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

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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

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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:

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

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