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Monitoring of the hydration of Portland concrete using embedded resistivity sensors: validation with modelling

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ABSTRACT

Reinforced concrete structures exposed to aggressive environments, such as nuclear and offshore structures, may be subjected to several hydric and ionic transfers that can affect their service life as well as their long-term durability. This type of structures may be sometimes difficult to access for inspection, thus several Non-Destructive testing Techniques (NDT) were developed in order to monitor and to assess such concrete structures.

The work presented in this paper consisted on studying the evolution of the hydration phase of a concrete formulated with CEM I, by evaluating its resistivity over time and depth using embedded resistivity sensors connected to a resistivity meter. Resistivity profiles obtained using these embedded sensors were compared to surface resistivity measurements carried out using a Wenner device. Moreover, this experimental campaign was validated by numerical hydration modelling, showing the evolution of the general kinetic coefficient of concrete with respect to time along its hydration phase.

Keywords: monitoring, resistivity, hydration degree, modelling

1. INTRODUCTION

Endogenous and exogenous attacks to which concrete structures can be subjected represent a major concern in the evaluation of the durability of these structures and their long-term performance. Destructive testing by local sampling of cores is not recommended for some types of structures, such as nuclear plants and offshore structures. Thus, several Non-Destructive Evaluation (NDE) techniques were developed in order to carry out a specific diagnosis of structures exposed to aggressive environments [1]. The work presented below is carried out within the DEMCOM French project which pays particular attention to the durability and NDE of maritime structures, of which tidal zones may be inaccessible for inspection. One of the main causes of degradation of these structures is the corrosion of reinforcement bars due to the penetration of chloride ions from seawater. The penetration of chloride is related to the durability properties of concrete such as the chloride diffusion coefficient. This property depends on the hydration of concrete as it governs the hydrated phases, the open porosity and the composition of the poral solution [6].

In the work presented below, the evolution of the hydration phase of concrete is monitored using embedded resistivity sensors developed by Badr et. al [2], that enable to evaluate resistivity profiles over time and over the entire thickness of the structure. The electrical resistivity of a material describes its ability to resist the flow of electric current, and is highly sensitive to water and chloride contents in concrete [3-4]. The Printed Circuit Board (PCB) sensor used in this work provides a good estimation of resistivity profiles and enables to study the gradient of the degree of saturation during the drying cycles of concrete [2].

The first part of this paper presents the experimental campaign (formulation of concrete, instrumentation with the PCB resistivity sensors and conditioning of the samples). In the second part, we report and discuss the results of the monitoring of the hydration phase, which are compared

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with hydration numerical modelling. This work will allow us to assess the capacity of electrical methods to follow the evolution of the hydration phase of concrete.

2. EXPERIMENTAL CAMPAIGN

2.1. Formulation of concrete

The aim of the experimental campaign is to study the behaviour of a Portland cement concrete during its hydration phase. The corresponding formulation is presented in Table 1 [5].

Table 1: Formulation of concrete

Components	kg/m ³
Gravel, 4-12 mm (Boulonnais)	1041.7
Sand, 0-4 mm (Boulonnais)	910.3
CEM I 52,5 N - SR 5 CE PM-CP2 NF HTS (Lafarge)	302.5
Superplasticizer MasterGlenium 201 (BASF)	2.94
Efficient water (Eeff)	151.7
Water-to-binder ratio (W/B)	0.5

2.2. Methods and instruments

Three cylindrical specimens with a diameter of 11 cm and a height of 18 cm were cast for the studied concrete formulation (Table 1), and were instrumented with a PCB resistivity sensor which has a ladder shape and is composed of 15 electrodes distributed on both sides of the PCB. The latter is placed at the centre of the specimen along its z axis (representing the thickness of the concrete sample), between two metal grids well anchored in concrete and serving for current injection [2] (Figure 1).

During the monitoring, one instrumented specimen is connected to a commercial resistivity meter: a Syscal Junior Switch 72 (from IRIS Instruments), that manages simultaneously up to 72 electrodes and injects an alternating current of very low frequency. The measurements were made according to the Transmission mode (Trans) [2]: an electric current is injected between two metal grids, and the potential drop is measured between two consecutive electrodes on the same side of the PCB. An additional measurement is made according to the Wenner configuration (Wen) by injecting a current and measuring the potential drop on 4 electrodes on one side of the PCB without using the grids [2].

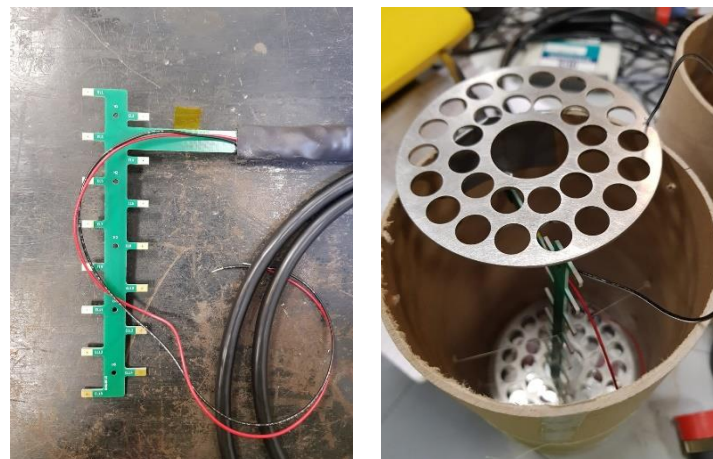


Figure 1: (a) PCB resistivity sensor with 15 electrodes, (b) instrumented mould before casting of concrete.

Moreover, 15 non-instrumented cylindrical specimens with a diameter of 11 cm and a height of 22 cm were cast and served for surface measurements using a Resipod Proceq device which operates in the Wenner configuration, and is therefore referred to as the surface Wenner device throughout this paper. The spacing between the electrodes is of 5 cm and the measurements were made along the lateral surface at mid height of the specimens. These measurements are made at different times of the curing period and are compared to the results obtained using the embedded sensors.

2.3. Curing of the specimens

The conditioning of the concrete specimens during the monitoring consisted on placing them in a tray containing a small quantity of water at a temperature of 20°C and a relative humidity of 95%. These conditions were regularly controlled using a thermo hygrometric (THR) probe along the period of cure. The latter lasted for 90 days instead of 28 days in order to allow a near stabilization of the hydration degree. Note that the period of cure was similar for both the instrumented and non-instrumented concrete specimens.

3. RESULTS AND DISCUSSION

3.1. Evolution of the apparent resistivity during the hydration phase

This part of the paper presents the results of the evolution of the apparent resistivity of concrete along its period of cure. Note that the observable measured in this experimental campaign corresponds to the apparent resistivity (ρ_a) given the heterogeneity of concrete (presence of water content gradients). The graph in Figure 2 shows a comparison between the apparent resistivity values obtained with the PCB embedded sensor (for both Trans and Wen configurations) and those obtained using the surface Wenner device. For surface measurements, the apparent resistivity value presented in this graph represents the average value of 15 measurements performed on each of the 15 specimens. Meanwhile, for the PCB_Trans configuration, the corresponding resistivity value represents the average value of 13 measurements obtained along the z axis, and the error bars represent \pm the corresponding standard deviation.

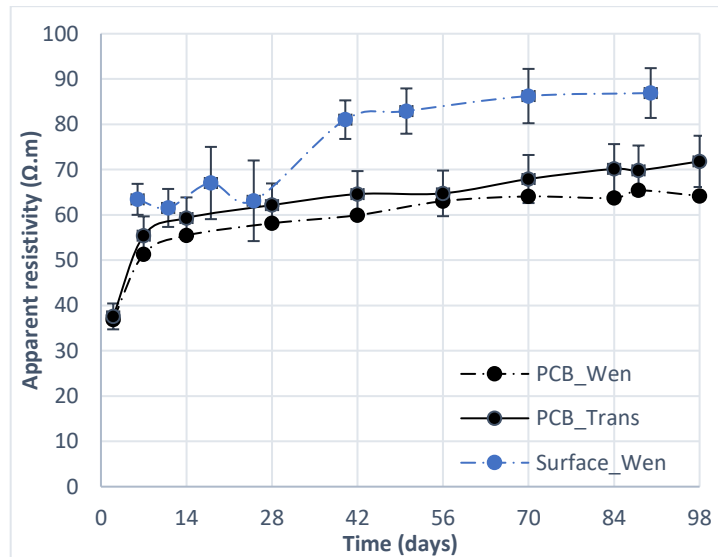


Figure 2: Evolution of the apparent resistivities obtained with the PCB sensor (Wen and average Trans) and the surface Wenner device with respect to time.

First of all, we can notice that the apparent resistivity values measured with the PCB sensor exhibit very similar magnitudes at all times for both configurations (Trans and Wen). The consistency between the two configurations was expected and validates the accurate response of the PCB sensor [2]. The apparent resistivity starts with a value of 35 $\Omega.m$ at a very young age (T_c+2 days, with T_c representing the casting time). It increases quickly during the first 28 days of cure to reach a value of 60 $\Omega.m$. Beyond T_c+28 days, this value increases very slowly until it stabilizes

approximately at $70 \Omega.m$ at T_c+70 days. The increase in the apparent resistivity at young age and its near stabilization at T_c+70 days allow us to assess the setting and hydration phase of the concrete along its curing period.

The apparent resistivity values obtained using the surface Wenner device appear to be higher than those obtained with the PCB sensor. For example, at young age (T_c+6 days), the apparent resistivity starts with a value of $65 \Omega.m$. It does not seem to increase during the first 28 days of cure, although some large uncertainty bars may partly hide the real trend. Then it starts to increase until it stabilizes at $86 \Omega.m$. Let us note that the rate of increase is quite similar for both surface and embedded measurements from T_c+40 to T_c+86 days. We explain these differences in apparent resistivity magnitudes by the difference between the two measurement techniques, including the fact that surface measurements are more prone to variations in electrical contact quality than embedded measurements (therefore the larger uncertainty bars), as well as the fact that the samples and the observation times are not the same for both datasets. However, we can notice that the two types of curves are globally consistent, showing a similar trend for both embedded PCB and surface Wenner measurements. Thus, we believe that our experimental resistivity monitoring can be a good proxy for the hydration phase of concrete, yet the comparison between the two resistivity techniques remains qualitative in order to validate the response of the PCB sensors during the hydration phase. That is why, only resistivity measurements obtained with the PCB sensors will be compared to numerical modelling, which was the major aim of this paper.

3.2. Comparison of experimental results with numerical hydration modelling

The results obtained in the experimental campaign are compared to numerical hydration modelling, in order to validate the capacity of the electrical measurements in showing the evolution of the hydration phase of concrete. That is why, the graphs in Figure 3 show a comparison between the apparent resistivity measured experimentally and the hydration degree obtained numerically by 3 different models: VCCTL [7], Avrami's equations [14] and Bernard et al. (2003) [15]. These 3 models are widely used in literature, therefore considered as reliable models to describe the hydration degree variation in function of time.

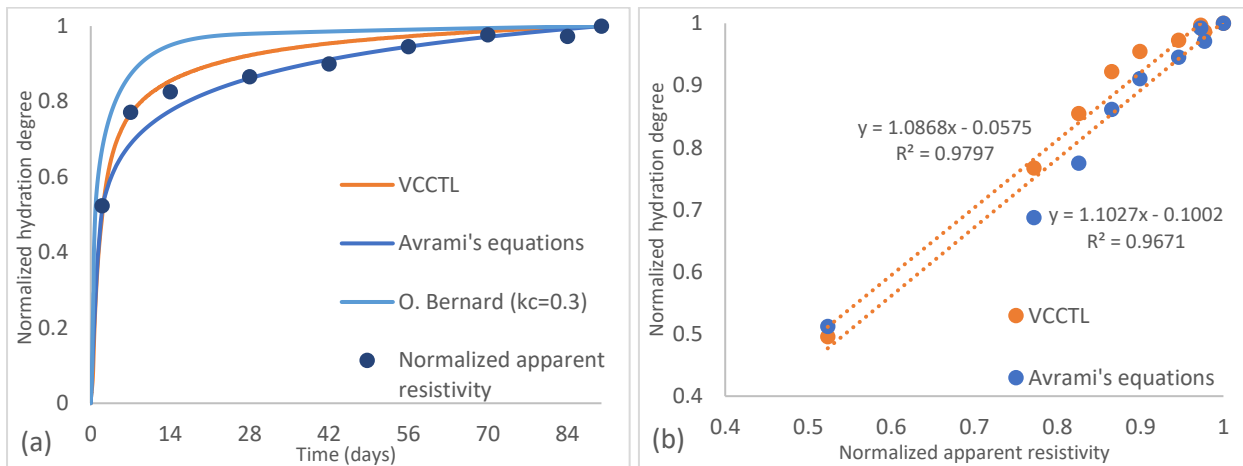


Figure 3: (a) Evolution of the normalized hydration degree and normalized apparent resistivity over time, (b) normalized hydration degree versus normalized apparent resistivity.

First of all, the Virtual Cement and Concrete Testing Laboratory (VCCTL) [7] is a virtual laboratory software based on the CEMHYD3D system where cement paste and concrete materials are computed in a virtual environment allowing the creation, hydration and estimation of the 3D cement material microstructure [8-12]. Whereas, Avrami's equations [13- 14] are best adapted to explain nucleation and growth events established empirically. They are used as an approximation for all Portland cements; as they are expected to react at similar relative rates. These equations present a basic kinetic model that provides acceptable fits for hydrated pastes. The third model used in this work is that of Bernard et al. [15] which is a multi-phasic kinetic model that describes the variation rates of each clinker phase hydration, by kinetics laws that link the reaction rate with the

chemical affinity. It is determined according to three processes: the dissolution of the phases, their nucleation and growth-controlled hydration and the diffusion of dissolved ions.

In order to provide a clear comparison while comparing the experimental results to those of the hydration modelling, both the hydration degree and the apparent resistivity (PCB_Trans) were normalized to their 90 days prediction and measured value respectively. Figure 3a shows the evolution of the normalized hydration degree and the normalized apparent resistivity during the period of cure. We can clearly observe the high correlation between the experimental and numerical data, confirming the capacity of resistivity measurements to follow the evolution of the hydration phase. Moreover, Figure 3b further validates the results above, showing a linear correlation between the normalized hydration degree (for VCCTL and Avrami's equations) and the normalized apparent resistivity.

4. CONCLUSION

The aim of the present paper is to study the hydration phase of concrete, experimentally by measuring apparent resistivities using embedded resistivity sensors, and numerically by calculating the hydration degree using 3 different models.

The experimental campaign consisted on studying the evolution of apparent resistivities measured in a Portland cement concrete during its hydration phase, using embedded resistivity sensors. Results show that the apparent resistivity increases quickly at young age of concrete, and almost stabilizes after 70 days of cure. Resistivity profiles obtained using the PCB embedded sensors were compared to surface measurements using a commercial Wenner device. Overall, both techniques were able to monitor the hydration phase of concrete, and the curves were almost close with small differences in resistivity magnitudes. Moreover, the experimental results were compared to a numerical hydration modelling using 3 different models. A clear coherence between the experimental and numerical curves was observed, showing a linear correlation between the relative hydration degree and the normalized apparent resistivity.

In the near future, a diffusion campaign will be carried out in order to provide further information regarding the effect of chloride penetration on the electrical resistivity of concrete. Moreover, not only electrical resistivity but also electrical chargeability (relaxation phenomenon due to the induced polarization of concrete) are to be recorded with our embedded sensors.

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