strength to the former one (WA) were compared statistically. Whether the difference between the averages is statistically significant or not was examined by paired sample t-test (Table 8). As a result of statistical analysis, in p=1% significance level, it has been determined that there is no significant difference between the average of two groups (0.014>0.01).

Table 8. T-test results for flexural tensile strength.

Group	N	Mean Value [MPa]	Std. Deviation [MPa]	t	Degrees of freedom (d_f)	p
ISF reinforced specimens	9	15.49	4.50	8.421	8	0.014
ELT wire reinforced specimens	9	12.06	3.87			

Load-deflection curves of the samples of which 3-point bending test was applied have been given in Fig. 8a and Fig. 8b; toughness values calculated depending on the load-deflection curves have been given in figure 9.

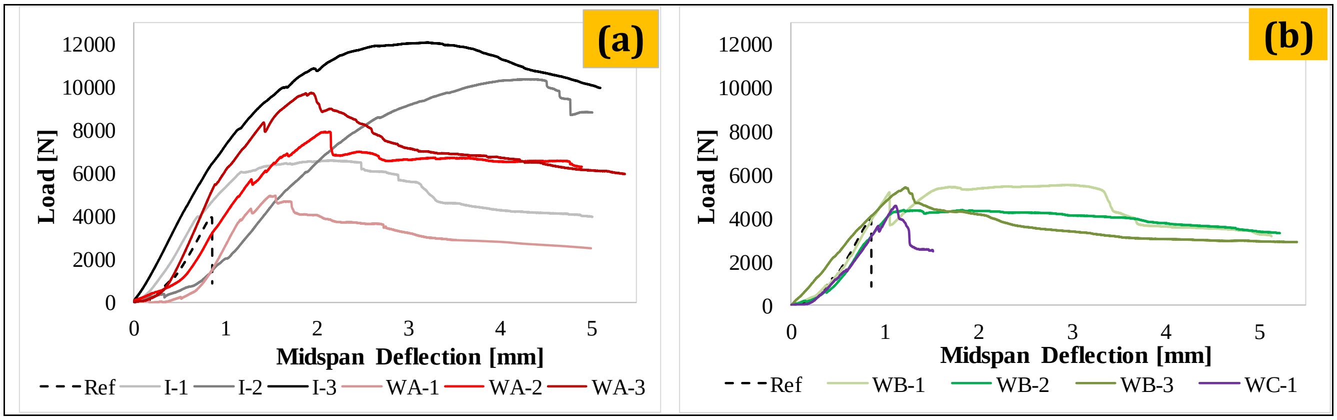

Figure 8. Load-deflection curves (a) Reference, I and WA series (b) Reference, WB and WC series.

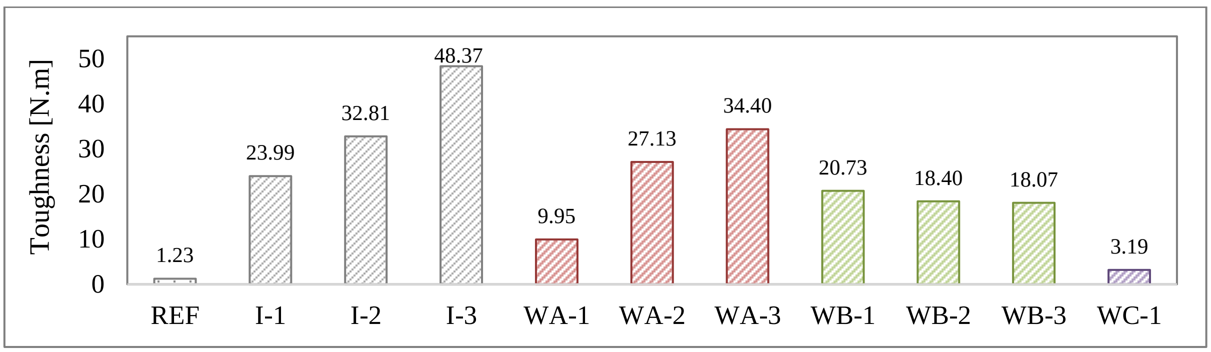

Figure 9. Fracture toughness values.

Similar to the flexural tensile strength results, some decrease in the toughness values of the samples has been seen (Fig. 9) as the fiber reinforcement transforms from industrial steel fiber into the waste tire wire. Nevertheless, the positive contribution of the fiber content, no matter what the fiber type included into the mixture is, are in the form of remarkable increases compared to the "reference" in toughness results, as reported increases much more than 100% by previous researches (Centonze *et al.* 2012; Mastali *et al.* 2018), as well. As can be seen from Fig. 8, non-fibrous SCC sample (reference) has acted a brittle behavior under the bending effect and was suddenly broken after the first crack and making a little amount of deflection (i.e. 1/500 of the span length). Unlike non-fibrous SCC, deflection-hardening and deflection-softening phases could be observed in fiber reinforced specimens. This also indicates improved ductility compared to conventional reference concrete, as confirmed by Zhong and Zhang (2020), as well. In other words, it is possible to state that as energy damping capacity increases as a result of fiber reinforcement, concrete ductility increases remarkably.

Containing 3% industrial steel fiber, I-3 sample that has the highest flexural tensile strength has had the highest fracture toughness value with 48.37 Nm, and another WA-3 having 3% fiber (A-type ELT wire) with 34.40 Nm has followed this sample. In addition to this, even WC-1 sample having the lowest toughness value (i.e., 3.19 Nm) among the fiber-reinforced samples has 2.5 times higher energy damping capacity compared to the reference series (i.e., 1.23 Nm). When the fiber reinforcement is the waste fiber having a low aspect ratio (Type-A), it has been observed that it is possible to have at least 8 times higher energy damping capacity, through the deflections reaching 1/90 of the span length. Besides, the positive effect of fiber inclusion can be seen in Fig. 8a, when examining the load-deflection graphs of WA series particularly. In the case of recycled steel fiber ratio was increased, first crack was delayed, which was in agreement with Caggiano *et al.* (2017) and Najim *et al.* (2018), as well. First cracks have been observed when the loads reached 4.14 kN, 5.60 kN and 8.28 kN at WA-1, WA-2 and

WA-3 specimens, respectively. Considering that brittle failure occurred immediately after the first crack in the reference concrete (i.e. 3.94 kN), it is possible to state that in each 1% increase of fiber content, 5.1%, 35.3% and 47.9% increases in the first crack load have been observed, respectively. In other words, although a slight increment (i.e. 5.1%) has been observed between the reference sample and WA-1, more dramatic increase (i.e. 35.3%) has been observed when the waste fiber inclusion was increased from 1% to 2%. As the specimens lost their load carrying capacity, mentioned first cracks became distinctly visible. Besides, the reason for the samples containing waste tire wire couldn't reach to the toughness value of the industrial fiber-reinforced samples is based on the reasons mentioned in flexural tensile strength section (such as geometrical irregularity of fibers, having a heterogeneous structure and adherence lost arisen due to residual rubber). This result is confirmed by Grzymski *et al.* (2019), as well. Moreover, it is well-known that hooked-end fibers are more successful at bridging the cracks.

As the fiber content increases, a regular increase has been observed in the toughness value of the WA series, and there has been a slight decrease in WB series. It has been thought that the reason for WB series gives higher results in the range of 1% than WA series might be related to having more number of fibers in the mixture. If the fiber content reaches to 2% and 3% on the other hand, a little amount of decrease has been observed in WB series containing B-type (having high aspect ratio) fiber (despite an increase has been expected). It's possible that this circumstance might be related to the "mixture homogeneity" particularly mentioned in the fresh concrete results (Fig. 10). This can also be understood through the low correlation coefficient (i.e. 0.45) obtained from WB series, unlike other series having high R^2 values.

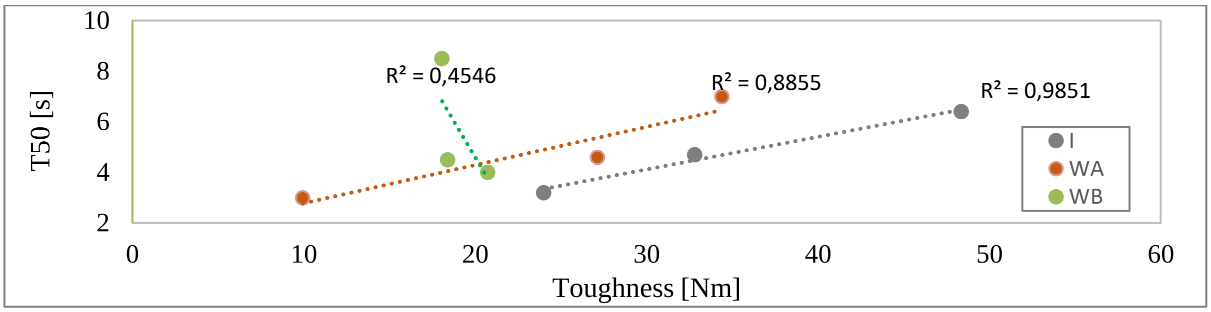

Figure 10. Correlation of fracture toughness and T50.

4. Cost analysis

Cost analysis was carried out to assess the economic benefits of the use of waste tire wires in the concrete industry. Therefore, the unit cost of the flexural tensile strength of all series was calculated (Table 9). The average values of material prices collected from suppliers in Turkiye were used for the cost analysis. The unit costs of flexural tensile strength were given in Table 9. "Unit cost" values in Table 9 represent the cost of the 1 m^3 concrete.

Table 8. Unit cost of flexural tensile strength ($/MPa).

Concrete Type	Ref.	I-1	I-2	I-3	WA-1	WA-2	WA-3	WB-1	WB-2	WB-3	WC-1	WC-2	WC-3
Unit Cost ($)	50.96	224.2	397.5	570.79	52.24	53.51	54.77	52.24	53.51	54.77	52.24	53.51	54.77
Flex. Tens. Str. (MPa)	6.30	10.50	16.60	19.30	7.90	12.70	15.60	7.90	7.00	10.90	7.30	0.00	0.00
Unit Cost of Flex. Tens. Strength ($/MPa)	8.09	21.36	23.95	29.57	6.61	4.21	3.51	6.61	7.64	5.03	7.16	-	-

Industrial steel fiber increased flexural tensile strength by 67%, 163% and 263% when used in the ratio of 1%, 2% and 3% respectively. However, as the cost of the concrete also increased due to the high cost of the fibers, the unit costs of the flexural tensile strength ($/MPa) also increased by 164%, 196% and 266% respectively. In all types of waste fiber (A, B and C), the unit cost of flexural tensile strength decreased to approximately one-third of that of industrial fiber, for the fiber content of 1%. In the case of the use of 2% and 3% fiber, unit cost decreases are more remarkable, as seen in Table 9. Besides, it must be stated that the most cost-effective concrete series of the study are WA-2 and WA-3 (i.e., 4.21 $/MPa and 3.51 $/MPa), while the series with industrial fiber have the unit cost per strength of more than 21.36 $/MPa.

5. Conclusions and comments

This experimental study was performed to create a new usage area for end-of-life tires (ELT) and to eliminate the environmental negative impacts. Conclusions obtained as a result of this study in which bead, cord and base wires obtained from ELT had been used in SCC production as a fiber-reinforcement, and therefore fresh concrete properties and mechanical properties had been examined, are summarized below:

1. While the increase of fiber content decreases workability to some extent, all samples having 1% and 2% fiber content are placed in between fluidity and viscosity values desired for SCC;
2. Although, as the aspect ratio increases, the production of the samples containing 2% and 3% fiber content has become more difficult; homogenous mixtures could be obtained with the fibers having low aspect ratio, even in high fiber ratios (i.e. 2% and 3%). Therefore, the aspect ratio was recognized as one of the most effective factor in optimum fiber content;
3. Increase of fiber content affected the aggregate granulometry in the concrete mixture negatively, led to mixing problems, and particularly decreased the compressive strengths;
4. The use of waste tire wire reduced the cost of the concrete, besides it improved the flexural tensile strength significantly. The most cost-effective series are WA-2 and WA-3 with their unit cost of the flexural tensile strength of 4.21 $/MPa and 3.51 $/MPa, respectively;
5. The unit cost of flexural strength of SCC mixtures with waste steel fiber was found to be only about 20% of the unit cost of flexural strength of SCC mixtures with industrial fiber content;
6. Greater first crack loads were obtained with the increase of high aspect ratio recycled steel fiber content;
7. When workability, mixture homogeneity, cost-effectiveness, and all of the mechanical performance results are taken into consideration, it is possible to state that the optimum waste fiber type and content is 2% by volume A-type waste fiber (the one with low aspect ratio);
8. Using the optimum ratio (2% by volume) of waste steel fiber, 22 times higher fracture toughness was obtained compared to the reference specimen, while an increase of approximately 102% in flexural strength and 14% in compressive strength was observed;
9. Any sort of fiber reinforcement led to considerable improvements particularly in parameters such as the flexural tensile strength and toughness;
10. Based on the statistical analysis (t-test), no significant difference between both compressive and flexural tensile strength mean values of the waste fiber-reinforced and industrial steel fiber-reinforced samples has been observed;
11. In general, although waste tire wires provide a positive contribution to the mechanical properties; they have disadvantages such as residual rubber their surfaces, geometric irregularity and having heterogeneous structure.

6. Recommendations

Within the scope of this study, it has been seen that the utilization of waste wires as fiber reinforcement in concretes having high workability such as SCC provides a contribution to the mechanical properties. In addition to improving the mechanical properties of the plain concrete by using recycled steel fibers obtained from end-of-life tires, it has been observed that it can be produced concrete that is comparable to industrial fiber reinforced concretes. However, it is thought that using clean and well-classified ELT wire can minimize the variability of the effect of this material on the mechanical properties of concretes. This study and further investigations will encourage the popularity of the usage of this waste material in concrete applications. In this regard, it has been thought that giving preference to this product considered as "waste" in future applications will be positive in terms of both environmental factors and countries' economy.

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