

## Sustainable fibre-concrete reinforcement using manufacturing by-products

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### Abstract:

*Introduction/purpose: Concrete is a material with very high compressive strength compared to very low tensile strength, which makes it brittle under tensile and bending stresses, with premature failure manifested by cracking. These stresses can be improved by reinforcing concrete with different types of fibres derived from industrial or other wastes.*

*Methods: In this context, this work aims to use industrial metal waste in concrete and compare it with metal fibre concrete to overcome this tensile strength deficiency. Two types of industrial fibres and two other types of waste were used, aluminium and steel waste (in the form of shavings) re-*

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covered from mechanical milling plants. The properties of the different fibre concretes in the fresh and hardened states are analysed and compared with natural non-fibre concrete.

*Results:* The experimental results suggest that incorporating such waste in concrete reduces the workability of concrete mixtures, improves the tensile strength of concrete, and reduces considerably its shrinkage without affecting its compressive strength.

*Conclusion:* Following a rigorous analysis of the obtained results, it was determined that the optimum percentage of recycled fibre in steel is 15%. The tensile strength at this level is comparable to that of industrial fibre-reinforced concrete. This finding is very relevant to the sustainable development strategy of the Algerian government, which promotes the improvement of characteristics and the conservation of natural resources.

*Key words:* fibre concrete, industrial fibres, dimensional variation, mechanical characteristics, metal waste, recovery.

## Introduction

For more than half a century, fibre-reinforced concrete has been the focus of major research efforts in the construction industry. Cement-fibre and concrete-fibre composites represent a major technological advance in many areas of construction and public works (Blazy and Blazy, 2021). In this context, one of the most important ways of improving the performance of concrete is to distribute fibres evenly throughout its volume, resulting in a material known as fibre-reinforced concrete. Several research projects aimed at developing high-performance cementitious matrices have stimulated interest in the use of all types of fibre-reinforced cementitious composites, as studied (BERNIER, 1991).

Several types of fibres of different sizes and shapes, made from many different materials are used; steel fibres are most commonly used, but glass, polypropylene, graphite or Kevlar fibres can also be used (Shah & Ribakov, 2011). A combination of factors, such as the properties of the fibre material, the ability to form bonds between the matrix and the fibres, the content and concentration of fibres in the composite, and the way in which the fibre-reinforced concrete is produced, determines the effectiveness of the fibre action and the resulting mechanical properties of the material (Zollo, 1997). The effectiveness of steel fibres is significantly influenced by their shape and proportions; the aspect ratio is the most important parameter describing the geometrical proportions of the fibres.

A further important factor is the shape of the fibre anchor, which prevents the fibre from being pulled out of the matrix. Fibres with hooked

or small heads at their ends are commonly used (Martinie et al, 2010; Shah & Ribakov, 2011). The addition of industrial or certain types of recycled fibres to concrete has a beneficial effect on several of its mechanical properties, such as tensile strength, shrinkage, crack resistance and ductility (Borg et al, 2016; Irki et al, 2017; Mohammadi et al, 2008; Pešić et al, 2016). As well as using industrial fibres to reinforce concrete, certain fibres can be recovered from by-products, and a number of researchers have investigated the mechanical behaviour of fibre-reinforced concrete (FRC) made from both industrial steel fibres and recycled steel fibres recovered from scrap tyres (Martinelli et al, 2015; Onuaguluchi & Banthia, 2018). In addition, the thinner and shorter fibres recovered from tyres were found to be significantly more rigid, giving the fibre-reinforced concrete (FRC) better mechanical parameters (Li et al, 2004a; 2004b). The result is more ductile products capable of limiting the propagation of damage while ensuring greater durability. These materials are very recent for a sector such as civil engineering, where innovation is difficult (BERNIER, 1991; Rossi & Harrouche, 1990).

There is a wide range of literature on the use of fibres to modify the properties of concrete. Fibres have different effects on the mechanical parameters of concrete - they can improve or deteriorate the properties, depending on the geometry and material of the fibres. It's important to study how the incorporation of recycled fibres affects the concrete and mortars' behaviour in order to explore their effective use as fibre reinforcement (Irki et al, 2018). A number of studies have tested cementitious and polymer matrices reinforced with natural recycled fibres (Abdelaziz et al, 2016; Fiore et al, 2014; Hbib et al, 2011; Irki et al, 2018), while Grzymiski et al. (2019) investigated the mechanical properties of concrete incorporating recycled fibres derived from machining waste.

This paper investigates the use of recycled aluminium and steel scrap from mechanical milling in the form of chips, incorporated into conventional vibrated concrete to ensure sufficient water tightness, avoiding high humidity or the presence of water which can cause corrosion of aluminium scrap in alkaline environments (CSTB, 2008), and describes the basic mechanical properties and compares them with industrial fibres. These studies are consistent with the current trend towards sustainable development, and, like other recycled fibres, may help to make effective use of machining waste.

## Experimental materials and methods

### Materials

In the present study, all mortar mixtures employed a local commercial Portland cement CEM II/B 42.5 sourced from Msila, Algeria. This cement has a Blaine fineness of 385 m<sup>2</sup>/kg, a density of 3.15, and an average compressive strength of 42.5 MPa at 28 days. It exhibits a low hydration rate and contains a limited amount of sulphides. Table 1 provides a summary of the cement's chemical composition.

Table 1 – Chemical analysis of *the* cement used in the experimental program

Chemical composition (wt %)						
SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	SO <sub>3</sub>	CaO	MgO	LOI
20.92	5.33	3.43	1.83	61.74	1.58	1.65

The coarse aggregates consisted of natural crushed limestone, with a maximum size of 20 mm and a specific gravity of 2530 kg/m<sup>3</sup>. For the fine aggregates, a blend comprising 40.17% fine roller sand with a fineness modulus of 1.00 and 59.83% coarse limestone crushed quarry sand was used, with a fineness modulus of 3.35. The overall fineness modulus of this combination was 2.80. These aggregates had a specific gravity of 2550 kg/m<sup>3</sup> and a water absorption rate of 1.52%. The physical and mechanical characteristics of the sands are shown in Table 2. Table 3 shows the characteristics of the fibres used for this purpose.

Table 2 – Aggregate characteristics

Characteristics	Fine aggregate		Coarse aggregate	
	roller sand (0/3)	crushed sand (0/5)	8/15	15/25
Finesse modulus	1.00	3.35	/	/
Bulk density (g/cm <sup>3</sup> )	2.48	2.54	2.50	2.53
Absolute density (g/cm <sup>3</sup> )	1.42	1.49	1.29	1.27
Sand equivalent test SE (%)	69.52	90.60	/	/
Water absorption (%)	1	1.8	0.70	0.80

The recycled fibres are incorporated into the concrete at a rate of 5, 10, 15, 20 and 25% by mass of the cement paste. These rates correspond to 0.5, 1, 2 and 3% by volume of recycled steel fibres and 0.25, 0.75, 1 and 1.25% by concrete volume of recycled aluminium fibres. On the other hand, the industrial fibres are incorporated at 1% by concrete volume.

Table 3 – Mechanical properties of the used fibres

Type of Fibre	FI50 (F1)	T30/50 (F2)	RS	RA
L (mm)	35	30	20	20
D /Thick (mm)	0.60	0.50	0.30	0.30
Width ( $\pm 0.1$ mm)	/	/	3	3
Aspect ratio (l/d)	58	60	66	66
Form	Wavy	hooked	spiral	spiral
Modulus of elasticity[GPa]	210	210	150	69
Elongation at break (%)	4	3.40	0.8	3
Tensile resistance [MPa]	1180	1000	890	120

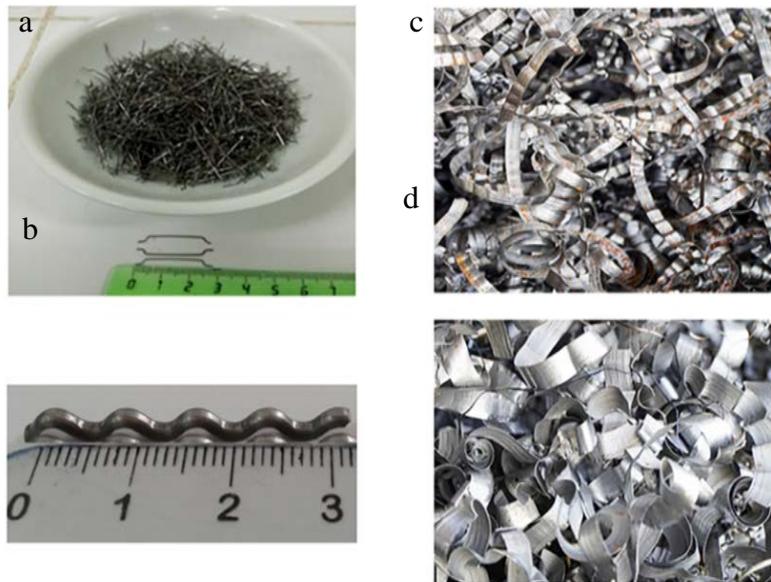


Figure 1 – (a) Industrial fibre (F1), (b) Industrial fibre (F2), (c) Recycled fibre (RS) and (d) Recycled fibre (RA)

### Method

The composition of the concrete, with a cement dosage of 350 kg/m<sup>3</sup>, was based on the BARON-LESAGE method developed at the Laboratoire des Ponts et Chaussées, Paris (Baron & Lesage, 1976), based on the optimisation of the granular skeleton in the concrete by varying the dosage of fine aggregate in relation to coarse aggregate. The flow time is measured by the LCPC Manibilimeter. This optimisation is shown in Figure 2.

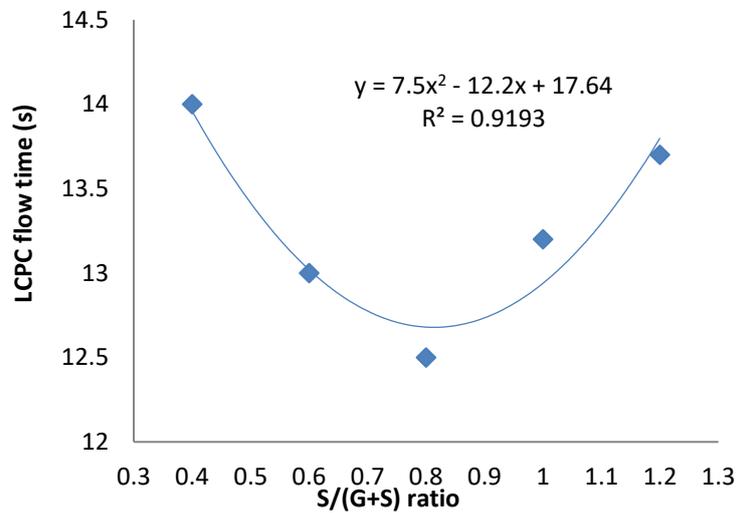


Figure 2 – Granular skeleton optimization

For all mixes, the fine aggregate/total aggregate ratio is kept constant at 0.8, by applying the recommendations of the Baron-Lesage method, summarised as follows:

- A constant W/C ratio for all mixtures is maintained; in this study this ratio is set at W/C= 0.4;
- Flow time is maintained between 8 and 13 seconds, measured with an LCPC maniabilimeter;
- To achieve the last condition, it is necessary to use a plasticizing adjuvant to obtain the desired workability. Table 4 shows the composition of the mixtures studied.

While RC represents the Reference Concrete, RS-C is the recycled steel concrete, and RA-C is the recycled aluminium concrete, whereas F1-C and F2-C are concretes based on f150 and T30/50 fibres respectively.

Table 4 – Concrete composition

	RC	F1-C	F2-C	RS-C (%)				RA-C (%)			
				5	10	15	20	5	10	15	20
<b>Cement (kg)</b>	350										
<b>Roller sand. (kg)</b>	326.77										
<b>Crushed sand (Kg)</b>	470.23										
<b>8/15 (Kg)</b>	106.33										
<b>15/25 (Kg)</b>	890										
<b>Water (kg)</b>	140										
<b>W/C</b>	0.40										
<b>S/(G+S)</b>	0.80										
<b>Fibre (kg)</b>	0	20		17.5	30	52.5	87.5	17.5	30	52.5	70
<b>Plasticizer (kg)</b>	1.75	2.45	2.10	2.10	2.275	2.450	2.62	2.27	2.45	2.45	2.62

## Experimental results and discussion

The results of the various tests on fresh and hardened concrete are shown below, representing the average of at least three test results.

The mixes must have practically constant workability in order to compare the results of the different types of concrete. A third generation plasticiser based on ether polycarboxylate, supplied by Granitex Algeria (Medaflo 30), was introduced to optimise a consistent flow time interval.

### *Workability of concrete*

In accordance with the recommendations of Standard NF P18-452 (AFNOR, 2017), the workability of the concretes produced is measured using an LCPC workability meter. A constant workability was optimised in order to compare the results in the hardened state, with the flow time considered to be between 10 and 12 seconds ( $\pm 0.5s$ ). The results of this stage are shown in Figure 3.

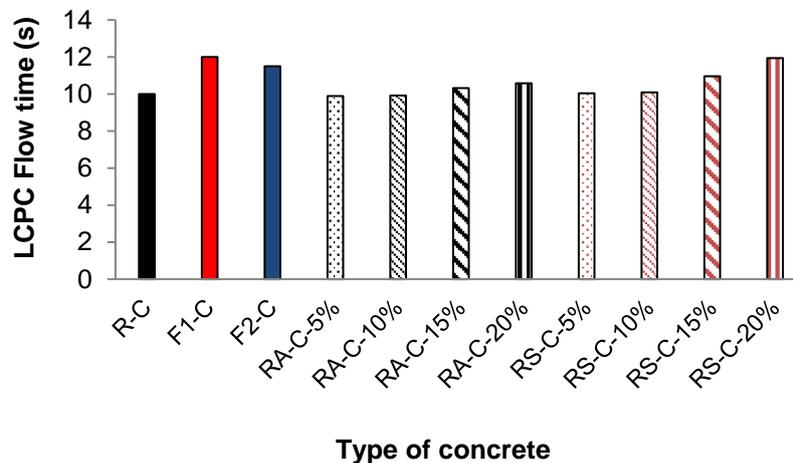


Figure 3 – Flow times for different types of concrete

The results show that the workability of the concrete decreases as the fibre incorporation dosage increases. For this test, the plasticizer dosage was varied to achieve comparable workability between the concretes. For low fibre dosages, workability comparable to the control concrete was recorded, but the higher the fibre dosage, the lower the workability and the concrete required a higher percentage of plasticiser, varying between 30% and 55% compared to the reference concrete. We can also see that the two types of recycled fibres show the same variation.

This finding has been confirmed by other researchers who have incorporated fibres and/or by-products as fibres in high-performance and self-compacting concretes (Borg et al, 2016; Centonze et al, 2012; Corinaldesi & Moriconi, 2011; Irki et al, 2017; Irki et al, 2018; Swamy & Mangat, 1974; Westerholm et al, 2008). On the other hand, industrial fibres affect workability more than recycled fibres, which may be due to the shape of the fibres and their high stiffness (Martinie et al, 2010).

### *Occluded air*

Incorporating fibres can change some properties in the fresh and cured state, including air content, which is measured in this study according to EN 12350-7 (CEN, 2009).

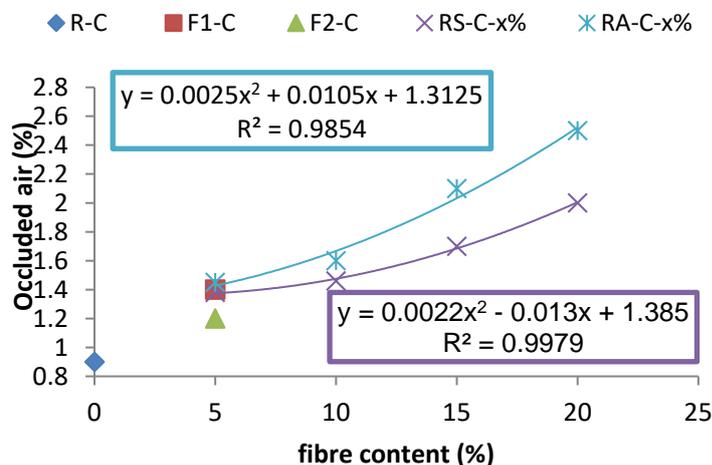


Figure 4 – Occluded air of concrete mixtures

It can be seen that for all the blends the entrapped air varies between 1.4 and 2.6%, which are considered reasonable values (Ortega-Lopez et al, 2021). The percentage of spherical pores in the blends increases as the recycled fibre dosage increases; the spiral shape of the recycled fibres favours the formation of micro-bubbles, and the formation of voids at the fibre/solid matrix interface as a result of air bubbles being entrapped by the fibres during the mixing process (d’Almeida et al, 2006; Pons Ribera et al, 2023; Sakami et al, 2020).

It is very important to investigate whether concrete properties improve by increasing air entrainment. Entrained air can improve freeze-thaw resistance, but it can also reduce the concrete density and decrease compressive strength as seen in Figures 5 and 6 (de Oliveira & Castro-Gomes, 2011; Irki et al, 2017; Irki et al, 2018; Savastano et al, 1999).

### *Bulk density*

The density of fresh concrete was calculated in accordance with Standard NF EN 12350-6 (12350-6, 2019), using the receptacle of the occluded air apparatus.

From the results obtained for density, a decrease in density was observed with increasing fibre dosage. Since the variation is in the order of 0.42% to 2.50%, this decrease is considered a moderate variation (Pons Ribera et al, 2023).

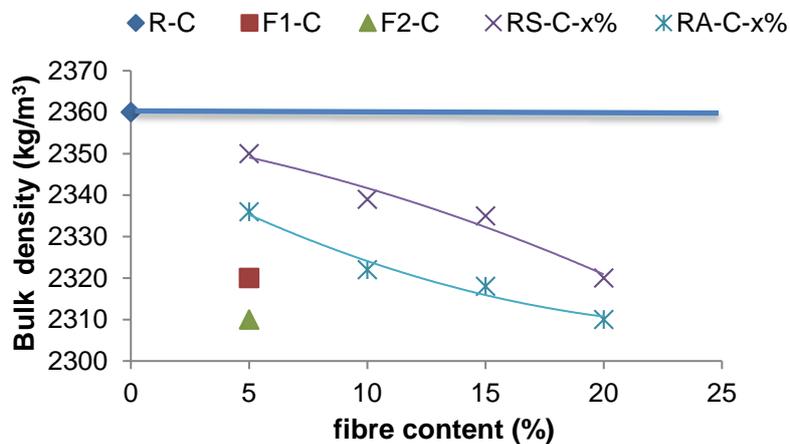


Figure 5 – Bulk density of concretes

The spiral shape of the fibres, which allows the cement paste to penetrate, may be responsible for this small reduction. Moreover, RAC-C-x% blends have a lower density than RS-C-x% blends because steel is known to have a higher density than aluminium. However, incorporating both types of fibre reduces concrete density.

The incorporation of fibres generates more voids at fibre/ matrix interface during the mixing process, causing an increase in porosity and a decrease in bulk density (Abani et al, 2015). Similar results were observed by Sakami et al. (2020), who reported a reduction in bulk density of up to 14.68% when 5% Alfa fibre reinforcement by mass was used.

### Compressive strength

The compressive strength of hardened mortar was measured using 100 mm cubic specimens at the age of 28 days, as per References EN12390-1 and EN12390-2 (EN, 2000, 2009b; EN, 2009b). The specimens were covered with plastic sheets, stored in the laboratory for 24 hours, and then cured in water at 20°C. Figure 6 presents the results for 7, 28, and 90 days of curing.

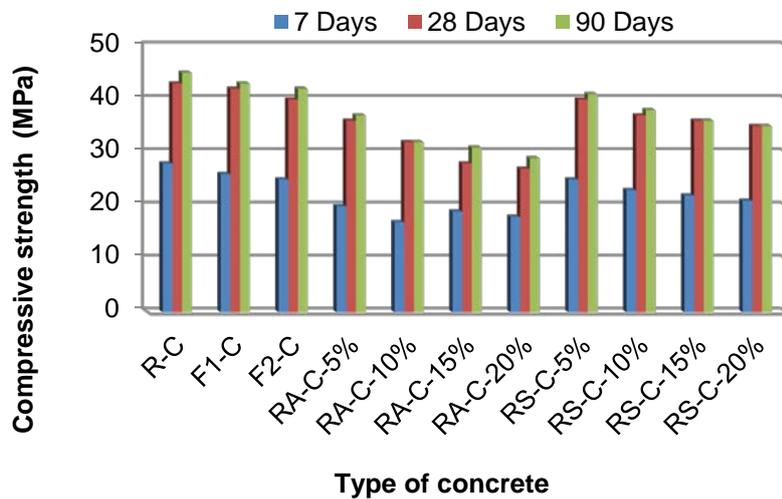


Figure 6 – Variation of the compressive strength with fibre type and amount

The results show that the incorporation of fibres (all types) affects the compressive strength of concrete (Irki et al, 2017; Irki et al, 2018; Savastano et al, 1999). The average reduction is from 7 to 10% for industrial fibres, from 16 to 35% for the RAC-C-x% series and from around 7% to 15% for RS-C-x% series, which is probably due to the decrease in compactness concretes by the increase of occurred air.

It should also be noted that the strength of concrete based on aluminium scrap is more affected. This may be due to the flexibility of this type of waste, whereas steel scrap shows a slight decrease in strength due to better mechanical properties.

Similarly, other researchers have reported that the decrease in compressive strength of SFRCs is due to the decrease in ductility and workability as the volume fraction of fibres increases. The inclusion of fibres leads to a change in failure mode from brittle to ductile failure (Borg et al, 2016; Centonze et al, 2012; Corinaldesi & Moriconi, 2011; Ferrara et al, 2007; Irki et al, 2017)

### *Flexural strength*

The splitting tensile strength was measured at 7, 28 and 90 days of age by a 3-point flexure test using a testing machine with a maximum load capacity of 30 kN according to EN 12390-5 (EN, 2009a). All moulds were covered with plastic sheeting and stored in the laboratory for 24 hours before demoulding. The moulds were cured in water at 20 °C.

The results show that the incorporation of industrial fibres significantly improves the flexural tensile strength. This improvement ranges from 34 to 45% and is due to the shape of the fibres (corrugated and hooked), which ensures better load transmission and adhesion to the concrete (Irki et al, 2017).

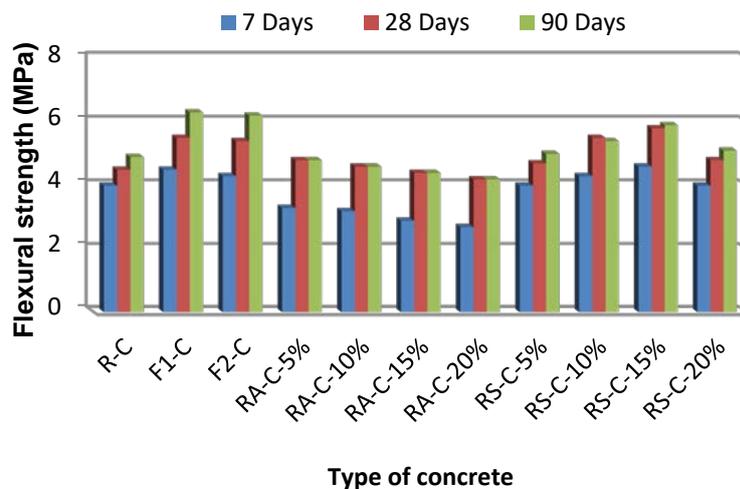


Figure 7 – Variation of the flexural strength with fibre type and amount

Looking at the strengths of the concrete series containing aluminium and steel waste, it can be seen that the RAC-C-x% series shows an inverse relationship with the incorporation of waste (fibres): the flexural tensile strength decreases as the percentage of waste increases. This variation is in the order of 4 to 16%. This is due to reduced concrete compaction resulting from increased porosity (Savastano et al, 1999). Contrary to the RS-C-x% series, the flexural tensile strength is comparable to the reference concrete at a low dosage (5%). After this amount, the strength is improved by 10 and 16% for the RS-C-10% and RS-C-15% mixes, respectively; above this percentage (RS-C-20%), the strength decreases. The increase in the flexural tensile strength confirms the good adhesion between the steel waste and the cementitious matrix, which allows a favourable load transfer up to the saturation level (20%), where the matrix becomes heterogeneous and begins to lose its mechanical properties (Bledzki & Gassan, 1999; Irki et al, 2018; Li et al, 2006).

## Conclusion

The use of recycled fibres in the reinforcement of concrete has the effect of modifying some of the properties of Fibre Reinforced concrete:

- (a) The granular skeleton of the concrete must be optimised before formulating fibre reinforced concrete.
- (b) In order to guarantee the workability of the fibre-reinforced concrete, the higher the fibre content, the greater the need for plasticiser, indicating a reduction in workability with increasing fibre content.
- (c) The incorporation of steel and aluminium fibres as well as industrial fibres reduces the density of the concrete. As the density of aluminium is lower than that of steel, concretes based on aluminium fibres have a lower density than those based on steel fibres.
- (d) The amount of occluded air generated during the mixing process increases as the recycled fibre content is increased, but is generally acceptable according to the standard.
- (e) The compressive strength of concrete reinforced with recycled fibres decreases with increasing fibre content. On average, this decrease is estimated to be 16 to 35% for concrete made from aluminium waste and 7 to 16% for concrete reinforced with steel waste. The strength of concrete made from steel is comparable to that of concrete reinforced with industrial fibres.
- (f) Contrary to the compressive strength, the tensile strength of SFR-C increases for industrial fibres (by about 20%).
- (g) Two phenomena were observed for the recycled fibre concretes: on the one hand, a gradual decrease in the flexural tensile strength for aluminium fibre concretes (from 2 to 12%) as the percentage is increased.
- (h) On the other hand, a gradual improvement of this strength up to 15% of the incorporation dosage (2 to 20% gain in strength), after this amount, the strength decreases.
- (i) The optimum percentage of recycled fibre in steel is 15%. the tensile strength at this level is comparable to that of industrial fibre-reinforced concrete.

The use of steel waste is very effective at a dosage of 15% by weight of cement and can be used for the reinforcement of non-structural elements that are subject to simple bending, such as manhole slabs, and sustainable pavements.

The results presented in this paper are part of a research project focusing on the valorisation of industrial waste by-products in civil engineering sector.

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Održivo ojačavanje betona vlaknima upotrebom nusproizvoda iz proizvodnje

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OBLAST: materijali

KATEGORIJA (TIP) ČLANKA: originalni naučni rad

**Sažetak:**

*Uvod/cilj: Beton je materijal sa veoma visokom kompresivnom, ali veoma niskom zateznom čvrstoćom, što ga čini krhim pri delovanju zateznih i savojnih naprezanja, pri čemu se prevremeni lom manifestuje pojavom pukotina. Ova naprezanja mogu se smanjiti ojačavanjem betona različitim vrstama vlakana dobijenih iz industrijskog ili drugog otpada.*

*Metode: U tom kontekstu, cilj ovog rada je primena industrijskog metalnog otpada u sastav betona i njegovo poređenje sa betonom ojačanim metalnim vlaknima radi prevazilaženja nedostatka zatezne čvrstoće. Korišćene su dve vrste industrijskih vlakana i dve vrste otpada, aluminijumski i čelični otpad (u obliku strugotina) dobijen iz postrojenja za mehaničku obradu. Svojstva svežih i očvrsljih betona sa različitim vlaknima analizirana su i upoređena sa prirodnim betonom koji ne sadrži vlakna.*

*Rezultati: Na osnovu eksperimentalnih rezultata može se zaključiti da primena ovakvog otpada u sastav betona dovodi do smanjenja obradivosti betonskih mešavina, poboljšanja zatezne čvrstoće i značajnog smanjenja skupljanja betona, bez uticaja na kompresivnu čvrstoću.*

*Zaključak: Nakon detaljne analize dobijenih rezultata, utvrđeno je da je optimalni procenat recikliranih čeličnih vlakana 15%. Zatezna čvrstoća na ovom nivou uporediva je sa čvrstoćom betona koji je ojačan industrijskim vlaknima. Ovo otkriće je posebno značajno za strategiju održivog razvoja Vlade Alžira koja promovise unapređenje karakteristika materijala i očuvanje prirodnih resursa.*

*Ključne reči: beton ojačan vlaknima, industrijska vlakna, dimenzionalne promene, mehaničke karakteristike, metalni otpad, oporavak.*

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