Electrical impedance as a technique for civil engineer structures surveillance. Considerations on the galvanic insulation of samples.

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Abstract. Since Electric Impedance Spectroscopy (EIS) has been widely used to determine physical properties of materials, it becomes necessary to evaluate different error contributions. In this work, it is studied the effect of the current leakage due to the lack of galvanic insulation from sample to ground, which could distort the results. In order to known the effects of ground coupling, an electric equivalent model is developed to distinguish between the contribution of the sample impedance and the stray impedance one. Model values agree with measured ones.

Keywords: Electrical impedance spectroscopy; galvanic insulation; ceramic materials.

1. Introduction

A Century ago, Schlumberger and Wenner among others in geoelectrical prospecting field located materials with commercial interest under earth (sub-soil) thanks to their differential electrical characteristics from soil. Half Century ago, Calleja (1952) studied electrical characteristics of cement and concretes in order to achieve better knowledge of other physical characteristics of these ceramic materials. Later, some authors studied in depth related subjects; as a few examples: (McCarter *et al* 1985, 1999), (Christensen *et al* 1994), (Xie *et al* 1994) or (Yoon *et al* 1996). These authors demonstrated good correlation between electrical and structural or mechanical characteristics of civil engineer materials.

In general, an electrical parameter is correlated with a mechanical parameter of interest. Often, the electrical characteristic measured is Electrical Impedance (EI), Electrical Impedance Spectroscopy (EIS) or its directly related parameters such resistivity or conductivity, mainly represented with two kinds of graphics (Nyquist or Bode). In some applications, Electrical Impedance Tomography (EIT) is drawn for image mapping. Sometimes, another electrical characteristic is measured (current, charge, voltage). Monitoring physical or mechanical parameters of structures or materials through electrical parameters has plenty of advantages: electrical measures are non destructive, usually easy to apply, with no risk and cheap (at least compared with other monitoring alternatives).

Today, some authors have measured with better accuracy, other authors have measured impedance changes during load or mechanical stress, others have analyzed (through impedance) components such fibers, or optimum SP dose, or even corrosion effects, etc. As a few examples: Christensen *et al* (1992), Gu *et al* (1995), McCarter *et al* (2004) have studied silica fume or fly ash behavior with electrical measurements. Andrade *et al* (1999) have studied hardening process through EI. Torrents *et al* (1998) have compared different superplasticizer dose effect on setting with a standard method (Vicat needle) and with conductivity. Cao and Chung (2001), Sun *et* al (2002) have compared different load situations in structures with changes in their electrical parameters. Even more, Cao et Chung (2001), Chung (2004) and Song (2006) have reported a kind of smartness in civil structures thanks to any electrical parameter or actuation.

However, at the same time or even a little bit earlier, around the nineties, other authors have reported a few limitations and difficulties in measuring with EI methods (Bari 1990), (Xie *et al* 1996), (Hsieh *et al* 1997), (Hwang *et al* 1997), (Edwards *et al* 1997), (Mason *et al* 1998). These reported limitations and others not reported yet probably are beneath the cause of all this success in lab results hardly transcend to field applications and economical savings.

In this work, we study the current leakage effect due to the lack of galvanic insulation from sample to earth as one of these undesired effects or limitations in materials characterization. In particular, we measure sample of advanced cement based materials (concrete with steel fiber reinforcement). If an EIS study on a sample does not take into account the current leakage effect, the results could be wrong. Our goal is provide a methodology for detecting and avoiding the measurement problem of lack of insulation in order to make EIS or related techniques more useful in field applications of material characterization.

2. Material and Methods

2.1. Sample preparation

Concrete prismatic samples (600x150x150 mm) were produced using CEM I 42.5 R Portland Cement. 2 types of calcareous sand used (passing 2 and 4 mm sieve) was mixed with a sand/cement ratio of 3.4. The water/cement ratio was 0.57. Aggregates were mixture gravel (passing 12 and 20 mm sieve). Polyfunctional additive was also added.

50 mm long and 1.05 mm diameter Twinplate steel hooked end fibers were randomly mixed in different proportions depending on the series measured. To study the electrical impedance dependence with the different fiber loadings, series of 0, 20, 30, 40, 50 and 70 kg/m^3 of fibers were tested.

The same steel fibers were used as electrodes for 4-wire measurements. Two electrodes were inserted at 5 and 10 cm from the sample edge (see figure 1) in the longitudinal axis of the sample and symmetrically to the transversal axis were dipped the other two. Approximately half the fiber was inside the bulk so the other half was available to connect each of the instrument terminals. Since it had to be placed into fresh paste, it allowed monitoring the bulk impedance from the moment it started to harden. To avoid electrode oxidation, fibers had to be isolated as a protection method and sanded down before measuring.

2.2. Measurement instruments

Electrical measurement parameters are usually performed with commercial instruments (Coombs 1995, p.27.7-13), (Agilent 2006). To avoid the electrode impedance appearing in the final result, 4-wire measurements are strongly recommended. 4-wire electrical impedance at low frequencies (below RF range) may be measured using an auto-balanced bridge for its suitability in accuracy, resolution, ease to automate and, with newer instruments, user friendly software.

We acquired data using a LF Impedance Analyzer HP4192A with a laboratory-made front-end based on a unit-gain instrumentation amplifier that allows 4-wire impedance measurements developed from an idea published by Gersing (1991). The Impedance Analyzer was controlled by a PC through a GPIB connection and software developed under a LabWindows/CVI platform. In each prismatic sample, we measured 20 points per decade from 10 Hz to 10MHz with 1.1 V_{rms} voltage excitation. Figure 1 shows this setup schematically.

To measure capacitive coupling a Promax GF1000 function generator and a LeCroy 9314L oscilloscope were used: we measured capacitance between all electrodes short-circuited and a metal platform (earth plane) where the prismatic sample was placed.

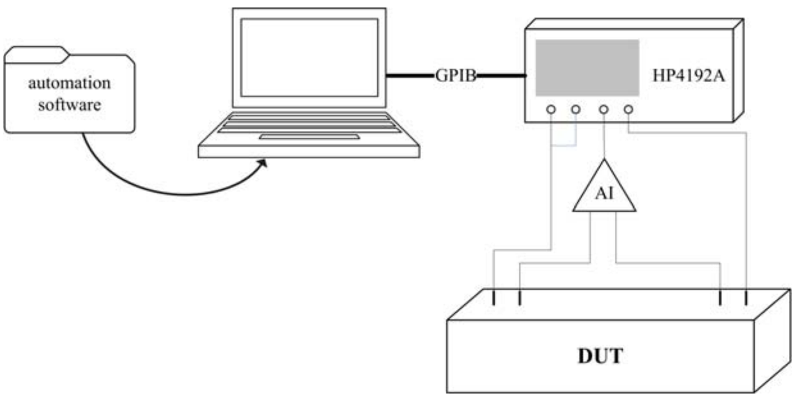

Figure 1. Schematic diagram of the complete instrumentation system performing 4-wire electrical impedance measurement on a 600x150x150 mm prismatic sample.

3. Results and discussion. Effects of earth coupling with prismatic samples

Concrete impedance, as many other similar composites, is mainly resistive at low frequencies, so a plateau behavior in the low frequencies is expected (see figure 3a, cross (x) trace). This behavior contributes with an R component in equivalent circuit models. A capacitive component, C, normally appears for frequencies over the MHz range as well as other secondary effects (RC) related to the degree of porosity of the material (Cabeza et al, 2002). Besides, it is possible a tiny inductive effect (an L in equivalent circuit models) because current flow along the sample and setup.

For safety reasons, the instrumentation equipment must to be electrically grounded [IEC 61140:2004]. A capacitive coupling between ground and the prismatic sample arises giving an additional way to electrical current to flow that is not detected by the measurement point in the 4-wire measurement. Coombs (1995, p. 27.16) describes a typical (insulated) 4-point measurement. Therefore, it becomes an important error source due to the difference between the injected and the detected current. Naturally, the bigger the sample is, the more important effects of this error are.

Not only the size of the bulk affects to the final analyzer reading but also the relative position between the sample and any earth point. Impedance measurement is supposed to be independent wherever the samples are placed, but if there is an unknown current leakage to earth, it will be impossible to repeat any measurement in a different place obtaining exactly the same results. Then, it is necessary to minimize the error placing the samples on an insulated environment or to quantify the error effects at every frequency range in order to avoid them when insulating is physically not possible.

Departing from other electrical models (Christensen et al, 1994), (Cabeza et al, 2002), it is essential to include in the model the effects of ground coupling. A simple circuit with 3 branches in T-shape can include the effect of ground coupling, where the two top shape parts model the bulk intrinsic impedance and the base T-shape part models the feasible coupling between sample and earth (figure 2).

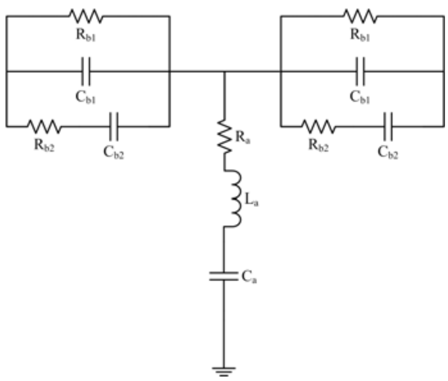

Figure 2. Impedance circuit based on RLC cell that models bulk impedance of samples and its undesired ground coupling.

The influence of ground coupling was evaluated placing the sample on an earth plane and on an insulating (timber) surface and comparing the results of both measures (with the same set up of figure 1). Since the sample is physically in contact with the metallic plane, it can be considered an extreme coupling value. An unexpected peak of impedance for frequencies from 10 kHz to 10 MHz is observed with its maximum around 1 MHz (figure 3a). As described in section *2.2. Measurement instruments*, capacitive coupling was quantified using the function generator and the oscilloscope obtaining values around 2 nF for the peak frequencies. This obtained value will be used to simulate an electrical model of the sample (see figure 3b).

To estimate the real values of the model components, the circuital model was adjusted to the measured data. Figure 3a shows the agreement between simulated rhombuses (♦) trace and measured triangles (Δ) trace values in order to confirm the validity of the proposed model. It can be observed that the value of the stray capacitance is the one manually measured previously. But even in that way, there is a slight discordance between both plots, especially in the surroundings of the coupling peak. That occurs mainly because of the electrode contribution combined with the earth coupling of the measured sample cannot be avoided (even with 4-wire measurements).

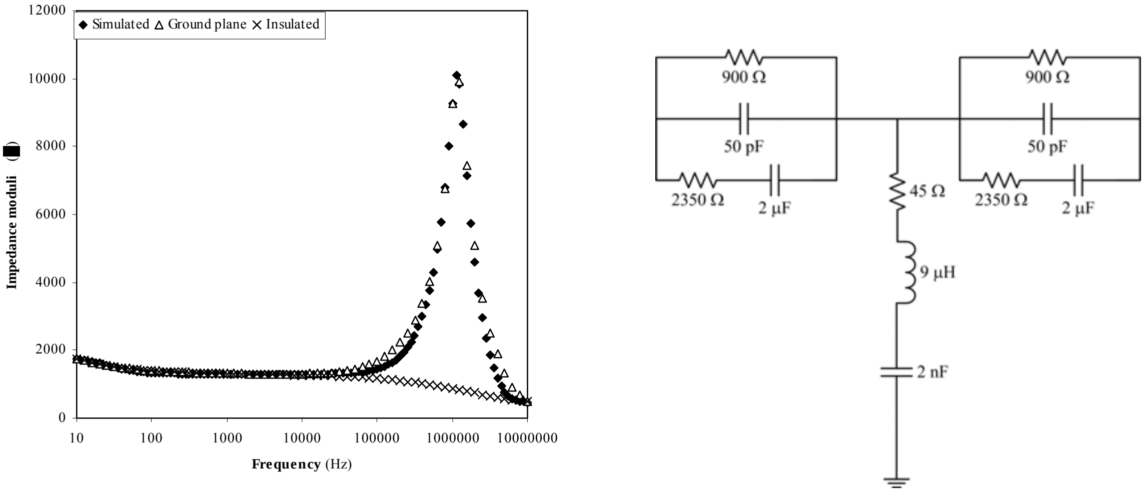

Figure 3. (a) Impedance moduli vs. frequency for sample measurements on ground plane triangles (Δ) trace, on an insulated environment crosses (x) trace and for simulated equivalent circuit rhombuses (♦) trace, and (b) simulated circuit agreeing with measured data.

Theoretically, 4-point measurements should cancel the effects of electrode impedance but since the capacitive ground coupling arises, it interferes with the auto-balanced bridge forming a voltage divider that causes a final contribution of the electrode impedance in the final reading which not only depends on the own electrode impedance but also on the ground coupling as well as on the intrinsic bulk impedance (1). This behavior introduces a limitation to the Gersing (1991) proposal and shows that 4-wire measuring does not always guarantee the absence of electrode contribution in the measurement. Circuital analysis of this phenomenon quantifies the value of this limitation:

$$\Delta Z_x = \frac{1}{2} Z_b \frac{Z_e}{Z_c} \quad (1)$$

where ΔZ_x represents the erroneous increment of measured impedance due to earth coupling, Z_b represents bulk impedance, Z_e models electrode impedance, and Z_c represents ground coupling. In this particular setup, electrode effects are remarkable for frequencies under 500 Hz and over 10 kHz, so an intermediate frequency is the optimum to minimize the external errors. For instance, in the simulated measurement (see figure 3a), the additional error due to the electrode contribution at 1 kHz is about 10 Ω, what represents 0.75% of relative error (increased up to 7.5% at 10 kHz). Otherwise, if a wrong frequency is chosen, errors could exceed 100%, becoming obviously unacceptable. In this experiment, it should be pointed out that measurements at 1 kHz minimize the interfering errors, so can be compared between samples. However, since the dimension of the interference depends on geometry, the optimum frequency must be carefully selected in each case.

4. Conclusions

A large number of techniques are based on measuring an electrical parameter with the purpose of studying another mechanical one. Among others, impedance measurements are particularly common, as using non-destructive techniques can becomes very useful for monitoring civil engineering structures as a technique for surveillance. An electrical model allows the direct comparison between different specimens or geometries. However, when the measured samples are big, a wide range of error sources should be evaluated, particularly those related with the ground coupling. Since the impedance analyzer assumes that the current injected is exactly the same as the detected, when an alternative current path arises, the detected impedance may be wrong. In order to avoid those errors, is necessary to study its influence at each frequency ranges. Otherwise, erroneous measurements could disguise the real values, and some disperse results be shown.

An equivalent circuit was obtained based on a parameter model, in order to simulate the effects of coupling between the sample and the earth points of the setup. It is useful to compare measurements done over an earth plane and on an isolated environment to quantify the stray capacitance but when measuring in field applications, sometimes is not possible to achieve the necessary isolation so the practical methods consist on working on the range of frequencies that minimize the error. The obtained electrical models help to understand the effects of ground coupling and are effective to choose the best frequency to work in each situation. In the experiments, measuring at 1 kHz was selected (with ground errors under 1%). When performing 4-wire measurements, modeling ground coupling is not only necessary to evaluate the effects of current leakage but also to notice the electrode contribution. Although it is supposed to be canceled by the 4-wire setup, ground coupling limits the range of correct operation since the measurements are not completely independent of the electrodes impedance.

5. Acknowledgments

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