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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 civil infrastructure. However, there are inconsistencies among international standards and guidelines regarding the consideration of carbon-steel fibres for the structural verification of SFRC exposed to corrosive environments. This paper presents a review of the published research regarding carbonation- and chloride-induced corrosion of SFRC, and proposes a deterioration theory for cracked SFRC exposed to chlorides and carbonation, based on the damage at the fibre-matrix interface. The review confirms an overall agreement among academics and regulators regarding the durability of uncracked SFRC exposed to chlorides and carbonation. Contrariwise, the durability of cracked SFRC is under discussion at the technical and scientific level, as there is a large dispersion on the experimental results and some of the mechanisms governing the corrosion of carbon-steel fibres in cracks and its effects on the fracture behaviour of SFRC are not fully understood.

Keywords: Steel Fibre Reinforced Concrete (SFRC), Corrosion Mechanisms, Chlorides, Carbonation, Cracks.

1. Introduction

Steel fibre reinforced concrete (SFRC) is a composite material, combining a cementitious matrix and a discontinuous reinforcement, consisting of steel fibres randomly distributed in the matrix. In this paper, the term SFRC refers to mix-designs based on Portland cement binders, with mix-proportions and elastic mechanical properties (i.e. in the uncracked 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 conventional 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 [1–3].

In particular, 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 good durability and performance in compression [4–9]. Nevertheless, the total replacement of conventional steel reinforcement is still controversial according to some experts, especially when the long-term durability of SFRC under severe chloride and carbonation exposure is addressed [10–13].

At present, there is no international standard available for the design of SFRC structures. However, an EN standard is currently in preparation. Moreover, the national guidelines available for design of SFRC are not coherent with respect to the applicability within certain exposure classes. Table 1 presents a summary of the main design recommendations for the EN 206 exposure classes: i) XC, hereafter referred to as “carbonation exposure”, and entailing the exposure to air, CO₂ and moisture; ii) XS, seawater exposure, comprising concrete exposed to chlorides from sea water; iii) XD, other-chloride exposure, covering chloride sources other than seawater, i.e. de-icing salts [14].

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)	[15]	w_k^{50}	0.30	0.30	0.30	0.10	0.10	0.10	0.10
		Δ_h^{50}	-	-	-	2.5	2.5	2.5	2.5
RILEM TC 162-TDF (EU)	[16]	w_k^{50}	0.30	0.30	0.30	Special	Special	Special	Special
		Δ_h^{50}	10	10	10	Special	Special	Special	Special
		Fibre	C-G-S	C-G-S	C-G-S	-	-	-	-
DBV-Merkblatt Stahlfaserbeton (DE)	[17]	w_k^{50}	0.30	0.30	0.20	0.20	0.20	0.20	0.20
		Δ_h^{50}	20	20	25	40	40	40	40
UNI/CIS/SC4:2004 (IT)	[18]	w_k^{50}	0.30	0.30	0.30	0.30	0.30	0.30	0.30
		* $\Delta_h^{>50}$	10	10	10	10	10	10	10
		Fibre	C-G-S	C-G-S	G-S	C-G-S	G-S	C-G-S	G-S
CNR-DT 204/2006 (IT)	[19]	w_k^{50}	0.30	0.30	0.30	0.30	0.30	0.30	0.30
		* $\Delta_h^{>50}$	10	10	10	10	10	10	10
		Fibre	C-G-S	C-G-S	G-S	G-S	S	C-G-S	G-S
NZS 3101-2:2006 (NZ)	[20]	w_k^{50}	0.30	0.30	0.30	0.20	0.20	0.20	0.20
TR-63 (UK)	[21]	w_k^{50}	0.30	0.30	0.30	0.30	0.30	0.30	0.30
EHE 2008 (ES)	[22]	w_k^{50}	0.30	0.30	0.30	Test	Test	Test	Test
		Fibre	C-G-S	C-G-S	C-G-S	G-S	G-S	G-S	G-S
DAfStb Stahlfaserbeton (DE)	[23]	w_k^{50}	0.30	0.30	0.30	N/A	N/A	N/A	N/A
		Fibre	C-G-S	C-G-S	C-G-S	-	-	-	-
Design guideline for structural applications of SFRC (DK)	[24]	w_k^{50}	0.30	0.30	0.20	N/A	N/A	N/A	N/A
		Fibre	C-G-S	C-G-S	C-G-S	-	-	-	-
AFTES-GT38R1A1 (FR)	[25]	w_k^{50}	0.20	0.20	0.20	0.15	0	0.15	0
		Fibre	C-G-S	C-G-S	C-G-S	C-G-S	G-S	C-G-S	G-S
SS-812310:2014 (SE)	[26]	w_k^{50}	0.50	0.50	0.40	0.30	0.20	0.30	0.20
		w_k^{100}	0.40	0.40	0.30	0.20	0.10	0.20	0.10
NB-Publication no. 7. Sprayed concrete for rock support:2014 (NO)	[27]	Fibre	C-G-S	C-G-S	C-G-S	**G-S	**G-S	**G-S	**G-S

Abbreviations: (N/A) Not applicable; (C) Carbon-steel steel fibres can be used; (G) Coated carbon-steel fibres can be used; (S) Stainless-steel fibres required; (Test) Experimental verification required; (Special) Special crack limitations required; (w_k) maximum crack width allowed, expressed in mm; (Δ_h) minimum sacrificial layer on exposed surfaces, expressed in mm; (XC, XS, XD) EN 206 exposure classes; (Δ_h^{50} , $\Delta_h^{>50}$, w_k^{50} , w_k^{100}) Design service life for 50 years, over 50 years and 100 years.

* The minimum sacrificial layer (Δ_h) shall be considered for a design service life superior to 50 years.

** Galvanized fibres may be considered provided that hydrogen formation at the zinc coating is prevented.

There is an overall agreement among the standards and guidelines regarding the design of SFRC under carbonation exposure, with a crack width limit in the range 0.20 – 0.40 mm for mild exposure conditions (i.e. XC2-3, immersed concrete and concrete sheltered from rain), presenting similar limitations to conventional reinforcement, Table 1. On the contrary, there is disagreement on the durability of SFRC exposed to cyclic wet and dry conditions (i.e. XC4), where some of the guidelines do not recommend the use of carbon-steel fibres in cracked SFRC [18,19].

The case of chloride exposure is more controversial, and four main design approaches can be identified, as shown in Table 1: i) crack limitation in the range 0.10 – 0.20 mm [15,17,20,26]; ii) special measures such as experimental validation [16,22]; iii) use of coated carbon-steel or stainless-steel fibres [18,19,27]; iv) no applicability for these exposure classes [23,24], or limitation to the uncracked state, i.e. the contribution of the steel fibres cannot be considered for the serviceability limit state [25].

Other national guidelines do not mention specific limitations for durability, but highlight the improved durability of SFRC relative to conventional reinforcement [21,28], refer to other guidelines and standards [29–31], or express imprecise recommendations for special measures under aggressive exposures [16,22,32].

The inconsistencies observed regarding the consideration of steel fibres for SFRC exposed to the most aggressive exposure classes, e.g. XC4, XS2-3 and XD2-3, indicate a limited understanding about the probability of fibre corrosion for exposed SFRC and its impact on the structural integrity of structures built of SFRC. In particular, the durability of cracked SFRC subjected to wet and dry cycles under chloride and carbonation exposure, for cracks below 0.30 mm, is in focus and under discussion at the technical level. Furthermore, these discrepancies suggest a limited understanding of the mechanisms governing chloride- and carbonation-induced corrosion of steel fibres in cracked concrete and its effects on the long-term mechanical behaviour of SFRC.

This paper reviews the existing literature investigating chloride- and carbonation-induced corrosion of steel fibres in concrete, evaluating the main variables influencing the durability of SFRC exposed to chlorides and carbonation, and mechanisms responsible for this deterioration. The paper is divided into two sections: SFRC exposed to chlorides (EN 206 exposure classes XS1-3, XD1-3 and XF3-4) and SFRC exposed to carbonation (EN 206 exposure class XC1-4). Each of those sections concludes with a discussion of the various mechanisms associated to the results presented on the experimental work and proposes deterioration models covering the corrosion of steel fibres for uncracked and cracked SFRC exposed to chlorides and carbonation.

2. Durability of SFRC exposed to chlorides

There is abundant research investigating the durability of SFRC exposed to different chloride contaminated environments, as shown in Table 2. However, there is a large amount of variables influencing the results, which hinders the direct comparison among studies, namely: i) quality of concrete; ii) type, material and quantity of fibres; iii) exposure time and conditions; iv) existence and size of cracks.

Table 2. List of studies investigating durability of SFRC exposed to chlorides

First author	Year	Ref.	Bind (kg/m ³)	w/c (-)	Fibre (steel) (type)	Fibre content (kg/m ³)	Exp. Class (EN)	Exp. type	Age (mo.)	Crack W _k (mm)	Crack crit. W _{k,crit} (mm)	Scr. layer Δ _h (mm)
Hannant	1975	[33]	393 480	0.49 0.75	L/M D	94 107	XS3	Field	11 57	Uncracked 0.10 – 0.30	0.10 – 0.30	5 – 17
Batson	1977	[34]	386	0.59	L S	62 123	XS3	Lab	2 6	0.10 – 0.20	0.10 – 0.20	-
Morse	1977	[35]	446	0.50	L D/M	119	XS3 XF4	Lab Field	2 18	Uncracked 0.25 – 3.20	0.25	1 – 5
Rider	1978	[36]	308	0.50 0.60	L/S D/E	94 101	XS3 XF4	Lab Field	9 12	0.10 – 0.20	** 0.25	1 – 13
Schupack (WES)	1976	[37]	468	0.45	L/B/S D	114	XS3 XF4	Field	132	Uncracked	-	3
Schupack (Long Island)	1972	[37]	560	0.46	L/B D/M	114	XS3 XF4	Field	120	Uncracked 0.10 – 0.60	0	2
Schupack (Australia)	1971	[37]	580	0.51	L D	160	XS3 *XC4	Field	120	Uncracked	-	3
Schupack (Battelle)	1978	[37]	445	0.45 0.62	L/B D/S	89 153	XS3 XD3	Lab Field	120	Uncracked	-	1 – 3
Kamal	1987	[38]	350	0.50	L M	60 120	XS2	Lab	12	Uncracked	-	3
Mangat	1987 1988	[39–44]	590	0.40	L/Z/S D/E	130 230	XS3 XC4	Lab Field	20 41	Uncracked 0.20 – 0.70	0.10 – 0.25	3 – 15
Kosa	1990 1991	[45,46]	530 860	0.42 0.70	L D	153	XS3 XC4	Lab (HT)	9	Uncracked 0.10 – 0.20	0	40
Weydert	1998	[47,48]	350	0.40 0.50	L/Z D/M	30 120	XS3	Lab	14 17	0.10 – 0.40	*** 0 – 0.10	1 – 10

O'neil	1999	[49]	468	0.45	L/B/S D/M	114	XS3 XF4	Field	216	Uncracked	-	2
Hansen	1999	[50,51]	305 358	0.38 0.52	L D	30	XS3	Lab	7 13	0.10 – 0.20	0.20	0 – 10
Balouch	1999 2010	[52–54]	250 470	0.36 0.78	L D	40	XS3	Lab	3 12	Uncracked 0.50	0.10	1 – 3
Dhanasekar	1999	[55]	475	0.36	L S	56	XS2	Lab	4	Uncracked	-	1 – 3
Nemegeer	2000	[56–58]	350	0.45	L/Z D	78	XS3 XC4	Lab	18	0.20 – 0.50	0.50	(1 – 5)
Mantegazza	2004	[59]	320	0.55	L D	39	XS3	Lab	2	0.20	** 0.20	-
Bernard	2004	[13]	420	0.42	L D	50	XS2	Field	24	0.10 – 1.00	0.10	-
Nordstrom	2005	[60,61]	510	0.30 0.42	L/M D	65 70	XD3 XC4	Field	60	Uncracked 0.10 – 1.00	0.10 – 0.20	(1 – 5)
Kopecksko	2008	[62]	300 400	0.42 0.54	L/M D	25 75	XD3 XF4	Lab	1	Uncracked	-	1
Serna	2008	[63]	350	0.50	L/Z D/S	60	XS3	Lab	12	Uncracked 0.50 – 1.50	* < 0.50	(1 – 5)
Roque	2009	[64]	362 446	0.37 0.44	L D	71	XS2 XS3	Lab	27	Uncracked 0.20	0.10 – 0.20	(1 – 5)
Graeff	2010	[65,66]	300 380	0.35 0.50	L D	47 51	XS3	Lab	10	Uncracked	-	(1 – 5)
Sanchez	2009	[67,68]	426	0.45	L-Z D	40	XS1 XC4	Field	18	Uncracked	-	(1 – 5)
Sun	2011	[69,70]	494	0.47	L/Z D	77	XS3	Lab	1	Uncracked	-	1
Buratti	2011	[71]	350	0.50	L D	25	XS3	Lab	8	0.50	0.50	-
Abbas	2014 2015	[6,72]	647	0.29	L D	60	XS3	Lab (HT)	16	Uncracked 0.20	0.20	3 – 5
Anandan	2014	[73]	449	0.30	L D	115	XS3	Lab	6	Uncracked	-	(1 – 5)
Kaufmann	2014	[74]	450	0.40	M D	35	XS3	Lab Field	12	0.50 – 1.20	* < 0.50	1 – 5
Bernard	2015	[75]	586	0.29	L D	40	XS1 XC4	Field	37	0.10 – 0.30	0 – 0.10	(1 – 5)

Abbreviations: (Bind) total binder content, expressed in kg/m³; (w/c) water to binder ratio; (Fibre) description of the steel fibre, being steel the steel type (L)ow- (M)edium- (H)igh-carbon and (S)tainless steel, the type of coating (B)rass- and (Z)inc-plated and the type of fibre cold-(D)rawn, melt-(E)xtract, cut-(S)heet or cut-(M)ill; (Dose) the quantity of steel fibres, expressed in kg/m³; (Exp. Class) the exposure class, according to the EN 206 standard classes; (Exp. type) the exposure type, being laboratory or field exposure; (Age) the exposure time, expressed in months; (crack) the state of the matrix prior to exposure, and characteristic crack width in mm; (Crack crit.) the critical characteristic crack width recommended by the authors, expressed in mm; (Scr. layer) the sacrificial layer, from the exposed surface, containing corroded steel fibres, expressed in mm.

() Values obtained from qualitative description of the exposed specimens

* The crack range studied is above the critical crack width for fibre corrosion-protection, i.e. outside SLS limits ($w_k > w_{k,crit}$)

** Consideration of critical corrosion by the author of the reference is based on small reductions on the mechanical properties, relative to an insufficient number of replicates tested.

*** The author of the reference observes non-critical corrosion observed at fibres bridging cracks for $w_k > w_{k,crit}$, but expect larger deterioration on the long-term and do not recommend cracked SFRC.

The test results published from the studies presented in Table 2, have been categorized and introduced in a database. The database contains the information of the design-variables characterizing the SFRC, exposure conditions and the main indicators defining the performance of SFRC after exposure, e.g. mechanical properties, chloride penetration depth, corrosion damage.

The database contains the performance indicators calculated systematically for each replicate reported in the literature, when available. The following order of preference was applied to pre-process and introduce the data: i) raw data published in tables or graphs was utilized to calculate directly the performance indicators; ii) centrality and dispersion indicators provided in tables and graphs, were included in the database as three records (i.e. the average value, the upper- and lower-bounds); iii) the value reported was entered as a single record in the database, if none of the former data sources were available or no information about the number of replicates was given. No correction or weighing factors have been applied to the original data. The performance indicators for the reference specimens, used to calculate the relative performance on exposed specimens, have been averaged to the arithmetic mean value.

The data has been evaluated using descriptive statistics, and the results presented comprise exploratory data analysis, presented in boxplots. Statistical modelling, i.e. linear regression analysis and principal component analysis, did not provide clear indication of correlation among the study variables, attributed to the limited amount of available data and the large variability among data sources, limiting further analysis.

Among those indicators, four variables are used to define the relative performance of exposed SFRC: i) the compressive strength ratio (Fig. 1a), tensile strength ratio (Fig. 1b) and residual-tensile strength ratio (Fig. 1c), expressed as the percentage-ratio of strength after exposure relative to the reference strength of the companion specimens; ii) the corrosion damage (Fig. 1d), expressed as the product of: the subjective classification of the corrosion damage at the fibres (converted to a 0 – 5 scale) and the ratio of the cross section of the specimen affected by fibre corrosion, as measured by the original authors, expressed as a percentage, i.e. being 0% undamaged and 100% fully damaged. When available, the description of the corrosion damage given by the original authors was verified through analysis of images published of the crack planes (i.e. digital image correlation) and detailed images of corroding fibres.

The limit of proportionality (LOP), when specimens were pre-cracked prior to exposure and re-tested after the exposure [33,65,74], has been included within the tensile strength ratio group, whereas the residual tensile strength ratio comprises investigations on the flexural and tensile toughness of the material [44,46,61].

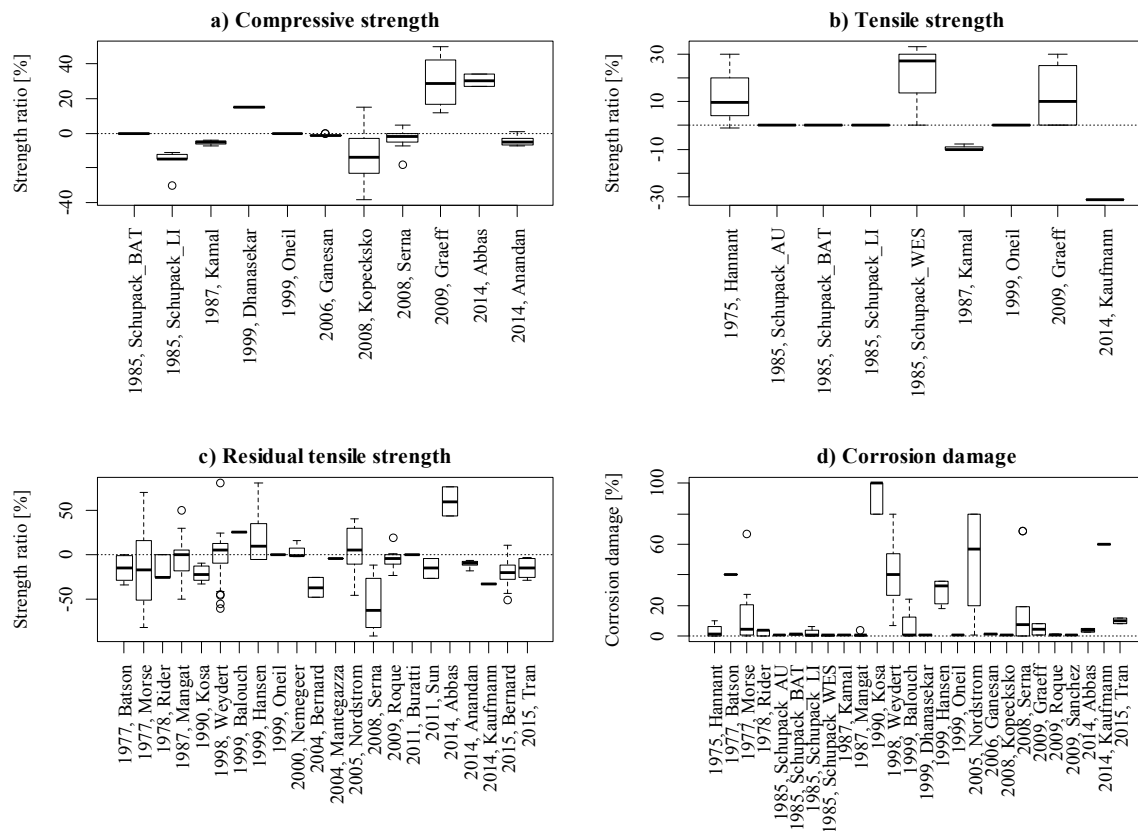


Fig. 1. Deterioration of SFRC exposed to chlorides, summary of results for: a) compressive strength ratio; b) tensile strength ratio; c) residual-tensile strength ratio; d) corrosion damage.

A direct comparison of the collected results reveals a large scatter within and between studies, indicating a great variability of the results depending on the material properties and exposure conditions. As an example, reference is made to the large variation (40 – 60%) observed on the residual-tensile strength ratio within some of the studies [35,43,50,61,63], Fig. 1c, or the large dispersion registered on the corrosion damage ratios between studies, Fig. 1d. Therefore, further analysis on the effects of each of the individual variables influencing the durability of SFRC exposed to chlorides is necessary to generalize the test results and research conclusions for SFRC structures exposed to chlorides.

2.1 Variables influencing the durability of SFRC exposed to chlorides

This review gathers the results and conclusions from published investigations available 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).

2.1.1.1 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. Laboratory conditions are expected to accelerate the deterioration processes for the same exposure times by a factor of around 1:50, depending on the exposure conditions and materials (i.e. one year of accelerated exposure is equivalent to 50 years of field exposure) [61].

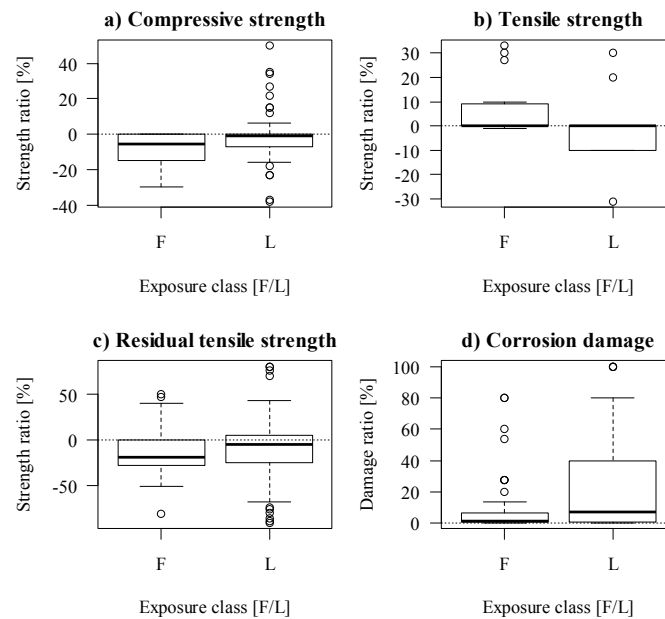


Fig. 2. Deterioration of SFRC exposed to chlorides, comparison of results for field (F) and laboratory (L) exposure for: a) compressive strength ratio; b) tensile strength ratio; c) residual-tensile strength ratio; d) corrosion damage.

The results presented in Fig. 2d, indicate larger corrosion damage for laboratory-exposed specimens, compared to field-exposure. However, the decay on mechanical properties does not follow the trend and field-exposed specimens tend to reach similar strength ratios within the large scatter previously mentioned (Fig. 2a-c). It is expected that the rest of test variables (e.g. crack width, type of fibres and quality of the concrete) have a large impact on the deterioration and would confound the direct comparison between the studies, hindering the elaboration of conclusions regarding the efficiency of laboratory and field exposure tests, e.g. the large dispersion observed at the residual-tensile strength ratios (Fig. 2c). There is limited research combining laboratory and field-exposed testing under comparable conditions and the available results are reported to be very sensitive to variations on the specimen dimensions [61] and exposure conditions [43,61].

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 CaCl₂ 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 [76,77].

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 uncracked and cracked ($w_k \leq 0.30$ mm) SFRC [13,33,35,40,43]. 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). Uncracked 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 densification of the matrix [33,40]. Similar results for specimens with small cracks ($w_k \leq 0.20$ mm),

suggest autogenous-healing of cracks and non-harmful corrosion on the fibres (i.e. limited cross-sectional reduction), leading to increased residual-tensile strength [13,35,40,44].

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 results, comprising limited damage of SFRC for both uncracked and cracked ($w_k \leq 0.20$ mm) scenarios [37,49,61,78–80]. The observations substantiate that corrosion of both cracked ($w_k \leq 0.20$ mm) and uncracked SFRC is limited to staining on external fibres, i.e. a sacrificial layer of 1 – 5 mm for uncracked SFRC and 10 – 25 mm for cracked SFRC, without additional corrosion-induced cracking or spalling of the matrix. The evolution of the mechanical behaviour and reduction in fibre cross section relative to shorter exposures suggests an early stabilization of the deterioration process during the first 2 – 3 years of exposure (e.g. calculated corrosion rates inside cracks at first year are four- to five-times the corrosion rates at five years) [61].

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 corrosion-induced damage of SFRC. Shorter exposures (up to six months) to average salinities (3 – 5 wt.-% NaCl and CaCl₂), typically show damage limited to staining at external surfaces (limited to outer 1 – 5 mm) on uncracked specimens, accompanied with negligible loss on compressive, flexural and residual-tensile strength [34,38,62,73,78,81,82]. Results on cracked SFRC indicate negligible residual-tensile strength loss for small cracks ($w_k \leq 0.20$ mm) [61,83]. At the same time, contradictory results showing significant reduction of the residual-tensile strength for cracked and uncracked SFRC are presented in [34,59,73,84,85].

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 uncracked SFRC, compared to shorter exposures, suggesting an early stabilization of the deterioration of the steel fibres [6,12,36,63,64]. Contradictory results are found for cracked SFRC; while 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 of the crack have been reported in e.g. [6,64,65,86], 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 have been presented in e.g. [46,48,63].

Alternatively, the use of salt-fog spraying has been less common among researchers. The exposure time did not influence the corrosion damage for uncracked specimens for shorter exposure times, i.e. exposures of 6 – 12 months showed similar damage, limited to surface staining of external fibres (sacrificial layer of 1 – 3 mm) [40,54,78,87]. 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) [44,53].

Partial- and full-immersion have been reported ineffective on accelerating corrosion of SFRC. Short exposures (below 4 months) revealed negligible damage on uncracked specimens, limited to stains at the surface [55]. 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 [78].

Early-age immersion of SFRC exposed to sodium chloride (i.e. curing of specimens in chloride solutions) and mixed-in CaCl₂ induced severe pitting damage on the fibres and significantly reduced the fibre pull-out resistance. These results contradict the moderate deterioration observed for uncracked SFRC tested with the previously mentioned exposure methods; which indicates 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 [84,88,89].

The use of elevated temperatures (e.g. 30 – 80 °C) to accelerate the corrosion of SFRC has been proven highly effective on increasing the deterioration of SFRC for shorter exposure times (3 – 6 months) [6,45,46,64]. However, substantial changes in the damage mechanisms are responsible for the accelerated deterioration at elevated temperature (e.g. > 50 °C), due to the alteration of the cement chemistry, i.e.

formation of Friedel’s salt, leading to a rapid disintegration of the matrix [6,45,46]. Temperatures of 30 – 40 °C in combination with wet and dry cycles led to more realistic deterioration [64], although, no companion data for SFRC exposed under standard temperatures (e.g. 20 °C) is available in the study, impeding the estimation of the acceleration factor at higher temperature.

2.1.1.2 Type, material and size of the steel fibre

Limited amount of research has focused on the influence of type, material and dimension of the steel fibres on the durability of SFRC exposed to chlorides. The EN-14889-1 standard [90] proposes a classification of steel fibres according to the production process, as shown in Fig. 3a.

Cold-drawn carbon-steel and stainless-steel for groups I, III and IV are specified according to EN 16120-2 and EN 10088-5, respectively in Fig. 3b [91,92]. According to this classification, the main design variables influencing the durability of SFRC to chlorides are: a) fibre type (e.g. production method); b) type of steel and coatings; c) fibre dimensions (i.e. length and diameter).

Cold-drawn wire, typically deformed with hooked-ends, is used in most of the durability investigations of SFRC [12,13,33,35,40,49,52,56,83]. Other types of fibres, such as cut-sheet fibres have been only used in some of the research [34,49], limiting the scope of interpretation.

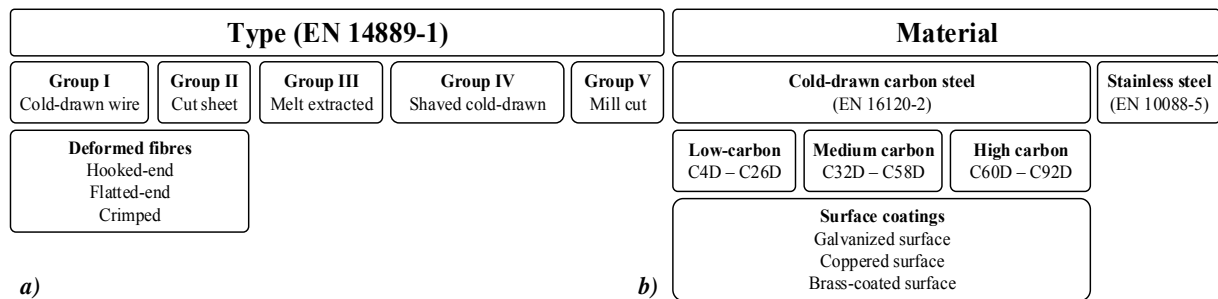
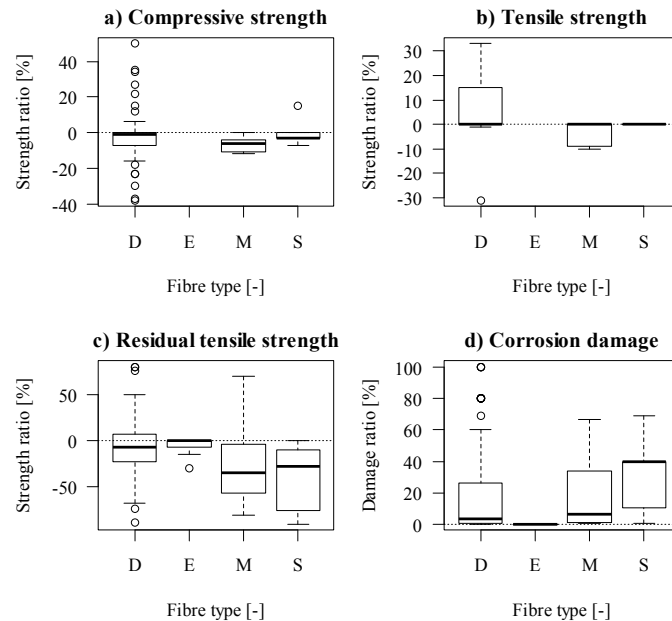


Fig. 3. Classification of steel fibres: a) type of steel fibre for concrete according to EN 14889-1 b) type of steel according to EN 10016-2 and EN 10088-5.

There is insight about significant variations of the likelihood 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, Fig. 4c-d, [12]. Conversely, cold-drawn and cut-sheet fibres showed a similar corrosion resistance under comparable exposure conditions, Fig. 4d, but the exposure of the latter resulted in larger reductions of the residual-tensile strength, Fig. 4c, [49,63]. The large corrosion resistance and negligible mechanical deterioration of melt extract fibres, Fig. 4c-d, responds primarily to the material properties, as this type of fibre is produced of stainless-steel [36,43].



Abbreviations: (Fibre type) type of fibre according to EN-14889-1: cold-(D)rawn, melt-(E)xtract, cut-(M)ill, or cut-(S)heet.

Fig. 4. Deterioration of SFRC exposed to chlorides, comparison of results for different types of fibre: a) compressive strength ratio; b) tensile strength ratio; c) residual-tensile strength ratio; d) corrosion damage.

Additionally, recent research indicates 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 [93].

Former research has reported increased resistance of stainless-steel to pitting corrosion relative to carbon-steel, limiting the formation of rust at the surface as well as ensuring negligible corrosion-damage in cracked SFRC [36,40,49]. 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 time-to corrosion initiation for pitting corrosion [12,69,78]; b) or alternatively showing a total protection against corrosion for long-term exposures (i.e. 6 – 12 months of accelerated exposure and 18 years of field exposure) [49,56,63].

The influence of the fibre dimensions on the electrochemical behaviour of SFRC exposed to chlorides is unclear. Contradictory results observed in [61], 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 of 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 [93]. Additionally, it has been reported that the fibre diameter plays a minor role on the initiation of corrosion of steel fibres, relative to the fibre length [93,94].

2.1.1.3 Quality of the concrete matrix

The quality of the concrete matrix has been suggested as a critical factor to consider when preventing chloride-induced corrosion of conventional steel reinforcement in concrete e.g. [76]. It is expected, that the main mix-design variables affecting the durability of conventional reinforced concrete have similar effects on SFRC, i.e. the water to binder ratio (w/b) and the type and quantity of binder.

A wide range of w/b ratios have been tested for SFRC, ranging from 0.30 – 0.70 [33,61,64,79]. An upper limit for w/b of 0.50 has been proposed by Granju and Balouch [52] for cracked and uncracked SFRC, ensuring a sacrificial layer less than 1 mm for uncracked SFRC and limited corrosion for small cracks ($w_k < 0.20$ mm). However, other research suggests lower values (e.g. w/b < 0.40 – 0.45) in order to ensure

durability of steel fibres in cracked SFRC [13,40,49,61]. An analysis of results presented in the literature indicates significantly higher degradation of the compressive strength (i.e. uncracked SFRC) for $w/b > 0.50$ (Fig. 5a), and larger corrosion damage for $w/b > 0.40$ for cracked SFRC (Fig. 5d). However, there is no clear trend on the detrimental effect on the residual-tensile strength for cracked SFRC, as shown in Fig. 5c. It should be noted, that there is limited data available regarding the impact of chloride exposure on the tensile strength of SFRC (Fig. 5b). The data available suggest a larger deterioration on the tensile strength at lower w/c ratios, discrepant with the observations on the compressive strength ratio and the expected corrosion behaviour of steel embedded in concrete, e.g. higher w/c ratios are expected to lead to larger corrosion damage.

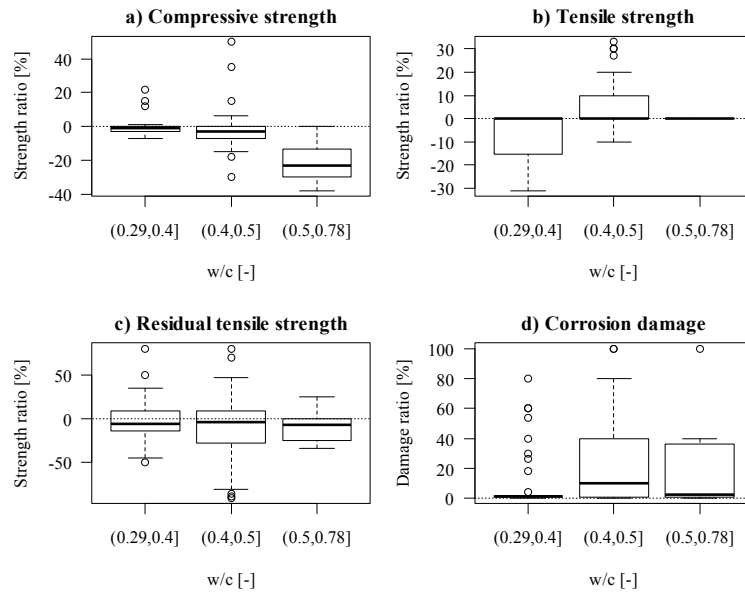


Fig. 5. Deterioration of SFRC exposed to chlorides, influence of the water to binder ratio on: a) compressive strength ratio; b) tensile strength ratio; c) residual-tensile strength ratio; d) corrosion damage.

Mineral admixtures (i.e. supplementary cementitious materials) are widely used, among others, to improve the durability of concrete subject to aggressive exposures [95]. 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 [37,49,51,63] or b) mineral cement replacements, i.e. Portland cement replacement with: fly ash, blast furnace slag or/and silica fume [6,12,43]. However, limited information is available on the efficiency of mineral admixtures on preventing chloride-induced corrosion in SFRC [41].

The minimum quantity of binder is specified in some of the principal design standards in Europe (e.g. EN-206 and national guidelines), this value ranges between 300 – 360 kg/m³, depending on the aggressiveness of the exposure class. However, these limitations are so far only applicable to conventional reinforcement [96]. A wide range of binder content (250 – 750 kg/m³) is found when comparing research related to chloride-induced corrosion on SFRC [6,40,53,54,64]. Nevertheless, there is strong criticism regarding the influence of the quantity of binder on the protection of steel against corrosion [97,98] and only limited information for SFRC can be found in the literature to elaborate definite conclusions.

2.1.1.4 Cracks

Limited corrosion damage is found in uncracked SFRC when sufficient concrete qualities are used, i.e. $w/c \leq 0.5$ [54]. 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 long-term damage [6,12,35,37,43,49,54,64]. The investigations on uncracked concrete reveal negligible corrosion damage (Fig. 6b), except for isolated outliers. However, some investigations report reductions up to 40% of the residual tensile strength (Fig. 6a), with a large scatter among studies.

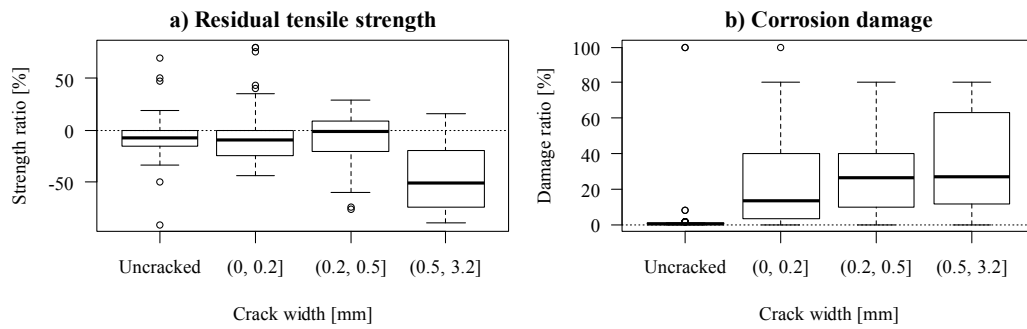


Fig. 6. Deterioration of SFRC exposed to chlorides, influence of crack width on: a) residual-tensile strength ratio; b) corrosion damage.

The durability of cracked SFRC is controversially discussed in the literature and conclusions can be divided according to three crack widths (w_k), labelled in this study as: a) wide cracks: $w_k > 0.5$ mm; b) narrow cracks: $0.5 \text{ mm} \geq w_k > 0.2$ 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. [12,35,44,53,83]. The formation of pits at weaker spots, i.e. the crack-bridging region of the fibres and the deformed areas, leads to a significant reduction of the fibre cross-section and provokes notable reductions of the residual-tensile strength (Fig. 6a), due to a subsequent change in the failure mode from fibre pull-out to fibre failure, after short periods under moderate exposure to chlorides [12,13,46,53,56,61,63]. 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 [44,46,53].

The risk of fibre corrosion in narrow cracks is controversial, and the results reported show a great variation on the corrosion damage and residual tensile strength ratios (Fig. 6a-b). 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 [12,13,33,34,44,46,63,75], 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 [12,63]. 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 [53,56].

However, there is research supporting that a significant share of the reduction on the residual tensile strength observed after exposure is related to the embrittlement of the SFRC due to densification of the matrix [13,75,99]. Since the hydration process promotes an increase on the compactness and strength of the matrix, and therefore alters the fibre-matrix bond and mechanical anchorage of the fibre, changing the failure mode from fibre pull-out to fibre yield. This issue may be solved by an adequate dimensioning of the fibre type, dimensions and steel strength, considering the long-term mechanical behaviour instead of the 28 days or early age maturity one [99].

Corrosion of steel fibres bridging hairline cracks is currently under discussion. There is a large scatter in the results presented in the literature, i.e. large variation of corrosion damage and residual strength ratios (Fig. 6a-b). Some research points towards limited corrosion of carbon-steel fibres bridging cracks smaller than 0.15 – 0.20 mm, accompanied by negligible reductions of the residual-tensile strength [6,44,51,53,56,61]. 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 [10,13,35]. For those crack limits, self-healing at the crack is commonly reported, often leading to greater peak residual-tensile strengths relative to unexposed SFRC [35,44,53,56,61].

Conversely, a share of the research refutes the existence of a crack width limit for corrosion of carbon-steel fibres, recommending the incompatibility of cracked SFRC exposed to chlorides. The argumentation is based on the fact that exposure times are insufficient to induce sufficient damage and early corrosion will

proceed until complete failure of the fibre [12,79] or else, results show a strong reduction on the residual tensile capacity during the exposure [34,46,59,83,84].

2.2 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, leading to the dissolution of iron and promoting a local reduction of the pH at the steel surface, initiating pitting-corrosion [95].

Following a generalized conceptual model for corrosion of steel in concrete [100], 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 and the corrosion process of the steel embedded in the contaminated concrete proceeds.

2.2.1.1 Transport properties of SFRC, chloride exposure

The transport properties of uncracked SFRC have been reported 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 [42,67,101–103]. Moreover, Abbas et al. [72,104] suggest a lower chloride penetration in uncracked SFRC relative to plain concrete, attributed in similar research to the arresting of micro-cracks by steel fibres during curing and handling [105].

The transport properties of cracked SFRC are also unaffected by the fibres, excluding the assumed crack arresting effect of the fibres, i.e. reduced cracking at same load conditions compared to plain concrete [72]. The build-up of chlorides in cracks due to wet-dry cycles, evaporation, and limited wash-out, increases the chloride concentration inside the crack. This leads to similar chloride concentrations inside the crack faces compared to external exposed surfaces, i.e. the crack faces act as free surfaces [51].

2.2.1.2 Chloride-induced pitting corrosion of steel fibres in concrete

It is generally assumed that 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. 7a [106]. 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) [107].

Significantly higher chloride threshold values have been found for SFRC, i.e. 2.1 – 5.6 wt.-% Cl/wt.-% cem tested in simulated pore solution [40,93], as shown in Fig. 7b. The higher resistance of carbon 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 [61,93].

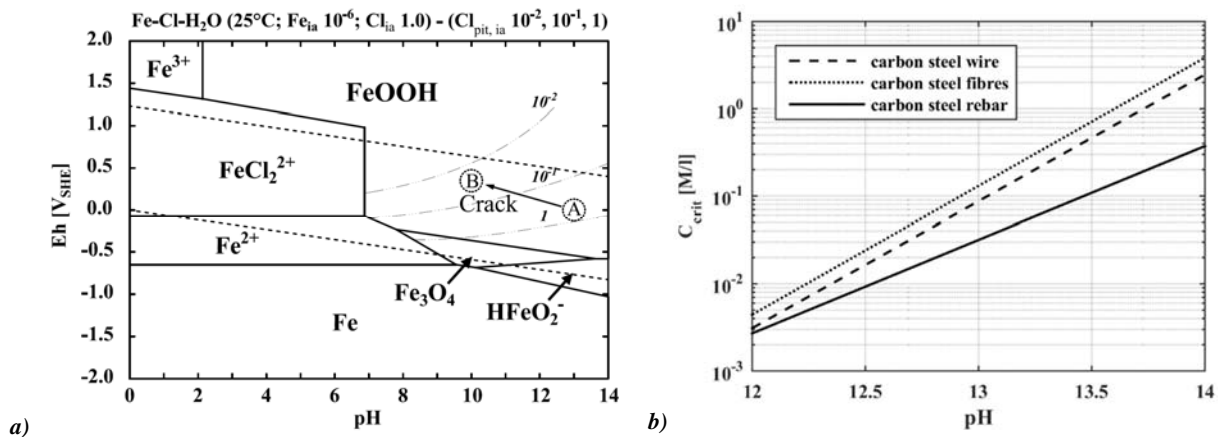


Fig. 7. Critical chloride concentrations for pitting corrosion on: a) Potential-pH diagram with superimposed pitting-potential curves for conventional steel, after Küter et al. [106], (A) indicative potential of steel in uncracked concrete and (B) indicative potential of steel in cracked concrete ; b) critical chloride content at different pH values for conventional steel and steel fibres, after Dauberschmidt [93,108].

Mechanisms governing chloride-induced corrosion of uncracked SFRC

The limited corrosion observed for uncracked SFRC exposed to chlorides, relative to conventional reinforcement has been primarily attributed to three components: a) the discontinuous nature of the fibres; b) the uniform steel surface due to the cold-drawing process; c) the dense and uniform fibre-matrix interfacial transition zone (ITZ) [61,94,108].

The positive influence of the discontinuous nature of the fibres on the improved corrosion resistance of uncracked SFRC exposed to chlorides, relative to conventional reinforcement, has been theorized by several researchers [61,108]. The greater stability against corrosion has been related to smaller potential difference along the steel surface and smaller cathode/anode ratios [61,108] compared to conventional reinforcement. Nevertheless, the impact of the fibre size-effect is still unclear, i.e. Mangat and Molloy [94] 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 chloride-induced corrosion of steel fibres in pore solution, compared to conventional steel, due to a more uniform surface structure of the steel, as proposed earlier by Mangat and Molloy [94].

There is limited research investigating the impact of galvanic coatings (e.g. zinc or brass alloys) on the corrosion mechanisms of steel fibres embedded in chloride contaminated concrete. There is overall insight on the protection given by zinc-alloy coatings under short-term chloride exposure [12,40,56,61,63], which raises the corrosion potential and reduces corrosion rates at the steel by consumption of the zinc coating in the anodic process [70]. However, some investigations concerning long term exposure of galvanized steel wire to chlorides in cracked and uncracked concrete show pitting corrosion at the steel surface similar to uncoated carbon-steel fibres [12,40,61]. Additionally, there is insight of increased risk of hydrogen embrittlement for galvanized high-carbon steel wire in alkaline media due to hydrogen development at the zinc coating before full passivation of the zinc layer [109], which may be minimized by pre-passivation treatment of the coating [110]. Other coatings, such as brass-alloys, are also expected to provide temporary protection against chlorides [49,78], due to the combination of the anodic protection provided by the zinc phases and the dense and stable copper oxide phases formed at high pH values even in the presence of chlorides [111,112]. However, there is insight of larger corrosion rates once the coating is removed due to local damage or large strains in the steel, due to galvanic coupling of the iron-copper phases [111].

Stainless steel fibres have been reported to provide full protection against chloride-induced corrosion in uncracked and cracked SFRC in the majority of published research [36,40,49]. However, most of the publications focus on macroscale investigations and there is limited knowledge on the particular protection and deterioration mechanisms. There is insight of pitting threshold values around 0.5M Cl^- (i.e. 3.5% NaCl) for certain high-strength stainless steel wires tested in pore solution (i.e. $\text{pH} = 12.5$), decreasing to 0.25M Cl^- at $\text{pH} = 9.5$ (i.e. carbonated or cracked concrete) [113].

This section will focus on the insight regarding the beneficial effects of a denser and more uniform fibre-matrix ITZ, as reported in [61,108]. In particular, Daubers Schmidt [108], discussed the presence of a larger and more uniform calcium hydroxide (CH) 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. 8b, the micro-structure of the steel fibre-matrix ITZ is composed of a significantly larger CH layer, followed by a thinner and denser “porous layer”, relative to conventional steel reinforcement (Fig. 8a). The duplex film, a $1 - 2\ \mu\text{m}$ bilayer structure composed of CH crystals deposited perpendicular to the steel surface covered by a single layer of calcium silicate hydrate gel (C-S-H), is reported to be similar for steel fibres [114] and conventional steel rebar [115].

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 [114]. Furthermore, it is expected that limited pores and defects occur at the fibre-matrix ITZ, as fibres “float” inside the fresh-concrete matrix similarly to the aggregates, hindering the formation of weak spots at the fibre surface where pitting corrosion might initiate [108].

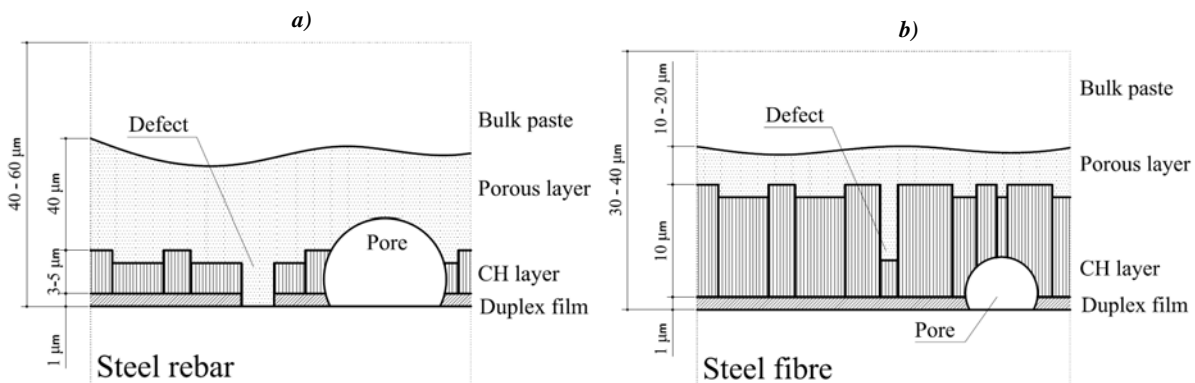


Fig. 8. Microstructure of the steel-matrix ITZ for: a) conventional steel, after Poole and Sims [115]; b) steel fibres, after Bentur et al. [114].

Mechanisms governing chloride-induced corrosion of cracked SFRC

The mechanisms responsible for corrosion in cracked SFRC are not well understood. A great share of publications base their conclusions on a critical crack width (e.g. $w_k < 0.20\ \text{mm}$), 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 [6,39,61]. Although in agreement with the abovementioned experimental data, this theory provides a limited explanation for the often 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 [53], corresponding to recent research on the impact of load-induced cracks on the corrosion of conventional reinforcement in chloride-contaminated concrete [116]. The protective role of the fibre-matrix ITZ prevents the initiation of pitting corrosion on the steel fibres of uncracked SFRC; once the matrix cracks, the strain in 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 of steel fibres is denser and more uniform than for conventional steel, as shown in Fig. 8. This layer acts as a protective coating (Fig. 9a): 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). However, there is limited data available on the properties and structure of the fibre-matrix interface; even though several investigations support the hypothesis of a denser interface with limited defects [61,108,114,117], recent studies show significant porosity surrounding the fibre [118,119].

- 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 a greater exposed area at the crack) and the shape of the fibres, i.e. Granju and Balouch [53] and Nemegeer et al. [56] observed localized corrosion damage at the hook and at the fibre region intersecting the crack. The damaged ITZ would provide a preferential path for transport of chlorides, metal ions and oxygen, promoting corrosion at the areas with greater damage (Fig. 9b). Whereas, it is presumed that the area of the fibre crossing and adjacent to the crack will be more susceptible to pitting corrosion and will have larger corrosion rates compared to the embedded steel [120,121]. Since the electrolyte inside the crack may present: higher chloride concentrations, higher oxygen mobility and lower pH values (i.e. due to carbonation and leaching) than the fibre interface, as presented in the indicative shift on the of the potential of the steel from point A to point B shown in Fig. 7a.
- 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 [122], recovering similar conditions to the original state “stage 1” (Fig. 9a). The fibre-matrix ITZ, rich in CH would assist the binding of chlorides and the corroding steel would eventually re-passivate. The increase in fibre roughness due to corrosion and expansion of the corrosion products, in combination with autogenous healing at the interface and the accumulation of products resulting from the chemical binding of chlorides (i.e. Friedel’s salt), may increase the fibre-matrix frictional bond (Fig. 9c), as suggested in [123]. Which would explain the improved residual-tensile strength observed in part of the literature [12,53,56,123]. Finally, a combination of hydrating cement, calcium carbonate, 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 [122].
- 4) Excessive damage at the fibre-matrix interface (i.e. due to larger strain) would result in delayed or defective healing at the ITZ at the regions with greater damage (e.g. deformed regions, fibre-crack intersection), which would result in 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. 9d), as reported in previous research [13,34,46,61].

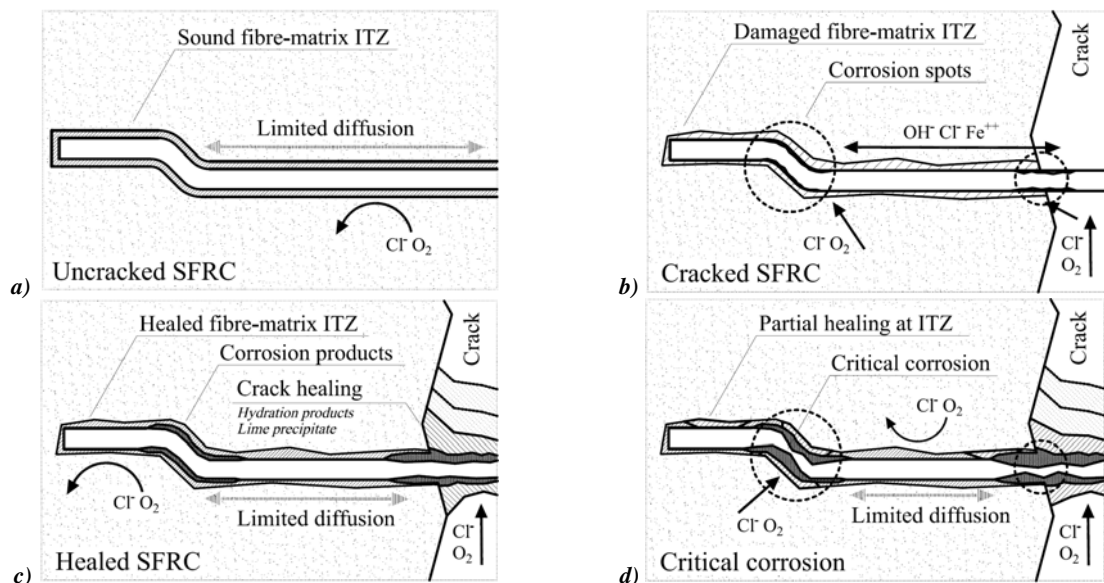


Fig. 9. Structure and corrosion mechanisms for SFRC exposed to chlorides, for: a) uncracked SFRC; b) cracked SFRC at an early stage; c) cracked SFRC after autogenous healing; d) cracked SFRC with critical corrosion on fibres.

3. Carbonation-induced corrosion of steel fibres in concrete

There is significantly less data available investigating the corrosion resistance of SFRC exposed to carbonation, compared to chloride attack, as shown in Table 3. Most of the research investigates uncracked SFRC and the exposure conditions often consist of a combination of several agents besides carbon dioxide (e.g. freeze-thaw, thermal loads, soft/acid water attack, airborne chloride attack), which confound the analysis of the direct effect of carbonation. The scarce data and the large amount of variables influencing the results hinders establishing solid conclusions and defining limit states, such as e.g. a critical crack width and sacrificial layer for long-term exposures.

Table 3. List of studies investigating durability of SFRC exposed to carbonation

First author	Year	Ref.	Bind	w/c	Fibre	Dose	Exp. class	Exp. type	Age	Crack w_k	Crack crit. $w_{k,crit}$	Scr. layer Δ_h
Hannant	1975	[33]	393 420	0.62 0.75	L D	94	XC4 XA3	Field	57	Uncracked	-	1 – 6
Schupack (Australia)	1971	[37]	580	0.51	L D	160	XC4 XS1	Field	120	Uncracked	-	3
Kamal	1987	[38]	350	0.50	L M	60 120	XC4	Lab	12	Uncracked	-	3
Kern	1991	[80]	580	0.47	L D	160	XC4	Field	276	Uncracked	-	1 – 2
Weydert	1998	[47,48]	350 400	0.40 0.50	L/Z D/M	30 120	XC4	Lab Field	17 120	0.15 – 0.40	** 0 – 0.10	5 – 15
Nemegeer	2000	[56–58]	350	0.45	L/Z D	78	XC4	Lab	18	0.20 – 0.50	0.50	(1 – 5)
Bernard	2004	[13]	420	0.42	L D	50	XC3 XC4	Field	24	0.10 – 1.00	0 – 0.10	-
Nordstrom	2005	[60,61]	500 510	0.30 0.42	M D	65 70	XC4 XD1	Field	60	Uncracked 0.10 – 1.00	0.10 – 0.20	1 – 5
Sanchez	2009	[67,68]	426	0.45	L-Z D	40	XC4 XS1	Field	18	Uncracked	-	1 – 5
Kaufmann	2014	[74]	450	0.40	M D	35	XC4 XF3	Field	12	0.50 – 1.50	* < 0.50	1 – 5
Bernard	2015	[75]	586	0.29	L D	40	XC3 XC4 XS1	Field	37	0.10 – 0.30	0 – 0.10	(1 – 5)

Abbreviations: (Bind) total binder content, expressed in kg/m^3 , without considering replacement efficiency factors; (w/c) water to binder ratio, without considering replacement efficiency factors; (Fibre) description of the steel fibre, being steel the steel type: (L)ow- (M)edium- (H)igh-carbon and (S)tainless steel, the type of coating (B)rass- and (Z)inc-plated and the type of fibre cold- (D)rawn, melt- (E)xtract, cut- (S)heet or cut- (M)ill; (Dose) the quantity of steel fibres, expressed in kg/m^3 ; (Exp. Class) the exposure class, according to the EN 206 standard classes; (Exp. type) the exposure type, being laboratory or field exposure; (Age) the exposure time, expressed in months; (Crack) the state of the matrix prior to exposure, and characteristic crack width in mm; (Crack crit.) the critical characteristic crack width recommended by the authors, expressed in mm; (Scr. layer) the sacrificial layer, from the exposed surface, containing corroded steel fibres, expressed in mm.

() Values obtained from qualitative description of the exposed specimens

* The crack range studied is above the critical crack with for fibre corrosion-protection ($w_{k,crit} < w_k$)

** Non-critical corrosion observed at fibres bridging cracks for $w_k > w_{k,crit}$, the authors expect larger deterioration on the long-term and do not recommend cracked SFRC.

There is limited data regarding the impact of steel fibre corrosion on the compressive and tensile strength of SFRC exposed to carbonation (Fig. 10a-b) [37,38]. However, the compressive and tensile strength are primarily related to the performance of the uncracked matrix. Fibre corrosion would only have an impact in case of corrosion-induced cracking of the concrete matrix, reported unlikely by several researchers [6,53]. The limited corrosion damage presented in studies investigating durability of uncracked SFRC supports the hypothesis that corrosion-induced damage in the matrix due to carbonation is minimal (Fig. 10d).

Conversely, significant corrosion damage has been reported for cracked SFRC (Fig. 10c) [12,61,74]; leading to significant detriment on the residual tensile strength for some of these studies [74]; or small average reductions with a large scatter for others [12,56,61] (Fig. 10c). However, the direct comparison of studies is obstructed by the large quantity of variables influencing the results (e.g. crack width, exposure time, exposure conditions, fibre properties, concrete quality) and the limited quantity of research available. Therefore, further investigation of the parameters influencing steel fibre corrosion in carbonated SFRC is required.

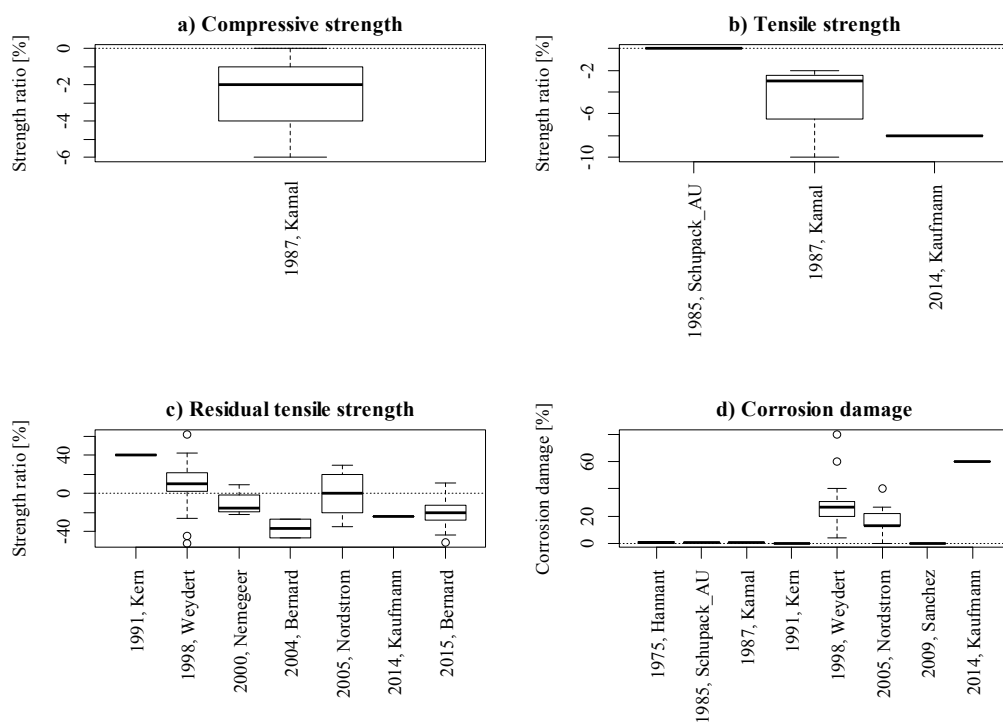


Fig. 10. Deterioration of SFRC exposed to carbonation, summary of results for: a) compressive strength ratio; b) tensile strength ratio; c) residual-tensile strength ratio; d) corrosion damage.

3.1 Influencing parameters

Carbonation-induced corrosion in SFRC is generally considered less aggressive than chloride-induced corrosion, as the carbonation process is much slower than chloride ingress and the risk of corrosion-induced cracking or spalling in SFRC is minimal [124]. The same classification as used for chloride-induced corrosion of SFRC will be used in the following for the discussion of the influencing parameters: 1) exposure conditions and age; 2) type and dimensions of the steel fibres; 3) quality of concrete matrix; 4) presence of cracks.

3.1.1.1 Exposure conditions and age

The exposure conditions are classified into field exposure and accelerated laboratory exposure. The results shown in Fig. 11d indicate a larger average corrosion damage for laboratory-exposed specimens. However, within the range of damage observed for field exposed specimens. The decay of mechanical properties

follows the opposite trend (Fig. 11b-c), as field-exposed specimens present lower strength ratios, within a large scatter. This remark could be explained by the additional damage caused by natural agents, such as erosion, freeze-thaw, or temperature variations, typically present under field experimentation. Furthermore, there is limited experimental data on the variation of compressive and tensile strength, Fig. 11a, available results indicate minimal strength variations, below 10% [38].

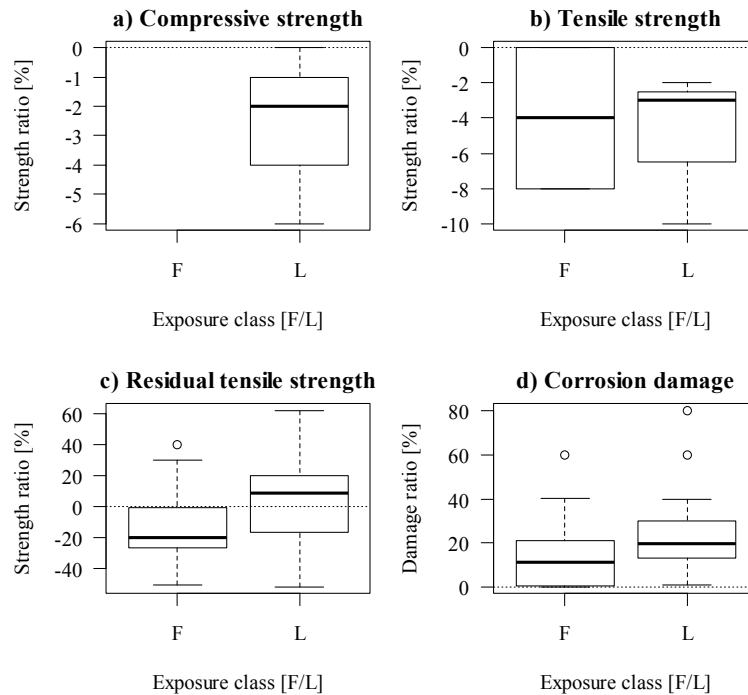


Fig. 11. Deterioration of SFRC exposed to carbonation, comparison of results for field (F) and laboratory (L) exposure for: a) compressive strength ratio; b) tensile strength ratio; c) residual-tensile strength ratio; d) corrosion damage.

Field exposure

Field tests for durability of carbonated SFRC comprise the exposure under atmospheric conditions and natural agents (e.g. rain, freeze-thaw, and direct insolation), extrapolating a limited exposure time to longer lifetimes. Variables such as temperature, CO₂ concentration and exposure-cycles (e.g. wetting-drying, freeze-thaw) are uncontrolled and might vary from: a) extreme conditions with large variations in temperature and/or moisture, freeze-thaw and high concentrations of carbon dioxide (e.g. outside exposure at industrial areas, urban areas exposed to exhaust gases); b) to milder conditions with lower CO₂ concentrations, even temperatures and dry conditions (e.g. rural areas, covered structures).

Exposure of SFRC to aggressive environments for short periods (less than 5 years) typically result in limited penetration of CO₂, primarily absorbed by the alkaline buffer of the concrete. Therefore, resulting in a shallow penetration of the carbonation front (i.e. internal area of the concrete with pH < 9 is less than 1 – 3 mm) and negligible damage due to corrosion of fibres, which typically concerns corrosion stains at the surface of uncracked SFRC [33,42,61,68]. In the presence of cracks, the carbonation front progresses up to 20 – 25 mm, with decreasing carbonation depth at the crack faces (e.g. 1 – 3 mm), resulting in limited mechanical damage [33]. Conversely, Bernard [13,75] suggests a similar deterioration of cracked SFRC subjected to 2 years of inland-atmospheric and seawater-immersed exposure, reporting severe corrosion of crack-bridging steel fibres and significant reductions of the residual-tensile strength.

Field exposure of uncracked SFRC for longer periods (5 – 20 years) results in greater carbonation depths (4 – 20 mm), with a great variability on the results depending on the conditions and time of exposure. Nevertheless, the damage of the SFRC due to corrosion of fibres is typically limited to staining at the surface

(outer 1 – 2 mm) with absence of cracking or spalling [12,37,49,80]. Conversely, the carbonation front inside cracks propagates at the first 3 – 5 mm of the inner crack faces (as described by the longitudinal cross-section A-A' in Fig. 12), decreasing up to depths of 20 – 40 mm inside the crack, and encountering heavy corrosion on fibres at the outer 2 – 5 mm (transversal cross-section B-B' in Fig. 12) [12,79].

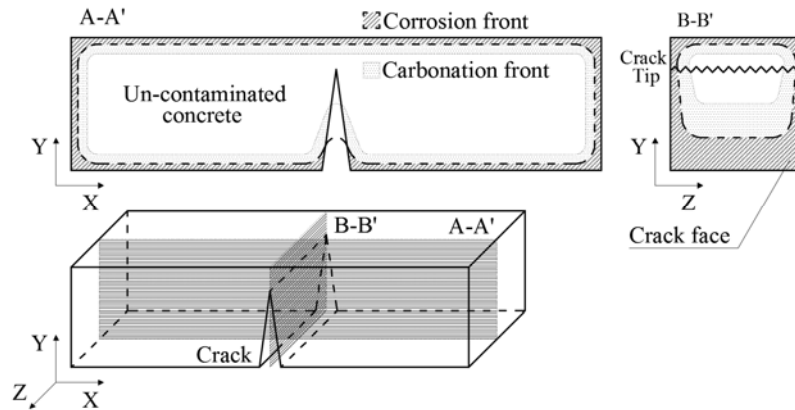


Fig. 12. Description of carbonation and corrosion front for carbonation exposure. A-A') longitudinal cross-section; B-B') transversal cross-section. Please note: dimensions for carbonation and corrosion penetration fronts are indicative.

Laboratory exposure

Laboratory exposure entails a stronger acceleration of the carbonation process. The main variables affecting the results are: a) type of exposure, e.g. standard carbonation testing, pre-carbonation, wet-dry cycles; b) CO₂ concentration; c) duration of the exposure; d) temperature and relative humidity.

Standard carbonation testing involves the use of a carbonation cell for smaller specimens, mainly in order to evaluate the progress of the carbonation front using chemical indicators (e.g. phenolphthalein), and additionally, assessing the corrosion of the embedded steel fibres [79,125]. These tests cause strong acceleration rates of the carbonation process (i.e. exposure for 56 days at 50 vol.-% CO₂ is equivalent to about 100 years of a mild environment), reaching carbonation depths of 50 – 60 mm, but conversely observing no signs of fibre corrosion [79,101,102,125].

The use of pre-carbonated specimens exposed to simulated atmospheric corrosion (e.g. wet-dry cycles) has been proven more effective reproducing actual corrosion of steel fibres. Weydert & Schiessl [12], exposed pre-carbonated SFRC beams (3 vol.-% CO₂ for 3 months) to a mild-environment (including rain and freezing) for 18 months, resulting in carbonation depths of 6 – 10 mm with corroding fibres at the outer 2 mm and negligible mechanical damage for uncracked SFRC. Conversely, the presence of cracks resulted in severe corrosion of the fibres in 20 – 80 % of the cross section of the beams, increasing for larger crack widths, but with limited effect on the residual-tensile strength.

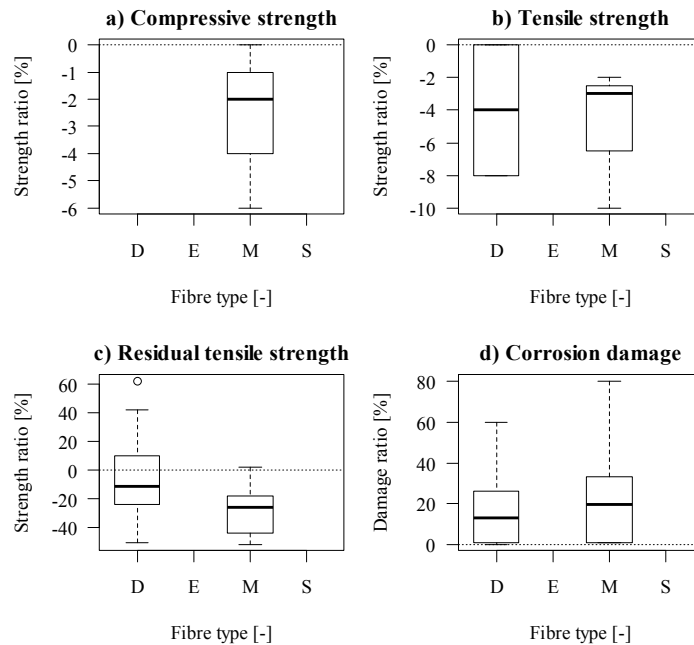
Nemegeer et al. [56], exposed uncracked and pre-cracked SFRC to wet-dry cycles with demineralized water and saltwater (5 wt.-% NaCl solution), employing a CO₂-rich environment during the drying cycles, for a total exposure time of 18 months. Results presented a shallow carbonation depth, below 2 mm, with limited rusting at the surface and no reductions of the residual-tensile strength for the uncracked specimens. The pre-cracked specimens showed limited carbonation at the crack faces (1 – 2 mm), accompanied by minor rusting of fibres bridging cracks and negligible reductions of the residual-tensile strength.

Alternatively, Kosa and Naaman [45,46], exposed pre-carbonated SFRC beams (50 vol.-% CO₂ for 21 days) to wet-dry cycles with saltwater (3.5 wt.-% NaCl) for 9 months, observing an increase of the corrosion damage relative to un-carbonated SFRC and larger reductions of the fibre diameter and residual-tensile strength.

3.1.1.2 Type and size of steel fibres

There is limited research focusing on the influence of the fibre type on the durability of SFRC subjected to carbonation. The classification as used for chloride-induced corrosion will be used in the following: a) fibre type; b) type of steel and coatings; c) fibre dimensions; d) volume fraction of fibres.

The majority of research focuses on cold-drawn steel fibres. Earlier research mainly deals with un-deformed cold-drawn wire [33,37,80], showing limited corrosion and mechanical damage, but lacking a detailed analysis of the fibre role. Recent studies focus on hooked-end fibres; agreeing on a reasonably good durability for uncracked SFRC, but disagreeing on the effect of cracks on fibre corrosion [48,79]. Alternatively, the comparison of cold-drawn wire with other fibre types (i.e. Mill-cut fibres) does not show significant differences on the electrochemical behaviour, possibly covered by the scatter of the results (Fig. 13d) [12,49]. However, the variation of the residual tensile strength after exposure shows a significantly larger deterioration for mill-cut fibres (Fig. 13c). There is limited experimental data available to explain the variations of compressive and tensile strength, and the reported results show minor strength variation for exposed SFRC with cold-drawn carbon-steel fibres and melt extract stainless-steel fibres (Fig. 13a-b), suggesting negligible damage of the matrix due to fibre corrosion.



Abbreviations: (Fibre type) type of fibre according to EN-14889-1: cold-(D)rawn, melt-(E)xtract, cut-(M)ill, or cut-(S)heet.

Fig. 13. Deterioration of SFRC exposed to carbonation, influence the type of fibre on: a) compressive strength ratio; b) tensile strength ratio; c) residual-tensile strength ratio; d) corrosion damage.

Carbon-steel fibres show an overall good performance in uncracked SFRC [12,13,80], but some studies report severe corrosion of fibres bridging cracks [12,79], which in some cases leads to significant reductions of the residual-tensile strength of the SFRC [13,74]. Stainless steel fibres have been reported to provide full long-term protection against corrosion, even for cracked SFRC [49]. Galvanized and brass-coated fibres showed a similar long-term behaviour to un-coated carbon-steel fibres [12,49,56,79]. Moreover, Ferrara et al. [79], reported higher corrosion rates for brass-coated fibres, attributed to copper-iron galvanic coupling at small flaws on the coating.

3.1.1.3 Quality of concrete

As assumed in the general practice, lower water to cement ratios are expected to produce a denser matrix, which leads to a lower penetration of CO_2 and consequently lower carbonation rates [76,95]. Water to binder ratios (w/b) in the range of 0.29 – 0.78 have been investigated [33,48,79,102,126]; showing an overall good

behaviour of SFRC against carbonation for $w/c < 0.50$, i.e. carbonation rates below $1.0 \text{ mm}/\sqrt{y}$ and corrosion limited to fibres directly exposed at the SFRC surface [12,79].

The analysis of the experimental data available reveals a lack of data for higher w/b ratios presenting contradictory results for the corrosion damage ratio (Fig. 14d). The results available are inconsistent and despite the decreasing average corrosion damage for lower water-binder ratios, the results overlap within a large scatter (Fig. 14d). The variations of the residual tensile strength reported for SFRC at low- ($w/b = 0.30 - 0.40$) and medium- ($w/b = 0.40 - 0.50$) water to binder ratios are similar, and present large variations, i.e. $\pm 20\%$ (Fig. 14c). The limited data available for the compressive and tensile strength ratios hampers the elaboration of conclusions based on published results (Fig. 14a-b).

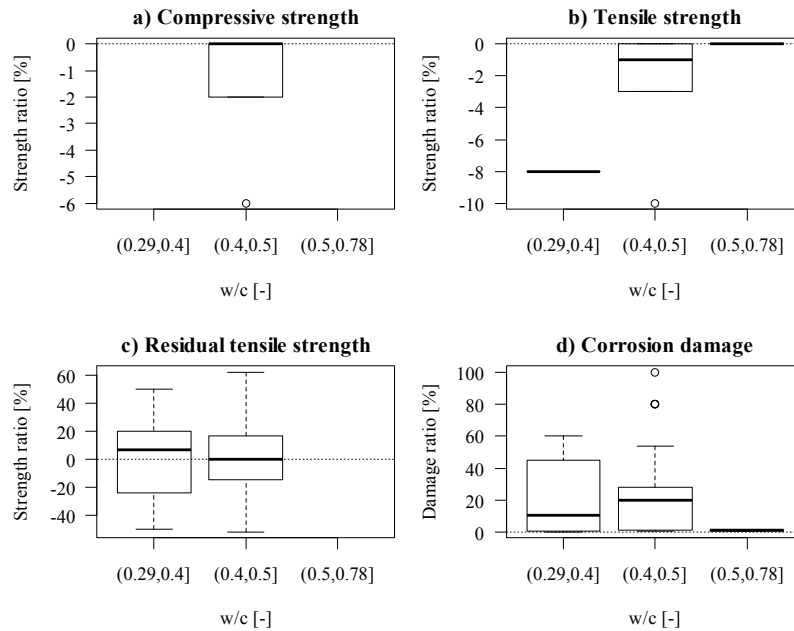


Fig. 14. Deterioration of SFRC exposed to carbonation, influence the water to cement ratio on: a) compressive strength ratio; b) tensile strength ratio; c) residual-tensile strength ratio; d) corrosion damage.

There is limited research focusing on the effect of the binder type and content on the corrosion resistance of SFRC subjected to carbonation, hindering the elaboration of design guidelines. A large share of the research typically uses plain Portland cement with contents ranging from $350 - 580 \text{ kg}/\text{m}^3$ [12,33,37,80], in some cases combined with minor mineral replacements [13]. The total binder content does not show a significant impact on the corrosion durability, relative to the other variables (e.g. crack width, water to binder ratios, exposure conditions).

3.1.1.4 Cracks

Carbonation of uncracked SFRC causes limited long-term damage, restricted to fibre corrosion progressing at low rates in the outer region of the carbonated area (i.e. $1 - 10 \text{ mm}$) and aesthetical damage with no cracking or spalling of the matrix [12,33,37,80], as seen from the collection of results presented in Fig. 15b. Negligible reductions of the residual-tensile strength of carbonated SFRC are reported in e.g., [12,33], even in combination with chlorides [12,46,56]. However, the large scatter observed for the results (Fig. 15a) has been related to the progressive embrittlement of the SFRC, i.e. for a 10-year period for some of the investigations [75,99]. Such a change of the fracture behaviour of SFRC has been linked to the continuous hydration and densification of the matrix, rather than the deterioration of the steel fibres [13,99]. A detailed discussion on the mechanisms is provided in chapter 3.2 of this paper.

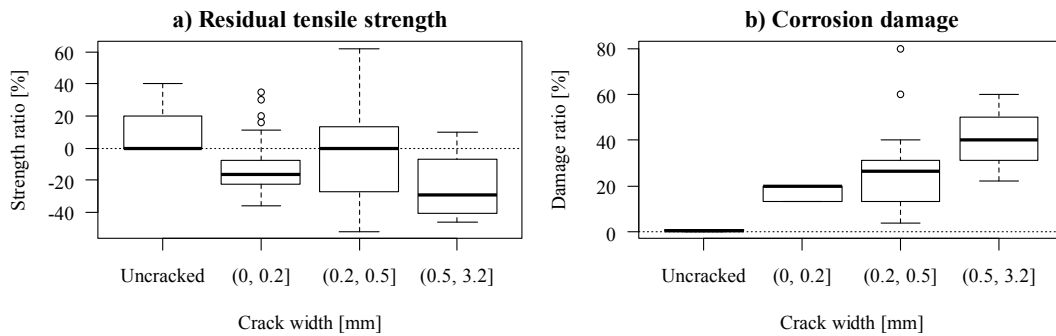


Fig. 15. Deterioration of SFRC exposed to carbonation, influence of the crack width on: a) residual-tensile strength ratio; b) corrosion damage ratio.

There is controversy regarding the durability of carbonated cracked SFRC, depending on the crack width, divided into: a) wide cracks, $w_k > 0.50$ mm; b) narrow cracks, $0.50 \text{ mm} > w_k > 0.20$ mm; c) hairline cracks, $w_k < 0.20$ mm.

The presence of wider cracks ($w_k > 0.50$ mm) promotes early initiation of corrosion of steel fibres bridging the crack (Fig. 15b), especially in the outer crack region (Fig. 12, transversal cross-section B-B'), covering up to 90% of the fibre's cross section for longer exposures [12]. Fibre corrosion inside cracks wider than 0.50 mm resulted in a significant loss of the residual-tensile strength (Fig. 15a), estimated around 30 – 40% by Bernard [13].

Narrow cracks (0.20 – 0.50 mm) resulted in initiation of corrosion of 70 – 90 % of the fibres bridging the crack (Fig. 15b), with limited reductions of the residual-tensile strength for long accelerated exposure [12]. Conversely, [13] and [74] reported a substantial decrease of the total energy absorption (30 to 40 % loss) of pre-cracked SFRC, at cracks wider than 0.20 mm, after 24 and 37 months of field exposure. These discrepancies regarding the deterioration on the residual-tensile strength of exposed SFRC for cracks wider than 0.20 mm are reflected in the large scatter presented in Fig. 15a.

The durability of carbonated SFRC with smaller cracks ($w_k < 0.10 - 0.20$ mm) is currently under discussion. Although initiation of fibre corrosion is found in the outer 10 – 40 % of the crack's cross-section (Fig. 15b), the residual-tensile strength at small deformations is unaffected and even slightly improved when compared to unexposed SFRC [12], accounting for negligible reductions of the total energy absorption for large deformations [13]. However, the large scatter reported among research for this exposure, as presented in Fig. 15a, complicates the definition of limit states, such as e.g. a critical crack width, for the most aggressive exposure classes (i.e. XC4).

3.2 Mechanisms of carbonation-induced corrosion in SFRC

Steel embedded in concrete remains passive due to the high alkalinity of the surrounding environment (i.e. pH 13 – 14). The dissolution of CO_2 into the pore solution through the concrete surface leads to the formation of carbonic acid (H_2CO_3), which reacts with the calcium hydroxide forming calcium carbonate, thus lowering the pH below 10 and promoting the de-passivation of the steel surface [95].

Following Tuutti's model for corrosion of reinforced concrete [100], the deterioration of SFRC due to carbonation can be divided into: a) initiation phase, where CO_2 dissolves into the pore solution, reacts with calcium hydroxide and progressively lowers the pH at the steel surface; b) propagation phase, once the pH of the electrolyte at the steel surface is lower than the pH threshold (pH < 8 – 9), the passive layer at the steel surface starts to dissolve and corrosion initiates.

3.2.1.1 Carbonation of SFRC

The initiation phase is governed by the progress of the carbonation front, which defines the region of the concrete with pH < 8 – 9, where corrosion of steel is expected to initiate, described in Fig. 16 as the process

A-B [106]. The rate of carbonation is highly dependent on several variables: e.g. the concentration of CO_2 at the surface, moisture content, concrete composition (e.g. w/c ratio and binder composition) and temperature. Carbonation rates for uncracked SFRC have been found similar to plain concrete (e.g. $k = 0.4 - 1.4 \text{ mm}/\sqrt{\text{y}}$), suggesting that the fibre-matrix interface does not provide a weaker path for CO_2 to diffuse into the concrete [67,79,102,125].

The presence of cracks increases the depth of the penetration front locally (Fig. 12); the crack faces act as new surfaces carbonating at a lower rate, e.g. calculated carbonation coefficients inside cracks and perpendicular to the crack faces are 70 – 80 % lower than the ones for external surfaces, and decrease along the crack depth [12,57].

3.2.1.2 Carbonation-induced corrosion of steel fibres

The propagation phase described in Tutti's model, corresponds to the initiation of corrosion, governed by the dissolution of the passive layer of the steel at decreasing pH (Fig. 16 B-C-D). When the pH of the electrolyte surrounding the steel interface decreases below the threshold for reinforcing steel (typically assumed in the range of $\text{pH} = 8 - 9$ for carbon-steel), the dissolution of the passive layer of iron oxyhydroxide at localized anodic sites (Fig. 16 C) promotes the initiation of corrosion, which would propagate through the dissolution of iron as Fe^+ ions, as presented in the active corrosion area of the Eh-pH diagram (Fig. 16 D) [106], reaching corrosion rates in the order of 5 – 50 $\mu\text{m}/\text{year}$ for conventional reinforcement in uncracked concrete [95,127].

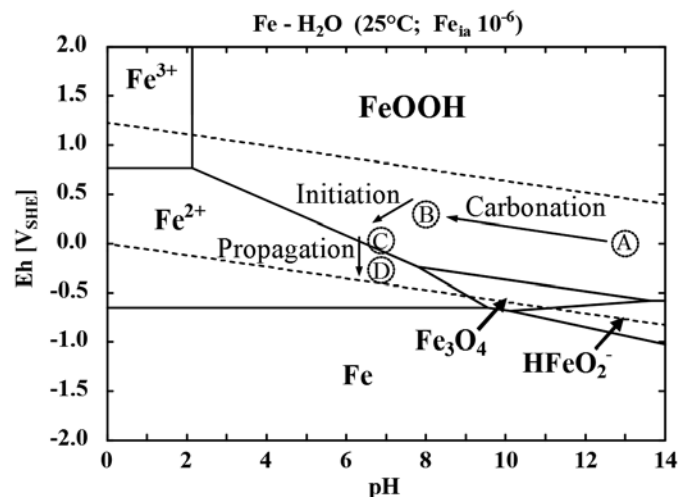


Fig. 16. Potential-pH diagram for conventional steel in carbonated concrete, pH-potential for: A) steel embedded in un-carbonated concrete (mixed potential); B) steel embedded in carbonated concrete (mixed potential); C) corrosion initiation of steel embedded in carbonated concrete, anodic region; D) corrosion propagation of steel embedded in carbonated concrete, anodic region. After Küter et al. [106].

There is limited research on the corrosion rate of steel fibres embedded in carbonated concrete. Nevertheless, the absence of steel fibre corrosion with cold-drawn carbon-steel wire embedded in uncracked carbonated SFRC, suggests an improved resistance to carbonation-induced corrosion. Published research presents limited corrosion in the outer 1 – 5 mm of the concrete regardless of the penetration depth of the carbonation rim (10 – 20 mm) [12,37,79,80]. The case of cracked SFRC is more complex; corrosion has been observed for most of the fibres bridging the crack, as the carbonation front propagates along the whole crack region. Severe corrosion is observed particularly at the outer crack rim, as shown in Fig. 12, whereas deeper fibres show milder signs of corrosion, i.e. rusting, [47,56].

The mechanisms governing carbonation-induced corrosion of steel fibres in uncracked SFRC have not been clarified yet, but it is expected that some of the mechanisms responsible for the increased resistance to chloride-induced pitting corrosion might apply as well for carbonation-induced corrosion: a) smaller dimension of fibres limiting the cathodic area and leading to slower corrosion rates; b) denser and more

uniform steel-matrix interface of SFRC, which effectively protects fibres against oxygen ingress and limits ionic transport at the steel surface.

There is limited data available investigating the chemical stability of coated steel fibres in carbonated SFRC. There is overall agreement regarding the full protection of galvanized steel fibres in uncracked carbonated SFRC, as presented in macroscopic investigations [12,56,79]. However there is disagreement on the stability of galvanized fibres inside cracks [12,56,61], since there is insight of fibre corrosion for long-term exposures [12,61]. Electrochemical testing of galvanized fibres embedded in un-carbonated concrete show limited corrosion rates at the coating, leading to passivation of the zinc coating at the fibre [70]. It is reported that carbonation of the uncracked concrete (i.e. $\text{pH} \approx 9.5$) promotes the formation of additional passive zinc-oxide phases, unless the concentration of carbonates (i.e. HCO_3^- , CO_3^{2-}) and alkali in the pore solution drops significantly, which leads to the dissolution of the zinc coating [128,129], such as in the case of leaching inside large cracks and at surfaces exposed to rain or running water [129,130].

Macroscopic investigations report higher corrosion rates on brass-coated carbon-steel fibres in cracked and uncracked SFRC under long-term exposures, relative to carbon-steel wire, attributed to galvanic coupling between the copper-steel phases at local damage in the coating [79]. These observations agree with the deterioration model proposed in [112], presented as a combination of: i) iron-zinc galvanic coupling, which decelerates the initiation of corrosion at the exposed steel through the consumption of the zinc phases, i.e. dezincification; ii) iron-copper galvanic coupling, which increases corrosion rates at the steel once the zinc is locally depleted.

Stainless steel fibres have been reported effective on preventing corrosion in cracked and uncracked SFRC subjected to carbonation in the long-term [49]. Published research indicates negligible corrosion rates for stainless steel wire tested in pore solution simulating carbonated concrete (i.e. $\text{pH} = 9.5$), showing an electrochemical behaviour similar to un-carbonated pore solution (i.e. $\text{pH} = 12.5$). However, there is insight of a large impact of a decreasing pH in the pore solution on the pitting corrosion resistance of stainless-steel wire embedded in carbonated concrete exposed to chlorides [113].

Mechanisms governing carbonation-induced corrosion of uncracked SFRC

The limited corrosion observed on steel fibres embedded in carbonated uncracked SFRC, relative to conventional reinforcement might be attributed to two of the main components influencing the improved resistance against chloride-induced pitting corrosion [61,94,108]: a) the discontinuous nature of the fibres; b) the dense and uniform fibre-matrix interfacial transition zone (ITZ). So far, there is, to the authors' knowledge, no research describing the relevance of these mechanisms or proposing a theory explaining the improved behaviour of SFRC against carbonation-induced corrosion relative to conventional reinforcement.

The positive influence of the discontinuous nature of the fibres on the improved corrosion resistance of uncracked carbonated SFRC, relative to conventional reinforcement, might be associated (as for chloride-induced pitting corrosion) to smaller potential difference along the steel surface and smaller cathode/anode ratios [61,108]. Criticism about the impact of the fibre size-effect for chloride-induced corrosion may apply as well for the carbonation scenario, where the length-effect for wire lengths in the range of 0 – 160 mm is negligible and the corrosion reaction might be anodically controlled [94].

The insight of the authors on this issue is that: even though the initiation of corrosion (i.e. depassivation) of the embedded steel may be anodically controlled, the small length (e.g. 30 – 70 mm) and discrete nature of the fibres relative to conventional reinforcement would limit the development of large potential gradients along each single fibre, reducing corrosion rates in the event of propagation of corrosion macro-cells, such as in the case of heterogeneous exposure conditions or localized defects at the steel interface. Similar behaviour (i.e. repassivation of the steel after initiation of corrosion) has been reported in cracked SFRC subjected to carbonation in wet-dry cycles [56]. In the event of fibre corrosion, the accumulation of expansive corrosion products would block the surrounding pore structure, limiting further diffusion of oxygen and ions through the steel-concrete interface, thus limiting further propagation of corrosion, as the expansive stresses originated from corroding steel fibres are not expected to induce cracking of the surrounding matrix [61,131]. It is expected as well that the densification of the cement microstructure

surrounding the fibres due to carbonation will limit ionic and oxygen transport at the interface [132,133], reducing corrosion rates in uncracked SFRC.

The role of a denser and more uniform fibre-matrix ITZ is expected to be of major importance for the corrosion protection of carbon-steel fibres in uncracked carbonated SFRC, as already theorized for chloride-induced corrosion [61,108]. The presence of a larger and more uniform calcium hydroxide (CH) layer around the fibre (Fig. 17b), as proposed by [108,114], would have a beneficial effect in two aspects: i) the denser ITZ would increase the protection of fibres in the bulk SFRC against oxygen ingress and would prevent ionic transport; ii) the thicker CH layer (i.e. 10µm), estimated two- to three-fold as for conventional steel (Fig. 17a-b), would provide a larger calcium-buffer for the absorption of H_2CO_3 and its densification due to the formation of calcium carbonate would potentially prevent further carbonation at deeper layers (i.e. the duplex film), see Fig. 17b.

Furthermore, the limited amount of pores and defects at the fibre-matrix ITZ, as fibres “float” inside the fresh-concrete matrix similarly to aggregates, would hinder the formation of weak spots where localized corrosion might initiate (Fig. 17b) [108]. It has been shown that these weaker spots represent the preferential points for initiation of reinforcement corrosion on conventional reinforcement in carbonated concrete [106].

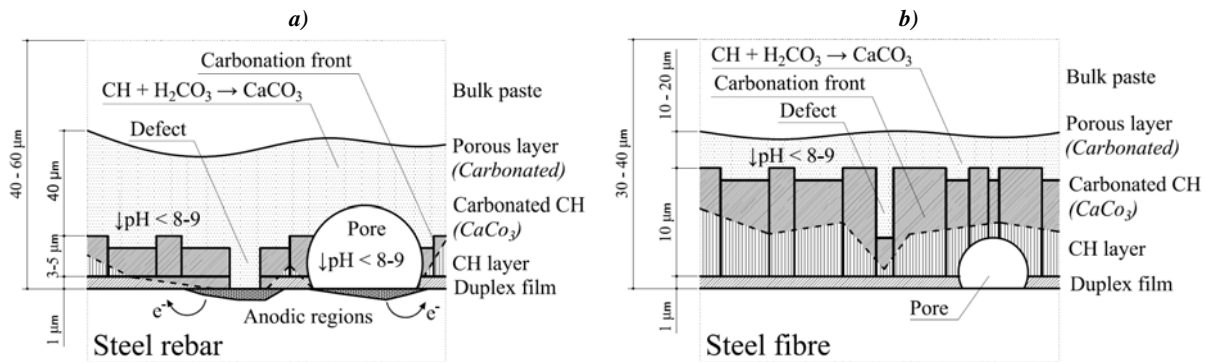


Fig. 17. Microstructure and mechanisms of carbonation-induced corrosion in uncracked concrete, for: a) conventional reinforcement; b) steel fibre reinforced concrete.

Mechanisms governing carbonation-induced corrosion of cracked SFRC

There is limited research available investigating the mechanisms responsible for carbonation-induced corrosion of carbon-steel fibres in cracked SFRC. The published investigations evaluate the performance of the exposed SFRC at the macroscale level, and conclusions are based on a critical crack width (e.g. $w_k < 0.10 - 0.20$ mm); where limited access of oxygen due to the natural tortuosity of the crack and sealing of the crack by autogenous-healing, calcium leaching and corrosion products prevents the evolution of corrosion at the fibre regions bridging the crack [56,61]. These observations provide a limited explanation for the increase of the peak residual strength and the decrease of the residual tensile strength for larger deformations, viz. “stiffening” effect, observed for cracked SFRC exposed to rainwater or wet-dry cycles [13,61,75,99,134].

Studies report a change in the failure mode of cracked SFRC ($w_k > 0.20 - 0.30$ mm), shifting from fibre pull-out to fibre yield, in particular at larger strains: e.g. 3 mm central span deflection (CMOD ≈ 2.6 mm) on ASTM C1609 beams exposed to coastal weather (i.e. XC4, XS1) [75], or 10 mm cumulative central deflection on ASTM C1550 round panels exposed to high relative humidity environments (i.e. XC3) [99].

However, there is an open discussion on the issue, as several practitioners attribute such changes to an inadequate selection of the fibre type and dosage [135,136], arguing that the change in failure mode obeys to the densification of the fibre-matrix interface, not accounted for at early-age testing, but on the other hand possible to be estimated via accelerated ageing and testing. Similar issues have been already discussed for other types of fibres, e.g. alkali-resistant glass fibres and cellulose fibres, concluding that the main mechanisms responsible for long-term embrittlement were related to the abovementioned densification of the fibre-matrix interface during time [124].

The authors suggest a model governed by the damage at the fibre-matrix ITZ, complementary to the deterioration model proposed for steel fibres in chloride-contaminated concrete, presented in the previous section. The protective role of the fibre-matrix ITZ prevents the initiation of corrosion of steel fibres in uncracked SFRC and hinders further hydration at the fibre-matrix interface; as the matrix cracks, the strain in the fibres bridging the crack damages the fibre-matrix ITZ, promoting corrosion at the exposed region of the fibre as the pH decreases. Autogenous-healing at the fibre-matrix interface improves the fibre-matrix bond and eventually hinders fibre corrosion. Four stages may be identified:

- 1) The dense and uniform steel-matrix ITZ surrounding the steel fibre acts as a protective ‘coating’ (Fig. 18a): limiting the access of oxygen and isolating the steel surface from the electrolyte (i.e. limiting ionic diffusion along the steel surface). The thicker and more uniform CH layer compared to conventional steel acts as a “calcium buffer” delaying the progress of carbonation at the steel-concrete interface.
- 2) When the tensile capacity of the concrete is exceeded, the matrix cracks and the strain at the fibre-matrix interface damages the ITZ (Fig. 18b). The damaged ITZ facilitates O_2 and ionic transport along the steel surface; the bridging region of the fibre acts as anode, while the embedded area will act as the cathode due to the pH gradient formed at the crack face (i.e. corrosion macro-cell), as presented for conventional reinforcement in [120]. Furthermore, the cracked interface provides a preferential path for the dissolution of calcium, towards the crack face, where the pH is lower due to access of surrounding water (e.g. rain, running water). The dissolved calcium depositing at the broken interface together with the hydration of un-hydrated cement facilitates the autogenous healing of the damaged fibre-matrix interface [122]. Finally, the pH at the inner faces of the crack will decrease as a combination of leaching and carbonation (i.e. ingress of CO_2 , dissolved as H_2CO_3 at the crack); carbonation of calcium at the fibre-matrix interface would further increase the density of the depositing healing products.
- 3) If the fibre does not reach a critical strain (i.e. critical crack width), the damaged fibre-matrix interface may heal completely [122], recovering to similar conditions as the uncracked state (Fig. 18a). The fibre-matrix ITZ, rich in CH would limit the decrease of the pH at the steel surface, re-passivating the steel at anodic regions (Fig. 18c). Carbonation of the healing products (e.g. calcium and C-S-H) at the interface would densify the surroundings of the fibre, improving the fibre-matrix mechanical bond; explaining the improved peak residual tensile strength reported in the literature [12,58,75]. Finally, the crack would progressively seal with un-hydrated cement, leaching, and corrosion products, limiting the diffusion of oxygen and CO_2 ; the surface of the fibres bridging the crack would serve as preferential surfaces for deposition of these compounds [122,137].
- 4) At larger strains, i.e. above critical crack width, excessive damage at the fibre-matrix interface would result in defective healing of the ITZ at the regions with greater damage (e.g. hooked ends, fibre-crack intersection), as shown in Fig. 18d. This defective healing may facilitate the evolution of fibre corrosion at anodic sites, as previously described in Fig. 18b, which would result in a progressive reduction of the fibre cross-section. Furthermore, progress of carbonation at the fibre-matrix interface and the surrounding matrix will increase the fibre matrix bond and mechanical anchorage of deformed fibres (e.g. hooked-end or crimped fibres). Once a critical cross-section reduction is reached (i.e. the tensile capacity of the steel is lower than 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 for larger strains would decrease, as reported in previous research [61,75,99]. In the case of a large increase of the fibre-matrix bond and mechanical anchorage due to autogenous healing and carbonation, the failure mode would change to fibre yield even for negligible corrosion of fibres, as the original design assumptions (e.g. post-crack behaviour at 28 days maturity) would be no longer applicable [75,99].

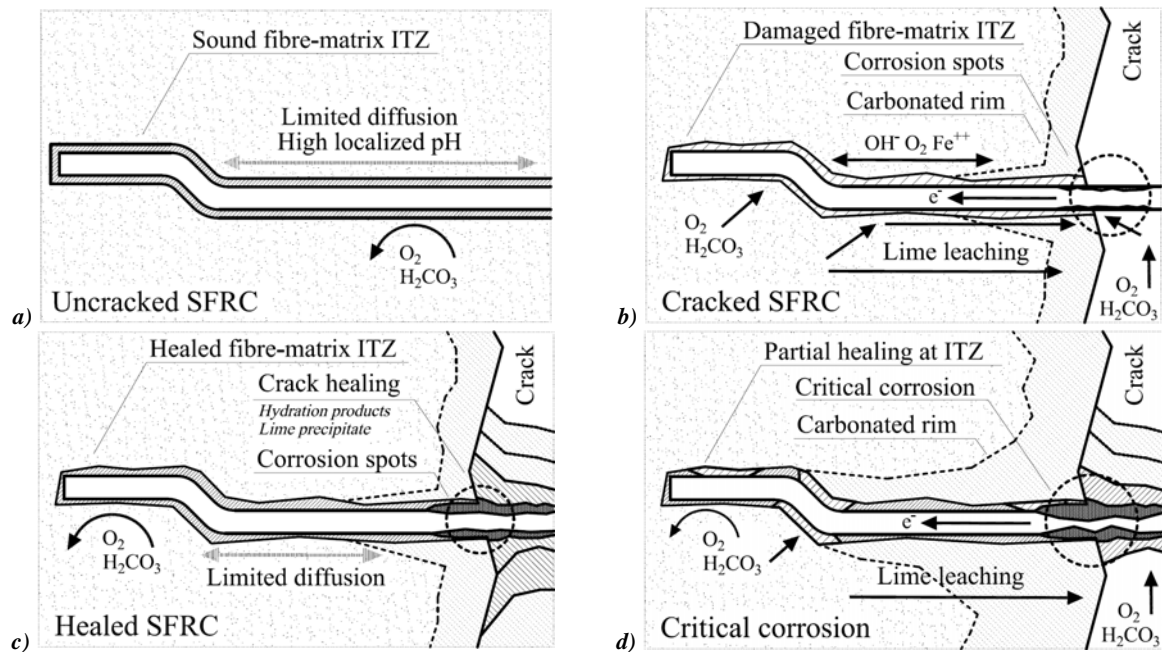


Fig. 18. Structure and corrosion mechanisms of carbonated SFRC, for: a) uncracked SFRC; b) cracked SFRC at an early stage; c) cracked SFRC after autogenous healing; d) cracked SFRC with critical corrosion of fibres.

4. Summary and discussion

A summary of the analysis of the existing literature on durability of SFRC exposed to chlorides and carbonation is presented in Table 4. The table classifies the results according to: mild carbonation exposure (EN 206 classes: XC2-3), aggressive carbonation exposure (XC4), mild chloride exposure (XS2, XD2) and aggressive chloride exposure (XS3, XD3). Furthermore, the case of mixed-in chlorides (e.g. 3.5% -wt. NaCl) is included, despite the fact that it is generally disapproved and not covered by standards.

For carbonation exposure, there is significant disagreement between the limitations stated in international standards and guidelines and the results extracted from published research, the latter being more restrictive with respect to limit states, such as the critical crack width for wet-dry cycles (XC4). The restrictions of the maximum crack width presented in the standards ($w_k \leq 0.20 - 0.40$ mm), seem somehow permissive when compared to the substantial corrosion damage ratios reported in the literature and the large scatter observed for residual tensile strength ratios (Fig. 15a-b). Conversely, for the least aggressive exposure classes (XC2-3), the limitations regarding the maximum crack width ($w_k \leq 0.30 - 0.50$ mm) might be too strict, if compared to the limited corrosion damage expected.

For chloride exposure, the results from the scientific literature partially agree with the limitations observed in the standards and guidelines. The limitations of the maximum crack width (w_k), in the range of 0.10 – 0.30 mm, proposed by some of the international standards and guidelines [15,17,26], are in agreement with the increased damage observed for 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 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).

Table 4. Summary table, design parameters and mechanical behaviour of SFRC exposed to chlorides and carbonation.

	Carbonation		Chlorides		Mixed-in chlorides
	Mild XC2-3	Aggressive XC4	Mild XS1-2 / XD1-2	Aggressive XS3 / XD3	
Maximum water/binder ratio	< 0.50 – 0.60	< 0.40 – 0.50	< 0.50	< 0.40 – 0.50	
Mineral additions	PC, SF	PC, SF	PFA, GGBS	PFA, GGBS	
Type of steel	Carbon-steel Galvanized	Carbon-steel Galvanized Stainless	Carbon-steel	Carbon-steel Stainless	-
Critical crack width (mm)	0.30 – 0.50	0 – 0.30	0.20 – 0.30	0 – 0.20	
Sacrificial layer (mm)	< 1	1 – 5	1 – 5	1 – 15	
Cracking / spalling	No	No	No	No	Yes
Compressive strength loss	None	None	None	* Low – none	Medium
Tensile strength loss	None	* Low – none	None	* Low – none	High
Residual tensile strength loss					
Uncracked	** Low – none	** Low – none	** Low – None	** Low – None	
Wide cracks ($w_k > 0.50$ mm)	Low	High	Medium	High	High
Narrow cracks ($w_k < 0.50$ mm)	Low	Medium	Medium	Medium – High	
Hairline cracks ($w_k < 0.20$ mm)	Low – none	Medium – none	Low – none	Medium – none	

Abbreviations: (PC) Portland cement; (SF) silica fume; (PFA) pulverized fly ash; (GGBS) ground granulated blast-furnace slag; (w_k) characteristic crack width.

* Detriment on elastic properties of SFRC related to chemical degradation of the matrix. Corrosion of steel fibres do not alter the structural integrity of the matrix.

** Embrittlement due to continuous hydration and carbonation shall be prevented by considering a larger matrix compressive strength, e.g. avoid fibre-yield failure by selecting medium- or high-strength steel fibres at appropriate doses.

The analysis of macro-scale investigations suggests significant differences of the durability of uncracked and cracked SFRC exposed to chlorides and carbonation, distinguishing two main scenarios: corrosion of cracked and uncracked SFRC.

There is an overall good understanding of the improved corrosion of carbon-steel fibres in uncracked SFRC, relative to conventional reinforcement. There is overall agreement among researchers regarding the durability of uncracked SFRC to chloride and carbonation exposure, despite the fact that the damage mechanisms are not fully understood, particularly for the case of carbonation-induced corrosion. Investigations of the topic indicate transport properties for uncracked SFRC similar to plain concrete, fibre corrosion is expected to occur at the outer 1 – 5 mm, without inducing cracking or spalling of the matrix due to the expansion of corrosion products.

Conversely, there are significant disparities between the experimental results from published research investigating the durability of cracked SFRC exposed to corrosive environments. There is no consensus regarding the design parameters that can guarantee the durability of cracked SFRC under chloride and carbonation exposure, namely: the maximum water to cement ratio, the critical crack width and the minimum sacrificial layer. A comparison of experimental results from former investigations, show a large scatter of the results (deviation of 20 – 50 % for the damage ratios) for similar design parameters, hindering the elaboration of solid conclusions.

The mechanisms governing the deterioration of the mechanical properties of SFRC exposed to chlorides and carbonation are not fully understood. Despite the fact that there is recent research investigating the mechanisms responsible of chloride-induced corrosion of carbon-steel fibres in uncracked SFRC, there is limited information on the mechanisms influencing corrosion inside cracks, the latter being the main issue concerning durability of SFRC. The authors propose a deterioration theory for cracked SFRC based on the damage at the fibre-matrix interface during fibre pull-out. However, there is limited information covering the damage of the fibre-matrix ITZ during pull-out and the development of autogenous healing of corroding SFRC is still unclear.

5. Conclusions

This paper reviews the existing literature investigating chloride- and carbonation-induced corrosion of SFRC. The paper reviews the main factors influencing the durability of SFRC exposed to corrosive

environments and analyses systematically the published experimental data on the deterioration of SFRC subject to chloride and carbonation exposure.

There is overall agreement among academics and regulators regarding the durability of uncracked SFRC exposed to chlorides (exposure classes: XC2-4) and carbonation (exposure classes: XS2-3, XD2-3). The superior durability against corrosion of carbon-steel fibres embedded in uncracked SFRC relative to conventional steel, obeys to three main components: the discrete nature of the fibres, the more homogeneous steel surface due to production processes of cold-drawn wire steel fibres (cold-drawing) versus a rougher surface for conventional reinforcing bars (hot-rolling mill), and the denser and more homogeneous fibre-matrix interface compared to conventional steel reinforcement.

The durability of cracked SFRC exposed to chlorides and carbonation is under discussion at the technical and scientific level. 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. However, the mechanisms governing corrosion of carbon-steel fibres in cracked SFRC subject to chloride and carbonation exposure are still unclear. In particular, the influence of fibre corrosion on the residual strength of SFRC is in focus and under discussion.

This paper proposes an alternative deterioration theory for corrosion of steel fibres bridging cracks in SFRC exposed to chlorides and carbonation, focusing on the damage and healing at the fibre-matrix interface. Further research in this field is required, in particular focusing on the damage and healing mechanisms at the fibre-matrix interface during partial fibre pull-out.

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