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FIRST INVESTIGATIONS OF IN SITU ELECTRICAL PROPERTIES OF LIMESTONE BLOCKS OF ANCIENT MONUMENTS

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Abstract

In situ rapid electrostatic investigations on calcareous stones of monuments bring information which strongly correlates with the stone geologic characteristics and proves to be efficient for provenance identification and successive restoration. With a portable device it is now possible to scan several thousand of blocks on a face of a monument in a few hours. The evolution of the religious building construction practices between XIIIth and XVIIth is studied. From the petro-physics point of view, results clearly indicate a marked linear correlation between electrical conductivity and dielectric permittivity. This fact that agrees with Maxwell-Wagner polarization modeling, confirms the part played by the clay content in the electric properties of dry carbonate rocks constituting the monument stones. A first test using X – Ray scattering analysis shows the part played by the relative content in illite, which is correlated with a decrease of the resistivity.

Key words

Ancient monument building practices, Clay, Dielectric permittivity and Electrical resistivity, of Stones, X-ray scattering.

<u>Introduction</u>

Stone buildings constitute an important part of our monument heritage and consequently a significant effort is involved in both their historical study and their preservation/restoration. Thus numerous questions are raised such as the characterization and identification of the cause(s) of the different weathering processes they suffered, the ancient builder’s know-how, or the determination of stone provenances. For this purpose, a wide variety of laboratory analyses was developed and applied (Rozenbaum 2007), but these studies necessitate sample collection over a limited number of stones which raises the issue of the choice of the sample location. They are also costly and possibly long.

To be systematic, the study of stones in ancient monuments (i.e. essentially religious buildings) necessitates the use of non-invasive techniques that totally respect the integrity of stones and coating. Among those techniques, the electrostatic one, which allows measurements of low frequency electrical properties over a significant part of the whole volume of a stone and without any direct contact with material under study, appears to be relevant. Its results bring information about major physical properties of sedimentary stones, namely the part taken in it by clay platelets and macroscopic effects of the pore arrangement. In principle, the signal obtained takes into account the responses of both the clay and water content, or volume wetness, of a block. This last parameter possibly depends on the meteorological conditions, and consequently it may introduce time variation dependence in the measurements. Nevertheless, it has been clearly established and confirmed by a published study that in old buildings water content remains low and constant beyond a depth of two or three centimetres into the blocks (Sass 2010). In this way, a steady “dry state“ should clearly characterize the steady time value of the internal water content of the blocks which no more depends on the atmospheric conditions.

As a result in dry calcareous materials, clay is practically the only source of ions and its electrical behaviour determines the values of conductivity and permittivity of stones. Then, clay content and arrangement in building blocks allows operating a typological classification of the stones in the main work and a first assessment of their mechanical behaviour.

The study of three different monuments built between the XIIIth and XVIIIth centuries is presented here and it is followed by some new paths opened by this first approach.

Method and instrument

In the electrostatic method, an open capacitor located near the surface of the medium under study injects into it an alternative current (Grard and Tabbagh 1991, Tabbagh *et al.* 1993, Kuras *et al.* 2006). The voltage resulting from the current flow inside the studied medium can be measured between different couples of poles located at distances imposed by the size, notably the depth, of the volume concerned by the investigation. If the dimensions of the poles are sufficiently small in comparison with their separation, they can be considered as points in the calculations. If this is not verified, they must be divided into a series of smaller elements, assumed to be point–like, and the effects of all the source pairs should be summed; an example is, when large metallic plates are used as poles. This geophysical method that represents an extension of the classical resistivity one can be, and has been, used in a wide variety of contexts: in urban areas (Panissod *et al.* 1998, Flageul *et al.* 2013), inside monuments (Dabas *et al.* 2000, Dabas and Titus 2001) or for permafrost studies (Hauck and Kneisel 2006, De Pascale *et al.* 2008) among others.

The main difficulty in the application of this method lies in the choice of the most suitable frequency. A compromise between three constraints is required:

1. The frequency f must be sufficiently high to ensure that the impedance of each pole is sufficiently low.
2. For a non-zero frequency, the effective conductivity is complex, $\sigma^* = \sigma + j\omega\varepsilon$; if the electrical conductivity σ is to be measured, the condition $\sigma >> \omega\varepsilon$ must be fulfilled ($\omega = 2\pi f$ is the angular frequency and ε the dielectric permittivity). However it is possible

to determine σ and ε by measuring the in–phase and the out of phase components of the voltage (Tabbagh *et al.* 1993).

3. In order to avoid induction effects that would reduce the depth to which materials could be investigated (Benderitter *et al.* 1994, Tabbagh and Panissod 2000) the induction number, $IN = \sigma\mu\omega L^2$, must verify $IN << 1$, where μ is the magnetic permeability and L the characteristic length of the instrument. As L lies in the decametric range, this last condition is easily fulfilled.

As for metric scale shallow depth ground exploration multipoles (Panissod *et al.* 1998), a single pair of current transmitting poles is adopted, with two pairs of voltage poles (hexapole). This device corresponds to the minimum requirement for the assessment of resistivity variations as functions of depth. In order to implement a compact array to analyse the stones in ancient monuments, a configuration close to the square array is adopted. The exact configuration of the array is displayed in Figure 1. Each pole has an area of 5 x 5 cm^2 and is located at the end of a 'leg' beneath the electronic box. The operational frequency range corresponds to the decade starting at 10 kHz; in the experiments presented below, it is fixed at 31.25 kHz. The capacitance of each pole is 2 pF in free air; this value increases when a material of greater permittivity is present in the vicinity of the pole. Six quantities, referenced to the internal trigger, are measured: the in–phase, I_p, and quadrature, I_q, components of the injected current and the voltage, V_p, and V_q of each pair of voltage poles. The variables measured in these conditions are the two complex impedances Z_1 or Z_2 where $Z_i = P_i + jQ_i$, the voltage in-phase and quadrature components being calculated by the expressions:

$$\mathbf{P} = \frac{V_p\, I_p + V_q I_q}{I_p^2 + I_q^2} \qquad \textbf{and} \qquad \mathbf{Q} = \frac{V_q\, I_p - V_p I_q}{I_p^2 + I_q^2}$$

The apparent properties are given by:

$$\rho = \mathrm{K}\frac{\mathrm{P}^2 + \mathrm{Q}^2}{\mathrm{P}} \qquad \text{and} \qquad \varepsilon = -\frac{1}{\mathrm{K}\omega}\frac{\mathrm{Q}}{\mathrm{P}^2 + \mathrm{Q}^2}$$

where K is the geometrical factor of each quadripole. If the distance, *h*, between the pole surface and the stone is small against the inter-pole distances the approximation *h=0* can be used and K is the same as for a galvanic injection, if not K must be calculated taking into account the exact geometry of each array. Moreover, tests of the effect of the spacing between the poles and the stone have been achieved. They don’t show observable differences if it remains less than 5 mm.

The measurement is driven by a small computer which also records the data. The injected current is normally less than 1mA. The depth at which the material is analysed is defined by the pole geometry, and is in the approximate range from 5 to 8 cm for the smaller dipole, and from 10 to 15 cm for the greater dipole.

For various test materials, good agreement was observed between measurements using multipole and those using galvanic contact resistivity measurements in which the electrode array accurately reproduced the pole geometry (Souffaché *et al*. 2010).

Measurements over three monuments

The three monuments are three churches or basilica located in the vicinity of Paris. They were all built with Lutetian calcareous stones, coming from several quarries located in the Parisian basin. These monuments are the basilica/cathedral of Saint–Denis (Seine Saint Denis), the “Sainte Chapelle” in Paris, and the Saint–Sulpice Church also in Paris.

Whereas the first two monuments contain essentially stones coming from quarries of the center of the basin (i.e. Paris itself or cities very close to the town like Montrouge or Clamart), the third one is made of stones of various origins; most of them came from remote quarries at Saint Leu or at Saint Maximin in the Oise department (60 km North of Paris) and also at Saint Pierre Aigle in the Aisne department (80 km North – East of Paris).

The geological approach is a good start for a first assessment of the results and it shows that the two types of stone–field are drastically contrasted. The " Paris– stone” (from Paris itself and its suburbs) is a very heterogeneous material (due to the presence of different beds) while the “Oise” stones are much more homogeneous and clearly different from the “Paris” stones.

Results

For all the results, chromatic charts of values are given in Figure 1 b

1) Saint Denis Basilica (Seine Saint-Denis, France)

The scanning of two sectors of the main face shows a quasi-random distribution of the resistivity, starting from 10 Ωm until more than 30000 Ωm (Figures 2 and 4); a similar random distribution is observed for the relative permittivity (Figures 3 and 5) without any geometrical order. This observation is in good agreement with what is known about the history of the monument. Since the XIIIth century at least seven restorations were successively made, without taking care of the geological homogeneity of the blocks and particularly without taking care of the nature of the preceding ones. Most part of substituted blocks shows almost all the variety of the observable geological banks in the quarries of Paris or suburbs without any organization. A very little part seems to come from the Oise or Aisne departments. The majority of the resistivity values are included between 300 and 10 000 Ωm (see Figures 2 and 3); smaller or larger values are few (below 300 Ωm and above 10 000 Ωm); similarly, the majority of the values of the relative permittivity are included between 5 and 1000 (see Figures 4 and 5).

2) "Sainte Chapelle” in Paris (Seine, France)

The scanning of two parts of the nave (Figures 6 and 8 for the resistivity, Figures 7 and 9 for the relative permittivity) shows a greater homogeneity than the scanning of Saint Denis basilica. Weak and strong values of resistivity (i.e. below 300 Ωm and above 10 000 Ωm) again are exceptional. These results are in fair agreement with the geological observations: nearly all the stones of the monument observable at the present time come from quarries of Paris, Bagneux or Charenton, and an insignificant part comes from quarries of the Oise department.

In fact, the monument did not suffer all the restorations which damaged the Saint Denis basilica, and a great part of its blocks are original.

3) Saint Sulpice church of Paris (Seine, France)

Built with the great architectural rigor of the classical century (17th) , the Saint Sulpice church of Paris reveals through its electrical scanning an impressive organization of the contrast; all the weak resistivity values are found in the basement; all the middle values are only present in the medium stage of the elevation, and all the strong values are at large elevations (Figure 10); analogous remarks can be made for the permittivity (Figure 11) , with an inversion in the order (strong values in the basement, middle values in the medium stage and weak values above); the essential issue is that a rigorous order can be also observed in the topography of the values.

This is in spectacular accordance with the geological observations; all the blocks of the basement come from quarries of Paris or Bagneux; all the blocks present in the medium stage of the elevation come from Saint Leu quarries (Oise department), and all the blocks at the height come from Saint Maximin quarries (Oise department also, but located in a higher geological layer than Saint Leu).

Discussion

In a dry calcareous material, the presence of clay and the arrangement of clay platelets in the pores control most of the electrical properties. At the surface of silicate – foils are counter ions which can tangentially move and ensure conductivity; the same are also responsible for the electrical polarization ensuring permittivity. If that double function is effective, the conductivity and the permittivity must be correlated. However, due to the unavoidable limitations of the instrument, the conductivity value should be small enough (resistivity above 50 Ωm) so that the permittivity can be easily measured.

The permittivity is plotted for two monuments as a function of conductivity. Figure 12 is relative to the Saint Denis basilica; a linear trend clearly appears in it. The analysis of the data gives a correlation coefficient equal to 0.70 (for 1400 data) which is a good indication to strengthen the perception of linearity. Figure 13 is relative to the Sainte Chapelle de Paris; the linearity appears all the more in it as the correlation coefficient equals 0.78 (for 780 data).

In order to analyze the clay content, an X–ray scattering analysis is undertaken over fifteen different samples. It shows a noticeable positive correlation (linear decrease) between the electrical resistivity and the relative concentration in illite (Figure 14). This observation is in accordance with Maxwell-Wagner effect modelling (Tabbagh *et al.* 2009) where this parameter is sensitive to the size and shape of the clay platelets and also with the known non-blowing character of illite. This suggests a link with the size of the pores and throats themselves.

Conclusion

The electrostatic hexapole used in this series of studies over three monuments has proved to be easy to implement and efficient to discriminate between the different types and origins of carbonate stones. The volume taken into account in the measurements corresponds to that of the whole stone and these measurements are repeatable. The study showed the evolution that took place for religious main building constructions with respect to the choice of the stones between the XIIIth and the XVIIth centuries. This technique should be considered as a new tool for the study and the management of historical buildings.

The ability to measure both electrical resistivity and dielectric permittivity of dry stones opens large new paths of research for a better assessment of the part played by different types of clay

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Figure captions

Figure1: View of the hexapole electrostatic device

Figure 1 b : Chromatic chart for figures 2 to 11

Figure2: Saint Denis basilica: Electrical resistivity of the north front of the porch

Figure3: Saint Denis basilica: Electrical permittivity of the north front of the porch

Figure4: Saint Denis basilica: Electrical resistivity of the North counterfort (developed) of the porch

Figure5: Saint Denis basilica: Electrical permittivity of the North counterfort (developed) of the porch

Figure6: Sainte Chapelle: Electrical resistivity of the counterfort number 107 (developed)

Figure7: Sainte Chapelle: Electrical permittivity of the counterfort number 107 (developed)

Figure8: Sainte Chapelle: Electrical resistivity of the counterfort number 109 (developed)

Figure9: Sainte Chapelle: Electrical permittivity of the counterfort number 109 (developed)

Figure10: Saint Sulpice church: Electrical resistivity of the first level of the north front

Figure11: Saint Sulpice church: Electrical permittivity of the first level of the north front

Figure12: Electrical permittivity as a function of the electrical conductivity for the measured stones of the Saint Denis basilica

Figure13: Electrical permittivity as a function of the electrical conductivity for the measured stones of the Sainte Chapelle

Figure14: Electrical resistivity as a function of the relative concentration of illite in the stones