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Combining NDT techniques for improved evaluation of concrete properties

Zoubir-Mehdi Sbartaï [a,*], Denys Breysse [a,1], Mathilde Larget [a,2], Jean-Paul Balayssac [b,3]

[a] Université de Bordeaux, I2M-GCE, CNRS, 351 cours de la Libération, 33405 Talence cedex, France
[b] Université de Toulouse, UPS, INSA, LMDC, 135 av de Rangueil, Toulouse, France

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A B S T R A C T

Developing a strategy for the management and maintenance of the built heritage is a key challenge for research. In this context, a large experimental program was implemented to develop a methodology for non-destructive testing (NDT) of concrete structures based on the determination of: (a) the sensitivity of the NDT techniques, (b) the uncertainty of the NDT measurements, and (c) the optimal combination of NDT techniques to enhance the evaluation of concrete properties.

This paper presents the strategy employed and the first results obtained from a comprehensive experimental database of NDT techniques. It also emphasizes how the variability of measurements can be taken into account and how statistical analyses can be used to evaluate the relevance of the available NDT techniques.

1. Introduction

Early stage evaluation of reinforced concrete (RC) is an important step in establishing a detailed diagnosis of existing structures. For this reason, assessing concrete properties using non-destructive testing (NDT) methods can play an important role in the process of RC structure management before any expensive maintenance is undertaken [1]. Among the main physical properties of concrete to be assessed are:

– Water (or moisture) content, for two reasons:
  1. A high value of water content can be a sign of bad quality of the material (often due to delamination), but it can also signify a potential vector of future damage is present, since water is an agent common to most deterioration processes (such as salt ingress, dissolution, freezing, and alkali aggregate reaction).
  2. Some NDT techniques are sensitive to several properties of concrete. For example, acoustic methods are used for evaluating mechanical properties (e.g. Young's modulus) but are also affected by moisture variation. Due to this double dependency, it is not easy to decide on the cause of the variation in the NDT measurement.

– Porosity, since it is an important factor that controls mechanical properties such as Young's modulus and strength, and also the durability of concrete (exposed to salt ingress, carbonation, etc.).

In the past decade, research has developed ways of testing the potential of NDT techniques to evaluate the condition of concrete. However, the measurement of NDT physical parameters such as velocity of ultrasonic waves, electrical resistivity or GPR (Ground Penetrating Radar) wave attenuation is disturbed by uncertainties due to various causes:

(a) The lack of accuracy and repeatability of the measurement process at a given point of the tested material.
(b) The variability of the material at different scales: in a limited volume assumed to be homogeneous, between samples of the same concrete mixture, or between two successive batches of the same mixture.
(c) On site, variability can also be induced in an originally homogeneous concrete by some contrast in environmental exposure conditions such as a variation of moisture or temperature.

Because of these possible variabilities, the diagnosis of RC structures becomes complex due to the difficulty of NDT data interpretation. For instance, in the case of detection of a damaged zone, it

* Corresponding author. Tel.: +33 5 40 00 35 96; fax: +33 5 40 00 35 95.
E-mail addresses: zm.sbartai@i2m.u-bordeaux1.fr (Z.-M. Sbartaï), denis.breysse@u-bordeaux1.fr (D. Breysse), mathilde.larget@u-bordeaux1.fr (M. Larget), jean-paul.balayssac@insa-toulouse.fr (J.-P. Balayssac).
[1] Tel.: +33 5 40 00 88 40; fax: +33 5 40 00 35 95.
[2] Tel.: +33 5 40 00 88 37; fax: +33 5 40 00 35 95.
[3] Tel.: +33 5 61 55 99 34; fax: +33 5 61 55 99 49.

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can be assumed that concrete properties (porosity, moisture, cracking, etc.) are significantly different in this zone from the values of a representative undamaged zone. The real challenge is to confirm that the difference between the NDT measurements in the two zones is effectively related to a difference in concrete properties, and not simply to cases a, b, or c above. The same question arises when comparing two measurements recorded at different times, e.g. for assessing material evolution. To provide reliable information to the expert of the diagnosis, it is then important to quantify the level of uncertainty of the measurements.

Another notable problem is the limitation of using only one NDT technique to directly evaluate one concrete property. For instance, GPR technology is sensitive to water saturation but also slightly sensitive to porosity [2], ultrasound is able to evaluate the modulus of elasticity but it is also sensitive to moisture and density [3,4], and so on. For these reasons, some researchers have proposed combining several techniques for concrete strength evaluation [5–8] or for detection and visualization in concrete structures [9,10], or the combination of several NDT parameters obtained with the same technique [11–13] in an attempt to confirm the diagnosis or to reduce the measurement noise. This original approach, which consists in combining NDT data, is promising but only if the additional cost is balanced by an enhancement of the diagnosis quality [14]. As reported above, knowledge of the evaluation quality is important in making a decision regarding additional cost or quality enhancement of the diagnosis. In addition, it is interesting to recognize whether the combination provides complementary or only redundant information. This information helps in the selection of the best combination for enhancing the evaluation of the desired concrete property.

This paper focuses on the implementation of a general strategy for enhancing the diagnosis of RC structures by NDT techniques. A large laboratory and on-site experimental programme has been implemented as a part of the French ANR project SENSO [15]. The first part of the strategy is based on the analysis of the quality and the sensitivity of many NDT techniques. In the second part, the complementarity or correlation between the selected NDT parameters is discussed and quantified for an optimal combination leading to improved concrete condition evaluation.

2. Experimental program and data analysis

2.1. Experimental program

The experimental program was implemented within the framework of the French national project "SENSO". The aim is to (a) evaluate the uncertainty of NDT measurements due to the imperfect repeatability and the material variability, (2) combine appropriate techniques in order to enhance the diagnosis of our built heritage. The program concerns a set of plain concrete samples of different mixtures. About 90 slabs (50 cm × 25 cm × 12 cm), implementing eight different compositions of concrete, were cast. The mixes covered a range of porosity sufficiently broad to be representative of what is classically found in structures. A large variety of NDT measurements were performed. These techniques can be summarized as follows:

- Electrical resistivity methods (Wenner and four-probe square array).
- GPR (Ground Penetrating Radar), direct wave analysis (arrival time and amplitude).
- Capacitive Method (3 frequencies of measurement).
- Ultrasonic surface waves method, with and without contact (velocity, attenuation, quality factor) [16,17].
- Ultrasonic waves in direct transmission (UPV).
- Impact echo (first peak frequency).

Table 1 summarizes the laboratory benchmark: mixtures, number of slabs, and the corresponding properties (degree of saturation, porosity, modulus of elasticity and strength). These properties were measured on cylindrical cores (modulus of elasticity, compressive strength, porosity) or by monitoring the slab's weight (degree of saturation). All the NDT measurements were performed on nine slabs (for each batch) for dry and saturated conditions and on three slabs for three intermediate levels of saturation (40%, 60%, 80%), as summarized in Table 1. For each slab, the different NDT techniques provided about 52 measured physical parameters (e.g. UPV, surface wave velocity, GPR amplitude, electrical resistivity, frequency of impact echo, etc.).

2.2. Methods for data analysis

After all the series of tests, about 12,700 numerical values have been included in a database. The first aim of the data analysis was to reduce this large set of values and to find the most relevant NDT parameters for the evaluation of each concrete property. (In this paper, only porosity and saturation are analyzed but the strategy is identical for other properties such as strength and modulus of elasticity).

In a first step, several indices were defined for the evaluation of the quality and the degree of sensitivity of each NDT measurement regarding each concrete property. The indices were defined using two statistical approaches (variance analysis and multiple

Table 1
Mixtures and characteristics (S is the water saturation).

Aggregates		Round siliceous						Round Siliceous	Crushed Siliceous	Crushed limestone
		0–14 mm						0–20 mm	0–14 mm	0–14 mm
W/C		0.30	0.45	0.55		0.65	0.80	0.55	0.55	0.55
Reference		G1	G2	G3	G3a	G7	G8	G4	G5	G6
Number of batches		1	1	2		1	1	1	1	1
Series	S (%)	Number of slabs								
Series 1	0	9	9	9	9	9	9	9	9	9
Series 3	40	3	3	3	3	3	3	3	3	3
	60	3	3	3	3	3	3	3	3	3
	80	3	3	3	3	3	3	3	3	3
Series 2	100	9	9	9	9	9	9	9	9	9
Porosity (%)		12.5	14.3	15.5	16.0	15.9	18.1	14.2	15.2	14.9
Modulus of elasticity (GPa)	0	35.75	30.92	29.72	28.91	29.18	22.86	30.76	33.32	39.36
	100	35.46	28.36	30.04	27.93	27.45	21.27	26.71	29.71	35.8
Strength (MPa)	0	77.2	55.6	–	46.0	44.0	27.0	47.0	53.0	44.0
	100	77.9	43.3	43.5	40.5	38.3	20.2	36.6	45.0	38.2

regression). Based on these indices, a ranking between the NDT parameters became possible for identifying the most relevant.

In a second step, and on the basis of a limited set of NDT parameters, the correlation and the complementarity between NDT parameters were analyzed by means of a data mining technique (principle component analysis, "PCA") [18].

The two steps (selection of individual parameters and use of best combination) are described with several practical examples, which show how the concrete properties can be better assessed in practice. It is also shown how the uncertainty on the estimated properties can be quantified.

3. Methodology for identifying the most relevant NDT parameters

3.1. Quality and sensitivity of NDT techniques

The relevance of a technique and of its corresponding physical parameters can be assessed by two criteria related to (1) the quality of the measurement (repeatability) and (2) the sensitivity to a given concrete property. Each of these criteria can be evaluated using two approaches:

Approach 1: Variance analyses at various scales.
Approach 2: The quality of the models (relationships) linking NDT parameters and concrete properties.

The following section describes the two approaches and defines how the criteria can be used to select the most relevant NDT parameters.

3.1.1. Approach 1: variance analysis for quality and sensitivity evaluation

The first approach is based on a statistical analysis of variability of the NDT measurements by calculating the variances (Eq. (1)) of the measurements and their corresponding coefficient of variation at four levels as presented in Fig. 1.

$$V = \frac{\sum_{i=1}^{n}(X - x_i)^2}{n} \quad (1)$$

X is mean of x_i values, x_i is the value of sample i and n is the number of samples.

In Fig. 1:

- Variance $V1$ (point scale) results from the imperfect repeatability of a measurement on the same point of the slab, at which measurements were repeated ten times;
- Variance $V2$ (specimen scale) results from the internal variability of the slab, due to the heterogeneity of the material. Ten measurements are carried out on the same slab by moving the sensor along a profile when this is feasible;
- Variance $V3$ (batch scale) estimates the variability of the material between slabs within a given batch. The mean values of the NDT parameter calculated on each slab are used for the calculation of $V3$.
- Variance $V4$ (global scale) results from the variability of the concrete property (porosity or saturation for the case of this study). It is calculated from the mean values obtained on all the measurements of one subset of the whole experimental programme. For example, the variability between the different batches at a fixed saturation degree is considered as the variance regarding the porosity ($V4_p$). The variability between the mean values for one batch at different degrees of saturation reflects the effect of water saturation variation and is named $V4_s$.

The intrinsic quality of an NDT parameter can be evaluated from the accuracy of the measurement at different scales. For a better evaluation of a concrete property using NDT technique, the uncertainty of repeatability ($V1$ and $V2$) must be as small as possible compared with the effect of concrete property variation. The limit of $V2$ is 0 if the repeatability of the measurement is perfect and the slab homogenous.

The sensitivity characterizes the ability of the NDT parameter to differentiate between concrete mixtures or between saturation conditions. In this logic, at least one of the two $V4$ values (either $V4_p$ or $V4_s$) must be as large as possible ($V4 \gg V2$). This ensures that the measured NDT parameter is able to detect a variation of concrete porosity or of the degree of saturation. The lack of sensitivity of a technique to a concrete property (the case when $V4$ is small) can, however, be of interest: if a first NDT parameter is sensitive to two concrete properties (X_1,X_2) while a second NDT parameter is only sensitive to X_1. The second measurement enables

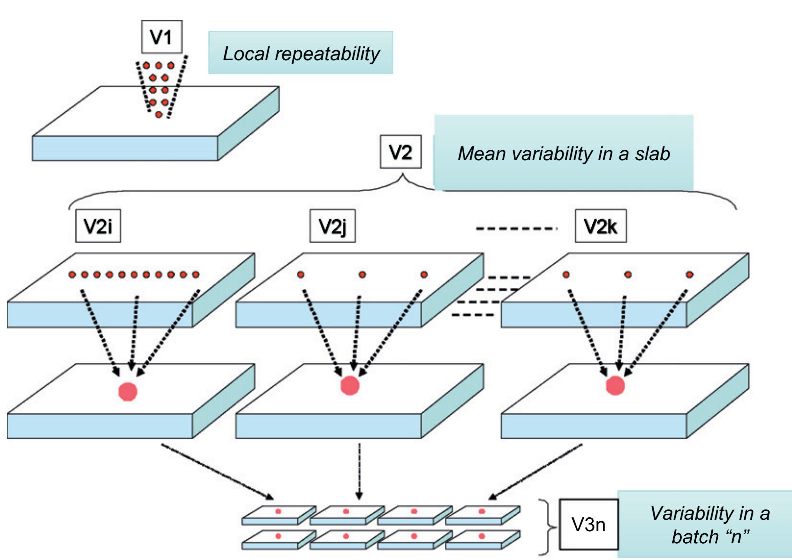

Fig. 1. Significance of the different variance levels V1, V2, and V3.

X_1 to be estimated first, after which X_2 is estimated from the first measurement. However, the issue at this stage is to estimate the degree of uncertainty of the two NDT parameters before selecting them for combination. Based on the above definition, *V*4 can be considered as the "signal" of the measurement, and *V*1, *V*2, *V*3 are the "noise" of measurement at different levels. For a better comparison between NDT parameters, the calculated variances are normalized and two indices are defined as follows:

1. The quality index (QI) results from the imperfect repeatability of the measurement, which is directly related to the accuracy of the local measurement. For a high quality measurement, *V*1 and *V*2 must be as low as possible in comparison with *V*3:

$$QI = -\log\left(\frac{V1}{V3}\right) - \log\left(\frac{V2}{V3}\right) \tag{2}$$

2. The sensitivity index (SI) is defined as the "signal to noise ratio" of the measurement with respect to a concrete property. Therefore, an NDT parameter is strongly sensitive to a concrete property if *V*4 is much larger than *V*3. In this study, two SI were proposed, the first for the sensitivity to saturation and the second for the sensitivity to porosity:

$$\mathrm{SI}_S = -\log\left(\frac{V3}{V4_s}\right) \tag{3}$$

$$\mathrm{SI}_P = -log\left(\frac{V3}{V4_p}\right) \tag{4}$$

3.1.2. Approach 2: multiple regression models for quality and sensitivity evaluation

3.1.2.1. The choice of models form. The first step concerns the identification of empirical relationships (models) linking the NDT parameters and concrete properties. This is also important with respect to the final objective, which concerns data combination of the selected NDT parameters for a better evaluation of concrete properties. Multiple linear regressions were chosen to obtain a first series of relationships. This was because the linear form is suitable for the majority of NDT techniques. For instance, the capacitive technique is linearly related to the volumetric water content of concrete [19] and also the velocity and amplitude of a GPR wave [20,21].

However, this kind of relation does not apply for some NDT techniques, such as electrical resistivity of concrete, for which the empirical Archie's model, a power law, is more suitable than linear relationships [22]. For this reason, for electrical methods, the logarithm of the resistivity was considered instead of the resistivity itself. The issue of linear models was also addressed for acoustic techniques. Experts in acoustic techniques confirmed that the relation between the velocity of ultrasonic waves and the porosity is almost linear between the saturated state and air-dry state [23]. However, the dependence on water saturation is not a monotonic function over the range [0%, 100%]. A minimum value of this NDT parameter was recorded on concrete slabs having a water saturation of about 30%. For lower saturation rates, the wave velocity increased. Considering that, in practice, concrete structures have saturation levels higher than 30%, concrete slabs which had been oven dried to reach 0% of water saturation were excluded from the data set on which models were calibrated and a linear model was kept.

Of course if alternative relationships (either theoretical or empirical) were available, they could also be considered instead of linear ones, following the same methodology. In this study, the priority was to develop the strategy of combination and not to improve the quality of regression models. For these reason, the choice was made by considering only empirical linear relationships identified through statistical analysis of the data set.

3.1.2.2. Identification of regression coefficients. Based on the above section, multiple linear regressions were statistically identified and selected for modelling the relations between NDT parameters and the concrete porosity and saturation pair, as presented in

$$\mathrm{NDT}_{(i)} = A_i(\pm E_a) \times S + B_i(\pm E_b) \times P + C_i(\pm E_c) \tag{5}$$

where $\mathrm{NDT}_{(i)}$ is the response of the NDT parameter *i* (*i* = 1–52); *S* is the degree of saturation and *P* is the porosity (both expressed as percentages); A_i, B_i and, C_i are the regression coefficients of the empirical model regarding the parameter $\mathrm{NDT}_{(i)}$; *E* is the standard error on the coefficients, calculated using the following equation:

$$E = \sqrt{\frac{1}{n-2}\left[\sum(Y-y)^2 - \frac{\left[\sum(X-x)(Y-y)\right]^2}{\sum(X-x)^2}\right]} \tag{6}$$

in which *n* is number of samples; *X* and *Y* are mean of *x* and *y* values, respectively, on the series of *n* samples; and *x* and *y* are the values of the sample.

Figs. 2 and 3 illustrate typical results of the multiple regressions identified, which show the response surface for the NDT parameters GPR travel time and the velocity of surface wave with respect to porosity and saturation. In fact, the figures show simulations of NDT measurements with respect to saturation (30–100%) and porosity (12–18%) variations based on multiple-regression models "empirical models identified on the experimental results".

It can be seen that the water content has the same effect on both parameters: an increase in the water content induces an increase in the velocity of the surface wave and an increase in the GPR travel time. In contrast, the effect of the porosity is opposite on these two parameters: increasing the porosity lowers the ultrasonic wave velocity and increases the GPR travel time. The very different orientation in space for the two regression planes reveals good complementarity between the surface wave velocity measurement and the GPR travel time.

3.1.2.3. Evaluation of the quality and the sensitivity of NDT techniques. To evaluate the quality of the relation between the NDT parameter and the concrete properties, two indices were considered. The first one was the determination coefficient R^2 (Eq. (7)) that represents the general quality of the regression with respect to at least one concrete property. R^2 increases:

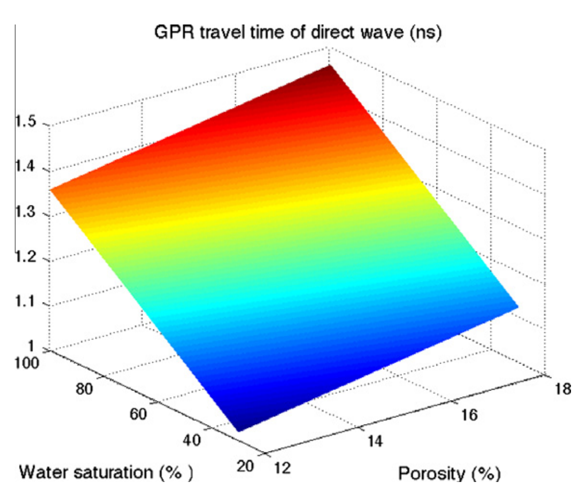

Fig. 2. Response surface of the GPR travel time variations with respect to water saturation and porosity.

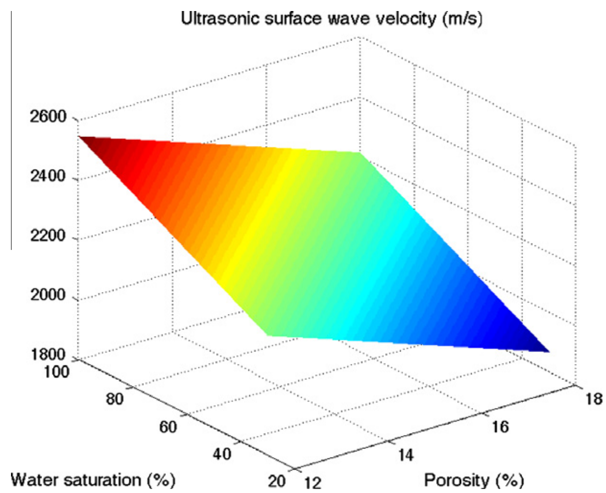

Fig. 3. Response surface of the ultrasonic surface wave velocity variations with respect to porosity and water saturation.

(a) if the measurements are of high quality (low level of noise "V1");
(b) if the model fits the experimental measurements well.

This statistical parameter (R^2) was then taken as the quality index (QI) of NDT parameters regarding concrete properties evaluation.

$$R^2 = \frac{[\sum(X-x)(Y-y)]^2}{\sum(X-x)^2\sum(Y-y)^2} \quad (7)$$

The second index was based on a significance test of the regression coefficients (A and B). Student tests were applied to the A (saturation) and B (porosity) coefficients for each NDT parameter. The test consists of comparing the ratio between σ_x (Eq. (8)) and the Student limit. This limit depends only on the probability (95% in this study) and the number of degrees of freedom of the model. The NDT parameter is strongly sensitive to concrete properties if at least one slope (A or B) is estimated with a smaller uncertainty (high value of σ_x at least equal to the Student limit, which was 2.036 in the case of this study).

$$\sigma_x = \frac{Co_x}{E_x} \quad (8)$$

where Co_x is the slope of the regression regarding concrete property (x); A_i for saturation and B_i for porosity; and E_x is the error in estimating the slope of concrete property (x) (see Eq. (6)).

From σ_x, two indices of sensitivity are proposed, one corresponding to the saturation sensitivity named SI_S and the other to the porosity sensitivity (SI_P). The NDT parameter is of good relevance if the two indicators ($QI = R^2$) and (SI) have high values, as it then gives useful information regarding the concrete properties evaluation. Typical results are presented in Table 2. In this table, a comparison between GPR amplitude and velocity of surface wave indicates that, on the one hand, both the velocity of the surface wave and the GPR amplitude present acceptable quality indices (QI larger than 0.62) and, on the other hand, the sensitivity indices show that GPR is only sensitive to saturation ($SI_p = 1.41$ is below the Student's limit of 2.036) whereas ultrasound is sensitive to both saturation and porosity.

Table 3
Selection criterion – comparison between the proposed approaches.

	Approach 1	Approach 2	Common
Selection criterion	QI > 0.6 SI > 0.5	QI > 0.4 SI > 2	
Number of selected NDT parameters	Ultrasound: 6 Impact-echo: 2 Capacitive: 0 Electrical: 4 GPR: 11 Total: 23	Ultrasound: 10 Impact-echo: 0 Capacitive: 2 Electrical: 3 GPR: 6 Total: 21	Ultrasound: 5 Impact-echo: 0 Capacitive: 0 Electrical: 3 GPR: 4 Total: 12

Table 4
List of the 14 selected NDT parameters from the different techniques.

Code	NDT techniques	NDT physical parameters
US_SW1	Ultrasonic	Pulse velocity of surface wave* (m/s)
US_SW2	Ultrasonic	SW phase velocity corresponding to the wavelength equal to 3 cm**
UPV	Ultrasonic	"UPV" Ultrasonic Pulse Velocity at 250 kHz (m/s)
US_Att	Ultrasonic	US attenuation
US_Q	Ultrasonic	US Quality factor
IE	Impact echo	IE peak frequency
CM	Capacitive method	Frequency Capacitive method (large size sensor)
ER_1	Electrical methods	Electrical resistivity, Four-probe square array (5 cm distance)
ER_2	Electrical methods	Electrical resistivity, Four-probe square array (10 cm distance)
ER_3	Electrical methods	Electrical resistivity with Wenner sensor (Ohm m)
GPR_Amp	Radar (GPR)	Peak to peak temporal amplitude of the GPR direct wave (1.5 GHz)
GPR_V	Radar (GPR)	Velocity of GPR direct wave (1.5 GHz) m/s
GPR_T1	Radar (GPR)	Direct travel time (offset 7 cm) of direct wave, ns
GPR_T2	Radar (GPR)	Direct travel time (offset 14.7 cm) of direct wave, ns

* Surface wave phase velocity obtained by a spectral analysis [17].
** Surface wave phase velocity obtained by a p–ω transform [16].

3.2. Expert's decision: selection of the relevant NDT parameters

The selection of the relevant NDT parameters for the concrete properties evaluation was based on the two proposed approaches: (a) variance analysis and (b) multiple regressions. The two approaches involve the calculation of the quality index (QI) and the sensitivity index (SI) for selecting the more relevant NDT techniques. The choice of the minimal values of the criteria QI and SI was done with NDT'expert. The NDT parameters selected by both

Table 2
Typical example of quality and sensitivity indices calculated using multiple regressions.

	QI	Coefficient (A) saturation			Coefficient (B) porosity		
	$=R^2$	Value	Error	SI_S	Value	Error	SI_P
Ultrasonic surface wave velocity	0.62	4.96	0.89	5.6	−55.90	14.13	3.91
GPR amplitude	0.70	−0.0016	0.0002	8.12	−0.0044	0.0031	1.41

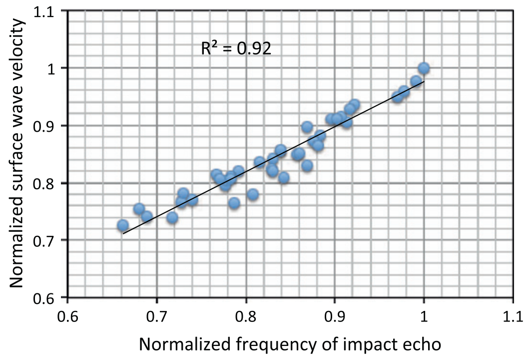

Fig. 4. Example of typical correlation between NDT techniques (impact echo frequency vs surface wave velocity).

approaches were systematically adopted. However, the experts decided to eliminate the redundant NDT parameters, e.g. GPR travel time measured at different offsets. At least 11 NDT parameters were selected as can be seen in Table 3. In a last step, a few NDT parameters measured by two different experts or systems were added to the 11 previously selected, to enable some comparisons, even if they did not satisfy the minimal values of QI and SI. Table 4 summarizes the final selection of 14 NDT parameters, based on the two selection approaches and the discussion with the NDT experts.

4. Methodology of combining NDT techniques

4.1. Analysis of the complementarity between NDT techniques

As presented above, NDT techniques (measured physical parameters) are subject to uncertainty due to the "relative" quality of the measurements and to the variability of the concrete. Moreover, evaluating concrete condition on the basis of one NDT technique is difficult since several concrete properties can affect a single NDT measurement. The combination of several NDT parameters can be useful for enhancing the quality of the diagnosis. For example, it is interesting to combine NDT parameters that are highly correlated in order to confirm a diagnosis, as can be seen in Fig. 4 (high correlation between the NDT parameters surface wave velocity and impact echo). Moreover, combining complementary NDT parameters, which are differently correlated to the concrete property considered (e.g. GPR and ultrasonic), can be interesting since it opens the way to the inversion of the equation system for evaluating concrete properties.

Due to the large number of NDT parameters, this analysis is difficult to implement and the systematic analysis of all possibilities among 14 parameters would be impossible in practice because of the time required. Data mining methods can be useful for illustrating correlations and complementarities between the NDT parameters. Principal Component Analysis (PCA) was performed using Matlab software.

Fig. 5 shows the variable positions in the first factorial plane F1-F2. In this analysis, the variables considered are the 14 selected NDT parameters and the pair of concrete saturation and porosity. The number of variables is then 16; each of them being represented on the figure by a vector. The direction and length of the vector indicate how each variable contributes to the two principal components. From this figure, it is clear that all the variables contribute significantly with comparable inertia, except the NDT parameters ultrasonic attenuation (US_Att), and ultrasonic quality

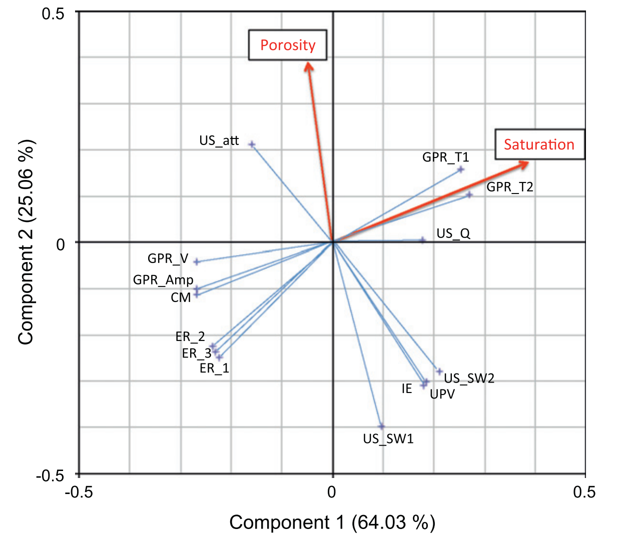

Fig. 5. Principal component analysis (first and second components), the numbers correspond to the index of the NDT parameters (codes of techniques are summarized in Table 4).

factor (US_Q), which make a smaller contribution. This is due de the low quality of these two NDT parameters regarding the evaluation of concrete porosity and water saturation. The interpretation of the graph is easier when one looks at the location of the porosity and saturation points (the angle is about 80° between the two axes, which means that they are roughly independent). The interpretation of the graph is based on these two identified axes.

Based on the analysis of the PCA, it is possible to optimize the number of NDT parameters used for the combination, analyzing the complementarity between NDT parameters, and detecting the redundant information. This can be carried out, particularly, using the coefficients of the variables calculated in the first and second components. The angles between individual NDT parameters, regarding PCA analysis, have been calculated and typical results for some NDT parameters are summarized in Table 5. These angles can be interpreted as follows:

- The NDT parameters are well correlated and can be used to confirm a diagnosis if the angle is close to zero or 180°.
- The complementarity between NDT parameters is very good if their position in the PCA corresponds to angles near 90°.

Based on this analysis, in Table 5, the NDT parameters having good complementarity are, for example, GPR amplitude and ultrasound surface wave velocity, which have an angle of 90.6°. The NDT parameters that are well correlated are for example impact echo and UPV, and also GPR and capacitive method. However, some NDT parameters can be considered as redundant, e.g. electrical resistivity measured with different sensors (see Table 4). Table 6 proposes some results that correspond to the best combinations of NDT techniques for the evaluation of concrete porosity and water saturation. This table suggests, for example, using Ultrasonic Pulse Velocity combined with GPR amplitude. This combination can be completed with other NDT parameters like, for example, impact echo as a mechanical method or electrical resistivity.

Although the results presented here are limited to porosity and saturation assessment, the same methodology can be used, following exactly the same steps, for other properties such as Young's modulus, compressive strength, etc. Moreover, other NDT techniques can be analyzed following the same methodology. However,

Table 5
PCA angles between the more relevant NDT parameters.

	Ultrasonic surface wave velocity (US_SW2)	UPV	Impact Echo	Capacitive Method	Electrical Resistivity (ER_3)	GPR amplitude (GPR_Amp)	GPR travel time (GPR_T2)
Ultrasonic surface wave velocity (US_SW2)	0						
UPV	9.6	0					
Impact echo	11.1	1.5	0				
Capacitive method	88.5	78.8	77.4	0			
Electrical resistivity (ER_3)	63.1	53.5	52	25.3	0		
GPR amplitude (GPR_Amp)	90.6	80.9	79.5	2.1	27.4	0	
GPR travel time (GPR_T2)	89.7	99.3	100.8	178.1	152.8	180.2	0

Table 6
Some combinations of NDT techniques and their additional techniques.

First method		Combined methods		Additional method	
Technique	Parameter	Technique	Parameter	Technique	Parameter
Ultrasonic	Ultrasonic Pulse Velocity (UPV)	GPR	Amplitude	Ultrasonic	Surface wave velocity (US_SW2)
		GPR	Travel time		
		Capacitive method	Frequency	Impact Echo	First peak frequency
		Electrical resistivity	Wenner sensor		

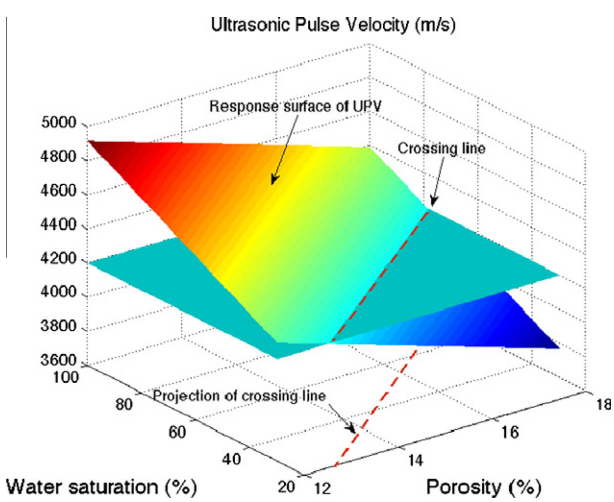

Fig. 6. Typical example of crossing between the UPV response surface and the measured value of UPV recorded on the corresponding slab.

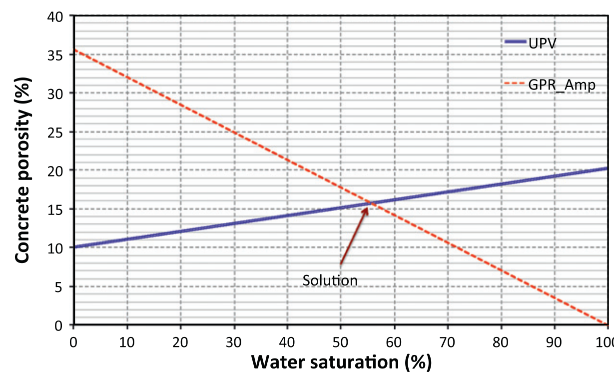

Fig. 7. Solution by combining Ultrasonic Pulse Velocity and the amplitude of GPR direct wave.

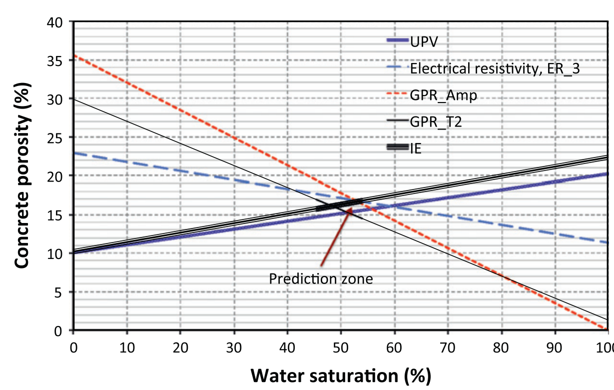

Fig. 8. Concrete properties evaluation by combining GPR, ultrasonic, impact echo and electrical resistivity.

combining all the techniques is not realistic since it would drastically increase the time and cost of the assessment, even though it would reduce its uncertainty. However, the practical result is that, based on the information synthesized in Table 6, the expert on NDT techniques can limit the inspection to a minimum set, regarding the available techniques and the allocated budget.

4.2. Combination of NDT techniques for the evaluation of concrete properties

The main objective of combining several NDT techniques is to improve the concrete structure diagnosis. Based on this analysis, an optimal combination of NDT techniques can be used for inverting the implemented multiple regressions, using a least squares method for example. Typical results of such an approach can be seen in Fig. 6, which represents the intersection in the porosity-saturation plane between the response surface of the NDT UPV and the measured NDT value (4200 m/s) on a concrete slab.

The projection of the intersection on the horizontal plane (porosity, water saturation) is a straight line of porosity vs saturation. A minimum of two NDT parameters having good complementarity are needed for the evaluation of the porosity-saturation pair after crossing the two horizontal projections for the two NDT parameters as can be seen in Fig. 7.

The coordinates of the common point (which belongs to the two straight lines corresponding to the two NDT measurements) represent the solution of the inversion, in which ordinate value is the predicted porosity and abscissa value is the predicted water saturation. To improve the diagnosis, it could be interesting to use several line crossings, which means several NDT measurements to confirm the evaluation.

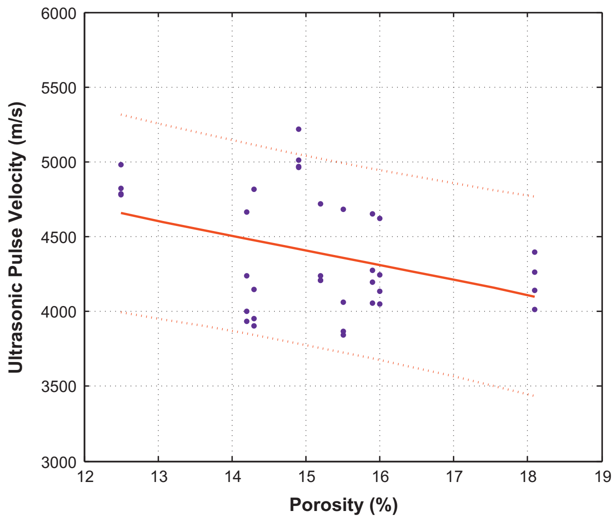

Fig. 9. Correlation between UPV and concrete porosity at moisture saturation varying from 30% to 100%.

Since the orientations of the planes in the 3D-space are very different, any pair of NDT values will provide a well-conditioned pair of equations, enabling a good inversion of the system. This can be seen in Fig. 8, which represents the projection on the horizontal plane (porosity, water saturation) for a given series of measurements. In fact, it represents the average measurements on three specimens from mix G7, w/c = 0.65. In this figure, the slabs named "slabs-1" were saturated slightly above a mean value of 51%, and had a measured porosity of about 16%. In this case, three NDT parameters were used: GPR attenuation and travel time, UPV, impact echo, and electrical resistivity. The complementarity of the techniques involved can be clearly seen since each line has a different slope. The figure shows that the information provided by combining these NDT techniques is very relevant. The combination indicates that this specimen has a mean porosity of 15.8% with absolute error of about ± 0.65 and water saturation of about 52.5% ± 3.5. The error between actual and calculated values is about 1.25% for porosity and 3% for water saturation. The uncertainty of prediction is of about 4.1% and 6.6% for porosity and saturation, respectively. However, using only one method, e.g. UPV, for moisture varying between 30% and 100% of saturation, the error of predicting the porosity is very high, as can be seen in Fig. 9. In fact, inverting the empirical model relating UPV to porosity provides a result of 17% porosity ± 6.2. The 95% prediction bound varies between 10.8 and 23.2 of concrete porosity. In this example, the concretes tested have a porosity of 16%. Therefore, in the case of unknown concrete moisture and using only the UPV parameter, the error in mean value is of about 6.3% (difference between actual value "16%" and predicted value "17%"). However, the uncertainty of prediction is very high and can reach 36.7%, whereas the combination provides an uncertainty of about 4.1%.

5. Conclusions

- Based on a large experimental program, variance analysis and multiple regression techniques were used to quantify the quality of some NDT techniques (e.g. Ultrasonic Pulse Velocity "UPV" and attenuation, electrical resistivity, GPR velocity and amplitude, etc.) and their sensitivity to concrete porosity, and water saturation. Specific statistical criteria were defined and used for selecting the most relevant NDT parameters. These criteria show that UPV and GPR velocity are among the NDT measurement of good quality regarding the evaluation of concrete porosity and saturation.
- The degree of complementarity between NDT techniques was quantified using Principal Component Analysis. Several combinations have been identified which appear to be very relevant, when porosity and water saturation have to be evaluated. For instance, this analysis shows a very interesting complementarity between acoustic methods (UPV, impact echo) and (GPR, electrical resistivity).
- By using data inversion, which combines the most relevant and complementary NDT techniques, porosity and water saturation were evaluated. The results show that the combination of NDT parameters improves the diagnosis by decreasing the predictive error compared with the use of only one technique. For instance, in the case of unknown concrete moisture and using only the UPV parameter, the uncertainty of predicting concrete porosity is very high and can reach 36.7%. The relative error is decreased to 4.1% when the measurement is combined with GPR or electrical resistivity.
- The approach presented in this paper is a generic one, which does not depend on the type of NDT measurement or on the material property to be assessed. It can be followed for other NDT techniques and material properties. Moreover, the illustrative examples considered the porosity/saturation degree pair, any other concrete properties, such as modulus of elasticity or strength, could be considered.
- Further works are in progress for improving the evaluation of concrete properties based on the mathematical inversion of the statistical models implemented. Another large data set regarding the evaluation of durability indicators such as chloride contamination or carbonation is also being analyzed. Currently, the developed methodology is being tested on site in order to confirm the efficiency of the approach implemented.

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