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CORROSION RESISTANCE OF STEEL FIBRE REINFORCED CONCRETE – A LITERATURE REVIEW

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ABSTRACT

Steel fibre reinforced concrete (SFRC) is increasingly being used in the construction of prefabricated segmental linings for bored tunnels, since it entails simplified production processes and higher quality standards. However, international standards and guidelines are not consistent regarding the consideration of steel fibres for the structural verification of SFRC elements exposed to corrosive environments, hampering the development of civil infrastructure built of SFRC. In particular, the long-term effect of exposure to chlorides is in focus and under discussion. This paper reviews the existing literature concerning chloride-induced corrosion on steel fibres, as well as the impact of steel fibre corrosion on the residual-tensile strength of SFRC. The review confirms the agreement among academics and regulators regarding the superior durability of un-cracked SFRC exposed to chlorides, relative to conventional reinforcement. However, the durability of cracked SFRC is still under discussion, as the mechanisms governing the corrosion of carbon-steel fibres in cracks and its effects on the fracture behaviour of SFRC are still unclear. Nevertheless, there is insight among several researchers concerning the existence of a critical crack width, below 0.20 mm, where corrosion of carbon-steel fibres is not critical and the structural integrity of the exposed SFRC can be ensured over the long-term. A doctoral project investigating chloride-induced corrosion of steel fibres on cracked SFRC has been initiated, in order to explore the governing deterioration mechanisms.

Keywords: Carbon Steel Fibre Reinforced Concrete, SFRC, Corrosion Mechanisms, Chlorides, Cracks.

1. Introduction

Steel fibre reinforced concrete (SFRC) is a composite material, combining a cementitious matrix and a discontinuous reinforcement, consisting of steel fibres uniformly distributed in the matrix. The term SFRC primarily refers to conventional mix-designs: typically based on Portland cement binders, with mix-proportions and elastic mechanical properties (i.e. in the un-cracked state) similar to conventional concrete. SFRC is increasingly being adopted for the production of in-situ and prefabricated concrete structures as: a) auxiliary reinforcement for temporary load cases, e.g. arresting shrinkage cracks, limiting cracks occurring during transport or installation of precast members, b) partial substitution of the main reinforcement, i.e. combined reinforcement systems, and c) total replacement of the conventional reinforcement in elements in overall compression, e.g. ground-supported slabs, tunnel linings, foundations, thin-shell structures. (di Prisco and Plizzari, 2004; Li, 2002; Serna et al., 2009).

The use of steel fibres as partial or total replacement of conventional reinforcement bars has become a popular solution for the construction of prefabricated segmental linings for bored tunnels, due to its overall superior durability and good performance in compression (Abbas, 2014; De-Waal, 1999; Plizzari and Tiberti, 2006; Rivaz, 2010; Schnütgen, 2003; Wallis, 1995). Nevertheless, the elimination of the conventional steel reinforcement is still controversial according to some researchers, particularly when the long-term durability of SFRC under severe chloride and carbon dioxide exposure is addressed (Halvorsen et al., 1976; Weydert and Schiessl, 1998; Winterberg, 2011).

At present, no international standard is available for the design of SFRC structures. However, an EN standard is currently in preparation. Furthermore, the national guidelines available for design of SFRC are not consistent regarding their applicability. **Table 1** presents a summary of the main design-limits for the EN 206 exposure classes (CEN, 2013).

Table 1. Summary table, design recommendations for SFRC exposed to chlorides and carbonation

Standard	Ref	Carbonation			Chlorides			
		XC2	***XC3***	***XC4***	***XS2***	***XS3***	***XD2***	***XD3***
ACI-544-1R-96 (US)	1	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.10$	$w_k < 0.10$	$w_k < 0.10$	$w_k < 0.10$	$w_k < 0.10$
RILEM TC 162-TDF (EU)	2	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$	Special	Special	Special	Special
DBV-Merkblatt Stahlfaserbeton (DE)	3	$w_k < 0.30$ $\Delta_h > 20$	$w_k < 0.30$ $\Delta_h > 20$	$w_k < 0.20$ $\Delta_h > 25$	$w_k < 0.20$ $\Delta_h > 40$	$w_k < 0.20$ $\Delta_h > 40$	$w_k < 0.20$ $\Delta_h > 40$	$w_k < 0.20$ $\Delta_h > 40$
UNI/CIS/SC4:2004 (IT)	4	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$ Coated	$w_k < 0.30$	$w_k < 0.30$ Coated
CNR-DT 204/2006 (IT)	5	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$ Coated	$w_k < 0.30$ Stainless	$w_k < 0.30$	$w_k < 0.30$ Coated
NZS 3101-2:2006 (NZ)	6	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.20$	$w_k < 0.20$	$w_k < 0.20$	$w_k < 0.20$
TR-63 (UK)	7	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$
EHE 2008 (ES)	8	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.30$	Test	Test	Test	Test
DAfStb Stahlfaserbeton (DE)	9	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.20$	N/A	N/A	N/A	N/A
Design guideline for structural applications of steel fibre reinforced concrete (DK)	10	$w_k < 0.30$	$w_k < 0.30$	$w_k < 0.20$	N/A	N/A	N/A	N/A
AFTES-GT38R1A1 (FR)	11	$w_k < 0.20$	$w_k < 0.20$	$w_k < 0.20$	$w_k < 0.15$	$w_k = 0$	$w_k < 0.15$	$w_k = 0$
SS-812310:2014 (SE)	12	$w_k < 0.40$	$w_k < 0.40$	$w_k < 0.30$	$w_k < 0.20$	$w_k < 0.10$	$w_k < 0.20$	$w_k < 0.10$

References: *1) ACI Committee 544 (2002); 2) RILEM (2000); 3)* DBV (2001)*; 4)* UNI (2004)*; 5)* CRN (2006)*; 6) New Zealand Standards (2006); 7) The Concrete Society (2007); 8) Spanish Development Ministry (2009); 9) DAfStb (2012); 10) SFRC Consortium (2013); 11) Guedon (2013); 12) Swedish Standards Institute (2014).*

Abbreviations: *(N/A) Not applicable; (Coated) Coated carbon-steel or stainless-steel fibres required; (Stainless) Stainless-steel fibres required; (Test) Experimental verification required; (Special) Special provisions required; (w_k) maximum crack width allowed, expressed in mm; (Δ_h) minimum sacrificial layer on exposed surfaces; (XC, XS, XD) EN 206 exposure classes.*

There is an overall agreement among the standards and guidelines regarding the design of SFRC under carbonation exposure, with a limit crack width in the range 0.10 – 0.30 mm for the most aggressive conditions (i.e. XC4, cyclic wet and dry), presenting similar limitations to conventional reinforcement.

The case of chloride exposure is more controversial, and four main approaches can be identified, as shown in **Table 1**: a) limit cracks to the range 0.10 – 0.20 mm (ACI Committee 544, 2010; German Society for Concrete and Construction Technology, 2001; New Zealand Standards, 2006); b) propose special measures such as experimental validation (RILEM, 2000; Spanish Development Ministry, 2009); c) require the use of coated carbon-steel or stainless-steel fibres (CRN, 2006; UNI, 2004); d) limit the applicability for these exposure classes (DAfStb, 2012; SFRC Consortium, 2013), or consider the un-cracked state, e.g. the contribution of the steel fibres cannot be considered under serviceability limit state (Guedon, 2013).

The inconsistencies observed regarding the consideration of the steel fibres for SFRC exposed to chlorides suggest a limited understanding of the mechanisms governing chloride-induced corrosion on steel fibres in concrete and its effects on the mechanical behaviour of SFRC. Therefore, this paper reviews the existing literature investigating chloride-induced corrosion of steel fibres in concrete, and evaluates the main variables influencing the long-term durability of SFRC exposed to chlorides. Finally, the paper discusses various mechanisms explaining the results presented on the experimental work and an alternative model covering the corrosion of steel fibres bridging cracks on SFRC exposed to chlorides.

2. Mechanisms of chloride-induced corrosion in SFRC

Steel embedded in uncontaminated concrete remains passive due to the high alkalinity of the concrete. The ingress and build-up of chloride ions into the matrix surrounding the steel disrupts the passive layer and reduces locally the pH at the steel surface, initiating pitting-corrosion (Bertolini et al., 2013).

Following a generalized conceptual model for corrosion of steel in concrete (Tuutti, 1982), the deterioration of SFRC exposed to chlorides can be divided into two stages: a) initiation phase, where dissolved chlorides penetrate into the concrete and reach the steel surface and, b) propagation phase, once the chloride threshold at the steel surface is exceeded the corrosion of the steel embedded in the contaminated concrete proceeds.

2.1 *Transport of chlorides in SFRC*

The transport properties of un-cracked SFRC have been proven similar to the properties of un-reinforced concrete. Contrary to earlier assumptions, the fibre-matrix interface does not provide a preferential path for the ingress of chlorides (Berrocal et al., 2014; Cangiano et al., 2005; Mangat and Gurusamy, 1987a; Sanchez and Alonso, 2009; T. Teruzzi et al., 2004). Moreover, Abbas et al. (2014) suggest a lower chloride penetration in un-cracked SFRC relative to plain concrete, attributed to the arresting of micro-cracks by steel fibres during curing and handling (Corinaldesi and Moriconi, 2012).

The transport properties of cracked SFRC are also unaffected by the fibres, excluding the assumed crack arresting effect of the fibres: reduced cracking at same load conditions compared to plain concrete (Abbas et al., 2014b). The build-up of chlorides in cracks due to wet-dry cycles, evaporation, and limited wash-out, increases the chloride concertation at the crack. This leads to similar chloride concentrations at the crack faces compared to external exposed surfaces, i.e. the crack faces act as free surfaces (Hansen et al., 1999).

2.2 *Chloride-induced pitting corrosion of steel fibres in concrete*

Once a critical concentration of chlorides (i.e. the critical chloride threshold) is reached at the steel surface, the steel de-passivates locally. Typically, this leads to initiation of pitting corrosion at weaker regions or micro-flaws in the oxide layer, as shown by the dotted lines in the Eh-pH diagram with superimposed pitting-potential (E_{pit}-pH vs Cl^-) curves, **Fig. 1a** (Küter et al., 2006). The literature suggests chloride threshold values in the range of 0.1 – 2.0 wt.-% Cl^-/wt.-% cem for conventional carbon-steel reinforcement, depending on several variables: e.g. oxygen concentration, pH, binder type, w/c ratio, steel grade, test conditions (e.g. temperature, measurement technique) (Angst et al., 2009).

Significantly higher chloride threshold values have been found for SFRC, i.e. 2.1 – 5.6 wt.-% Cl^-/wt.-% cem (Dauberschmidt, 2014; Mangat and Gurusamy, 1988), as shown in **Fig. 1b**. The higher resistance of cold-drawn steel fibres towards initiation of pitting corrosion is explained by the combination of several factors: a) more uniform steel surface due to the cold-drawing process, which restrains the initiation of pitting-corrosion; b) smaller dimension of fibres limiting the cathodic area and leading to slower corrosion rates; and c) denser and more uniform steel-matrix interface of SFRC, which effectively protects the fibres against chlorides and oxygen ingress (Dauberschmidt, 2014; Nordström, 2005).

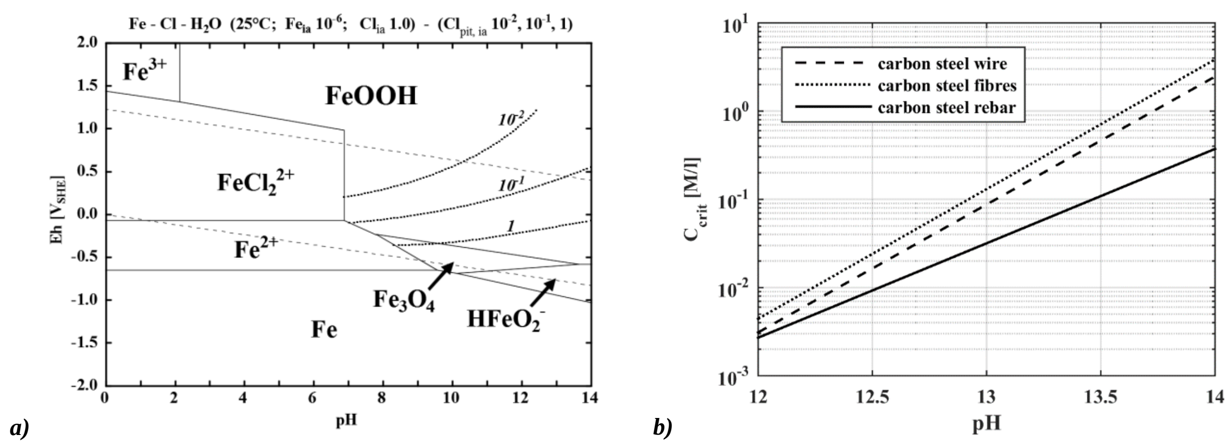

Fig. 1. Critical chloride concentrations for pitting corrosion on: a) Potential-pH diagram with superimposed pitting-potential curves for conventional steel, after Küter et al. (2006); b) critical chloride content at different pH values for conventional steel and steel fibres, after Dauberschmidt (2006, 2014).

3. Variables influencing the durability of SFRC exposed to chlorides

There is limited research investigating the influence of the main variables affecting the durability of SFRC exposed to chlorides. Therefore, this review gathers the results and conclusions from the main investigations in the field and classifies them according to: 1) exposure conditions and age; 2) type and size of the steel fibres; 3) quality of the concrete matrix; 4) structural integrity of the SFRC matrix (i.e. cracks).

3.1 *Exposure conditions and age*

The exposure conditions for testing the durability of SFRC subjected to chlorides can be divided into two groups, field exposure and laboratory exposure under accelerated conditions.

Field exposure

Field tests comprise the exposure of several SFRC test coupons to in-situ exposure conditions at representative locations, using a limited exposure time (e.g. 1 – 20 years) to extrapolate the durability of SFRC structures to longer exposures. Variables such as temperature and exposure-cycles are uncontrolled and may vary from: a) extreme conditions, with large temperature variations and shorter cycles (e.g. seawater splash- or tidal-zone, splash of de-icing brines at road margins); b) to milder conditions, with even temperatures and longer cycles (e.g. partial immersion). Moreover, the salinity of the aqueous media may vary in the range of 3.0 – 3.8 wt.-% NaCl for sea exposure up to 20 – 30 wt.-% NaCl, or $CaCl_2$ for de-icing brines. It should be mentioned that accumulation and crystallization of salts at cracks and crevices might increase this concentration up to four-fold values (Bentur et al., 1997; Gjørv, 2009).

Exposure of SFRC specimens for shorter periods (e.g. 1 – 3 years) to coastal environment, seawater or de-icing salts, showed limited damage for both un-cracked and cracked ($w_k \leq 0.30$ mm) SFRC (Bernard, 2004; Hannant and Edgington, 1975; Mangat and Gurusamy, 1988; Mangat, 1987; Morse and Williamson, 1977). The damage was limited to aesthetics due to the rusting on external fibres, with a maximum depth of damage of a few millimetres (an assumed sacrificial layer would range between 1 – 5 mm). Un-cracked specimens showed negligible reduction in compressive and flexural strength, along with increased residual-tensile strength which can be attributed to a higher fibre-matrix friction as a result of limited corrosion of fibres and continuous hydration of the matrix (Hannant and Edgington, 1975; Mangat and Gurusamy, 1988). Similar results for specimens with small cracks ($w_k \leq 0.20$ mm), suggest self-healing of cracks and non-harmful corrosion on the fibres (i.e. limited cross-sectional reduction), leading to increased residual-tensile strength (Bernard, 2004; Mangat and Gurusamy, 1988, 1987b; Morse and Williamson, 1977).

Extended exposure times (5 – 20 years) to analogous aggressive conditions (e.g. seawater splash- or tidal-zone, splash of de-icing brines at road margins) provide similar positive results, comprising limited damage of SFRC for both un-cracked and cracked ($w_k \leq 0.20$ mm) scenarios (Ferrara et al., 2004; Hoff, 1987; Kern and Schorn, 1991; Nordström, 2005; O'Neil and Devlin, 1999; Schupack, 1985). The observations substantiate that corrosion of both cracked and un-cracked SFRC is limited to staining on external fibres (sacrificial layer of 1 – 5 mm) without cracking or spalling of the matrix and the deterioration stabilizes at the initial months of exposure. The negligible deterioration observed on the mechanical behaviour relative to shorter exposures indicates an early stabilization of the deterioration process during the first year of exposure (Nordström, 2005).

Accelerated laboratory conditions

A larger number of controlled variables is found for laboratory exposure: a) type of exposure; b) the type of salt (e.g. sodium chloride or calcium chloride); c) salinity; d) duration of the exposure; e) temperature, among others. This section classifies former research based on the type of exposure.

The use of wet-dry cycles has been proven an effective method to accelerate the corrosion-induced damage of SFRC. Shorter exposures (up to six months) to average salinities (3 – 5 wt.-% NaCl and $CaCl_2$), typically show damage limited to staining at external surfaces (limited to outer 1 – 5 mm) on un-cracked specimens, accompanied with negligible loss on compressive, flexural and residual-tensile strength (Anandan et al., 2014; Batson, 1977; Ganesan et al., 2006; Hoff, 1987; Kopecskó and Fenyvesi, 2008; Narayan and Ramakrishnan, 2013). Results on cracked SFRC indicate negligible residual-tensile strength loss for small cracks ($w_k \leq 0.20$ mm) (Frazão et al., 2015; Nordström, 2005). Contradictive results, showing significant reduction of the residual-tensile strength for cracked (Alizade et al., 2016; Anandan et al., 2014; Batson, 1977; Chen et al., 2015; Mantegazza and Gatti, 2004) and un-cracked SFRC, are presented in (Alizade et al., 2016; Anandan et al., 2014; Batson, 1977; Chen et al., 2015; Mantegazza and Gatti, 2004).

Extended exposures (from 6 months to 3 years) to wet-dry cycles at average salinities, i.e. 3 – 5 wt.-% NaCl, generally showed similar results for un-cracked SFRC, compared to shorter exposures, suggesting an early stabilization of the deterioration of the steel fibres (Abbas, 2014; Rider and Heidersbach, 1978; Roque et al., 2009; Serna and Arango, 2008; Weydert and Schiessl, 1998). Contradictive results are found for cracked SFRC: a) positive results for smaller cracks ($w_k \leq 0.20$ mm), entailing minor corrosion of the fibres, negligible reductions of the residual-tensile strength and self-healing at the crack (Abbas, 2014; Graeff et al., 2009; Kim et al., 2011; Roque et al., 2009); b) severe fibre corrosion and strong loss of residual-tensile strength for larger cracks ($w_k > 0.20$ mm), leading to further deterioration for longer exposures (Kosa and Naaman, 1990; Schiessl and Weydert, 1998; Serna and Arango, 2008).

Alternatively, the use of salt-fog spraying has been less common among researchers. The exposure time did not influence the corrosion damage for un-cracked specimens, exposures of 6 – 12 months showed damage limited to surface staining of external fibres (sacrificial layer of 1 – 3 mm) (Balouch et al., 2010; Hoff, 1987; La-Palme et al., 1985; Mangat and Gurusamy, 1988). While, for cracked SFRC, extended exposure times to salt-fog spray (up to 3.5 years) revealed significant fibre corrosion and residual-tensile strength loss for larger cracks ($w_k > 0.20$ mm) (Granju and Balouch, 2005; Mangat and Gurusamy, 1987b).

Partial- and full-immersion were ineffective on accelerating corrosion of SFRC. Short exposures (below 4 months) revealed negligible damage on un-cracked specimens, limited to stains at the surface (Dhanasekar and Hudson, 1999). Whereas longer exposures (up to 10 years), resulted in limited corrosion in the outer 3 mm of the specimens and slight reductions on the flexural strength during the initial 2 years (Hoff, 1987).

Finally, early-age immersion of SFRC exposed to sodium chloride (i.e. curing of specimens in chloride solutions) and mixed-in $CaCl_2$, induced severe pitting damage on the fibres and significantly reduced the pull-out resistance. Suggesting the incompatibility of marine curing of SFRC, and proves the inadequacy of this method to test the corrosion resistance of SFRC under accelerated chloride exposures (Alizade et al., 2016; Banthia and Foy, 1989; Janotka et al., 1989).

3.2 The type, material and size of the steel fibre

Limited amount of research has focused on the influence of the type, material and dimension of the steel fibres on the durability of SFRC exposed to chlorides. The EN-14889-1 standard (EN, 2006) proposes a classification according to the production process, as shown in **Fig. 2a**.

Cold-drawn carbon and stainless steel fibres for the groups I, III and IV are specified according to EN 10120-2 and EN 10088-5, respectively in **Fig. 2b** (EN, 2011, 2009). According to this classification, the main design variables influencing the durability of SFRC to chlorides would be: a) fibre type (e.g. production method); b) type of steel and coatings; c) fibre dimensions (i.e. length and diameter).

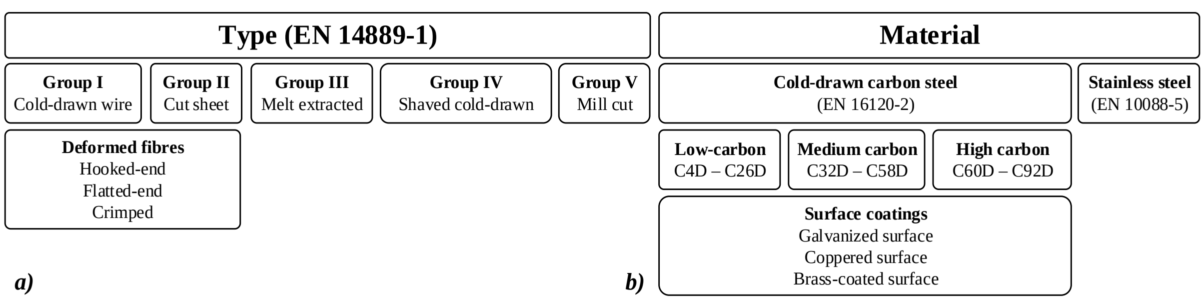

Fig. 2. Common types of steel fibres for concrete according to EN 14889-1 and steel types according to EN 10016-2 and EN 10088-5.

Cold-drawn wire, typically deformed with hooked-ends, is used in most of the durability investigations of SFRC (Balouch, 1999; Bernard, 2004; Frazão et al., 2015; Hannant and Edgington, 1975; Mangat and Gurusamy, 1988; Morse and Williamson, 1977; Nemegeer et al., 2000; O'Neil and Devlin, 1999; Weydert and Schiessl, 1998). Other types of fibre, such as cut-sheet fibres have been only used in some of the research (Batson, 1977; O'Neil and Devlin, 1999), limiting the scope of interpretation.

There is proof for variations of the threat of fibre corrosion and damage depending on the type of steel-fibres, e.g.: mill-cut fibres showed larger probability of corrosion and stronger reductions on the residual-tensile strength of SFRC, relative to cold-drawn wire (Weydert and Schiessl, 1998). Conversely, cold-drawn and cut-sheet fibres showed a similar response under comparable exposure (O'Neil and Devlin, 1999; Serna and Arango, 2008). Additionally, recent research proved that deformed cold-drawn steel fibres (e.g. hooked ends) have a higher probability for initiation of chloride-induced corrosion, relative to un-machined cold-drawn steel wire, due to early initiation of pitting corrosion at micro-flaws at the bended regions (Dauberschmidt, 2014).

Former research has proven increased resistance of stainless steel to pitting corrosion relative to carbon-steel, limiting the formation of rust at the surface as well as guaranteeing negligible damage in cracked SFRC (Mangat and Gurusamy, 1988; O'Neil and Devlin, 1999; Rider and Heidersbach, 1978). Conversely, coated steel fibres (i.e. brass- or zinc-plated) showed contradictory results: a) reaching a similar long-term performance compared to carbon-steel wire, extending the initiation time for pitting corrosion (Hoff, 1987; Sun et al., 2011; Weydert and Schiessl, 1998); b) or alternatively showing a total protection against corrosion for long-term exposures (Nemegeer et al., 2000; O'Neil and Devlin, 1999; Serna and Arango, 2008).

The influence of the fibre size on the electrochemical behaviour of SFRC exposed to chlorides is unclear. Contradictory results observed in Nordström (2005), showed increased corrosion rates for longer steel fibres at initial times of exposure to NaCl but opposite results for water-exposed specimens, accompanied with a large scatter on the results. Whereas a limited effect of the wire length on the corrosion of carbon-steel wire embedded in concrete exposed to chloride solution was observed by Mangat and Molloy (2000). Additionally, it has been proven that the fibre diameter plays a minor role on the initiation of corrosion of steel fibres, relative to the fibre length (Dauberschmidt, 2014; Mangat and Molloy, 2000).

3.3 The quality of the concrete matrix

The quality of the concrete matrix has been proven to be of high influence when preventing chloride-induced corrosion of conventional steel reinforcement in concrete (Bentur et al., 1997). It is expected, that the main design variables affecting the durability of conventional reinforced concrete have similar effects on SFRC, i.e. water to binder ratio and the type and quantity of binder.

A wide range of w/c ratios have been tested for SFRC, ranging from 0.30 – 0.80 (Ferrara et al., 2004; Hannant and Edgington, 1975; Nordström, 2005; Roque et al., 2009). An upper limit for w/c of 0.50 has been proposed by Granju and Balouch (2005) for cracked and un-cracked SFRC, ensuring a sacrificial layer less than 1 mm for un-cracked SFRC and limited corrosion in small cracks ($w_k < 0.20$ mm). However, other research suggests lower values (e.g. w/c < 0.45 – 0.40) in order to ensure durability of steel fibres in cracked SFRC (Bernard, 2004; Mangat and Gurusamy, 1988; Nordström, 2005; O'Neil and Devlin, 1999).

Mineral admixtures (i.e. supplementary cementitious materials) are widely used, among others, to improve the durability of concrete subject to aggressive exposures (Bertolini et al., 2013). A substantial share of the research on SFRC uses either: a) blended cements optimized for aggressive exposures, e.g. EN 197-1 type CEM II (Hansen et al., 1999; O'Neil and Devlin, 1999; Schupack, 1985; Serna and Arango, 2008); b) or mineral cement replacements, i.e. Portland cement replacement with: fly ash, blast furnace slag or/and silica fume (Abbas, 2014; Mangat, 1987; Weydert and Schiessl, 1998). However, there is limited information about the efficiency of mineral admixtures on preventing chloride-induced corrosion on SFRC (Mangat and Gurusamy, 1987c).

The minimum quantity of binder is specified in some of the principal design standards in Europe (e.g. EN-206 and national guidelines). A wide range of binder content (250 – 750 kg/m^3) is found when comparing research related to chloride-induced corrosion on SFRC (Abbas, 2014; Balouch et al., 2010; Granju and Balouch, 2005; Mangat and Gurusamy, 1988; Roque et al., 2009). Nevertheless, there is strong criticism regarding the influence of the quantity of binder on the protection of steel against corrosion (Medagoda-Arachchige, 2008; Mehta, 1977) and there is limited information for SFRC to elaborate conclusions.

3.4 Cracks

Limited corrosion damage is found in un-cracked SFRC when adequate concrete qualities are used, i.e. w/c ≤ 0.5. The potential damage due to extended exposures is restricted to formation of rust at the surface and light fibre corrosion in the outer 1 – 5 mm, appearing during the initial months of exposure but resulting in negligible damage (Abbas, 2014; Balouch et al., 2010; Mangat, 1987; Morse and Williamson, 1977; O'Neil and Devlin, 1999; Roque et al., 2009; Schupack, 1985; Weydert and Schiessl, 1998).

The durability of cracked SFRC is controversial, conclusions can be divided into three crack widths (w_k): a) wide cracks: $w_k > 0.5$ mm; b) narrow cracks: 0.5 mm $\geq w_k > 0.2$ mm; c) hairline cracks: $w_k \leq 0.2$ mm.

There is general consensus regarding the high probability of corrosion on carbon-steel fibres bridging cracks wider than 0.5 mm e.g. (Frazão et al., 2015; Granju and Balouch, 2005; Mangat and Gurusamy, 1987b; Morse and Williamson, 1977; Weydert and Schiessl, 1998). The formation of pits at the crack-bridging region of the fibres leads to a significant reduction of the fibre cross-section and provokes notable reductions of the residual-tensile strength after short periods under moderate exposure to chlorides (Bernard, 2004; Granju and Balouch, 2005; Kosa and Naaman, 1990; Nemegeer et al., 2000; Nordström, 2005; Serna and Arango, 2008; Weydert and Schiessl, 1998). Crack widths larger than 0.5 mm, show no evidence of self-healing in the cracks and despite local damage at the crack region, there is no extended damage due to cracking or spalling of the adjacent matrix caused by fibre corrosion (Granju and Balouch, 2005; Kosa and Naaman, 1990; Mangat and Gurusamy, 1987b).

The risk of fibre corrosion in narrow cracks is controversial. A greater share of the research supports the scenario in which carbon-steel fibres corrode up to critical reductions of the fibre cross-section in the long-term (Batson, 1977; Bernard, 2004; Hannant and Edgington, 1975; Kosa and Naaman, 1990; Mangat and Gurusamy, 1987b; Serna and Arango, 2008; Weydert and Schiessl, 1998), leading to substantial decay of the residual-tensile strength of SFRC exposed to chlorides. The use of galvanized steel fibres extended the time to initiation but did not prevent the propagation of corrosion for longer exposures (Serna and Arango, 2008; Weydert and Schiessl, 1998). Other results indicate limited corrosion of carbon-steel as well as no corrosion for galvanized and stainless steel fibres bridging narrow cracks, together with minor loss of residual-tensile strength (Granju and Balouch, 2005; Nemegeer et al., 2000).

Corrosion of steel fibres bridging hairline cracks is currently under discussion. Some research points towards limited corrosion of carbon-steel fibres bridging cracks less than 0.15 - 0.20 mm, accompanied by negligible reductions of the residual-tensile strength (Abbas, 2014; Granju and Balouch, 2005; Hansen et al., 1999; Mangat and Gurusamy, 1987b; Nemegeer et al., 2000; Nordström, 2005). More restrictively, other investigations point towards crack limits of 0.05 - 0.10 mm, in order to avoid corrosion on carbon-steel fibres bridging cracks, ensuring negligible reductions of the residual-tensile strength (Bernard, 2004; Halvorsen et al., 1976; Morse and Williamson, 1977). For those crack limits, self-healing at the crack is commonly reported, often leading to greater peak residual-tensile strengths relative to unexposed SFRC (Granju and Balouch, 2005; Mangat and Gurusamy, 1987b; Morse and Williamson, 1977; Nemegeer et al., 2000; Nordström, 2005). Conversely, a share of the research refutes the existence of a limit crack width where corrosion of carbon-steel fibres does not initiate, recommending the incompatibility of cracked SFRC exposed to chlorides. The argumentation indicates: 1) that the test times used are insufficient and the early corrosion observed will proceed until complete failure of the fibre (Ferrara et al., 2004; Weydert and Schiessl, 1998); 2) else, the results show a strong degradation during the exposure (Alizade et al., 2016; Batson, 1977; Frazão et al., 2015; Kosa and Naaman, 1990; Mantegazza and Gatti, 2004).

4. Summary and discussion

A summary of the analysis of the existing literature on durability of SFRC exposed to chlorides is presented in **Table 2**. The table classifies the results according to: mild exposure (EN 206 classes: XS2, XD2) and aggressive exposure (EN 206 classes: XS3, XD3). Furthermore, the case of mixed-in chlorides (e.g. 3.5% - wt. NaCl) is included, despite it is generally disapproved and not covered by the standards.

The results from the scientific literature partially agree with the limitations observed in the standards and guidelines. The limitations on the maximum crack width *(w_k)*, in the range 0.10 – 0.30 mm, proposed by some of the international standards and guidelines (ACI Committee 544, 2010; German Society for Concrete and Construction Technology, 2001; Swedish Standards Institute, 2014), are in agreement with the increased damage observed at narrow cracks ($0.50 > w_k > 0.20$ mm) compared to hairline cracks ($w_k \leq 0.20$ mm).

Nevertheless, there is still disagreement at the technical and scientific level regarding the extent of fibre corrosion and reduction of residual tensile-strength of the SFRC. Nonetheless, the significantly lower degree of deterioration observed for immersed exposures (XS2, XD2) is not covered by most of the standards and guidelines, which tend to overestimate the deterioration and apply similar limitations to aggressive exposures (XS3, XD3).

The analysis of macro-scale investigations suggests significant differences of the durability of SFRC between un-cracked and cracked SFRC exposed to chlorides, distinguishing two main scenarios: corrosion in cracked and un-cracked SFRC. Nevertheless, the large number of variables involved and the uncomplete understanding of mechanisms governing the deterioration process of these two scenarios, hinder the elaboration of solid conclusions. The main theories are discussed in the following paragraphs.

Table 2. Summary table, design parameters and mechanical behaviour of SFRC exposed to chlorides.

	Mild (immersed) (XS2, XD2)	***Aggressive (wet – dry) (XS3, XD3)***	***Mixed-in chlorides***
Maximum water/binder ratio	< 0.50	< 0.40 – 0.50	-
Mineral additions	GGBS, PFA	GGBS, PFA	
Type of steel	Carbon-steel	Carbon-steel Stainless	
Critical crack width (mm)	0.10 – 0.20	0.00 – 0.20	
Sacrificial layer (mm)	1 – 3	2 – 5	
Cracking / spalling	No	No	Yes
Compressive strength loss	None	Low – none	Medium
Tensile strength loss	None	Low – none	High
Residual-tensile strength loss			
Un-cracked	None	None	High
Wide cracks ($w_k \geq 0.50$ mm)	Medium	High	
Narrow cracks ($0.50 > w_k > 0.20$ mm)	Medium	High	
Hairline cracks ($w_k \leq 0.20$ mm)	Low – none	Mid – none	

Abbreviations: *(PFA) pulverized fly ash; (GGBS) ground granulated blast-furnace slag; (w_k) characteristic crack width.*

Mechanisms governing chloride-induced corrosion of un-cracked SFRC

The limited corrosion observed for un-cracked SFRC exposed to chlorides, relative to conventional reinforcement has been primarily attributed to three components: a) the discontinuous nature of the fibres; a) the uniform steel surface due to the cold-drawing process; c) the dense and uniform fibre-matrix interfacial transition zone (ITZ) (Dauberschmidt, 2006; Mangat and Molloy, 2000; Nordström, 2005).

The positive influence of the discontinuous nature of the fibres on the improved corrosion resistance of un-cracked SFRC exposed to chlorides, relative to conventional reinforcement, has been theorized by several researchers (Dauberschmidt, 2006; Nordström, 2005). The greater stability against corrosion has been related to smaller potential difference along the steel surface and larger anode/cathode ratios (Dauberschmidt, 2006; Nordström, 2005). Nevertheless, the impact of the fibre size-effect is still unclear, i.e. Mangat and Molloy (2000) suggest a negligible length-effect for wire lengths in the range of 0 – 160 mm and an anodically-controlled reaction (i.e. the oxidation rate of iron limits the redox reaction).

The beneficial role of the cold-drawing process for steel-wire fibres has been shown by Dauberschmidt (2006) who observed a greater stability against corrosion of steel fibres, compared to conventional steel, due to a more uniform surface structure of the steel, as proposed earlier by Mangat and Molloy (2000).

Nevertheless, this paper will focus on the insight regarding the beneficial effects of a denser and more uniform fibre-matrix ITZ (Dauberschmidt, 2006; Nordström, 2005). In particular, Dauberschmidt (2006), discussed the presence of a larger and more uniform calcium hydroxide (C-H) layer around the fibre, which results in an increased protection of fibres in the bulk SFRC against chloride and oxygen ingress. As shown in **Fig. 3b**, the micro-structure of the steel fibre-matrix ITZ presents a significantly larger C-H layer, followed by a thinner and denser "porous layer", relative to conventional steel reinforcement (**Fig. 3a**). The overall thickness of the fibre-matrix ITZ is expected to be smaller, compared to conventional reinforcement, which would explain the similar bulk chloride diffusion coefficients between SFRC and plain concrete observed in the literature (Bentur et al., 1985). Furthermore, it is expected that limited pores and defects arise at the fibre-matrix ITZ, as fibres “float” inside the fresh-concrete matrix similarly to the aggregates, hindering the formation of weak spots where pitting corrosion might initiate (Dauberschmidt, 2006).

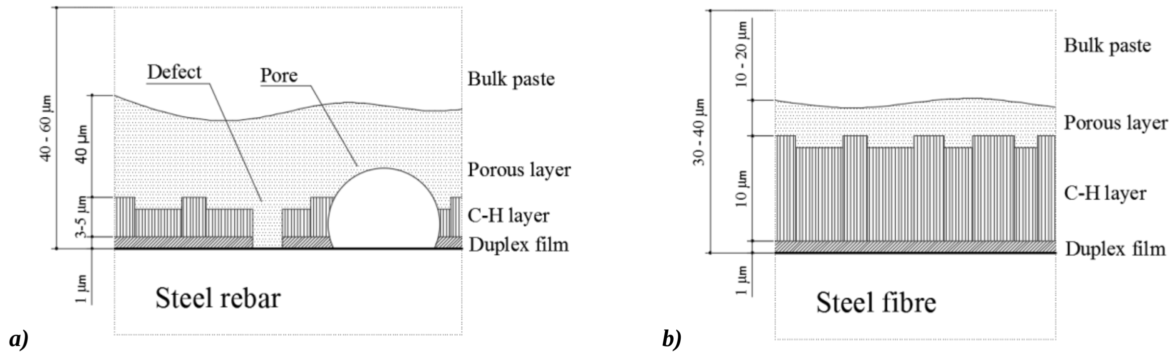

Fig. 3. Microstructure of the steel-matrix ITZ for: a) conventional steel, after Poole and Sims (2015); b) steel fibres, after Bentur et al. (1985)

Mechanisms governing chloride-induced corrosion of cracked SFRC

The mechanisms responsible for corrosion in cracked SFRC are uncertain. A great share of publications base their conclusions on a critical crack width (e.g. $w_k < 0.20$ mm), where ingress of chlorides and oxygen is limited and autogenous-healing and corrosion products completely seal the crack within a short time, preventing the evolution of corrosion at the fibre section bridging the crack (Abbas, 2014; Mangat and Gurusamy, 1987d; Nordström, 2005). Although in agreement with the abovementioned experimental data, this theory provides a limited explanation for the observed increase on the residual strength of cracked SFRC exposed to chlorides.

The authors suggest a model governed by the damage at the fibre-matrix ITZ, as suggested by Granju and Balouch (2005), corresponding to recent research on the impact of load-induced cracks on the corrosion of conventional reinforcement in chloride-contaminated concrete (Michel et al., 2013). The protective role of the fibre-matrix ITZ prevents the initiation of pitting corrosion on the steel fibres of un-cracked SFRC; once the matrix cracks, the strain at the fibres bridging the crack induces the damage at the ITZ, promoting corrosion at the weakest regions. Four stages may be identified:

1) The steel-matrix ITZ on steel fibres is denser and more uniform than for conventional steel, as shown in Fig. 3. This layer acts as a protective coating (**Fig. 4a**): preventing the access of aggressive agents (e.g. oxygen, chlorides), binding the free chlorides surrounding the steel surface, and isolating the steel surface from the electrolyte (i.e. limiting ionic diffusion along the steel surface).
2) When the tensile capacity of the concrete is exceeded, the matrix cracks and the fibre-matrix bond is “activated”. The strain at the fibre-matrix interface damages the ITZ. The extent of this damage is directly related to the strain (i.e. larger crack widths induce larger damage at the ITZ) and the shape of the fibres, i.e. Granju and Balouch, (2005) and Nemegeer et al. (2000) observed localized corrosion damage at the hook. The damaged ITZ would provide a preferential path for diffusion of chlorides, metal ions and oxygen, promoting corrosion at the areas with greater damage (**Fig. 4b**).
3) In the case that the composite does not reach a critical strain (i.e. up to a critical crack width), the damaged fibre-matrix interface would eventually heal (Homma et al., 2009), recovering similar conditions to the original state “stage 1” (Fig. 4a). The fibre-matrix ITZ, rich in C-H would assist the binding of chlorides and the corroding steel would eventually re-passivate. The expansive effect of the corrosion products and the products resulting from the chemical binding of chlorides (i.e. Friedel’s salt), would increase the fibre-matrix frictional bond (Fig. 4c). Which would explain the improved residual-tensile strength observed in part of the literature (Granju and Balouch, 2005; Nemegeer et al., 2000; Weydert and Schiessl, 1998). Finally, a combination of un-hydrated cement, lime leaching, corrosion products and salt crystals would eventually seal the crack, limiting the ingress of chlorides and oxygen; the fibres bridging the crack would serve as preferential surfaces for deposition of these compounds (Homma et al., 2009).

4) Excessive damage at the fibre-matrix interface (i.e. due to larger strain) would result on delayed or defective healing at the ITZ at the regions with greater damage (e.g. deformed regions, fibre-crack intersection), which would result on a progressive and localized reduction of the fibre cross-section due to corrosion. Once a critical cross-section is reached (i.e. the tensile capacity of the steel is lower that the fibre-matrix bond strength) the failure mode of the SFRC would change from fibre pull-out to fibre yield and the residual-tensile strength would decrease (**Fig. 4d**), as reported in previous research (Batson, 1977; Bernard, 2004; Kosa and Naaman, 1990; Nordström, 2005).

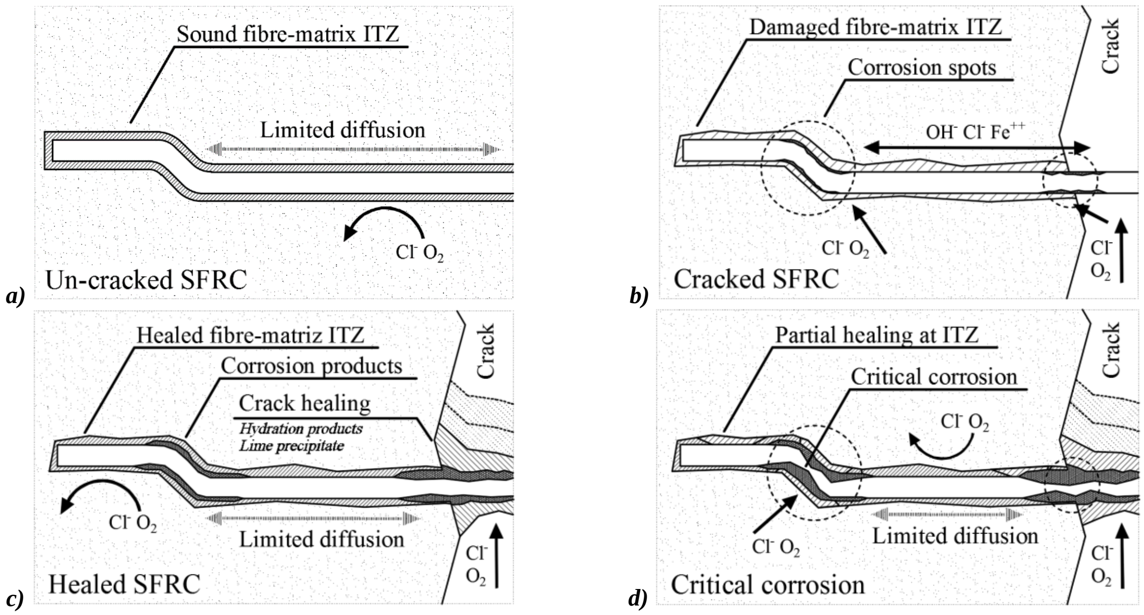

Fig. 4. Structure and corrosion mechanisms on: a) Un-cracked SFRC; b) Cracked SFRC at an early stage; c) Cracked SFRC after autogenous healing; d) Cracked SFRC with critical corrosion on fibres.

However, there is limited information covering the damage of the fibre-matrix ITZ during pull-out and the development of autogenous healing on corroding SFRC is still unclear (Bentur and Mindess, 2006; Homma et al., 2009; Kim et al., 2014). Therefore, a doctoral project has been initiated to explore this issue and provide experimental data relating the proposed damage mechanisms on the micro-scale to the macro-scale mechanical behaviour of SFRC exposed to chlorides.

5. Conclusions

The literature review shows agreement among academics and regulators regarding the superior durability of un-cracked SFRC exposed to chlorides relative to conventional reinforcement. Nevertheless, the durability of cracked SFRC is still under discussion. There is substantial insight among academics regarding the existence of a critical crack width, below 0.20 mm, where fibre corrosion is limited and the structural integrity of SFRC can be ensured for long-term exposures. Nevertheless, the mechanisms governing corrosion of carbon-steel fibres in cracked concrete and particularly the influence of fibre corrosion on the residual strength of SFRC are still unclear, hindering the elaboration of detailed guidelines for durability-design of SFRC. This paper proposes an alternative deterioration theory for corrosion of steel fibres bridging cracks in SFRC exposed to chlorides, focusing on the damage and autogenous healing at the fibre-matrix interface. A doctoral project has been initiated to explore these mechanisms in depth.

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