SELF-COMPACTING CONCRETE REINFORCED WITH TYRE RECYCLED STEEL FIBRES

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SUMMARY: An experimental study is presented on the development of steel fibre-reinforced concrete mixes, that are suitable for thin overlays in new and damaged concrete surfaces. To minimise the effort required for casting and compacting, the study aimed at developing concrete mixes that can be classified as self-compacting. Thus, a range of fresh concrete properties were examined to assess the workability of these mixes; the compressive and flexural strength was also examined experimentally. In total, six mixes were examined including a plain concrete mix; five types of short steel fibres were trialled: Recycled Tyre Steel Fibres with a dominant length range of 5 to 15 mm, and four types of Tyre Steel Cord Filaments, each type cut to a specific length. Three fibre contents were trialled (25, 50 and 100 kg of fibres per m^3 of concrete), but preliminary results indicated that the self-compacting properties (i.e. filling and passing ability, viscosity as well as segregation resistance) are diversely affected for concrete mixes with fibre contents greater than 25 kg/m^3. The main conclusion of this study was that screed mixes containing short Tyre Steel Cord Filaments can be classified as self-compacting. While, the mix containing Recycled Tyre Steel Fibres did not fulfil the acceptance criteria set for passing ability. However, this does not imply that this fibre type should not be used in fibre-reinforced overlays of concrete surfaces, since conventional rebars are not expected to be used in such applications and, thus, passing ability is not considered crucial for this type of application. The bending test results indicated that the longer Tyre Steel Cord Filaments as well as the Recycled Tyre Steel Fibres are effective in providing crack bridging at high crack-openings.

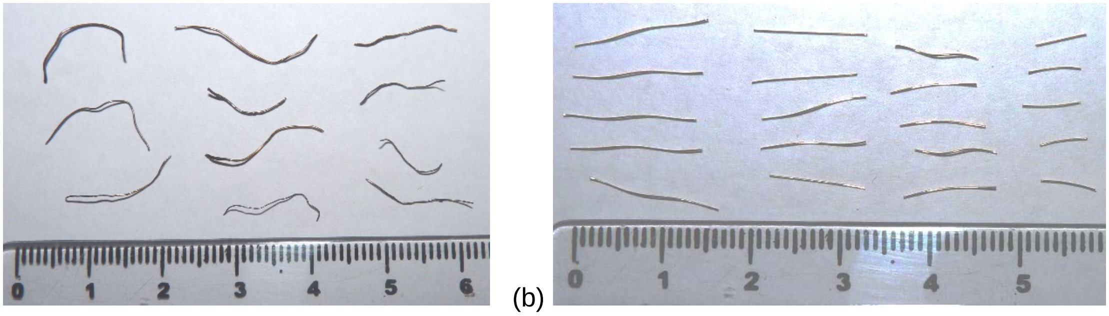
KEY WORDS: Self-compacting concrete, End-of-Life tyres, recycled steel fibres, screeds.

1 INTRODUCTION

The implementation of a number of European Union (EU) environmental directives and policies, including the recent EU action plan on Circular Economy [1], is actively promoting the reuse and recycling of products and materials that otherwise would have been either disposed of to landfill or incinerated for energy recovery.

A typical example of such material is End-of-Life (EoL) tyres that are increasingly recycled to recover valuable materials, mainly rubber and steel wires. The recycled rubber is used in a diverse range of high-added value applications and products; while the recycled steel wires are mainly used as scrap feed in steel manufacturing. This is despite the fact that these steel wires are highly engineered material with exceptional strength characteristics (e.g. tensile strength over 1000 MPa). To this end, extensive research activities, carried out since the early 2000s, have successfully demonstrated that tyre-recycled steel wires can be used as fibre reinforcement in concrete, provided that they are clean of rubber and their length ranges between 15 to 25 mm [2-7]. To achieve these specifications, the tyre-recycled steel wires normally require further processing, which often yields large quantities of relatively shorter steel wires (length less than 15mm) that are not considered effective in bridging concrete cracks. Hence, these short wires (Figure 1a) are sent to steel kilns instead of being used in high-added value applications.

Another example of reused/recycled material is tyre-cord steel filaments, which arise as “surplus material” of tyre manufacturing, and in fact are the same material as the tyre-recycled steel wires. The only difference between the two material is their length and the fact that the filament surface is not contaminated with rubber dust. To use effectively the tyre-cord steel filaments in concrete, it is necessary to cut them to specific lengths, for instance 15 mm (e.g. Figure 1b).



(a) (b)

Figure 1: Short steel fibres used in the study: (a) tyre-recycled steel wires and (b) tyre-cord steel filaments

The experimental study, reported in this paper, aimed at developing steel fibre reinforced concrete (SFRC) mixes that are suitable for thin overlays in new and damaged concrete surfaces; to this end, the study examined the suitability of the short steel fibres, described above. To minimise the effort required for casting and compacting the concrete, the study aimed at developing concrete mixes that can be classified as self-compacting. Thus, a range of fresh concrete properties were examined to assess the workability of these mixes; the compressive and flexural strength was also examined experimentally.

The reported research is undertaken as part of the European research project “Anagennisi”, funded by the EC’s 7th Framework Programme and aims at promoting material recycling of EoL tyres through the development of innovative and high-added value applications in concrete construction for all the tyre components.

2 EXPERIMENTAL PROGRAMME

In total, six concrete mixes were examined including a plain concrete mix. The experimental study aimed at examining three fibre contents per mix (i.e. 25, 50 and 100 kg of fibres per m^3 of concrete), but preliminary results of a pilot mix (containing tyre steel-cord filaments, 15 mm long) indicated that only mixes with 25 kg of fibres (per m^3 of concrete) can be classified as self-compacting according to EN 206-9 [8] and EFNARC [9]. Figure 2 shows the reduced filling and passing ability of SFRC containing 100 kg of fibres per m^3 of concrete. Thus, the study considered only the fibre content of 25 kg of fibres per m^3 of concrete.

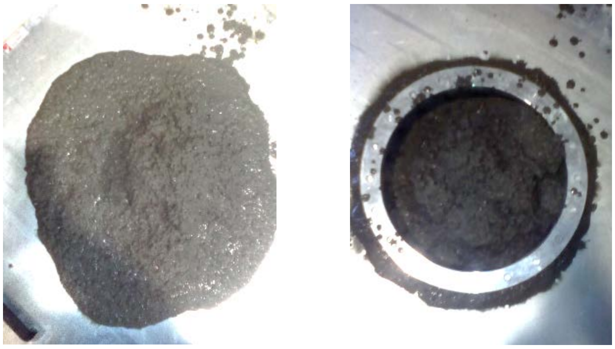


Figure 2: Slump-flow (left) and J-ring (right) testing of SFRC with 100 kg of TCF-15 per m^3 of concrete

2.1 Materials, mixing and curing

Five types of steel fibres were used (Table 1): tyre-recycled steel fibres (RTSF) with a dominant length range of 5 to 15 mm, and tyre-cord steel filaments (TCF) with four different lengths (i.e. 6, 9, 12 and 15 mm). The study used cement CEM II /A-L 42.5 N, manufactured locally. Furthermore, imported silica fume and pulverised fuel ash were used as supplementary cementitious materials. To achieve the desired self-compacting properties, the study used a commercial superplasticizer, based on modified polycarboxylates. The aggregate used in this study were crushed limestone aggregates (0/4, 4/10 mm) as well as crushed calcareous sandstone (0/4 mm). The aggregate were manufactured at local quarries and Figure 3 shows their gradation.

Table 1: Geometrical and mechanical properties of steel fibres

Fibre type	Length (mm)	Diameter (mm)	Aspect ratio (l/d)	Tensile strength (N/mm^2)	Shape
Sorted RTSF	5 - 15 (85% of fibres)	0.1-0.2	varied	~2000	Irregular (wavy)
TCF-6	6	0.2	30	~2000	Straight
TCF-9	9	0.2	45	~2000	Straight
TCF-12	12	0.2	60	~2000	Straight
TCF-15	15	0.2	75	~2000	Straight

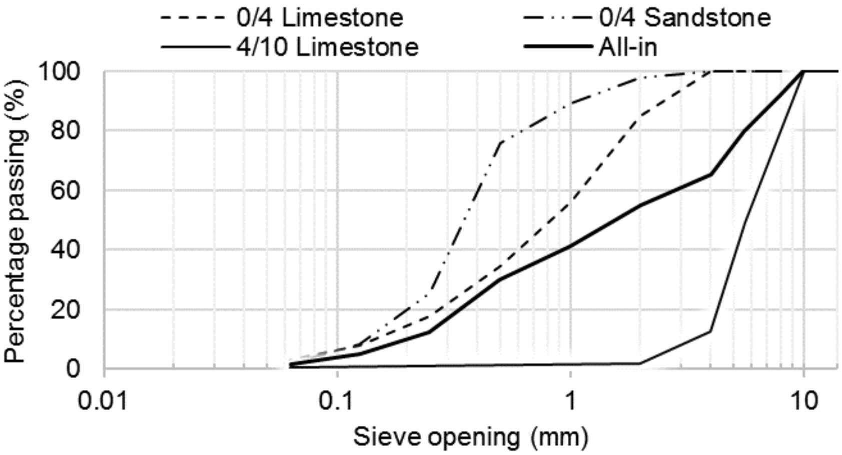


Figure 3: Gradation curves of fine and coarse aggregate

The absolute volume method (as elaborated by Gambhir [10]) was utilised for the derivation of the design mix for plain-concrete, which was also used as the basis for the five SFRC mixes (Table 2).

Table 2: Mix proportions of plain and SFRC mixes (based on SSD condition of aggregate)

Material type	Plain Concrete mix (kg/m^3)		RTSF (kg/m^3)		TCF-6 (kg/m^3)		TCF-9 (kg/m^3)		TCF-12 (kg/m^3)		TCF-15 (kg/m^3)	
	SSD	Actual	SSD	Actual	SSD	Actual	SSD	Actual	SSD	Actual	SSD	Actual
Crushed limestone 10 mm	580	569	580	598	580	586	580	588	580	588	580	586
Crushed limestone 0/4 mm	565	596	565	576	565	576	565	583	565	583	565	559
Crushed calcareous sandstone 0/4 mm	320	345	320	336	320	327	320	334	320	334	320	337
CEM II /A-L 42.5 N	315	315	315	315	315	315	315	315	315	315	315	315
Pulverised Fly Ash	70	70	70	70	70	70	70	70	70	70	70	70
Densified Silica fume	70	70	70	70	70	70	70	70	70	70	70	70
Superplasticizer	6	6	7	7	7	7	7	7	7	7	7	7
Potable water	256	212	256	211	256	231	256	216	256	216	256	239

The six concrete mixes were prepared in the laboratory at room temperature of 20° C. A drum concrete mixer (60 litre capacity) was used for the mixing. A conventional mixing sequence was applied to produce the mixes; the steel fibres were (manually) added last with continuous operation of the mixer. The specimens were not compacted to assess the effect of the added superplasticizer on the self-compacting properties.

The preparation of each mix was followed by a series of fresh concrete tests (slump-flow [11], V-funnel [12], L-box [13], J-ring [14] and sieve segregation [15]). The L-box and J-ring tests were undertaken to evaluate the passing ability of the concrete, while the slump flow and V-funnel tests were carried out to assess the filling ability of the mixes. The sieve segregation test was undertaken to assess the segregation resistance.

For each mix, nine cubes (150 mm) and three prisms (150x150x600mm) were also cast for compressive and flexural testing, respectively. A day after casting, all specimens were immersed in water (at room temperature). The cubes for compressive testing were removed a day prior to testing, while the prisms were removed at an age of 28 days and stored at controlled conditions until the day of testing. The flexural tests (CMOD controlled) were carried out according to EN 14651 [16], with the only modification that a 4-point testing arrangement was applied.

3 EXPERIMENTAL RESULTS

3.1 Fresh Concrete Properties

Table 3 outlines the results of the fresh concrete tests undertaken to assess the filling and passing ability, viscosity and segregation resistance of the six mixes.

The L-box results indicate that only the RTSF mix did not fulfil the acceptance criteria of EN 206-9 and EFNARC [2] for the passing ability. This could be attributed to the irregular shape of RTSF. Furthermore, the mix with TCF-9 fibres satisfied marginally the PL2 class of EN 206-9 and the minimum criterion of EFNARC. While, the J-ring test results indicate that only the mixes with TCF-9 and TCF-12 fibres satisfied the criteria of EN206-9 and EFNAC; the mix with TFC-6 fibres satisfied marginally these criteria.

The slump-flow of the six concrete mixes fulfilled the acceptance criteria of EN206-9 and EFNARC for the filling ability of self-compacting concrete. However, the V-funnel time fulfilled only the EN 206-9 viscosity criteria.

The sieve segregation results indicate that the EN 206-9 classes for segregation resistance were clearly satisfied by the plain concrete mix and the SFRC mixes with TFC-6 and TFC-15 fibres. While the remaining mixes marginally satisfied the SR1 class.

Table 3: Results of fresh concrete properties

Concrete Mix	Passing ability ratio PL (L-box)	Passing ability ratio PJ (mm) (J-ring)	Slump-flow (mm)	Viscosity (V-funnel) t=10 s	Viscosity (V-funnel) t=5 minutes	Segregation portion (%)
Plain	1.01	14	785	2.3	2.6	14.4
RTSF	0.69	16	740	2.5	2.7	20.6
TCF-6	0.82	11	745	2.5	3.2	19.7
TCF-9	0.78	10	740	2.4	2.7	21.2
TCF-12	0.85	10	720	2.8	3.1	20.9
TCF-15	0.94	21.3	710	2.6	3.3	17.5
EN206-class	PL2 ≥ 0.8 (3 bars)	PJ2 ≤ 10 (16 bars)	0.66m ≤SF2≤0.75m 0.76m≤SF3≤0.85m	VF1<9s	VF1	SR1 ≤ 20 SR2 ≤ 16
EFNARC criterion	0.8 ≤ PL ≤ 1.0	0 ≤ PJ ≤ 10	0.65 m ≤ SF ≤ 0.8 m	6s ≤ t ≤ 12s	6s ≤ t ≤ 15	-

3.2 Hardened Concrete Properties

Figure 4 outlines the results obtained from the compressive cube tests at an early age, 7 and 28 days. The results demonstrated that there was a steady strength development with time; at the age of 28 days, the cube-strength class of 40 MPa was achieved by the four SFRC mixes with TCFs. The SFRC mix with RTSF reached a cube-strength of 45 MPa, and this was more than double the early age strength. Furthermore, the results indicate that the compressive cube strength was marginally improved by fibre addition (in the range of 8 to 17%). At this fibre content, the concrete density was not adversely affected (apart from the case of the mix with RTSF), and this indicates the beneficial effect of the chemical additive on the concrete's void content [17] (as observed during the casting of the specimens). Air-content tests of fresh concrete prisms indicated that the void content ranged from 3.5% to 4.9% (TCF-6: 4.5%, TCF-9: 4.9%, TCF-12: 4.7%, TCF-15: 4.6% and RTSF: 3.7%).

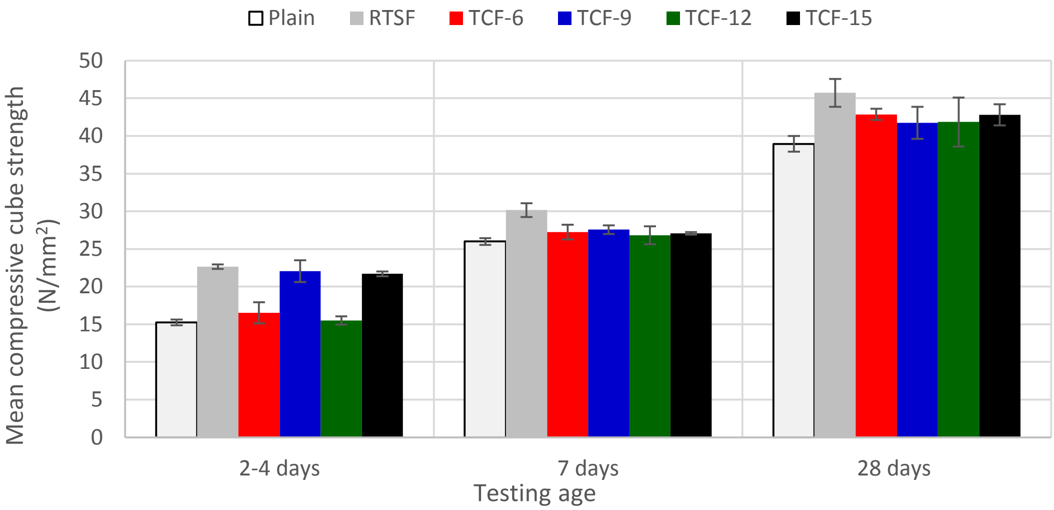


Figure 4: Compressive cube strength for the six concrete mixes at different ages

Figure 5 outlines the results of the flexural tests for the 5 SFRC mixes. The effect of fibre length is clearly demonstrated, where the mix with the longest fibres (i.e. TCF-15) exhibited the highest flexural strength amongst the 5 mixes. The RTSF mix exhibited a similar behaviour with the TCF-12 mix, but failed at a much lower crack-mouth-opening displacement. This is because the length of the RTSF fibres is variable (ranged from 5-15 mm). Furthermore, the TCF-15 and TCF-12 fibres satisfy the conformity criteria of EN 14889-1 for steel fibres (i.e. achieve a flexural tensile stress of 1.5 and 1 MPa at a CMOD of 0.5 and 3.5 mm, respectively) [18]. The test results also indicated that the prisms failed without exhibiting an extended tail in their post-peak response, as normally expected for concrete [19].

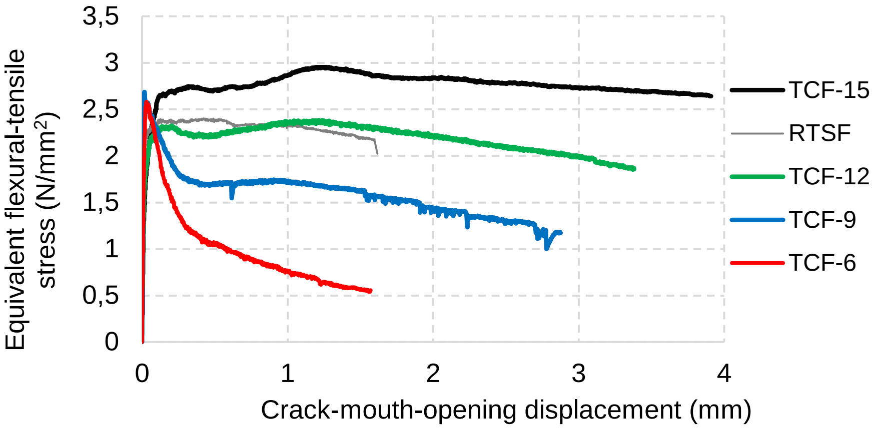


Figure 5: Results of the flexural tests of SFRC prisms

4 DISCUSSION AND CONCLUSIONS

This paper examined the development of self-compacting SFRC mixes for use as thin overlays in new and damaged concrete surfaces. The use of short tyre-recycled steel wires as well as tyre-cord steel filaments was trialled in the study, aiming to promote the reuse of these fibrous materials in high-added value applications in concrete construction.

Preliminary results of the fresh concrete tests indicated that SFRC mixes with high fibre contents (i.e. 50 and 100 kg of fibres per m^3 of concrete) have reduced passing and filling ability. Furthermore, some fibre agglomeration was also observed for these fibre contents. Thus, the study focused on the fibre content of 25 kg of fibres per m^3 of concrete.

The mixes reinforced with the tyre-cord steel filaments fulfilled the consistency criteria, set for the passing activity of self-compacting concrete. While the mix containing tyre-recycled steel wires did not satisfy these acceptance criteria. Furthermore, the test results showed that the six concrete mixes fulfilled the consistency criteria adopted for the filling ability of self-compacting concrete; while only three mixes fulfilled the consistency criteria for the segregation resistance of self-compacting concrete. However, the other three mixes have the potential to pass this criterion with marginal changes in their mix design.

The 28-day compressive (cube) strength class of 40 MPa was achieved by the four steel fibre-reinforced concrete mixes containing tyre-cord steel filaments; while the strength class of 45 MPa was attained by the mix containing tyre-recycled steel wires. As expected, fibre addition improved marginally the compressive strength of the mixes (in the range up to 17%). It is worth noticing that similar densities were obtained for the plain-concrete and the fibre-reinforced mixes, and this is an indication that fibre addition did not adversely affect the concrete’s void content.

The bending test results demonstrated the effect of fibre length on the post-peak flexural characteristics of concrete; the mix with the 15mm tyre-cord steel filaments exhibited the best flexural behaviour while the mix with 6mm tyre-cord steel filaments exhibited the worst behaviour. Furthermore, the results indicated that concrete reinforced with relatively short steel fibres (e.g. 6mm and 9mm tyre-cord filaments) does not exhibit an extended tail in their post-peak response.

Conventional steel rebars are not expected to be used together with steel fibre-reinforced concrete screeds and, hence, the mixes developed in this study are suitable for use as overlays of concrete surfaces. This is despite the fact that the developed mixes did not pass all the criteria set for self-compacting concrete, especially the passing ability which relates directly to steel rebar reinforcement.

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