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Tyre rubber waste recycling in self-compacting concrete

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Abstract

Rubberised self-compacting concrete was prepared containing different amounts of untreated tyre waste and their mechanical and microstructural behaviour are investigated and discussed in this paper. The fresh and hardened properties of such materials are compared with those of a typical reference formulation of self-compacting concrete. A comparison of the obtained compressive strengths with literature data confirms that self-compacting technology helps binding rubber phases.

Keywords: Tyre rubber; Waste management; Concrete; Mechanical properties; Microstructure

1. Introduction

The possibility of making concrete tough has been generally pursued by introducing rubber phases among the traditional components (cement, water and aggregates) and this idea has been largely investigated using, for this purpose, recycled grinded tyre rubbers [1–6]. Different kinds of tyres have been employed as partial substitute of natural aggregates in concrete: scrap tyres obtained by simple grinding without further purifications thus including steel and textile fibres in their composition [1,3], crumb rubber obtained by cryogenic process [1], milled tyre rubbers treated with sodium hydroxide solution to achieve a better adhesion with the cement paste [6], scrap truck tyre rubber [4], tyres tread [2], etc. However, regardless the different nature, size and composition of used tyre rubbers, a meaningful decrease in concrete compressive strength with the increasing amount of rubber phase in the mixture was always detected. Although the so far obtained rubberised concrete generally shows a tougher behaviour with a gradual failure of the samples than traditional concrete, it generally does not exhibit suitable compressive strength for structural applications.

On the other hand, concrete has undergone several changes in its formulation and technology to become stronger and durable: with this purpose fly ashes [7,8], fly ashes and polymers [9–11], silica fume [12,13], superplasticizer, etc. have been added to the traditional mix and recently self-compacting characteristics have been achieved for tailored preparations [14]. Self-compacting concrete (SCC), although developed with the aim to make easier compaction, is a new type of concrete that attains higher compressive strength and durability in comparison with ordinary Portland cement concrete (OPCC), thanks to the addition of fine filler and proper admixtures, i.e. superplasticizers and modifying viscosity agents [15–17]. The combination of these components leads to a mixture that does not require vibrations on placing, with time and cost saving of building site procedures. However, in spite of the fine filler presence (usually with an average size about 10–30 μm) promoting the formation of very compact microstructure and allowing high values for compressive strength, the failure behaviour in SCC is still brittle.

The possibility to design self-compacting rubberised concrete (SCRC) appears particularly attractive because this new material might join the characteristics of SCC (high flowability, high mechanical strength, low porosity, etc.) with the tough behaviour of the rubber phase, thus leading to a building material with more versatile performances. Previous studies [18,19] have been carried out to verify the feasibility of SCRC: self-compacting rubberised mortars were prepared to evaluate the optimum amount of tyre rubber that could be introduced in the mix avoiding severe loss of compressive strength and still maintaining the self-compacting characteristics. The best results

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for workability and mechanical strength were obtained when sand fraction was replaced by tyre waste of similar grain size, instead of the substitution of fine filler fraction with equivalent grain size tyre rubber waste.

Accordingly, in this work, three different concrete mixes were designed with the same water/cement (W/C) and water/powder (W/P, with P=cement+fine filler) ratios, but containing respectively 0, 22.2 and 33.3 vol.% of grinded tyre rubber as fine aggregate in substitution of sand: their self-compacting characteristics and final mechanical behaviour are reported and discussed.

2. Experimental details

2.1. Concrete mix design

The following materials were used: CEM II/A-LL 42.5 R (EN 197/1) as binder, alluvial coarse aggregates (4/16 mm) and sand (0/4 mm) roughly combined according to Fuller grain size distribution as traditional aggregates and commercially available calcium carbonate, with an average grain size of approximately 8 μm, as fine filler. The tyre rubber (TR) aggregates were obtained by mechanical grinding of tyre rubber waste: therefore they may still contain small amounts of steel and fabric residues. Two different grain size distributions were chosen: scrap (ST) and crumb (CT) tyres with size ranges 0.5 to 2 mm and 0.05 to 0.7 mm, respectively. They were sorted out to conform to sand grain size distribution (55% ST, 45% CT), approximately according to Fuller curve, and were used without any surface treatment to investigate the effect of untreated tyre particles on final properties of SCC. Commercial products were used as admixtures: an acrylic based superplasticizer (SP, Dynamon SP1, Mapei) and a biopolymer based viscosity modifying agent (VMA,Viscofluid SCC/10, Mapei).

SCC compositions are reported in Table 1. SCC-A mix is a formulation for self-compacting concrete, with water/cement and water/powder mass ratios of 0.53 and 0.34, respectively, adjusted in previous works [20,21]. The same W/C and W/P mass ratios were used in SCC-B and SCC-C where respectively 22.2 and 33.3 v/v% of sand were replaced by tyre rubber wastes (Table 1). The concrete mixes were prepared in a laboratory concrete mixer (60 l) where coarse and fine aggregates, tyre rubber, filler and cement were fed in this order and mixed for 2 min; 75% of the water and the admixtures with the remaining water were then added. The admixtures were added, as reported in Table 1, to obtain self-compacting properties, which were determined for all the mixes according to test methods developed by other authors [22] and Italian standards UNI 11041 and 11045. The amount of superplasticizer increased with the amount of tyre rubber wastes in concrete. Total mixing time, starting from the introduction of concrete components, was usually about 12 min for each mix.

Table 1
Mix design of concrete samples (W/C: water/cement ratio; W/P: water/powder ratio, P: cement+filler; sand density: 2.5 g/cm^3; tyre rubber density: 0.9 g/cm^3)

Tyre rubber (v/v% of sand)	SCC-A	SCC-B	SCC-C
	0	22.2	33.3
Gravel (kg/m^3)	617	617	617
Sand (kg/m^3)	986	767	657
$CaCO_3$ (kg/m^3)	196	196	196
Tyre rubber (TR) (kg/m^3)	–	79	118
CEM II/A-LL (kg/m^3)	370	370	370
Water (kg/m^3)	195	195	195
W/C	0.53	0.53	0.53
W/P	0.34	0.34	0.34
VMA (wt.% over P)	0.39	0.39	0.39
SP (wt.% over P)	0.84	0.97	1.15

Table 2
Fresh concrete tests results

Tyre rubber (v/v% of sand)	SCC-A	SCC-B	SCC-C
	0	22.2	33.3
Slump flow test (mm)	630	630	700
J-ring test (mm)	580	580	680

3. Results and discussion

3.1. Fresh concrete behaviour

Fresh concrete tests were carried out: slump flow test (UNI 11041) and J-ring test (UNI 11045) were performed to evaluate flowability of concrete also in the presence of obstacles (such as steel bar reinforcements). The cohesiveness and the absence of segregation of the mixtures were visually estimated. In Table 2, the average diameter of the spread concrete after slump flow and J-ring tests is reported. Slump flow test results are greater than 600 mm for all the mixes as prescribed by Italian standard and different authors [23]. The decrease of spread concrete measured after J-ring test was ≤50 mm as required by UNI 11045 and concrete width after test was uniform, thus showing that all the mixes containing tyre wastes have good ability to flow and pass in the presence of obstacles. Concrete viscosity was determined measuring the time (t_{500}) required to reach a 500 mm spread diameter in the slump flow test: for all the formulations t_{500} was ≤5 s, according to the limit value of 12 s reported in Italian standard (UNI 11041). The introduction of the investigated amount of tyre rubber particles in concrete does not influence in significant way the fresh concrete behaviour.

3.2. Hardened concrete behaviour

Concrete cubic samples (150×150×150 mm) were cast without any mechanical compaction and cured for 28 days at

Table 3
Mechanical and physical properties of SCC-A, SCC-B, SCC-C

Tyre rubber (v/v% of sand)	SCC-A	SCC-B	SCC-C
	0	22.2	33.3
S_c (MPa)	33.0	24.7	20.2
E_{dyn} (GPa)	33.0	26.6	23.9
Water absorption (%)	7.5	7.8	8.3

Fig. 1. SCRC cubes after rupture.

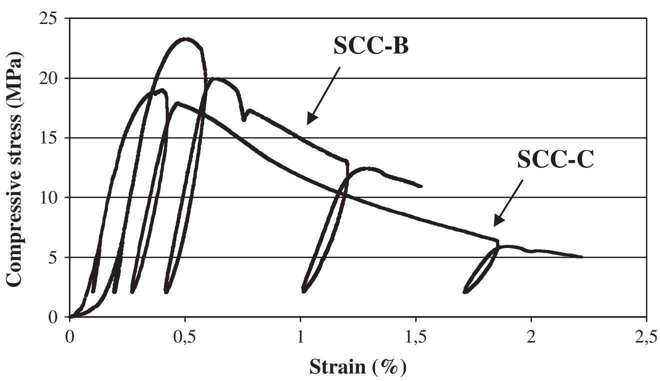

Fig. 2. Stress–strain curves for SCC-B and SCC-C.

20 °C and R. H.>95%. Mechanical properties were then determined as average value on five samples by an Amsler–Wolpert machine with a constant strain rate of 50 mm/min (compressive strength S_c) and an Ultrasonic equipment (dynamic elastic modulus E_{dyn}) (Table 3). As shown in Fig. 1, the typical rupture shape of traditional concrete was obtained also for SCRC cubes.

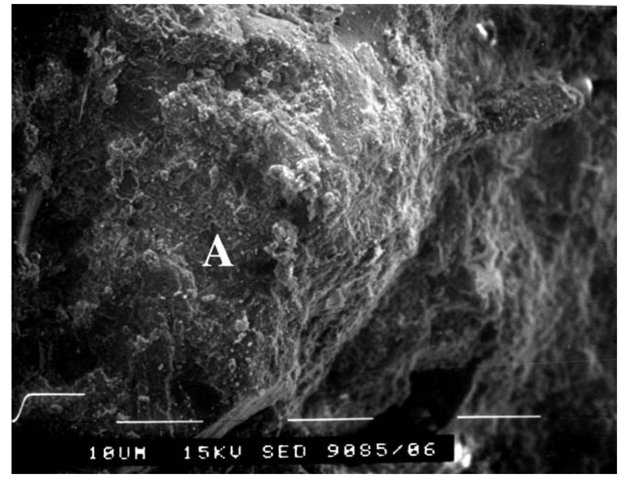

Fig. 4. SEM observations of sample SCC-C (160×, marker 10 μm). (A) Rubber particle partially covered with cement paste.

Water absorption (WA%) measurements were carried out on hardened concrete samples, at atmospheric pressure, according to UNI 7699 to evaluate the effects of tyre rubber wastes addition on concrete microstructure. The obtained values (Table 3) indicate a very slight increase in porosity with the rubber phase in the mixes, probably due to some deviations of rubber particles from sand grain size distribution and/or a slightly higher air amount trapped during mixing procedure of rubberised concrete.

As expected, the introduction of tyre rubber wastes in self-compacting concrete formulation leads to a general lowering of mechanical properties. The decrease in strength and stiffness is strictly connected with the presence of the rubber phase: under compressive load, tyre rubber particles debond from cement paste causing voids that unavoidably make failure easier [24].

Load–displacement curves were recorded under compressive test for the mixes SCC-B and SCC-C at a constant strain rate of 15 mm/min: the relevant stress–strain plots are reported in Fig. 2.

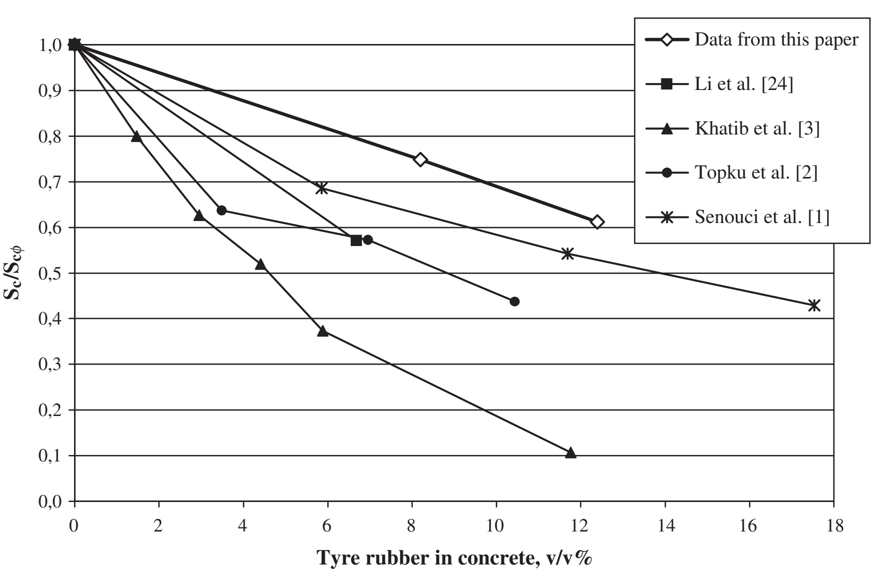

Fig. 3. Compressive relative strength as function of tyre rubber volume in concrete.

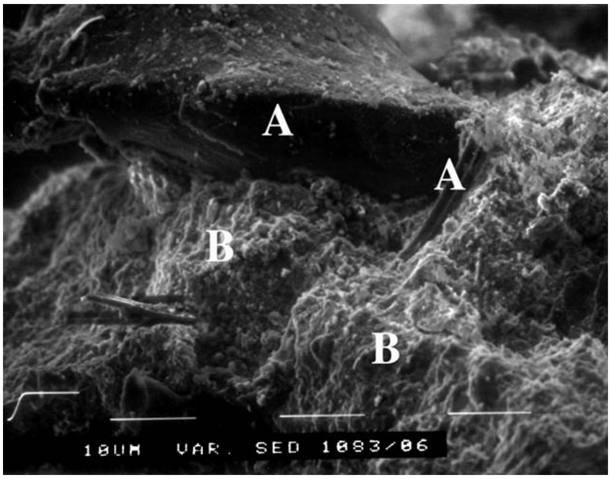

Fig. 5. SEM observations of sample SCC-C (160×, marker 10 μm). (A) Rubber particle; (B) cement paste.

It is noteworthy that for SCC-B and SCC-C the maximum stress occurs for strain around 0.5%, when OPCC usually does not overcome 0.2–0.3% (not reported for clarity sake) [25], thus showing that tyre rubber wastes increase concrete deformability. After the maximum stress, further unloading/loading cycles show that compressive strength gradually decreases indicating that samples are not completely fractured due to the presence of rubber phase and can withstand post-failure loads with deformations increasing with the rubber tyre waste content.

With the aim to verify if the self-compacting technology is more fruitful in preparing rubberised concrete than traditional one, a comparison of the results of present study with those of previous investigations is reported in Fig. 3. The relative strength S_c/S_{c0} (S_c and S_{c0} being the compressive strengths of rubberised concrete and reference concrete, respectively) is plotted as a function of volume rubber content over the total concrete volume. It can be easily observed that the relative strength obtained for SCRC samples decreases, but less than those calculated from literature data. This behaviour can be ascribed to a microstructural improvement due to the use of self-compacting technology: in fact, the cement matrix, enriched by filler presence, might firmly embed the finest rubber phases, although tyre particles did not previously undergo any surface treatment.

Effective adhesion between tyre rubber and cement matrix seems to occur as verified by scanning electron microscopy (SEM Philips 501 B) carried out on the undisturbed fracture surface resulting from compressive test. For SCC-C, Fig. 4 shows a tight microstructure: tyre particle appears well covered by cement matrix as also seen in Fig. 5, where other tyre residues are evident. The high flowability and the cohesiveness of the fresh concrete, obtained thanks to the addition of admixtures and fine filler, seem help a strict contact between organic and inorganic phases.

4. Conclusions

Self-compacting technology seems really suitable for preparing concrete with more versatile mechanical behaviour adding large volumes of tyre rubber wastes, even without any surface treatment, in its mix design. The following conclusions can therefore be drawn:

– SCRC requires slightly higher amount of superplasticizer than SCC to reach self-compacting properties, keeping constant water/cement and water/powder weight ratios
– concrete compressive strength and stiffness decrease with increasing amount of rubber phase in the mix, but the obtained values are higher than those of ordinary Portland cement concretes admixed with similar amounts of tyre rubber wastes
– significant concrete deformability before failure and capability to withstand post-failure loads with some further deformations are exhibited by SCRC due to the tyre rubber waste presence
– SCRC porosity is only poorly affected by the presence of significant amount of rubber phase in comparison with that of ordinary SCC.

Self-compacting technology seems therefore to be promising to control microstructure of the new SCRC in order to obtain more versatile and innovative mechanical behaviour for SCC uses. Of course, these findings are based on the present results and further SCRC formulations are needed to strongly confirm the effective superiority of self-compacting rubberised concrete over plain rubberised concrete reported in literature. Size, origin and amount of tyre rubber particles included in mix design may exert different effects on concrete microstructure: further researches will be focussed on the investigation of these aspects as strictly related with physical and mechanical properties of the final product. Moreover, as tyre particles should exhibit insulating behaviour typical of rubber materials, SCRC appears very attractive also for the production of noise reducing pavement: investigations in this field are currently running.

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