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Investigation into the mechanical properties of structural lightweight concrete reinforced with waste steel wires

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The study of concrete incorporating different waste fibres has started to increase rapidly due to economic reasons and positive environmental effects. In the study reported here, waste steel wires from steel reinforcement and used formworks were blended with structural lightweight concrete, with the aim of replacing commercial steel fibres of controlled quality with recycled fibres. Compression, tensile, flexural and impact tests were performed to assess the mechanical properties of 28 d old concrete specimens reinforced with mixed waste steel wires, mixed steel fibres as well as plain concrete. The percentages of fibres examined in the fibre reinforced concrete (FRC) specimens were 0·25%, 0·50% and 0·75% (volume fraction of the concrete). With varying fibre contents, similar trends were observed in all the types of FRCs studied. It was thus concluded that waste steel wires could be used as a suitable alternative to industrial steel fibres for structural lightweight concrete applications.

Notation

d	diameter of concrete cylinder
I_5, I_{10}, I_{20}	toughness indices
l	length of concrete cylinder
P	maximum applied load indicated by the testing machine
$R_{5,10}$, $R_{10,20}$	residual strength factors
T	splitting tensile strength
V_f	fibre content (% volume fraction of concrete)

Introduction

Structural lightweight aggregate concrete (LWAC) has been used in many different applications for several decades, including buildings, bridges, floors and partitions (Shafigh *et al.*, 2011; Yasar *et al.*, 2003). It is a popular material in the construction industry due to its exclusive benefits of tensile capacity, low coefficient of thermal expansion and superior heat and sound insulation capability (Alshihri *et al.*, 2009; Duzgun *et al.*, 2005; Hassanpour *et al.*, 2012; Sengul *et al.*, 2011; Tanyildizi, 2008; Yasar *et al.*, 2003). In construction, the use of lightweight concrete leads to reduced dead load, so earthquake forces are smaller, reduced structural and non-structural member dimensions and thus decreased associated costs (Altun and Aktas, 2013; Duzgun *et al.*, 2005; Libre *et al.*, 2011; Topcu, 1997).

However, the inferior mechanical properties of lightweight concrete have eliminated its use for high load-bearing structural members (Arisoy and Wu, 2008; Gao *et al.*, 1997; Hassanpour *et al.*, 2012). Conventional concrete is a brittle material with low shear capacity and bending strength (Hassanpour *et al.*, 2012; Shah and Ribakov, 2011; Slater *et al.*, 2012; Withers and Bhadeshia, 2001). These characteristics are also apparent in LWAC for the same compressive strength (Balendran *et al.*, 2002; Domagala, 2011) due to the existence of lightweight aggregates that are relatively weaker than the cement matrix; LWAC also has low resistance to crack propagation (Naaman and Reinhardt, 2003). The addition of steel fibres to concrete is beneficial, as this decreases the aforementioned brittleness and spalling (Kandasamy and Murugesan, 2011; Pawade *et al.*, 2011; Wui *et al.*, 2013). The incorporation of steel fibres is also widely used for reducing the brittleness of LWAC (Arisoy and Wu, 2008; Chanh, 2004; Kayali *et al.*, 2003; Pawade *et al.*, 2011).

The properties of steel-fibre-reinforced concrete (SFRC) have been examined in the past and improved tensile strength has been reported (Altun and Aktas, 2013; Mohammadi *et al.*, 2008). It has also been reported that adding steel fibres to lightweight concrete increases the load-carrying capacity while preventing the opening of macro-cracks and reducing the width of micro-cracks, as well as providing some resistance to dynamic and impact loads (Aslani, 2013; Ghasemi Naghibdehi *et al.*, 2014).

Although many research studies have been conducted on the use of steel fibres for reinforcing concrete, it is not the most economical solution. The use of waste fibres arising from, for example, milling, manufacturing machinery and the textile industry is considered an effective alternative (Altun and Aktas, 2013). The reuse of raw waste materials is often seen as the most effective way to 'recycle' waste materials into products that can be used as viable alternatives, thus conserving resources and reducing environmental impacts. In many cases, however, mechanical, chemical or biological procedures are carried out to recycle the waste materials. All these methods are energy consuming and could be environmentally harmful in terms of air, water and soil pollution. The use of raw material such as waste steel wires does not produce these harmful effects, but is environmentally friendly (Süleyman Gökçe and Şimşek, 2013; Wang, 2010).

Wang *et al.* (2000) conducted studies on the mechanical properties of fibre-reinforced concrete (FRC) using recycled fibres including tyre cords/wires, carpet fibres, feather fibres, steel shavings, wood fibres from paper waste, as well as high-density polyethylene fibres. They reported that concrete with the addition of recovered industrial fibres could have similar mechanical properties to common FRCs, although a higher dosage rate may be required to match the performance. Li *et al.* (2004) utilised waste tyres in two forms (fibres and chips) in concrete. They reported that the performance of concrete dosed with fibres rather than chips was better in terms of strength and stiffness (Li *et al.*, 2004). Ghailan (2005) used waste industrial fibres as aggregate replacement in a concrete mix and reported that the stiffness of the reinforced concrete was higher than that of plain concrete, and a comparatively high corrosion resistance against salts and acids was achieved. Neocleous *et al.* (2006) evaluated the flexural properties of concrete members reinforced with recycled steel fibres from waste tyres and concluded that the use of these fibres had a great effect on improving the post-peak behaviour of the FRC. Meddah and Bencheikh (2009) investigated the mechanical properties of waste metallic and polypropylene fibres of various lengths. They found that, for waste fibre additions of more than 1·5% volume fraction of the concrete, the compressive strength of the composite concrete decreased. Meddah and Bencheikh (2009) also reported that a mixture of waste fibres of differing lengths produced the best load-carrying capacity and flexural properties. Aiello *et al.* (2009) also studied the mechanical properties of concrete reinforced with recycled steel wires from waste tyres; the results obtained using waste fibres were comparable to those using industrial steel fibres and might thus be a promising candidate for use in FRC (Aiello *et al.*, 2009). Jala (2012) reported an increased concrete compressive strength using recovered waste fibres from milling and machining. Recently, Jang *et al.* (2014) investigated the influence of adding thin film transistor liquid crystal display (TFT-LCD) waste glass with an appropriate ratio of activator on binder in mortar. The obtained results showed that utilising TFT-LCD as an admixture decreased alkali–silica reaction expansion and enhanced the workability and compressive strength of the mortars (Jang *et al.*, 2014).

In the current research, 105 specimens were prepared and the viability of replacing industrial steel fibres with waste steel wires was investigated using two types of fibre in structural lightweight concrete. Compression, tensile, flexural and impact tests were conducted on 28 d old waste steel fibre reinforced concrete and concrete reinforced with commercial steel fibres. This paper presents the results of the experimental programme.

Experimental investigation

Cement matrix

Ordinary type 2 Portland cement (ASTM C150) with a bulk density of 1160 kg/m^3 was used for all the concrete mixtures. Perlite aggregate with a bulk density 93 kg/m^3 and 5 mm maximum size was used. The fine aggregate was natural river sand with a specific gravity of 1·52 and maximum size of 5 mm. Both sand and perlite aggregates were batched in dry conditions. A commercial liquid super silica gel (SSG) at a constant supply of 8% of the cement content was used in all the samples.

Fibres

Two types of steel fibres were used – waste steel wires and commercial hooked-end steel fibres. Waste steel wires found as such constitute the main waste material found in the construction sites in which steel reinforcement as well as formworks were highly used.

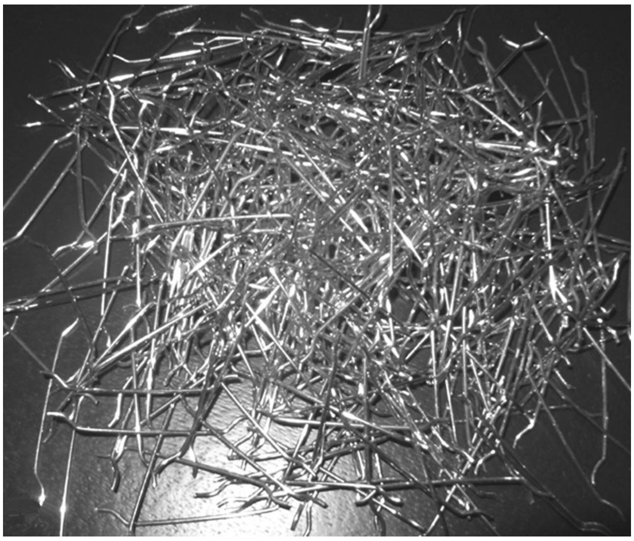
The sizes of both types of fibre were made similar in order to make the results comparable. The length and diameter of the industrial steel fibres were 50 mm and 1·2 mm respectively whereas the length and diameter of the waste steel wires were 50 ± 10 mm and 1·2 mm respectively. The density of the fibres was approximately 7850 kg/m^3 and their tensile strength 1100 MPa. Regarding the actual shape of the fibres, cut waste steel wires were used as a comparison against virgin hooked-end steel fibres (Figure 1). The percentages of reinforcing fibres examined were 0·25%, 0·50% and 0·75% volume fractions of the concrete.

Mixture composition

Lightweight perlite concrete – the volumetric mixing of cement, sand, perlite aggregate, steel fibres, water and SSG – was used for the preparation of all the samples. For all mixtures, a water/cement (w/c) ratio of 0·4 was used while the amount of SSG was constant. Table 1 details the mix proportions. The first four letters of the mix name indicate the type of fibre used – waste steel wires (WFRC) or industrial steel fibres (SFRC); the number following symbolises the fibre content in volume per cent.

To prepare the lightweight aggregate fibre reinforcement, perlite and sand were first dry mixed for 1 min. Then, cement was added to the mixer while running and mixing was continued for another minute. During the mixing operation, the fibres were added and all the materials were mixed for another 2 min. The required amount of a mixture containing water and SSG was then slowly added to the mixer, while mixing was continued for 3 min. Specimens were

(a)



(b)

Figure 1. (a) Cut waste steel wires; (b) standard hooked-end steel fibres

Mix	Perlite	Sand	Cement	Volume fraction of fibre: %	w/c	SSG: %
Plain	2	1	2	0·00	0·4	8
WFRC0·25	2	1	2	0·25	0·4	8
WFRC0·50	2	1	2	0·50	0·4	8
WFRC0·75	2	1	2	0·75	0·4	8
SFRC0·25	2	1	2	0·25	0·4	8
SFRC0·50	2	1	2	0·50	0·4	8
SFRC0·75	2	1	2	0·75	0·4	8

Table 1. Volumetric mixes of FRC specimens

formed by pouring at least three layers of concrete into moulds. Once the moulds were full, the concrete specimens were vibrated for a period of 8–12 s to ensure good compactness.

The specimens were kept in the laboratory for 24 h under constant ambient temperature. Then, all the specimens were stored in a water tank at a constant temperature of 20 ± 2°C for 28 d, until the day of the experiments.

Test method

From each mixture, three samples were tested after 28 d of curing. A total of 105 cubic, cylindrical, prismatic and disc specimens were prepared for subsequent testing.

Compression test

A total of 21 cubic specimens of dimensions $100 \times 100 \times 100$ mm were prepared for compression testing according to ASTM C39-03 (ASTM, 2003). The tests were performed using a digital automatic testing machine and a load rate of 0·15 MPa/s.

Splitting tensile test

A total of 21 cylindrical specimens (150×300 mm) were prepared for splitting tensile testing conforming to ASTM C496-04 (ASTM, 2004). The tests were performed using a digital automatic testing machine with a load rate of 0·7 MPa/min. A suitable jig was used to position the concrete cylinder: as loading started, the centre of jig, the centre of specimen and the centre of thrust of the spherical bearing block were aligned.

The splitting tensile strength T of the specimens was calculated as

$$T = 2P/\pi ld$$

where P is the maximum applied load indicated by the testing machine, l is the length of the cylinder and d is its diameter.

Flexural test

Flexural tests were conducted on 21 prismatic specimens with dimensions of $500 \times 100 \times 100$ mm in accordance with ASTM C1018-97 (ASTM, 1997). A universal three-point loading machine of 1000 kN loading capacity was employed. The load-carrying capacities and mid-point displacements of the specimens were recorded. The rate of increasing net mid-span deflection was adjusted to 0·1 mm/min. Load–deflection curves were then plotted and the magnitudes of toughness indices (I_5, I_{10} and I_{20}) and residual strength factors ($R_{5,10}$ and $R_{10,20}$) were evaluated. The toughness indices were calculated by determining the area under the load–deflection curves up to the predetermined deflections as proposed in ASTM C1018-97 and dividing it by the area up to the first-crack deflection.

Impact test

A total of 42 disc specimens (diameter 150 mm and thickness 640 mm) were prepared for impact testing according to the recommended method proposed by ACI Committee 544 (ACI, 1999). Due to the use of fibres of 50 mm length, the test specimens were cut from a full-size cylinder to minimise preferential fibre alignment (ACI, 1999; Nataraja *et al.*, 2005).

According to the drop weight impact test method, the disc specimens were struck by repeatedly dropping a 4·5 kg hammer from a height of 45 cm. The load was transferred from the hammer to the specimen through a 64 mm steel ball placed at the centre of the disc specimen (Nataraja *et al.*, 2005). The initial and ultimate failure points were evaluated, testifying the impact resistance of the specimens: the initial failure point is the number of blows required to cause the first visible crack in the specimen and the ultimate failure point is the number of blows after which the disc specimen fails and comes into contact with three of the four steel lugs of the test equipment (Badr *et al.*, 2006; Nataraja *et al.*, 2005). The impact load was time independent.

Results and discussion

Compressive strength

Figure 2 shows the compressive strength results for WFRC specimens, SFRC specimens and plain concrete specimens. The compressive strength of the perlite lightweight concrete used for the plain and FRC specimens was 18·86–24·26 MPa and its density was 1708·5–1800·0 kg/m^3. This type of concrete is known as structural lightweight concrete (ASTM, 2002). It was found that an increase of waste wire content and industrial steel fibre from 0 to 0·25% increased the compressive strength of WFRC and SFRC specimens by approximately 5% and 18% respectively compared with the plain concrete specimens. The compressive strength of the FRC specimens with 0·50% volume fraction of the concrete increased significantly, reaching peak values of 24·08 MPa and 24·84 MPa for WFRC and SFRC respectively.

However, compared with the plain concrete, the compressive strength of both WFRC and SFRC decreased (by 8% and 3% respectively) when further increasing the fibre or wire content from 0·50% to 0·75%. It is worth noting that the compressive strength for the highest level of fibre content (0·75%) is lower than that of the plain concrete. This decrease in compressive strength for this fibre content may be due to difficulties in scattering and condensing the fibres in the concrete. This phenomenon has been discussed elsewhere (Hassanpour *et al.*, 2012).

Splitting tensile strength

The splitting tensile strength results for plain concrete and FRC specimens are shown in Figure 3. As can be seen, the addition of fibres greatly increased the splitting tensile strengths. Compared with the plain concrete specimens, the splitting tensile strengths of WFRC and SFRC specimens increased by an average of 28% and 26·33% respectively for fibre ratios of 0·25%, 0·50% and 0·75%. Similarly, Gao *et al.* (1997) reported that an addition of steel fibre from 0 to 2% volume fraction of the concrete increased the splitting tensile strength from 4·95 to 8·80 MPa. Ultimately, the increase in splitting tensile strength is based on the connection between the fibres and the cement matrix. In fact, adding fibres at only 0·25% increases the splitting tensile strength significantly. This shows that, with any addition of fibres, the

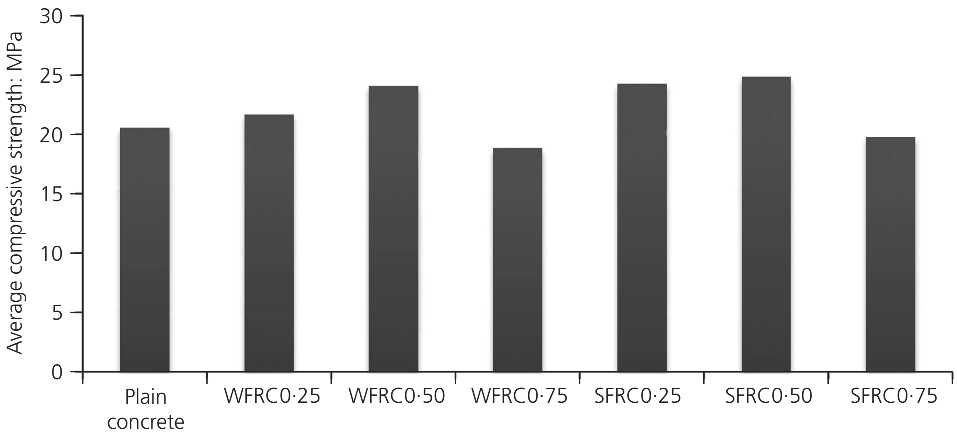


Figure 2. Average compressive strength of WFRC, SFRC and plain specimens

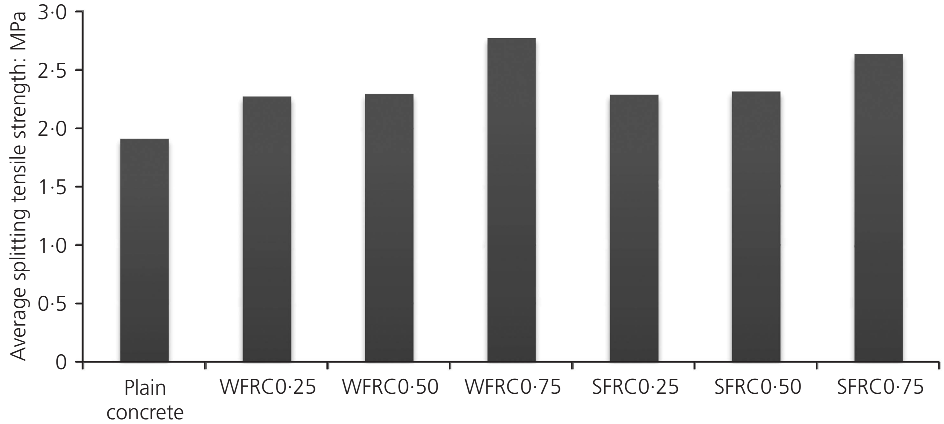
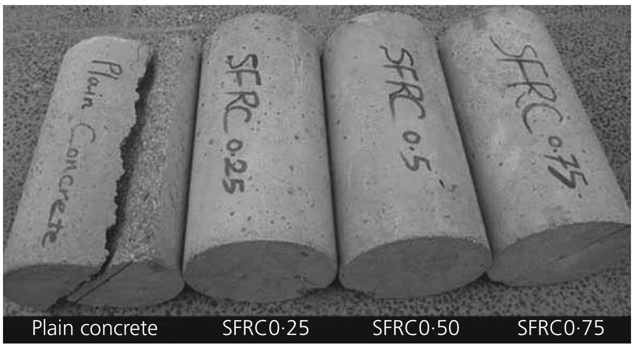


Figure 3. Average splitting tensile strength of WFRC, SFRC and plain specimens

splitting tensile strength of FRC specimens will be improved remarkably, as noted by Shafigh *et al.* (2011) and Balendran *et al.* (2002).

Figure 4 shows the plain concrete rupture with brittle failure following the tensile strength peak. Conversely, the FRC specimens showed only small surface cracks in the direction of the load transfer, across the length of the specimens. Fibres thus play a significant role in making concrete capable of resisting crack propagation.

(a)



(b)

Figure 4. Comparison of failure patterns of plain and FRC specimens after splitting tensile strength: (a) WFRC; (b) SFRC

Flexural strength

The flexural test results of the different mixes are summarised in Table 2. Each result is the mean value recorded from three tests. All values of the first-crack strength (FCS) of FRC specimens were higher than those of the plain concrete specimens. Similarly, the first-crack deflections were higher with increasing the fibre percentage due to increased ductility of the FRC specimens. The maximum FCS of the FRCs is 3·745 MPa, which is 40% higher than the FCS of the plain concrete specimens; this value relates to WFRC0·75%. The corresponding maximum FCS of SFRC is approximately 29% higher than that of the plain concrete.

In order to determinate the energy absorption capability and toughness of flexural specimens, the toughness indices and residual strength factors were assessed as suggested in ASTM C1018-97 (ASTM, 1997). The toughness indices relate to the ability of FRC specimens to transfer stresses across a cracked section and this is considered as their energy absorption capacity. Table 2 shows that increasing the volume fraction of fibres increases the toughness indices for both WFRC and SFRC specimens. The toughness indices of WFRC specimens are higher than those of SFRC specimens at 0·25% and 0·75% fibre contents, while the values are very similar for both concrete types for 0·50% fibre content.

Moreover, the toughness indices of WFRC0·50 and WFRC0·75 are almost equal. This reveals that the post-peak area in the load–deflection curves increased in a proportional manner compared with the pre-peak area. In contrast, the toughness indices of SFRC0·50 are significantly higher than those of SFRC0·25 or SFRC0·75. Therefore, in the case of 0·50% fibre content, the post-peak area increased significantly compared with the pre-peak area, whereas in other SFRCs the post-peak area increased proportionally to the pre-peak area (Figures 5 and 6).

	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	0·00	2·676	0·642	—	—	—	—	—
WFRC0·25	0·25	3·027	0·853	2·58	4·14	6·56	31·2	24·2
WFRC0·50	0·50	3·312	1·087	4·26	7·31	11·47	61·0	41·6
WFRC0·75	0·75	3·745	0·946	4·13	7·28	11·91	63·0	46·3
SFRC0·25	0·25	3·515	0·855	2·29	3·61	5·85	26·4	22·4
SFRC0·50	0·50	3·295	1·005	4·65	8·09	12·00	68·8	39·1
SFRC0·75	0·75	3·440	1·480	3·42	4·95	6·67	30·6	17·2

Table 2. First-crack strength, first-crack deflection, toughness indices and residual strength factors of specimens in bending specimens

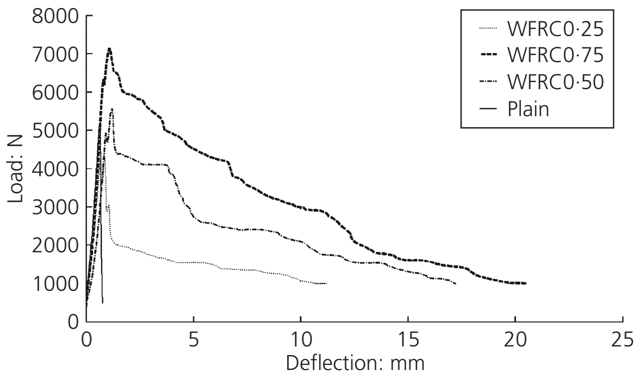


Figure 5. Flexural load–deflection curves of WFRC and plain specimens

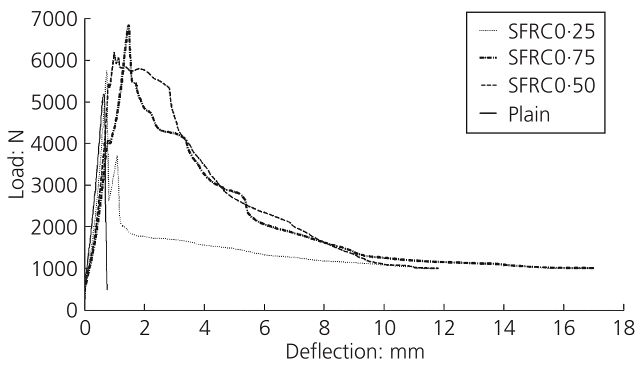


Figure 6. Flexural load–deflection curves of SFRC and plain specimens

The residual strength factors represent the average level of strength retained after occurrence of the first crack as a percentage of the FCS over a predetermined deflection interval (ASTM, 1997). Table 2 shows that higher residual strength factors are achieved with increasing fibre content, and concrete specimens reinforced with waste steel wires produced higher residual strength factors than their industrial steel fibre counterparts.

Figures 5 and 6 show average load–deflection curves for different percentages of fibre content for WFRC and SFRC specimens respectively. The plain specimens without fibre tested under bending action failed in a brittle manner once the peak load was reached. They broke into two pieces suddenly, and the small area under the load–deflection curve illustrates the small amount of energy absorbed. The FRC specimens exhibited ductile behaviour due to the characteristic bond between the fibres and the cement. Analysis of the load–deflection curves reveals that the first crack was followed by a sharp drop in the load-carrying capacity and then a descending curve follows, leading to ultimate failure. The results show that the ultimate deflection of specimens WFRC0·75 and SFRC0·75 is respectively about 32·0 and 26·5 times greater than that of the plain concrete specimens.

The absolute toughness index (or absorbed energy) is assessed by estimating the total area under the load–deflection curve up to ultimate failure. Figure 7 shows that all the indices of the FRCs are higher than those of plain concrete. WFRC0·75 shows the highest energy absorption, with an average value of 6276·63 kg mm, about 28·5 times higher than that of plain concrete. The absorbed energy of SFRC0·75 is 3585·994 kg mm, considerably lower than that achieved by WFRC0·75.

Impact strength

The values of first-crack resistance and ultimate resistance were also averaged, having considered six specimens for each mixture. As shown in Table 3, the number of blows required to cause the first visible crack and the number of blows needed for ultimate failure increase with increasing fibre content. The plain concrete specimens presented brittle behaviour and very low resistance after the initial crack, with specimens taking fewer blows reaching ultimate failure earlier. The FRC specimens were able to bear considerably more blows up to ultimate failure. The increase in post-crack resistance is absolutely dependent on fibre content

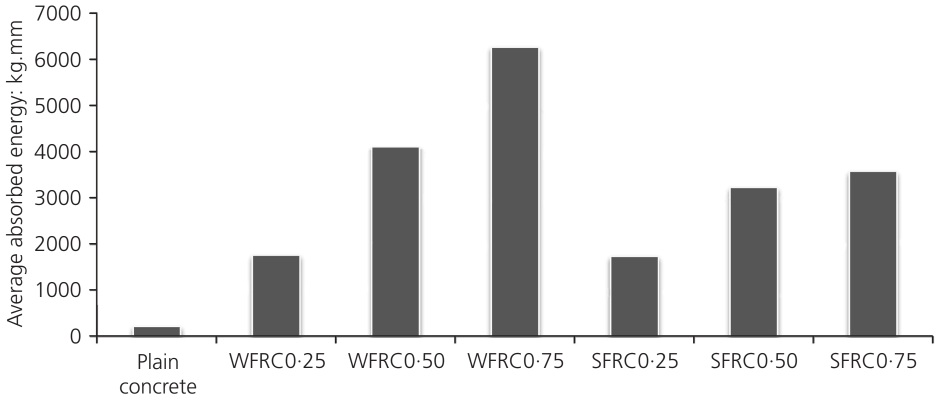


Figure 7. Average amount of absorbed energy by bending samples in kg.mm

	First-crack resistance (FCR): number of blows	Ultimate resistance (UR): number of blows	Increase in resistance from FCR to UR: %	FCR_{FRC}/FCR_{Plain}	UR_{FRC}/UR_{Plain}
Plain	2	3	50·00	—	—
WFRC0·25	3	28	833·33	1·5	9·33
WFRC0·50	3	36	1100·00	1·5	12·00
WFRC0·75	3	53	1666·67	1·5	17·67
SFRC0·25	3	31	933·33	1·5	10·33
SFRC0·50	4	48	1100·00	2·0	16·00
SFRC0·75	4	67	1575·00	2·0	22·33

Table 3. Impact test results

(e.g. 833% to 1667% for WFRC specimens and 933% to 1575% for SFRC specimens). Consequently, a significant improvement in impact load resistance is essentially achieved by increasing the volume fraction of both types of fibre in structural lightweight concrete.

Because the fibres span across the cracks, the impact energy of hammer blows can be absorbed, crack propagation within the concrete is prevented and splitting of the concrete into small pieces is also minimised. For SFRC specimens, better performance was achieved under impact action: the specimens resisted more blows than the WFRC specimens due to the hooked-end steel fibres and thus further interlocking between the fibres and the concrete. The impact resistance of SFRC0·75 and WFRC0·75 was respectively about 17 and 13 times greater than that of the plain concrete specimens. One way to improve the impact strength of WFRC specimens would be to use a larger amount of steel waste wires, thus increasing the splitting tensile strength.

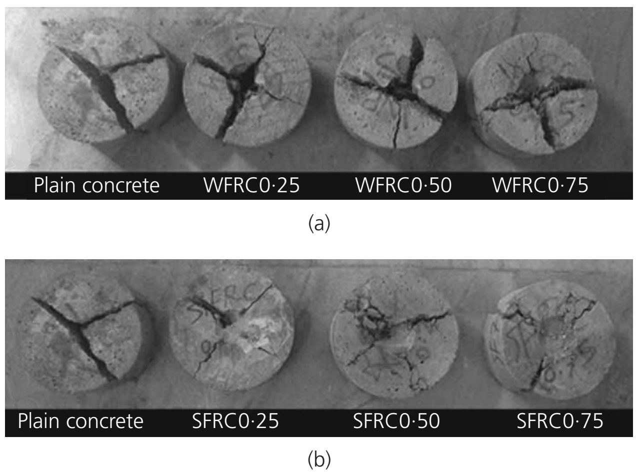


Figure 8. Comparison of failure patterns of FRC specimens after impact testing: (a) WFRC; (b) SFRC

Upon impact testing, the plain concrete specimens broke into three pieces, implying a brittle failure mode (Figure 8). The FRC specimens presented at least four large polar cracks due to the more uniform stress distribution in the concrete. The width of cracks in the SFRC samples was smaller than those in the WFRC specimens. This again indicates that the SFRC specimens possess higher impact resistance due to the more effective bridging of fibres across the cracks.

Concluding remarks

The mechanical properties of structural lightweight concrete reinforced with waste steel wires (WFRC) were experimentally investigated. The results were compared to the mechanical properties of lightweight concrete reinforced with commercial steel fibres (SFRC) and plain concrete.

Incorporating waste wires or industrial steel fibres up to 0·50% volume fraction of concrete in structural lightweight concrete increases the compressive strength. However, the addition of more than 0·50% volume fraction of concrete decreases the compressive strength. These increasing and decreasing strength trends with respect to fibre content were the same for both types of fibres considered. The FRC specimens showed considerably higher splitting tensile strengths than the plain concrete specimens, even for low volumes of fibres. The overall performance in terms of splitting tensile strength was better in WFRC specimens than SFRC specimens. It is remarkable that even very small quantities of fibres can help in preventing the brittle failure of lightweight aggregate concrete.

The maximum flexural strength and energy absorption was obtained by WFRC0·75 specimens: the energy absorption of WFRC0·75 was 28·5 times greater than that of plain concrete and 75% higher than that of SFRC0·75. Furthermore, the addition of waste steel wires at 0·75% volume fraction of the lightweight concrete led to an eighteen-fold increase in ultimate impact resistance compared with the plain concrete specimens. While this improved the impact resistance significantly, it was still lower than that of SFRC0·75 due to the hooked shape of the commercial fibres.

In conclusion, the use of waste steel wires is considered suitable for certain applications, acting as micro reinforcement. The direct reuse of such wires is a viable, economic and environmentally friendly method for replacing the more expensive industrial steel fibres.

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