Monitoring chloride-induced corrosion of carbon steel tendons in concrete using a multi-electrode system

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HIGHLIGHTS

- A novel multi-reference-electrode (MuRE) was proposed and studied.
- Nickel and stainless steel were the more stable metals for the reference electrode.
- The MuRE is able to detect and locate the chloride-induced corrosion.
- The proper length of each wire is influenced by the cover and the resistivity.
- The maximum allowable length/cover ratio to detect the localized corrosion is 50.

ARTICLE INFO

ABSTRACT

To monitor real-time the occurrence of localized corrosion in reinforced concrete structures a novel multi-reference electrode is proposed, consisting of a series of metallic wires placed head-to-tail able to measure the corrosion potential of a carbon steel tendon or a rebar network. Available embeddable or portable reference electrodes give the local potential of the rebar; with the new system, a single potential reading can give the corrosion condition of a wide area. Copper, nickel and stainless steel were tested as candidate metallic materials: laboratory tests allow verifying their stability in alkaline condition. The ability to detect and locale corrosion was demonstrated on mortar and grout specimens, cast to simulate chloride-induced corrosion on post-tensioned tendons.

1. Introduction

Carbon steel reinforcements and tendons are in passive condition in pristine concrete, due to the high alkalinity of the water pore solution: a thin layer of iron oxides covers the steel surface, reducing corrosion rate to practically negligible values, lower than 1 µm/y [1]. Concrete carbonation and chlorides penetration are the two main causes of corrosion initiation. In the first case, carbon dioxide penetrating into concrete from the atmosphere reacts with the alkaline compounds of the pore solution, promoting a reduction of pH to almost neutrality: carbon steel passivity is destroyed and corrosion propagates on all rebar surface in contact with the neutralized concrete, provided the presence of water and oxygen.

Corrosion rate is in the range of tens of µm/y, up to 100 µm/y [1]. Chloride-induced corrosion initiates once a critical chloride threshold is reached at the rebar level: the passivity is locally destroyed and corrosion propagates at a very high corrosion rate, typically in the range of 1 mm/y [1]. In the presence of high strength steels, such as tendons for pre-stressed or post-tensioned structures, brittle fracture due to hydrogen embrittlement may occur, promoting possible catastrophic collapse of the structure. In fact, once a localized corrosion attack occurs, acid condition sets up at the pit tip, producing hydrogen atoms and promoting hydrogen embrittlement on susceptible steels [1–3].

Prevention of corrosion begins in the design phase, accordingly materials and prevention techniques are selected, concrete is properly cast and cured. International standard EN 206 [4] and Eurocode 2 [5] suggest W/C ratio, concrete cover, cement type and curing time to achieve the designed service life according to the environmental aggressiveness. As regard pre-stressed or

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post-tensioned concrete structures, from 90's more attention was paid in establishing technical specifications, selecting materials, for instance the use of drawing steel instead of quenched and tempered steels, defining design strategies to avoid the risk of brittle fracture [2–5].

In very severe working condition, if a very long service life is required, additional protection techniques may be used, such as corrosion resistant bars, concrete coating, corrosion inhibitors, cathodic protection or prevention [6–8]. Prevention of corrosion continues throughout the entire service life of the structure with scheduled inspection, maintenance and above all monitoring [2–5].

The latter is of paramount importance for the safety of a reinforced concrete structure: visual inspection, chloride content determination, carbonation measurements, acoustic emission, ultrasonic and magnetic methods, resistivity measurements, are all useful to define the concrete quality, its pollution and presence of cracks [9–15].

The measurement of the free corrosion potential is essential to monitor the corrosion process of reinforcing steel in concrete [7,16–18]. Rebar potential is measured with respect a portable or embedded reference electrode by means of a high impedance voltmeter (>10 MΩ). The most used portable electrode is the copper/copper sulphate reference electrode (CSE), consisting in a copper rod immersed in a saturated copper sulphate solution. It is typically used in potential mapping, the only recognized and standardizes non-destructive technique for a direct assessment of reinforcement corrosion [7,18–19]. American standard ASTM C876 [18] describes the procedure to perform a potential mapping and it gives a guideline to interpret the readings. The measured potential corresponds to the equipotential surface intercepted by the local reference electrode, place on the external surface of the concrete, or embedded into it. The standard states: the probability of corrosion is very low if rebar potential is more noble than −200 mV CSE, whereas the probability of corrosion is very high if the rebar free corrosion potential is more negative than −350 mV CSE [18]. The experience with potential mapping of the last 20 years has been included in a RILEM recommendation [19], confirming the reported thresholds.

Various solid reference sensors embeddable in concrete have been developed [20–28]. They are very useful for long-term corrosion monitoring of concrete structures in freely corroding condition as well as in the presence of cathodic protection [20–21]. Moreover, the use of remote monitoring requires reference electrode with an extended stability [22–23]. The embedded electrodes must obey some conditions: inert to chemical and thermal changes in concrete, not polarizable, long-term stability and cost effective. The long-term stability of reference electrodes is a critical issue [16,20,24]. Among embedded reference electrode the most studied are manganese dioxide (MnO_2), also used as pH and humidity sensors, and titanium rods activated with mixed-metal oxide [21,22,25–28]. MnO_2 sensor seems to be the most stable and reliable potential sensor electrode for concrete structures. However, the long-term stability of the embedded MnO_2 sensor in concrete is essential for online monitoring applications [21,22].

Even if local reference electrodes are very stable and reliable, they measure a local value corresponding to the intercepted equipotential surface. Then, to monitor the corrosion condition of a wide reinforced concrete structures, or to control the initiation of corrosion on long carbon steel tendons, several local reference electrodes should be installed, or expensive potential mapping should be performed [29].

To cope this problem, a new wire-type reference electrode was proposed: the wire can be placed along the rebar network or along the tendon, and a single potential reading can give the corrosion condition of a wide surface area. Firstly, laboratory tests were performed to understand the meaning and the reliability of the

potential reading performed by a wire reference electrode; results are reported in [30]. In this paper, a new conceived reference electrode for pitting corrosion monitoring is presented; it consists of a series of Multiple wire-type Reference Electrodes (named MuRE) placed head-to-tail to cover the whole rebar network, or the whole length of a carbon steel tendon. Each reference electrode has a proper active length in relation to the geometry of the structure and the concrete or grout resistivity. Aim of the paper is to determine the stability of the metallic materials selected as reference electrode in alkaline condition and to define the proper length of a single reference electrode wire in order to realize a MuRE system suitable for detecting the occurrence of chloride-induced corrosion on long carbon steel tendons, especially those encased in polymeric ducts.

2. Experimental

Four metallic wires, 0.8 mm in diameter, were tested as reference electrodes: copper, nickel, austenitic stainless steel UNS S31600 and oxidized austenitic stainless steel. Chemical composition of the metal wires is reported in Table 1. Oxidation of stainless steel was achieved in a furnace at 800 °C for 20 min.

Stability in alkaline environment and ability to detect chloride-induced corrosion were tested.

2.1. Stability in alkaline environment

Stability of the four selected metallic materials was tested in two slabs ($200 \times 100 \times 50$ mm), cast with a commercial grout using Ordinary Portland Cement CEM II 42.5 R and W/C ratio 0.3, to reduce the risk of bleeding. A commercial super-plasticizer was added in dosage 4% by cement weight to produce a flowable, pumpable, non-shrinkable, non-segregating grout. The super-plasticizer was a chloride-free powder admixture, for specific use in the production of grouts for post-tensioned cables in prestressed concrete structures.

For each metal, a 300 mm long wire was placed in the specimen. Metal potential was measured with an external CSE reference electrode placed on the top of the specimen by means of a wet sponge (Fig. 1). Potential was detected for the first 5 days with a data logger (frequency 0.1 Hz), then with manual periodical measurement for next three months.

2.2. Chloride-induced corrosion detection

Carbon steel tendons encased in grouted plastic ducts were simulated with a polymeric cylindrical cell, 50 mm in diameter and 2500 mm in length, containing a carbon steel rebar, 10 mm in diameter. Cover, D, was 20 mm (Fig. 2).

For each metallic material, three multi-reference-electrodes (MuREs) were prepared with different L/D ratio (5, 15 and 40 respectively), where L is the length of one active wire and D is the grout cover. Being the polymeric cell 2500 mm long and the cover 20 mm thick, a single wire of the three multi reference electrodes is 100 mm, 300 mm and 800 mm long, respectively. Accordingly, 26, 9 and 3 electrodes has been installed for the MuRE with L/D ratio 5, 15 and 40, respectively. A linear continuous

Table 1
Chemical composition of selected metallic materials.

	Si	Ti	Cr	Mn	Fe	Ni	Cu	Mo
Copper (Cu)	–	–	–	–	–	–	100.00	–
Nickel (Ni)	1.17	3.76	–	0.61	–	94.95	–	–
AISI 316 (SS)	1.13	–	19.05	1.72	62.22	12.20	–	3.67