CONCRETE REINFORCED WITH RECYCLED STEEL FIBRES FROM SCRAP TIRES: A CASE STUDY

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Abstract

High amount of End of Life tires (ELTs) are generated every year around the world with their related negative impact on the environment. One of the strategies to reduce this impact is represented by the recovery of the constituent materials to be reused as raw materials in different technologies, including concrete products.

The introduction of steel fibres into a concrete matrix to improve its mechanical characteristics is quite known and established in FRC technologies. Generally, steel fibres are used as discontinuous reinforcement of the concrete matrix to limit the cracking growth and to enhance the post-cracking behaviour. Thus, the obtained concrete is characterized by an improvement of its toughness and its post-cracking residual strength.

The results of an experimental campaign, carried out at the University of Salento, will be discussed herein. This work is a part of a wider research project aiming to introduce recycled materials as new raw constituents in concrete mixtures such as in the production of precast panels. The results of experimental work underline the good reproduction of the laboratory scale in production plant. In addition the realized precast panels did not show shrinkage cracks or oxidation of the unplaster surface.

Keywords: FRC, Recycled fibres, Toughness, Precast panels

1. Introduction

The manufacturing technology of reinforced concrete with the use of steel fibres to improve its mechanical properties is well known and commonly used in civil engineering. Generally, this technology uses steel fibres as discontinuous reinforcement of the concrete matrix to limit the cracking growth following the load application. Thus, the obtained concrete is characterized by an improvement of the typically brittle behaviour of the ordinary matrix, mainly referring to toughness and post-cracking behaviour [1, 2, 3, 4, 5].
The experimental work is a part of a research project, based on the development and the characterization of fibre reinforced concrete with recycled steel fibres (Fig.1).

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Fig. 1: Recycled steel fibres

The project is mainly focused on the development of construction technologies with the recycling of materials from ELTs in concrete. Thus the surplus value of environmental and ecological benefits and the significant reduction in landfilling of ELTs is achieved without losing the properties of the traditional concrete. Based on the results already obtained by the authors [6, 7], the aim is to use the steel as reinforcement in concrete matrix obtaining a new material with physical and mechanical properties that can be compared to those of the reference concrete. In the specific case study, discussed in this paper, a new concrete mix was designed for its application in precast panel elements.

2. Experimental Investigation

The preliminary mix-design has been defined with the precasting company (Petito Prefabbricati s.r.l.) on the basis of their usual precast panels production system. To this goal a reference mixture, usually used for the production of panels (with a thickness of 16 cm) and thin panels (thickness 6 cm), was identified.

Generally, a concrete mix should guarantee an adequate workability to allow the correct processing times during the concrete casting. In the present context this characteristic plays an important role because the production of an ordinary double layer precast panel usually needs almost one hour to be completed. The other important limit for the proposed application is the mechanical strength achieved after 24 hours because this is the usually elapsing time between the end of casting and the panel handling. As a consequence of these remarks, the minimum characteristics required for the new reinforced mixture were a workability class at least S4 (fluid concrete), according to [8], a compressive strength after 24 hours $R_{cm(1)}$=35 MPa and a compressive strength after 28 days, $R_{cm(28)}$=55 MPa.

The variable parameters of the whole experimental work were the type of mixture (Ordinary or Fibre Reinforced) and the type of steel fibres (Industrial or Recycled), The ordinary concrete was used as a reference to compare the obtained results, in terms of fresh and hardened properties.

2.1 Materials

Ordinary Portland cement, according to the requirements of the National Standard [9], was used for the mixtures. An high-range water-reducing admixture was added to improve the fresh concrete workability. Water, limestone aggregates and locally available sand were also used. Three different grain sizes were used for all the mixtures, the sieve analysis [10] is illustrated in Fig.2.

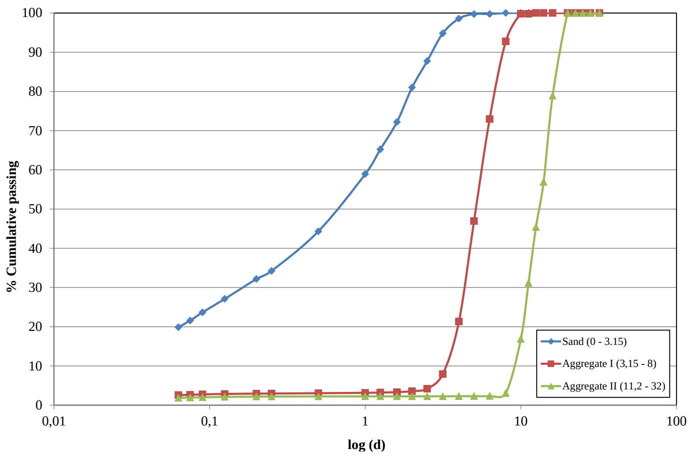

Fig. 2: Granulometric distribution

The concrete reinforced with industrial steel fibres (ISF) was realized with hooked end fibres (length/diameter=50) while the recycled steel fibres (RSF) are characterized by different geometrical dimensions and they also present many irregular wrinkles, as can be observed in Fig.1. The geometrical characterization analysis of the fibres was performed on a sample of 1.000 specimens, randomly extracted after the shredding process of ELTs. This analysis is essential to evaluate the variability of the geometrical dimensions (i.e. length and diameter) of this type of fibres, which is their main problem because it enhances the tendency of a SFRC mixture to produce balling of fibres in the freshly mixed state. The main results are: average equivalent length=24.55 mm (C.O.V.=74.87%); average diameter=0.31 mm (C.O.V.=10.73%); equivalent aspect ratio=88.37 (C.O.V.=46.79%).

2.2 Mix design

The main issue during the optimization of the mix is the tendency of the recycled steel fibres to bundle within the fresh concrete. It is well-known that the workability of a fibre reinforced concrete is negatively affected as the quantity of fibres increases [11, 12, 13]. But this represents a crucial aspect during the development of an optimal mix when recycled steel fibres are used, as discussed by the authors in previous research works [6, 7]. Generally, the recycled steel fibres are recovered by a shredding process of tires, followed by the separation of steel from the rubber through an electromagnetic procedure. Thus, the fibres are characterized by an irregular shape and a variable length. This variation in geometrical dimensions is the main reason of the previous cited tendency to bundle. In order to limit this negative behaviour, a batch mixer with a vertical axis, a fixed tank and four rotating arms was used. A homogeneous distribution of the fibres into the concrete was achieved due to the friction produced during the mixing process.

The development of the new mix-design was carried out in two steps: the first one was the optimization of the mixture (20 litres each) on the basis of the requested properties, in terms of a minimum compressive strength (35 MPa at 24 hours) and workability (minimum S3). On the basis of the reference mix, normally used for the supplier’s production of precast panels, several compositions were realized in order to achieve the required properties. Once obtained the optimal rheological and mechanical properties of the plain concrete, the fibre reinforced concrete was optimized. In this case a further slight variation of the aggregate distribution was needed as well as adding a high-efficiency viscosity modifying admixture, which allowed higher fluidity avoiding segregation. After the definition of the optimal mixtures, the second phase was the realization of three larger mixtures (approximately 170 litres each) in order to evaluate the mechanical behaviour of the proposed concrete respect to both plain concrete and industrial fibre reinforced concrete. In the Tab.1 the specifications of each final concrete mix, which was named with its own code (Plain Concrete - PC, Industrial Steel Fibre Concrete - ISFC and Recycled Steel Fibre Concrete - RSFC), are shown.

Tab.1: Concrete composition

		PC	ISFC	RSFC
Sand (0-3.15)	[kg/m^3]	971	965	965
Aggregate I (3.15-8)	[kg/m^3]	342	340	340
Aggregate II (11.2-20)	[kg/m^3]	552	548	548
Water reducing admixture	[kg/m^3]	3.2	3.25	3.25
Viscosity modifying admixture	[kg/m^3]	---	0.12	0.35
Fibres	[kg/m^3] [%v]	--- ---	32 0.41	25 0.41

The cement content (CEM II A-LL 42.5R), the water content and the w/c ratio were always constant for each mix, equal to 380 kg/m^3, 170 l/m^3 and 0.45 respectively. In the mix-design definition was also taken into account the different densities of the two utilized types of fibres: 6.10 kg/dm^3 for recycled steel fibres and 7.82 kg/dm^3 for industrial steel fibres.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In this section the results in terms of fresh and hardened concrete are presented and discussed. Both workability tests and entrapped air and density measurements were carried out in the fresh state. While compressive tests were executed on the hardened concrete.

3.1 Fresh properties

Workability is considered to be a measure of the work needed to compact the wet concrete, but it could also quantify the ability of a fresh concrete to fill the mould properly without reducing the concrete’s quality. As reported in [14], slump test is not appropriate for quantitative measures of workability when referring to SFRC; however this test has been used as a quality control test to monitor the SFRC consistency from smaller batches to bigger ones. In fact, even if the slump test does not directly measure the work required to compact the concrete, it gives good indications on the workability in terms of comparison between concrete mixes and, above all, is simple to perform. A minimum of two slump tests were performed on the fresh concrete for each mixture. According to [8], the class of consistency for each average slump values (mean value of two data) was identified. The percentage of entrapped air in the concrete sample was measured according to [15] as well as the fresh concrete density. The fresh properties of each concrete are resumed in Tab.2.

Tab.2: Fresh properties

	Slump [mm]	Fluidity grade	Air [%]	Density [kg/m^3]
PC	21	S4	2.2	2400
ISFC	22	S4	2.6	2411
RSFC	20.5	S3	1.9	2425

3.2 Hardened properties

Generally, a satisfactory concrete requires specific properties in the hardened state. As stated above, in this case study a compressive strength after 24 hours $R_{cm(1)}$=35 MPa and a compressive strength $R_{cm(28)}$=55 MPa were the minimum requirements. As well known, compressive strength is the capacity of a material or structure to withstand axially directed compressive forces. When the limit of compressive strength is reached, the material crushes. To ensure the achievement of such properties, quality control and acceptance testing were obviously a part of the experimental work. In the following Tab.3 the results collected during the compressive tests, according to [16], are resumed.

Tab.3: Compressive properties

	PC	ISFC	RSFC
$R_{c(1)}$ [MPa]	36.8 ± 0.2	37.5 ± 0.1	37.0 ± 0.1
$R_{c(28)}$ [MPa]	55.7 ± 1.2	55.4 ± 1.4	60.0 ± 1.2

The experimental results reported in the Tab.4 confirm that the presence of fibres usually have only a minor effect on compressive strength, as stated in the available guidelines [14, 17, 18] and alters the mode of failure of the specimens by making the concrete less brittle. The obtained results are also in agreement with the available literature [1, 5], where it has been demonstrated that the fibres do not have significant effects on the compressive strength of the reinforced concrete. On the other hand, a concrete reinforced with steel fibres is generally characterized in terms of flexural toughness and first-crack strength, which can be evaluated through bending test on concrete notched beams. As well known, the main effect of the steel fibres is its bridging action once cracking in the matrix has occurred.

To estimate this mechanical propriety, four beams for each concrete type (Tab.2) were cast to carry out flexural tests according to [19]. In particular, a notched beam (150 mm x 150 mm x 600 mm) is subjected to a four-point bending test using crack mouth opening displacement (CMOD) control. During the test, the crack tip opening displacement (CTOD) of the notch was recorded by two other clip-on transducers. The experimental program is still running, but in the following Fig. 3 the available curves Load vs. CTOD for plain concrete (PC_1 and PC_2 curves), industrial fibre reinforced concrete (ISFC_1 and ISFC_2 curves) and recycled fibre reinforced concrete (RSFC_1 and RSFC_2 curves) are shown.

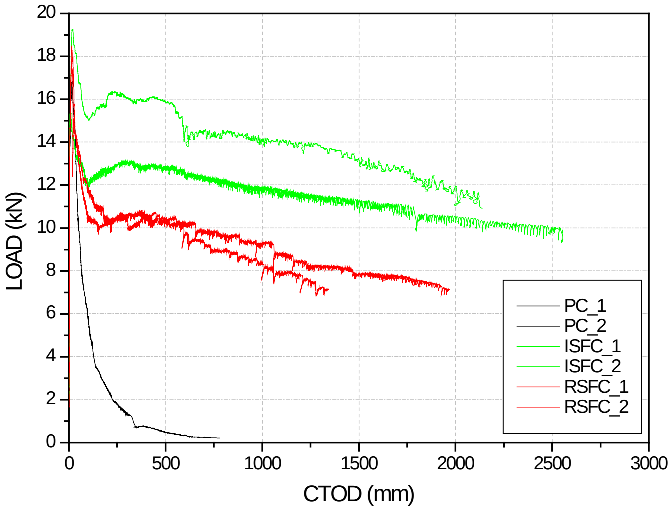

Fig. 3: Flexural behaviour

Basically, flexural toughness can be defined as the area under the complete Load-CTOD curve. Thus, according to the Fig.3, the positive effect of the steel fibres added to the concrete matrix is confirmed: the presence of steel fibres modifies the typical fragile behaviour of the plain concrete (black curves) into a more ductile behaviour, characterized by a larger area under the load-deformation curve. It can be also observed that samples made with ISF (green curves) have greater residual strength if compared with RSF ones (red curves). The next step of this analysis will be the testing of all the realized notched beams, the analysis of the collected data and their classification according to [19] in terms of first crack strength (f_{If}), equivalent strengths ($f_{eq(0\text{-}0,6)}$ and $f_{eq(0,6\text{-}3)}$) and ductility indexes (D_0 and D_1).

4. Application

The most interesting part of the whole experimental campaign has been the application of the proposed concrete in the partner's production plant for the realization of some prototypes of precast panel. In this phase, only two mixtures have been applied: the plain concrete, as a reference, and the recycled steel fibre concrete.

The main problem during this phase was the proper dosing of the mixtures' components according to the optimal ones (Tab.2): as well known the laboratory conditions were very far from the company service conditions. First of all there was a different control of the aggregates' humidity and this aspect is very important in order to avoid introducing more water than needed. The second crucial aspect was the elapsed time for the introduction of the recycled steel fibres into the mixer, due to their balling tendency. Finally, the last problem was the different environmental conditions (temperature and relative humidity), which vary day by day. As a consequence, the final mixtures resulted slightly modified respect to those defined under laboratory conditions, as resumed in Tab.4.

Tab.4: Concrete composition

		PC	RSFC
Sand (0-3.15)	[kg/m^3]	935	911

Aggregate I (3.15-8)	[kg/m^3]	340	328
Aggregate II (11.2-20)	[kg/m^3]	528	521
CEM II A-LL 42.5R	[kg/m^3]	382	360
Water	[l/m^3]	204	204
Water reducing admixture	[kg/m^3]	3.56	3.83
Fibres	[kg/m^3] [%v]	--- ---	21 0.34

A total number of eight panels have been realized according to the experimental program reported in Figure 4 along with all the geometrical details of the panels and their internal reinforcement.

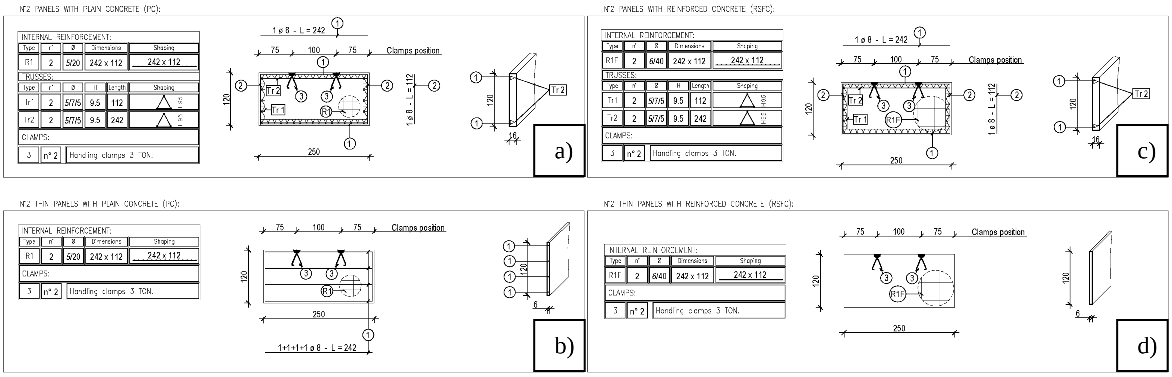

Fig. 4: Panels' details: a) panels with PC; b) thin panels with PC;
c) panels with RSFC; d) thin panels with RSFC

The fresh and hardened properties of both plain and reinforced concrete realized in the production plant are summarized in Tab.5 and it can be easily argued that they are quite similar to those found (Tab. 2 and Tab.3) in the preliminary study on smaller scale.

Tab.5: Fresh properties

	Slump [mm]	Air [%]	Density [kg/m^3]	$R_{c(4)}$ [MPa]	$R_{c(28)}$ [MPa]
PC	21	2.1	2390	45.0	39.0
RSFC	22	2.8	2344	53.6	50.0

In this preliminary study, the main objective was the design of non-structural panels, because the field-testing of the proposed material is still in the early stages. Thus, the experimental work on the prototypes has been focused on the drying shrinkage monitoring and on the effect of the atmospheric exposure. In fact, the presence of steel fibres near the external surface could lead to oxidation phenomena. For that reason two of the realized panels were exposed to external environmental conditions in order to evaluate any different behaviour with respect to the others. In the following Figure 5, different steps of the panels' realization are shown.

Fig. 5: Production of the panels: a) steel moulds; b) casting; c) prototypes

In the graph shown in Fig.6 the drying shrinkage for both mixtures is plotted. Even though the shrinkage is negligible for both mixtures, the slightly higher value of the RSFC mix is basically due to the different a/c ratio, (0.56 for RSFC vs. 0.53 for PC).

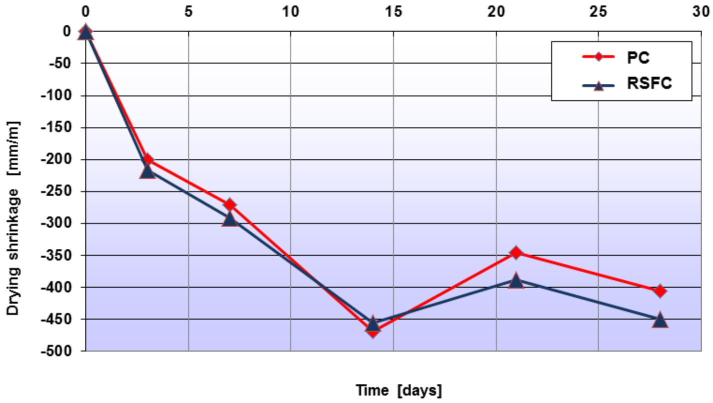

Fig. 6: Drying shrinkage

Finally, in Fig. 7, one of the panels exposed to external environmental conditions is shown. As can be observed that, after three month from the cast, there are no shrinkage cracks and there are no evident fibres' oxidation phenomena.

Based on the above discussed results the good performance of this materials seem compatible with the prevented applications. The result suggests to continue the experimental work concerning the application on full-scale precast elements fabricated with the same mixtures.

Fig. 7: Air exposed panel

5. Conclusions

A new type of steel fibre reinforced concrete, introducing recycled steel fibres from waste tyres into the concrete matrix was studied. The first results of the research encourage the use of steel recovered from ELTs in concrete elements, even though there is a few literature about this topic. On the basis of the authors' background and taking into account the presented results, the following remarks can be drawn:

- A good mix-design allowed to identify the optimal mixtures, by satisfying the requirements of the precast company, avoiding the negative effect of the fibres on the workability of the concrete matrix, and controlling the air entrapment.
- The post-cracking behaviour of the RSFC confirmed that the brittle behaviour of the plain concrete could be avoided adding recycled steel fibres. Furthermore, the collected experimental data shown that the positive effect of the recycled steel fibres on the toughness of the concrete matrix is very close to that found for industrial steel fibres.
- It has been verified that the proposed concrete could be suitable for its use in this type of application, as long as the necessary precautions are taken in terms of adequate mix-design, such as strict control of the aggregates' characteristics.
- Even if further research is strongly needed, the results of the present research are in the direction of a successful use of this sustainable material. Medium and large scale tests will be able to confirm in the future this expectation.

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