BEHAVIOUR OF CONCRETE REINFORCED WITH RECYCLED STEEL FIBRES EXPOSED TO CHLORIDE CONTAMINATED ENVIRONMENT

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Abstract

Recycled steel fibres recovered from post-consumer tyres can be used to improve the mechanical performance of concrete, especially in terms of post-cracking behaviour, and to reduce costs. Recycled steel fibres are seen as an interesting alternative of concrete reinforcement due to the associated environmental benefits.

Even though some studies were carried out on the mechanical performance of concrete reinforced with steel fibre reinforced concrete (SFRC), there is a lack of studies on the durability behaviour of this concrete

This paper aims to provide means for the better understanding of SFRC with recycled fibres exposed to chloride environment. Specimens were subjected to up to 10 months of wet-dry cycles and the results were obtained in terms of loss in the mechanical properties. No major effect is expected when SFRC with recycled fibres is exposed to chloride contaminated environment.

Keywords: steel fibres; post-consumer tyres; recycling; chlorides; durability.

1. Introduction

The use of recycled steel fibres recovered from post-consumer tyres has been investigated for more than ten years and the University of Sheffield has leaded the studies in this area [1].

Most of the works carried out on the addition of recycled steel fibres into concrete [2-8] focused on the mechanical performance of the concrete, and almost no studies were undertaken on the long-term performance of the concrete reinforced with recycled steel fibres. Aiming to bridge this gap of information, this research aims to provide means for

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the better understanding of the long-term performance of steel fibre reinforced concrete (SFRC) with recycled fibres.

The corrosion aspect is one of the most important issues to be addressed when dealing with any kind of steel reinforcement. Therefore, this work investigates the behaviour of SFRC with recycled fibres when exposed to chloride contaminated environment.

1.1 Process to obtain the recycled steel fibres

The recycled fibres used in this research were obtained by the shredding process of post-consumer tyres. This process is a mechanical treatment at which scrap tyres pass through various rotating discs on parallel axes that cut tyres in small pieces (shreds) of approximately 50-300 mm. These shreds pass through the rotating discs again, with reduced distance between the discs, to provide to provide smaller tyre chips of about 10 to 50 mm. During this stage the steel fibres are detached from rubber and collected using magnets. Textile residues are removed from the steel fibres by blowing the residues away or by a vacuum system.

The fibres used in this study through a post mechanical treatment to clean and sort the fibres by specific geometric features, such as the range of length and diameter, which make them suitable to reinforce concrete.

Sieving is normally required to get the range of length required for fibres to improve the mechanical behaviour and also to avoid balling during mixing of concrete.

1.2 Corrosion of SFRC with industrially produced steel fibres – a literature review

Most of the studies on the corrosion of SFRC show that its performance (especially mechanical) is not affected when exposed to chloride contaminated environments, as elaborated below.

Mangat and Gurusamy [9] explain that steel fibres do not affect the ingress of chlorides by diffusion in concrete. In this case, the diffusion coefficient in SFRC is governed mainly by the hydration and permeability of the concrete, and no influence is caused by fibre addition.

Mangat et al. [10] compared the flexural performance of un-cracked specimens subjected to 2000 marine cycles with the corresponding specimens cured in air. They found out that specimens subjected to corrosion presented considerably higher flexural strength than the ones cured in air. The post-peak behaviour was not affected by corrosion, which means that the interfacial bond between the concrete and the fibre was not reduced.

Various other studies on the corrosion of SFRC have reported that corrosion did not penetrate into the concrete fibres and that most signs of corrosion were aesthetic [11-13], and not in terms of reduction in performance. Balouch et al. [13] say that the porosity of concrete is the main factor dominating the corrosion of SFRC. According to the authors, the skin of concrete (up to 2 mm cover) is more porous than the centre of concrete elements, thus explaining the corrosion spots near the surface.

Mangat and Gurusamy [11] explain that the interfacial zone between the fibre and the matrix is composed mainly of segregated lime, and as such it is more effective in protecting thin fibres than conventional reinforcement bars. This rich lime layer acts as a high alkalinity barrier which prevents the ingress of chlorides to the steel fibres.

Other theories were also developed to explain the lack of corrosion in SFRC. The Concrete Society [12] says that the area of fibres (which act as cathode) is small compared to the anodic zones, which leads to low rates of corrosion. Following the same idea, Bentur [14] says that corrosion may be restricted due to the lack of electrical conductivity between the fibres, possibly caused by their discrete nature, improved matrix microstructure and denser interfacial transition zone compared to conventional rebar. The theories do not contradict each other, hence, the lack of corrosion in steel fibres is probably due to a combination of the theories rather than by a single explanation.

2. Materials and mix proportions

Prisms and cubes of SFRC with recycled fibres were cast and exposed to chloride contaminated environment after 28 days curing in mist room (20 ± 2ºC and RH ≥ 90%). Wet (conventional plastic concrete) and RCC (roller compacted concrete) were examined. The fibre content for recycled steel fibres was 6% by mass of concrete. Industrially produced steel fibres were also used to cast specimens, at the content of 2% by mass of concrete. The amount of 6% recycled fibres is supposed to give similar flexural behaviour as 2% industrially produced fibres. Hence, the industrially produced fibres were used for comparison purposes. The mix proportions used are shown in Table 1.

Tab. 1 Mix proportions of wet and RCC.

Mix type	Mix label	Fibre content and type	Cement [kg/m^3]	PFA [kg/m^3]	Aggregate [kg/m^3]	Water [kg/m^3]	w/c
Wet	W-2I (2% industrial) W-6R (6% recycled)	2% industrial, 6% recycled	305	75	830 (fine); 1000 (coarse)	135	0.35
RCC	R-2I	2% industrial	240	60	2125	150	0.50
RCC	R-6R	6% recycled	240	60	2100	155	0.52

The cementitious material is a combination of 80% CEM I and 20% PFA (pulverised fuel ash). The chemical composition of both binders is shown in Table 2.

Tab. 2 Chemical composition of CEM I and PFA.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3
CEM I	20.39	0.27	4.52	2.68	0.054	0.93	64.14	0.28	0.412	0.238	2.604
PFA	51.48	1.03	25.14	8.66	0.060	1.71	2.69	1.09	2.753	0.327	0.374

Wet mixes were cast with river (fluvial dragged) aggregates (both fine and coarse aggregates), whilst RCC mixes were cast with crushed basalt. The RCC aggregates comprised of both fine and coarse aggregates in the same gradation curve. The gradation of aggregates is shown in Figure 1.

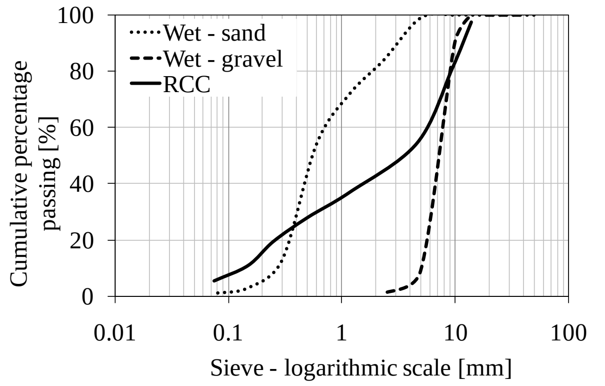


Fig. 1: Gradation curves of wet and RCC aggregates.

The recycled fibres used in this study have an average diameter of 0.2 mm and tensile strength of around 2000 MPa. The recycled fibres supplied had a length ranging from 4-22 mm.

The industrially produced fibre used in the experiment is a loose cold-drawn wire fibre with a conical head at each end. The fibre length of the fibres is 54 mm and the diameter is 1.0 mm, with tensile strength of around 1100MPa. Figure 2 shows the appearance of both recycled and industrially produced fibres.

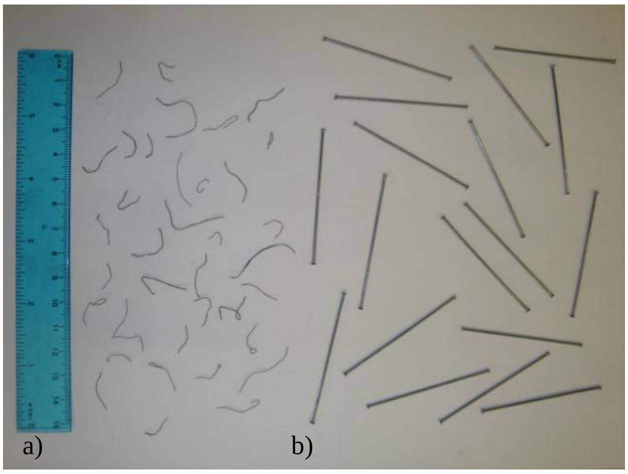


Fig. 2: Appearance of a) recycled and b) industrially produced steel fibres.

3. Chloride Contaminated Environment – Wet-dry cycles

Corrosion was accelerated in SFRC specimens by intermittent wet and dry cycles. The cycles were carried out using immersion of specimens in salt solution for 4 days (Figure 3a) followed by a dry period in a standard laboratory environment for 3 days (Figure 3b). The concentration of salt solution used for the wet cycles was 3% NaCl.

Prisms (150 x 150 x 550 mm) and cubes (150 mm) were placed into a frame inside containers in such a way that the specimens were at least 20 mm apart from each other, thus allowing the contact of the solution with all surfaces of the specimens. Each container has the capacity to accommodate twelve prisms and twelve cubes. The corrosion simulation method used is based on the methodology proposed by Kosa and Naaman [15].

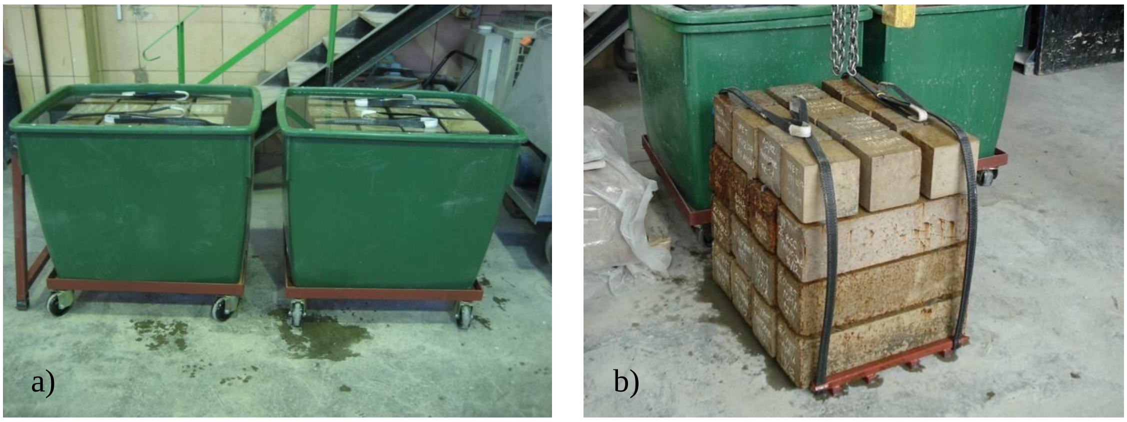


Fig. 3: a) wet and b) dry cycles of corrosion simulation.

Due to the periodicity of the tests and the heavy weight of the specimens, the immersion and removal of specimens in and out of solution was undertaken by using an overhead crane. Figure 4 shows specimens being removed from the containers.

Fig. 4: Overhead crane used to immerse and remove specimens out of solution.

Specimens were subjected to 5 and 10 months of wet-dry cycles. Residual compressive and flexural strengths were determined after each period of corrosion simulation, as explained in the following section.

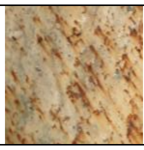
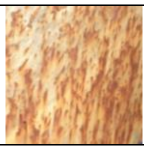
4. Results and discussion

Specimens were removed from wet-dry cycles after 5 and 10 months of corrosion and the results are presented in terms of visual analysis and mechanical performance.

4.1 Visual analysis

Specimens were examined externally before subjecting them to compressive and flexural strength tests. From the external visual analysis, a scale of deterioration could be developed for the purpose of this research, as shown in Table 3.

Tab. 3 Scale of superficial deterioration due to rust.

Scale of deterioration	0	1	2	3	4	5
External appearance						

Non-corroded specimens are considered as level 0 while the most corroded specimens are considered as level 5. Industrially produced fibres usually present the lowest amount of rust on the surface compared to the recycled fibres, and for this reason they occupy the lowest levels of deterioration (values in the range of 0-3). Recycled fibres occupy the highest levels of deterioration (values in the range of 3-5) due to the geometric characteristics of the fibres, which lead to a much higher number of recycled fibres (and more points of corrosion) compared to the same content of industrially produced fibres.

4.2 Residual mechanical performance

4.2.1 Compressive strength

The compressive strength was performed according to BS EN 12390-3 [16]. The results of compressive strength after 5 and 10 months of corrosion are shown in Figure 5. Each column in the graphs represents an average of three specimens. The compressive strength after 5 and 10 months of wet-dry cycles was compared with non-corroded specimens after 28 days of curing.

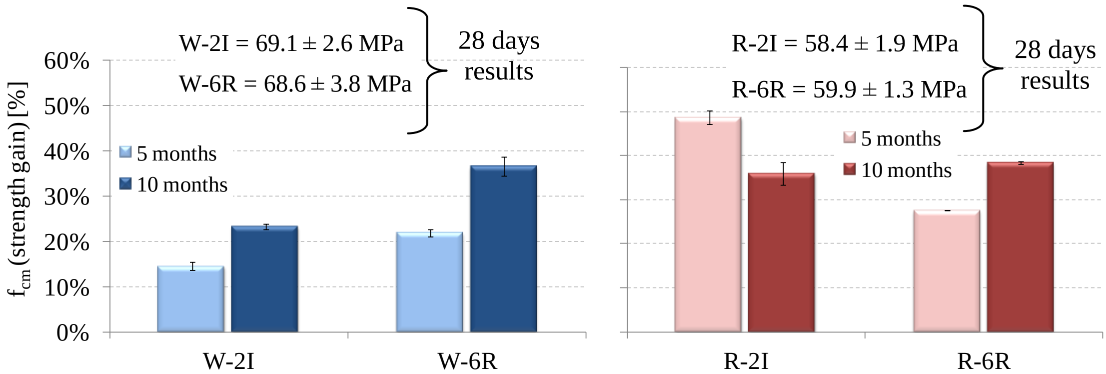


Fig. 5: Compressive strength after corrosion for a) wet and b) RCC mixes.

It can be seen that there is a considerable increase of strength after corrosion simulation; the main gain is observed after 5 months of wet-dry cycles. This can be attributed to ageing of the concrete compared to the 28 days specimens. The immersion in water during the wet phase of the cycles may also have contributed to the strength increase by providing good curing conditions to the specimens.

After 10 months of corrosion simulation, the strength gain is very close to the gain obtained at 5 months of corrosion, indicating that most of the hydration of the cementitious material was completed at 5 months.

To compensate the effect of ageing, the compressive strength of the samples was predicted at the ages of 5 and 10 months after corrosion (plus 28 days of curing), by the BS EN 1992-1-1 [17] – Eurocode-1, following the equation below. This strength is used to normalise the results (by subtracting the effect of ageing) and the gain in strength over what is expected from ageing is shown in Figure 6.

$$f_{cm}(t) = \beta_{cc}(t)\, f_{cm} \quad (1)$$

Where: $f_{cm}(t)$ is the mean compressive strength at t days (t days assumed as 5 and 10 months); f_{cm} is the mean compressive strength at 28 days; $\beta_{cc}(t)$ is the coefficient depending on the age t of concrete $\beta_{cc}(t) = \exp\left\{ s\left[1 - \left(\frac{28}{t} \right)^{0.5} \right] \right\}$ and s is coefficient depending on the cement class (assumed as 0.25).

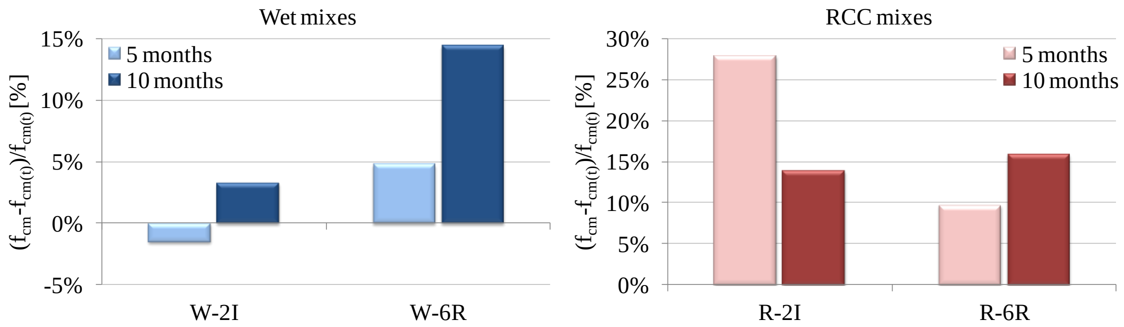


Fig. 6: Comparison between predicted and real compressive strength after exposure to wet-dry cycles.

In all cases (except W-2I), a higher compressive strength is obtained. The predicted strength gain is lower for wet than for dry mixes. This is probably because the equation to predict strength gain is based on conventional concrete and not RCC.

The above equation is valid for the curing conditions following the recommendations of BS EN 12390-2 [18], which does not apply to the conditions experienced during the wet-dry cycles. Theoretically, standard curing should provide better conditions than the wet-dry cycles. Even though the curing conditions of the wet-dry cycles were not as effective as standard curing, the specimens subjected to corrosion still show better behaviour. This can lead to two hypotheses: 1) wet-dry cycles up to 10 months do not affect the compressive strength of SFRC and 2) corrosion may be playing a beneficial role in the compressive strength, especially in terms of improving the bond between fibres and matrix due to the formation of a thin layer of rust.

4.2.2 Flexural strength

Flexural strength tests were performed according to RILEM [19], following a third-point configuration. Figure 7 shows the results of flexural strength at the limit of proportionality f_{LOP} based on Che's [20] approach. Each column in the graphs represents an average of three specimens. The RCC results for 5 and 10 months of wet-dry cycles are higher than the results of the control specimens (28 days), which again indicates ageing of concrete. As noticed for the compressive strength, specimens exposed to up to 10 months of wet-dry cycles do not present loss in the structural bearing capacity.

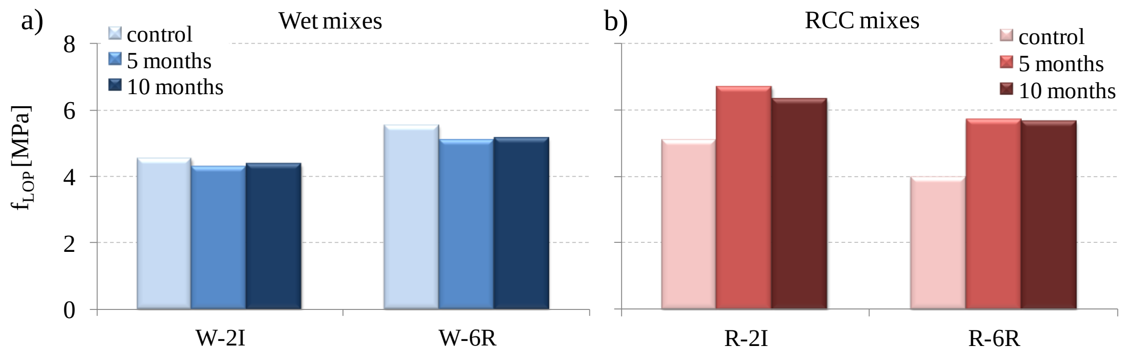


Fig. 7: f_{LOP} at 5 and 10 months of corrosion simulation.

Wet mixes have most of the results of f_{LOP} for both 5 and 10 months slightly lower than the control specimens. However, this seems to be mainly due to the variability associated with the casting of the specimens, since the specimens tested at 28 days were not the same as the ones tested at 5 and 10 months of wet-dry cycles.

5. Conclusions

Recycled steel fibres recovered from post-consumer tyres were added as reinforcement for concrete. SFRC with recycled fibres were exposed to wet-dry cycles up to 5 and 10 months. The main findings obtained from this work are listed below:

- After wet-dry cycles, specimens were examined externally in terms of amount of rust in the surface and a scale of external deterioration, ranging from 0 (lower amount of rust) to 5 (higher amount of rust) was proposed. Specimens with industrially produced fibres show the lowest levels of deterioration whilst specimens with recycled fibres present the highest levels of deterioration. This is due to the geometric characteristic of the recycled fibres, which leads to a higher amount of fibres compared to industrially produced fibres (for the same fibre content).
- The mechanical performance of specimens exposed to wet-dry cycles was compared with control specimens (28 days of curing). There is an increase in both compressive and flexural strength at the limit of proportionality after 5 and 10 months of wet-cycles compared with the control specimens. This is mainly due to ageing of concrete and the improved curing condition caused by the wet phases of the cycles.
- Overall, specimens exposed to wet-dry cycles did not present loss in the mechanical performance and the main consequence of corrosion simulation is in terms of

superficial rust. This conclusion is in line with other studies undertaken on the corrosion behaviour of SFRC, as explained in section 1.2.

Acknowledgements

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