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Corrosion of steel fibre reinforced concrete from the cracks

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Abstract

The corrosion of steel fibres in the cracked section has been under investigation by many researchers since the last 15 years. It is reported widely that in case of steel fibres reinforced concrete (SFRC), corrosion is less active as compared with steel bars. In the cracked section, the durability of the material depends on the performance of the bridging capacity of the fibres embedded in the concrete. The corrosion of the fibres not only could produce the spalling of concrete but it could also reduce the sectional area of the fibres, turning the durability of structures in danger. This study focuses on those two aspects of fibre corrosion. The tests were performed on cracked SFRC samples with 0.5-mm crack mouth openings (CMOs) exposed to marine-like environment for 1 year. The results confirm the small sensitivity of SFRC to corrosion. Surprisingly, they made appear an increase of the flexural strength after corrosion. The factors affecting the corrosion of the fibres and the reasons for the increase in flexural strength after corrosion are discussed.

Keywords: E. Fibre reinforcement; Corrosion; Steel fibres

1. Introduction

Fibre addition in the concrete brings a better control of its cracking and improves its mechanical properties. Particularly, it imparts to the material a postcracking load-carrying capacity inducing pseudoductility, which decreases its fragile character.

Various types of fibres can be used successfully. The metal and, more particularly, steel fibres are most largely employed. Initially used in pavements and slabs on soil, their applicability is now extended to the case of structural elements such as piles, beams and self-supporting cladding elements (generally prefabricated), spread linings, and repairs or reinforcements of tunnels, walls, or floors.

The behaviour of steel fibre reinforced concrete (SFRC) started to be well known in the case of a first short-term loading; the durability of their vital character in the structural applications remains still largely to be explored. The long-term behaviour of operational structures reinforced with steel fibre in the cracked mod depends on their capacity of effort taken by the fibre between the two lips of cracks. This is conditioned, on the one hand, with mechanical creep and fatigue effect, on the other hand, with corrosion of fibres.

This work is centred on corrosion attack through the cracks of the fibres in SFRC. On the one hand, that may result in a bursting of cement matrix by swelling accompanying the development of corrosion products. On the other hand, the crack-bridging capacity of the fibres can be weakened by the corrosion, which reduces their section.

In the literature, all the authors agree on the point that the corrosion arising from cracks is less severe in the case of SFRC and, surprisingly, often finishes into an increase in the flexural strength [1–7].

This study applies to the development of the corrosion in SFRC and to the increase in the flexural strength after corrosion. It is a part of a wider study including the corrosion from the external surface and the eventual efficiency of corrosion inhibitors [8].

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2. Experimental programme

2.1. Specimens preparation and treatment

Concrete prisms of 10×10×50 cm dimension were prepared with W/C=0.60 and a CEM I 52.5 cement to achieve a 28-day compressive strength of 40 MPa. The same series of tests was carried out with a CEM II 32.5 cement to see the effect of additives included in CEM II. The concrete composition common to both series is presented in Table 1. The fibres used were hooked steel wires, 60 mm in length and 0.8 mm in diameter. The prisms were kept in a humidity room for 24 h, covered with polyethylene sheet. Then they were demoulded and were cured in the laboratory air for 1 week. Subsequently, they were cracked in three-point flexure as will be described later. Afterwards, they were exposed for 1 year to a marine-like environment in a chamber providing cycles of 1 week salted fog at 3.5 g/l of NaCl alternating with 1 week of dryness. The chosen salinity of the fog is the average of different seas and oceans, as given in Table 2.

The prisms were cracked at three positions, as shown in Fig. 1. In the fog room, they were positioned in such a manner that the cracks remain in vertical position, as shown in Fig. 2. In this way, during the periods of salted fog, the water could penetrate in the cracks, and during the periods of dryness, the water accumulated in the cracks could drain by gravity, allowing air, and its oxygen, to arrive in quantity on the corrosion sites. It results in one of the most severe conditions in regard with corrosion. Half of the prisms had their cracks sealed, and for the other half, the cracks were kept open to corrosive environment. The sealing was assured by plastic adhesive tape, 1.5 cm wide, on all the length of the crack. Moreover, the protection was reinforced by marine silicon mastic, as presented in Figs. 3 and 4. Both types of prisms, opened and sealed ones, were placed simultaneously in the fog room.

2.2. Cracking of the prisms

The cracking of the prisms was performed after 7 days of curing in the laboratory air. The prisms were loaded in three points bending on a span of 20 cm. The machine was controlled by the true deflection at midspan measured by the so-called "Japanese yoke" method. Meanwhile, the crack mouth opening (CMO), measured by an LVDT sensor, was monitored. The details of the experimental fittings are illustrated in Figs. 5 and 6.

The deflection was increased at a rate of 10 μm/min until the CMO reached 0.8 mm, so that, after unloading, the remaining CMO was close to 0.5 mm.

Table 1
Composition of concrete

Composition in kg/m^3	Concrete
Cement CPA CEM I 52,5 or CPJ CEM II 32,5	320
Sand 0–5 mm	725
Gravel 5–12 mm	1088
Water	192
W/C	0.60
Fibres	40

Table 2
Salinity of different seas and oceans

Sea and oceans	Salinity total NaCl+ secondary salts (g/l)
Pacific Ocean	34 à 37
Atlantic Ocean	34 à 37
Mediterranean Sea	38 à 41
Black Sea	18 à 22

2.3. Testing of the specimens after corrosion

Both types of prisms, cracks opened and sealed, were tested after 1-year exposure to the aggressive marine-like environment. Before testing, they were allowed to dry for 7 days in laboratory air. The test consisted of measuring the residual mechanical behaviour after corrosion. The procedure was the same as for the initial cracking, but it was then continued until a deflection approaching 5 mm.

3. Results

A representative selection of the experimental load–deflection curves is presented in Figs. 7–9.

3.1. Guide for load–deflection curves interpretation

The test specimens having been precracked, the peak of the load–deflection curves represents the load at which the fibres have started slipping on reloading. The postpeak behaviour represents the evolution of the crack-bridging capacity of the fibres as they are progressively dislodged from the material.

The corrosion may act in different manners, with the following different effects:

(a) If the strength of the fibres is affected by the corrosion, a decrease of the peak load is expected, accompanied by an embrittlement of the postpeak behaviour.
(b) If the autohealing of the crack has occurred during marine spray, restoring a part of the concrete continuity through the crack, the peak load is expected to increase. Afterwards, once this restored continuity is broken, the postpeak curve is expected to rejoin one of the noncorroded (protected) prisms.
(c) If, in the absence of crack healing, corrosion of the fibres would increase their grip and their following friction in the cement matrix, it is expected to observe a uniform gain in strength at the peak and in the following postpeak portions of the curve.

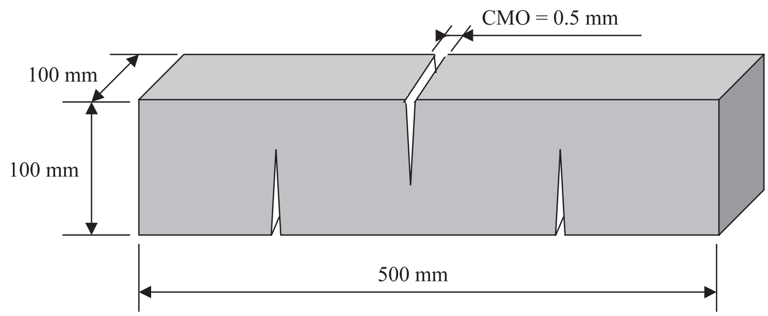

Fig. 1. Crack positions.

3.2. Discussion on the experimental curves

All the results with cement CEM I 52.5 and CEM II 32.5 including additives are of the Type (c) above. The lower strengths of CEM II 32.5 prisms are in accordance with the lower grade of the cement. Compared with the protected prisms (noncorroded), the ones with opened cracks exhibit a uniform gain in strength at the peak and in the following postpeak phases. This behaviour implies the following:

- Although having 1-year exposure to marine-like environment, the crack-bridging strength of the fibre reinforcement was not weakened by corrosion.
- A light corrosion is expected to have developed at the surface of the fibres, enhancing their bond and their further friction with the cementitious matrix.

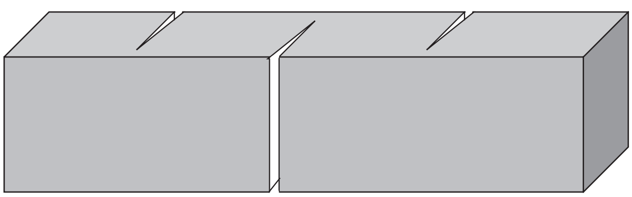

Fig. 2. Position of the prisms in the fog room.

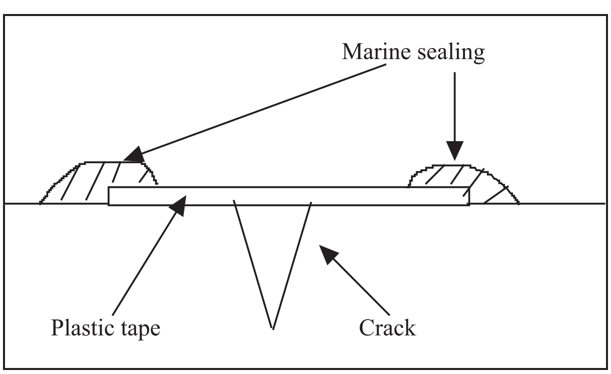

Fig. 3. Sketch of cracks protection.

Fig. 4. Cracks protection.

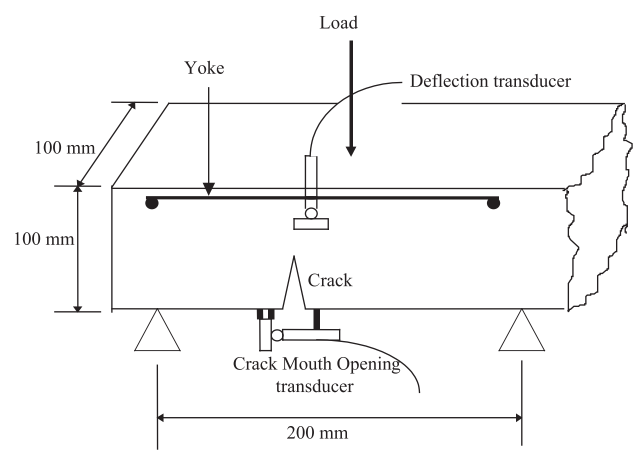

Fig. 5. Sketch of the cracking of the prism.

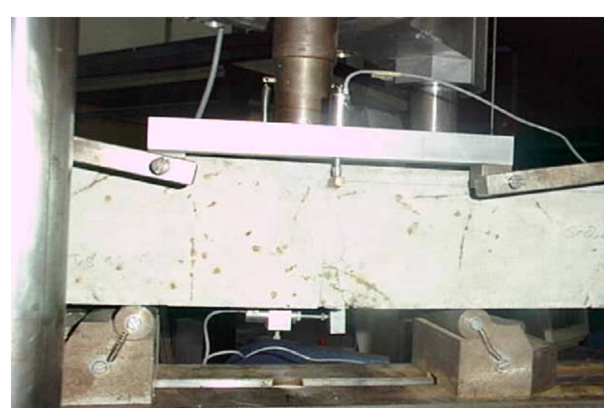

Fig. 6. Photograph of the cracking of the prism.

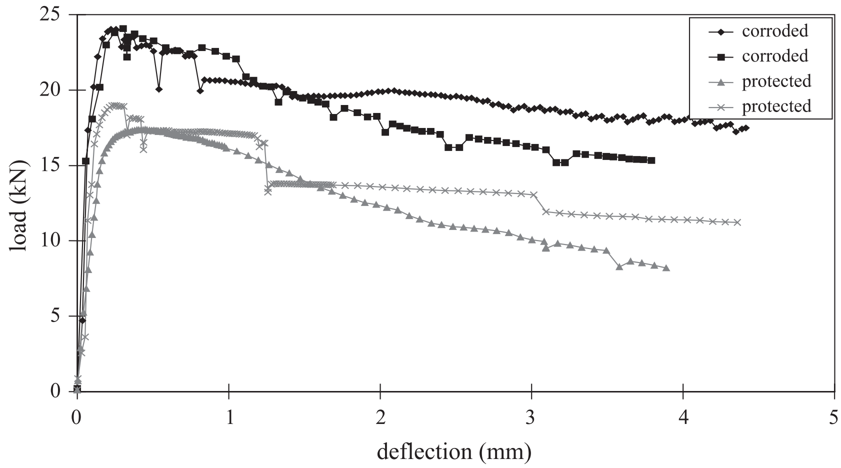

Fig. 7. Incidence of corrosion on fibres strength: cement CPA CEM I 52.5.

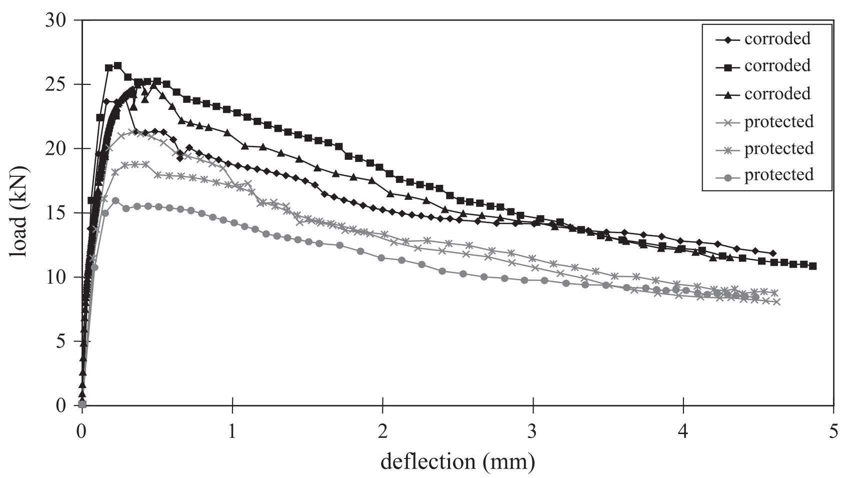

Fig. 8. Incidence of corrosion on fibres strength: cement CPA CEM I 52.5 (continued).

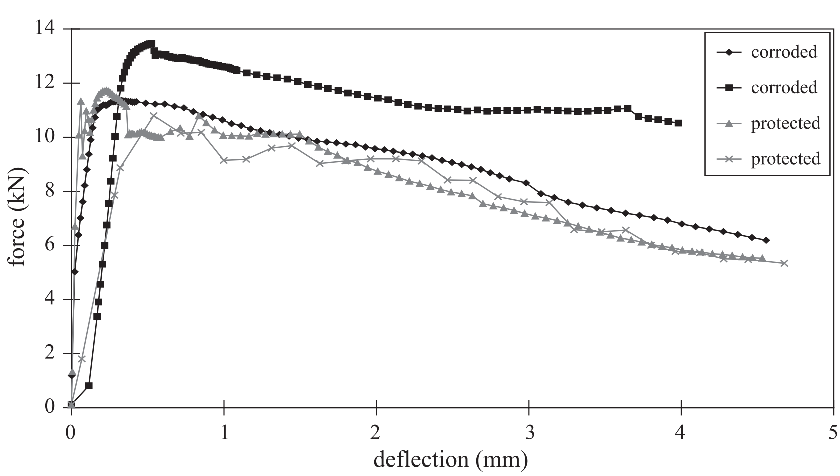

Fig. 9. Incidence of corrosion on fibres strength: cement CPJ CEM II 32.5.

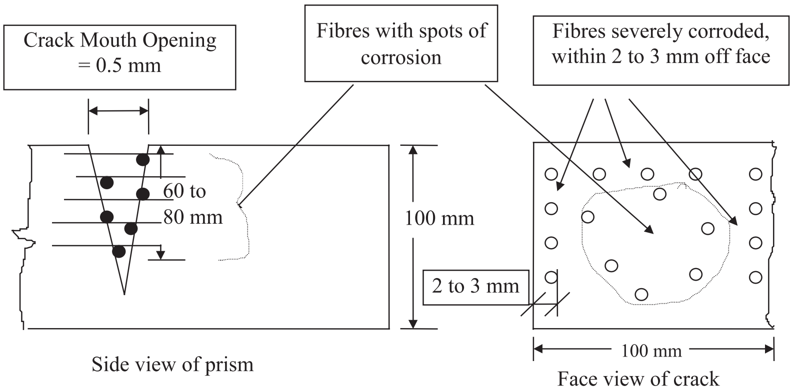

Fig. 10. Corrosion of the fibres observed in the crack.

Such an increase of strength after exposure to marine environment for several years has already been observed by Mangat and Gurusamy [5,6]. They attributed it to autohealing.

Although autohealing may exist in cracked samples submitted to water ingress, it cannot be the explanation of the strength increase observed on our samples. Indeed, among all the load–deflection curves obtained in this test series, none exhibited the behaviour typical of autohealing (Type b above). Moreover, no evidence of hydration products deposit inside the cracks was brought by the visual observation, presented in the next paragraph.

4. Visual examination

4.1. Observations

After the flexure test, each prism has been carefully broken following the path of each investigated crack. Each face of these cracks and emerging fibres was examined visually and with a magnifying glass. The following features, illustrated in the sketches and photographs of Figs. 10–12, were observed:

- No concrete bursting or sapling was provoked due to the corrosion of the fibres.
- No deposit of any kind was found in the cracks; thus, no evidence of healing.
- All the fibres within a rim 2 to 3 mm wide from the external surfaces of the sample were severely corroded.
- Excluding this rim, only a light corrosion of the fibres with no reduction of their section was observed. This corrosion was concentrated, on the one hand, at the emerging point of the fibres in the crack and, on the other hand, at the level of the hooked end of the fibres. A much lighter corrosion was sometimes visible along the length of the fibres.
- The above feature spread until a depth of 60 to 80 mm along the crack path (see Fig. 10). Assuming that the crack was wedge shaped, at this depth, it was about 0.1 mm wide. It follows that no corrosion should be expected from the cracks thinner than about 0.1 mm.

4.2. Analysis and interpretation

Complementary tests were carried out on specimens where the crack was replaced by a saw cut. Saw cutting, instead of cracking, prevented any pull out of the fibres, and their bond with the cement matrix remained undisturbed and sound. After 1-year exposure to the marine-like environment (the same as for the cracked specimens), the cut ends of the fibres on the sawed section of the samples exhibited very severe corrosion, but this one did not penetrate more than about 1 mm inside the concrete. Deeper, all the fibres more than 1 mm apart from the external surfaces of the samples were free of corrosion.

When a crack is involved, the fibre pull out breaks the tight and protective fibre–concrete contact, and the resulting distressed contact opposes less protection against corrosion. The extra loosening of the contact by the scraping of the

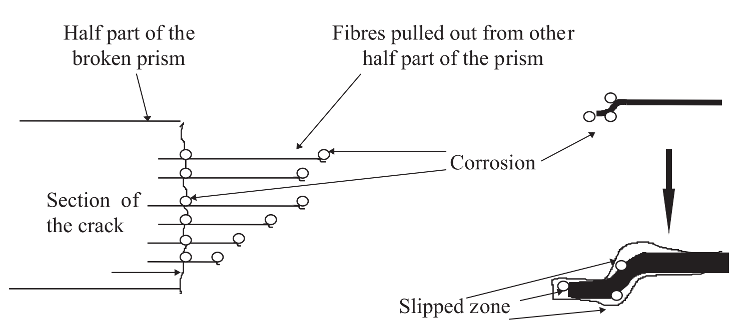

Fig. 11. Detail of corrosion observed on the fibres emerging from the crack section.

Fig. 12. Photograph of the corroded fibre in the crack.

concrete sheath by the pulling out of the fibres makes the matter worse. Especially, the condensation of water and subsequent corrosion turns possible in the loosened areas. In this respect, as illustrated in the sketch of Fig. 11, the end and the hook of each fibre are privileged sites because significant gaps between the cement matrix and the fibre are created.

A separate study of corrosion ingress from the surface [9], also in the absence of any mechanical stressing or straining, showed that, in the case of the high-porosity concrete matrix used for these tests (W/C=0.6), although chloride had penetrated several millimetres inside the concrete, only the fibres with a concrete cover thinner than 1 mm were corroded. The same study showed also that when W/C $\leq$0.5, the minimum concrete cover to avoid fibres corrosion from the surface is dropped to a couple of 1/10 mm.-

The distress of the fibre–concrete bond caused by crack opening turns corrosion easier. Then, it is expectable that the corrosion ingress from the external surfaces can penetrate deeper than 1 mm. It is the proposed explanation for the rim 2 to 3 mm deep of severely corroded fibres. In this respect, this corrosion rim would be the result of corrosion from the external surfaces, facilitated by cracking, which distressed the fibre–concrete bond. That is consistent with the observation that the thickness of the rim is not related with the actual local opening of the crack.

5. Conclusion

Our results confirm that steel fibres are less vulnerable to corrosion than steel bars are. After 1 year exposure to marine saline fog:

- there is no corrosion in the parts of the cracks thinner than about 0.1 mm,
- in the wider parts of the cracks (the tested samples had CMOs=0.5 mm), a light corrosion of the fibres with no reduction of their section was observed,
- only the fibres crossing the crack within a 2- to 3-mm rim from the external faces of the specimens exhibited extensive corrosion,
- and lastly, no concrete bursting or sapling due to corrosion of the fibres was observed.

A comparison with cut specimens, exposing the fibres to corrosion even more drastically than from a crack, but in which there is no distress of the fibre–concrete contact, clearly indicates that the major factor facilitating corrosion is the breaking of the tight fibre–cement matrix bond. The breaking of this bond is the consequence of the slipping of the fibres accompanying the crack opening.

Moreover, the strength of cracked samples exposed 1 year to marine saline fog was not weakened, but, surprisingly, it was increased. Contrary to the proposal of other authors, this increase is not consistent with autohealing. From the visual observation of the cracked sections and from the analysis of the load–deflection curves in flexion, our conclusion is that this gain in strength results from the light corrosion of the fibres. Too light to depress the fibre's load-bearing capacity, the corrosion makes the external surface of the fibres less smooth, then the slipping of the fibres in the concrete matrix is more difficult, and the overall strength is increased.

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