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Corrosion of steel bars embedded in fibre reinforced concrete under chloride attack: State of the art

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ABSTRACT

This literature review summarises the influence of fibres on the main parameters governing corrosion of conventional reinforcement. The ability of fibres to suppress crack growth has proven to decrease permeation in cracked concrete while chloride diffusion, in uncracked concrete, seems to remain unaffected by the addition of fibres. Steel fibres in concrete are considered to be insulated owing to the high impedance of the passive layer. However, they will become conductive if they are depassivated. Although low carbon steel fibres may suffer severe corrosion when located near the concrete surface or bridging the cracks, embedded fibres will remain free of corrosion despite high chloride contents. Published experimental observations indicate that fibres had little influence on the corrosion rate of rebars. Steel fibres improved corrosion resistance of rebars moderately; this is mainly attributed to a reduced ingress of chlorides due to arrested crack growth.

Contents

1. Introduction

Under most conditions, well-designed and executed reinforced concrete structures present good durability. The high alkalinity of the pore solution of the concrete provides the ideal environment whereby embedded reinforcement can be protected from corrosion. Under these conditions, a very thin, dense, and stable iron-oxide film is formed. This film, often referred to as passive layer, greatly reduces the ion mobility between the steel and surrounding concrete; thus, the rate of corrosion drastically drops and becomes negligible [1]. Nevertheless, corrosion remains one of the major problems affecting reinforced concrete structures [2]. Corrosion damage on reinforcement and prestressing steel has been identified as the primary cause of a significant number of structural failures over the past centuries and represent a high cost

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to society in terms of repairs, monitoring, and replacement of structures [3].

The most common causes of corrosion initiation in reinforcement are (i) an ingress of carbon dioxide from the atmosphere decreasing the alkalinity of the pore solution and (ii) the local depassivation of steel due to the presence of chlorides at the reinforcement level [4]. The latter occurs when sufficient chlorides build up at the reinforcement surface, i.e., the chloride concentration exceeds a certain limit known as the critical chloride content [5]. This tends to cause localised breakdown of the passive film, a phenomenon termed *pitting corrosion* [6], provided enough water and oxygen are available at the surface of the reinforcement. This phenomenon may result in a serious local loss of the cross section of the bars in the affected regions while the surrounding regions remain virtually unaffected.

Several reports showed that water permeation in cracked concrete rapidly increases as the crack width grows larger than a certain threshold, e.g., [7, 8]. Crack width has also been identified as one of the primary factors influencing the autogenous healing of cracks in concrete [9]. Hence, when cracks exceed a certain threshold, they play an essential role in the transport of aggressive agents and is therefore imperative to the service life of concrete structures to effectively control these cracks. Current regulations and design codes define permissible crack widths, i.e., maximum allowed crack widths, based on the exposure conditions, as a way of ensuring the durability of reinforced concrete structures, cf. [10, 11]. Even though several authors have investigated the impact of cracks on the initiation and propagation of corrosion, e.g., [12–23], the effect of cracks on durability is still debated. The only consensus amongst researchers is that if the cracks were to exceed a certain size, i.e., are too large, they will negatively impact durability. However, according to a study carried out by Otieno et al. [20], it is not possible to determine a universal crack width limit.

The advantages of using fibres in structural members have been demonstrated in a number of research investigations, e.g., [24, 25]; despite this fact, their use in structural applications is still limited. One explanation is the lack of codes and regulations, but also the fact that the fibres are not aligned in the direction of the principal stress and the uncertainties in the distribution of the fibres throughout the cementitious matrix, which makes it unlikely that fibres will completely replace conventional reinforcement in large structural members [26]. In fact, fibres are predominantly used in pavements, industrial floors, and slabs on grade to control the crack width, mostly due to plastic and drying shrinkage [27], although they are also used for tunnel linings, as sprayed concrete and precast segmental linings. Nevertheless, closely spaced fibres can improve the toughness and tensile properties of concrete and significantly contribute to controlling and reducing crack widths. Besides, it has been found that steel fibres, in general, have a higher corrosion resistance than conventional reinforcement. For example, Raupach *et al.* [28] reported that fibres embedded in concrete show significantly higher critical chloride contents (up to 4.7% Cl^-), although fibres located at the surface, at depths of up to 6 mm, are susceptible to corrosion, see, e.g., [29–31]. Therefore, it might be advantageous to use fibre reinforcement as a complement to traditional reinforcing bars to provide crack control mechanisms in civil engineering structures and get rid of congested reinforcement layouts often needed to meet the strict crack width limitations required in the current structural codes.

However, owing to the limited research and experience available in this field, the use of steel fibres raises questions as to when they are used in combination with conventional reinforcement in chloride environments. Some of these questions are related to the influence the fibres may have with respect to chloride ingress and moisture transport. However, the main issue that has yet to be dealt with is if there is a risk of higher corrosion rates when conductive fibres are present in the concrete matrix. Another aspect, only mentioned a few times in the literature, is the potential ability of fibres to become sacrificial anodes, which raises questions regarding the risk of galvanic corrosion between fibres and conventional reinforcement bars.

Through an extensive review of the existing literature, the present study aims to investigate the influence of steel fibres on chloride induced corrosion of reinforcing bars embedded in concrete. Since the studies investigating corrosion of steel bars in fibre reinforced concrete are scarce, in first place, the effect of steel fibres on the most relevant parameters governing corrosion of reinforcement in concrete, including cracking, permeability, chloride ingress, and resistivity, is analysed by examining published data from experimental investigations. Subsequently, the reported results from research studies combining steel fibre and conventional reinforcement have been compared. Based on that, the potential benefits and challenges of using steel fibres in combination with reinforcing bars in concrete structures exposed to chlorides are discussed. Moreover, the literature review will highlight some key aspects of the combined use of steel bars and fibres that have yet to be fully understood and that may require further research.

2. Influence of fibres on cracking of concrete

Since the first studies on steel fibre reinforced concrete (SFRC) by Romualdi and his colleagues (see, e.g., [32]) in the early 1960s, a significant amount of research has been carried out to gain a deeper understanding of the mechanical properties and the fracture process of this material. According to Naaman and Reinhardt [33], the tensile behaviour of cementitious materials may be classified as either strain softening (a quasi-brittle material) or pseudo-strain-hardening. Strain softening materials present localised cracks and loss of stress once the matrix cracks. Conversely, pseudo-strain hardening materials exhibit multiple-cracking up to the post-cracking strength, which is higher than the cracking strength. This behaviour is schematically represented in Fig. 1.

The need for high fibre volume fractions and relatively high-performance concretes in order to obtain a pseudo-strain hardening behaviour, added to the low efficiency of fibres caused by their random position and orientation throughout the concrete matrix, today poses an important impediment to the total replacement of conventional reinforcing bars in large structural elements. However, fibres in combination with steel bars could be used to improve the mechanical response of reinforced concrete elements.

Over the past years, several authors have investigated this possibility by studying the influence of fibre reinforcement on the mechanical response of reinforced concrete elements subjected to pure tension, see, e.g., [35–41]. The general agreement is that specimens containing steel fibres exhibit increased tension stiffening, even at large deformations, and transverse cracks are narrower and more closely spaced than in plain concrete specimens. The typical crack patterns observed in pure tension tests are illustrated in Fig. 2.

In a study by Jansson et al. [42], pull-out tests with short embedment length were carried out to investigate the influence of steel fibres on reinforcement bond for fibre contents up to 1.0% by volume. Although the pre-peak behaviour seemed to remain unaffected by the presence of fibres, after cracking the fibres provided a confinement effect comparable to that provided by stirrups. Fibres effectively controlled the splitting crack growth thereby changing the failure mode from splitting to pulling out of the rebar.

In a recent thesis from Denmark Technical University, Larusson [43] investigated the bond slip and tension stiffening mechanisms in reinforced tie elements made of engineering cementitious composites (ECC) using 2% vol. poly-vinyl alcohol (PVA) fibres. Using an innovative test setup with partially exposed reinforcement, in combination with high definition digital image correlation (DIC) techniques, the formation and propagation of cracks at the interface between the reinforcement and concrete matrix were monitored and quantified at a micro-scale. The results showed that ECC elements consistently presented multiple cracking with considerably smaller crack widths as opposed to RC where a wide localised crack tended to form. Furthermore, the slip and opening displacements measured at the interface revealed