Cement and Concrete Composites 89 (2018) 216–229

Contents lists available at ScienceDirect

Cement and Concrete Composites

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

Electrical resistivity measurements in steel fibre reinforced cementitious materials

Carlos G. Berrocal [a, c, *], Karla Hornbostel [b, d], Mette R. Geiker [b], Ingemar Löfgren [a, c], Karin Lundgren [a], Dimitrios G. Bekas [e]

[a] Chalmers University of Technology, Division of Structural Engineering, Sweden
[b] Norwegian University of Science and Technology, Department of Structural Engineering, Norway
[c] Thomas Concrete Group AB, Sweden
[d] Norwegian Public Roads Administration, Norway
[e] University of Ioannina, Department of Materials Science and Engineering, Greece

ARTICLE INFO

Article history:
Received 22 February 2017
Received in revised form
6 February 2018
Accepted 18 March 2018
Available online 19 March 2018

Keywords:
Steel fibre reinforcement
Cement-based materials
Dielectric properties
Impedance spectroscopy

ABSTRACT

This paper reports results from experiments aimed at better understanding the influence of fibre dosage and fibre geometry on the AC frequency needed to determine the DC resistivity of cementitious materials containing steel fibres. Impedance spectroscopy and DC galvanodynamic measurements were performed on mortar prisms with varying fibre reinforcement to determine the matrix resistivity (related to ionic current within the pore solution) and composite resistivity (accounting for both ionic current and electronic current through the fibres). The results showed that adding steel fibres did not significantly affect the DC nor the AC matrix resistivity of the mortar prisms. However, the steel fibres yielded a drastic reduction of the frequency associated to the AC matrix resistivity from ~1 kHz in plain mortar to ~1 Hz in steel fibre reinforced mortar. These findings revealed the need to adequately adjust the frequency in AC resistivity measurements of steel fibre reinforced cementitious materials.

1. Introduction

Fibre reinforcement has been successfully used to replace conventional reinforcement in various applications such as industrial floors and slabs on grade for crack control purposes, in precast tunnel lining segments to withstand the loads arising during the construction phase or as sprayed concrete for rock strengthening [1–3], with steel fibres being the most widely used fibre type. It has been shown that, in combination with traditional reinforcing bars, fibre reinforcement can provide crack control mechanisms that effectively control and reduce crack widths [4–6]. Consequently, using fibres could be beneficial also in other civil engineering structures to meet the crack width requirements specified in current structural codes [7,8]. Moreover, by limiting the crack width and changing the internal crack morphology, fibres have been found to decrease the permeation of cracked concrete and increase its self-healing capacity [9–12]. Therefore, fibre reinforcement could reduce the ingress of moisture and other detrimental agents into cracked concrete, e.g. Cl^-, and thus potentially delay initiation of reinforcement corrosion in structures exposed to chloride environments [13,14].

The resistivity of a material describes its ability to withstand the transfer of charge, which in plain concrete occurs as a current flow of electrically charged ions dissolved in the pore solution. Consequently, the resistivity of concrete can be used to indicatively describe the resistance to chloride ingress [15,16] and the current flow between the anode and the cathode in reinforcement macro-cell corrosion [17,18]. For most exposure conditions, a correlation is observed whereby the corrosion rate in the reinforcement increases as the resistivity of the concrete decreases and, although resistivity alone may not be sufficient to assess the corrosion rate of reinforcement in concrete, as shown by the large scatter found in the literature [19], the resistivity of the concrete may still provide valuable information regarding the durability of the structure.

Over the past years, several studies investigating the durability of steel fibre reinforced concrete (SFRC) have reported that the addition of steel fibres to the concrete resulted in a significant decrease of the electrical resistivity when measured under

* Corresponding author. Chalmers University of Technology, Division of Structural Engineering, Göteborg SE-41296, Sweden.
E-mail address: carlos.gil@chalmers.se (C.G. Berrocal).

https://doi.org/10.1016/j.cemconcomp.2018.03.015
0958-9465/

alternating current (AC) at different fixed frequencies [13,20–24]. Contrary to what it could be anticipated, experimental investigations on the influence of steel fibres on corrosion of conventional reinforcement revealed that in addition to a certain delay of corrosion initiation [13,14,25], the corrosion rate of reinforcement, measured using polarization techniques, was not affected by the incorporation of steel fibres [25–28]. The latter observation could be explained by the short length and disperse nature of the fibres throughout the concrete matrix, which would require the existence of an unrealistically high electric field to enable current conduction through them, as experimentally shown by Solgaard et al. [29].

The apparent contradiction among reported results of resistivity and corrosion rates in SFRC may arise from the measurement technique commonly used to assess the resistivity. AC measurements are generally preferred to assess the resistivity of cementitious materials in order to avoid errors induced by polarization of the electrodes or variation of the properties over time due to ion migration [30]. However, corrosion is an electrochemical process involving direct current (DC) and thus, the relevant parameter that needs to be assessed is the DC resistivity. For plain cementitious materials with high moisture contents, it has been shown that AC measurements at frequencies in the range of 100 Hz to 10 kHz are suitable to accurately assess the DC electric resistivity [31]. However, in a recent investigation [32], it was observed that steel fibres significantly reduced the AC resistivity of concrete when measured under an excitation frequency of only 126 Hz. This finding reveals that the frequency range considered suitable to determine the resistivity of plain cementitious materials might not be applicable to cement-based materials incorporating steel fibres.

Electrochemical Impedance Spectroscopy (EIS) is a technique used to measure the impedance of a system over a range of frequencies. EIS has been extensively used in the past to study the hardening process of cement as well as the dielectric properties of hardened cement-based materials [33–37]. In a Nyquist plot, ($-Z_{Im}$ vs Z_{Re}), the impedance spectrum of plain cementitious materials is characterized by a single arc describing the material behaviour (material arc) and a spurious arc occurring at lower frequencies ascribed to polarization effects at the sample-electrode interface (electrode arc) [38], see Fig. 1. The value of the real impedance axis at the cusp between both arcs is regarded as the electric resistivity of the material, which is comparable to the resistivity measured under DC.

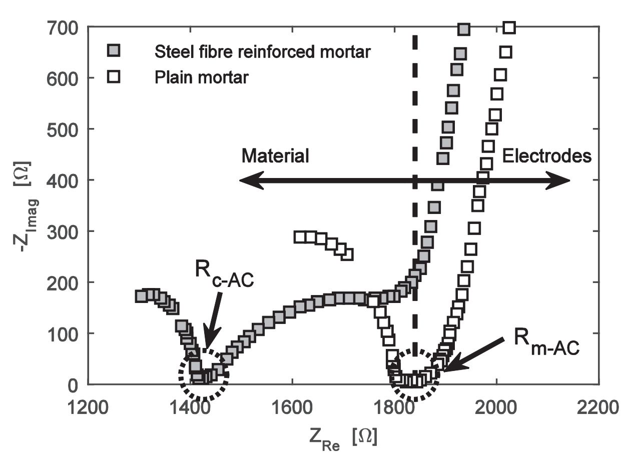

Fig. 1. Impedance spectra for a plain mortar prism and a 0.5% vol. short steel fibre reinforced mortar prism, at 28 days of hydration. Indicated are the AC matrix resistivity, $R_{m\text{-}AC}$, related to ionic current within the pore solution, and the composite resistivity, $R_{c\text{-}AC}$, accounting for both the ionic flow and the electronic current through the fibres.

The incorporation of conductive fibres, e.g. steel or carbon fibres, into the matrix of a cementitious material at fibre dosages below the percolation threshold results in a notable change of the impedance spectrum, as reported in several studies [39–43]. When impedance data is presented in a Nyquist plot, the most apparent change attributable to the addition of conductive fibres is a subdivision of the material arc into two arcs (see Fig. 1). This feature, sometimes referred to as 'dual-arc' [39], reveals that cementitious materials incorporating conductive fibres possess two characteristic points, the matrix resistance and the composite resistance, both of which describe the behaviour of the material at different frequency ranges. The matrix resistance, $R_{m\text{-}AC}$, represents the resistance to ionic current through the pore solution acting as electrolyte, which is the relevant parameter associated to the durability of the material (comparable to DC resistance, $R_{m\text{-}DC}$) and corresponds to the junction between the middle material arc and the rightmost spur resulting from polarization effects at the matrix-electrode interface. The composite resistance, $R_{c\text{-}AC}$, occurring at higher frequencies, corresponds to the cusp between the two material arcs and accounts for the combined transfer of ionic current through the electrolyte and electronic current through the conductive fibres [42]. Note that the subscripts $-_{AC}$ and $-_{DC}$ will be consistently added hereafter to differentiate between measurements carried out under AC fields and under DC fields.

Most of the existing work involving EIS of cementitious materials containing conductive fibres aims at explaining the origin of dual-arc effect, which has been attributed to the high impedance of the passive layer formed on the surface of the steel fibres [39,42]. At low frequencies, the passive layer insulates the fibres whereas it becomes short-circuited at high frequencies thereby allowing current to flow through the fibres. The effect of varying the fibre length on the impedance of cementitious materials was investigated in Ref. [41], where a series of experiments combining EIS and four point DC measurements showed that the AC matrix resistivity of cementitious materials containing conductive fibres was in good agreement with the resistivity measured under DC. In a more recent study by Suryanto et al. [44], the authors showed that the mid-frequency arc of an engineered cementitious composite containing polyvinyl alcohol and steel fibres occurred at lower frequencies for increasing steel fibre contents. However, detailed information about the variation of the impedance response of cementitious materials due to the addition of conductive fibres in terms of the excitation frequency is very scarce and, particularly, the frequency needed to determine the AC matrix resistivity of cementitious materials with conductive fibres has not yet been specifically investigated.

In the present paper, EIS was employed to study the influence of the fibre length, fibre diameter and fibre dosage on the impedance response of specimens made of steel fibre reinforced mortar (SFRM). Complementary four-point DC galvanodynamic measurements were performed to determine the resistivity of the specimens under DC, which is the parameter indicative of the material durability. The results were combined to evaluate the frequency range needed to assess the AC matrix resistivity of steel fibre reinforced cement-based materials. Additionally, the impedance results were used to investigate the effect of the different steel fibre reinforcement features on the dielectric properties of SFRM, which might be of interest for a number of non-structural applications such as electromagnetic shielding or self-monitoring structures [45]. It should be noted that this investigation is limited to cases where fibres do not form a continuous electric path inside the matrix, i.e. where the fibre dosage is below the percolation threshold and the length of the fibres is shorter than the electrode separation.