Case Studies in Construction Materials 11 (2019) e00259

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Mechanical performance of concrete made of steel fibers from tire waste

S.M Samindi M.K Samarakoon[a,*], Pål Ruben[a], Jørgen Wie Pedersen[a], Luis Evangelista[a,b]

[a] Department of Mechanical and Structural Engineering and Materials Science, University of Stavanger, Norway
[b] Instituto Superior de Engenharia de Lisboa (ISEL-IPL), Lisbon, Portugal

ARTICLE INFO

Article history:
Received 4 February 2019
Received in revised form 31 May 2019
Accepted 7 June 2019

Keywords:
Recycled steel fibres
Manufactured fibres
Tire waste
Mechanical properties

ABSTRACT

Currently, the disposal of used tires is a worldwide challenge, due to their non-degradability. Therefore, recycling has become a potential solution for managing such waste. During recycling, materials such as rubber and steel are recovered from the used tires. The use of steel fibres, recovered from tire waste, as a raw material to reinforce concrete is an environmentally friendly and economically viable solution to manage the end-products of tire recycling. Few studies have been carried out to study the behaviour of fibre-reinforced concrete made using steel fibres recovered from tire waste. However, it has been found that there is the potential to reuse steel fibres recovered from tire waste (RF) as an alternative building material to manufactured steel fibres (SF). Nevertheless, more research is needed to verify that the structural performance of recycled fibre reinforced concrete (RFRC) is similar to that of manufactured fibre reinforced concrete (SFRC). Therefore, this study focuses on the laboratory testing of the mechanical properties of RFRC and compares them with those of SFRC. Moreover, the flexural performance of reinforced concrete beams cast with RF and SF have been tested to compare their performance.

1. Introduction

Currently, worldwide every year, about one billion tires end their service life; more than 50% of these are discarded, mainly by burning or landfilling, without any treatment [1]. These tires can be recycled or reused as fuel in cement kilns, as building material in asphalt pavements or as aggregates in concrete. When the used tires are recycled, the steel fibres in tire waste can be recovered from shredding, cryogenic or pyrolysis processes [2]. During the recovery of material from the recycling of used tires, more than 500,000 tonnes of steel fibres could be recovered annually in Europe [2]. Hence, it is important to find an economical and environmentally friendly solution to manage the recycled steel fibres recovered from tire waste.

In general, manufactured steel fibres (SF) are used to reinforce concrete structures. The fibre reinforced concrete improves the mechanical properties (i.e. tensile strain capacity and ductility) and controls crack propagation by bridging the cracks and transmitting tensile force across them to enhance the post-cracking tensile behaviour. According to the research findings, there is the potential to reuse recycled steel fibre from tire waste (RF) as an alternative building material to

* Corresponding author.
E-mail address: samindi.samarakoon@uis.no (S.M.S.M.K. Samarakoon).

https://doi.org/10.1016/j.cscm.2019.e00259

manufactured steel fibres (SF) [2–5]. In addition, the cost of RF (i.e. approximately 150 euro/ton) is ten times less than that of SF (i.e. approximately 1500 euro/ton) [6]. Therefore, the use of RF in concrete can also be an attractive economical solution.

However, it is vital to verify that the performance of recycled fibre reinforced concrete (RFRC) is similar to that of manufactured steel fibre reinforced concrete (SFRC) and is within a satisfactory level. Little research has been carried out to study the mechanical properties of RF and post-cracking behaviour. There are no or very few studies on the flexural behaviour of reinforced beams made of RF concrete. Therefore, it is crucial to carry out further research on the behaviour of RFRC. This study focuses on the possibility of using steel fibre recovered from the shredding process to replace SF. Laboratory experiments have been carried out to determine the mechanical properties of RFRC and to study the flexural behaviour of reinforced concrete beams made of RFRC and to compare it with that of reinforced concrete beams made of SFRC.

2. Research on use of steel fibres recovered from tire waste in concrete

According to previous research findings, steel fibres recovered from the recycling of tire waste have the potential to be used as a material to prepare fibre reinforced concrete [2, 3 and 4]. Moreover, experiments have been carried out to find the mechanical properties of RFRC: its compressive strength [4,6,7 and 18], flexural strength [3,4] and pull-out behaviour [3]. A summary of the experiments is given in Table 1.

Based on the experimental findings, some authors [7,18] indicated that the compressive strength could be even smaller after addition of RF. On the other hand, some other authors [3,4] indicated that there is an increase of compressive strength but it is not significant. For instance, Aiello et al. [3] found that the pull-out behaviour of RF is similar to that of SF and that there is no significant change in compressive strength due to different fibre dosage. However, Aiello et al. [3] has found a slight increase of compressive strength with increasing the dosage of RF and SF when the same water quantity has been maintained in the concrete mixtures. This finding could be endorsed by Yazici et el [19]. and Atis and Karahan [20] who have observed increase of compressive strength in SRFC while increasing the dosage of SF. Moreover, this phenomenon could be explained by the effective contribution given by the confinement of the fibre reinforcement on the specimen which delay the material failure. However, it is vital to test larger number of specimens to validate the increase of compressive strength in RFRC. In addition, it could be observed a reduction in compressive strength after addition of steel fibres due to the physical difficulties in providing a homogeneous distribution of steel fibres within concrete [21].

According to the findings of Bjegovic et al. [6] and Papakonstantinou and Tobolski [7], the modulus of elasticity of concrete has not been significantly increase while increasing the dosage of RF. Leone et al [18] has observed that splitting tensile strength of RFRC and SFRC have slightly decreased compared with reference concrete. Hu et al. [4] studied the flexural performance of RFRC and compared it with that of concrete made up of manufactured fibres. In addition, they found no variation in the average compressive strength due to different fibre dosage. Papakonstantinou and Tobolski [7] found that concrete mixtures with steel beads recovered from tire waste were more workable when the fibre content was less than 4%. Moreover, there was no significant reduction in the compressive strength when the fibre dosage was less than 2%. Considering the above fact, in this study, a steel fibre dosage of 0% to 1% by volume has been selected.

Most of the current research has been carried out to compare the behaviour of RF with that of normal concrete without fibres, and very few studies compare the mechanical performance of RFRC with that of SFRC. Therefore, more research is needed to verify that the performance of RFRC concrete is similar to that of SFRC concrete. In spite of being clear that SF perform mechanically better than RF, the analysis of these materials has to be considered also in an environmental footprint standpoint. And it is possible that the somehow weaker performance of RF can be largely compensated by its Life Cycle Assessment.

Hence, the experimental work discussed in this paper is aimed to study the mechanical properties of concrete reinforced with steel fibres recovered from tire waste, in terms of fresh concrete properties (i.e. slump/flow board, density, air content) and hardened properties(i.e. compressive strength, tensile strength, secant modules of elasticity and fracture properties). Furthermore, the flexural behaviour of reinforced concrete beams made of RFRC are compared with that of reinforced concrete beams made of SFRC.

Table 1
Testing of RFRC.

	Length of fibres/diameter	Dosage of fibre	Testing
Aiello et al. [3]	15 mm – 25 mm 0.17 mm – 0.2mm	0.13%–0.46% by volume	Compressive strength, pull-out test, flexural strength test
Hu et al. [4]	15 mm – 40mm Average 0.1 mm	10 kg/m^3–30 kg/m^3	Compressive strength, pull-out test, flexural strength test
Bjegovic et al. [6]	Less than 15 mm 0.2mm	15 kg/m^3–30 kg/m^3	Compressive strength, modulus of elasticity, slump test, density
Papakonstantinou and Tobolski [7]	20 mm to 60mm 0.3mm – 1.3mm	2% to 8% by volume	Compressive strength, splitting tensile strength, toughness, modulus of elasticity, density
Leone et al [18]	1-13 mm 0.10 mm -0.45 mm	0.46 % by volume	Compressive strength, tensile strength, flexural strength, toughness, shear strength

3. Material and methods

3.1. Properties of RF

3.1.1. Aspect ratio

The aspect ratio can be defined as the fibre length divided by an equivalent fibre diameter. A typical aspect ratio ranges from about 30 to 150 for lengths of 6 mm to 75 mm [8]. According to previous research, the fibres with a larger aspect ratio showed better efficiency in improving the flexural response. In this study, 100 RF were grabbed randomly and the length and the diameter of each fibre was measured. A variation in diameters of 0.25 mm to 1 mm was found. The variation of lengths was 20 mm to 65 mm. The aspect ratio of each fibre was calculated, and the frequency of occurrence of the aspect ratio is given in Fig. 1. According to Fig. 1, the mean value of the aspect ratio is about 100, and standard deviation is 37.47.

3.1.2. Density of RF

Most of the previously published literature has considered the density of RF as the same as that of the SF, assuming that the RF are free from impurities/tire particles or that separation of impurities/tire particles from the RF has taken place before mixing with concrete. During this study, RF received from Ragn-Sells Dackåtervinning AB, Sweden, were used without any separation of impurities/tire particles. Therefore, the density of RF with impurities/tire particles was estimated as an average value of 3014 kg/m^3.

3.1.3. Steel content in RF

The steel content of the RF was determined through pyrolysis. To perform the pyrolysis, initially, three fibre samples were dried, to make sure that the weight of any moisture did not interfere with the results from the test. The samples were dried overnight in a drying cabinet at 100 degrees Celsius and weighed again before commencing the pyrolysis. Heating the material up to 600 degrees Celsius without any access to oxygen meant that, aside from steel, most of the material would evaporate or turn into finer particles, which would be sucked out of the oven by the extractors, leaving only ash behind. By setting the oven to 600 degrees, the burning of the nylon fibres was ensured, as it would turn to ash at temperatures around 500 degrees Celsius [9]. At this temperature, the rubber was also certain to incinerate, with an ignition temperature of 316 degrees Celsius. The pyrolysis was performed three times, one for each sample. After the pyrolysis, the steel was quite easily extracted from the rest of the materials by using a magnet to lift them up, while shaking them lightly, so that the ash and other burnt particles would drop off. The steel was weighed, and, by dividing by the initial weight of the fibres, the percentage of steel content and other materials could be determined. It was found to be about 91% steel and 9% impurities.

3.1.4. Tensile strength of steel fibres

Tests were conducted to estimate the tensile strength of the recycled steel fibres. The chosen sample consisted of 20–30 fibres of different shapes and different diameters and lengths. It was difficult to obtain a representative average value for the tensile strength of RF. The variation of tensile strength of the measured fibres lies in the range of 400–1600 MPa. The average value is 870 MPa and the standard deviation of 584 MPa. The large dispersion of results may be due to local damage in the RF induced during tire shredding through plastic deformation of the steel mesh.

3.2. Properties of SF

Manufactured steel fibre (type: DE 35/0.55 N) with end hooks was used in this study to compare the results with RF. Table 2 gives the density, length, diameter and tensile strength of SF fibres. Fig. 2 shows pictures of recycled fibres and manufactured fibres.

As it can be seen in Table 2, the main differences between SF and RF is their density, tensile strength and aspect ratio, being that the latter two properties have direct influence over mechanical performance.

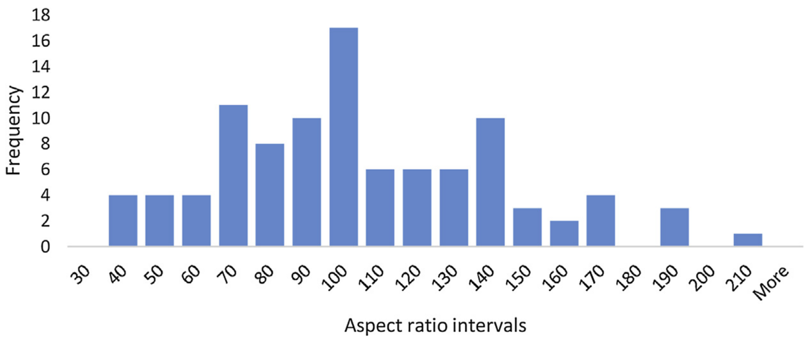


Fig. 1. Histogram of the aspect ratio for RF.

Table 2
Properties of RF and SF (Note: S.D. refers to standard deviation).

Properties	RF	SF (Steel fibre DE 35/0.55 N)
Average density (kg/m^3)	3014	7200
Average length (mm)	37 (S.D. 11.8)	35
Average diameter (mm)	0.42 (S.D. 0.33)	0.55
Mean aspect ratio (L/d)	100 (S.D. 37.47)	63.5
Average tensile strength (MPa)	870 (S.D. 584)	1250

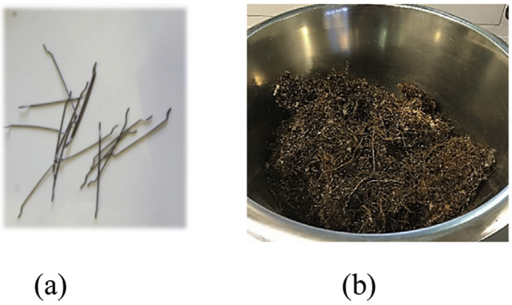


Fig. 2. (a) Manufactured steel fibres (b) Sample of recycled fibres from tire waste.

3.3. Proportioning of concrete mixture

Five concrete mix designs were prepared using the Particle-Matrix model [10] method. The aggregate consisted of 8/16 mm aggregates supplied from Velde, Norway, and 0/8 mm sand from Årdal, Norway. Standard fly ash CEM II of 42.5 MPa strength was used. Superplasticizer Dynamon SX-N was used to improve the workability of the concrete. Both recycled and manufactured fibres of 0%V, 0.5%V and 1%V were considered in this study. The final mix design is given in Table 3. Moreover, 0% RC refers concrete mixture without fibres or Reference concrete. Likewise, 0.5% RFRC and 1% RFRC refers concrete with recycled fibre content 0.5% and 1% by volume respectively. 0.5% SFRC and 1% SFRC refers concrete with manufactured fibre content 0.5% and 1% by volume respectively.

A concrete mixer with a capacity of around 200 litters was used to prepare the five concrete mixtures given in Table 3. Initially, dry materials were mixed together, starting with aggregate, followed by sand, cement and fibre. The RF were tangled together; therefore, they were separated by hand before adding to the mixture. All the dry materials were mixed for one minute before water was added. After mixing for another minute, the superplasticizer (i.e. Dynamon SX-N) was added. The process continued with blending in the admixture for two minutes, before giving it a two-minute rest period. Finally, there were three extra minutes of mixing, completing the mixing phase.

3.4. Properties of fresh concrete

Fresh concrete properties have been evaluated in terms of slump/flow, density and air content and are given in Table 4. The slump test was carried out according to NS-EN 12350-2: Testing fresh concrete, Part 2: Slump-test [11]. The density was estimated using NS-EN 12350-6: Testing fresh concrete, Part 6: Density [12]. The air content in concrete was found using NS-

Table 3
Composition of concrete mixtures in 1 m^3.

	Concrete Mixtures				
	0%RC (Mix I)	0.5%RFRC (Mix II)	1%RFRC (Mix III)	0.5%SFRC (Mix IV)	1%SFRC (Mix V)
Cement (kg)	329	325	329	329	329
Gravel (8 mm/16 mm) (kg)	833	830	821	827	821
Sand (0/8 mm) (kg)	1033	1023	1008	1033	1025
Water (kg)	177	172	187	169	170
Dynamon SX-N (kg)	3	3	3	3	3
Steel fibres (recycled) (kg)	–	15	30	–	–
Steel fibres (manufactured) (kg)	–	–	–	39	78

Table 4
Properties of fresh concrete.

	0% RC	0.5% RFRC	1% RFRC	0.5% SFRC	1% SFRC
Slump (mm)	Not applicable	215	183	165	50
Flow (mm)	535	430	385	358	205
Density (kg/m^3)	2360	2400	2320	2360	2370
Air content (%)	0.3	1	2.5	2.1	2.6

EN 12350-7: 2009: Testing fresh concrete, Part 7: Air content pressure methods [13]. The air content was measured immediately after completing the mixing phase.

According to the results, it can be seen that the slump of the concrete mixture is significantly decreased when increasing the fibre content. However, the slump of the reference mixture was not able to be measured because of flowing of 0% RC concrete mixture. In addition, the density of fresh concrete does not differ significantly among all the mixtures. It can also be seen that the air content significantly increases by 1.5% while increasing fibre content from 0.5% to 1% in RFRC. However, it has not been observed a significant (i.e. 0.5%) increase of air content while increasing fibre content from 0.5% to 1% in SFRC. The recycled fibres have been tangled and contaminated with scrap rubber particles which may be led to increase significantly the air content. On the other hand, it seems that air content increases linearly with the increase of RF.

3.5. Properties of hardened concrete

After the curing of the specimens (i.e. covering each specimen with plastic sheets at 20^{0}C), the compressive strength, splitting tensile strength and modulus of elasticity were estimated. The compressive strength test was performed after 28 days of casting for a cube of 150 mm X 150 mm X 150 mm, according to NS-EN 12390-3 [14]. After 42 days of casting, the secant modulus of elasticity was estimated using NS-EN 12390-13 [15] for cylindrical specimens of 300 mm X 150 mm. The splitting tensile strength was estimated according to NS EN 12390:2009 [16] for concrete cylinders of 300 mm X 150 mm. The average values of specimens are given in Table 5, as well as the variation of mechanical performance relative to the reference concrete (Δ_{RC}), as well as the variation measured between SFRC and RFRC having the same amount of fibres ($\Delta_{RF/SF}$). According to the results, it can be seen that the secant modulus of elasticity has not changed significantly due to the addition of fibres.

As it can be seen in Table 5, the use of fibres led to an increase in compressive strength relative to the reference concrete between 4.8 and 20.2%, being that SF were generally more effective. Comparing the compressive strength between RFRC and SFRC, it was possible to see that there was a decrease of about 11% and 6%, for the 0.5%V and 1.0%V, respectively. In terms of splitting tensile strength, RFRC show an increase in resistance of 18.3 and 14.2% over RC, for 0.5%V and 1.0%V incorporation ratios, respectively. When compared to SFRC, RFRC shows a loss of performance over about 10% and 16%, respectively. Nevertheless, these results show that it is viable to include RF in concrete and achieving increased performance, especially for tensile strength, the main benefit obtained from fibres.

In this study, the air content was measured immediately after completing the mixing phase. Then, after casting of samples, a mechanical vibrator was used to expel entrapped air in samples with CF. Therefore, expelling of trapped air may contribute to an increase of the compressive strength. Moreover, for the specimens without SF and RF a sudden ejection of materials was observed at the collapse, while for RSFRC a more ductile collapse was observed similar to findings of Aiello et al. [3]. This confirms that the effect of confinement may be able to reduce transversal deformation of specimen and increase its compressive strength.

Table 5
Properties of hardened concrete.

Average values	0% RC	0.5% RFRC	1% RFRC	0.5% SFRC	1% SFRC
Initial secant modulus of elasticity (GPa)	20.6	21.3	21.2	22.3	22
Stabilized secant modulus of elasticity (GPa)	25.5	26.7	25.5	26.6	26.7
Δ_{RC} (%)	–	3.4	2.9	8.3	6.8
		4.7	0.0	4.7	4.7
$\Delta_{RF/SF}$ (%)	–	−4.5	−3.6	–	–
		0.4	−4.5		
Compressive strength (MPa)	29.2	30.6	32.9	34.3	35.1
Δ_{RC} (%)	–	4.8	12.7	17.5	20.2
$\Delta_{RF/SF}$ (%)	–	−10.8	−6.3	–	–
Splitting tensile strength (MPa)	2.18	2.58	2.49	2.86	2.97
Δ_{RC} (%)	–	18.3	14.2	31.2	36.2
$\Delta_{RF/SF}$ (%)	–	−9.8	−16.2	–	–

3.6. Fracture properties of RFRC and SFRC

The fracture behaviour of concrete with fibres was studied using the wedge splitting test, as given in NT Build 511 [17]. The experiment set up was shown in Fig. 3(a) and (b). Cubes with specimen sizes of 150 mm × 150 mm × 150 mm were prepared according to NT Build 511. However, during this testing, instead of the water curing recommended in NT Build 511, the specimens were covered with plastic sheeting after casting and kept under 20^{0}C. Three specimens from each concrete mixture were prepared for the test. A vertical load was applied at a constant rate of 0.15 mm/min. Both the vertical loading 'Fv' and the crack mouth opening displacement (CMOD) were monitored during the test with a frequency of 10 Hz. During the tests, the vertical force (F_v) and CMOD were recorded. Fig. 3 shows the variation of the vertical force vs. CMOD in a set of samples.

The horizontal force or the splitting force (Fsp) can be estimated using Eq. (1), as given below:

$$F_{sp} = \frac{F_v}{2 \cdot \tan(\alpha)} \tag{1}$$

Where

'F_V' is the vertical force and 'α' is the angle of the wedge device (shown in Fig. 3(b)).

Using Eq. (1), 'Fsp' is estimated and Table 6 shows the average values of horizontal and vertical force.

As it can be seen in Fig. 4, the presence of fibres, regardless of their type increases greatly the strain energy of the concrete, with larger CMOD and peak load, for the 1.0%V SFRC family. This is related to the bridging capacity of the fibres, which is more prominent for those with specific anchorage systems, such as the ones used in this research. The RFRC specimens show steeper softening curves, probably due to the de-bonding of each fiber and their irregular length.

3.7. Four-point beam testing

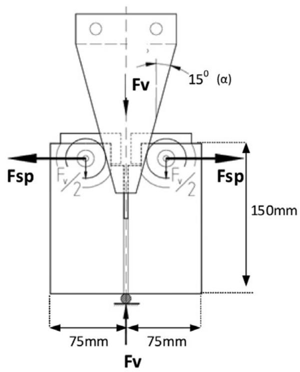
A four-point static bending test was performed to study the load vs. deflection behaviour of reinforced concrete beams with RFRC and SFRC. The beams were tested within 39–43 days after casting. All the beams were stored after casting at a temperature of 20^{0}C at the laboratory. Fig. 5 shows the experimental set up and the steel reinforcement arrangement inside the beam. Five beams were cast, and the theoretical failure load of the reference beam (i.e. 0% RC, without fibres) was about 220 kN.

According to the results of the beam testing given in Fig. 6, a 0% RC beam could reach the maximum load of 251.2 kN, but the beam was not able to hold the load while increasing the deflection. Therefore, the beam was failed when the midspan deflection was 54.7 mm. Moreover, the ultimate load of the 0.5% RFRC beam was 245.3 kN, which was slightly less than that of 0% RC. However, the 0.5% RFRC beam was failed when it reached a midspan deflection of 84.8 mm. This means that the addition of 0.5% RF enhanced the ductility behaviour of the beam. The 0.5% SFRC beam could reach the ultimate load of 259.6 kN, and the midspan deflection at failure was 76.9 mm. When comparing 0.5% RFRC and 0.5% SFRC, it can be seen that they have similar ductile behaviour. Moreover, the 1% RFRC beam and the 1% SFRC beam also showed good agreement by reaching the midspan deflection of 91.7 mm and 97.7 mm, respectively.

4. Discussion and conclusions

In this study, the performance of RFRC was studied using different laboratory testing to see the opportunity to replace SF. Initially, the mechanical properties of recycled fibre reinforced concrete and manufactured fibre reinforced concrete were

(a) Experimental setup for the WST



(b) Principle of applying the splitting load

Fig. 3. (a) Experimental setup for the WST Fig.3 (b) Principle of applying the splitting load [6].

Table 6
Results of the wedge splitting test.

	Average value of maximum vertical force (N)	Average value of the maximum horizontal splitting force (N)
0% RC	1830	3415
0.5% RFRC	1723	3216
1% RFRC	1813	3384
0.5% SFRC	2060	3844
1% SFRC	2810	5243

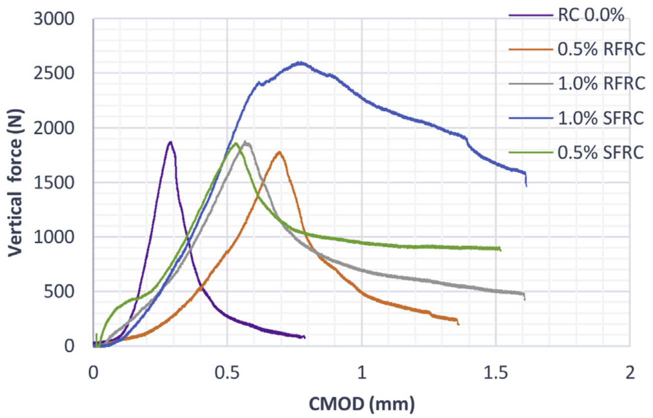


Fig. 4. Variation in vertical force vs. CMOD.

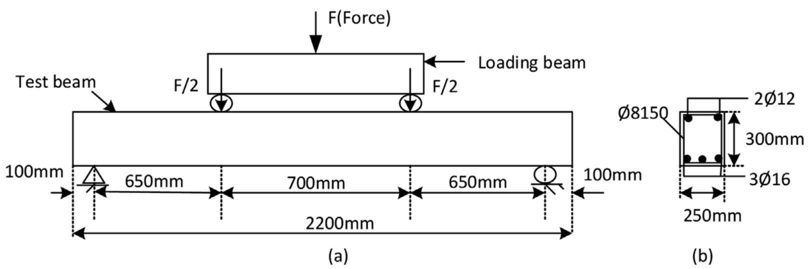


Fig. 5. (a) Dimensions of the beam and test set up (b) cross section of the beam.

investigated. When comparing, the properties of fresh SFRC and RFRC, increase of fibre content in the both SFRC and RFRC mixtures, decreases in slump was observed. However, there was no significant difference among the densities of fresh concrete.

According to the results, it can be seen that the secant modulus of elasticity is not significantly changed due to the addition of fibre. The percentage increase of the initial secant modulus of elasticity due to the addition of SF is 7–8% and due to the addition of RF is 2–3%. However, the percentage increase of the stabilized secant modulus of elasticity is about 5% for both SFRC and RFRC. This finding validates the findings of Bjegovic et al. [6] and Papakonstantinou and Tobolski [7] where there is no significant increase in secant modulus of elasticity of concrete.

Moreover, the compressive strength of concrete has been increased by 5–12% after adding RF and 17–20% after the addition of SF. This results compiles with the findings of Yazici et el. [19] and Atis and Karahan [20] for addition of SF and Aiello et al. [3] for the addition of RF. However, the percentage of increase of the compressive strength may be dependent on the factors: size, shape, aspect ratio, volume fraction, orientation and surface characteristics of fibres, ratio between fibre length and maximum aggregate size, volume ratio between long and short fibres and concrete class. [21].

It could be seen an increase of splitting tensile strength of RFRC and SFRC compared with reference concrete. However, there is no significant increase observed while increasing the dosage of fibre content in RFRC and SFRC. However, this does not give good agreement with the findings of Leone et al [18] where the authors have observed slight decrease of the splitting

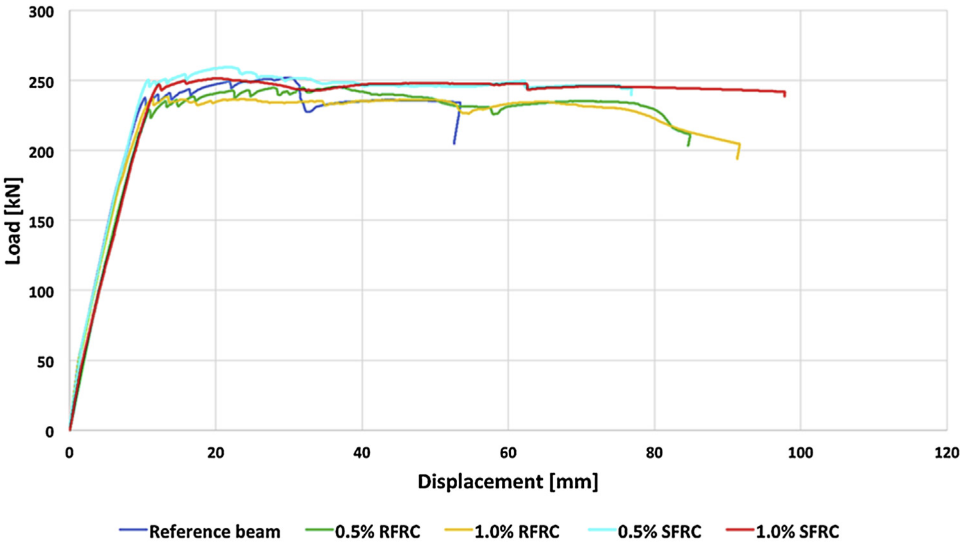


Fig. 6. Load vs. displacement (i.e. midspan deflection).

tensile strength. However, according to Yazici et el [19]. and Atis and Karahan [20], for SFRC, they have observed increase of splitting tensile strength while increasing the fibre dosage which shows a good agreement with the results of this study.

One of the aims of the addition of fibre to concrete is to enhance the fracture properties. According to the results, the addition of neither RF nor SF significantly changes the horizontal splitting force. Moreover, vertical force vs. CMOD shows that the addition of 0.5% and 1% RF improves the post-cracking behaviour but not the same as SFRC. For certain practical reasons, the specimens were not tested until they failed. Therefore, further research is needed to investigate the fracture properties (i.e. fracture energy and characteristic lengths) in detail.

The four-point beam test results show that addition of 0.5% RF enhanced the ductility behaviour of the beam. When comparing 0.5% RFRC and 0.5% SFRC, it can be seen that they have similar ductile behaviour. Moreover, the 1% RFRC beam and the 1% SFRC beam also showed good agreement, by reaching the mid span deflection of 91.7 mm and 97.7 mm, respectively.

Conflict of interest

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

References

[1] B.S. Thomas, R.C. Gupta, V.J. Panicker, Recycling of waste tire rubber as aggregate in concrete: durability-related performance, J. Clean. Prod. 112 (Part 1) (2016) 504–513.
[2] K. Pilakoutas, K. Neocleous, H. Tlemat, Reuse of tyre steel fibres as concrete reinforcement, Proc. ICE – Eng. Sustain. 157 (3) (2004) 131–138 ISSN 1478-4629.
[3] M.A. Aiello, F. Leuzzi, G. Centonze, A. Maffezzoli, Use of steel fibers recovered from waste tyres as reinforcement in concrete: pull-out behaviour, compressive and flexural strength, Waste Manage. 29 (6) (2009) 1960–1970 2009/06/01/.
[4] H. Hu, P. Papastergiou, H. Angelakopoulos, M. Guadanini1, K. Pilakoutas, Flexural performance of steel fiber reinforced concrete with manufactured and recycled tyre steel fibers, Construction Materials for Sustainable Future (2019) University of Zagreb, Faculty of Civil Engineering, Zagreb, Croatia, pp. 904–911. ISBN 978-953-8168-04-8.
[5] K. Bethoft, S.M.S.M.K. Samarakoon, L. Evangelista, B. Mikalsen, Performance of recycled and commercial fiber reinforced concrete beams in combined action with conventional reinforcement, SynerCrete'18: Interdisciplinary Approaches for Cement-Based Materials and Structural Concrete: Synergizing Expertise and Bridging Scales of Space and Time, Vols. 1 & 2(2018) .
[6] D. Bjegovic, A. Baricevic, S. Lakusic, D. Damjanovic, I. Duvnjak, Positive interaction of industrial and recycled steel fibers in fiber reinforced concrete, J. Civ. Eng. Manage. 19 (2013) 50–60.
[7] C.G. Papakonstantinou, M.J. Tobolski, Use of waste tire steel beads in Portland cement concrete, Cement Concrete Res. 36 (September (9)) (2006) 1686–1691.
[8] F.F. Wafa, Properties and applications of fiber reinforced concrete, JKAU: Eng. Sci. 2 (1990) 49–63.
[9] T. Cafe, Physical Constants for Investigators, (2007) . (Accessed 4 March 2017) http://www.tcforensic.com.au/docs/article10.html.
[10] S. Smeplass, Chapter 4 - fresh concrete - proportioning, TKT4215 – Concrete, Technology 1. Course Compendium, (2014) .
[11] Standard Norge, NS-EN 12350-2:2009 Testing Fresh Concrete - Part 2: Slump Test, (2009) .
[12] Standard Norge, NS-EN 12350-6:2009 Testing Fresh Concrete - Part 6: Density, (2009) .
[13] Standard Norge, NS-EN 12350-7:2009: Testing Fresh Concrete - Part 7: Air Content Pressure Methods, (2009) .
[14] Standard Norge, NS-EN 12390-3:2009 Testing Hardened Concrete - Part 3: Compressive Strength of Test Specimens, (2009) .
[15] Standard Norge (Ed.), NS-EN 12390-13:2013 Testing Hardened Concrete - Part 13: Determination of Secant Modulus of Elasticity in Compression, 2013.
[16] Standard Norge, NS-EN 12390-6:2009 Testing Hardened Concrete - Part 6:Tensile Splitting Strength of Test Specimens, (2009) .

[17] Wedge Splitting Test Method, 511, Nordic Innovation Centre, Oslo, Norway, 2005 NT Build.
[18] M. Leone, G. Centonze, D. Colonna, F. Micelli, M.A. Aiello, Fiber-reinforced concrete with low content of recycled steel fiber: Shear behaviour, Constr. Build. Mater. 161 (2018) 141–155, doi:http://dx.doi.org/10.1016/j.conbuildmat.2017.11.101.
[19] S. Yazici, G. Inan, V. Tabak, Effect of aspect ratio and volume fraction of steel fiber on the mechanical properties of SFRC, Constr. Build. Mater. 21 (2007) 1250–1253.
[20] C.D. Atis, K. Karahan, Properties of steel fiber reinforced fly ash concrete, Constr. Build. Mater. 23 (2009) 392–399.
[21] J. Tejchman, J. Kozicki, Experimental and Theoretical Investigation of Steel-fibrous Concrete, 1st edition, Springer, 2010 ISBN 978-3-642-14602-2.