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

3
4 Blaise Souffaché, Pauline Kessouri, Philippe Blanc, Julien Thiesson, Alain Tabbagh

5
6 **Abstract**

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

18
19 **Key words**

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

22
23 **Introduction**

24 Stone buildings constitute an important part of our monument heritage and
25 consequently a significant effort is involved in both their historical study and their

26 preservation/restoration. Thus numerous questions are raised such as the characterization and
27 identification of the cause(s) of the different weathering processes they suffered, the ancient
28 builder's know-how, or the determination of stone provenances. For this purpose, a wide
29 variety of laboratory analyses was developed and applied (Rozenbaum 2007), but these
30 studies necessitate sample collection over a limited number of stones which raises the issue of
31 the choice of the sample location. They are also costly and possibly long.

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

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

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

53

54 **Method and instrument**

55 In the electrostatic method, an open capacitor located near the surface of the medium
56 under study injects into it an alternative current (Grard and Tabbagh 1991, Tabbagh *et al.*
57 1993, Kuras *et al.* 2006). The voltage resulting from the current flow inside the studied
58 medium can be measured between different couples of poles located at distances imposed by
59 the size, notably the depth, of the volume concerned by the investigation. If the dimensions of
60 the poles are sufficiently small in comparison with their separation, they can be considered as
61 points in the calculations. If this is not verified, they must be divided into a series of smaller
62 elements, assumed to be point-like, and the effects of all the source pairs should be summed;
63 an example is, when large metallic plates are used as poles. This geophysical method that
64 represents an extension of the classical resistivity one can be, and has been, used in a wide
65 variety of contexts: in urban areas (Panissod *et al.* 1998, Flageul *et al.* 2013), inside
66 monuments (Dabas *et al.* 2000, Dabas and Titus 2001) or for permafrost studies (Hauck and
67 Kneisel 2006, De Pascale *et al.* 2008) among others.

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

- 70 1. The frequency f must be sufficiently high to ensure that the impedance of each pole is
71 sufficiently low.
- 72 2. For a non-zero frequency, the effective conductivity is complex, $\sigma^* = \sigma + j\omega\varepsilon$; if the
73 electrical conductivity σ is to be measured, the condition $\sigma \gg \omega\varepsilon$ must be fulfilled (ω
74 $= 2\pi f$ is the angular frequency and ε the dielectric permittivity). However it is possible

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

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

82 As for metric scale shallow depth ground exploration multipoles (Panissod *et al.*
83 1998), a single pair of current transmitting poles is adopted, with two pairs of voltage poles
84 (hexapole). This device corresponds to the minimum requirement for the assessment of
85 resistivity variations as functions of depth. In order to implement a compact array to analyse
86 the stones in ancient monuments, a configuration close to the square array is adopted. The
87 exact configuration of the array is displayed in Figure 1. Each pole has an area of $5 \times 5 \text{ cm}^2$
88 and is located at the end of a 'leg' beneath the electronic box. The operational frequency
89 range corresponds to the decade starting at 10 kHz; in the experiments presented below, it is
90 fixed at 31.25 kHz. The capacitance of each pole is 2 pF in free air; this value increases when
91 a material of greater permittivity is present in the vicinity of the pole. Six quantities,
92 referenced to the internal trigger, are measured: the in-phase, I_p , and quadrature, I_q ,
93 components of the injected current and the voltage, V_p , and V_q of each pair of voltage poles.
94 The variables measured in these conditions are the two complex impedances Z_1 or Z_2 where Z_i
95 = $P_i + jQ_i$, the voltage in-phase and quadrature components being calculated by the
96 expressions:

$$97 \quad P = \frac{V_p I_p + V_q I_q}{I_p^2 + I_q^2} \quad \text{and} \quad Q = \frac{V_q I_p - V_p I_q}{I_p^2 + I_q^2}$$

98 The apparent properties are given by:

99
$$\rho = K \frac{P^2 + Q^2}{P} \quad \text{and} \quad \varepsilon = - \frac{1}{K\omega} \frac{Q}{P^2 + Q^2}$$

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

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

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

113

114 **Measurements over three monuments**

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

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

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

129

130 **Results**

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

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

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

146

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

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

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

157

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

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

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

172

173 **Discussion**

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

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

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

193

194 **Conclusion**

195 The electrostatic hexapole used in this series of studies over three monuments has proved to
196 be easy to implement and efficient to discriminate between the different types and origins of
197 carbonate stones. The volume taken into account in the measurements corresponds to that of

198 the whole stone and these measurements are repeatable. The study showed the evolution that
199 took place for religious main building constructions with respect to the choice of the stones
200 between the XIIIth and the XVIIth centuries. This technique should be considered as a new
201 tool for the study and the management of historical buildings.

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

205

206

207

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215

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258

259

260

261 **Figure captions**

262 Figure1: View of the hexapole electrostatic device

263 Figure 1 b : Chromatic chart for figures 2 to 11

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

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

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

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

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

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

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

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

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

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

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

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

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

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