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Corrosion resistance of steel fibre reinforced concrete - A literature review

Victor Marcos-Meson[a,b,c,*], Alexander Michel[a], Anders Solgaard[b], Gregor Fischer[a], Carola Edvardsen[b], Torben Lund Skovhus[c]

[a] *Department of Civil Engineering, Technical University of Denmark, Copenhagen, Denmark*
[b] *COWI A/S, Copenhagen, Denmark*
[c] *VIA Building, Energy & Environment, VIA University College, Horsens, Denmark*

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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.

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, CO_2 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].

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

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[*] Corresponding author at: Department of Civil Engineering, Technical University of Denmark, Copenhagen, Denmark.
E-mail address: vicmes@byg.dtu.dk (V. Marcos-Meson).

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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} Δ_h^{50}	0.30 –	0.30 –	0.30 –	0.10 2.5	0.10 2.5	0.10 2.5	0.10 2.5
RILEM TC 162-TDF (EU)	[16]	w_k^{50} Δ_h^{50} Fibre	0.30 10 C-G-S	0.30 10 C-G-S	0.30 10 C-G-S	Special Special –	Special Special –	Special Special –	Special Special –
DBV-Merkblatt Stahlfaserbeton (DE)	[17]	w_k^{50} Δ_h^{50}	0.30 20	0.30 20	0.20 25	0.20 40	0.20 40	0.20 40	0.20 40
UNI/CIS/SC4:2004 (IT)	[18]	w_k^{50} $\Delta_h^{>50}$[a] Fibre	0.30 10 C-G-S	0.30 10 C-G-S	0.30 10 G-S	0.30 10 C-G-S	0.30 10 G-S	0.30 10 C-G-S	0.30 10 G-S
CNR-DT 204/2006 (IT)	[19]	w_k^{50} $\Delta_h^{>50}$[a] Fibre	0.30 10 C-G-S	0.30 10 C-G-S	0.30 10 G-S	0.30 10 G-S	0.30 10 S	0.30 10 C-G-S	0.30 10 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} Fibre	0.30 C-G-S	0.30 C-G-S	0.30 C-G-S	Test G-S	Test G-S	Test G-S	Test G-S
DAfStb Stahlfaserbeton (DE)	[23]	w_k^{50} Fibre	0.30 C-G-S	0.30 C-G-S	0.30 C-G-S	N/A –	N/A –	N/A –	N/A –
Design guideline for structural applications of SFRC (DK)	[24]	w_k^{50} Fibre	0.30 C-G-S	0.30 C-G-S	0.20 C-G-S	N/A –	N/A –	N/A –	N/A –
AFTES-GT38R1A1 (FR)	[25]	w_k^{50} Fibre	0.20 C-G-S	0.20 C-G-S	0.20 C-G-S	0.15 C-G-S	0 G-S	0.15 C-G-S	0 G-S
SS-812310:2014 (SE)	[26]	w_k^{50} w_k^{100}	0.50 0.40	0.50 0.40	0.40 0.30	0.30 0.20	0.20 0.10	0.30 0.20	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[b]	G-S[b]	G-S[b]	G-S[b]

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.

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

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

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.

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