Mechanical properties of self-compacting concrete with recycled bead wires

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Abstract
This paper investigates the properties of self-compacting concrete with waste steel bead wires obtained as a result of the separation of waste tires. Waste steel bead wires were added to concrete between 1% and 5% by weight with an increment of 1%. In total, 54 cubes, 6 cylinders and 6 beams were cast, cured and tested in according to various standards to obtain the compressive, splitting tensile and flexural strengths, respectively. In addition, 6 cubes were left in salty water solution with a salt concentration of 4% for 120 days and tested in compression. A scanning electron microscopy (SEM) was also conducted on samples after failure. Test results showed that short time corrosion of steel fibers does not affect the mechanical properties. Also, the increase in the ratio of steel fiber was found to contribute positively to the mechanical properties of concrete up to 4%, beyond which, mechanical properties were reduced. Finally, in the samples subjected to bending tests, it has been found that a 6-fold increase in bending strength compared to the reference (non-fiber) sample was achieved in case of steel fiber ratio of 4% and 5%.

Keywords: Recycling, waste steel fibers, Non-Destructive, electron scanning microscopy, self-compacting.

Introduction

All around the world, disposal of waste tire rubber causes a major environmental problem. 1.5 billion tires are approximately manufactured annually worldwide (Tiwari, Singh, & Nagar, 2016). The quantity of such 88 abandoned tires is estimated at about 1200 million by the year 2030. The total number of tires to be discarded 89 including the stockpiled tyres is estimated to be about 5000 million (Eiras et al., 2014; Shu & Huang, 2014; Siddique & Naik, 2004; Tiwari et al., 2016; Weiguo et al., 2013). The average life of a typical car tire is accepted as five years, however, this period may vary considerably depending on many factors (Weissman, Sackman, Gillen, & Monismith, 2003) . The current practice of destroying millions of tires every year by burning or storing them is not acceptable as it leads to serious ecological problems. For the last decade, the construction sector aims to ensure sustainability by researching more environmentally friendly raw materials and recycling of waste materials. In recent years, increased work on the recycling of waste materials(Çimen, Saltan, & Keskin, 2015; Erdogmus, 2014) (Centonze, Leone, & Aiello, 2012; Gabor, Agnes, & Sandor, 2018; Gesoğlu, Güneyisi, Khoshnaw, & İpek, 2014; Mohsen, Saeed, Abolfazl, & Mana, 2017; Shu & Huang, 2014; Son, Hajirasouliha, & Pilakoutas, 2011; Thomas & Gupta, 2016) has accelerated the process. From these waste materials, in particular, the contribution of the steel fibers, on which researchers have been working on over the last 20 years, to concrete has revealed that it significantly improves mechanical properties and impact strength of concrete (Afroughsabet, Biolzi, & Monteiro, 2018; Babayev, Gürbüz, & Anadut, 2017; Djelloul, Menadi, Wardeh, & Kenai, 2018; Kim, Kim, Ha, & Kim, 2007; Koksal, Gencel, Unal, & Durgun, 2012; Koksal, Sahin, Beycioglu, Gencel, & Brostow, 2012; Köksal, Yiğit, Yerlikaya, & Şahin, 2005; Koroglu & Ozdoner, 2016; Sengul, 2016; Wang, Wu., & Li, 2000; Yavuz, Güler, Korkut, & Türkmenoğlu, 2016; Zhang & Li, 2012). In the last decade, steel wires from waste tires obtained from economical, innovative, environment-friendly industrial recyclable waste tires have been the interest of researchers (Bdour & Al-Khalayleh, 2010; Bjegovic, Bariceviv, & Lakusic, 2012; Domski, Katzer, Zakrzewski, & Ponikiewski, 2017; Koroglu, 2016, 2018). In addition, limited numbers of studies have been conducted on the behavior of concretes in salty environments (Babayev, 2016; Yüzer, 1998).

In this study, the effect of adding steel wires obtained from waste car tires to self-compacting concrete on mechanical properties of the concrete and how the mechanical properties will change when exposed to salty water were examined. In addition, the adherence of waste wires to concrete was examined in micro-dimension by taking SEM images.

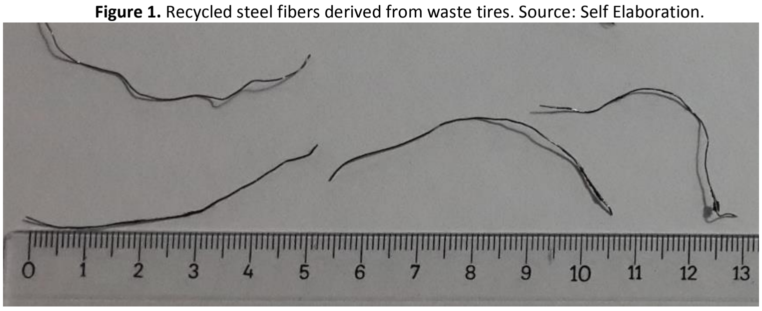
In all samples prepared, crushed sand (0-4 mm) was used as fine material and crushed stone (4-8 mm) was used as coarse aggregate. The maximum aggregate size used in the study was chosen as 8 mm. Dry unit volume weights saturated specific gravity and water absorption rates of the aggregates were calculated and given in Table 1. The aggregate content used in all samples was the same.

Table 1. Grain density and water absorption test results of aggregates. Source: Self Elaboration.

Aggregate	Dry unit weight (g/m^3)	Saturated unit weight (g/m^3)	Water absorption ratio (%)
0-4 mm	2.64	2.75	2.1
4-8 mm	2.61	2.63	0.9

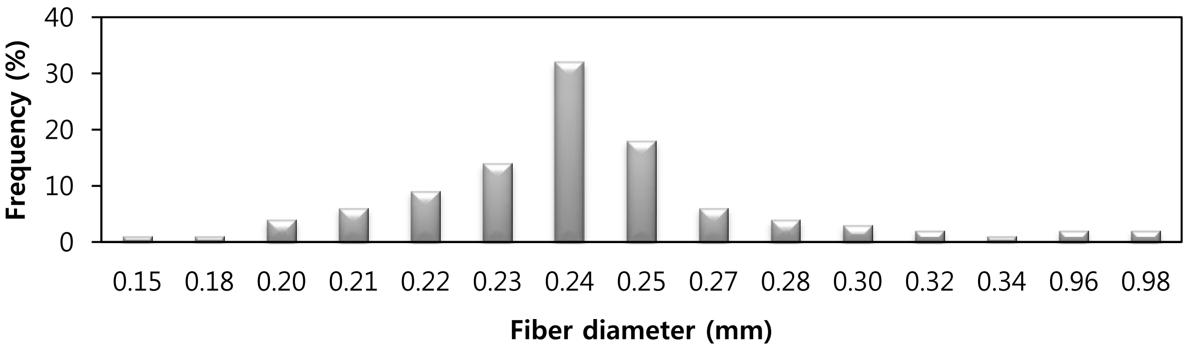
Recycled steel wires produced from waste tires used in the study were obtained from a licensed recycling company located in Konya. The supplied waste wires have quite different diameters, lengths and even shapes (Figure 1).

Figure 1. Recycled steel fibers derived from waste tires. Source: Self Elaboration.



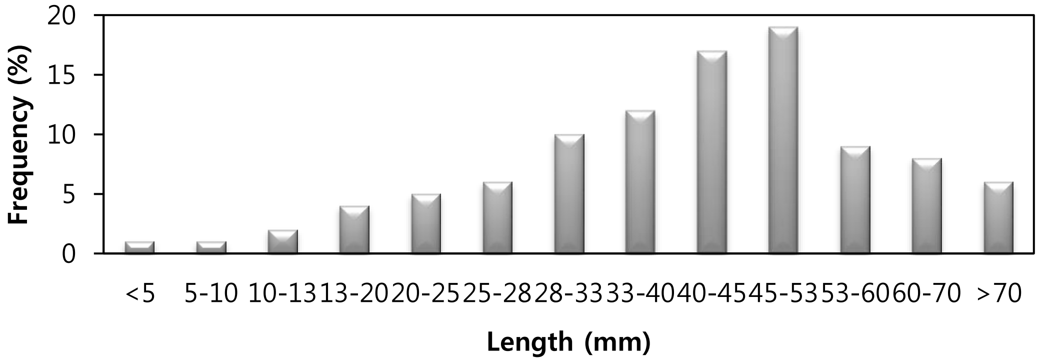
Detailed characterization was performed (Figures 2 and 3) by cleaning steel wires first then measuring the length and diameter of the randomly selected 900 samples of steel wire. It was determined with the micrometer measurement that selected steel wire diameters range from 0.15 to 0.98 mm. Also, as shown in Figure 2, it was determined that the selected steel wire diameters were stacked between 0.22-0.27 mm.

Figure 2. Frequency distribution of recycled steel fibers diameter measurements. Source: Self Elaboration.



The length of the selected waste wires was measured with the help of caliper. Figure 3 shows the distribution of wires according to their length; it is seen that the average distribution of wires varies between 30 mm and 60 mm.

Figure 3. Frequency distribution of measured fiber lengths. Source: Self Elaboration.



Determination of tensile strength of steel wires obtained from waste tires was carried out and microscopic images of wires were also obtained from the central laboratory of the existing university. The tensile tests were performed with an electromechanical dynamometer Instron machine in a displacement controlled way. Tensile tests were carried out by holding three randomly selected steel wires from the beginning and end. The average strength of steel wires is calculated as 2134 MPa as a result of the applied force being divided by the cross-sectional area.

CEM I 42.5 R cement was used in all test specimens. The cement content is the same in all concretes. Cement initial set is between 135-205 min. The specific surface area is 3000 cm^2/g and the specific gravity is 3.15 g /cm^3. Chemical analysis results of cement are given in Table 2.

Table 2. Chemical analysis of Portland Cement CEM I 42.5 R. Source: Self Elaboration.

Chemical composition (%)								
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Cl
19.70	4.97	3.58	64.25	0.91	0.17	0.77	2.65	0.011

Basic ingredients of concrete used for the production of test samples are water, cement, fine and coarse aggregate, steel wires and super plasticizer. Self-compacting concrete was produced by mixing in an open-air concrete mixer of 0.25 m^3 capacity. Firstly, CEM I 42.5 R cement was added to the concrete mixer with fine and coarse aggregates. After 60 sec dry mix, determined amount of water was added slowly to obtain a homogeneous mixture. In order to determine the amount of water is needed to make the aggregate in saturated surface dry state, mechanical properties of aggregates was determined before. Later, the super plasticizer is added to enhance the concrete workability. Lastly, the concrete formed by adding recycled waste steel wires with the proportion of 1%, 2%, 3%, 4% and 5% as weight were taken into the molds. Mixture ratios of the prepared concrete are given in Table 3.

Table 3. Concrete mix proportions. Source: Self Elaboration.

Cement (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Super plasticizer (kg/m^3)
480	200	1396	404	32

In order to determine the workability of fresh concrete flow-table tests were performed. Flow-table test results on self-compacting concretes based on the amount of recycled waste steel wire are shown in Table 4.

Table 4. Flow table test results of self-compacting concrete. Source: Self Elaboration.

Concrete Type	Slump Flow (mm)
K-0 (0% fiber)	680
K-1 (1% fiber)	610
K-2 (2% fiber)	530
K-3 (3% fiber)	480
K-4 (4% fiber)	420
K-5 (5% fiber)	340

As shown in Table 5, the increase in the amount of waste steel wire in concrete decreased the flow diameter of concrete.

For the determination of the mechanical properties of hardened concrete, 54 cubes of 100x100x100 mm size, 6 cylinders of 100x200 mm size and 6 prismatic samples of 100x100x400 mm were produced. The produced concrete was taken to the curing pool and kept until the experiment time. In addition, 6 cube samples were left in a salty solution of a salt ratio of 4% for 28 days and 120 days.

After the samples taken from the curing pool on day 28 were kept for 1 day in laboratory, cube samples were subjected to uniaxial compression test, cylinder samples were subjected to tensile splitting strength test. A loading rate was applied in accordance with BS 1881-127:1990 (Institutions, 1881).

Test method, in which generally cylindrical samples are used, was applied according to ASTM C496 / C496M-04 (ASTM-C496, 1994). As shown in Fig. 4, the sample is laid on the test press in a way so that the sample axis is parallel. Pressure applied through test press is maintained in a way that loading speed is 0.016 N / mm ^{2}/se (ASTM-C496, 2011) until the sample breaks and the breaking load (P) is measured. In such loading, the refraction pattern of the cylinder sample is as splitting the sample into two parts. Tensile strength of concrete is obtained from Equation 1, below.

$$\sigma_{Ç} = \frac{2\,P}{\pi\,L\,D} \qquad (1)$$

In this equation, P is the compressive load at failure, L length of the cylinder sample, D is the diameter of the cylinder sample.

Figure 4. Splitting tensile test. Source: Self Elaboration.

Results

As a result of the experiments, the compressive strength and splitting tensile strength results of reference sample and samples with different fiber ratios are given in Table 6. Also, water absorption and density determination were made for each sample (Table 5).

Table 5. Compressive strength and splitting tensile strength results. Source: Self Elaboration.

Concrete Type	Water Absorption (%)	Density (g/cm^3)	$f_{cu}(MPa)$ Compressive Strength	$f_{ts}(MPa)$ Splitting Tensile Strength
K-0 (0% fiber)	5.11	2.16	20.29	2.71
K-1 (1% fiber)	5.24	2.22	20.18	3.14
K-2 (2% fiber)	5.50	2.41	23.93	3.82
K-3 (3% fiber)	5.58	2.47	21.15	4.16
K-4 (4% fiber)	5.49	2.49	25.60	4.84
K-5 (5% fiber)	5.93	2.58	24.35	4.86

100x100x400 mm beam samples were prepared as shown in Figure 5 for the determination of the flexural strength of concrete. The samples were loaded under two points at a distance of L/3 from supports. According to ASTM C 293(ASTM-C293, 1994) standards, the flexural strength of concrete   is calculated from Equation 2.

$$\sigma_{tp} = \frac{3PL}{2bh^2} \quad (2)$$

where P is the total applied load, L the length of the sample, b section width and h section height.

Figure 5. Test setup for performing the four point bending test. Source: Self Elaboration.

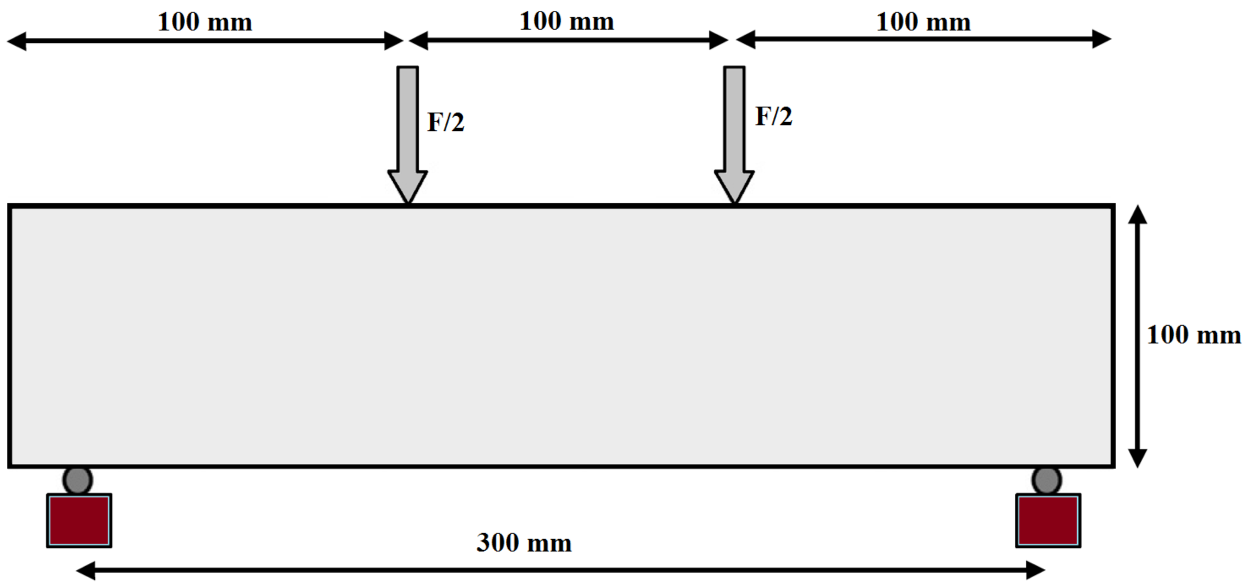
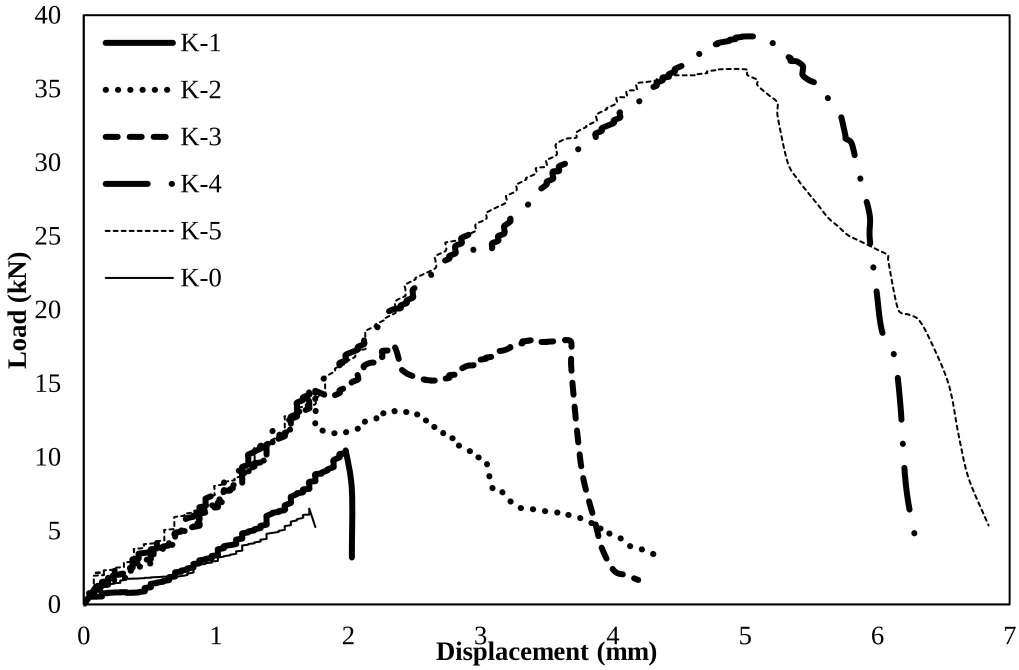


Figure 6. Load-displacement curve of each test sample. Source: Self Elaboration.



The load-displacement curve of each test sample is given in Figure 6. Figure 6 shows that an improvement in ductility of the samples was observed due to increased fiber ratio. However, after the fiber amount exceeds 4%, reduced strength and reduced energy consumption capacity were observed.

During the 4 point loading test, micro-cracking was observed in tensile region when the tensile strength of concrete matrix was reached. Steel beads stabilized the crack development until reaching the maximum load. However, fibers began pulling out from the concrete matrix when maximum load was reached. When the first pull-out failure was developed, a sudden decrease on load capacity was observed. This sudden decrease is explicit on the specimen K-2, K-3 and K-4 that can be seen in Figure 6. During macro cracks widened, fiber pull-out was developed towards the beam depth. As seen in Figure 7 because of crack development neutral axis was moved towards the compression zone of beam specimen. Therefore, the equilibrium of the beam section under the neural axis was effectively continued by fiber bridging zone that resisted fiber pullout. Finally, fibers completely pulled out that led the failure of the beam specimen. In all beam specimens, failure was observed in the moment constant zone of the beam and no fiber breakage failure was observed. Pulled out fibers on cracked face and pull-out failures on concrete matrix can be seen clearly in Figure 8.

Figure 7. Failure mechanism of concrete matrix under 4 point loading. Source: Self Elaboration.

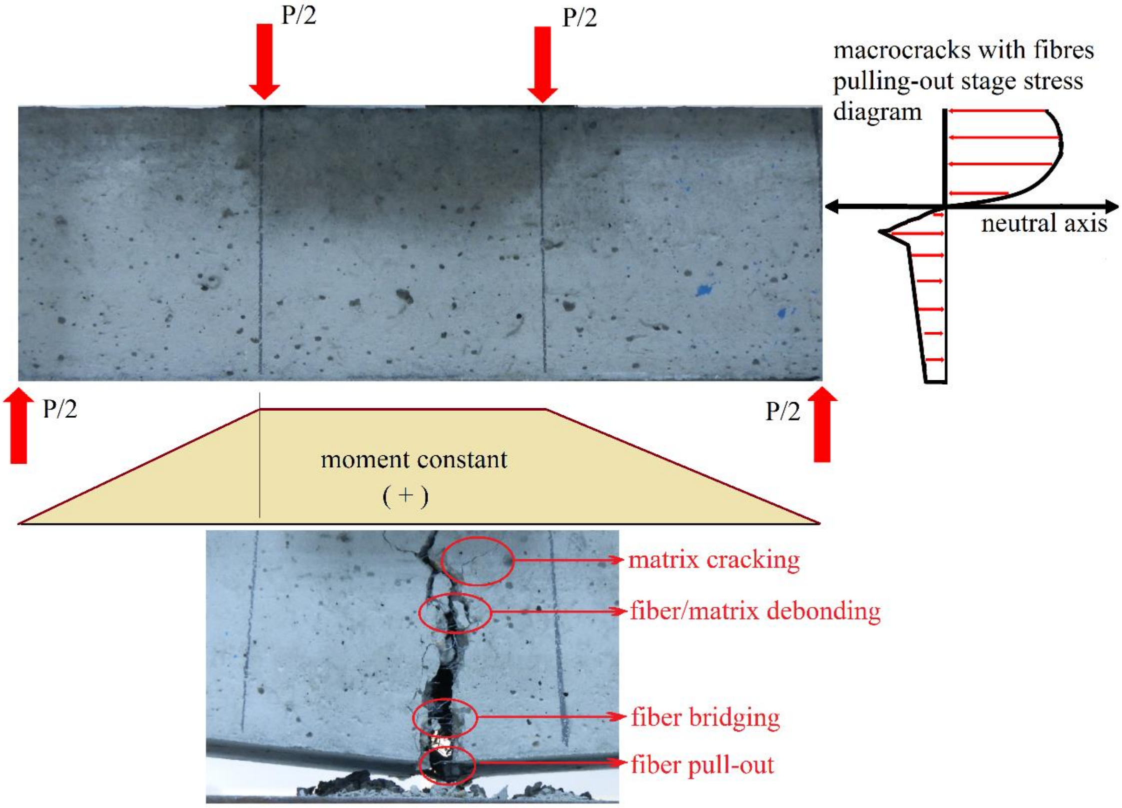
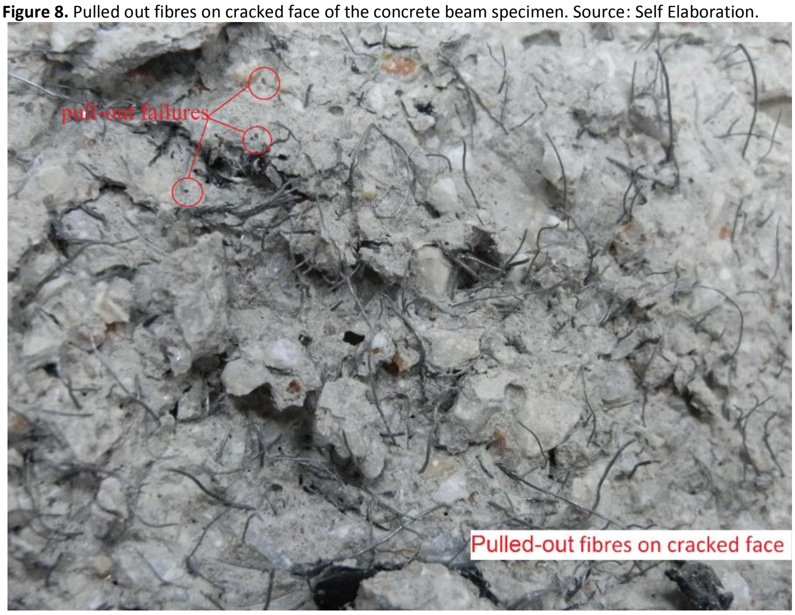
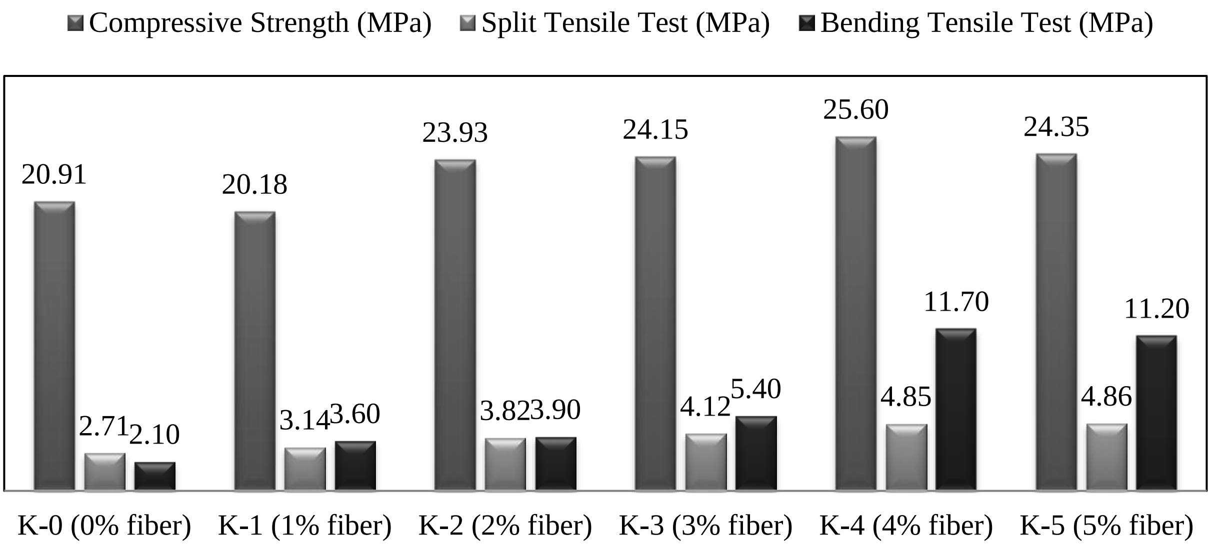


Figure 8. Pulled out fibres on cracked face of the concrete beam specimen. Source: Self Elaboration.



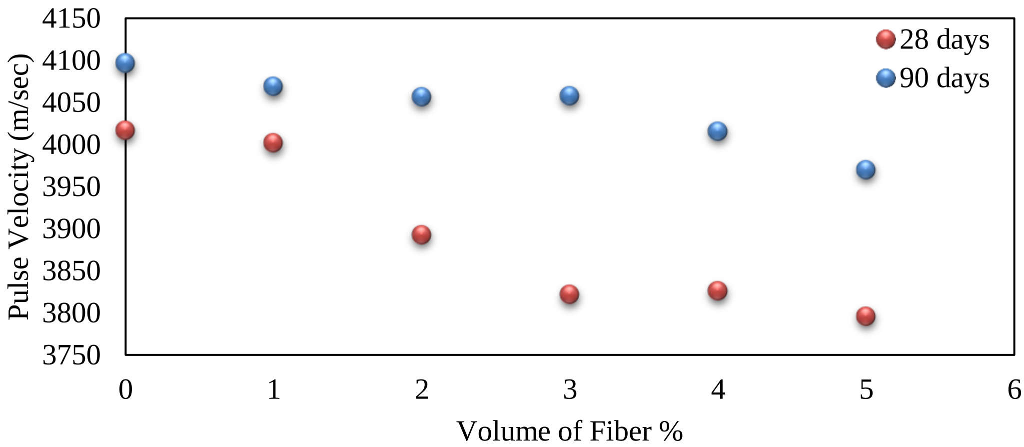
Compressive strength, bending strength and splitting-tensile strength results are shown in Figure 9. The optimum fiber ratio was realized in the sample with 4% for all three test results.

Figure 9. Compressive strength, bending strength and splitting-tensile strength results. Source: Self Elaboration.



Additionally, ultrasonic pulse velocity method which requires evaluating the travel time, over a measured path length of a pulse of ultrasonic waves is used in order to estimate the strength of concrete samples. In ultrasonic pulse velocity, test velocity is calculated as a path length over travel time (Kobaka & Katzer, 2011; Myers & Ekenel, 2007). The measurement of ultrasonic pulse velocity is applied for the 28 days and 90 days cured concrete and effect of the volume of steel fibers on Ultrasonic Pulse Velocity (UPV) for cube samples are given in Figure 10.

Figure 10. Effect of the volume of steel fibers (%) on UPV for cube samples. Source: Self Elaboration.

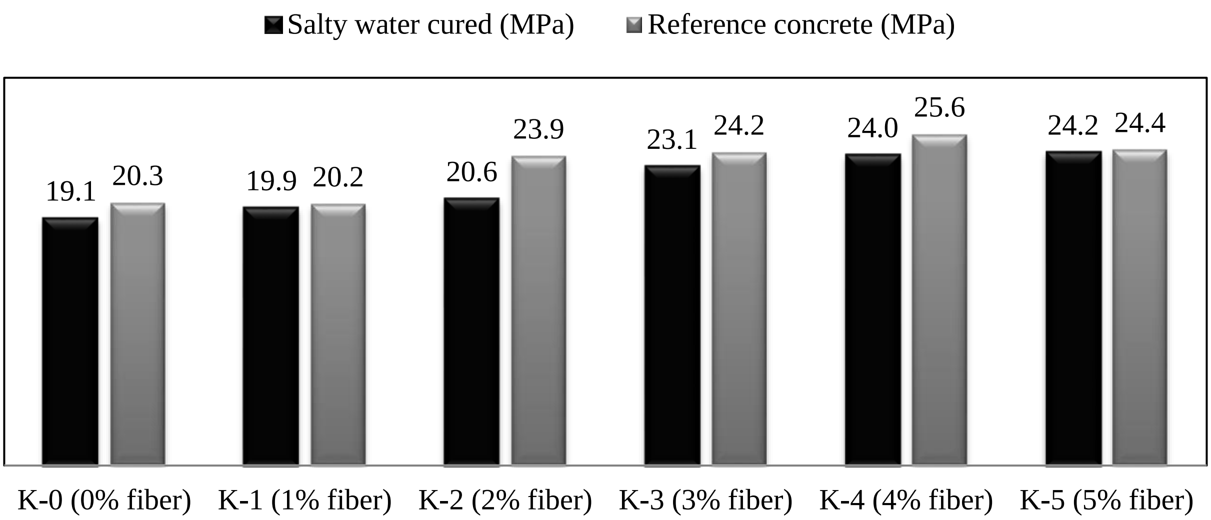


Fiber addition have not improved the UPV of cube samples unlike compressive strength of concrete. The reason is that since self-consolidated concrete were used, increased fiber addition caused more void formation which reduce the workability of the concrete matrix. Therefore, it is assumed that the speed of wave propagation reduces and lower UPV value was ensued.

In K-0, K-1, K-2, K-3, K-4, and K-5 mixtures, fiber reinforced concrete samples were kept in salty water with salt content of 4% by weight for 120 days. The material content and quantity are the same both in the samples kept in salty water and those that were cured in water. Before curing in salty water, initial stress on the cube specimens were applied. Firstly, cube specimens were cured in water for 28 days and stressed initially up to 30% of ultimate compressive load capacity. This process was applied in order to start micro cracks on concrete to initiate the corrosion development.

Micro cracks accelerate the penetration of water and chloride ions to concrete specimens, causing corrosion of steel bead wires. Every kilogram of salty water has approximately 40 grams of dissolved salt contains sodium (Na+) and chloride (Cl-) ions. After 90 days immersed in salty water, specimens were cured in room condition for 30 days to observe the corrosion of steel. For the cube specimens compression test were conducted after 120 days and the average compression test results of the samples stored in salty water are shown in Figure 11.

Figure 11. Compression test results of the samples stored in salty water. Source: Self Elaboration.



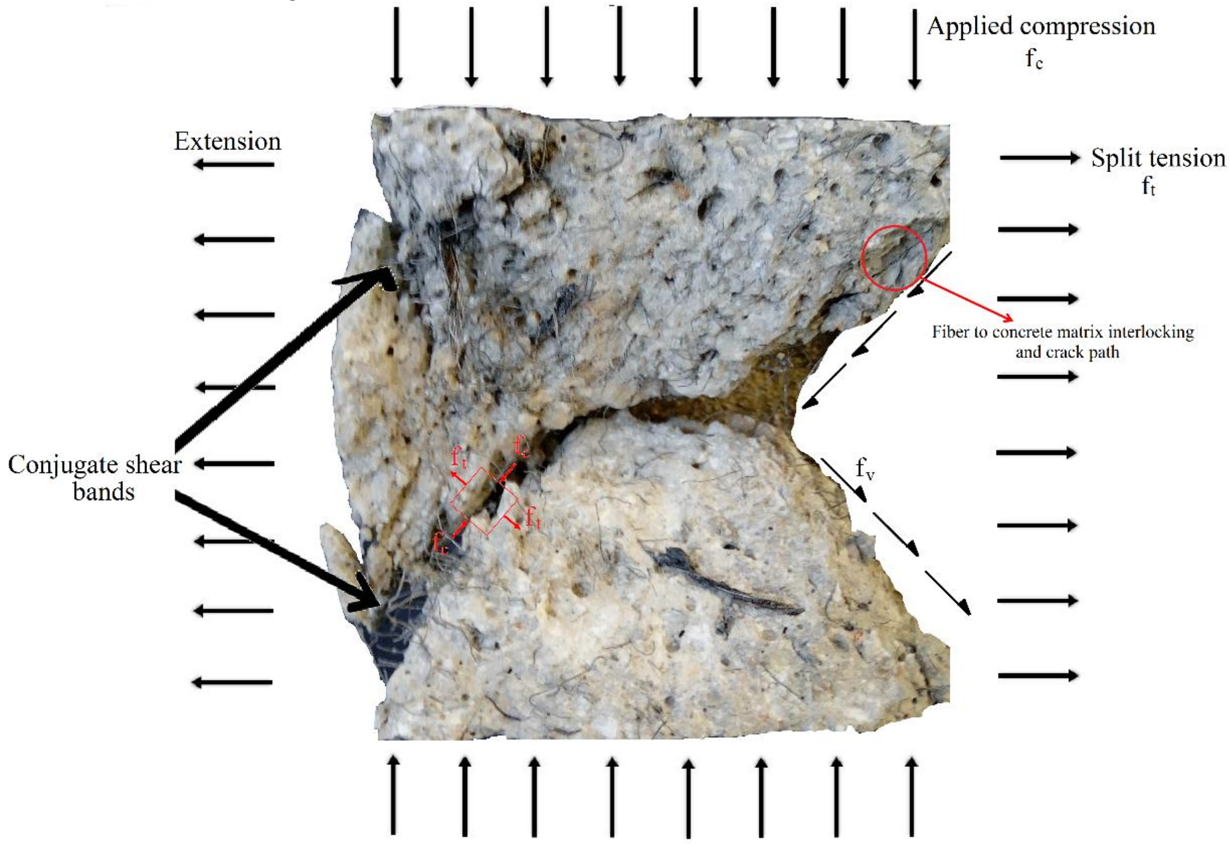
No significant decrease in the strength of concrete is observed as seen in Figure 11. When the specimens compared with that cured in salty water or cured in normal water. Corrosion of steel bead wires are concentrated on the surface of the cubes. Concrete matrix interlocking was observed between corroded steel beads and cement mortar due to increased volume of corroded steel beads. Additionally, salt particles were observed on the surface of the cubes (Figure 12).

Figure 12. Failure model of corroded steel bead concrete cube. Source: Self Elaboration.

When the failure mechanism of steel bead concrete cubes is observed under compression, it is clearly seen that the failure strength is dominantly effected by the tensile strength of dispersed phases (fibers). Even under compression loading, failure mechanism of the concrete specimens was caused by reaching the principal tensile strength of concrete matrix causing a shear failure on the shear band. The strength of composite concrete was increased by adding steel beads in the concrete matrix. The increase of compressive strength can be explained by fiber reinforcing mechanism that while aggregate particles carry the axial loading, fibers and aggregates were interlocked because of compressive loading. During the increase of axial loading, the interlock and friction between the particle and fiber has become stronger while splitting tension was withstand both by the friction and the bond between steel beads and cement paste.

And finally, fiber-aggregate-binder interlock mechanism was broken after reaching the principal tensile strength of concrete and pull-out of steel beads resulted the fracture of steel bead reinforced concrete (Figure 13).

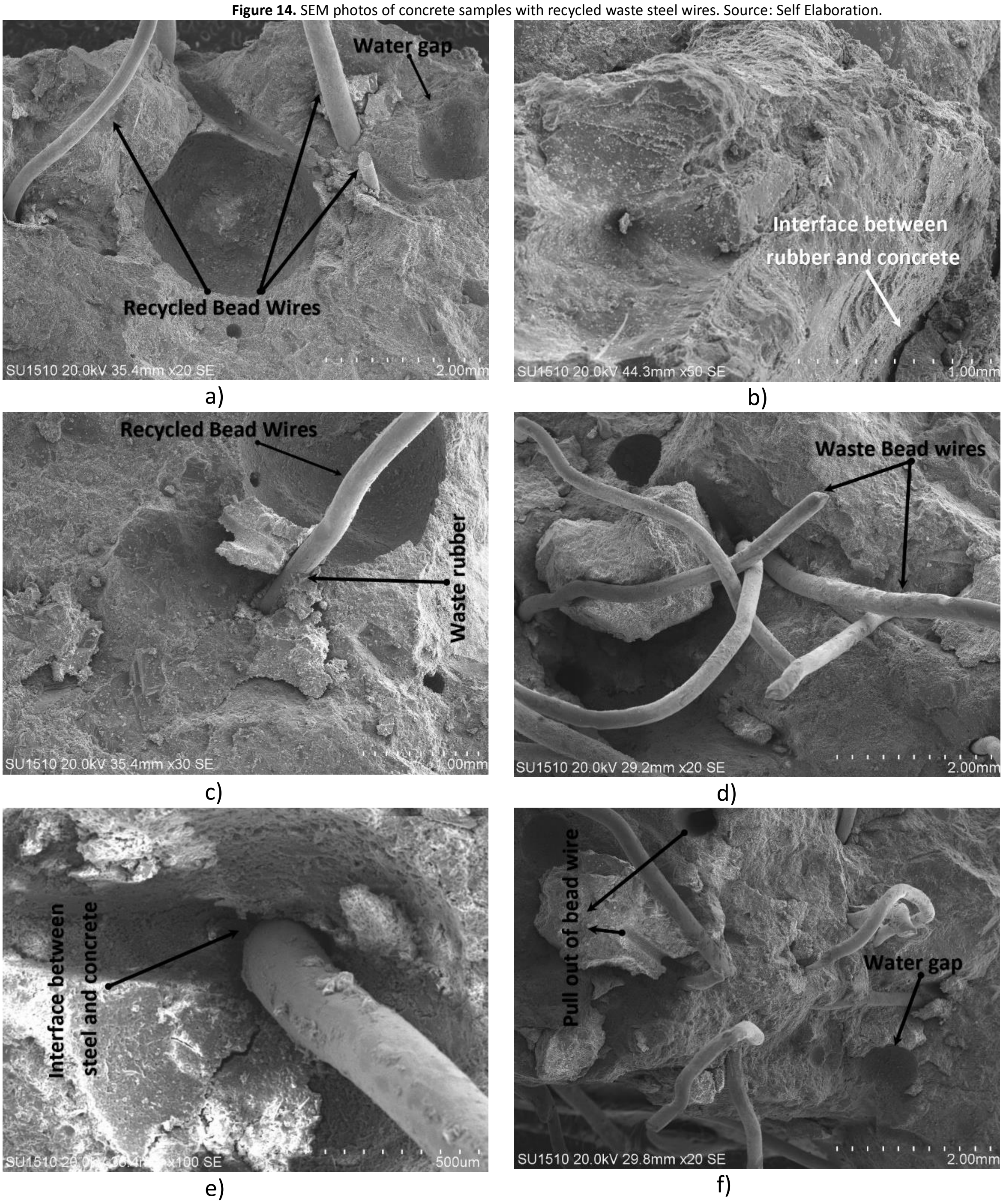
Figure 13. Failure mechanism of corroded steel bead concrete cube. Source: Self Elaboration.



Microscopic SEM analysis of the concrete samples in which recycled waste steel wires were used and which were cured in normal water for 28 days are shown in Figure 14. As shown in Figure 14.a, there is no breakage in steel fibers and a pull-out is seen in the fibers. Part of waste rubber and interfacial crack between concrete are seen in Figure 14.a and Figure 14.b. it is observed that steel fibers are deformed and pulled out of steel fibers are occurred but no failure is occurred on steel fibers. Dislocations on the steel fibers and concrete interface occurring under bending loads can be seen in Figure 14.b.

The distortion of the steel fiber matrix interface under loading can be seen in Figure 14.c. It can be assumed that, delay of this distortion decreases ductility while increasing bending strength. The distortion of the steel fiber matrix interface is seen in detailed SEM photo in Figure 14.d. Delay of this distortion increases fracture toughness. However, energy dissipation capacity reduces under bending loads. Pull-out surface and water gaps can be seen clearly in Figure 14.e. Stiffness of deformed steel fibers is broken at cracked edges and stripped. Dense chemical bond between steel fiber and matrix is seen in Figure 14.f.

Figure 14. SEM photos of concrete samples with recycled waste steel wires. Source: Self Elaboration.



Conclusions

In this paper, an experimental study was carried out in order to evaluate the mechanical properties of self-compacting concrete with recycled bead wires. The effect of exposure of self-compacting concrete with recycled bead wires to salty water were also examined. The following conclusions can be drawn on the basis of results of experimental studies.

- As the proportion of fiber added into concrete increases, higher compressive strength, splitting tensile and bending strengths were obtained.
- Optimum fiber ratio was determined as 4% beyond which the amount of fiber added to concrete negatively affected the mechanical properties of concrete.

- Test studies show that excess fiber added in concrete reduced the workability of concrete and reduced flow diameter in flow table test.

- No significant decrease was observed in the strength capacity of steel fiber concretes kept in salty water for 120 days despite the decrease in the strength of the concrete by being damaged due to the effect of salt.

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