Construction and Building Materials 79 (2015) 165–172

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental study on the properties of corroded steel fibres

Gang Chen [a,b], Muhammad N.S. Hadi [b,*], Danying Gao [a], Liangping Zhao [a]

[a] Research Centre of New Style Building Material and Structure, Zhengzhou University, Zhengzhou, Henan 450002, China
[b] Faculty of Engineering and Information Sciences, University of Wollongong, NSW 2522, Australia

HIGHLIGHTS

- Steel fibres were corroded using two methods: drying–wetting cycles and current.
- The two corrosion methods show pitting and uniform corrosion respectively.
- Pitting corrosion leads to higher decrease in tensile strength compared to uniform corrosion.
- Pitting induces a significant reduction in elongation giving a brittle failure.

ARTICLE INFO

Article history:
Received 7 February 2014
Received in revised form 10 November 2014
Accepted 27 December 2014
Available online 22 January 2015

Keywords:
Steel fibre
Corrosion
Mechanical properties

ABSTRACT

In this study, low carbon steel fibres were corroded to various corrosion degrees by cycling in 3.5% NaCl solution and 60 °C oven, and by applying a designed current density of 20 mA/cm^2. Then the corrosion characters and corrosion degree on tensile strength of the two types of corroded steel fibres were investigated. It was found that the cycles induce pitting and the current induces relatively uniform corrosion. The results of tensile test show that the actual tensile strength of steel fibres was reduced in the case of pitting, while it was marginally affected by uniform corrosion. As the corrosion degree increased, both of the nominal tensile strength and elongation of the two types of corroded steel fibres decreased. In addition to weight loss, local section loss at the pits is the main reason for further degradation of the mechanical properties of steel fibres and gives a brittle failure.

1. Introduction

Steel fibres in concrete are widely used for roads, bridges, tunnels, marine structures and some other main building structures [1]. However, steel fibres just like steel bars, could be corroded by chloride ions in certain environments.

Cases of performance degradation and resistance attenuation of structures, mainly due to the effect of severe corrosion of steel bars, are common occurrence and were studied by many researchers [2–6]. The performance of a steel bar may not be affected significantly by a thin layer of corrosion. However, the effect of a thin layer of corrosion on the performance of a steel fibre whose equivalent diameter is much smaller than steel bar diameter, is particularly serious [7]. Jin et al. [8] analysed the relationship between the diameter of a steel bar and the thickness of corrosion layer. They concluded that the steel bars with various diameters usually have the same corrosion thicknesses in the same corrosive condition. In this case, the steel bar with smaller diameter should have a higher corrosion degree. Similarly, the steel fibre can be considered as a very small steel bar in diameter compared to normal steel bar. Once they are exposed to a corrosive environment, the corrosion rate of steel fibre will be much higher than that of a steel bar.

In normal conditions, the steel fibres are protected by concrete and not easy to be corroded. The physical protection is provided by dense and relatively impermeable structure of concrete, while the chemical protection is provided by high alkalinity (pH > 13.5) of the pore solution in concrete [9]. At this high alkalinity, steel is passivated in the presence of oxygen probably as a result of the formation of an extremely thin film [10,11]. Unless the chloride ions penetrate into the steel fibre concrete and exceed the critical threshold value of corrosion, this film cannot be destroyed and believed to protect the surface of steel fibre from corrosion. Therefore, even in a corrosive environment, such as deicing salt and sea water containing chloride ions with relatively high concentration, only steel fibres embedded in very shallow concrete cover which can easily be in contact with surface diffused chloride ions are susceptible to corrosion [12,13].

However, when the steel fibres are exposed to concrete cracks over a certain width, thus giving access of chloride ions, water

* Corresponding author. Tel.: +61 2 4221 4762; fax: +61 2 4221 3238.
E-mail address: mhadi@uow.edu.au (M.N.S. Hadi).

http://dx.doi.org/10.1016/j.conbuildmat.2014.12.082
0950-0618/

and oxygen, they will be corroded easily. Granju et al. [14] exposed the cracked steel fibre reinforced concrete (SFRC) to a marine-like environment for one year and then evaluated the corrosion of steel fibres located in cracked sections. Their results indicated that there is absence of corrosion in the parts of the cracks thinner than about 0.1 mm, while a little corrosion was observed in the wider parts of the cracks with 0.5 mm mouth openings and extensive corrosion appears in the fibres crossing the crack within a 2–3 mm rim from the external faces of the samples. Moreover, no concrete busting or spalling was observed due to corrosion. Testing the specimens showed an increased strength gain from the rough surface of steel fibres with little corrosion. But when the corrosion reaches a severe degree, the degraded strength affected by corrosion could not resist the tensile stress. Meanwhile, the corroded steel fibres acting as a bridge in cracks no longer have better performance on anti-cracking, enhancement, toughening for SFRC [7,15].

Kosa et al. [7] studied the effects of the corrosion degree on the mechanical performance of SFRC using two series of specimens. One was to expose cracked, carbonated and high permeability specimens with clean steel fibres into cycles of intermittent drying and wetting for varying period and solution temperatures, while the other one was for specimens with steel fibres pre-corroded by similar cycles. The results obtained from the loading tests of the two series showed a similar trend: their overall mechanical properties presented a deteriorating trend caused by increasing reduction of minimum fibre diameter; the severely corroded steel fibres in the specimen underwent breakage in tension and bending, and gave rise to a noticeable reduction in toughness as well as peak strength of tension and bending for specimens. Similarly, Regina [15] conducted mechanical tests on concrete specimens with the steel fibres pre-corroded to 0%, 12.5% and 50% reduction in the minimum fibre diameter using drying–wetting cycles. The observation indicated that the failure type of steel fibres was changed from typical pullout to fracture with increasing corrosion degree. The experimental results demonstrated that fibre corrosion less than 12.5% had no effect on the shear capacity, while 50% corrosion led to a decreased shear strength of the beam by 24%. Furthermore, the toughness and ductility of SFRC were affected by corrosion to a much higher extent than the shear strength.

Obviously, the properties of steel fibres affected by corrosion are directly related to the performances of SFRC. However, the corrosion characteristics and the effect of corrosion degree on the mechanical properties of steel fibres are barely studied by researchers and are investigated in this paper.

2. Experimental programme

2.1. Test samples and corrosion methodology

The experimental programme of this study was carried out at the Engineering Laboratories of the University of Wollongong. A total of 70 low carbon hooked steel fibres glued in bundles with the same length of 60 and 0.75 mm diameter were separated and used for this experiment. In order to achieve the desired corrosion degrees within a short time, the accelerated corrosion technique was adopted for the corrosion of steel fibres.

The first group of 35 steel fibres, named Group D, corroded using drying–wetting cyclic method at the same time. Each cycle consisted of 1 h of saturation in a 3.5 wt% NaCl solution (mixing industrial sodium chloride with tap water of pH 7.4–7.7 [16], concentration similar to seawater with 3.2–3.6 wt% [7]) at ambient temperature (20–27 °C), followed by 11 h of drying at 60 °C in an oven. The solution was renewed every four cycles. The desired corrosion period was set for 5–60 days.

For comparison, the second group of 30 steel fibres, named Group G, was corroded using galvanostatic method. Fig. 1 shows a schematic representation of the corrosion set-up of this method, which is described as follows: one end of the prepared steel fibre was hung on the inside wall of a plastic tank containing 5 wt% NaCl solution for improving the conductivity. The top and exposed end with 5 mm in length of every sample was connected to the anode of a HP Harrison 622B power supply in parallel. Its cathode was connected to a hollow stainless steel bar immersed in NaCl solution. The current density i of 20 mA/cm^2 was adopted in this accelerated corrosion. The desired corrosion degree η, 2–80% in weight loss rate, was achieved by applying a constant current I (A) for the period of corrosion time t (s) assessed from the Faraday law:

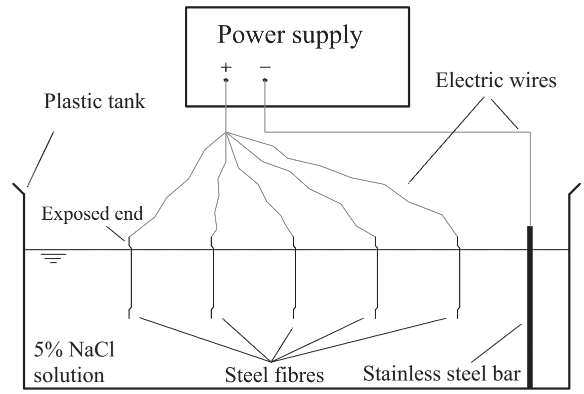

Fig. 1. Schematic representation of the set up for accelerated corrosion using galvanostatic method.

$$t = \frac{\eta WzF}{MI} \tag{1}$$

$$I = A \times i \times 10^{-3} \tag{2}$$

where W is the weight of original steel fibre (g), z is ionic valency, $z = 2.5$ (mean value for Fe^{2+} and Fe^{3+} of corrosion products [2]), F is Faraday's constant, $F = 96{,}500$ C/mol, M is the atomic weight of ferric ion, $M = 56$ g/mol, A is surface area (cm^2).

To ensure the accuracy of corrosion results, in the process of corrosion, the loading current I was checked and corrected to a right value regularly based on the current density i and residual surface area A:

$$A = 2\sqrt{\frac{\pi l}{\rho} \cdot W(1-\eta)} \tag{3}$$

where ρ is the density of steel, $\rho = 7.9$ g/cm^3.

The last group of five clean steel fibres, named Group C, served as control. After corrosion, the three groups of steel fibres, Group D, Group G and Group C, were prepared for tensile test to investigate their mechanical properties.

2.2. Tensile test and measurement of corrosion

The Instron 4302 with a load capacity of 10 kN was used for the tensile test. To make it possible to obtain a stable grip, both hooked ends (5 mm in length at either end) of every steel fibre of the three groups were cut off. Then the middle straight fibre with 50 mm in total length was preserved for testing. In this test, each sample was wrapped by paper mesh to protect it from premature breakage caused by grip teeth and to sustain a uniform load. The gap between the two grips was adjusted to 1.5 mm and the ramp rate was set at 0.3 mm/min. The real-time load and extension were collected by data taker at a rate of two readings per second.

In order to measure the corrosion degree of the corroded steel fibres after tensile test, the two pieces of each fractured fibre were cleaned to remove the corrosion using fine sand paper and brush. Then, the weight was measured by a scale and their corrosion degree was assessed using weight loss rate.

3. Results and discussion

3.1. Visual inspection

As can be seen in Fig. 2, the controls of Group C had a smooth surface, while the surface appearance of the corroded samples of Group D presents a correlation with the period of drying–wetting cycles. A rough layer of hard corrosion products with a reddish brown colour appears on the sample surface exposed to cycles for 5 and 10 days. When exposed for 20–60 days, the colour of the surface gradually deepen to dark reddish brown which is the result of increased mass of attached corrosion products. Meanwhile, many raised spots were distributed on the surface. In terms of the samples experienced for 50 and 60 days, the corrosion layer with flaky and blocky corrosion became thicker, and easy to drop off. After surface cleaning, all of the corroded samples displayed