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# Monitoring of electrical properties of slag concrete during hydration phase using embedded resistivity sensors

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## Résumé

*Le travail présenté ici se déroule dans le cadre du projet ANR-DEMCOM, qui accorde une attention particulière aux ouvrages maritimes dont certaines zones se trouvent inaccessibles pour l'inspection. L'objectif de ce travail est d'utiliser des techniques d'évaluation non destructive (END) adaptés aux environnements agressifs, notamment le système « échelle » multi-électrodes basé sur des capteurs noyés permettant de suivre les profils de résistivité électrique, propriété du béton très sensible à la teneur en eau et en chlorures [1]. Le travail ci-dessous a pour but d'étudier la capacité de ces capteurs à évaluer la résistivité électrique, au jeune âge, de 3 formulations de béton : un béton formulé avec du CEM I et deux bétons avec 30% et 50% de laitier. Ces derniers ont été soumis à un suivi temporel en utilisant un résistivimètre programmable permettant d'enregistrer les profils de résistivité en fonction du temps et de la profondeur, dans le but d'analyser le comportement des 3 bétons et la modification de leur microstructure pendant leur hydratation. Les profils de résistivité obtenus tout au long de la période de cure ont mis en évidence l'effet du laitier sur les différences de cinétique d'hydratation et également sur les différences de composition de solution porale. Ce dernier point reste à investiguer dans le futur.*

## Abstract

*The work presented below takes place within the ANR-DEMCOM project, which pays particular attention to maritime structures, some areas of which are inaccessible for inspection. The objective of this work is to use non-destructive evaluation (NDE) techniques adapted to aggressive environments, in particular the embedded resistivity sensor in order to monitor electrical resistivity profiles, a property of concrete that is very sensitive to water and chloride content [1]. This article presents a study on the capacity of these sensors to evaluate the electrical resistivity of 3 formulations of concrete: a concrete formulated with CEM I and two concretes with 30% and 50% of slag. These latter were subjected to automatic monitoring using a programmable resistivity meter allowing to register resistivity profiles over time and depth in order to analyze the behavior of these 3 concretes, and the modification of their microstructure during the hydration phase. The resistivity profiles obtained throughout the curing period highlighted the effect of slag on the differences in the hydration kinetics as well as on the differences in the composition of poral solution. This latter will be further investigated in the future.*

**Keywords:** NDE, resistivity, slag, hydration

# 1. Introduction

The ANR-DEMCOM project deals with reinforced concrete (RC) structures exposed to marine environment. It aims to develop a new eco-design method to maximize the service life and to minimize the environmental impacts and costs of RC structures subjected to chloride ingress. The penetration of chlorides coming from sea water leads to the initiation of reinforcement corrosion, causing the long-term degradation of concrete structures. Several NDE techniques were developed in order to monitor the behavior of concrete exposed to aggressive environments [2], yet not all of them are adapted to offshore structures of which tidal zones are inaccessible for inspection. That is why, an embedded resistivity sensor was developed by Badr et al. [1] in order to determine water content profiles in concrete and to monitor wetting and drying cycles.

The principle of this embedded sensor is based on the evaluation of resistivity profiles over time and depth, a property of concrete that represents its ability to resist to the circulation of electric current. Numerous works in literature highlighted the sensitivity of electrical resistivity to hydric and ionic content, given that the flow of electric current is due to the diffusion of free electric charges carried by the cations and anions of the interstitial solution [3-5]. The Printed Circuit Board (PCB) sensor developed by Badr et al. [1] has a ladder shape consisting of a number of electrodes distributed along the z axis (representing the depth of the concrete structure), thus it proved its ability to estimate accurately resistivity gradients over the entire thickness of the structure and to study the gradient of the degree of saturation at different times of its drying cycle.

This paper presents an experimental campaign carried out using these embedded sensors in order to monitor the behavior of 3 concretes formulated with slag, a common mineral addition particularly added to concrete structures in marine areas, given its positive effect on the durability of concrete thanks to its micro-structure [6]. The paper starts with a presentation of the experimental campaign: the 3 formulations of concrete, the instruments used as well as the curing period. Then, the results of the monitoring are presented and discussed in order to conclude on the effect of slag on the behavior of concrete during its hydration phase.

## 2. Materials and methods

### 2.1. *Formulation of concretes*

Adding mineral additions to Portland cement can influence the products as well as the kinetics of its hydration. As mentioned above, blast furnace slag is commonly used in marine environments. When mixed with Portland cement, it reacts with calcium hydroxide (also known as Portlandite  $\text{Ca}(\text{OH})_2$ ) formed during the hydration phase and forms secondary hydrated calcium silicates. This pozzolanic reaction helps in decreasing, on one hand, the porosity and the critical pore diameter of concrete and increases, on the other hand, its mechanical resistance [6][7]. Moreover, the presence of slag modifies the chemical composition of the poral solution which causes the decreasing in its conductivity [10].

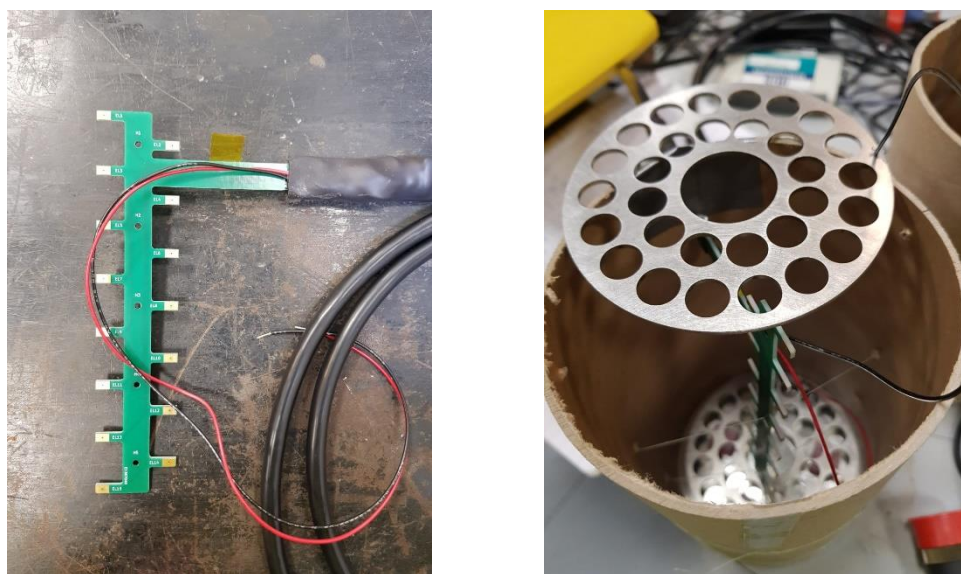
For this reason, our study is carried out on 3 formulations of concrete: a concrete formulated with 100% of CEM I and two other concretes formulated with 30% and 50% of slag, in order to study their behavior during the hydration phase and pozzolanic reactions. The concrete formulation is similar to that of Ben Fraj [7] and is presented in Table 1 below:

	<b>C100-0</b>	<b>C70-30</b>	<b>C50-50</b>
<b>Components (kg/m<sup>3</sup>)</b>	<b>0% slag</b>	<b>30% slag</b>	<b>50% slag</b>
Gravel, 4 – 12 mm (Boulonnais)	1041.7	1040.7	1038.8
Sand, 0 – 4 mm (Boulonnais)	910.3	909.3	907.6
CEM I 52,5 N - SR 5 CE PM-CP2 NF HTS (Lafarge)	302.5	211.8	151.3
Slag Ecocem	0	90.8	151.3
Superplasticizer MasterGlenium 201 (BASF)	2.94	3.68	3.53
Efficient water	151.3	169.4	166.4
water-to-cement ratio (W/C)	0.5	0.8	1.1

**Table 1:** Formulations of the 3 concretes

## 2.2. Methods and instruments

In this paper, we are interested in studying the influence of different rates of replacement of clinker by slag on the resistivity measurements of concrete at early age. Three cylindrical specimens with a diameter of 11cm and a height of 18cm were casted for each of the formulations above, yet one single specimen of each formulation is monitored. Each specimen was instrumented using a resistivity embedded sensor [1] with 15 electrodes distributed on both sides of the PCB. This latter was placed on the center of the specimen along the z axis, between two stainless steel grids well anchored in concrete serving for current injection when the measurements are performed in the Transmission mode [1]. Views of the sensor and an instrumented mould are presented in Figure 1.



**Figure 1:** Instrumentation of the specimens: (a) the PCB resistivity sensor, (b) instrumented mould

The PCB sensors are linked to the commercial resistivity meter, SYSCAL Junior Switch 72 from IRIS Instruments, with an acquisition system managing simultaneously up to 72 electrodes and injecting a very low frequency alternating current.

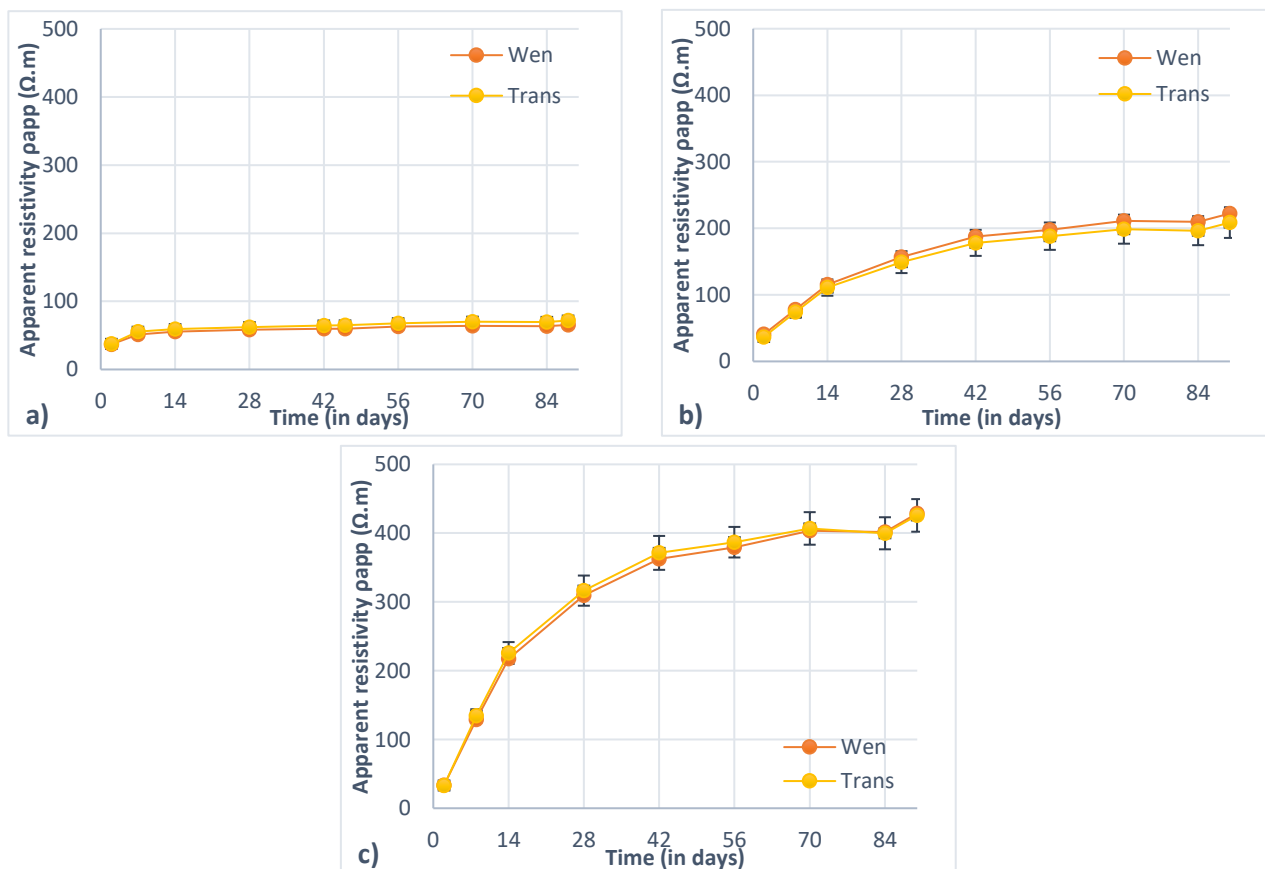
### 2.3. Experimental campaign

The three concrete specimens were subjected to an automatic monitoring using the SJ72 throughout their curing period. This latter consisted on placing the concrete specimens in a tray containing a small quantity of water, at a temperature of 20°C and a relative humidity of approximately 95%. These conditions were regularly controlled by a thermohygrometric probe along the curing period, which lasted for 3 months instead of 28 days given the presence of slag and the time that pozzolanic reactions take to be nearly achieved.

In order to obtain resistivity profiles over depth and time, most of the measurements are done according to the Transmission configuration (Trans): the resistivity meter injects an electrical current by the two stainless steel grids and measures the potential drops between pairs of consecutive electrodes on the same side of the sensor. Only one measurement based on the Wenner configuration (Wen) is done, by injecting a current and measuring the potential difference on 4 electrodes on one side of the sensor without using the grids [1].

## 3. Results and discussion

If  $T_c$  represents the casting time of the concrete specimens, then resistivity measurements begin at  $T_c + 2$  days and were retrieved for each specimen at different time intervals along its curing period. The graphs below present, for each specimen, the evolution of the apparent resistivity with respect to time for both configurations. For the Trans mode, the calculated value of the apparent resistivity represents the average of the 13 apparent resistivities measured along the  $z$  axis, and the error bars represent the corresponding standard deviations.

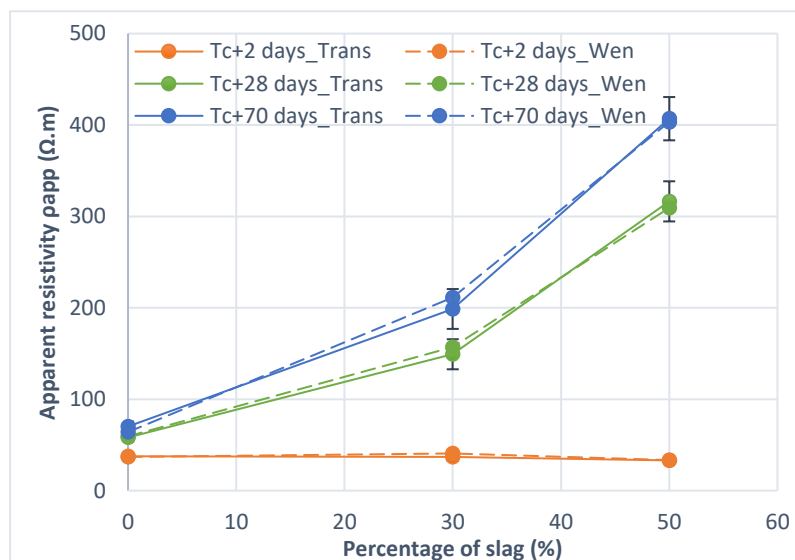


**Figure 2:** Evolution of the apparent resistivity calculated for both configurations with respect to time: (a) concrete with 0% slag, (b) concrete with 30% slag, (c) concrete with 50% slag

Figures 2-a, b and c show the effect of slag on the resistivity measurements. First of all, we can notice that for the 3 concrete specimens, the resistivity values have similar magnitudes for both configurations, Trans and Wen, which was expected [1]. For the concrete with 0% of slag, the apparent resistivity reaches a value of 60  $\Omega\cdot\text{m}$  after 28 days of curing and increases very slowly until it stabilizes at approximately 70  $\Omega\cdot\text{m}$  during the two other months. Meanwhile, the apparent resistivities reach, after 28 days of cure, a value of 150  $\Omega\cdot\text{m}$  and 300  $\Omega\cdot\text{m}$  for specimens with 30% and 50% of slag respectively. These values continue to increase up to 70 days of cure, with a higher rate for the concrete with 50% of slag. Beyond 70 days, the apparent resistivity almost stabilizes for both concretes at a value of 200  $\Omega\cdot\text{m}$  and 400  $\Omega\cdot\text{m}$  for 30% and 50% of slag respectively.

We can conclude that the higher the rate of replacement of clinker by slag, the higher the apparent resistivity is. These results agree with that of Teng et al. [8], who explained the increasing of resistivity by the densification of the microstructure of concrete containing slag, due to pozzolanic reactions forming secondary calcium silicates. This increase in resistivity values can be also explained by the decrease in the quantity of mobile hydroxide ions consumed during pozzolanic reactions, which results in decreasing the conductivity and thus, increasing the resistivity of concrete [9-11].

In order to validate the results above, the evolution of the apparent resistivity is plotted with respect to the percentage of slag for both configurations, at 3 different time intervals: 2, 28 and 70 days of cure. The graph in Figure 3 shows once again the similarity between the resistivity values obtained for both of the configurations (Trans and Wen). It also shows that at a very young age (2 days of cure), resistivity values are almost similar for the 3 percentages of slag, with an approximate value of 35  $\Omega\cdot\text{m}$ . As we pursue the curing of the 3 specimens, we can clearly notice the difference of the resistivity values for each percentage of slag, showing that a higher percentage of slag results in higher values of apparent resistivities.



**Figure 3:** Evolution of the apparent resistivity with respect to the percentage of slag

## 4. Conclusion

The aim of the present paper is to study the effect of slag on the electrical resistivity of concrete during its hydration phase using embedded resistivity sensors. Three concrete specimens, formulated with 0%, 30% and 50% of slag, were instrumented with a “multi-electrode” embedded resistivity sensor previously developed, and monitored throughout their curing period using a commercial resistivity

meter. Results show that the apparent resistivity of the concrete increases with the increasing of the percentage of slag. In fact, the presence of slag affects the porosity of the material, as well as the composition of its poral solution, which will therefore affect the hydric and ionic content of concrete comparing to normal Portland cement. These results are in agreement with several studies that highlighted the strong effect of slag on the electrical properties of concrete.

Further research will be carried out in order to study the ability of our sensor and experimental procedure to evaluate Induced Polarization (IP) profiles in the time domain, also known as chargeability of concrete. This latter is an electrical property of concrete that measures, the relaxation of a material previously subjected to a polarization by an electrical field. Moreover, a diffusion campaign will be performed on the slag concrete specimens in order to provide further information regarding the effect of slag on the diffusion of chloride ions.

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