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Mechanical behavior of concretes containing waste steel fibers recovered from scrap tires

Ozkan Sengul

Istanbul Technical University, Faculty of Civil Engineering, Istanbul, Turkey

HIGHLIGHTS

- Steel fibers recovered from scrap tires were used to produce fiber reinforced concretes.
- The strength of the concretes were not affected with the use of waste fibers.
- Toughness of the concretes increased substantially with the waste fibers.
- Results obtained were similar to those expected from commercial steel fibers.
- Optimization process indicated that use of waste fibers may be more desirable.

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ABSTRACT

The paper presents the results of an experimental program in which steel fibers recovered from scrap tires were used to produce fiber reinforced concretes. Waste fibers having different geometrical characteristics were used in the mixtures at different percentages. To have reference concretes, a plain mixture without fibers and one mixture containing a commercial steel fiber were also prepared. Some mechanical properties such as compressive strength, splitting strength and flexural strength were determined. Load-deflection behaviors including the post-peak responses were monitored by means of a closed-loop bending test set-up. Test results showed that the fibers recovered from scrap tires affected the mechanical behavior of concrete similar to the commercial fibers. Depending on the geometrical properties of the fibers and fiber content, the descending branch of the load-deflection curves were modified with the use of waste fibers, thus affecting the toughness of the concretes. Comparison of these curves indicated that the performances of the waste fibers were lower when compared to the commercial fiber used. Based on the test results obtained and the relative costs of the mixtures, a multi-objective simultaneous optimization technique was also performed to determine the optimum fiber type and content. This procedure indicated that the use of waste fibers can be optimized for producing fiber reinforced concrete.

1. Introduction

An average lifespan of a typical car tire is considered to be five years, although this period may differ significantly depending on many factors [1]. According to International Organization of Motor Vehicle Manufacturers, more than 90 million motor vehicles (including passenger cars, trucks, and busses) were produced in 2014 and this amount is expected to increase in the coming years [2]. The total number of the vehicles on roads is estimated as approximately 1.2 billion by the same organization. Considering that each vehicle has at least four tires, it can be calculated that more than 4.8 billion tires are in use today. Due to the continuous production of vehicles, it may also be assumed approximately 4 billion used tires are generated each year. The increasing trend of vehicle production indicates that this amount will continue to increase in the future. Some of these used tires can be regrooved or coated and reused as second hand tires. The remaining tires and the ones after the reuse are termed as end-of-life tires and considered as scrap. Safe disposal of such high amounts of scrap tires is a major challenge. Since they became an important environmental issue, land filling or stock piling of these tires is no longer allowed in Europe or US [3,4]. With enforcement of stricter laws, realization of their economical benefits and also increase in environmental consciousness, the recycling rate of the scrap tires is now higher than 85% in US, Europe and Japan, which makes them one of the most recycled products [5–7].

A typical tire consists of approximately 47% rubber, 22% carbon black, 17% steel cords, 5% fabrics, and the remaining percentage

E-mail address: sengulozk@itu.edu.tr

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consists of some other minor additives [8]. Due to the high carbon content of tires, the energy produced by combustion of rubber is higher than that of coal [6] and tire-derived fuel is an alternative to the fossil fuels. According to Rubber Manufacturers Association, in 2013, 53% of the scrap tires in US were utilized as energy sources in cement kilns, paper manufacturing mills and other power generation plants [9]. More than 32% of the recycled tires are processed for material recovery and other uses [9,10]. There may also be innovative uses of scrap tires, such as strengthening of structures [11]. Scrap tires can be recycled by mechanical process or pyrolysis technique. In the mechanical method; the steel cords in the tires are pulled out by a punch-like mechanism, the tire is shredded and the remaining steel is collected by magnetic separators. The application of the mechanical method may vary from one recovery plant to another. Crumb rubber (rubber granule) and steel cords are obtained by the mechanical process. Pyrolysis method used for recycling, however, decomposes the tire by thermochemical process [12]. With the pyrolysis method, carbon black and oil are also obtained in addition to the steel. Some of these recovered materials find applications in new material production. For example, the recovered rubber is used for the production of floor mats or playground surfaces [13]. There is also extensive research on concretes containing crumb rubber or rubber chips in which the aggregates are replaced by rubber [14–20]. Unfortunately, the steel recovered from scrap tires are not used in new material production and used only for the partial replacement of raw materials in the iron production industry. A market analysis, however, indicated that there can be important demand for this recovered steel [21]. The steel cords provide strength and rigidity to the tires. Due to their high strengths, these cords may also be utilized in various industrial applications. They usually have circular cross sections but some may have a rectangular cross section and their diameters usually vary between 0.1 and 2 mm. Both the mechanical and geometrical properties of these recovered steel cords can be similar to commercially available steel fibers used in concrete; therefore it may be possible to use them in concrete technology.

Although there are many studies available on the use of recovered rubber, studies on the use of recovered steel are very limited. There are only a handful of studies available on the use of waste fibers recovered from scrap tires for producing steel fiber reinforced concretes. However, there is growing interest in the use of these waste steel fibers in concrete. One of the drawbacks of fibers recovered from scrap tires is the variation in geometrical properties of these fibers. Unlike the commercially available steel fibers, both the diameters and lengths of the fibers recovered from scrap tires may vary [22–24], and some of them may be too long to produce fiber reinforced concrete, so they have to be classified before use. The pull-out behavior of the recovered fibers may be similar to those of the commercial fibers which may be attributed to the irregular undulations of the fibers as a result of the shredding process that can increase mechanical bonding [24,25]. Mechanical properties of concrete containing waste steel fibers may be improved due to the crack-bridging effect of the fibers in concrete similar to the concretes produced with commercial fibers [26–29]. Available studies indicated that the theoretical models recommended for the mechanical behavior of steel fiber reinforced concretes produced with commercial fibers, may give different results when different recovered steel fibers are used [30–32]. Production of steel fibers is energy intensive, thus expensive process, and use of the waste fibers for fiber reinforced concrete production can reduce the need for steel fiber production, thus contribute to sustainability of concrete industry. It should also be noted that the prices of the waste fibers are significantly lower compared to those of the commercial steel fibers. Thus, it may be possible that these low cost, waste materials can be turned into value-added, marketable products. However, having a better understanding of the effects of waste steel fibers on the properties of concrete and establishing their applicability as a reinforcement in concrete is needed for industrial scale applications.

The main objective of the work presented herein is to provide more information about the effects of steel fibers recovered from scrap tires. An experimental investigation was carried out, the results of which are presented in this paper. Waste steel fibers having different geometrical properties were used to produce concrete mixtures. A concrete containing commercial steel fiber was prepared for comparison. A plain concrete without any fibers was also produced. The details of the experimental program are presented below.

2. Experimental

2.1. Materials

2.1.1. Cement and aggregates

An ordinary Portland cement (CEM I 42.5 according to EN 197-1) was used in the concretes. Locally available natural aggregates, a natural sand with the size of 0–1 mm, and three crushed stone aggregates having sizes of 0–4, 4–12, and 12–22 mm were used. Both the aggregate grading and the maximum size of aggregate were the same in all the concretes produced. The same superplasticizer was also included to achieve enough workability for the different mixtures.

2.1.2. Fibers

At the beginning of the experimental study, waste steel fibers recovered from scrap tires were obtained from different tire recycling plants. Some of these fibers were containing rubber and textiles, and also rubber attached on the fiber surfaces. In addition, some steel fibers had significant variations in their diameters. High deviations in geometrical properties of the fibers and other materials such as rubber may substantially reduce both the effectiveness of the fibers and performance of the fiber reinforced concretes. According to information given from the recycling plants, such problems are mostly due to the recycling procedures of the plants and can be solved by some adjustments in the recovery procedures.

Among the various waste fibers received, three of them, recovered by different tire-recycling companies were selected for the experimental study. There were several reasons for selecting those particular fibers. The selected fibers were free from any rubber or textiles that might affect the concrete properties. The fibers also had consistent geometrical properties and their average diameters were not the same, thus it was possible to obtain various fiber aspect ratios that can represent different fibers and compare the effect of fiber geometry. The geometrical characterization of the fibers was made by the measurement of their diameters and lengths on samples of randomly selected 500 fibers from each fiber type. Table 1 shows the geometrical characterization of the fibers used.

The code W in Table 1 indicates the waste steel fibers recovered from scrap tires and the numbers (0.3, 0.6, or 1.4) following W stand for the average diameter of fibers in millimeters. As seen from Table 1, the diameters of the waste steel fibers were not the same for a given type of fiber and there was a large variation, which may probably be due to recycling of different tire types together, differences in tires produced by various manufacturers and also various steel cords present in the tires. According to the information given by the tire recovery companies that the fibers received from, the fibers W0.6 and W1.4 were recovered by pyrolysis, but W0.3 by mechanical method.

Among the fibers considered in this study, the one with the 0.3 mm diameter shown in Fig. 1 was a convoluted fiber with an average straight length of 52 mm. The straight length of the fiber was used in the calculation of the fibers aspect ratio. The other two waste fibers (W0.6 and W1.4), however, were straight fibers and they had much longer lengths (such as 30–40 cm) when received. Since it was not possible to use them for fiber reinforced concrete production, these fibers (W0.6 and W1.4) were cut into 50 mm lengths (Figs. 2 and 3). As a result, there was no scatter in the lengths of these fibers when used in concrete, as it was possible to cut them into any length. The reason for selecting 50 mm was to have similar lengths for the waste fibers used. In addition, since the diameters of the waste fibers were different, it was also possible to obtain different fiber aspect ratios with the use of the same length of 50 mm. As seen in Table 1, these ratios were between 37 and 179 for the waste fibers. The waste fibers W0.3 and W1.4 were single fibers. The fiber W0.6, however, actually composed of six single steel wires wrapped together to form cords. Cutting the cords into the length of 50 mm did not affect the cord and the wires continued to stand together. However, as it will be explained in the discussions section, some of the individual fibers forming W0.6 type of fiber separated from each other during the concrete productions. Fig. 2 shows two W0.6 fibers, and to demonstrate the structure of this fiber, the individual wires forming the fiber were separated by hand for one of these fibers and it is also shown in the same figure.

Table 1
Geometrical characteristics and tensile strength of the steel fibers used in the study (average ± standard deviation).

Designation	Type	Diameter (mm)	Length (mm)	Average aspect ratio (length/diameter)	Tensile strength (MPa)
W0.3	Waste steel fiber	0.29 ± 0.07	52 ± 17	179	–
W0.6	Waste steel fiber	0.62 ± 0.12	50 ± 0	81	1330 ± 185
W1.4	Waste steel fiber	1.37 ± 0.24	50 ± 0	37	1160 ± 140
C	Commercial steel fiber	0.90 ± 0.00	60 ± 0	67	1000

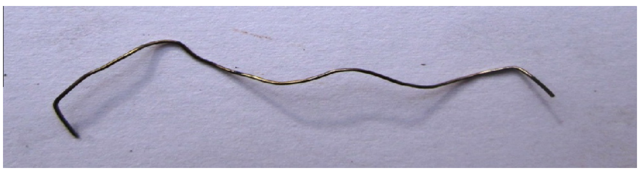

Fig. 1. The fiber W0.3.

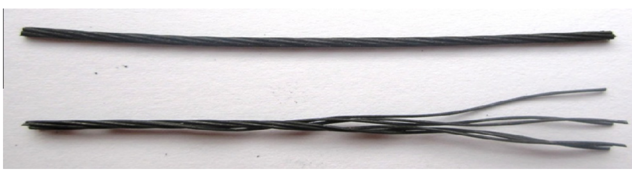

Fig. 2. The fiber W0.6.

Fig. 3. The fiber W1.4.

A steel fiber commercially available in many countries was also used in the study for comparison with the waste steel fibers. This commercial fiber was coded as C and with a diameter of 0.90 mm and a length of 60 mm; its aspect ratio was 67. Being an industrial product, there was no variation in the dimensions of this fiber. The commercially fiber had hooked ends, while the waste fibers used had straight ends. Comparison of fibers having straight ends to one with hooked ends may be criticized that there will be difference in bonding, which will affect the results obtained. The reason for selecting this particular commercial fiber was that it is one of the most widely used fibers in Turkey and it is known to have a good performance in producing steel fiber reinforced concrete. Therefore, when a new type of fiber is introduced into Turkish market, it is one of the fiber types usually used for comparison.

Since the lengths of W0.6 and W1.4 were long enough (approximately 30–40 cm) before cutting into shorter length (50 mm), it was possible to determine the tensile strength of these fibers. The fiber W0.3, however, was not tested due to its short length. Twenty-five fibers from each of these fiber types were tested. The results of the fibers that ruptured close to or within the grips were discarded when calculating the tensile strengths. As seen from the test results given in Table 1, the strengths of the fibers were 1330 and 1160 MPa, which indicates that both were made from high strength steels. The tensile strength of the commercial fiber shown in Table 1 was the declaration of the fiber producer and was taken from the technical data sheet of the fiber.

2.2. Mixture proportions

Table 2 shows the mixture compositions of the produced concrete. They were prepared in three series and each waste steel fiber type was used in one of them. As seen in Table 2, the concrete mixtures were designated with W0.3, W0.6 or W1.4, which shows the type and diameter of the fiber used. The numbers (5, 10, 15, etc.) following the fiber code indicate the amount of the fiber used in the mixture. A plain concrete without any fibers (concrete coded as P) and one with the commercial fiber (coded as C-20 in Table 2) were also prepared. The content for the commercial fiber was chosen as 20 kg/m^3 because this amount is widely used for the particular fiber and also to have coinciding contents of waste fibers and commercial fiber. In total, 12 different mixtures were cast in the experimental study. All the specimens were demoulded 24 h after casting and they were stored in lime saturated water with a constant temperature of 20 °C until testing.

2.3. Test procedures

Compressive strengths of the concretes were determined according to EN 12390-3 [33]. The tests were performed with an automatic compressive testing machine having a maximum capacity of 2000 kN. The rate of loading was 0.6 MPa/s and it was kept constant for all the concretes tested. Tensile splitting strength tests were conducted in accordance with EN 12390-6 [34]. Packing strips made of hardboard were placed on the plane of loading. A constant rate of loading as 0.6 MPa/s was applied for all concretes in tensile splitting strength tests. All the tests were performed at the age 56 days. It was the author's decision to perform the tests at this age to ensure that the concrete is well cured during sawing to notch the prism specimens. The bending strength and fracture energies of the concretes were determined using three point bending testing on 100 × 100 × 500 mm prismatic samples. It may be criticized that larger prisms of 150 × 150 × 700 mm are generally used for the testing of fiber reinforced concretes. The volume of this specimen, however, is 3.4 times larger than that of the 100 × 100 × 500 mm prism specimens. The study is based on the comparison of concretes containing different fiber types and the mixture proportions were same in all concretes produced. The amounts of the waste fibers received from recycling plants were limited. Therefore, to use these fibers more effectively and obtain more number of mixtures and samples, the 100 × 100 × 500 mm specimens were cast instead of 150 × 150 × 700 mm samples. For all the prism samples, the tests for the determination of the fracture energy were obtained in accordance with the recommendation of RILEM 50-FMC Technical Committee [35]. In order to force the crack to propagate along a desired path, wet sawing was used to notch the prism specimens and their effective cross sections were reduced to 100 × 83 mm. Specimens were rotated over 90° around their longitudinal axes and then sawn through the width of the specimens at mid-span. The notched beam specimen and the testing set-up are schematically shown in Fig. 4. The load was applied by a closed-loop testing machine and the deflections were measured simultaneously by using two linear variable displacement transducers. The load-deflection curves were used for evaluating the fracture energy. It may be criticized that the international standards are based on parameters derived by the load-crack mouth opening displacement (CMOD) response. However, the load-deflection curves are also defined in EN 14651 [36] and residual strengths can be determined for specific deflection values. The relationship between CMOD and deflection values is also given in EN 14651. Thus, in this study, load-deflection curves were used for characterizing the toughness of concretes. Typical load-deflection curve is shown in Fig. 5. The area under the load versus deflection at mid span curve is a measure of the fracture energy of the material.

Since the fiber reinforced concretes have shown a ductile behavior under flexural loads, the tests were finalized when the deflection at midpoint has reached up to 4 mm and the fracture energy was calculated for this deflection. It can be seen from Fig. 5 that, the energy at this chosen deflection (i.e. 4 mm), however, is not totally dissipated and even for this deflection, the load carried by the specimen is still not zero. Fracture energy of specimens can be calculated as follows:

$$G_F = \frac{(W_0 + mg\delta_0)}{A_{lig}} \tag{1}$$

where G_F: fracture energy (N/m), W_0: area under load versus deflection curve (N/m), m: weight of the specimen, g: gravitational acceleration (9.81 m/s^2), δ_o: deflection of specimen at failure, and A_{lig}: effective cross-section of the specimen.

The flexural strength is calculated by using the equation given below:

$$f_{fnet} = \frac{3Pl}{2B(D - a_0)^2} \tag{2}$$

where f_{fnet}: flexural strength (MPa), P: maximum load (N), l: span (mm), a_o: notch depth (mm), B: width and D: height of the specimen (mm). Compressive and splitting strength tests of the concretes were determined on the half prisms obtained after flexural testing. Slump tests were also performed on the concretes during casting.

Table 2
Compositions and some fresh properties of fresh concretes.

Materials (kg/m^3)	P	W0.3-5	W0.3-10	W0.3-15	W0.6-10	W0.6-20	W0.6-30	W0.6-40	W1.4-20	W1.4-40	W1.4-60	C-20
Cement	366	365	367	364	363	368	368	376	362	362	363	364
Water	183	182	184	182	182	184	184	188	181	181	182	182
Superplasticizer	4.9	4.9	4.9	4.9	4.9	4.9	4.9	5.0	4.9	5.0	4.9	5.1
Fiber	0.0	4.9	9.8	14.8	9.9	19.7	29.5	39.7	19.8	39.8	59.7	20.2
Fiber type	No fiber	Waste fiber W0.3			Waste fiber W0.6				Waste fiber W1.4			Commercial fiber
Sand (0–1 mm)	314	312	314	311	311	315	314	320	310	308	308	310
Sand (0–4 mm)	635	631	636	629	628	636	635	646	626	623	623	628
C.S.I (4–12 mm)	382	380	382	378	378	383	382	389	377	375	375	378
C.S.II (12–22 mm)	571	568	572	565	565	572	571	581	563	560	560	555
Unit weight	2456	2448	2470	2449	2442	2456	2469	2450	2444	2454	2477	2442
Slump (cm)	14	9	7	6	10	4	1	0	14	16	7	16

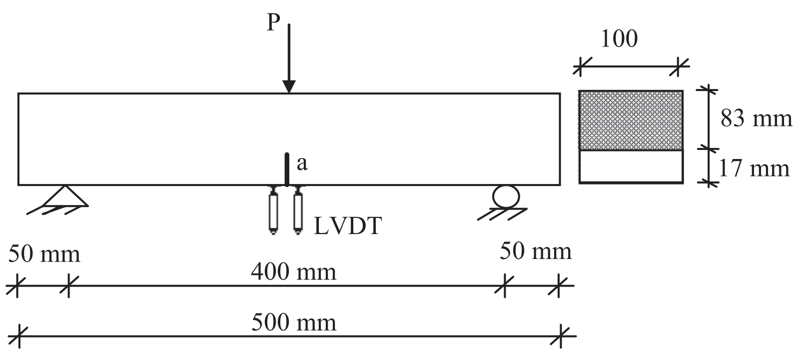

Fig. 4. Schematic representation of the three point bending test.

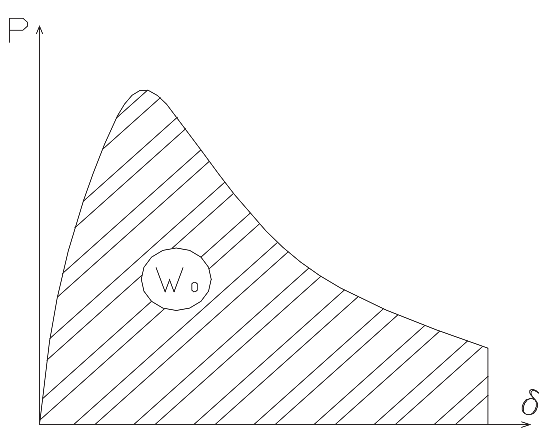

Fig. 5. Typical load-deflection curve.

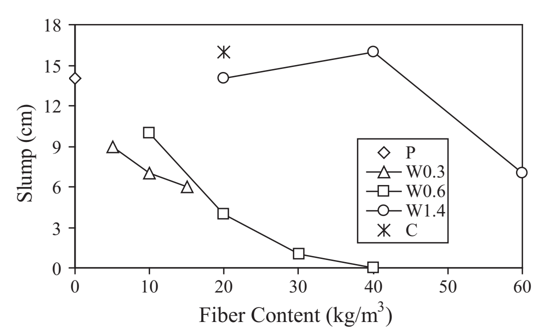

Fig. 6. Effect of waste fibers on slump of concrete.

3. Experimental results and discussion

3.1. Workability

Fig. 6 shows the effect of waste fibers on the slump of concrete. The slump was reduced with increasing fiber content. Such a result is expected for steel fiber reinforced concretes. Inclusion of fibers forms a network structure in concrete which restrains the slump of concrete. As presented in Table 2, the superplasticizer content was same in all concretes. This approach for mixture design may be criticized, and it may be suggested to increase the superplasticizer amount to maintain similar workability in fiber reinforced concretes. In this study, however, the admixture content was kept constant. As a result, when the fiber content increased, lower slumps were obtained. Using higher amounts of the waste fibers was not possible due to the bundling of the fibers at higher contents, especially for the W0.3 waste fiber which had irregular shapes and very high fiber aspect ratio. Even the content of 15 kg/m^3 was the highest possible content for this fiber.

The effect of fiber properties on the slump was significant as seen in Fig. 6. For example, for the fiber content of 20 kg/m^3, the mixture containing the commercial fiber had the slump value of 16 cm, while it was 14 cm and 4 cm for the W1.4 and W0.6 fibers, respectively. Since both W0.6 and W1.4 had the same length, it may be concluded that the increase in fiber aspect ratio reduced the slump. For a given fiber content and same fiber length, this reduction is mainly due to the increase in the number of fibers when the aspect ratio is higher (that is, the diameter of the fiber is smaller). As mentioned in Section 2.1.2 and also shown in Fig. 2, the fiber W0.6 was in strand form consisting of individual fibers and they kept their forms after cutting into the length of 50 mm. However, during the concrete production, it was observed that some of the individual fibers forming W0.6 separated from each other (as shown in Fig. 2) and became single, separate fibers; thus increasing both the number of fibers in the mixture and the aspect ratio of these fibers, which, as a result, reduced the slump even further. Although the fiber W0.3 was used in smaller amounts, it affected the slump more than the others, which may be attributed to the very high aspect ratio and the irregular fiber shapes. The fiber having the largest diameter had less effect of slump and even higher slump at 40 kg/m^3, which shows that the smaller aspect ratio (as a result, lower number of fibers) did not change the slump. It seems that slump in concrete containing the commercial fiber (coded as C) was slightly higher than the plain mixture, but these results may be considered the same and may be concluded that the fiber content used for this fiber did not affect workability.

All the concretes were compacted on the same vibration table. As seen from the test results, some of the mixtures had slump values between 0 and 4 cm. However, no problems were encountered during the compaction and in order to place them more effectively, vibration was applied for a longer period for these low slump concretes. After the completion of flexural strength testing, the prisms were broken into two pieces in order to investigate the distribution of the fibers. It was observed that the fiber distributions were homogeneous for all the mixtures. To illustrate the waste steel fiber distribution in concretes, specimens of the mixtures containing 20 kg/m^3 and 40 kg/m^3 of the W0.6 fiber were cut with a diamond saw and the cross sections obtained are shown in Fig. 7. In this figure, the white colored circular or elliptical dots are the steel fibers. Visual examination indicated that even though the workability of these mixtures were low, the fiber distributions of the waste steel fibers were random and they were dispersed homogenously in the concrete produced without clumping.

3.2. Compressive strength

Compressive strengths are shown in Table 3 and also in Fig. 8. The 56-day strength of the plain concrete without any fibers was 69.3 MPa. As seen from the test results, there were slight variations in the compressive strengths due to the use of steel fibers. The concrete with the commercial fiber (C-20) had the lowest strength which was 9.4% lower than that of the plain mixture. This reduction in strength is higher than what is normally expected in fiber reinforced concretes and may be due to the scatter of results [24,37]. For the concretes containing waste fibers, however, the reductions obtained for some mixtures were less. The highest compressive strength was 75.4 MPa and obtained with the waste steel fiber W0.6 at a content of 40 kg/m^3. Although a higher strength was obtained, it is known that steel fibers generally do not change the compressive strength of concrete, especially when macro-dimensional fibers are used, as in this study. The fibers may be considered partly hybrid due to scatter in their geometrical properties and the shorter fibers may have slightly affected the test results. However, when all the test results are taken into account, it may be concluded that compressive strengths of the mixtures containing the waste fibers were similar to that of the plain mixture (Fig. 8 and Table 3). The reductions or increases in the strength of these concretes may be attributed to the natural scatter of the test results.

Table 3
Mechanical properties of concrete.

Mixture code	Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Fracture energy (N/m)
P	69.3	6.7	5.6	152
W0.3-5	69.5	5.6	7.4	457
W0.3-10	65.8	6.5	5.1	625
W0.3-15	70.6	6.6	7.2	1146
W0.6-10	64.1	6.0	5.7	559
W0.6-20	64.7	7.2	5.4	947
W0.6-30	71.5	7.9	7.7	1357
W0.6-40	75.3	9.0	9.4	1893
W1.4-20	68.7	6.8	6.8	521
W1.4-40	69.1	7.2	6.7	1136
W1.4-60	63.6	7.0	6.7	1388
C-20	63.1	6.9	6.5	2322

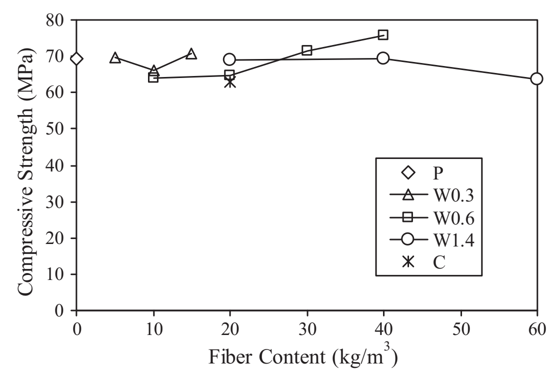

Fig. 8. Effect of waste fibers on the compressive strength.

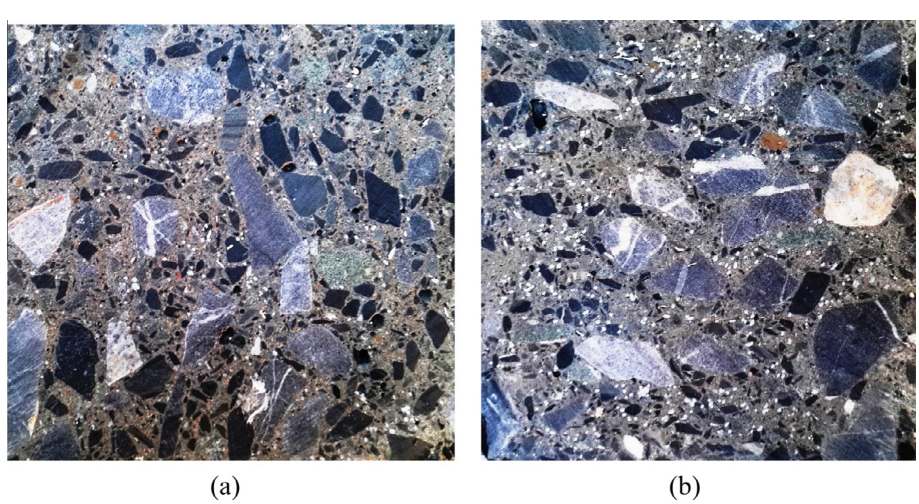

Fig. 7. Cross sections of concretes containing. (a) 20 kg/m^3 of W0.6 fiber. (b) 40 kg/m^3 of W0.6 fiber.

3.3. Splitting tensile strength

Fig. 9 shows the effect of waste steel fibers on the splitting tensile strength of concrete. Due to the configuration of the splitting test, tensile stresses are generated within the specimen and if there are fibers in the mixture, the opening and propagation of the crack are controlled by the steel fibers along the fracture plane. As seen from the test results, except two mixtures (W0.3-5 and W0.6-10), the splitting strengths of the mixtures containing fibers were almost the same or higher than that of the plain concrete. It seems that as the fiber content increased, splitting strengths also increased but these increases were very small except for the concretes containing W0.6 type of steel fiber. This may be due to the fact that the individual fibers forming W0.6 became separated during mixing (Fig. 2) and as a result the number of fibers per unit area was actually higher, which might have affected the test results. The natural scatter of the test results might also have a role in these results. Mixtures produced by W1.4, which has the lowest aspect ratio (and largest diameter) also gained almost the same splitting strength compared to that of the plain concrete. As seen in Table 3 and Fig. 9, except two concrete mixtures (W0.6-30 and W0.6-40), the splitting tensile strengths of the concretes containing waste fibers were almost the same as that of the one with commercial fiber. The result obtained with the commercial fiber was also similar to the plain concrete. Based on the test results obtained, it may be concluded that the waste fibers may slightly improve splitting strength depending on the amount and type of the fiber.

3.4. Flexural strength

Flexural strengths of the concrete mixtures are presented in Fig. 10. They were determined according to Eq. (2) and the net cross section was used in the calculations in order to determine the bending capacity. The flexural strength of the concrete containing W0.6 fiber increased with higher fiber content, but this trend was not obtained for the other two waste fibers. As seen in Fig. 10, the flexural strengths did not change for the concretes containing different amounts of W1.4 fiber. Conflicting results were obtained for the W0.3 fiber for which, higher strengths increases were obtained for the fiber contents of 5 and 15 kg/m^3, but an important reduction (approximately 30% compared to 5 kg/m^3 fiber content) were recorded for the concrete produced with 10 kg/m^3 fiber. Such a behavior was not obtained in the splitting test, which also indicates the tensile strength of concrete. The flexural strength was obtained on notched specimens, in which the cracks are forced to propagate along the notch. In splitting test, however, the crack propagation takes place through the weakest plane. As a result, the reason behind these changes may be the scatter of the flexural strength test results although 5 specimens were tested for each mixture. As presented in Fig. 10, the flexural strength of the mixture containing 20 kg/m^3 of the commercial fiber was higher than that of the plain concrete. When the flexural strengths of the concretes with waste fibers are compared to that with the commercial fiber, it can be seen that the strengths were similar. For the same fiber content of 20 kg/m^3; the strength of the concrete produced with W0.6 was about 17% lower, however, that of the W1.4 was almost the same as the strength of the concrete containing commercial fiber (Fig. 10 and Table 3). According to these test results, it seems that the waste fibers do not have adverse effect on the flexural strength of concrete.

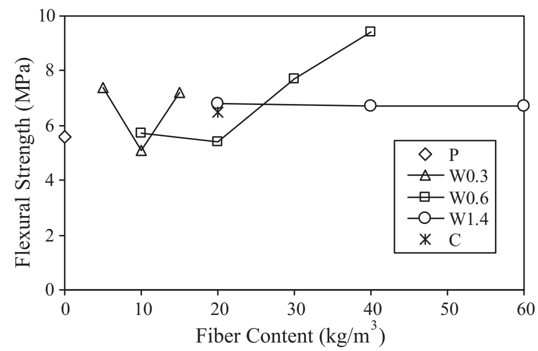

Fig. 10. Effect of waste fibers on the flexural strength.

3.5. Load-deflection curves and fracture energy

Load-deflection curves of some concretes are presented in Figs. 11 and 12. For each mixture, a typical test result was used in these figures. Fig. 11 shows the complete load-deflection curves of the concretes containing different amounts of W0.6 type of waste fiber and the curve obtained for the plain concrete has been included. As presented in this figure, the results obtained for the waste fibers were similar to those that might be expected from commercial steel fibers available in the market. The ability of fiber reinforced specimens to absorb energy was substantial, although the displacements were recorded until the specified value of 4 mm. As seen in Fig. 11, the ascending branches of the curves were similar for the plain concrete and the ones with 10 kg/m^3 and 20 kg/m^3 of waste fiber. The peak loads obtained in these concretes were also similar. The mixtures containing 30 and 40 kg/m^3 of the W0.6 fiber, however, reached higher peak loads. After the formation of the first crack, the strain hardening behavior in the ascending branch of the curve is an indication of the high performance of these concretes. The reason behind these higher strengths may be the higher amounts of fibers that limit the propagation of the cracks. After the peak load, a sudden reduction in load was

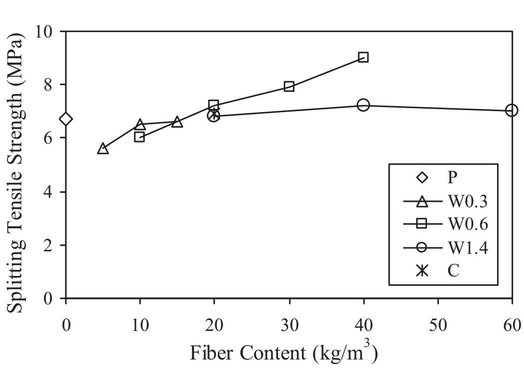

Fig. 9. Effect of waste fibers on the splitting tensile strength.

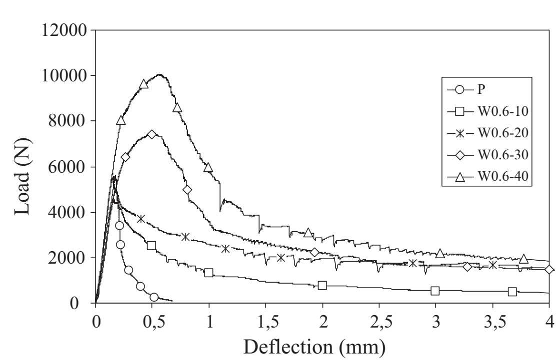

Fig. 11. Effect of waste fiber content on the load-deflection curves of concrete.

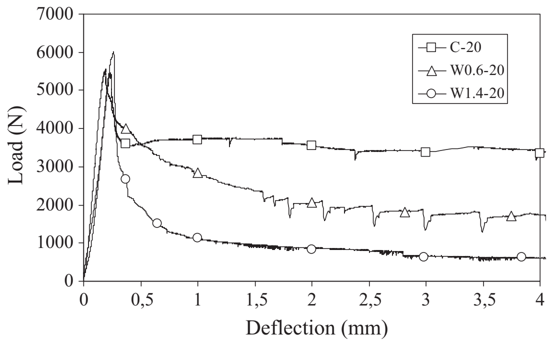

Fig. 12. Effect of fiber type on the load-deflection curves of concrete (for the same fiber content of 20 kg/m^3).

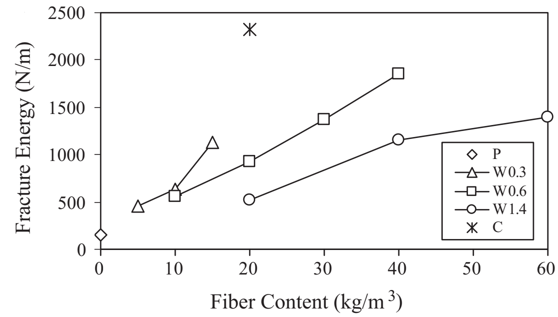

Fig. 13. Effect of waste fiber content on the fracture energy.

recorded for plain concrete, which is typical in concretes without fibers. However, when fibers were included in the mixture, the post peak response part of the curves were modified and these mixtures sustain higher loads. As seen from Fig. 11, the descending branch of the load-deflection curve became less steep with fibers. After the cracking of the matrix phase, fibers bridge the cracks and they continue to transfer load along the crack, thus restrain the opening and propagation of the cracks, and as a result, prevent the steeper gradients of the softening branch.

Fig. 12 compares the effect of different fibers for the same fiber content of 20 kg/m^3. Since the fiber W0.3 was used up to 15 kg/m^3 (Table 2) this fiber was not included in this figure. The ascending branches of the load-deflection curves were almost identical for the concretes compared. However, the descending parts of the curves obtained differ substantially even though the fiber contents were the same. The post peak descending branch obtained for the concrete produced with W1.4 was the steepest among these concretes. These differences in behavior may be attributed to the properties of the fibers. W1.4 fiber had the lowest fiber aspect ratio which means; larger diameter for the same fiber length. The fiber W0.6, on the other end, had higher aspect ratio, that is, smaller diameter. Even though the fiber contents were the same, the difference in the fiber geometry corresponds to different number of fibers for a given volume. If fiber length is invariant, higher fiber aspect ratio results in higher number of fibers for the same volume. As mentioned in Section 2.1.2 and shown in Fig. 2, the individual fibers forming W0.6 separated during the concrete production. Although the same fiber content was added into concrete, the separation of the individual fibers of W0.6 also increased the number of fibers bridging the cracks, which may be an additional reason for the better performance of this fiber when compared to the W1.4. The concrete containing the commercial fiber had higher strength for a given deflection. As seen in Fig. 12, after the peak point and an important reduction in the load up to a deflection of approximately 0.5 mm; the load carried by this concrete decreased slightly up to the measured deflection of 4 mm. Thus, it may be concluded that load-deflection performance of the concrete containing the commercial fiber was the best among the concretes compared. The reason behind this result may be the hooked ends of the commercial fiber used, which increases the bonding of the fiber. The waste fibers, however, had straight ends which might have limited their performance compared to the commercial one. Compared to the hooked end commercial fibers, waste fibers with straight ends may be pulled out easier, thus affecting the results obtained. Therefore, the results presented in Fig. 12 may also be accepted as a reflection of the effect of fiber end geometry.

Using these test results, residual flexural tensile strength of the concretes may also be calculated. According to EN 14651 [36], residual strength is the fictitious stress at the tip of the notch which is assumed to act in an uncracked mid-span section, with linear stress distribution, of a prism subjected to the centre-point load corresponding to a given deflection or given crack mouth opening displacement. Although the specimen dimensions used in this study do not fully comply with the dimensions given in this standard, the residual strength of the concretes may still be calculated since all the samples were the same and their complete load-deflection curves were obtained up to the same deflection of 4 mm. The residual strength can be calculated for different deflections. For example, when a deflection of 1 mm is selected, the residual strength of the plain concrete is zero, but this strength increases substantially with the use of fibers. For example, for the residual strengths were 2.5 MPa and 3.2 MPa for the concretes W0.6-20 and W1.4-40, respectively. As the content of the fibers increase higher residual strengths can be obtained due to the more limitation of the crack propagation by fibers. Fiber type also affects the residual strength. This behavior is reflected in both load-deflection curves (Figs. 11 and 12) and also in fracture energies of the concretes.

Fracture energies or toughnesses of the concretes were obtained by Eq. (1) and the results are presented in Fig. 13. As seen from these results, substantial increases were obtained by the use of fibers and these increases in the fracture energy depend on both the fiber properties and also fiber content. These increases in toughness may be accepted as the indication of changes in the ductility of concretes. If a relative ductility is calculated by determining the ratio of the fracture energy of fiber reinforced concrete to that of the plain concrete without any fibers, it may be seen that ductility of the fiber reinforced concretes are substantially higher. For the W0.3 type of fiber, compared to plain concrete, the fracture energy increases more than 7-fold for the content of 15 kg/m^3. When W0.6 fiber was used, this increase was approximately 6 and 12-fold for the contents of 20 and 40 kg/m^3, respectively. As seen in Fig. 13, the result obtained for the commercial fiber was even higher which may probably be due to the differences in fiber end geometry. High toughness is one of the main reasons behind the application of fiber reinforced concretes and those obtained with the waste fibers were substantially higher than plain concrete. Based on the test results obtained, it may be concluded that the waste steel fibers may be used for the production of fiber reinforced concretes although the toughness values may be smaller compared to the commercial fiber used in this study.

4. Optimization

By using obtained test results and the cost of the concretes, an optimization procedure was also performed in the study. Optimization may be defined as the selection of the most suitable solution among the alternatives. Optimization procedure can be basically summarized as defining the performance criteria for the decision, independent and dependent variables affecting this

Table 4
Relative costs of concretes.

Mixture	P	W0.3-5	W0.3-10	W0.3-15	W0.6-10	W0.6-20	W0.6-30	W0.6-40	W1.4-20	W1.4-40	W1.4-60	C-20
Relative cost	0	0.49	0.98	1.48	1.49	2.96	4.43	5.96	2.97	5.97	8.96	20.20

decision, and formulation of the parameters [38,39]. In case of selecting the concrete mixture, optimization objectives may vary, such as strength, durability, workability or some other properties. The independent variables related to this decision may be the mixture proportions used in different concretes. The dependent variables (for example, strength of concrete) usually change according to the independent variables. The dependent variables (or responses) are compared based on the optimization objectives. The optimization is based on the tested mixtures. If there is only one criterion, for example only the compressive strength, the mixture having the highest strength can be selected directly and there is no need for an optimization. In concrete, however, there may be varying or conflicting performance criteria. A simple example of such confliction may be the heat generated in concrete in which, for given materials, increase in cement content may increase the strength but also the heat generated due to the hydration of cement. In such cases, optimization methods may provide a mathematical basis for the comparison of alternatives and determining the optimum mixtures to meet varying performance criteria. Since optimization usually involves considering several responses simultaneously, a multi-criteria optimization technique was used to determine the optimum mixture among the concretes produced.

In this study, desirability functions were used for the optimization of multiple responses simultaneously [39–42]. Individual desirability functions (d_j), which takes a value between 0 and 1, were obtained for each response and in order to maximize or minimize the individual responses, they were calculated by Eq. (3) or Eq. (4), respectively [43,44].

$$d_j = \left[\frac{Y_j - \min f_j}{\max f_j - \min f_j}\right]^{t_j} \tag{3}$$

$$d_j = \left[\frac{\max f_j - Y_j}{\max f_j - \min f_j}\right]^{t_j} \tag{4}$$

where d_j: the individual desirability function, Y_j: the current response, and, $\min f_j$ and $\max f_j$ are the lowest and the highest values of the *jth* response included in the optimization, respectively. The power value t_j is a weighting factor of the *jth* response. Any factor that may affect the decision process can be included in the optimization as a response and individual desirability function of this response may be calculated.

After the calculation of the individual desirability functions, they were combined as in Eq. (5) to obtain an overall desirability function (D), which is the geometric mean of the individual desirability functions;

$$D = (d_1 \times d_2 \times d_3 \times \ldots \times d_m)^{\frac{1}{m}} \tag{5}$$

where m is the number of the responses.

The value of overall desirability function (D) also varies between 0 and 1; where 0 is unacceptable and 1 is the most desirable [43–45]. As this value increases, the mixture becomes more desirable. The mixture having the highest value of the overall desirability function indicates that the mixture is the optimum solution for the given responses and criteria.

Costs of the mixtures are also important and more economical mixtures are usually preferred if the other properties are satisfactory. When an alternative material is investigated, one of the first questions that may arise is its price. In this study; in addition to the mechanical properties, the costs of the concretes were also considered as a response in the optimization. The costs of the mixtures were calculated and a very simple approach was selected for this cost analysis. Since the content of the materials, except the fibers, were almost the same, thus do not affect the cost of the concrete, only the amount of the fibers were taken into account for the cost analysis. The mixture costs were obtained simply by multiplying the fiber content by the fiber unit price. The information on the prices of the waste steel fibers was given by the tire recycling plants. It appeared that the prices of the waste steel fibers were approximately 6–10% of the price of the commercial fiber. In this study, the W0.6 and W1.4 fibers were cut into the lengths of 50 mm. The cost of this cutting process was also determined by a market analysis and it corresponds to approximately 5% of the price of the commercial fiber. For the optimization process, the relative costs of the mixtures were calculated in which the unit price of the commercial steel fiber was taken as 1 unit and that of the waste fiber as 0.10 units. The cost of the cutting was accepted as 0.05 units and included in the unit prices for W0.6 and W1.4 fibers. As a result, the relative unit price of these two waste fibers increased to 0.15 units. The relative costs of the concretes calculated based on these assumptions are given Table 4.

The mechanical properties (given in Table 3) and cost of the concretes (in Table 4) were included in the optimization as the responses. Higher mechanical properties but lower costs are preferred for concrete mixtures. Thus, the individual desirability functions for compressive strength, splitting tensile strength, flexural strength and fracture energy were determined by Eq. (3), which maximizes these responses. The desirability function for cost, however, was minimized using Eq. (4). It was assumed that these responses have the same importance, thus the weighting factor was accepted as 1. Using these five individual desirability functions (four mechanical properties and cost), the overall desirability function was obtained according to Eq. (5) in which $m = 5$. The individual and overall desirability functions are shown in Table 5.

As seen in Table 5, for a particular response that is maximized, the mixture having the highest test result also have the highest individual desirability function value, which is 1.00. The one with the lowest test result, however, has the value of 0.00. For the minimized response, this scalarization approach is the opposite, in which the mixtures with highest and lowest test result have the values of 0.00 and 1.00, respectively. The overall desirability functions calculated for the mixtures are also given in the same table. As presented in Table 5, the concrete containing 40 kg/m^3 of the W.0.6 type of waste steel had the highest overall desirability value (0.89), which indicates that this mixture maximizes the mechanical properties and minimizes the cost, and within the limits of this study, this mixture is the optimum one among the twelve mixtures prepared. The concrete prepared with the same fiber but fiber content of 30 kg/m^3 had the second highest overall desirability (0.66), which means that it is the second optimum mixture. As seen from this table, the concrete containing commercial fiber had the highest fracture energy; however, the overall desirability of this concrete was 0.00 due to its highest cost. The overall desirability of the plain concrete was also 0.00 because of its lowest fracture energy. Comparison of different concretes can also be made using this method. For example, when the W0.6-20 mixture is compared with W1.4-20, it can be seen that the overall desirability of

Table 5
Desirability functions of the mixtures.

Mixture code	Individual desirability functions of;					Overall desirability function
	Compressive strength	Splitting tensile strength	Flexural strength	Fracture energy	Relative cost	
P	0.51	0.32	0.12	0.00	1.00	0.00
W0.3-5	0.53	0.00	0.53	0.14	0.98	0.00
W0.3-10	0.24	0.26	0.00	0.22	0.95	0.00
W0.3-15	0.63	0.29	0.49	0.45	0.93	0.52
W0.6-10	0.09	0.12	0.14	0.19	0.93	0.19
W0.6-20	0.14	0.47	0.07	0.36	0.85	0.27
W0.6-30	0.68	0.68	0.60	0.56	0.78	0.66
W0.6-40	1.00	1.00	1.00	0.79	0.71	0.89
W1.4-20	0.47	0.35	0.40	0.17	0.85	0.39
W1.4-40	0.50	0.47	0.37	0.46	0.70	0.49
W1.4-60	0.05	0.41	0.37	0.57	0.56	0.30
C-20	0.00	0.38	0.33	1.00	0.00	0.00

W1.4-06 is higher, thus this mixture is considered more desirable. The results of this optimization procedure indicate that the use of waste fibers may be more desirable compared to commercially available steel fibers.

5. Conclusions

Based on the results obtained, the following conclusions could be drawn:

1. Geometric properties such as diameters of the waste steel fibers recovered from scrap tires may change significantly. There may also be materials such as rubber in the fibers. The fibers that have consistent properties and free from rubber etc. can be preferred for the production of steel fiber reinforced concretes.
2. Both the geometrical properties and content of the waste fibers affected the workability of concrete similar to what may be expected from commercial steel fibers.
3. The compressive strength, flexural strength and splitting tensile strength of the concretes were not affected significantly with the use of waste steel fibers recovered from scrap tires.
4. The descending branch of the load-deflection curves obtained in bending, thus the residual strength and toughness of the concretes were modified with the use of waste fibers and the results obtained were again similar to the behavior of ordinary steel fiber reinforced concretes. The test results showed that waste steel fibers obtained form scrap tires can be used for producing steel fiber reinforced concretes.
5. Multi-objective optimization performed indicated that the use of waste fibers may become a more desirable solution for steel fiber reinforced mixtures.

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