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Waste Steel Wires Modified Structural Lightweight Concrete

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Nowadays, the use of different waste fibers in concrete has started to increase rapidly due to some reasons such as economic savings and positive effects on the environment. In this study, waste steel wires taken from reinforcement and formwork which were previously utilized in construction projects, were employed in structural lightweight concrete (SLWC). The objective was to investigate the possibility of using this type of fiber as reinforcement in the SLWC. Compressive, tensile, flexural and impact tests were performed for investigating the mechanical properties of 28-day reinforced lightweight concrete specimens with the waste wires. The percentage of wire in the fiber reinforced concrete (FRC) was 0.25%, 0.5% and 0.75% in the volume fraction of the concrete. According to the results, by using waste wires, flexural, tensile and impact characteristics of SLWC were effectively improved. Moreover, it was concluded that waste steel wires could be used as a suitable micro reinforcement in the SLWC.

Keywords: *structural lightweight concrete, fiber reinforced concrete, waste steel wire, environment*

1. Introduction

For several decades, the structural lightweight aggregate concrete has been used in many different applications such as, buildings, bridges, floors, partition walls, and etc.[1,2]. Structural lightweight concrete is a popular material in construction industry due to some substantial benefits such as good tensile capacity, low coefficient of thermal expansion and superior heat as well as sound insulation capability[2-7]. Furthermore, using lightweight concrete in construction decreases the dead load of the structures and further earthquake forces which reduce the risk for human's life. This feature allows to decrease the dimensions of structural and non-structural sections and cost of the construction[4,8-10]. Nonetheless, there are some defects in mechanical properties of lightweight concretes, which have prevented it from being used as load bearing structural members in construction industry[3,11,12]. Furthermore, concrete is a brittle material with low shear capacity and bending strength[3,13-15]. These characteristics are more obvious in lightweight concrete than conventional concrete for the same compressive strength[16,17] due to existence of lightweight aggregates which are relatively weaker than the cement matrix while they also have low resistance against crack propagation[18]. Therefore, it is found out that addition of steel fiber in concrete mixture can decrease the mentioned brittleness[19,20]. This method is commonly used for reducing lightweight aggregate concrete brittleness[12,19,21,22].

In last decades, many research studies have been done to evaluate the properties of steel fiber reinforced concrete (SFRC)[23]. It has been reported that addition of the steel fibers into the lightweight concrete enhances the load-carrying capacity, prevents opening of the macro cracks, and decreases the width of micro cracks with an improved resistance against dynamic, impact, and sudden loads. Moreover, steel fibers also improve the tensile strength of fiber reinforced concrete[10,23].

Although many of research studies have conducted on FRC, this composite material is not relatively economical. Therefore, from an economical and environmental point of views the use of waste fibers recovered from different industrial procedures such as milling, manufacturing and textile industry can be considered as an effective alternative for the origin materials[10]. Alongside these benefits, direct reuse of raw waste is becoming the most convenient recycling way which can be used as a viable alternative for our resources and could save our environment. In many cases, some procedures such as mechanical, chemical and biological are carried out to recycle such a waste. All these methods are energy-consuming and could be harmful for the environment by the emission of pollution into the air, water and soil[24].

Wang et al. reviewed some studies on mechanical properties of FRC by using some recycled fibers including tire cords/wires, carpet fibers, feather fibers, steel shavings, wood fibers from paper waste, and high density polyethylene. They reported that recovered industrial fibers could have same effect as origin fibers on mechanical properties of FRC. Although a higher dosage rate may be required to match the performance[25]. Guoqiang et al. utilized waste tires in two forms of fibers and chips in concrete. They have reported that the performance of fibers in concrete is better than chips and strength and stiffness of fiber reinforced concrete is higher than chips reinforced concrete[26]. Ghailan used waste industrial fibers as aggregates in concrete and reported that stiffness modulus of reinforced concrete with waste steel fibers is higher than plain concrete and comparatively high corrosion resistance against salts and acids was achieved[27]. Neocleouset al. evaluated the flexural properties of concrete reinforced with tire-recycled steel

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fiber. They reported that recycled steel fibers (RSF) from waste tires have a great effect on improving the post peak behavior of FRC[28]. Meddah and Bencheikh investigated the mechanical properties of waste metallic and polypropylene fibers with different lengths in concrete. They have reported that adding waste fibers more than 1.5% of volume fraction of concrete decreases the compressive strength of composite concrete. According to their study, the incorporation of waste fibers in different lengths leads to the best load-carrying capacity and flexural properties[29]. Aiello et al. studied the mechanical properties of a concrete reinforced with recycled steel wires from waste tires. They have reported that results obtained from using waste fibers are comparable with industrial steel fiber reinforced concrete, and steel fiber from waste tires can be a promising candidate for obtaining FRC[30]. Mostafa Jala has reported that using waste fibers recovered from milling and machining in concrete increases the compressive strength of concrete[31].

In this research, by using waste steel wires in structural lightweight concrete, a number of specimens were prepared and the compatibility of this type of fiber as reinforcement in lightweight concrete was investigated. In this way, compressive, tensile, flexural and impact tests on 28-days age of waste steel fiber reinforced concrete were conducted. This paper represents the results of this experimental study.

2. Experimental Investigation

2.1. *Material*

Following materials utilized in the present research:

2.1.1. Cement matrix

Ordinary Portland cement according to ASTM C150-02[32], type 2 cement with a bulk density of 1160 kg/m^3 was used for every concrete mixture.

Perlite lightweight aggregate due to its bulk density 93 kg/m^3 with a 5mm maximum size was used.

Natural river sand with a maximum size of 5 mm, specific gravity of 1.52, SSD water absorption of 1.37%, and SSD density of 2512 kg/m^3 was used in this study. Both natural river sand and perlite aggregates were batched in a dry condition. A commercial super silica gel with a constant supply of 8% by weight of the cement content was used in all of the samples.

2.1.2. Fibers

In this investigation, waste steel wires which are the major wastes in building workshops and construction projects were used in the lightweight concrete. These wires are produced in reinforcement, formwork, and other procedures. The shape of the wires was almost straight.

Cut waste wires by the length and diameter of 50±10 mm and 1.2 mm, respectively were used (See Figure 1). Three batches with volume fractions of 0.25%, 0.5% and 0.75% of waste wire reinforced concrete were prepared.

2.2. *Mixture composition*

For preparation of all the samples, lightweight perlite concrete, which is the volumetric mixing of cement, sand, perlite aggregate, steel fibers, water, and super silica gel was used. For all mixtures, a water–cement ratio (w/c) of 0.4 (by weight) was used and the amount of super silica gel was constant. Table 1 represents the details of the mixture proportions.

The FRC mixtures were defined by the following notations: WFRCX. The first four letters (WFRC) stand forwaste fiber reinforced concrete. WFRCs followed by a number (X): which symbolizes the fiber content in volumetric percent.

For the preparation of the fiber reinforced lightweight aggregate concrete, perlite and natural river sand were first mixed in the dry state for one minute. Then, the cement was added to the mixer, and mixing was continued for another one minute. While the mixing operation was in progress, the fibers were added and materials were mixed for further 2 minutes. Alongside the continuous addition of the fibers, a spontaneous effort was made to prevent fibers from getting clumped. Finally, the required amount of a specific mixture containing water and super silica gel was slowly added to the mixer and mixing was continued for a period of 3 minutes. Moulding process of the specimens was performed by pouring at least three layers of concrete in the moulds. After

Figure 1. Cut waste steel wires.

Table 1.Volumetric proportions of concrete mixtures.

Mixture code	Perlite	Sand	Cement	Volume fraction of fiber (%)	W/C	Super silica gel (%)
Plain	2	1	2	0	0.4	8
WFRC 0.25	2	1	2	0.25	0.4	8
WFRC 0.5	2	1	2	0.5	0.4	8
WFRC 0.75	2	1	2	0.75	0.4	8

filling the moulds, the concrete specimens were compacted using a vibrating table for a period of 8 to 12 seconds. The variation of vibrating time was due to the insignificant reduction of workability by adding higher content of wires. On the other hand, this insignificant influence was controlled by increasing the time period of vibrating of the WFRCs.

After the moulding process, specimens were kept at temperature of 20°C in the laboratory for a time period of 24 hours. Then all the specimens were taken apart and were continuously stored in the water tank at a constant temperature of 20±2°C for 28 days, until the experiment day.

2.3. *Test method*

For each concrete mixture, three samples were tested at the 28 days of curing. A total of 60 cubic, prismatic, cylindrical and disk specimens were prepared for compressive, flexural, splitting tensile and impact tests.

2.3.1. Compression test

A total of 12 cubic specimens by dimensions of 100×100×100 mm were prepared for compressive testing according to ASTM C 39-03 standard[33]. The tests were performed using a digital automatic testing machine with the load rate of 100 kg/sec.

The compressive strength of the specimens was calculated by dividing the maximum load attained during the test to the total cross-sectional area of the specimen.

2.3.2. Splitting tensile test

A total of 12 cylindrical specimens (150×300mm) were prepared for splitting tensile test, conforming to the ASTM C 496-04[34]. The test was performed by a digital automatic testing machine with the load rate of 100 kg/sec. A suitable jig was used for ambulate the concrete cylinder. As the loading started, the center of jig, center of specimen and center of thrust of the spherical bearing block were positioned along a unique axis.

After the test, the splitting tensile strength of the specimens was calculated as follows:

$T = 2P/\pi ld$

Where:

T = splitting tensile strength, psi [MPa],

P = maximum applied load indicated by the testing machine, lbf [N],

l = length, in. [mm], and

d = diameter, in. [mm].

2.3.3. Flexural test

The flexural test was conducted on 12 prismatic specimens with dimensions of 500×100×100 mm, in accordance with ASTM C 1018-97 Standard[35]. A universal three point loading machine of 1000 KN loading capacity was employed for flexural testing. As per ASTM C 1018-97[35] for performing the flexural experiments the samples were rotated to 90 degree to its original position when disassembled and were placed on the support system of flexural testing machine. The loading and mid-point displacement values observed during the experiment were recorded automatically on computer. The rate of increasing Net Mid-Span deflection was adjusted to 0.1 mm/min.

After the test, load-deflection curves of specimens were plotted and the values of toughness indices (I_5, I_{10} and I_{20}) and residual strength factors ($R_{5,10}$ and $R_{10,20}$) were calculated. According to ASTM C 1018-97[35], by determining the area under the load-deflection curves up to the specific deflections and dividing it by the area up to the first-crack deflection, toughness indices were obtained.

2.3.4. Impact test

A total of 24 cylindrical (disc) specimens having diameters of 150 mm and thickness of 64 mm were specified for impact testing in accordance with recommended method by ACI Committee 544.2R-89[36]. Due to use of fibers having length of 50 mm, the test specimens were cut from a full-size cylinder to minimize alignment of the preferential fibers[36,37].

According to drop weight impact test method, disk specimens were struck by 4.5 kg dropping hammer from the height of 45cm, repeatedly. The load was transferred from the hammer to the specimen through a 64 mm steel ball which is placed at the center of the disc specimen[36]. In this test, two specifications with the names of ‘initial’ and ‘ultimate’ failures that quantify the impact resistance of the specimens were evaluated.

The initial failure is the number of blows required to cause the first visible crack in specimen and the ultimate failure is the number of blows after which disc specimen fails and touches three of the four steel lugs of the test equipment[37,38].

3. Results and Discussion

3.1. *Compressive strength*

Table 2 and Figure 2 show the results of compressive strength of WFRC in comparison to plain concrete. Obtained compressive strengths and densities of concrete specimens were within the ranges of 18.5-23.8 MPa and 1708.5-1800 kg/m^3, respectively. As per ASTM C 330-02a, these kind of concretes are classified as structural lightweight concretes[39]. As it can be seen from Figure 2, increase in waste steel wire content from 0% to 0.25%, increases the compressive strength of WFRC by about

Table 2. Compressive tests results of all specimens.

Specimen	Plain	WFRC 0.25	WFRC 0.5	WFRC 0.75
1	21.73	18.31	23.55	18.3
2	19.71	21.54	24.24	19.44
3	19.1	21.02	23.1	17.76
Average	20.18	20.29	23.63	18.5
St. Dev.	1.38	1.73	0.57	0.86

5% compared to plain concrete. The compressive strength of WFRC at the ratio of 0.5% has increased significantly and reaches a peak of 23.62 MPa. By adding more wires up to 0.75% not only compressive strength of WFRC has not increased, but also it decreases dramatically, even 8% lower than the plain concrete. This decrease in compressive strength in highest fiber content (0.75%) may be due to the difficulty of scattering the fibers in lightweight concrete. It has been reported in the literature that the compressive strength of waste tires reinforced concrete increased slightlyor sometimes unaffected by the presence of irregular geometricwaste tires[30]. Moreover, it has been reported that using higher content of the incorporation of waste metallic fibers (WMF) and polypropylene fibers (WPF) resulted in higher porosity and lower compressive strength of FRC[29].

3.2. *Splitting tensile strength*

Table 3 and Figure 3 show the results of splitting tensile strength of plain and WFRCs specimens. Obtained test results show that by the utilization of waste steel wires in lightweight concrete splitting tensile strength of concrete increases, effectively. Compared to the plain concrete, the splitting tensile strength of WFRC is increased by approximately 28% on average through the addition of fibers at ratio of 0.25%, 0.5% and 0.75% in volume fraction of the concrete. This indicates that even by just incorporating 0.25% volume fraction of fiber into lightweight concrete, splitting tensile strength of WFRC increases, significantly. This is in accordance with the results of Shafigh and Balendran[1,17]. The addition of 0.5% waste steel wire did not significantly change the splitting tensile strength of the lightweight concrete. However by using more wires, the splitting tensile strength of WFRC 0.75, increases by about 45%. This indicates that waste steel wires have a great effect on splitting tensile strength of WFRCs, especially for high contents of fibers. These results coincide with the finding of previous studies. They have reported that splitting tensile strength of the recycled steel fiber reinforced concrete (RSFRC) and standard steel fiber reinforced lightweight concrete (SFRC), dramatically improved with increasing the volume fraction of fibers[40,41].

As Figure 4 illustrates, plain concrete ruptured after the tensile test into two halves, which is an indicator of brittle behaviour of unreinforced concrete; while WFRCs kept their integrity and only tiny surface cracks on the length of the specimens appeared. This implies that waste steel wires play a significant role to make the concrete capable of resisting crack propagation and tensile forces. In general, it can be concluded that, improved splitting tensile strength of WFRCs isattributed to the proper bond of wires to the cement matrix and bridging the wires across the cracks.

3.3. *Flexural strength*

The results of flexural tests of various mixtures are represented in Table 4. The data is the mean value of three test results. The results indicate that all values of first-crack strength (FCS) of WFRC specimens are higher than that of plain concrete. Also, the first-crack deflections of flexural specimens are increased by increasing the fiber percentage compared to plain specimens. The maximum amount of first-crack strength of WFRCs is 3.745 MPa, which is 40% more than the first-crack strength of plain samples. This value is related to waste steel wire reinforced concrete with 0.75% by volume fraction of fibers.

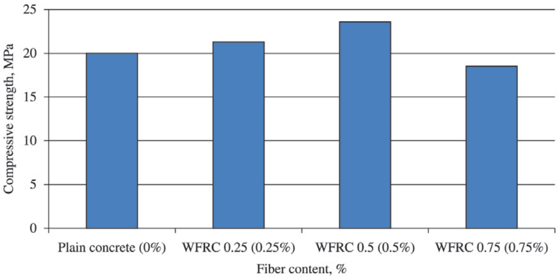

Figure 2. Average compressive strength of WFRC and plain specimens.

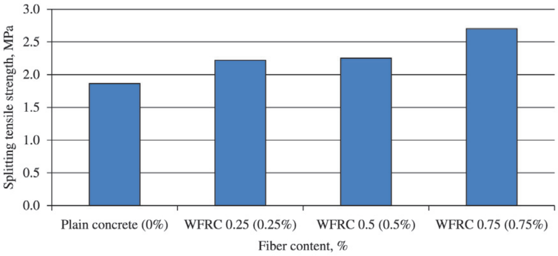

Figure 3. Average splitting tensile strength of WFRC and plain specimens.

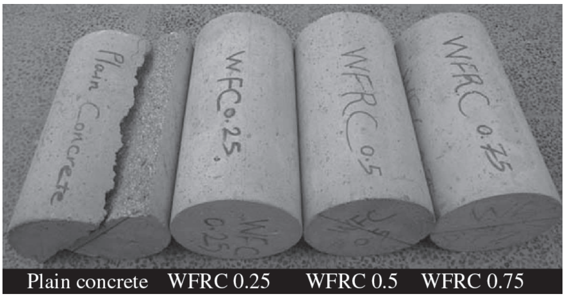

Figure 4. Comparison of failure pattern of WFRC and plain specimens after splitting tensile test.

Table 3. Splitting tensile tests results of all specimens.

Specimen	Plain	WFRC 0.25	WFRC 0.5	WFRC 0.75
1	20.2	21.83	23.75	27.8
2	18.25	22.05	21.44	25.21
3	17.73	22.99	18.78	28.47
Average	18.73	22.29	21.32	27.16
St. Dev.	1.30	0.62	2.49	1.72

Table 4. The values of first-crack strength, first-crack deflection, toughness indices and residual strength factors of bending specimens.

Specimen code	$V_{f\,(\%)}$	First-crack strength (MPa)	First-crack deflection (mm)	Toughness indices			Residual strength factors	
				I_5	I_{10}	I_{20}	$R_{5,10}$	$R_{10,20}$
Plain	0	2.676	0.642	-	-	-	-	-
WFRC0.25	0.25	3.027	0.853	2.58	4.14	6.56	31.2	24.2
WFRC0.5	0.5	3.312	1.087	4.26	7.31	11.47	61	41.6
WFRC0.75	0.75	3.745	0.946	4.13	7.28	11.91	63	46.3

In order to determine the energy absorption capability and toughness of flexural specimens, toughness indices and residual strength factors are assessed as suggested by ASTM C 1018-97 standard test[35].

Toughness indices indicate the ability of FRCs to transfer stresses across a cracked section and can be considered as the energy absorption capacity of FRC specimens. It can be observed from Table 4 that increasing the volume fraction of fibers ameliorates the toughness indices.

The results of Table 4 show that the toughness indices of WFRC 0.5 and WFRC 0.75 are approximately equal. This reveals that the post-peak area in the load-deflection curves of these specimens has been increased compared to pre-peak area (See Figure 5).

Residual strength factors (RSF) represent the average level of strength retained after the first-crack as a percentage of the first-crack strength over a specific deflection interval[35]. It can be observed from Table 4 that by increasing the fiber content, higher amounts of RSFs are achieved. The mentioned results coincide with previous findings of Aiello et al. regarding use of steel fibers recycled from waste tires in concrete. They have concluded that a high percentage of the fiber content leads to increase of the peak load in the load-deflection curves, increase of the residual strength after cracking, and improvement of the toughness[30].

In Figure 5 the average of three load-deflection curves are plotted for different percentages of fiber, (All of the load-deflection curves have been presented in Appendix 1, separately). According to the load-deflection curves and flexural experiments, the behavior of specimens under bending experiment can be classified into two types. The first one is related to those specimens without fiber. These samples broke in a brittle manner and once reaching the peak load they separated into two pieces, suddenly. The area under the load-deflection curves of these specimens, which signifies the energy absorption capacity, is insignificant.

The second behavior was shown by WFRC specimens. These specimens exhibited a ductile behavior due to bond characteristic between fibers and cement across the cracks. In these samples, fibers which were randomly spread across the crack resisted the propagation of cracks and hindered a sudden failure of composite concrete. The load-deflection curves of these specimens after the first-crack is followed by a sharp drop in load and then a deep curve ultimately leads to ultimate failure. These results show that ultimate deflection of WFRC0.75 concrete composition is about 32 times greater than the plain concrete.

The absolute toughness is assessed by determining the total area under the load-deflection curves up to ultimate failure. Figure 6 shows the absolute toughness or absorbed energy by WFRCs in comparison to the plain concrete. It can be seen from this chart that the absolute toughness of WFRCs is significantly higher than plain concrete. The highest amount of energy absorption is achieved by WFRC 0.75 specimens. On average, it is equal to 6277 kg.mm and this value is about 28.5 times higher than that of the plain concrete.

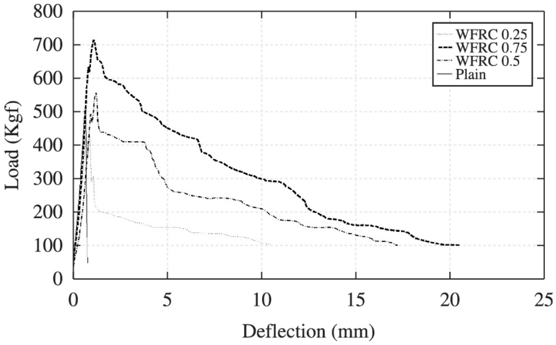

Figure 5. Comparison of the flexural load-deflection curves of WFRC and plain specimens.

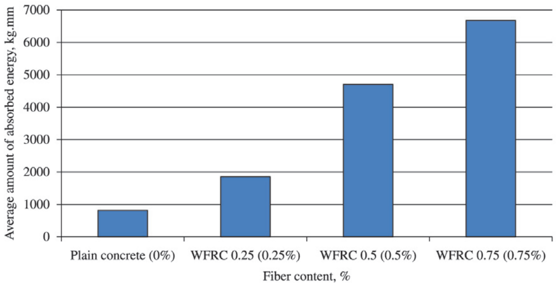

Figure 6. Average amount of absorbed energy by bending samples in kg.mm.

3.4. *Impact strength*

The results of impact test are represented in Table 5. Values of the first-crack resistance (FCR) and ultimate resistance (UR) are the average results of six specimens for each mixture. As it can be seen, the number of blows required to cause the first visible crack as well as the number of blows for ultimate failure increases by increasing fibers in mixtures. Plain concrete showed brittle behavior and did not have much resistance after the initial crack. These specimens with few blows reached the ultimate failure. However, fiber reinforced concrete specimens were able to bear much more blows up to the ultimate failure. This increase in post crack resistance, depending on fiber

Table 5. Impact test results.

Specimen code	First crack resistance (FCR) blows Ave, (St. Dev.)	Ultimate resistance (UR) blows Ave, (St. Dev.)	Increase in resistance from FCR to UR (%)	FCR_{WFRC} / FCR_{PC}	UR_{WFRC} / UR_{PC}
Plain	2 (1.73)	3 (1.15)	50.00	-	-
WFRC 0.25	3 (1.15)	28 (2)	833.33	1.5	9.33
WFRC 0.5	3 (1.15)	36 (2.64)	1100.00	1.5	12.00
WFRC 0.75	3 (0.57)	53 (6)	1666.67	1.5	17.67

content, was 833% to 1667% for WFRC specimens. According to this result, by increasing volume fraction of wires in structural lightweight concrete, a substantial improvement in the impact resistance is achieved. These results coincide with the previous findings of Wang et al. on lightweight aggregate concrete. They asserted that both FCR and UR greatly improved by including steel fibers and by higher fiber content, a greater improvement of impact resistance was achieved[42].

Fibers, by spanning across the cracks absorbed the impact energy of hammer blows and prevent from progression of cracks within concrete and also avoided the splitting of concrete into small pieces (See Figure 7). The impact resistance of WFRC 0.75 is about 13 times higher than the plain concrete.

Figure 7 shows the specimens after ultimate failure in impact test. As it can be seen, plain concrete specimens are separated into three pieces after the test. It implies that brittle failure mode has been encountered in the specimens. In contrast, FRCs, because of the uniform stress distribution in concrete, failed by at least four polar cracks.

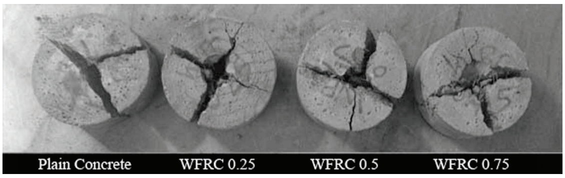

Figure 7. Comparison of failure pattern of WFRC and plain specimens after the impact test.

4. Conclusions

In this study the mechanical properties of structural lightweight concrete reinforced with waste steel wires were experimentally investigated.

Generally, the incorporation of waste wire up to 0.5% in structural lightweight concrete increases the compressive strength of the WFRC. However, the addition of more than 0.5% volume fraction of waste wire decreases the compressive strength of the WFRC.

WFRC has considerably higher splitting tensile strength than the plain concrete even at low volume of fibers. Even very low volume fraction of waste wires prevented WFRC from brittle failure.

Based on the flexural test results, the maximum flexural strength and maximum energy absorption was obtained by WFRC 0.75 specimens. This value was 28.5 times greater than the plain concrete.

Addition of waste steel wires at 0.75% by volume fraction of lightweight concrete led to a thirteen-fold increase in ultimate impact resistance of WFRCs compared to the plain concrete.

It can be concluded that, due to the suitable strength and mechanical properties of the waste steel wire reinforced lightweight concrete compared to the plain lightweight concrete, waste steel wires could be a reasonable choice as steel fiber reinforcement in structural lightweight concrete.

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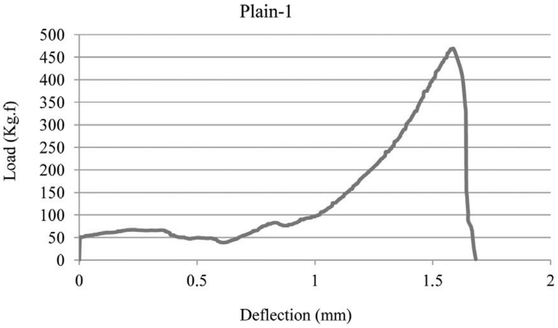
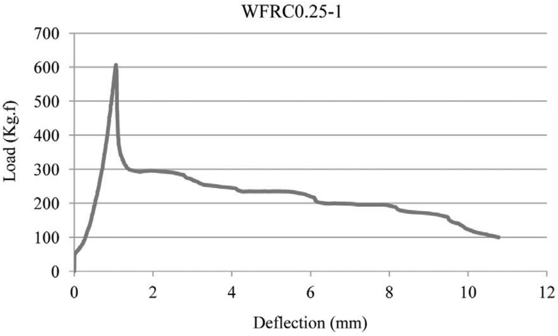
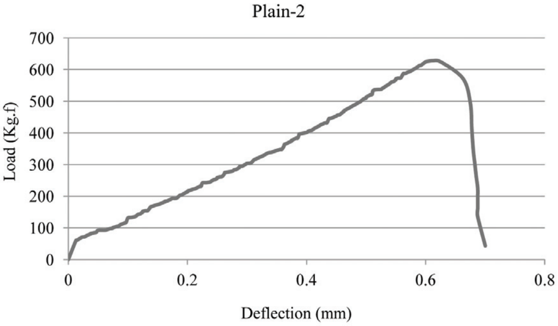
Appendix 1.



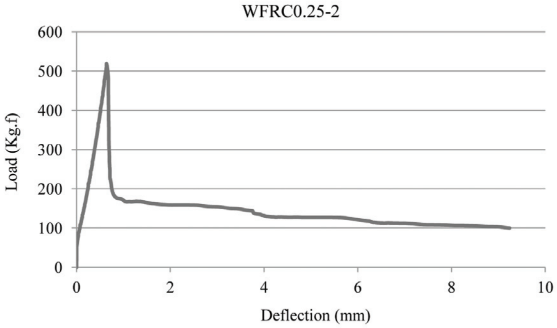
Flexural load-deflection curve of Plain-1



Flexural load-deflection curve of WFRC0.25-1



Flexural load-deflection curve of Plain-2



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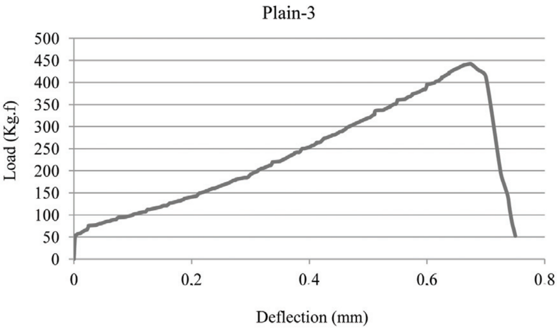

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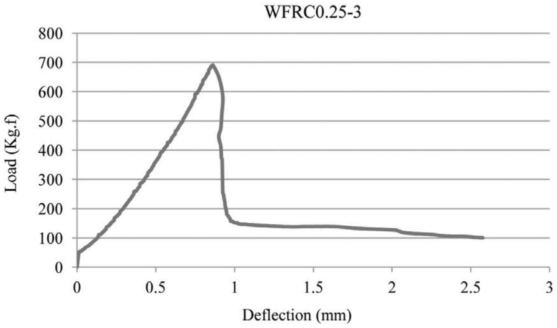

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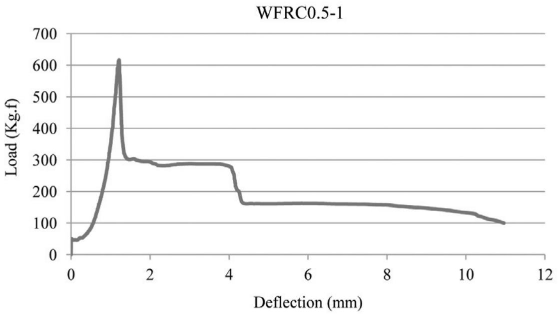

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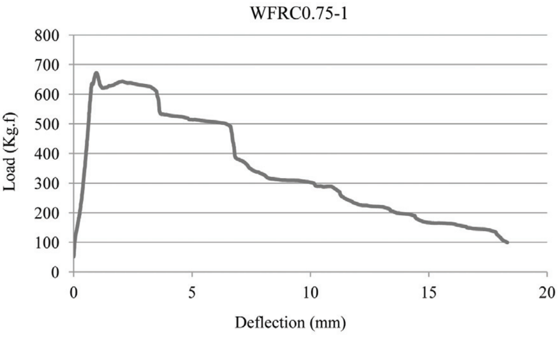
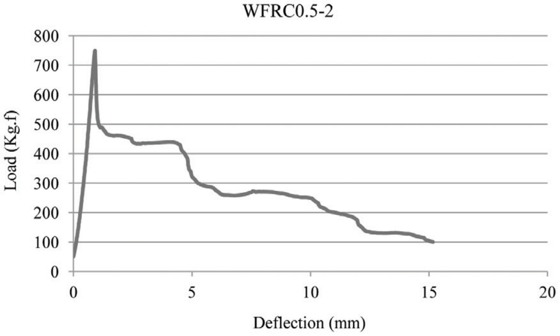
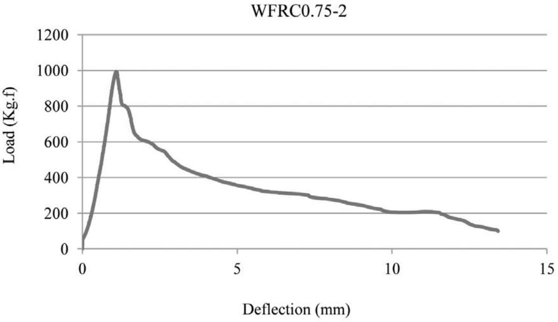


Flexural load-deflection curve of WFRC0.75-1

Appendix 1. Continuação..



Flexural load-deflection curve of WFRC0.5-2



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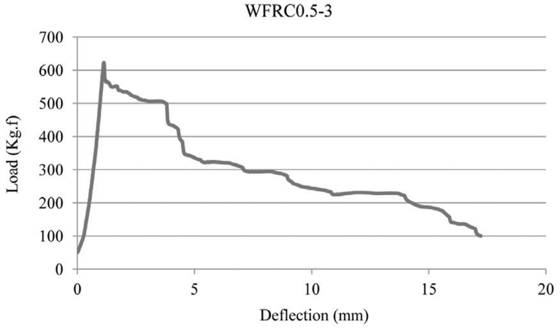
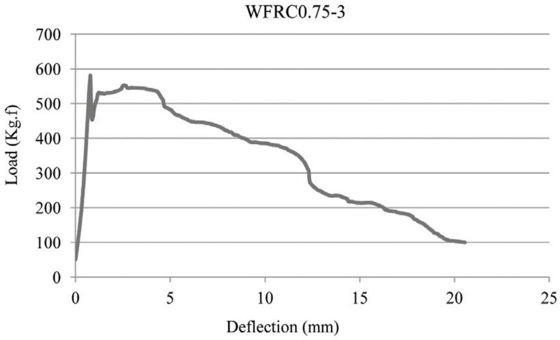


Flexural load-deflection curve of WFRC0.5-3



Flexural load-deflection curve of WFRC0.75-3