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Corrosion Durability of Recycled Steel Fibre Reinforced Concrete

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Abstract

Steel fibre reinforced concrete (SFRC) is known by its excellent performance when compared to conventional concrete. The use of steel fibres in concrete may contribute to improve properties such as crack and impact resistance, shrinkage reduction and toughness, by preventing/delaying crack propagation from micro-cracks to macro-cracks. In some cases it may be used as a replacement to conventional steel reinforcement or to high quality aggregates in roller compacted concrete.

Industrial steel fibres can be found in a wide range of types, aspect ratios and properties. However, steel fibres are dispersed in all directions and for the same flexural capacity a larger volume of fibre is required than for conventional reinforcement, thus increasing costs. An alternative to industrial fibres comes from the recycling industry through the use of steel from post-consumer tyres. Even though fibres reclaimed in this process are not uniform and have variability in size, experiments at the University of Sheffield have demonstrated that they can be used to enhance the mechanical properties of concrete. In addition to enabling a good mechanical behaviour, these fibres could become an interesting reinforcing alternative due to their lower cost and associated environmental benefits.

Since the concrete produced with recycled fibres is a new material, the study of its durability becomes mandatory before applying it to large scale structures. This research aims to provide means for better understanding of the deteriorative processes that may contribute to the performance reduction of SFRC with recycled fibres. For that, fatigue process, shrinkage, freeze-thaw and corrosion of these fibres are discussed. For the latter property, a complete experimental plan has been already carried out by accelerating corrosion by wet-dry cycles. The results in terms of visual observations show that corrosion affects negatively the appearance of SFRC specimens. The mechanical properties, through the analysis of flexural and compressive tests, are not affected by corrosion after 5 months of wet-dry cycles.

KEY-WORDS: RCC, Steel fibres, corrosion, durability

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1 INTRODUCTION

When steel fibres are added to concrete, the possibility of corrosion of the fibres is a durability parameter that requires special attention. Corrosion is a very common pathological manifestation occurring in ordinary reinforced concrete (RC), and also one which causes more damage to structures, and thus, analysing the effects of this phenomenon in SFRC is of great importance. Several studies have already been carried out considering the corrosion on SFRC (Mangat and Gurusamy, 1987 and 1988; Granju and Balouch, 2005; Kosa and Naaman, 1990). However, the conclusions presented in these works are not sufficient to attest the corrosion resistance of SFRC.

Besides industrial fibres, this research will also analyse the use of recycled steel fibres, produced from post-consumer tyres. This type of fibres can be used as an alternative to the high cost of industrial fibres and also as an environmentally friendly material. Since the concrete with these fibres is considered as a new material, no studies can be found in the literature. The same can be extended to practical applications, on which no durability resistance has been attested so far.

In ordinary RC, steel bars are protected by the passive oxide layer due to the high pH of the concrete and the presence of calcium-hydroxide. In SFRC, however, fibres are randomly distributed inside concrete. This means that some fibres are not protected by the alkalinity of concrete because their concrete cover is near zero (Mangat and Gurusamy, 1988). There are three hypotheses to explain the consequences of corrosion in SFRC. In the first, a decrease of peak loads and an embrittlement of the post peak behaviour is expected to occur; in the second, it is assumed that rust formation will increase friction between the fibre and the cement matrix, which can lead to an uniform gain in strength; and finally, the third hypothesis is related to autohealing of cracks, which restores concrete continuity through the crack and increases the peak load (Granju and Balouch, 2005). The first hypothesis is also attested by Nordstrom (2000) who says that structures with relatively thin steel fibres may have the load capacity reduced due to a decrease of the fibre diameter. The author also adds that this reduction in performance may be highlighted in cracked specimens.

Nordstrom (2000) cites that steel fibres may corrode at a lower rate than conventional reinforcement when both are placed in the same conditions. It is also assumed that the rate of degradation in SFRC may not be linear.

The focus of this paper is to present the study, developed to evaluate the corrosion durability of concrete for pavement applications. For that, ordinary wet mixes were studied as well as dry mixes compacted by rollers. The latest one (RCC) is a dry Portland cement concrete which has zero-slump. In pavement application, which is the focus of the research reported in this paper, RCC is placed by using asphalt

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pavers, equipped with heavy duty dual tamping screed, and compacted by rollers. The majority of studies currently undertaken on steel fibre reinforced (SFR)-RCC are focused on investigating of the mechanical properties. Steel fibres in RCC may be used as a replacement for high quality materials and may also enhance RCC's weak properties, such as low performance against fatigue and tensile stresses and low resistance against crack propagation.

1.1 Procedures to accelerate corrosion in SFRC specimens

Corrosion is usually considered as a long-term process. The effects of the corrosion phenomenon in real structures are dependent of the aggressivity level of the environment, the concrete quality and the maintenance procedures, if they exist. For this reason, techniques to accelerate corrosion in concrete specimens are often used in research centres. Several studies can be found on the techniques to accelerate corrosion in ordinary RC specimens (El Maaddawy and Soudki, 2003). However, there is a lack of studies and standards considering the best way to accelerate corrosion in SFRC.

Some studies found out that the best way to undertake corrosion tests is by using a salt-spray chamber (Mangat and Gurusamy, 1987 and 1988), while others believe that dry-wet cycles is the best technique (Granju and Balouch, 2005 and Kosa and Naaman, 1990), and finally, some of them prefer to expose the specimens directly to a real marine environment (Mangat and Gurusamy, 1988). Electrochemical tests usually used to accelerate corrosion in ordinary RC are not recommended for SFRC. Steel fibres may provide a continuous electrical path between the edges of the specimen. This will lead to fibres more corroded than others, thus invalidating the test. Even though there are some studies on accelerated corrosion techniques of SFRC, the number of researches is still insufficient to attest the best technique to do it.

2 EXPERIMENTAL PROGRAMME

An experimental plan has been carried out to measure the losses in terms of mechanical properties in SFRC and SFR-RCC specimens due to corrosion. For that, prisms (150x150x550mm) and cubes (150mm) were cast to evaluate the performance against flexural and compressive strength tests, respectively. A visual investigation was also performed by analysing the external and internal surfaces of the specimens.

2.1 Mix proportion

For the purpose of this research, SFRC and SFR-RCC specimens were cast following the concrete mix proportions shown in Table 1. The mixes have already been studied in previous experiments carried out in The University of Sheffield (Angelakopoulos et al., 2008) on which the main purpose was to investigate concrete pavement applications. The main difference between the mixes presented in the table is the amount and type of steel fibre. Plain concrete (without any fibre addition) was also cast to quantify the improvement in the performance caused by both fibre types. The amount of industrial fibres was chosen considering that 2% (by mass) is the average content used in practical applications. The recycled fibre content (6% by mass) was chosen because this is the possible amount which gives approximately the same flexural performance as 2% industrial fibres.

Table 1 – SFRC and SFR-RCC mix proportion per cube meter of concrete.

Mix	Cem [kg]	Sand [kg]	Aggre gate [kg]	Water [kg]	Super plastic [%]	Air entrainer [%]	Industrial fibres [% by mass - kg/m³]	Recycled fibres [% by mass - kg/m³]
SFRC1	380	833	1004	133	0.7%	0.135%	-	-
SFRC2	380	833	1004	133	0.9%	0.135%	2% - 47	-
SFRC3	380	833	1004	133	1.3%	0.135%	-	6% - 141
SFR-RCC1	300	-	2092	160.3	-	-	-	-
SFR-RCC2	300	-	2092	160.3	-	-	2% - 51	-
SFR-RCC3	300	-	2092	160.3	-	-	-	6% - 153

Cement used for wet mixes is a low energy cement (LEC), which consists of granulated blast furnace slag, secondary constituents, calcium sulphate and additives. Corrosion protection is due to the pH around 11.8 to 11.9. For RCC mixes, the cement used was Type II - limestone, which has a corrosion protection slightly higher than the LEC, through the pH around 13.

The gradation curve for the wet mix round aggregate 10mm and RCC crushed aggregate blend 14mm is presented in the figure below.

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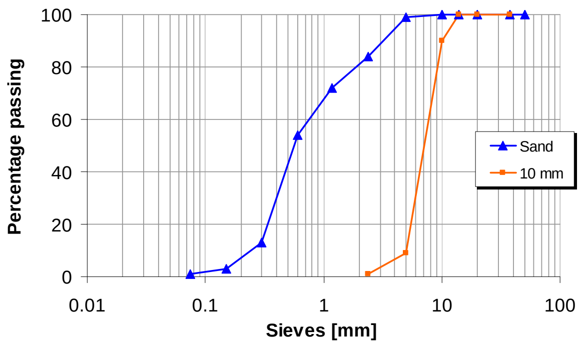
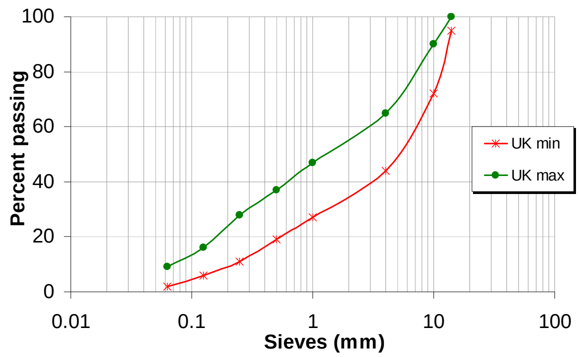


a)



b)

Figure 1 – Gradation curve for the coarse aggregate. a) wet mixes; b) RCC mixes

The industrial fibre used, termed I2C1/54, had a cone at each end (Figure 2a), an aspect ratio of 1/54 and tensile strength of 1100N/m². Recycled fibres were obtained from post-consumer tyres, through mechanical treatment and 90% of the fibres had length in the range of 3-11 mm. Figure 2b illustrates these fibres.

Specimens were cast in steel moulds and compacted by an external vibrating machine (wet mixes) or hydraulic hammer (RCC mixes). All specimens were demoulded 24h after casting and then placed for 27 days in the mist room with controlled temperature and relative humidity (+20°C and RH≥95%). After this period, specimens were subjected to wet-dry cycles in order to accelerate corrosion in the fibres, as explained in more detail in the next section.

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a) industrial fibres

b) recycled fibres

Figure 2 – Appearance of fibres.

2.2 Acceleration of corrosion

As mentioned before, there is no standard on the best technique to accelerate corrosion in SFRC specimens. Furthermore, all studies carried out in the area show different techniques and no correlation among them is presented.

For the purpose of this research, the procedures used to accelerate corrosion were by immersing RCC specimens in a container with chloride solution (3% of NaCl) for 4 days followed by a period of 3 days of drying at ambient temperature. Wet-dry cycles allow both the penetration of chlorides and the presence of oxygen, in order to develop the corrosive process. Figure 3 shows the wet and dry phases of the test.

a) specimens immersed in saline solution – 4 days

b) specimens drying at ambient temperature – 3 days

c) return to salt solution – end of cycle

Figure 3 – Steps of the wet-dry cycles – acceleration of corrosion.

Plastic spacers were used to separate the specimens from each other (by at least 10mm). The procedures to take the specimens out and in the containers were performed mechanically by an overhead crane (see above figure) which resulted in less than 5 minutes the time spent in each procedure. These experiments are

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considered as long-term tests and are expected to include 5 and 10 months of continuous cycles.

3 ANALYSIS OF THE RESULTS

This section presents the main results regarding the losses in performance due to corrosion attack after 5 months of continuous wet-dry cycles. The results after 10 months of corrosion acceleration will be obtained in autumn 2008.

3.1 Visual analysis

A series of pictures have been taken to visualize the various stages of corrosion testing before starting the corrosion cycles (Figure 4); at 2 months and half (Figure 5), and finally, at 5 months (Figure 6). For the latter, following the flexural and compressive strength testing of the specimens (at month 5), a visual examination was carried out (Figure 7) to asses the internal effects of corrosion (i.e. inside the samples).

Figure 4 shows the specimens just after being taken out from the mist room.

a) specimens being positioned in the frame before corrosion

b) specimens ready for the beginning of cycles

Figure 4 – Specimens before corrosion accelerating procedures.

It is clearly observed in the pictures that, during curing, some of the specimens have already been externally corroded. This is especially noticed for the RCC prisms reinforced with recycled fibres. Despite this fact, all other samples seem to present no signs of corrosion.

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a) overall view of the samples | b) view of corroded RCC sample with recycled fibres | c) view of corroded RCC sample with industrial fibres

Figure 5 – Specimens after 2.5 months of corrosion accelerating procedures – external analysis.

Figure above shows the specimens when taken out from the solution after 2.5 months of accelerated corrosion. It is noticed that the samples with more superficial corrosion effects are those already corroded after curing (RCC with recycled fibres). A large amount of rust is observed in Figure 5b, which changed completely the specimen's colour. In this same set of specimens, spalling of small parts of concrete occurred by just using little effort. Figure 5c shows industrial fibres with a great amount of corrosion. This is especially observed in the fibres which were already exposed to the surface of the RCC specimens due to compaction limitations during casting. These specimens are not as rusty as those with recycled fibres. Wet mixes did not present as high corrosion signs as the RCC mixes.

a) overall view of the samples | b) view of corroded RCC sample with recycled fibres | c) view of corroded RCC sample with industrial fibres

Figure 6 – Specimens after 5 months of corrosion accelerating procedures – external analysis.

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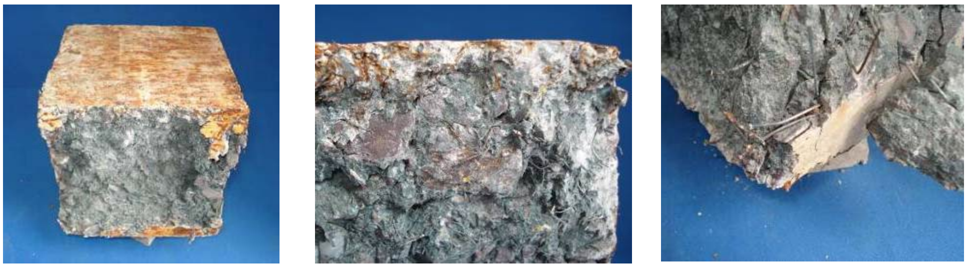
Figure 6 shows that after 5 months of corrosion acceleration, the same comments explained for 2.5 months apply regarding the external appearance of the specimens. The level of the superficial damage, however, has increased from the previous assessment. Wet mixes presented only few signs of external rust, usually on the fibres positioned near the specimen surfaces.

The external effects of corrosion produce a brownish colour all around the specimens. This appearance, when noticed in real structures, may be responsible for uncomfortable feelings in users.

An observation of the internal appearance of the concrete after testing the specimens was also performed. The purpose of this was to verify if the salt solution is able to penetrate inside concrete, thus causing corrosion of fibres in different depths of the specimens (Figure 7).



a) RCC sample with recycled fibres after compressive test

b) detail of inside sample's edge – little recycled fibres corroded

c) detail of inside sample's edge – industrial fibres partially corroded

Figure 7 – Specimens after 5 months of corrosion accelerating procedures – internal analysis.

Figure 7a shows that the effects of corrosion, such as rusty appearance, can be seen only externally. Figure 7b, for instance, shows that just a small layer (around 10mm) inside the sample presented few signs of corrosion (for RCC samples with recycled fibres). Figure 7c shows the edge of a RCC sample with industrial fibres; corrosion took place only in the fibre surface exposed to the environment. In the same fibres, the surface anchored to concrete presented no corrosion, as it was protected by the alkalinity of concrete. Wet mixes did not present any sign of internal corrosion.

3.2 Flexural strength

The test was performed according to the RILEM TC 162-TDF (2002) by controlling the crack mouth opening displacement in a four-point flexural test.

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Specimens were notched transversally in the bottom centre (25mm depth) to stimulate the crack to open in that region. Figure 8 shows a specimen during testing.

Figure 8 – Specimen in the flexural test.

The results in terms of flexural strength obtained from the peak loads are presented Figure 9.

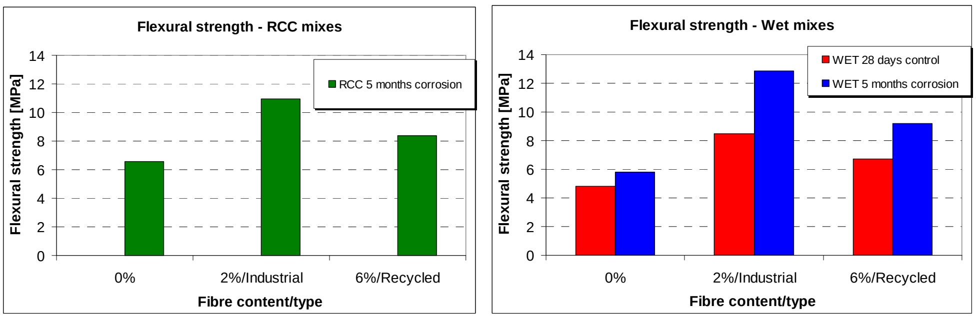

Figure 9 – Flexural strength results for RCC and wet mixes.

It can be observed that for the wet mixes there is an increase of the flexural strength capacity of the samples after 5 months of corrosion when compared to the ones tested at 28 days. This increase is possible caused by the difference in the age of the specimens. Results for RCC control specimens for 28 days will be available by autumn 2008. However, it can be observed that even when corroded, the RCC specimens with fibres presented better performance when compared to the plain concrete.

Figure 10 shows bending load versus vertical displacement results (average of two LVDT positioned at each side of the specimens). By considering typical results of

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flexural test of SFRC, it seems that there are no changes on the post crack behaviour of a corroded SFRC specimen compared to a non- corroded one.

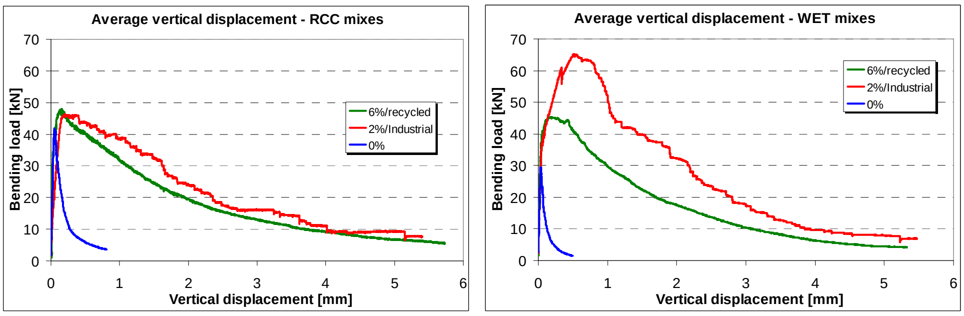

Figure 10 – Flexural test results after 5 months of corrosion accelerating procedures.

3.3 Compressive strength

Compressive strength tests were performed according to the British Standard BS EN 12390-3 (2002). Specimens were tested after being subjected to 5 months of continuous wet-dry cycles. The results obtained are presented in Figure 11.

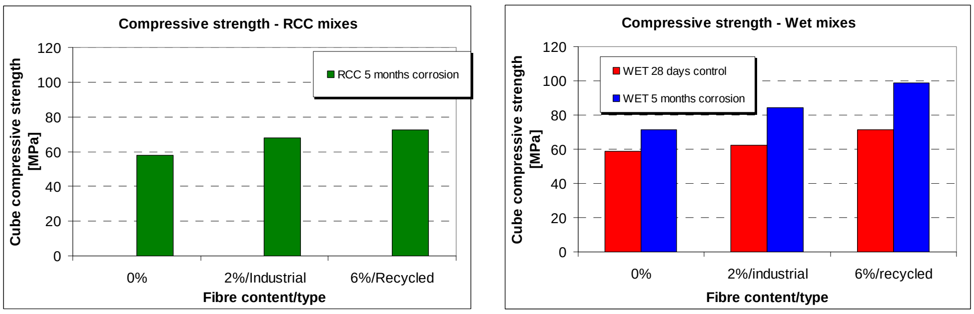

Figure 11 – Compressive strength results for RCC and wet mixes.

Following the same behaviour as the flexural test, it can be observed that samples subjected to 5 months of corrosion presented better results when compared to the control samples (wet mixes at 28 days). Same comments regarding the missing control samples (28 days) for the RCC mixes in the flexural strength test is applied to this case (results will be available in autumn 2008).

Industrial fibres present better performance than recycled fibres in the flexural test. However, recycled fibres showed high compressive capacity than industrial fibres.

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4 DISCUSSIONS AND CONCLUSIONS

The following items explain the main conclusions obtained from this work.

The wet-dry procedures used to accelerate corrosion in SFRC can be considered as a good technique to imply corrosion in concrete specimens in a small period of time.

In terms of external analysis, specimens reinforced with industrial fibres presented less damage than the ones with recycled fibres. The internal analysis showed that both fibre types presented limited signs of corrosion. RCC specimens seem to develop more external rust.

Considering the flexural behaviour of corrosion SFRC, it was observed that the performance of specimens was not reduced by corrosion attack. The same conclusion can be extended to compressive results, which showed that, even if specimens are externally corroded, this has no influence on the compressive strength capacity of the samples. The increase in the capacity observed for corroded wet mixes when compared to those at 28 days is probably due to the age of the specimen.

Compressive and flexural results presented in this paper showed that specimens with 2% industrial fibres have similar performance as those with 6% recycled fibres. Industrial fibres presented better performance in flexural tests while the opposite was noticed in the compressive test.

The overall analysis of the results demonstrated that when SFRC specimens are subjected to 5 months of continuous wet-dry cycles, corrosion of fibres can be noticed only externally. Just few signs of corrosion can be visualised internally and both external and internal visual effects do not interfere on the mechanical capacity of the samples. When used in pavements, if SFRC and SFR-RCC is covered with asphalt layer, the possible uncomfortable feeling caused by the rusty appearance can be reduced or even ignored.

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