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How to combine several non-destructive techniques for a better assessment of concrete structures

D. Breysse [a,*], G. Klysz [b], X. Dérobert [c], C. Sirieix [a], J.F. Lataste [a]

[a] University of Bordeaux, GHYMAC, France
[b] L.M.D.C., University of Toulouse, France
[c] Laboratoire Central des Ponts et Chaussées, University of Nantes Atlantique, France

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Abstract

Non-destructive techniques are often seen as a practical and efficient way to assess the structural state of existing reinforced concrete structures. However, assessment cannot be reduced to measurement and interpretation, and asset managers and structural engineers often need a quantitative assessment. It is here that a combination of several techniques can offer precious help. This paper intends to show what kind of improvement can be expected from the combination of techniques. Examples are taken from series of on-site case studies and laboratory experiments. The focus is on the assessment of water content and concrete quality.

Keywords: Concrete; Electrical properties; Humidity; Non-destructive techniques; Physical properties

1. For an efficient and rational use of the combination of techniques

For the maintenance of their reinforced concrete structures, engineers need to know their state of health. When detecting or getting suspicion of possible pathology from visual inspection, they need to know first the origin of this problem, then if there is a possible evolution and more over at what rate, and finally what is the level of the problem, its extent and location.

Non-destructive techniques (NDT) can assess the state of health of structures, but they can only provide an indirect approach to their performances. Then, the aims of NDT can be classified as being able to: (a) detect (a defect or a variation of properties, between two structures or inside one structure), (b) build a hierarchy (i.e. to rank on a scale), regarding a given property, between several areas in a structure or between several structures, (c) quantify these properties, e.g. compare them to allowable thresholds. Detection, ranking and quantification can be regarded as three levels of requirements, the last being the strongest. Much research has been devoted to the development of techniques or of data processing for a better assessment of building materials. Some authors have tried to synthesize the abilities of techniques with respect to given problems [1,2] or to define the most promising paths for future developments [3]. The general agreement is that the quality of assessment can be limited due to sources of uncertainties arising at various levels and caused: by the testing method, by systematic interferences with the environment, by random interferences (due to material intrinsic variability), by human factor influence and by data interpretation [4]. Thus, an improved assessment can be looked for by reducing any of these sources of uncertainties.

Many case studies exist where several techniques have been combined on a given structure (or on laboratory specimens), but we think that real added value will be obtained only when the question of coupling has been correctly analyzed [5]. This added value can be defined in terms of: (a) accuracy of estimation of properties, (b) relevance of physical explanations and diagnosis, (c) shorter time to reach a given answer.

Table 1 illustrates the sensitivity of four different non-destructive techniques to several important properties of concrete. It is drawn from a national review of the state of the art recently established in France [6] and from results obtained in a

* Corresponding author. GHYMAC, University Bordeaux 1, Avenue des Facultés, 33405 Talence Cedex, France. Tel.: +33 5 40 00 88 40.
E-mail address: d.breysse@ghymac.u-bordeaux1.fr (D. Breysse).

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Table 1
Supposed sensitivity of NDT to several important concrete properties

	Radar	Capacity (frequency)	Electrical resistivity	Ultrasonic
Water content	Velocity: − Amplitude: −	−	−	Velocity: + Attenuation: −
Porosity	−	−	−	Velocity: YES (+ if saturated, − if dried)
Chloride content	Velocity: − Amplitude: 0	0 ?	− ?	0
Rebars	Bias		Bias	Bias

The + and − signs correspond to the positive and negative sensitivity respectively; ? indicates uncertainty.

benchmark research program [7]. The + or − signs correspond to the positive (consequence varies with cause) or negative (consequence varies against cause) sensitivity. Two remarks can be made:

- when two parameters to which a given technique is sensitive are varied simultaneously, one cannot identify the reason for the observed variation without additional information. Such is usually the case when a variation in water content (due to varying environmental conditions) is superimposed on a variation in the concrete microstructure (porosity of the paste for instance). In this case, it is not possible to make a direct link between the observed variation of the measured property (wave velocity, electrical resistivity, ...) and the physical cause. This is, of course, a crucial point for diagnosis since a variation of the microstructure can reveal some defect or damage when the variation in water content (which can also depend on the microstructure, since the water content in a highly porous saturated concrete will be larger than in a dense saturated concrete) also depends on the environmental framework (temperature, exposure to the sun, dominant wind, etc.),
- the combination of two non-destructive techniques can provide additional information only if the sensitivity to the two parameters is different for the two techniques.

Let us look a bit further into this question, using a very general model. If one considers, for instance, two measured properties P1 and P2 and material parameters X1 and X2 to be evaluated, assuming the following dependencies:

$$P1 = f1(X1, X2) \text{ and } P2 = f2(X1, X2) \quad (1)$$

the efficiency of the combination will increase with increasing values of G:

$$G = [(\partial P1/\partial X1)(\partial P2/\partial X2) - (\partial P1/\partial X2)(\partial P2/\partial X1)] \div [(\partial P1/\partial X1)(\partial P2/\partial X2)] \quad (2)$$

When looking for interesting combinations, one has therefore to consider the sign and values of the four partial derivatives ∂Pi/∂Xi, $i=\{1, 2\}$. The priority is therefore the identification of techniques whose "crossed-sensitivity" is different, i.e., if one assumes that ∂P1/∂X1 and ∂P2/∂X2 have the same sign, techniques fulfilling:

$$SGN(\partial P1/\partial X2) \neq SGN(\partial P2/\partial X1). \quad (3)$$

If the usual NDTs do not satisfy this condition, the only perspective will be to find techniques that maximize the upper term in the expression for G.

A second important factor is the quality of the measurement. Since the measurements $M1$ and $M2$ will differ from the "true" properties $P1$ and $P2$, the better the reproducibility, the better the efficiency of coupling. One can write

$$M1 = P1 + E1 \text{ and } M2 = P2 + E2 \quad (4)$$

where the errors $E1$ and $E2$ depend on the quality of the measurement and on its sensitivity to a series of noise factors (low scale material variability, local conditions on the material-sensors coupling, external conditions, noise of electronic devices, etc.). We have even shown [7] that, in some extreme cases, with a high level of measurement noise, the use of a second technique can decrease the quality of the estimation!

In fact, the combination of techniques can have less ambitious objectives. That will be illustrated in different ways through the series of investigations presented in the following. The paper will refer to four possible types of combinations which will be illustrated by five examples (either measurements in laboratory and on real sites) all drawn from experiments performed in the frame a Research National Project [7]:

- Type [A]: comparison of results obtained via two or more techniques, so as to confirm measurements and recorded variations,
- Type [B]: comparison of results obtained via two or more techniques, so as to improve the interpretation of results,
- Type [C]: use of a "quick" technique to have a first rough mapping, followed by a second "slow" technique in the areas selected in the first step,
- Type [D]: use of a second technique to identify a parameter so as to correct its effect on the first measurement. This helps to eliminate a bias factor in the first measurement and to improve accuracy and quality of interpretation.

2. Case studies illustrating combination of techniques for the assessment of concrete properties

2.1. Type [A] combination — confirmation of test results obtained via different techniques

The combination of three techniques (infrared thermography, electrical resistivity and capacitance) to assess the water content/damage state of material along a profile is described in detail in [8] and [9].

In this case study, a precast concrete duct in which some damage (crack patterns) had been identified, was inspected through five different techniques (for radar, the high density of rebars prevented any interesting processing of results, and reliable ultrasonic measurements were impossible with the device used

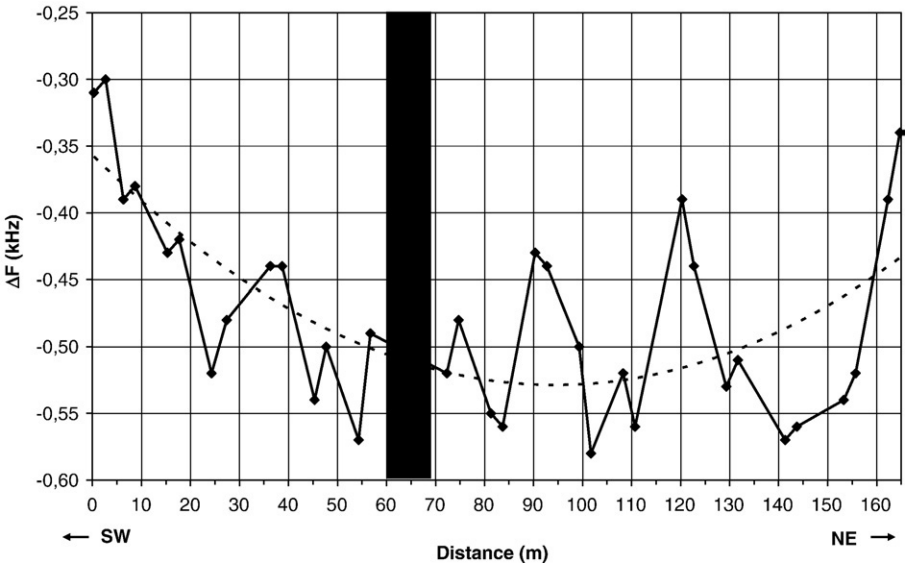

Fig. 1. Capacimetry: longitudinal profile of frequency (keystone).

because of the curvature of the surface). The longitudinal variations of the three measured properties along the duct profile show striking similarities (Figs. 1–3) which gives weight to any of the three measurements which could have been done alone. This is a direct illustration of a Type [A] combination. However, the measurements, even combined, do not provide any information about the "Why" of these variations. Two opposite interpretations can be formulated:

- It is possible to consider that the material damage varies along the abscissa, with, among other consequences, an increase in porosity, which leads to lower frequencies, lower resistivities and lower temperatures in the mid part of the duct, due to higher water content in the saturated concrete,
- It is also possible to explain the variations in the water content profile by environmental conditions (the duct facing south-west on its left-end and north-east on its right-end), which favor a relative drying of the concrete cover near both ends. In this case, the longitudinal variations can be explained without any damage or cracking.

Going further in the interpretation requires a more detailed analysis of the parameters influencing each property measured, so as to be able to invert the system of Eq. (1).

This Type [A] of combination has also been carried out in another case study. The specimens, made of various types of concrete in the 25 MPa–120 MPa range of one-month compressive strength had been subjected to marine attack (in

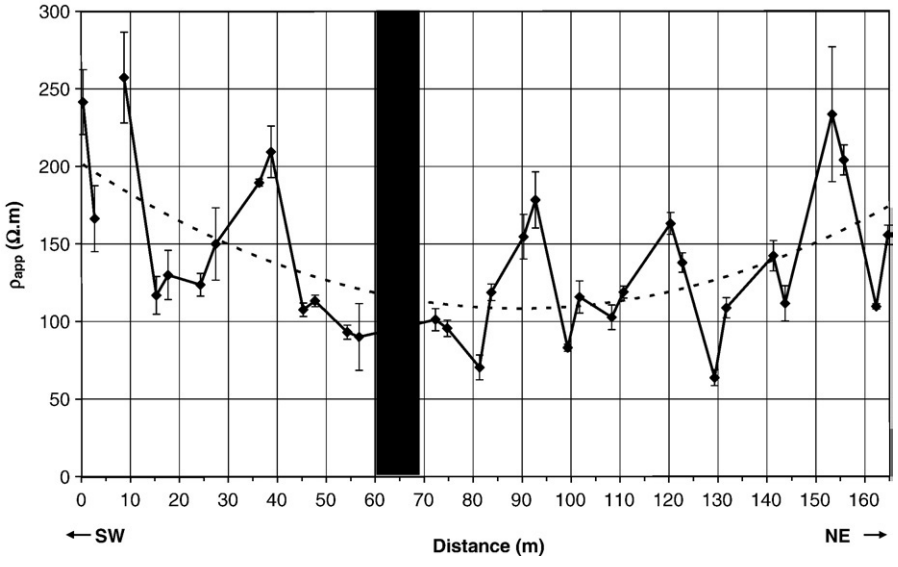

Fig. 2. Average values and error bars of electrical resistivity measured in three points, along the keystone of the duct.

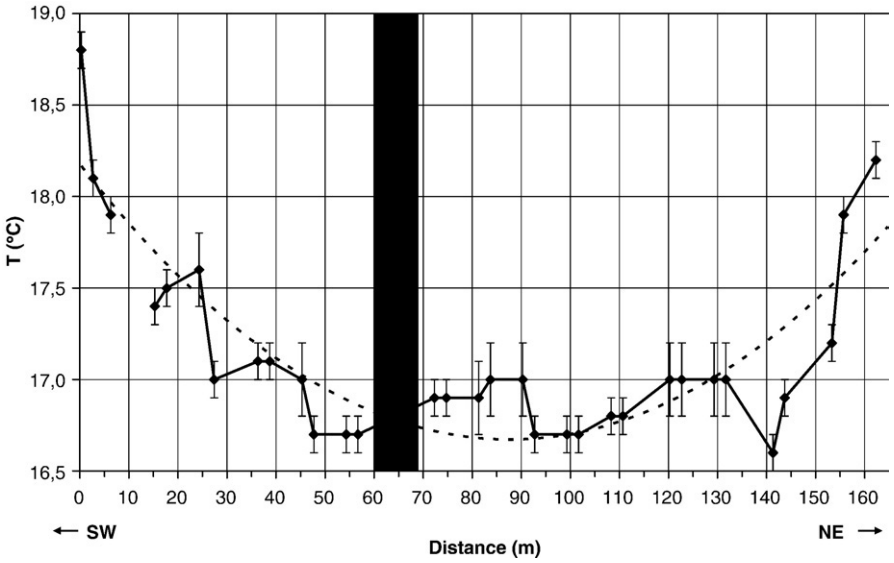

Fig. 3. Average values and error bars of the surface temperature of the keystone measured with a thermal image (0.38 × 0.46 m^2).

the tidal domain in La Rochelle harbor) for several years. The specimens were blindly investigated and ranked by various destructive techniques. Fig. 4 illustrates how the electrical resistivity varied with the concrete mix.

The very high sensitivity of resistivity to concrete strength is confirmed here. It enables to rank strengths for similar concretes (normal concrete, or concrete with fly ash addition or silica fume addition) kept in comparable environments. Fig. 4 also confirms that various types of concrete cannot be directly compared: here the resistivity of M30CV (compressive strength 30 MPa with fly ash additions) is larger than that of M50 (normal concrete, compressive strength 50 MPa). Measurements performed by [10] had yet shown the larger resistivity of concrete with silica fume addition, this increase being larger for low *w*/*c* ratios.

The ranking between specimens obtained via electrical resistivity measurements [11] was confirmed via radar measurements and capacimetry. However, as was the case in the first case study, this confirmation (Type [A] combination) tells nothing about the physical explanation. The physics involved in any of the non-destructive techniques is sensitive to many microstructural parameters (porosity and connectivity, properties of the particles...) as well as to parameters depending on environmental conditions (water content, chloride content...). Thus, the variation of a single physical property (radar attenuation, electrical resistivity, capacity...) can have various alternative explanations. For instance, the variation in electrical resistivity could have been due to a variation in porosity (which changes greatly between different mixes), water content (which changes with time due to the tidal effects) or chloride content. It is the reason why it is important to try to make the part between all these possible causes before interpretation.

2.2. Type [B] combination: improvement of the test results interpretation obtained via different techniques

Our research project provided us with the opportunity to develop this type of combination on several structures. This will be illustrated here in the case of a bridge wall near Lilles, Nord (Fig. 5). The inspected area, below the deck, is subject to alcali-aggregate reaction (AAR), and some cracking patterns can be seen at the concrete surface. The same profile, approximately 12 m long, was inspected through radar and electrical resistivity measurements. The visible damaged area was localized between 9.8 m and 12.4 m.

Both the techniques are potentially sensitive to AAR, since damaged areas are wetter. A higher value of water content increases the attenuation of the direct wave amplitude (radar) and decreases the resistivity. Thus the AAR assessment is only indirect, since the two techniques take advantage of water content sensitivity.

Figs. 6 and 7 show the results obtained on a 20-cm mesh (here any point represents the average of three neighboring measurements, so as to reduce the E1 and E2 noises of Eq. (4), the electrical resistivity is obtained using a 5-cm-square device). For both curves, the longitudinal profiles indicate a slow variation

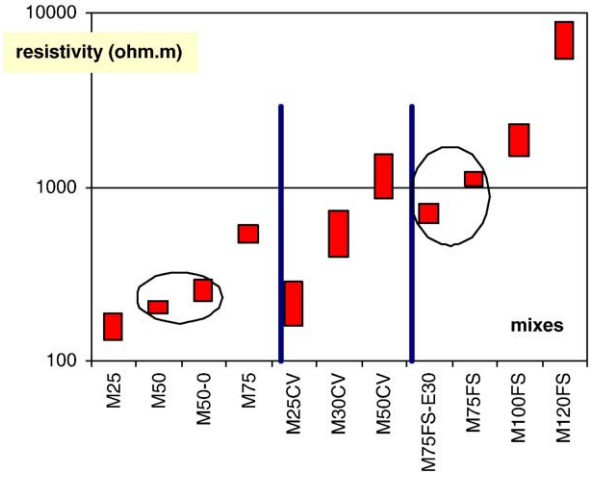

Fig. 4. Range of variation of electrical resitivity for 10 concrete mixes of various strengths.

Fig. 5. View of the bridge. Orange line below the deck gives the location of the profile. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(decrease of radar amplitude, decrease of resistivity for electrical measurements) and a drop at the right end, more contrasted for radar.

Fig. 8 illustrates the relations existing between the two measurements. Despite what appears as "noise" (the variations seen on the resistivity values between 2 and 8 m in the 200–400 Ω m range are not correlated with any "structured" variation visible on radar measurements), two sets of points can be clearly distinguished:

- the first set corresponds to large values of the radar amplitude (>11 800) and the resistivity (>400 Ω m),
- the second set corresponds to low values of the radar amplitude (<10 800) and the resistivity (<150 Ω m).

It is important to note that these sets are not randomly spatially distributed. The first set is located at the left end of the profile (facing South) and the second at the right end of the profile.

The similarity of shapes between the two profiles is a good argument to justify the combination of the techniques. It helps the interpretation since one can focus first on information which can be given by both techniques. (In a second step, it could be interesting to analyze whether some physical basis can explain the variations in the resistivity profile which were considered as "noise" in the first step.) The physical interpretation then stands on a more reliable basis:

- The variations at the left end can be interpreted as corresponding to drier material, probably due to environmental conditions (this end faces South),
- The variations at the right end can be interpreted as corresponding to the area where the alkali-aggregate reaction develops, as was confirmed through visual inspection.

Another study [12], performed on the Bell's Corner experimental site (Ottawa region, Canada) was devoted to the comparison provided by impact-echo, infrared thermography, electrical resistivity and radar measurements for assessing the alkali-aggregate reaction on concrete blocks of various mixes. It has shown that radar measurements (specially magnitude of the direct wave) is the best promising method, when electrical resistivity is also sensitive to other factors, which makes data interpretation difficult.

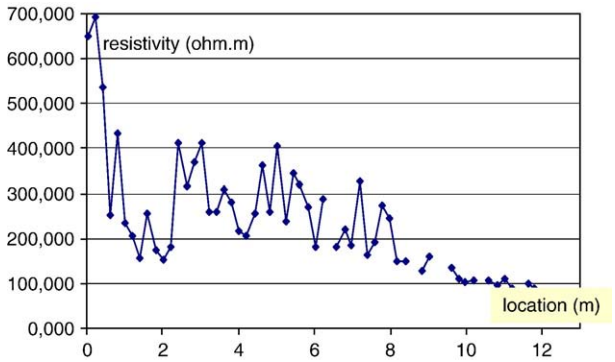

Fig. 6. Electrical resistivity profile.

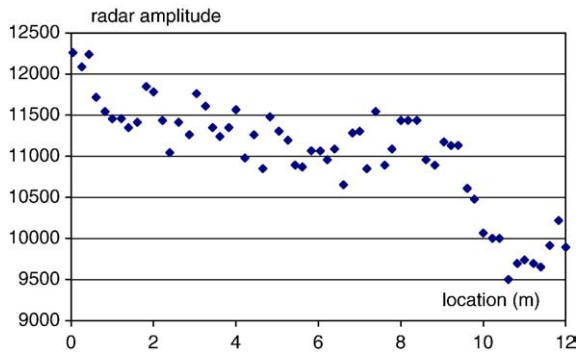

Fig. 7. Radar profile of the direct wave amplitude.

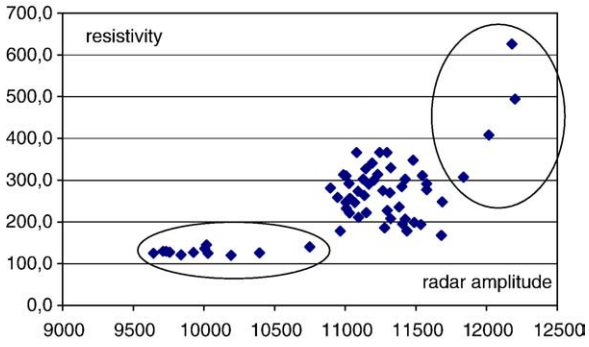

Fig. 8. Correlation between measurements obtained via the two techniques.

In any case, the diagnosis of alkali-aggregate reaction is not direct, since it is only done through the variations in water content which can be directly assessed by a simple visual inspection. In the case described here, NDT measurements provide however a more accurate estimation of the extent of the area affected by the chemical reaction. Another contribution is that they enable to quantify the material properties, opening the way towards the definition of critical values, which could be used for other structures, or for areas where the damage is not visible, but where NDT measurements would indicate values approaching critical values.

2.3. Type [C] combination — application of different techniques for "quick" localization of defected areas and then detailed inspection by "slow" but more accurate measurements

Some techniques have the particular advantage of enabling a quick overview of the structure, because they use a quickly moving set of sensors or because they are wide-field. This is the case, for instance, for infrared thermography, which can be used to monitor a large scene with an optical sensor that can be located at a distance from the surface under investigation [13].

It is thus fruitful to use this technique in a first step and to investigate the areas where some interesting patterns are identified in greater detail (with a technique requiring more time or heavier equipment). A case study on the Empalot bridge, near Toulouse, provided us with such an opportunity. Fig. 9 shows the infrared and visible pictures of one slab on the lower face of the deck. The two pictures were taken at the same time.

The surface temperature range here is 13.5–14.5 °C. The whitish areas indicate lower temperatures. Three such areas can be seen on the infrared picture:

- the first one, on the left side of the red contour (which corresponds to an area where surface concrete has fallen) is the lower face of a transversal beam, which is not at the same distance than the deck surface,
- the two others, on the right side of the red contour do not correspond to any visible defect.

Since delamination was suspected on this 60-year-old bridge, these areas (and the full deck surface) were thoroughly investigated (with radar, electrical measurements, sonic waves and capacimetry), and the delamination was confirmed. Thermography gave information on the existence and extension of the affected area from a distance, when all other techniques required heavy equipment (truck and platform) to reach the concrete surface and handle measurement devices. The potential interest of such a combination is to provide information quickly, which helps the expert define and plan detailed investigations. The interest of the second technique will be to provide quantitative information on material properties, since it is not straightforward to derive them from surface temperature measurements.

Of course, the information gathered with the quick technique can also be processed to help the diagnosis. For instance, the variations of the temperature differences over the day between the delaminated area and the "good" surrounding concrete can be processed so as to give an estimation of the delamination depth. This kind of analysis however remains at a development stage [14]. If the surface is of easy access, it remains more simple to use sonic techniques which will provide the same type of information.

Another promising Type [C] coupling possibility has been recently identified [15], by combining stress wave measurements and dynamic elastic Young's modulus on thin disks from cores. Even if one of these two techniques cannot be considered as NDT, the interest is that the combination of NDT (stress-waves) and another technique provides very useful information for assessing near-surface gradients in fire or frost damaged

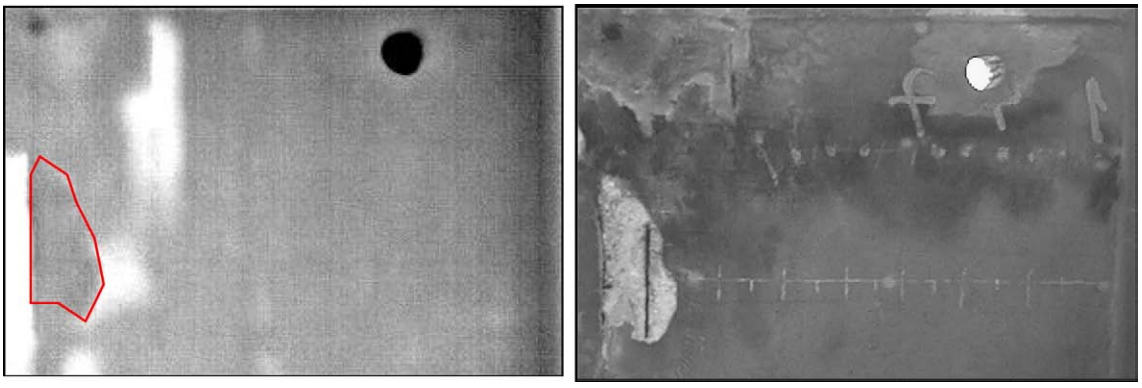

Fig. 9. Infrared thermography and visible picture of the same slab.

concrete. In this case, the NDT is used both for locating where coring is the more relevant and for calibrating the results in terms of layering.

3. Combination of techniques to uncouple influent factors (Type [D] approach)

It has been pointed out that the main difficulty in diagnosis comes from the fact that several factors can explain the same measurements. It is therefore crucial to develop a strategy enabling the effects of each factor to be uncoupled. We will illustrate how this can be done in practice below.

3.1. Combined influences of porosity and saturation rate

For the assessment of concrete, it is important to be able to differentiate between the effects of porosity and those of water content since the latter can change quickly with time, and the former cannot. It is also a key step towards the quantification of sensitivity ($\partial Pi/\partial Xi$ of Eq. (2)), which has been noted in Section 1 as a challenging task.

The relations between the microstructural properties of concrete (mainly porosity) and its overall properties (strength or electrical resistivity) have been under study for a long time. Archie's historic empirical model [16], applying to rocks and relating resistivity (or conductivity) to porosity, has been used for cementitious materials. Archie's law can be written, in its more general expression:

$$\rho = a\rho_w \Phi^{-m} S^{-n} \quad (5)$$

where ρ and ρ_w are the resistivity of the body and that of the pore fluid respectively, Φ is the open porosity and S is the saturation rate; a, m and n are empirical parameters, the m value being explained in terms of tortuosity of the pore space. According to Archie, the m value ranges between 1.8 and 2.0 for sandstone and is about 1.3 in unconsolidated sands. This formula can be enriched to take the percolation threshold into account, but we will restrict ourselves to the original one here. The same kind of power function between porosity and saturation rate on one hand and transfer properties on the other hand has also been developed by Van Genuchten [17] and applied by many authors to soils as well as to concrete [18].

Regarding concrete, a lot of parameters related to the mixture, to its curing process or to its environment can influence the properties like it has been shown in recent state-of-the-art paper [19].

Several authors have tried to use the Archie's law in cementitious materials, but there is no agreement regarding the estimated values of m and n. These values of m are 2.15 for 28-day and 3.21 for 29-year cement mortar [20], 5.77 for fresh cement slurries [21] and only 1.73 [22] or 1.20 [23] for concrete, but in this last case the porosity is replaced by the paste fraction. Some authors have also expressed the resistivity as a function of the porosity and water content [24], which can be simply expressed as a function of Φ and S. When this dependence is expressed and the data of [24] are re-analyzed under the shape of Eq. (5), they lead to $n=1$ and to $m=6.93$. The least one can say is that no general agreement has been reached, since the value of m ranges between less than 2 and 7!

3.2. Modeling combined influences of porosity and saturation rate on electrical resistivity

Adapting a methodology used in rock geophysics to concrete [25], used the combination of resistivity measurements and acoustic measurements to uncouple the effects of saturation rate and porosity, since Wyllie's empirical formula states that the velocity of longitudinal waves depends on porosity and Archie's law states that resistivity depends on both porosity and saturation rate [26]. Here, specific sets of experiments have been performed to identify the dependence between resistivity and the internal parameters of the concrete paste. These experiments consist in two stages which will be described in the following.

3.2.1. Combining information from various sources to identify Archie's exponents

The first set (Fig. 10) consisted of measurements on various concretes (OPC, FAC, HPC) which could be considered as saturated ($S=1$, since the measurements were performed as the tide was going out, as soon as the specimen was out of the water), in La Rochelle harbor [11]. These specimens had been designed and cast in the frame of High Performance Concrete National Research Programme. The water to cement ratio varies from 0.26 to 0.96 and three types of concrete are studied (normal concrete, or high performance concrete, with either fly ash addition or silica fume addition). There are about 5 years old and they have been placed in this portuary environment since their young age. The properties which had been measured were:

- compressive strength ranging from 23.5 to 127.5 MPa,
- water porosity ranging from 7.4% to 15.0%.

The second set (Fig. 11) consisted of measurements on a series of laboratory specimens of ordinary concrete (320 kg/m^3 of CEM I 52.5 cement, $w/c=0.61$), whose properties are $f_{c28}=25$ MPa, water porosity=0.179. They have been progressively dried in a controlled environment. The resistivity was measured for

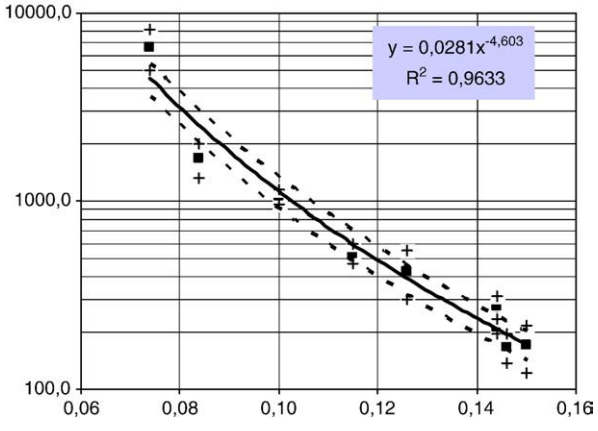

Fig. 10. Porosity versus resistivity (Ω m), La Rochelle specimens.

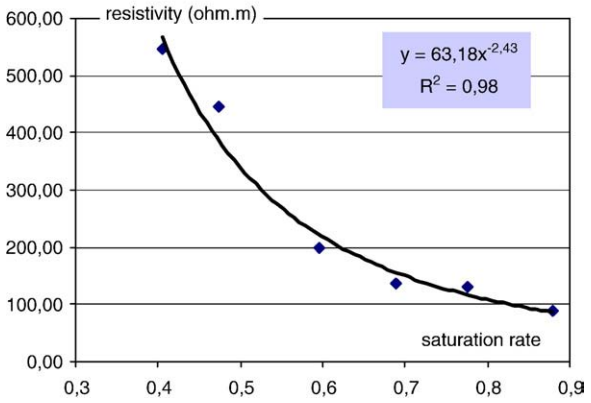

Fig. 11. Saturation rate versus resistivity (Ω m), Toulouse slabs.

saturation rates in the 0.4–0.9 interval. This procedure had been followed by [27] who had shown a large increase of resistivity between saturation and $S=0.4$ (resistivity multiplied by 30 to 1000 according to the *w/c* ratio).

The dashed lines on Fig. 10 correspond to plus/minus one standard deviation from the average, to account for the variability of measurements. The points respectively correspond to average (squares), min and max measured values (crosses) for each specimen. The regression curves by a power function gives:

$$\rho = 0.0281\Phi^{-4.603} \text{ in the first case } (S = 1 \text{ and varying porosity}) \quad (6)$$

$$\text{and } \rho = 63.18S^{-2.43} \text{ in the second case } (\text{fixed porosity and varying saturation}). \quad (7)$$

These two formulas are in very good agreement, since, although they were obtained in independent contexts and for different concretes, if we equate the two expressions with $S=1$ in expression (7), we obtain $\Phi=0.187$, which is very close to the true value (0.179).

The value obtained for the m exponent (4.60) is compatible with the literature, but we have seen above that this is not a very convincing argument. Combining the influences of Φ and S, we obtain:

$$\rho = 0.0281\Phi^{-4.603}S^{-2.43}. \quad (8)$$

3.2.2. Assessing the exponents from an unique set of specimens

This empirical relation (8) cannot be seen as a proposal for a "universal relation" between porosity, water content and electrical resistivity, since the two sets of specimens used for identifying the empirical exponents (m and n) have different characteristics. Thus it is important to check, on a common set of specimens, if this relation can be confirmed and if some consistency regarding the exponents can be found.

We had the opportunity, through a new collaborative project (ANR-SENSO) to perform additional experiments. The whole program is not detailed here, since its aim is mainly focussed on the combination of various non-destructive techniques and on the assessment of the epistemic and aleatoric uncertainties at various levels when performing measurements on concrete. More information on the experimental strategy is provided in [28].

The set of specimens studied here consists in 72 plain concrete slabs, corresponding to 9 different mixes (the more influential varying parameter in the mixes is the *w/c* ratio, ranging 0.35 to 0.90), with 8 specimens cast for each mix. The water porosity is controlled on twin slabs from the same mix (also used for destructive tests). It ranges from 12.5% to 18%. Electrical measurements are performed with the four-probes device described above, with two sizes of the device (5 cm and 10 cm) which enable to investigate the material at two different depths. The saturation rate is controlled, since the measurements are performed at several levels of saturation:

- "dry" specimens, which have been kept in the oven at 80 °C under weight stabilization,
- "saturated" specimens, after immersion and having waited enough time for weight saturation,
- and intermediate levels of water saturation, ranging in the 40%–80% interval, drying being controlled to reach these target levels.

Thus, it is possible, from the analysis of resistivity measurements, to quantify both influences of porosity and saturation rate on the electrical resistivity. It must be added that the experimental strategy, focussing on the uncertainty analysis, consists in repeating the measurements on several points for each specimen and each series of measurements, such as to quantify the variability [28]. This point is however not discussed here.

Assuming the Archie's law can describe the resistivity versus porosity and saturation rate dependency, a unique set of (m, n) exponents is derived for the whole series of measurements (here 36 values for each of the two device sizes). It leads to:

$$\rho = 0.0221\Phi^{-4.74}S^{-2.88} \text{ for the 5 cm device} \quad (9)$$

and to

$$\rho = 0.0337\Phi^{-4.23}S^{-2.58} \text{ for the 10 cm device.} \quad (10)$$

More over, the confidence intervals have been calculated for both exponents. They are about +/−20% for a 95% level of confidence. Fig. 12 enables comparison between the experimental value and the calculated value (from Eqs. (9) and (10)). It shows a very good agreement on more than two decades, whatever the device size. Further analysis will be performed to see what are the reason for the slight discrepancy on some specimens, since many causes can be invoked. For instance, the saturation rate is only globally controlled, but can it will be estimated with higher specimens from the specimen weight. Another reason is that one mix is made with a different aggregate (calcareous instead of silica), and has therefore different electrical properties.

It can be noted, in addition, that the m and n values provided by this new series of experiments are of the same order of

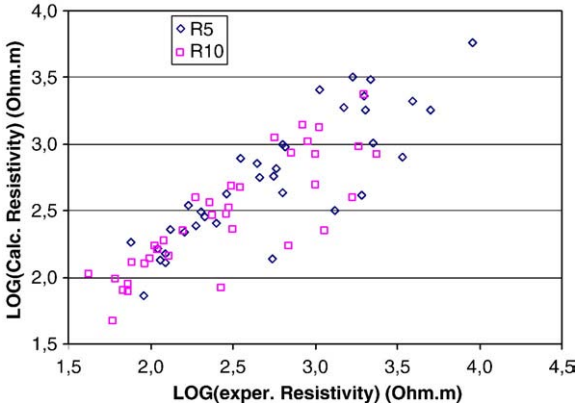

Fig. 12. Comparison between experimental resistivity and calculated resistivity in a log–log scale.

magnitude than those which had been identified in Eq. (8) from a totally different set of specimens. This stability can provide ways towards the identification of values which can characterize usual concretes.

3.2.3. Analyzing consequences on reliability of estimation

Our purpose is here to show how, even if one would have an "exact model" (assuming for instance that Eq. (8) or (9) is "true"), one would need additional information such as to make the part between all contributing factors (namely here porosity and water content, but, in a larger context, also chloride content, aggregate type and other factors...). This has, of course, to be put in relation with what had been explained in Sections 2.1 and 2.2, and it is developed on a simple example in the following.

3.3. Combination of electrical resistivity measurement and capacimetry

The resistivity measurements suffer from some lack of repeatability, due to the imperfect reproducibility of the measurement process at a given point, and to the spatial variability at small scale in relation with material heterogeneities [28]. This can be seen on Fig. 10 since the dotted line indicate an uncertainty of plus/minus one standard deviation in resistivity measurements. The coefficient of variation of these measurements is usually about 7 to 10%. From the scatter in resistivity measurements, one can deduce the uncertainty on the estimation of porosity (S being known) or saturation rate (Φ being known).

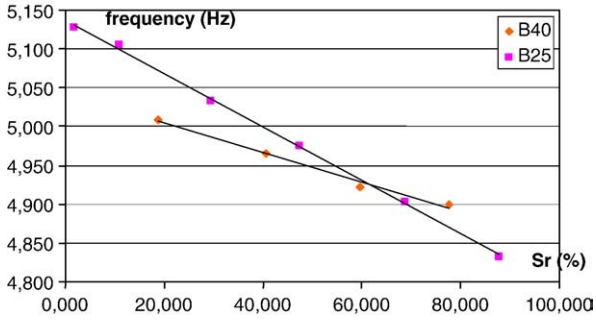

Fig. 13. Experimental correlation between frequency (in Hz) measured with the capacimeter and saturation rate for two concrete mixes.

Table 2
Comparison of sensitivity regarding a saturation rate variation

Property P	$M_{80\%}$	$M_{90\%}-M_{80\%}$	$M_{70\%}-M_{80\%}$	$\Delta M^+/M$	$\Delta M^-/M$
A (radar)	13 023	−673	673	−5.45%	+5.45%
V (acoustical) m/s	2390	27	−27	+1.13%	−1.13%
f (capacity) Hz	4.865	−0.034	0.034	−0.70	+0.70%
ρ (resistivity) Ω m	103.5	−33.7	50.0	−32.6%	+48.3%

$Mx_{\%}$ denotes the value of the measurement for the property P, for Sr=x%.

Considering a +/−10% uncertainty on the resistivity measurement, and taking average values for m and n exponents (m=4.5 and n=2.7), linearization of Archie's law for small variations leads to +/−10/4.5=+/−2.1% for porosity relative uncertainty and +/−10/2.7=+/−3.6% for saturation relative uncertainty. If we assume for instance a condition with (porosity=15% and saturation rate=80%), the absolute uncertainty is then +/−0.3% for porosity and +/−2.5% for saturation rate. These uncertainties are small regarding the material heterogeneity. They however correspond to an optimistic situation, when one parameter has to be identified, the other being known. When the two parameters are unknown, the uncertainty is magnified.

More generally, the quality of the estimation will depend on both the quality of the NDT measurement and the sensitivity of the measurement to the parameter which has to be quantified. We will see that on another example. The experimental program on the laboratory specimens mentioned in Section 3.2. has shown a linear dependency between Sr and the frequency measured (in Hz) with the capacimeter. We obtained f=5.137−0.34 Sr for a 25 MPa concrete and f=5.04−0.192 Sr for a 40 MPa concrete. These two regressions were obtained with a very high correlation. The frequency is linearly dependent on water content, but the sensitivity (i.e. slope of the regression line) depends on the porosity (Fig. 13). If this measurement is performed alone, it is, once more, impossible to distinguish between S and Φ. The idea is, of course, to combine both measurements, since the sensitivity matrix (G expression (1)) can now be identified, the partial derivative being drawn from the (f, Sr) relation.

Some words must be said about the sensitivity and the reproducibility of measurements, on the laboratory specimens mentioned in Section 3.2. Data in Table 2 provide the sensitivity estimates for four techniques, taking a +/−10% variation of Sr around a reference value of 70%. We note that the sign corresponds to what was expected in Table 1.

Table 3
Comparison of sensitivity and reproducibility

Property P	Sensitivity S	Variance reproducibility R	S/R
A (radar)	Average	Low	High
V (acoustical) m/s	Low	High	Low
f (capacity) Hz	Low	Very low	High
ρ (resistivity) Ω m	High	Average	High

The values $\Delta M^+/M$ and $\Delta M^-/M$ give the relative variation of M consecutive to a +/− 10% variation of Sr. It suffices to divide them by ΔSr/Sr (=10%/80%=1/8) to obtain an estimate of the relative sensitivity of P to Sr. The sensitivity to saturation rate variations is much larger for electrical measurements than for capacimetry (ratio about 40/1).

However one must also consider the variance reproducibility of the measurement: if a property is very sensitive to Sr but has a low reproducibility (high variance), there is a risk of the effect of the variation (which is what we are looking for) being masked by the measurement noise. To rank the properties according to their efficiency, the relevant criterion is thus the sensitivity to variance reproducibility ratio (Table 3).

Since the f or A measurements have a better reproducibility than the resistivity measurement, they can be used to some profit. A more general understanding of the more efficient couplings then requires the full knowledge of the sensitivity (∂Pi/∂Xi in Eq. (2)) and of the reproducibility (Var Mi in Eq. (4)) in the site context. It must be added that, although the sensitivity values come from the physics involved and thus can be assumed to be given, the variance reproducibility can be improved with the development of techniques and expertise.

4. Perspectives

We have tried to show by a few examples drawn from measurements on laboratory specimens and from on-site case studies what kind of difficulties one encounters when trying to combine non-destructive techniques for concrete assessment. This work has been undertaken during a research program which has also enabled us to identify the influences of saturation rate and porosity on several types of measurements, not all of which (radar, ultrasonic velocity) have been covered fully in this paper (refer to [7] for more details). As pointed by [4], difficulties arise from the lack of reliability of measurements themselves (due to devices, protocol or user), from the spatial natural variability of the material, or from the difficulty to uncouple the influence of environmental conditions. The main difficulty probably lies, however, in the fact that any physical parameter than can be measured through non-destructive techniques depend on several material and environmental parameters whose effects are very difficult to uncouple.

Our purpose was mainly here to point the fact that what is often called "combination" is in fact no more than just the use in the following of several techniques. We have tried to formulate this problem of combination and material assessment, to show how complex is the challenge to be addressed.

The first examples of combination have shown how several techniques can mutually strengthen their empirical conclusions. However, it must be pointed that material diagnosis requires additional expertise to interpret NDT results. A well promising type of combination is that of Type [3], when a quick technique is used before a more detailed program is defined. It is the reason why infrared thermography deserves interest.

Using the empirical expressions derived from Archie's law on the one hand and the sensitivity analysis on the other, it has been shown that it seems possible, at a formal level, to uncouple the mixed effects of two influencing parameters and thus to improve the diagnosis of the structure, since some quantitative assessment of material parameters as crucial as porosity or water content can be obtained. Before using this approach for practical applications, additional research is required, mainly to identify the relations between the properties (porosity, water and chloride content, microcracking...) and the measurements in a more systematic way for a large enough set of concretes. Such an experimental program is currently under development at a national level (SENSO-project, funded by the National Research Agency). Its purpose is to build a wide database, for various types of concrete, enabling the identification of the respective influences of material parameters (water/cement ratio, aggregate size and type, water content...) on non-destructive results provided through many NDT (acoustical, radar, electrical, capacimetry, IR thermography...) for plain and ageing concrete (effects of carbonation, chloride content and cracking are to be addressed). Many efforts will be devoted to the assessment of the "G" functions of Eq. (2) and to the uncertainties attached to all measurements (variability being assessed at several levels: point of measurement, specimen, mix...).

Of course, although they have not been considered here, semi-destructive techniques (like rebound hammer or pull-out [29]) could be analyzed in the same state of mind, since the same coupling methodology can be used combining one non-destructive and one semi-destructive technique.

Other last interesting perspectives have come to the light during the research program: the radar measurements have shown [30], for non-saturated concrete, that the direct wave amplitude depends only on the saturation rate while the wave velocity depends on both saturation rate and chloride content. Using the same formalism as described in this paper, it is probably possible to quantitatively assess the chloride content of structures using only NDT.

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