INFLUENCE OF STEEL FIBRES ON CORROSION OF REINFORCEMENT IN CONCRETE IN CHLORIDE ENVIRONMENTS: A REVIEW

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Abstract

This paper presents various durability aspects of steel-fibre reinforced concrete (SFRC). Published research results show that due to the limited length of the fibres and the casting conditions, steel fibres embedded in concrete show no corrosion signs despite high chloride concentrations. It was also reported that due to the fibres' ability to arrest crack-width propagation, permeability was positively affected for cracked concrete compared with plain concrete. Recent research suggested that some of the fibres might be interconnected and in contact with the ordinary steel reinforcement, forming a galvanic couple where the fibres would act as sacrificial anodes protecting the rebar and reducing or even stopping the corrosion process. Based on reviewed durability properties, it is argued that steel fibres could be used in reinforced concrete (RC) structures exposed to chloride environments to improve their overall durability performance. However, further experimental results supporting this hypothesis are needed.

Keywords: durability, corrosion, steel, fibre, concrete, SFRC, permeability, chloride

1. Introduction

Steel embedded in concrete is normally protected against corrosion by a passive oxide film due to the alkaline environment provided by the concrete. However, if sufficient build-up of chlorides occurs at the reinforcement, e.g. when the concrete is exposed to seawater or de-icing salts, this tends to cause localised breakdown of the passive film, a phenomenon termed *pitting corrosion*. This can result in serious local loss of the bars' cross section in the affected regions while the surrounding regions remain virtually unaffected, if sufficient water and oxygen are available at the reinforcement surface.

Macro cracks play an essential role in the transport of aggressive substances. To effectively control these cracks is therefore imperative with respect to the service life of concrete

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structures. As a way to ensure the durability of reinforced concrete structures, current regulations define the maximum allowed crack widths, based on exposure conditions.

Even though the effect of cracks on the initiation of corrosion has been dealt with by several authors such as Beeby [1] and Tuutti [2], the effect of cracks on durability is still debated. The only consensus amongst researchers is that if the cracks exceed a certain size, i.e. are too large, they will have a negative impact on durability. Although, according to a study carried out by Otieno et al. [3], determining a universal crack width is not possible.

Application of steel fibre reinforced concrete (SFRC) has mostly been limited to pavements, industrial floors and slabs on grade due to the random distribution and orientation of the fibres, which results in a loss of efficiency as compared to conventional reinforcing bars. Nevertheless, the closely spaced fibres can improve the toughness and the tensile properties of concrete and significantly contribute to controlling and reducing the crack widths Therefore, it would be advantageous to use steel fibres as a complement to traditional reinforcement for crack control.

However, the use of steel fibres combined with traditional steel reinforcement in chloride environments raises questions as there is limited research done in this field. Some of these questions are related to the influence fibres may have with respect to chloride ingress and moisture transport. The main issues that have yet to be dealt with are the potential risk of galvanic corrosion due to the different steel types used in the fibres and in the traditional reinforcement, and the risk of higher corrosion rates due to lower resistivity of SFRC.

These concerns are the main reasons why the use of steel fibres combined with ordinary reinforcement in chloride environments is questioned today. Therefore, a study of the aforementioned issues, through a review of the existing literature is carried out to determine the key aspects which require further investigation.

2. Influence of steel fibres on cracking of concrete

While conventional reinforcing bars are efficiently placed according to the direction of the principal tensile stresses, fibres are randomly oriented. Because of this, fibres cannot replace conventional steel reinforcement but can be incorporated into the cement matrix to improve the response of reinforced cracked concrete. In particular, fibre reinforcement mainly enhances the toughness of the concrete’s brittle matrix and leads to a more ductile material behaviour. The increased ductility is due to the ability of the fibres to transfer tensile stresses across a crack.

Since the first studies on SFRC in the early 1960s, a significant amount of research has been carried out to achieve deeper understanding on the mechanical properties of the material. In particular, special attention has been given to experimental observation of reinforced concrete members in direct tension, i.e. tie elements, to study the cracking process and tension stiffening effect. Abrishami and Mitchell [4], studied the influence of steel fibres in this type of elements and determined that splitting cracks were effectively controlled by adding fibres and that transverse cracks were smaller and more closely spaced than were in specimens without steel fibres. In a similar study Bischoff [5], concluded that the ability of SFRC to transfer tension across cracks led to reduced crack spacing and increased tension stiffening, both of which contribute to an improved crack control. The effect of fibres on crack width and crack spacing are schematically depicted in figure 1a and 1b.

By means of X-ray techniques and a contrast medium, Otsuka et al. [6] investigated the bond cracking around a ribbed bar in fibre reinforced composites. The observations from their tests showed that despite the primary cracks do not extend during the loading process, a number of internal cracks, mostly growing from the bar ribs, accumulate even after the yield point of the reinforcing bar. A comparison with previous studies on reinforced plain-concrete elements showed that the crack width on the surface was much smaller when fibres were included. Thus, not only the crack width is altered by adding fibres but the entire cracking profile is expected to be modified, as shown in figure 1c and 1d where the typical internal crack pattern in a reinforced concrete tie element is compared for RC and for SFRC.

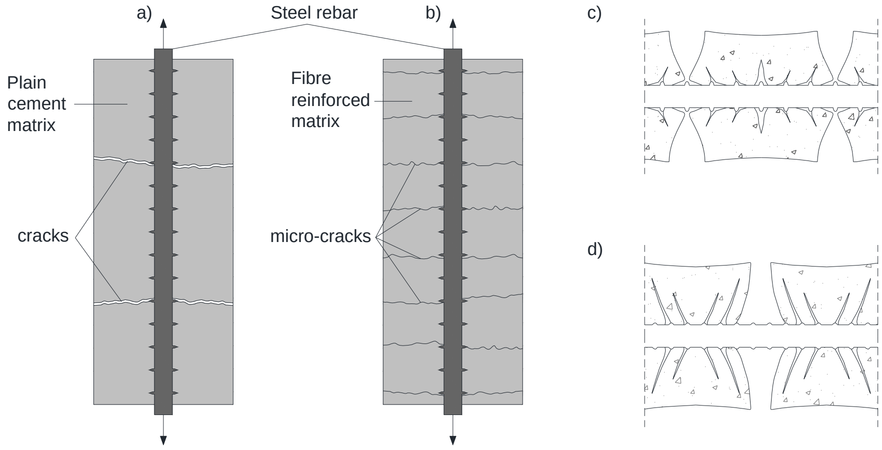

Fig. 1: a) and b): Crack pattern in RC and SFRC elements subjected to tension. Sketch of main internal crack for tie elements: c) for RC; d) for SFRC (after [6])

3. Influence of steel fibres on physical properties

3.1 Transport mechanisms

The degradation processes of concrete are governed by transport mechanisms which can be roughly divided into transport in the bulk material and transport in micro- and macro-cracks. The relevant transport mechanisms in the bulk material include ionic diffusion, gas diffusion, liquid sorption, gas permeability and liquid permeability.

Permeability of concrete, which can be defined as the penetration of a fluid through its pores under a pressure difference, is considered one of the most important transport mechanisms and can be directly related to the concrete's durability [7]. In sound concrete, the permeability is attributed to the capillary porosity of the cement paste and it decreases as the w/c ratio decreases and as the hydration proceeds [8].

Mangat and Gurusamy [9], studied the influence of adding different types of steel fibres on chloride penetration and found that fibres had an insignificant effect in sound concrete. For cracked concrete, the addition of fibres had a marginal effect for cracks below 0.2 mm but became significant for cracks above 0.5 mm. Rapoport et al. [10] found that permeability of concrete was not affected by cracks below 0.1 mm but above that value, an increase in the fibre volume caused a decrease in permeability for cracks widths up to 0.5 mm. This is in agreement with the results obtained by Aldea et al. [11] who determined that fibre reinforcement provides improved resistance to water permeation. They also stated that two different crack thresholds exist: one below which permeability is not affected, and one above which the flow rate increases significantly. In another study, Sánchez et al. [12] investigated several durability indicators such as mercury porosity, chloride diffusion and chloride migration in self-compacting cementitious composites. The results showed that minor variations were introduced by the addition of fibres. Similar results can be found in a report from the University of Florida [13], where permeability, absorption and bulk diffusion tests were performed on concrete mixes with different types of fibre reinforcement. For steel fibre concrete, tests showed that the performance was similar or slightly better compared with plain concretes. Teruzzi et al. [14], prepared mixes for 3 different exposure conditions, with and without fibres, and found no significant effects on chloride diffusion or oxygen permeability attributable to the presence of fibres in concrete. They concluded that the interfacial zone around the fibres does not act as a preferential path for penetration of detrimental agents.

3.2 Resistivity

The electrical resistivity of a material describes its ability to withstand the transfer of charge. In the case of concrete it can be directly related to the ion migration in the porous concrete microstructure. The resistivity of concrete may vary between values in the order of few tens of $\Omega\cdot$m to many thousands of $\Omega\cdot$m depending on the porosity, pore volume and pore distribution, on the connectivity and the degree of saturation of the pore net and pore solution characteristics [8].

Resistivity of concrete is considered to be an important parameter for describing the corrosion rate of reinforced concrete structures. Alonso et al. [15] monitored the corrosion rate and simultaneous electrical resistance values of reinforcing bars embedded in mortars made with six different types of cements, and exposed to varying moisture conditions. They noted that electrical resistivity appeared to be the factor controlling the maximum corrosion rate in aerated specimens. Morris et al. [16] aimed at establishing a corrosion evaluation criterion based on concrete electrical resistivity measurements. They stated that the concrete resistivity can be used as a parameter to evaluate the risk of rebar corrosion regardless of the mix design and environmental exposure conditions. A literature review of research concerning the relationship between the electrical resistivity of concrete and the corrosion rate of embedded reinforcement is available in [17].

Experimental observations on resistivity of SFRC are limited. However, results from several investigations confirm that the addition of steel fibres will cause a drop in the concrete resistivity due to the fibres' conductivity when compared with plain concrete, see e.g. [18]. In a recent study, Solgaard et al. [19] investigated the influence of volume fraction and moisture content on electrical resistivity of SFRC. Experimental results show that resistivity of concrete tends to decrease as the fibre volume increases although moisture content may have a much higher impact on resistivity. However, the influence of the degree of saturation was lower for SFRC.

Results reported by Erdelyi et al. [20] confirm the strong influence of the moisture content on electrical resistivity, but in their study, the addition of steel fibres decreased the resistivity to very low values independently of the volume fraction. They concluded that the overall susceptibility to corrosion of FRC or reinforced FRC increases because the overall electrical resistance decreases due to the steel fibres and therefore it should be advised to keep the inner part of the structures dry as much as possible. This contradicts the findings of Grubb et al. [21], who investigated the effect of steel microfibers on corrosion of steel reinforcing bars. They measured lower electrolytic resistance for steel fibre reinforced cement based materials; however, this was not related to the corrosion rate, as opposed to standard mortar specimens where a lower electrolytic resistance implied an increased corrosion rate.

4. Corrosion of steel fibres in chloride environments

In corrosion terms, the total life span of a concrete structure with conventional reinforcement can be divided into two periods of time: initiation and propagation. The initiation period is considered as the time required by the external aggressive agents to penetrate into the concrete and cause the depassivation of the reinforcing steel. During the propagation period the steel reinforcement corrodes, and the safety of the structure is reduced. In figure 2, a schematic representation of the service life of a structure, according to Tuutti´s model, is shown.

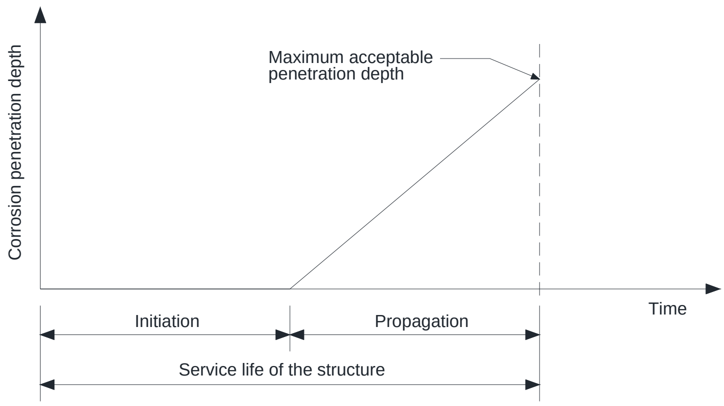

Fig. 2: Tuutti’s service life model (after [8]).

Despite the principles governing corrosion in conventionally reinforced concrete being equally applied to steel fibre reinforced concrete, the results from several investigations, see e.g. [18], [22–25], suggest that steel fibres present an improved performance compared with conventional reinforcing steel.

For fibre concrete it is inevitable that some of the fibres will be very close to the concrete surface. Thus these have a very small, almost negligible, cover depth. This should make fibres especially susceptible to external agents, and consequently, high degradation would be expected for these fibres when exposed to extreme environments. This has been experimentally confirmed, where fibres located at depths up to 3 mm suffered severe corrosion whereas the rest of the fibres, i.e. those fully embedded inside of the concrete, remained free from corrosion [24], [26]. For early ages of exposure, it has also been reported that corrosion of superficial fibres is accompanied by substantial stain rust appearing at the concrete surface [27]. However, it was found that decreasing the water-cement ratio of the concrete mix can effectively reduce the amount of damage in the fibres, as well as limit the region where fibres are prone to suffer severe corrosion to depths as small as 0.2 mm, [28], [29].

In general, no adverse effects on the structural integrity have been observed for sound, uncracked elements when exposed to marine environments [18], [30], [31], but ordinary carbon-steel fibres tend to corrode when cracks develop at the surface. A critical crack width, below which corrosion of fibres passing through the cracks is prevented, has been estimated to values ranging between 0.10 and 0.25 mm ([22], [24], [32]). Apparently, the critical crack width is strongly dependent on the type of fibre used. Mangat and Gurusamy [22] found that no corrosion was detected in melt-extract fibres for cracks below 0.94 mm, while Nemegeer et al. [18] found that cracks up to 0.5 mm had no adverse effect on corrosion on zinc-coated fibres despite the coating being consumed at some places.

The critical chloride content, or chloride threshold value, represents a basic concept that most of the current service life models today rely on. The critical chloride content is generally accepted to be in the range of 0.4-1.0% Cl^- (by weight of cement) for conventional reinforced concrete structures, but has been found to be much higher for steel fibres. Mangat and Gurusamy [23] showed that fibres embedded in concrete remained free from corrosion for chloride concentrations up to 1.7% Cl^-. This is in agreement with the results of Janotka et al. [33], who found that the necessary concentration of chloride to initiate corrosion in steel fibres was at least 3 times higher compared with conventional reinforcing steel. Also Dauberschmidt [25] reported that fibres embedded in concrete, with pH values over 12, show significantly higher critical chloride contents, up to 5.2% Cl^-.

The increased resistance to corrosion of the steel fibres have been attributed to a combination of factors: a) the short length of the steel fibres, which impedes large potential differences along the fibre and thus limits formation of distinct anode and cathode regions; and b) the casting conditions (floating in the concrete matrix as opposed to bar reinforcement) which allow for formation of a very thin well-defined concrete-steel interfacial layer rich in $Ca(OH)_2$ without the presence of voids at the interface as occurs for ordinary reinforcement.

5. Corrosion of steel reinforcing bars in steel fibre reinforced concrete

Despite the increased utilization of steel fibres and that fibres have already been successfully used as structural reinforcement in precast pre-stressed beams or tunnel lining segments, steel fibres today cannot replace the conventional reinforcing bars in most civil engineering structures. Therefore fibres are only used as complementary reinforcement in many cases. However, today the simultaneous use of steel fibres and conventional reinforcing steel is not allowed in chloride environments by Swedish regulations, due to concerns with fibres accelerating the corrosion process and shortening the life span of the structure.

Some researchers have directed their investigations towards this particular topic during the last few years, in order to discern whether the potential risks exist or conversely whether the fibres could contribute to improve the overall durability performance. Someh and Saeki [34], tried to exploit the mechanical improvements of SFRC and the anodic protection that zinc provides to steel, by adding zinc-coated steel fibres to concrete. Their results showed that steel bars embedded in this type of concrete remained free from corrosion for a period of 6 months while bars embedded in plain concrete exhibited pitting corrosion after 3 months. This occurred despite the chloride concentration was clearly higher in the former one.

The results from an experiment carried out by Roque et al. [13], in accordance with ASTM G 109, showed that the corrosion rate in terms of electrical current was considerably higher for SFRC compared with plain concrete. The authors concluded that steel fibres should not be used in combination with steel reinforcing bars in chloride environments. However, discrepant results were derived from the observations by Grubb et al. [21], who performed several electrochemical test on steel bars embedded in cylinders of plain and steel microfiber reinforced mortars. Their specimens were submerged in aerated 3.5% NaCl solution, and their corrosion current measurements indicated that steel microfiber reinforced mortar had better corrosion resistance than did plain mortar. They suggested that the formation of a passive layer for steel in a cement based matrix is an oxygen intensive process and therefore the extensive amount of surface provided by the addition of steel microfibers could act as localized sinks and draw oxygen away from the steel reinforcing bar. Nevertheless, they concluded that the mechanisms causing reduced corrosion rates in the microfiber reinforced specimens could not yet be clearly identified and required further investigation.

In a series of tests reported by Kobayakawa et al. [27], the influence of fibres on corrosion of conventional reinforcement was studied. Two types of fibre reinforcement were used: one with polyethylene (PE) fibres, another with a blend of PE and steel fibres. Specimens with the different fibres and with plain concrete were exposed to wet-dry cycles with a 3%NaCl solution. Corrosion was impressed through current with a potential difference of 3V using a DC power device. The amount of corrosion estimated from the current measurements showed that PE fibres improved the corrosion resistance with respect to plain concrete. A further improvement was achieved by adding also steel fibres. Actual corrosion measurements, by weight loss of steel, confirmed this trend, although large overestimations of the corrosion rates were obtained in the current measurements for the concrete containing steel fibres, which the authors attributed to the interference of steel fibres. More recently, Mihashi et al. [35], further discussed the results from the same series of tests. They reasoned that due to the random distribution of fibres within the concrete, some of these may be interconnected in the cover zone and touch the reinforcing bar, which could cause the fibres to become “sacrificial anodes” due to their proximity to the cathodic region. They also argued that for natural corrosion the passivity of fibres would first break down due to the early presence of aggressive agents like chloride and oxygen. Those fibres in contact with steel reinforcement would become anodes thus reducing the corrosion in the steel bar. In those fibres which are not in contact with the steel reinforcing bar, the corrosion rate would be expected to be small due to the improved corrosion resistance of the fibres.

6. Conclusions

This paper aims at determining the viability of using steel fibre reinforcement in combination with conventional steel reinforcement in chloride environments as a way to improve durability of reinforced concrete structures. Through a review of the existing literature, a study of durability aspects of SFRC has been presented and the following concluding remarks can be drawn: (1) The cracking process of SFRC elements, which leads to smaller and closely spaced cracks, results in reduced permeability of cracked concrete; (2) The addition of fibres in sound concrete does not significantly modify the migration and diffusion transport properties of concrete, since the interfacial zone between fibre and mortar does not represent a weak zone for ingress of detrimental agents; (3) The electrical resistivity of concrete will be unavoidably decreased by adding steel fibres; however, unlike for plain concrete, that does not necessarily imply higher corrosion rates. Furthermore, some results indicate that fibres may actually act as sacrificial anodes and thus protect the steel reinforcing bars. Despite most of the findings in this review suggest that fibres could be used in reinforced concrete structures exposed to chloride environments to improve the overall durability performance the review has found some contradictory results from different investigations. Furthermore, the mechanisms that cause reduced corrosion rates are not yet fully understood and require further research. Therefore additional experimental results from tests specifically aimed at comprehending these mechanisms would be extremely valuable.

References

[1] A. W. Beeby, "Cracking: what are crack width limits for?," *Concrete*, vol. 12, no. 7, pp. 31–33, 1978.

[2] K. Tuutti, "Corrosion of steel in concrete," *CBI Report 4:82, The Swedish Cement and Cocnrete Institute.*, p. 468, 1982.

[3] M. B. Otieno, M. G. Alexander, and H.-D. Beushausen, "Corrosion in cracked and uncracked concrete – influence of crack width, concrete quality and crack reopening," *Magazine of Concrete Research*, vol. 62, no. 6, pp. 393–404, Jan. 2010.

[4] H. H. Abrishami and D. Mitchell, "Influence of steel fibers on tension stiffening," *ACI Structural Journal*, vol. 94, no. 6, pp. 769–776, 1997.

[5] P. H. Bischoff, "Tension Stiffening and Cracking of Steel Fiber-Reinforced Concrete," *Journal of Materials in Civil Engineering*, vol. 15, no. 2, pp. 174–182, Apr. 2003.

[6] K. Otsuka, H. Mihashi, M. Kiyota, S. Mori, and A. Kawamata, "Observation of Multiple Cracking in Hybrid FRCC at Micro and Meso Levels," *Journal of Advanced Concrete Technology*, vol. 1, no. 3, pp. 291–298, 2003.

[7] N. Banthia, "Fiber reinforced concrete for sustainable and intelligent infrastructure," *SBEIDCO*, pp. 337–350, 2009.

[8] L. Bertolini, B. Elsener, P. Pedeferri, and R. B. Polder, *Corrosion of Steel in Concrete*. Weinheim, FRG: Wiley-VCH Verlag GmbH & Co. KGaA, 2003.

[9] P. S. Mangat and K. Gurusamy, "Chloride diffusion in steel fibre reinforced marine concrete," *Cement and Concrete Research*, vol. 17, pp. 385–396, 1987.

[10] J. Rapoport, C.-M. Aldea, S. P. Shah, B. Ankenman, and A. Karr, "Permeability of Cracked Steel Fiber-Reinforced Concrete," *Journal of Materials in Civil Engineering*, vol. 14, no. 4, p. 355, 2002.

[11] C. Aldea and S. Shah, “Durability Enhancements of Cracked Concrete by Fibers,” *ACI Special Publication*, pp. 1–14, 2011.

[12] M. Sanchez, M. C. Alonso, and B. Barragán, “Durability performance of Plain and Fiber Reinforced self-compacting concrete,” *PHi- Planta de Hormgón Internacional, N^{o}2*, pp. 62–64, 2009.

[13] R. Roque, N. Kim, B. Kim, and G. Lopp, “Durability of Fiber-Reinforced Concrete in Florida Environments,” Tallahassee, FL, 2009.

[14] T. Teruzzi, E. Cadoni, G. Frigeri, S. Cangiano, and G. A. Plizzari, “Durability aspects of steel fibre reinforced concrete,” in *6th RILEM Symposium on Fibre-Reinforced Cocnretes*, 2004, no. September, pp. 625–634.

[15] C. Alonso, C. Andrade, and J. A. González, “Relation between resistivity and corrosion rate of reinforcements in carbonated mortar made with several cement types,” *Cement and Concrete Research*, vol. 18, no. 5, pp. 687–698, Sep. 1988.

[16] W. Morris, a Vico, M. Vazquez, and S. . de Sanchez, “Corrosion of reinforcing steel evaluated by means of concrete resistivity measurements,” *Corrosion Science*, vol. 44, no. 1, pp. 81–99, Jan. 2002.

[17] K. Hornbostel, C. K. Larsen, and M. R. Geiker, “Relationship between concrete resistivity and corrosion rate – A literature review,” *Cement and Concrete Composites*, vol. 39, pp. 60–72, May 2013.

[18] D. Nemegeer, J. Vanbrabant, and H. Stang, “Brite Euram program on steel fibre concrete subtask: durability : corrosion resistance of cracked fibre reinforced concrete.,” in *International RILEM Workshop on Test and Design Methods for Steelfibre Reinforced Concrete*, 2003, pp. 47–66.

[19] A. O. S. Solgaard, M. Geiker, C. Edvardsen, and A. Küter, “Observations on the electrical resistivity of steel fibre reinforced concrete,” *Materials and Structures*, Jun. 2013.

[20] A. Erdélyi, E. Csányi, K. Kopecskó, A. Borosnyói, and O. Fenyvesi, “Deterioration of steel fibre reinforced concrete by freeze-thaw and de-icing salts,” *fib.bme.hu*, vol. 2006, pp. 33–44, 2008.

[21] J. a. Grubb, J. Blunt, C. P. Ostertag, and T. M. Devine, “Effect of steel microfibers on corrosion of steel reinforcing bars,” *Cement and Concrete Research*, vol. 37, no. 7, pp. 1115–1126, Jul. 2007.

[22] P. Mangat and K. Gurusamy, “Permissible crack widths in steel fibre reinforced marine concrete,” *Materials and structures*, pp. 338–347, 1987.

[23] P. S. Mangat and K. Gurusamy, “Long-term properties of steel fibre reinforced marine concrete,” *Materials and structures*, pp. 273–282, 1987.

[24] J.-L. Granju and S. Ullah Balouch, “Corrosion of steel fibre reinforced concrete from the cracks,” *Cement and Concrete Research*, vol. 35, no. 3, pp. 572–577, Mar. 2005.

[25] C. Dauberschmidt, “Untersuchungen zu den Korrosionsmechanismen von Stahlfasern in chloridhaltigem Beton,” *PhD-thesis. Technischen Hochschule Aachen*, 2006.

[26] P. S. Mangat and K. Gurusamy, “Long term properties under marine exposure of steel fibre reinforced concrete containing pfa,” *Materials and Structures*, vol. 21, pp. 352–358, 1988.

[27] A. Kobayakawa, D. Homma, H. Mihashi, and K. Shimozawa, “Corrosion durability of fiber reinforced cementitious composites,” in *Proceedings of the 2nd RILEM workshop on concrete durability and service life planning*, 2009, no. 1, pp. 311–318.

[28] K. Kosa and A. Naaman, “Corrosion of steel fiber reinforced concrete,” *ACI materials Journal*, vol. 13, no. 4, pp. 239–245, 1990.

[29] S. U. Balouch, J. P. Forth, and J.-L. Granju, “Surface corrosion of steel fibre reinforced concrete,” *Cement and Concrete Research*, vol. 40, no. 3, pp. 410–414, Mar. 2010.

[30] K. Kosa, A. E. Naaman, and W. Hansen, “Durability of Fiber Reinforced Mortar,” *ACI materials Journal*, no. 88–M38, pp. 310–319, 1991.

[31] N. Buratti, C. Mazzotti, and M. Savoia, “Long–Term Behavior of Cracked SFRC Elements Exposed to Chloride Solutions,” *ACI Special Publication*, pp. 1–14, 2011.

[32] D. Wimpenny, W. Angerer, T. Cooper, and S. Bernard, “The use of Steel and Synthetic Fibres in Concrete under Extreme Conditions,” in *24th Biennial Conference of the Concrete Institute of Australia*, 2009.

[33] I. Janotka, L. Krajcí, K. Komlos, and D. Frtalová, “Chloride corrosion of steel fibre reinforcement in cement mortar,” *The International Journal of Cement Composites and Lightweight Concrete*, vol. 11, no. 4, pp. 221–228, 1989.

[34] A. K. Someh and N. Saeki, “The Role of Galvanized Steel Fibers in Corrosion-Protection of Reinforced Concrete,” in *Proceedings of Japan Concrete Institute*, 1997, vol. 19(1), pp. 889–894.

[35] H. Mihashi, S. Faiz, U. Ahmed, and A. Kobayakawa, “Corrosion of Reinforcing Steel in Fiber Reinforced Cementitious Composites,” *Journal of Advanced Concrete Technology*, vol. 9, no. 2, pp. 159–167, 2011.