Moisture and corrosion monitoring in concrete: On site electrochemistry vs. Evanescent Field Dielectrometry

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Abstract

In the field of historic concrete, the most deleterious decay mechanism is rebars corrosion. Therefore, it is crucial to be able to detect corrosion, or conditions necessary to generate corrosion, such as moisture content. As the main non-destructive onsite diagnosis tools for reinforced concrete, which are based on electrochemistry, can be disturbed either by intrinsic (salts content) or extrinsic parameters (environmental conditions) it appeared interesting to explore alternative methods. In that aim for a few years, a new technique, based on Evanescent Field Dielectrometry (SUSI©), is being developed to monitor water and salt presence in concrete.
The aim of this study was to compare the performances of the SUSI© system to that of standard electrochemical techniques (resistivity, half-cell potential and linear polarization resistance, performed with a Gecor10©, and a Wenner probe), for the detection of the risk of corrosion in concrete exhibiting different types of pollution. In that purpose, both types of techniques were tested on reinforced concrete slabs made with the same concrete, and either artificially carbonated, or chloride polluted (introduced in the mix or by wet-dry cycles). Tests were performed outdoors, in similar environmental conditions for all the slabs.
The results confirmed the added value of the EFD technique, as it was able to produce critical information on corrosion risk, by producing data both on moisture and salts contents.

1. Introduction

Evaluation of the corrosion risk and corrosion activity constitutes an essential part of the diagnosis of reinforced concrete buildings as it is the main and most deleterious decay phenomenon observed. If onsite electrochemical techniques to assess resistivity, half-cell potential or LPR have shown their efficiency for such diagnosis on reinforced concrete, several limitations were evidenced, for example in the case of chloride pollution. On another hand, in the field of wall-painting, a new technique named SUSI©, dedicated to water and salt content monitoring, based on Evanescent Field Dielectrometry, was initiated in Italy (1). For a few years, the technique is being developed to be applied to concrete. A first study comparing standard resistivity measurements and the SUSI© system revealed the added value of SUSI© in evaluating distinctively the presence of water and salts (2). The purpose of the tests presented in this paper was to try to correlate moisture and salts presence with corrosion activity, and therefore to try to reach a more complete level of diagnosis.

2. Materials and methods

2.1 Specimen

Four slabs (60x60x7cm) were cast in 2007, using a CEM I concrete, with a mix designed in accordance with the EN1766 (Table 1 and Figure 1). Each slab was reinforced with 4 smoothed carbon steel bars (Fe24), 1 cm in diameter, with a concrete cover of 2 cm on one side and 4cm on the other. The slabs were demoulded 24h after casting and were submitted to a 28 days cure in water.
One slab (T) was kept sound and considered as a reference. In the second slab (G), 5% of NaCl (by weight of cement) were introduced in the mix. In the third slab (I), an external chloride pollution was simulated by wet-dry cycles in a salted solution (NaCl, 35 g/l) until an 0.4% chloride content by weight of cement (corresponding to the admitted threshold for chloride-induced-corrosion initiation (3)(4)) was reached at the rebars level, with a decreasing gradient of concentration from the surface in contact with the salted solution (0-10mm : 3.96% Cl^- by WC; 14-24mm : 1.96%; 29-39mm : 0.38%). Finally, the fourth slab (C), was artificially carbonated (preconditioning : 14 days at 50°C; followed by 7 days at 20°C, 60%RH ; artificial carbonation : 20 months at 20°C, 50%RH and 1% CO2). Then the 4 slabs were exposed to natural ageing in a yard of the Parisian suburb. After a little more than 10 years of exposure, Slab G (chlorides introduced in the mix) exhibits superficial corrosion spots and cracking along one of the rebars and slab C in winter appears to be the most humid and shows biological covering.

Table 1. Mix design

Cement	Holcim© CEM I 52.5 N CE CP2 NF
Cement content	275 kg/m^3
Aggregates	Palvadeau - Max diameter = 1.6 cm
Water/Cement ratio	0.7

2.2 Measuring techniques

2.2.1 Resistivity mapping

Two techniques were used to perform the resistivity measurements: the disc and the Wenner one (5) (6).
The disc method consists in measuring the resistance (R=ohmic drop) between a small diameter disc (D = disc diameter) placed on the concrete surface and a large counter-electrode (a rebar on which a connection must be realized). Then the resistivity (ρ) of the concrete can be derived from equation 1 (5). In this study, the disc-method measurements were performed with a Gecor10©, equipped with a 2cm in diameter stainless steel disc, with in its centre a copper/copper-sulphate reference electrode, and the connection was realized directly to the visible part of one rebar.

$$R = \frac{\rho}{2D} \qquad (1)$$

A Wenner or 4-points probe is generally composed of 4 equally spaced electrodes. The technique consists in inducing a current through the two outer electrodes, and to measure the resulting potential drop with the 2 inner electrodes. From the resulting resistance (R), the resistivity (ρ) can be calculated according to equation 2 (6), "a" being the electrode spacing. In this study, the Wenner probe used was a Resipod©, with a 5cm spacing.

$$\rho = 2\Pi aR \qquad (2)$$

Results of resistivity measurements were interpreted according to the RILEM recommendation (6) (Table 2).

Table 2. Resistivity ranges and associated corrosion risks, according to the RILEM recommendation (6).

Resistivity (kΩ.cm)	Corrosion risk
>100	Negligible
50-100	low
10-50	Moderate
<10	High

2.2.2 Half-cell potential mapping

Half-cell potential measurements were carried out using a Gecor10©, equipped with a copper-copper sulphate reference electrode, according to the RILEM recommendation (7).

2.2.3 Linear polarization resistance mapping

Corrosion current density was evaluated according to the RILEM recommendation (8), with a Gecor10©, using the Linear Polarisation Resistance technique. The device is composed of a 3 electrodes set-up : a working electrode which is the reinforcing steel; a copper/copper sulphate reference electrode; and a stainless steel disc as counter electrode. The LPR measurements were performed with a 100s pulse duration and with a confinement assessed by a modulated guard ring (polarised zone : 65 mm rebar length below the sensor), the ohmic drop being taken into account in the first step of an automated sequence of measurements. The electrical conductivity was provided by a wet sponge.

Results of LPR measurements were interpreted according to the RILEM recommendation (8) (Table 3).

Table 3. Corrosion levels thresholds recommended by the RILEM (8).

Icorr (µA/ cm^2)	Corrosion level
Icorr > 1	High
0.5 < Icorr < 1	Moderate
0.1< Icorr < 0.5	Low
Icorr < 0.1	Negligible

2.2.4 SUSI©

As water is a strongly polar material, when concrete is weakly polar, the contrast between the permittivity of water (ε'~80) and that of concrete (ε' ~ 5 to 15), can be derived from dielectric spectroscopy. The SUSI© system was designed to achieve such measurements. It is composed of a resonant sensor operating in the microwave domain (1-1.5 GHz), a scalar network analyzer and a computer equipped with a dedicated numerical code. The outputs considered by the SUSI© system are a resonance frequency in the material considered (fr), from which a frequency shift (Δfr: between the resonance frequency in the material fr and that in the air f0) is calculated according to equation 3 (with f0=1362.79 MHz for the actual SUSI probe); and a resonance line-width (Lw;), respectively related to the average dielectric constant of the material monitored (ε'), and to the dielectric losses (ε'').

$$\Delta \mathrm{fr} = \frac{\mathrm{f0} - \mathrm{fr}}{\mathrm{f0}} \qquad (3)$$

Through an inversion procedure (9), the SUSI© system leads to two secondary parameters: MC (moisture content, directly proportional to the frequency shift Δfr) and SI (salinity index, inversely related to the quality factor of the probe (Q), or to the resonance line width Lw). Thus, the moisture content in the considered material can be related to a function (Ψ) of the dielectric constant and loss factor according to simplified equations 4 and 5 (1), when the frequency shift is related to the Ψ function according to equation 6 (α and β being constants obtained by dielectric measurements at two moisture contents: dry and saturated states (8)).

$$\Psi = \frac{\varepsilon' - 1}{\varepsilon''} \qquad (4)$$

$$\mathrm{MC}(\Psi) = \frac{1}{\Psi} - \frac{1}{\Psi 0} \qquad (5)$$

$$\Delta \mathrm{fr} = \alpha + \beta \Psi \qquad (6)$$

Concerning the salt content, it is approached by a so called "salinity index", inversely related to the quality factor of the probe (Equation 7), or to the resonance line width. This index is strongly dependent on the conductivity of the material but weakly dependent on the real part of the permittivity.

$$\mathrm{SI} = \frac{\mathrm{fr f0}}{2 \Delta \mathrm{fr}^2} \Delta\left(\frac{1}{\mathrm{Q}}\right) \qquad (7)$$

With the actual probe, the region considered by the measurement probe is approximately semispherical, with a radius of 2cm; the measurable moisture content is ranging between 0 and 20% (water mass fraction) and the range of the usual salinity index is varying between 1 (corresponding to an electrical conductivity of about 0.4Sm-1) and 10. In that range of moisture content, it has been shown (9), that the relation between Δfr and MC is almost linear, and that the ionic conductivity has a negligible influence on it. Considering the salinity index, it has been demonstrated (1) that it is

almost independent on the moisture content as far as the moisture content is higher than 3% (moisture content necessary to find soluble salts in solution).
The results of mass moisture content and salinity index presented in this paper were adjusted after calibration on the concrete chosen for the study.

2.3 Experimental protocol

Tests were performed outdoors, after a long period of rain in January 2018, in a yard of the Parisian suburb (France), with a temperature of 12.4°C and a relative humidity of 63.6°C. Measurements were realized on the cast face of the slabs, with a concrete cover of 4cm. For each slab, mappings were performed with, depending on the technique used, distinct amounts of measurements points (Figure 1): 9 out of the rebars for the 2 resistivity and the SUSI techniques, 3 per rebar for the LPR (12 measurements), and 21 for the half-cell potential (both on and out of the rebars).
For almost all the techniques only one measurement on each point was considered after checking the absence of deviation. Only for the Wenner technique, the results presented in this paper correspond to the average of 3 measurements.

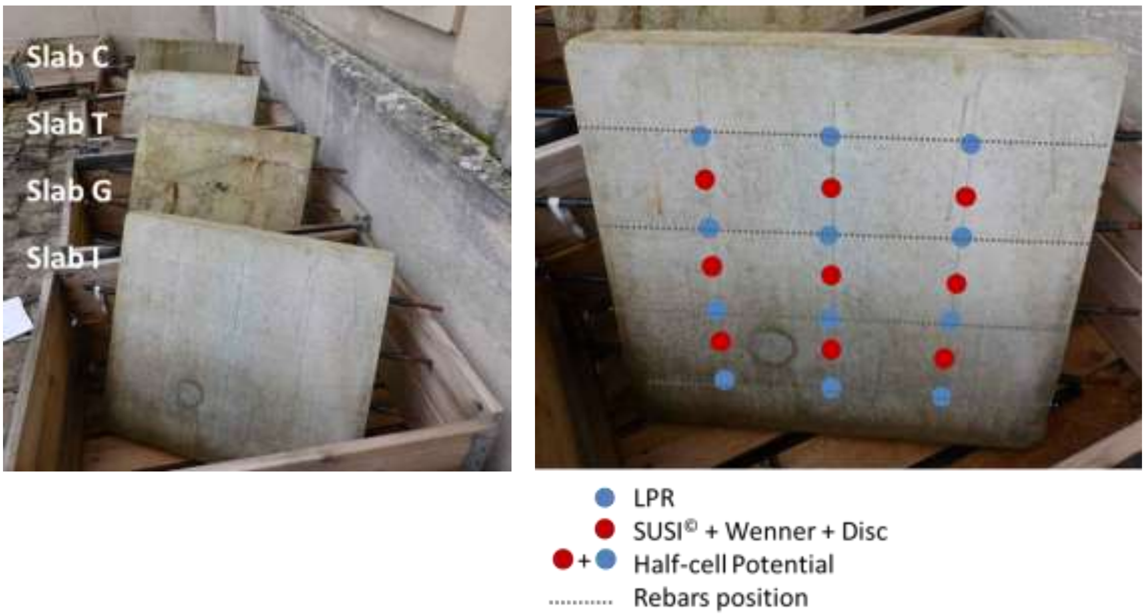

Figure 1. Four specimens considered and implementation of the testing protocol.

3. Results and discussion

First of all whatever the technique, if mapping was performed, for comparison purpose between the techniques, only average values per slab will be presented in this paper.

Considering the resistivity measurements (Figure 2), it is first to be noted that depending on the device used, noticeable differences were observed specially for the carbonated slab (C), the slab with external chloride pollution (I) and the reference slab (T). Similar discrepancies were observed in a previous study (2) and were attributed to the fact that the volume concerned by the measurements differs with both techniques.

Thus the spacing of the electrodes of the Wenner probe being of 5cm, the depth concerned by the measurement might be higher (10) than that of the disc method. Considering the RILEM recommendations (6), whatever the technique, the corrosion risk was high for slab G (internal chloride pollution); it was moderate for slab I (external chloride pollution) and low for slab C (carbonated). For the reference slab (T), the conclusion differs from one technique to another (moderate for the Wenner method, low for the disc method).

Dealing with half-cell potential measurements (Figure 3), quite homogeneous values were obtained on the 4 slabs, with only small gradients, ranging between 32mV for slab C, 37mV for slab G, 44mV for slab T and 57mV for slab I. Considering the average values, potentials measured on slab G (average G = -571mV) were clearly lower than that of slabs C (average C= -455mV) and slab I (average I = -405mV), which were quite similar. The lowest values being measured on the reference slab (average T =-72mV).

By combining the resistivity and potential mappings, the conclusions were evident for slab G, with the higher corrosion risk; and for the reference slab T, with a negligible risk of corrosion. For slab I and slab C, the evaluation was less contrasted, with a moderate risk for slab I, despite a noticeable chloride pollution; and for slab C with a low corrosion risk considering resistivity, and a little higher one considering the potential mapping.
In coherence with this evaluation of the corrosion risk, the average corrosion current (Figure 4) evaluated for slab G was the highest (1.275µA/cm²) and indicative of a high corrosion level according to the RILEM recommendation (8). For slab C (0.279µA/cm²) and slab I (0.328µA/cm²), the corrosion current derived from the LPR measurements were indicative of a low level of corrosion, with nevertheless a surprisingly high value for the carbonated concrete, despite a quite high resistivity, and a quite low value for slab I considering its chloride pollution. From the moisture contents obtained with the SUSI© system (Figure 5), derives a piece of explanation concerning the behaviour of the carbonated slab C; as it appears to be the most humid, which was confirmed by the visual observations. Finally, if the salinity index (Figure 6), clearly evidenced a higher salt content in slab G, explaining its lowest resistivity; it also showed that the values obtained for slab I were not that much different from that of slabs C and T, which could mean that the chloride content in slab I is not that high. It could be interesting to measure the chloride contents in slab I after 10 years of exposure to natural ageing in order to evaluate possible lixiviation or binding processes.

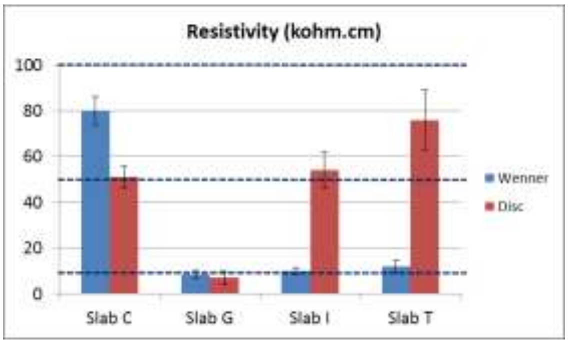

Figure 2. Average resistivity. The corrosion risk thresholds recommended by the RILEM (6) appear in blue-dotted-lines

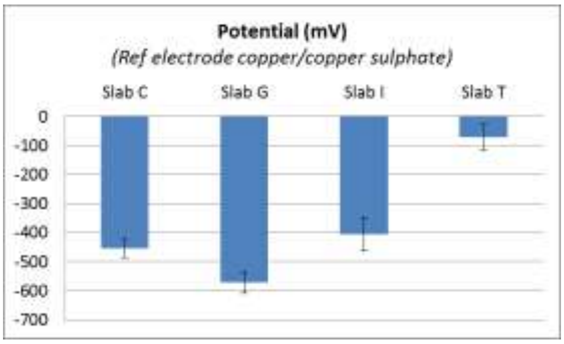

Figure 3. Average half-cell potential values.

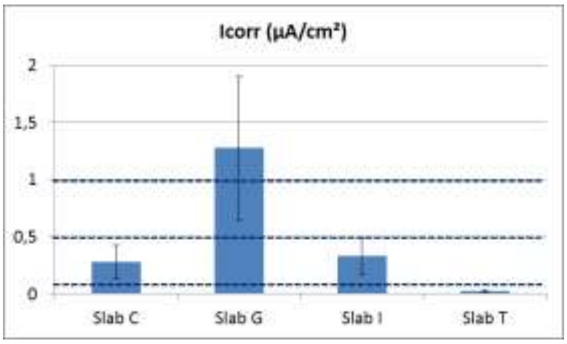

Figure 4. Average corrosion current density values per slab. The corrosion level thresholds recommended by the RILEM (8) appear in blue-dotted-lines

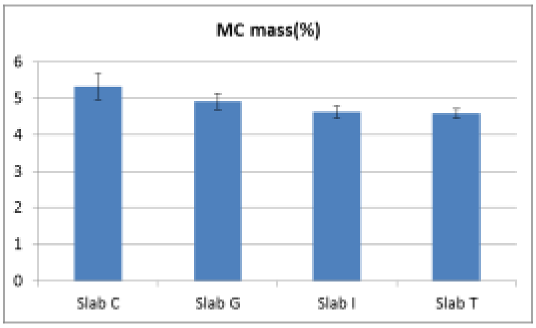

Figure 5. Average mass moisture content per slab.

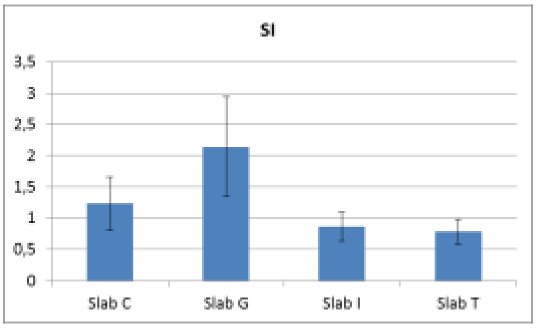

Figure 6. Average salinity index per slab.

3. Conclusions

In this study, in the aim of increasing the accuracy of the diagnosis of the corrosion of rebars embedded in concrete, a new technique, SUSI© based on Evanescent Field Dielectrometry was compared to the well-known panel of electrochemical methods (resistivity, half-cell potential and LPR). The specimen considered were 4 reinforced concrete slabs, respectively artificially carbonated (slab C); chloride contaminated by an external (slab I) or an internal source (slab G); or sound (slab T). Tests were carried out in winter 2018, after 10 years of exposure to natural ageing in the French Parisian suburb. The electrochemical measurements clearly evidenced the highest corrosion activity for the slab G with 5% of NaCl (by WC) introduced in the mix, and which was affected by rust stains and cracking; and the lowest corrosion activity corresponding to the reference slab T. For the carbonated slab, the resistivity and potential mappings were leading to quite distinct conclusions, but noticeable corrosion current densities were observed. The measurements performed with the SUSI© system could explain this behaviour by evidencing the highest moisture content in the carbonated slab, which was confirmed by visual observations.
Finally, the salinity index evaluated with the SUSI© system, could explicate the lowest values of resistivity measured on slab G, but also the low corrosion activity for slab I, as the highest salinity index was obtained on slab G, when the salinity index of slab I was comparable to that of slabs C and T.
As a conclusion, the SUSI© system evidenced a clear added value and appears to be an interesting complementary tool to standard electrochemical measurements, in the assessment of corrosion activity in reinforced concrete structures. Further studies are

already scheduled to confirm these first results, for example in dryer conditions. New developments of the SUSI© system are also planned, with the creation of a second probe that could allow to investigate deeper zones, but also perform moisture content and salt profiles.

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