NON-DESTRUCTIVE ASSESSMENT OF CONCRETE DAMAGE: INTEREST, DIFFICULTIES AND RESEARCH NEEDS

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Abstract. Damage assessment of reinforced concrete structure is required for maintaining the building and infrastructures asset at a good level of performance. Non-destructive techniques provide a way towards this assessment. They however suffer from several shortcomings, since are only indirect measurements of engineering properties, and they are sensitive to many influent factors. In addition, the influence of material variability is not easy to sort out of the measurement variability, when it has a big influence on the assessment reliability. Some main results of several cooperative research programs are discussed, highlighting the conditions for a better use of combination of several non-destructive techniques. It is shown how to quantify and account for material variability and for the influence of environmental potential bias factors. Data are taken both from in-site measurements and laboratory studies. Applications are analyzed for corrosion assessment and for in-site strength assessment.

Keywords: Corrosion, damage, material variability, non destructive assessment, reliability, strength assessment

1. Interest and Key Challenges of Non Destructive Assessment of Concrete

For the maintenance or the refurbishing of their structures, engineers need to assess their condition. 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

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the level of the problem, its extent and location. Another common objective is the quantitative evaluation of the safety level of the structure. Any parameter useful for this safety quantitative evaluation will be called "*engineering property*". The more common are stiffness (Young's modulus) and strength. Non-destructive techniques (NDT) can be used to assess the structural condition, even if they only provide an indirect approach to their performances (De Lorenzis and Nanni, 2004). 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 and the more difficult one.

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 (Bungey and Millard, 1996; Uemoto, 2000; Breysse and Abraham, 2005) or to define the most promising paths for future developments (OECD, 1998). The general agreement is that the quality of assessment is 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 (Gehlen et al., 2006). Thus, reducing any of these sources of uncertainties can provide for an improved damage assessment.

Among the main challenges about concrete assessment, one can cite:

- *Stiffness and strength assessment.* The knowledge of the elasticity modulus or the compressive strength of concrete is necessary to perform any structural evaluation. They can be evaluated from coring, which offers only an image of the properties at the point where the specimens have been taken. Thus it is difficult to obtain a representative view of the mechanical properties, since the material as well as the damage level can be highly spatially variable. NDT provides an interesting alternative since it enables to easily cover wide areas, the difficulty being to correlate the values of the physical measurements obtained via NDT to the mechanical properties. Rebound measurement and ultrasonic pulse velocity (UPV) are among the more adapted NDT regarding this purpose (Malhotra, 1981) and a recent European standard has given formal solution on how concrete strength from in-situ testing (NF EN 13791, 2007).
- *Water content (or moisture content) assessment*, for two reasons: a large value of water content can be the sign of the bad quality of the material (often due to delaminating in concrete), but it can also be the sign that a

potential vector of future damage is present, since the water is the more common agent for deterioration (salt ingress, dissolution, freeze...). Many NDT are sensitive to both a material condition parameter (e.g. Young's modulus) and to water content. Due this double dependency, one cannot easily decide what is the cause of the measured variation in the NDT parameter.

– *Corrosion assessment*, since many reinforced concrete structures suffer severe damage due to corrosion (due to chlorides in marine environment, de-icing salts, or other causes). The cost of corrosion is estimated to be about 3–4% of GNP in Western countries. The material and structural assessment of such structures is a key point when one wants to evaluate its residual capacity, to design a reinforcing solution or to plan maintenance. Some techniques have been standardized which enable to assess the material condition of corroding structures but it will be seen that many questions still remain unanswered.

These three questions regard partly mechanical assessment, partly durability assessment, but the boundary between the two domains is not well defined, since the mechanical properties of tomorrow are often dependent on the deterioration process of today.

2. Non-Destructive Evaluation of Concrete: Objectives, Means and Difficulties

2.1. DIFFICULTIES COMING FROM THE COMBINED INFLUENCE OF MANY FACTORS

When wanting to address material condition, the expert can try to get only a qualitative view, for instance by identifying spatial variations in the measured parameters. He can be more ambitious, wanting to quantify these variations, for instance because he needs some input values for structural computations before repair or for reliability assessment. If expertise is required in the first case, it is not sufficient in the second one that also requires a validated methodology such as to ensure the quality of estimates. Much research has been devoted to the development of techniques or of data processing for a better assessment of building materials. 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 (Dérobert et al., 2005). 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 (Breysse and Abraham, 2005) and from results obtained in a benchmark research program (Balayssac, 2005). The + or − signs correspond to a positive (consequence varies with cause) or negative (consequence varies against cause) sensitivity.

TABLE 1. Supposed sensitivity of NDT to several important concrete properties ("0" denotes no significant influence, "?" denotes uncertainty)

	Radar	Capacimetry	Electrical resistance	Ultrasonic waves
Water content	Velocity: – Amplitude: –	–	–	Velocity: + Attenuation: −
Porosity	–	–	–	Velocity: YES (+ if saturated, − if dried)
Chloride content	Velocity: – Amplitude: 0	0?	–?	0
Re-bars	Bias		Bias	Bias

It is crucial to understand why and how the combination of techniques can bring some added value. 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 establish a direct link between the observed variation of the measured property (wave velocity, electrical resistance ...) 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 context (temperature, exposure to the sun, dominant wind...).
- 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.

Several levels of uncertainty arise, some from physical considerations, others from the measurement process itself, and a third part from the material variability. One needs to take some insight in the physics of the involved phenomena for a better understanding. The physical property measured with the NDT is usually not the parameter one wants to evaluate. Let us call:

– Y the property that we are looking for (dimension, strength, modulus, durability…) and
– T the measured property (electrical resistance, magnitude or time of arrival of a signal…)

The assumption on which NDT is based is that a correlation exists between Y and T, for instance between a length and the time of arrival of a signal. However, this correlation is not perfect, since, in fact, these two properties are usually macroscopic properties which result from some combination of physical material properties at the micro-scale (porosity, water content, crack-shapes, connectivity, strength of bonds in the composite…). Let us denote with X these basic physical properties.

Figure 1 illustrates what kind of relations can exist between various material properties and why NDT interpretation is so much a complex task. The black and gray arrows denote some correlation between properties and the red arrows denote some sensitivity of a technique to parameters. At the center, one finds material properties X (in blue boxes), which are representative of the material: porosity and connectivity on one hand, water content and saturation rate on the other hand. The former can be considered as constant with time (at least at short term, since they can vary due to chemical processes), while the latter can vary due to environmental changes, since timber, concrete or stone are hygroscopic materials. On the left part of the diagram, one has the engineering properties Y which are related the material properties (gray double arrows), even if the relations are very complex. Finally, on the right part, one has physical properties T measured through NDT (here electrical conductivity and UPV), which depend on material properties (red double arrows) but also on some bias factors, for instance temperature at the time of the measurement (orange arrows). Environmental factors have also been taken into consideration, they influence the T factors, probably because they interfere on X properties.

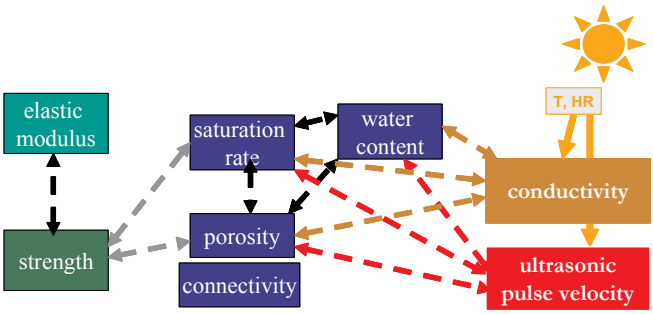


Figure 1. Generic diagram of relations between engineering properties, physical parameters, NDT measurements and sources of noise

This graph shows that:

- The assessment of Y parameters does not reduce to a direct and simple Y = f(T) relation.
- Any existing correlation between two techniques (here radar and resistance) will also follow a very complex way, which must be understood before being used.

When addressing the question of quantification, a common problem is that the NDT measurements can be sensitive to both the engineering parameter (like strength or stiffness), which are mainly stable with time, and to the water content, which can vary at short term according to environmental conditions. If it is the case:

- One cannot tell if the measured variations result from a variation in the engineering parameter or in the water content.
- One has to account for this sensitivity if he wants to quantify the engineering parameter.

This question is a central one, since it is the main cause that weakens the practical ability of NDT. Considering that a measurement is sensitive to a first parameter (whose value is expected) and to one or several "bias factors", the effects of these "bias factors" have to be eliminated during the data processing.

2.2. THE POSSIBLE ADDED-VALUE OF COMBINATION OF TECHNIQUES

The combination of techniques can follow various objectives, like for instance confirming with a second technique what has been observed with a first one, zoning the area where a more sophisticated investigation will be performed in the following, decreasing the number of borings. These questions have recently been formalized (Breysse et al., 2008a) with a series of practical examples. A more ambitious objective can be to use two (or several) techniques relying on the fact that a second technique can provide additional information, enabling to reduce uncertainty or to eliminate a bias factor to which the first technique is sensitive. This point will be detailed here.

The generic problem comes from the use of ONE NDT, which is sensitive to TWO parameters. In this situation, a second technique, also sensitive to these two parameters (or only to the second one) can enable to capture and eliminate the effect of the second one. The second parameter can be a material property (internal) or an environmental one (e.g. air temperature and humidity whose changes with time and environmental conditions will affect all electrochemical measurements).

In practice, since this problem has been known from a long time, engineers have developed strategies to account for it, for instance by building and using some charts in which the correction is accounted for. One of the best known example is that of the "SonReb" method in which Ultrasonic Pulse Velocity (UPV) and rebound number are used to estimate on site concrete strength (Malhotra, 1981). The water content influence is a key question, since many common NDT used to quantify heterogeneities and potential damage (UPV, ground penetrating radar, resistance ...) are also sensitive to water content. Thus, how is it possible to make the part between the two potential causes of variation of the measurements?

Figure 2 shows the variation of compression wave velocity (frequency 250 kHz) as a function of the 28 days compressive strength of six concrete mixes, measured both on saturated specimens and on specimen maintained at a 40% saturation rate. It shows how the measured parameter (here UPV) is sensitive to both sources of variations. Thus any measurement of UPV without any additional information would be totally unable to make the part between the two possible explanations, whose magnitude of influence is comparable.

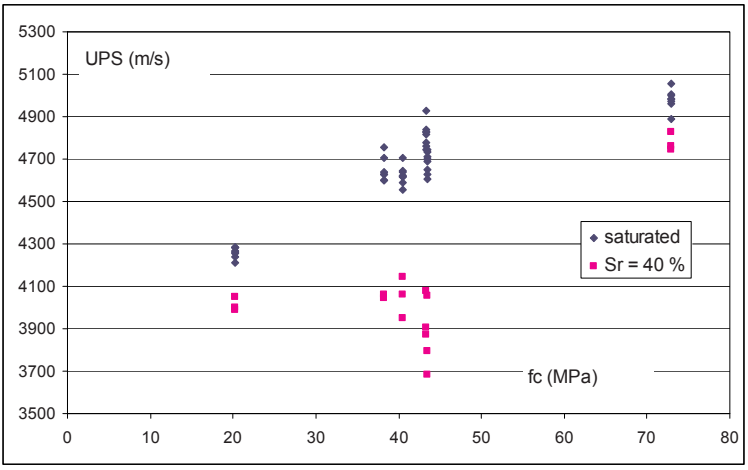


Figure 2. Influence of saturation rate and concrete properties on UPV

2.3. DIFFICULTIES ARISING WHILE COMBINING TECHNIQUES FOR IMPROVING THE ASSESSMENT

Many authors have pointed the fact that the comprehension and modeling of the relations between X, Y and T values is difficult. For instance (Popovics, 2001) has written: "Unfortunately, improvement cannot come from science because there is no theoretically justifiable relation between strength and pulse velocity

even for homogeneous, linearly elastic materials, let alone for concrete. Considerable value can, however, still be derived from formulas for improved nondestructive strength estimation obtained by circumventing the lack of scientific approach and selecting an engineering approach: mathematical modeling".

One way is the development of empirical laws, based on statistical analysis or on models, like the Mori-Tanaka model. Literature study shows that many empirical models have been proposed for relying UPV and strength and/or modulus. We will not question here their theoretical validity but only their practical ability to be used for a more accurate material assessment. These correlations are somehow material dependent and calibration curves must be used, for instance from cores on which both series of measurements are performed. Another difficulty comes from the fact that both physical and mechanical properties depend on various influent factors (intrinsic like porosity or varying with exposure like water content). As long as these factors are not mastered, the calibration will itself be of poor quality.

The "SonReb" (from sonic and rebound") method has been proposed to offer an original way for strength assessment, using charts made of a series of curves (for different rebound values) giving the strength as a function of UPV. This approach has been used for all types of concrete, including young age concrete (Soshiroda et al., 2006) and high strength concrete (Pascale et al., 2000; Khan et al., 2004). The question of the calibration of such curves is a key point, since many kinds of mathematical expressions are available in the literature (IAEA, 2002) providing an extensive state-of-the-art. The best correlation laws can be identified from an extensive experimental program (Samarin, 1991; Soshiroda et al., 2006) varying aggregate type and age of concrete, but this is not adapted to the context of practical in-situ assessment. We will show in Section 5 that fundamental limits can be encountered and that the real added value of combination will depend on several factors, whose each of them can be quantified. Let us have a look first on the influence of water content on the measurements.

Sonic and ultrasonic measurements are the more widely used NDT for the condition assessment of building materials. The first reason is that, for elastic materials, it exists a theoretical relation between the velocity of longitudinal waves and the elasticity modulus:

$$E = c\, V_L^2\, \rho \qquad \text{or} \qquad V_L^2 = E \,/\, c\rho \tag{1}$$

where V_L is the velocity of longitudinal waves, ρ is the mass density and c is a constant which depends on the Poisson's ratio. Thus, assuming linear elasticity and providing a value to ν and ρ will lead to a direct assessment of Young's modulus.

One question is that of the influence of the water content on measurements. The variation in moisture or in water content can change both volumetric mass (by replacing air by water, assuming the total volume remains unchanged) and modulus (changes in the internal stresses due to capillarity forces for low wat er content f.i.). The dependence to water content however shows contrasting results, depending on the material. These effects have been widely studied in timber construction and, at a lesser degree in stone construction, where non-linear effects have been encountered (Homand and Duffaut, 2000; Ezzdine et al., 2008). In concrete, to the best of our knowledge, few studies have been devoted to this question. The dominant paradigm was that the wave velocity increases with the water content. Recent results obtained within the SENSO project have proved that the behavior is, opposite to what was supposed, similar to that of limestone (Villain et al., 2008). Figure 3 shows some of these results. In fact, a "dry" concrete can be obtained (with some difficulties) in the laboratory but it does not correspond to a common situation in practice.

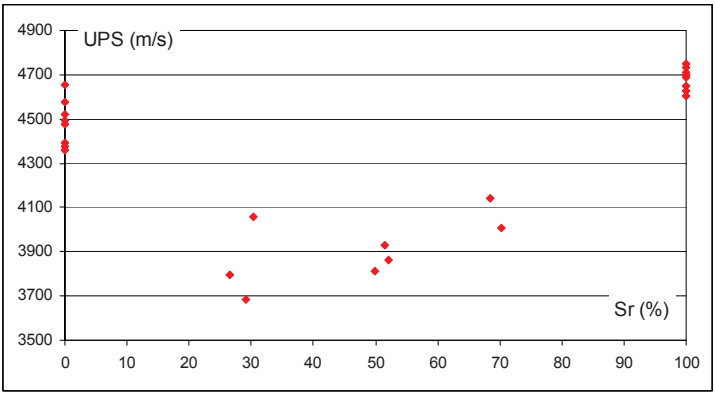


Figure 3. Variation of the UPV with saturation rate (one concrete mix)

Since the minimum point on the saturation/velocity curve seems to be around 40%, the assumption of velocity increase with large water content can be seen as a good approximation in the practical range of use. However, extrapolating any relation identified in this domain to the dry material would be grossly erroneous. In Eq. (1), there is a conflicting influence between the increase of the mass density and that of the Young's modulus. One has also to remain careful with too simplistic explanations based on the linear elastic model, since many other effects, among which viscosity can be invoked for explaining the exhibited response.

These non-monotonous variations have to be superimposed to those due to other factors: contrast between different materials (for instance different concrete

mixes), heterogeneity in the material, temperature effects... We must account for these questions when addressing the question of material assessment.

3. Variability and Reliability of Assessment: A Corrosion Case Study

3.1. USUAL MEANS FOR ASSESSING CORROSION

Corrosion of reinforced concrete infrastructures, often due to chloride ingress, has practical consequences on the condition and safety level of infrastructures. To reduce the cost of maintenance and repair while keeping these infrastructures at a correct level of safety, managers can use non-destructive techniques to assess the condition state. When relevant models are used, life cycle cost analysis becomes possible and the maintenance of structures can be optimized (Stewart, 2005; Li, 2004). The non-destructive assessment of corrosion is usually carried out by combining the following three techniques (NEA, 2002):

- Half cell potential measurements, which provide an indication of likelihood of corrosion activity at time of testing, through a value of potential (ASTM C876-91 standard puts in relation the value measured and a probability of corrosion).
- Measurement of the concrete resistance, which informs about the moisture content in the concrete.
- These two first measurements give no information about the corrosion rate, which can be estimated by measuring the polarization resistance, which gives an indication of corrosion rate of the reinforcement at time of testing.

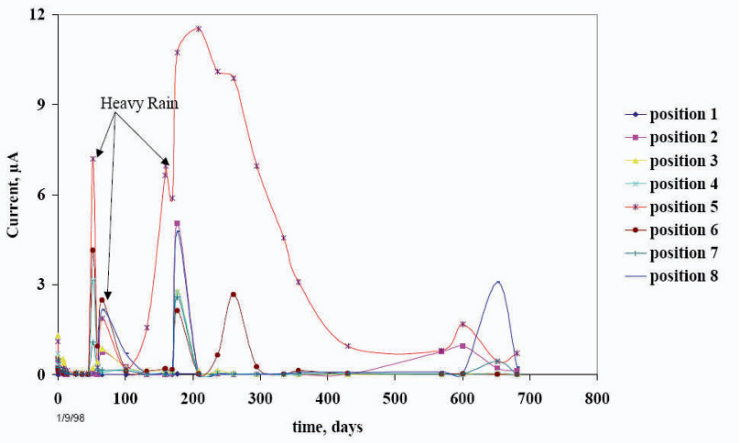


Figure 4. Temporal variability of the current of corrosion (in µA) and its relation with humidity (After Klinghöfer et al., 2000)

A value of the corrosion current density i_{corr} is derived, whose magnitude is put in relation with the corrosion rate (e.g. the corrosion is said to be negligible if it is lower than 0.1 $\mu A/cm^2$ and high if it is larger than 1 $\mu A/cm^2$). The problem is however more difficult regarding interpretation. Standards only provide some information on thresholds which have to be considered as "relative thresholds" and need to be taken with a lot of care.

It is well known that all these techniques must be used by qualified and experienced operators, and that they mainly provide qualitative data (or relative variations) instead of quantitative ones. The main reason is that NDT only give information at the time of the measurement, and that this information is very sensitive to environmental conditions (Jäggi et al., 2001; Burgan Isgor and Ghani Razaqpur, 2006), as it can be seen on Fig. 4.

Continuous monitoring combined with NDT on Skovdiget bridge, near Kopenhagen has shown that, due to temperature effects, NDT inspections during autumn months tend to provide conservative measurements of the corrosion potential (and thus corrosion risk). The corrosion development is itself very dependent on moisture content and temperature, which are responsible for the electrolyte continuity (pore connectivity) and for the oxygen availability at the steel surface. Moisture influences the electrical resistance, which is the most comprehensive parameter determining the corrosion current. Since moisture and temperature vary with time, and may also vary from place to place in the concrete, an assessment of concrete that should be independent of these variations becomes difficult. Since many influencing factors can explain any observed variability of the measurements, it is important to quantify these potential effects, such as to sort out any "real signal", i.e. real variation with time or space, of the effective corrosion degree (Breysse et al., 2007).

Collective efforts have been undertaken in the recent years to gather data about time and space variability in relation with service life prediction and structural reliability (Duracrete, 2000; Samco, 2006). The measured on-site variability can be due either to material and exposure conditions variability or to uncertainty in the measurement process (e.g. lack of repeatability or influence of environmental conditions at the time of measurement). The first cause is representative of the structure and of its condition. The spatial variability of the material properties results from the construction process and concrete placing. It must be accounted for in a probabilistic approach, the residual service life becoming a probabilistic variable, whose value is distributed in the structure (Stewart, 2001; Li, 2004). The second type of uncertainties can be reduced with a more cautious approach and with the modelling of environmental effects on the measurements. Data obtained at the laboratory, repeating for instance electro-chemical measurements under varying ambient conditions, can be processed and used for this purpose. In fact, the vast majorities of probabilistic studies

whose purpose is to analyze the consequence of material variability on the structure reliability do not make the part between the two components of variability: the real one (random uncertainty), due to the material, and the superimposed one (epistemic uncertainty), which only comes from imperfect knowledge one has of the structure after measurement.

3.2. BARRA BRIDGE CHARACTERISTICS AND INVESTIGATION PROGRAM

The structure. The Barra Bridge is located on km 0 + 824 of E.N.109-7 over Ria de Aveiro. It has a 578 m length, between the support axes on the abutments. The central span has 80 m and the access viaducts, symmetric as refers to the central span, have 249 m, each being formed by seven spans of 32 m and a last one of 25 m (Fig. 5).

In a first inspection made in the Barra Bridge (in May 2006), two piers and one of the abutments were inspected. The piers were the P13 and P15, which are in land, and the abutment was the E2. The inspected zones are on the right part of the bridge, which is the farthest from the sea, since the sea is about 300–500 m from the left end of the bridge. Regarding their location respectively to the river, the inspected areas on the piers are denominated as "upstream" and "downstream" (depending on what column it is referred to) and in "left" and "right" side.

Figure 5. Barra Bridge

The inspection included visual observation of the structure, the selection of different areas to be studied (differing in elevation, part of pier and side), concrete cover over the reinforcements in the selected areas, half cell potential and corrosion rate measurements. Cores were extracted for laboratory tests, mainly for chloride characterization but also for concrete compressive strength and for microstructural characterization.

In pier 13, six areas were analyzed, three in the left side of the pier and three in the right side (Fig. 6). Concrete cover, potential and corrosion rate measurements were performed and cores were taken in five of those areas. In the last one, it has been only proceeded to concrete coring.

These areas are denominated as follows: 13JE (2.5 m) – downstream, left side at about 2.5 m above ground level; 13JE (10 m) – downstream, left side, above 10 m; T13E – transverse beam, left side; 13MD (2.5 m) – UPVtream, right side at about 2.5 m; 13MD (10 m) – UPVtream, right side, above 10 m; T13D – transverse beam, right side.

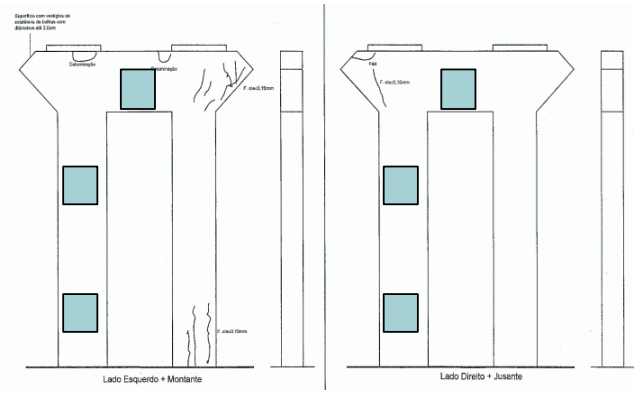


Figure 6. Location of investigated areas on pier 13 (*left* face and *right* face)

3.2.1. *Spatial Variability*

The cover was measured using a scanning cover depth meter. The mapping of corrosion potential was performed with a German Instruments GD-2000 Mini Great Dane system, and the determination of the corrosion rates was done by the polarization resistance method using the equipment GeCor 6. The detailed results of each area, regarding the cover of each rebar, the potential values and the corrosion rate measurements were analyzed in terms of variability. For instance, regarding the 13MD (10 m) area (whose size is about 1 m^2), the investigation performed on 15 May 2006 has provided:

- A corrosion current density i_{corr} in the 0.085–0.359 $\mu A/cm^2$ interval
- A half cell potential (measured with $Cu/CuSO_4$ reference electrode) varying from −72.7–30.4 mV
- A cover depth between 29 and 35 mm (horizontal re-bars) and 38–40 mm (vertical re-bars)
- A carbonation depth (from cores) between 10 and 14 mm

Therefore, the 13MD (10 m) area, which can be regarded as a "homogeneous" area regarding the corrosion degree (at least from visual inspection) exhibits some spatial variation of its characteristics. It is thus interesting to analyze the reasons of this variability and to understand if it requires a statistical analysis or if it suffices to consider representative values (either mean values or conservative estimates) to have a good image of the area.

3.2.2. *Temporal Variability and Consistency*

A second series of investigations was undertaken two months later (on 27 July 2006), to check the stability of the non-destructive results with time, and to gather additional information. The two series of measurements have been

performed in different atmospheric conditions (this information was not recorded at the time and place of the measurements):

- On 15 May 2006, the temperature was average (about 20°C) and the weather was rather dry (RH about 80%)
- On 27 July 2006, the temperature was higher (about 25°C) but the weather was wet (RH about 90%)

Regarding the 13MD area, the results were:

- A corrosion current density i_{corr} in the 0.363–0.783 μA/cm^2 interval,
- A potential (measured with Cu/$CuSO_4$ reference electrode) varying from –47.5 to −17.3 mV.

This shows that the non destructive results (corrosion current density or potential) cannot be simply viewed as reference values, which can be compared to normalized threshold, and that a correct assessment of the structural condition requires a lot of care. It is well known that the environmental context (mainly temperature and humidity) can influence the electrical response of the structure.

However, the repeatability of the NDT measurements can be checked by comparing the two series of measurements (Fig. 7). On this area 13JE (but the same conclusions has be drawn for others areas), the overall consistency between the two series of measurements is good, even if one has some scatter. The "local noise" which corresponds to the scatter is about +/− 15 mV.

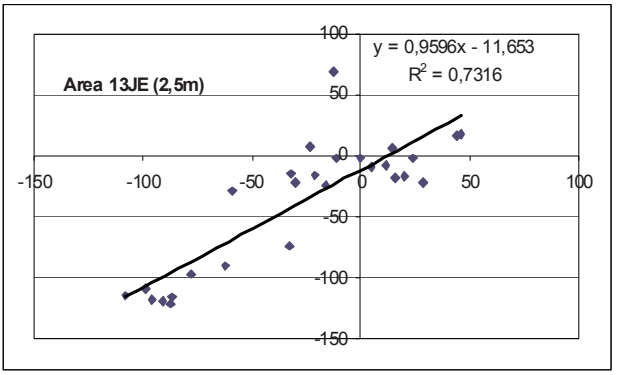


Figure 7. Repeatability of potential measurements (in mV) for area 13 JE

Regarding the measured values for the corrosion current density, they are very different for the two series of measurements, as summarized in Table 2. The average value of i_{corr} has been multiplied by about 2 between May and July (multiplying factor = 1.86 calculated on 11 measurements on Pier 13).

TABLE 2. Average values for i_{corr} ($\mu A/cm^2$) measurements at two different times

Area	May	July	Difference (%)
13 JE	0.31	0.62	+98
13 MD	0.31	0.53	+75
13 – : T beam	0.22	0.48	+123
all	0.29	0.54	+86

3.2.3. *Cover Depth Variability*

All data regarding cover have been synthesized, such has to quantify the variability at various scales (within an area, within a pier, for the whole bridge). A significant difference has been noted between horizontal and vertical re-bars (due to obvious design reasons), with an average cover depth that is 7–8 mm larger for vertical rebars. A significant difference has also been noted between Pier 13 and Pier 15, which can only be explained by variability in the rebar positioning:

- Pier 13: average horizontal cover depth 29.1 mm, average vertical cover depth 37.7 mm
- Pier 15: average horizontal cover depth 37.3 mm, average vertical cover depth 44.8 mm

More detailed measurements of cover depth have been performed during the second series of investigations, to quantify the longitudinal variation of cover depth along a given rebar. For instance, one has measured between 30 and 35 mm when the cover depth had at first been estimated as being 34 mm. The coefficient of variation (c.o.v.) along a rebar is between 3% and 10%, with an average value of 7%. For a given 1 m^2 area, and a given set of re-bars (horizontal or vertical) the c.o.v. ranges between 9% and 16%. It jumps to 20–30% if one combines the two directions of reinforcements in a given area. This value is much larger than that of an individual rebar. When a whole pier is considered, the coefficient of variation is about 30%.

3.3. LABORATORY ANALYSIS AND DEVELOPMENT OF A CORRECTION PROCESS

3.3.1. *Experimental Program Definition and Analysis*

Moisture content in the concrete and humidity are the most influencing factors affecting the corrosion development, but also the electrochemical properties assessed via non-destructive techniques. It is also well known (Andrade and Alonso, 1996; Gonzalez et al., 1996) that other influencing factors are the quality of concrete, the chloride content, the oxygen content. Since the measurements are also performed through the cover concrete, the cover depth also appears as a

potential influent parameter. Thus an experimental program has been designed such as to quantify the influence of some of these parameters on the corrosion development and on the current of corrosion.

Specimens were cast with two w/c ratios (0.45 and 0.65) and two cover depths (1 and 3 cm). Two prisms with 20 × 20 × 25 cm^3 were prepared for each concrete type and cover depth. Chlorides have also been added to the mix, such as to ensure the initiation of corrosion (3% total chlorides related to cement content). All specimens were subjected during ten months to varying conditions regarding relative air humidity (20% < RH < 100%) and temperature (2°C < T < 50°C). Regular measurements of polarization resistance have been performed, from which corrosion current density has been deduced.

Statistical analysis has been performed on the whole series of measurements, such as to identify the most influencing factors and to provide, via multi-linear regression analysis, a quantitative model for i_{corr}. Due to the fact that the i_{corr} values can vary in a large range, $\ln(i_{corr})$ values have been considered in the model. As it was expected from previous studies, moisture is the most important parameter. Figure 8 shows how it is positively correlated with $\ln(i_{corr.})$, the diagram excluding RH = 100% values, since this value involves different physical phenomena limiting the corrosion rate. Accounting for the linear influence of RH for explaining $\ln(i_{corr})$ variability reduces by a factor of 2 the total experimental variance.

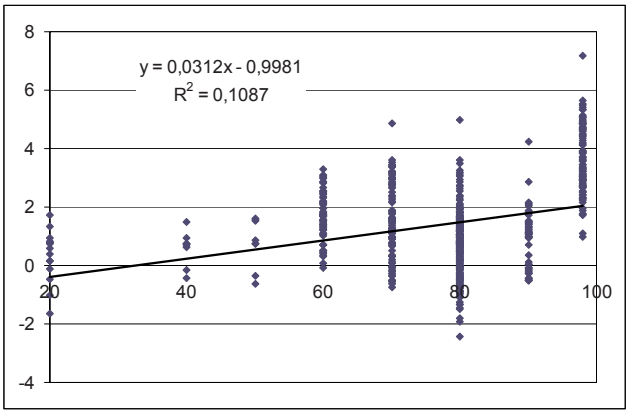


Figure 8. Correlation between RH (in %, x-axis) and $\ln(i_{corr.})$ (y-axis)

The other parameters bring less information but the effect of temperature, cover depth and water to cement ratio are significant. Each of them leads to an additional reduction of variance of about 10%. Two other parameters (total time since the beginning of experiment, and time elapsed since the beginning of the

new level of (RH, T) are not statistically significant). The multi-linear regression analysis leads to:

$$\ln i_{corr} = 0.0312\ RH - 4736/T + 1.695\ w/c - 0.391\ d + 14.589 \quad (2)$$

Thus the resulting model can be written as:

$$i_{corr} = A\ e^{0{,}0312\ RH}\ e^{-4736/T}\ e^{-0.391\ d}\ e^{+1.695\ w/c} \quad (3)$$

where RH is the air relative humidity (in %), T is the air temperature (in K), d is the cover depth (in cm), w/c is the water to cement ratio, A is a constant (in $\mu A/cm^2$).

This empirical model quantifies the combined influence of the four parameters (RH, T, d, w/c) on the measured value of the corrosion current density. The unexplained variance of the model which accounts for the combined influence of these four parameters is only 36% of the total experimental variance, giving an idea of the "quality" of this model. It must be added that the model can only be used for RH < 100%, since when the concrete is saturated the involved mechanisms are different. It thus makes possible the correction of the measurements to cancel the effects of these parameters when they are varying with time and/or space. The model can also be fitted with renormalized variables, such as to have coefficients without units. The model confirms that the corrosion current density is larger when RH increases, T increases and d decreases. It also confirms that the temperature and moisture are the most influencing parameters. For instance:

– It is multiplied by a factor 1.37 if RH varies from 80% to 90%.
– It is multiplied by a factor 1.70 if T varies from 15°C to 25°C.
– It is multiplied by a factor 1.48 if d varies from 3 to 2 cm.

3.3.2. *Correction Process for Temporal and Spatial Variability*

If we focus on the influence of the variation of the (RH and T) environmental parameters and of the cover depth on the i_{corr} measured value for a given concrete, it is possible to define an arbitrary reference set $S_{ref} = \{RH_{ref}, T_{ref}, d_{ref}\}$ and to consider the real set S = {RH, T, d} at the place and time of the measurement. Since i_{corr} is measured with S, the question is to correct it (using a multiplying factor), such as to obtain an $i_{corr\ ref}$ reference value which would have been measured under the conditions of the reference set. The obtained reference value would then be independent of any time variation in the environmental conditions (temperature, humidity) as well as of any spatial variation in the cover depth of rebars. Writing Eq. (3) a first time for the real set S and a second time for the reference set S_{ref}, thus eliminating A, it comes:

$$i_{corr\ ref} = k\ i_{corr} \quad (4)$$

with

$$k = e^{0,0312\,(RH - RHref)}\, e^{-4736(\,1/T - 1/Tref)}\, e^{-0,391\,(d - dref)} \quad (5)$$

Considering the following arbitrary reference set: {RH_{ref} = 80%, T_{ref} = 293 K, d_{ref} = 3 cm}, one can calculate the correcting factor for any set at the time and place of measurement. The Table 3 gives some examples of such correcting factors for various sets. The last series on Table 3 gives the factor (k = 0.558) by which one would have to multiply the July measurements to compare them with the May measurements. It is totally compatible with what has been observed on site (1/1.86 = 0.54), but the lack of any accurate recording of atmospheric conditions prevents us to conclude further on this point.

TABLE 3. Correcting factor on i_{corr} for several sets ({RH_{ref} = 80%, T_{ref} = 20°C, d_{ref} = 3 cm})

RH (%)	T (°C)	d (cm)	k	RH (%)	T (°C)	d (cm)	k
65	20	3	1.597	80	35	3	0.455
95	20	3	0.626	80	20	2	0.676
80	5	3	2.390	90	25	3	0.558

Equation (5) giving k value can also be helpful in interpreting the level of significance of any spatial variation that can be noted on site, when T and RH can be assumed as constant (during the series of measurements). Variations in measured values of i_{corr} can be due either:

- To a different degree of intensity of corrosion, which is the purpose of NDT measurement
- To the variation of an influent parameter, like the cover depth
- To the variation of any other influent parameters (for instance local micro-structure of concrete) or to any noise in the measurement process

It is easy to quantify the variability on i_{corr} resulting from any variability on the cover depth. The cover depth variability has been assessed on the Barra Bridge at three scales: that of a given rebar, that of a 1 m^2 area (Area 13MD for

TABLE 4. Measured variabilities of cover and of corrosion current density at three scales (c.o.v. indicates coefficient of variation)

Scale	c.o.v.(d)	c.o.v.(i_{corr})
One rebar	7% (between 3% and 10%)	Not enough measurements
1 m² area	9–16%	15% (on 5 measurements in May) to 22% (on 4 measurements in July)
Pier 13	20–30%	36% (11 measurements)

instance), that of the whole series of measurements on a given Pier (Pier 13 for instance), all re-bars being combined in the same population. Table 4 summarizes the measurement results. Variations in the corrosion current density can be expected as a result of the measured variability on cover depth (independently from any variability in the environmental conditions and noise measurement).

If we consider d = 3 cm as a central reference value, it appears that the measured variability (c.o.v. = 36% at the scale of the pier) can logically be expected as a consequence of the simple variability of cover depth at the same scale.

3.3.3. *Generalizing the Approach to Improve the Material Condition Assessment*

The correction factor expression Eq. (5) has been fitted from the laboratory experiments and it remains empirical. One has all reasons to think that it would have been slightly different with another concrete mix. However, the expression can be assumed to be, more generally:

$$k = e^{a\,(RH - RHref)}\, e^{-b(\,1/T - 1/Tref)}\, e^{-c\,(d - dref)} \qquad (6)$$

a, b and c being positive constants which would have to be fitted in any particular case (given structure, given concrete, given history...). The strategy to fit their value is however simple. It would suffice, on the studied structure, to monitor the current of corrosion under varying ambient conditions (24 h would suffice to have varying T, and perhaps few weeks to cover a wide range of variations for RH). Thus a and b can be derived from the regression between i_{corr}, RH and 1/T.

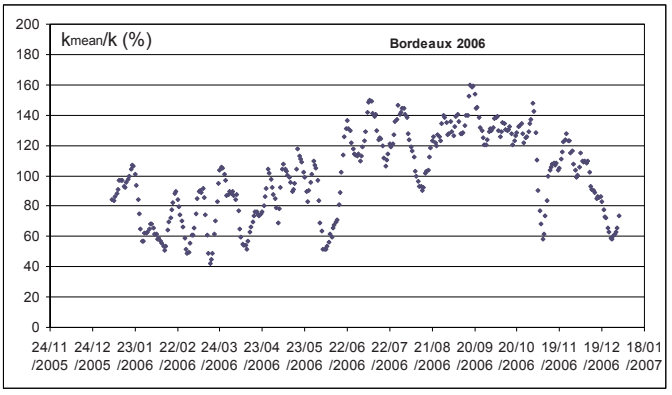


Figure 9. Ratio between k_{mean} (yearly average of k) and k (averaged on 1 week)

We can also apply the empirical model of Eq. (5) to the question of the representativity of a punctual measurement of corrosion rate. For this, we have used meteorological chronicles recorded in the city of Bordeaux, France, which is located 40 km from the Atlantic Ocean, in Atlantic climate. For the year 2006, we have considered average daily temperature and air moisture and computed the value of k coefficient according to Eq. (5) (one must keep in mind that k is the value by which one must multiply what is measured to obtain "what would have been obtained with" reference condition measurements).

The k value varies in a large range, from less than 1 during summer (the meteorological conditions approaching the reference ones) to more than 4 or 5 on some dry and cold days of winter and spring. The average value over the whole 2006 year equals $k_{mean} = 1.72$. If one considers that, for active corrosion, i_{corr} is directly proportional to the steel loss, this value is representative of the corrosion intensity over the year. Thus any isolated measurement of i_{corr}, during a "random" day, only provides a random estimation of this corrosion intensity, which is an overestimation if the measurement is performed during summer (corrosion is, in our case, more active than average between mid-June and end of October) while it is an underestimation if it is provided at other periods. Figure 9 highlights this point by quantifying the k_{mean}/k ratio, which can be put in parallel with the relative corrosion activity along time. It is wholly compatible with what was illustrated on Figure 4 from on-site monitoring of structures.

Thus this kind of model opens interesting tracks towards a more reliable assessment of corrosion, enabling to replace the results of punctual measurements in a wider panorama, being assumed that meteorological information (at the time of the measurements as well as for the usual service condition) are known.

4. Variability and Reliability of NDT: Point of View from the Lab

4.1. AN AMBITIOUS APPROACH FOR UNCERTAINTY MODELLING IN NDT: THE SENSO PROGRAM

An effective optimal combination of techniques for a better assessment of material properties requires one knows:

- The existing relations (whatever linear or not) between what we will name "observables" (T parameters in Section 2, that can be directly measured, like R and V in the SonReb method) and what we will call "indicators" (X and Y parameters in Section 2, that we want to assess, like strength and modulus in the SonReb method)
- The magnitude of uncertainties linked to each assessed value of observable quantities

SENSO, is the name of a specific research program which has been designed under the auspices of French National Agency of Research (ANR) such as to quantify both these relations and these uncertainties for a large series of NDT observable quantities and concrete material properties (indicators), namely: strength, modulus, porosity, water content, carbonation depth, chloride content, magnitude of micro-cracking. The full program will not be described here, but only the methodology used for gathering useful data, building the relevant relations and performing first improved assessments.

The first part of the programme consists in analyzing the effects of water content and porosity variations on the NDT observables for several concrete mixes, on laboratory specimens. Specimens are concrete slabs taken from nine mixes in which are varied w/c (from 0.30 to 0.90), kind, size and shape of aggregates. Eight slabs have been cast for each mix and all NDT measurements are performed on all slabs. The first series of measurements is focused on porosity and water content influence, thus the saturation of slabs is controlled, and varied from a "saturated" reference state to a "dry" one. Many NDT techniques have been used by five research teams and consist in radar measurements, acoustical measurements, electrical measurements, infrared thermography measurements and capacimetry measurements. Each technique can provide a series of observable quantities (f.i., for radar, velocity, magnitude or attenuation at several frequencies, shape of the signal...), thus about 60 observable quantities have been defined and estimated on each specimen.

Knowing the various sources of variability, the measurement process is defined such as to quantify, for each observable, several variance estimators (Fig. 10).

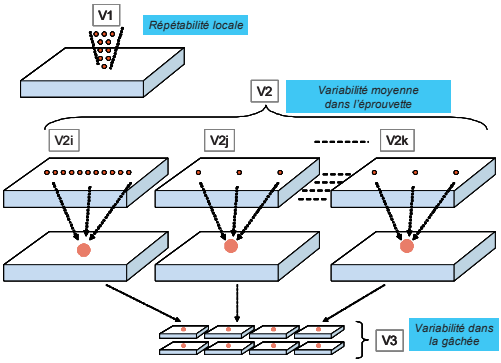


Figure 10. Meaning of V1, V2 and V3 variances

V1 comes from the lack of local repeatability of any measurement, at a given point, when the measurement is done several times. It is estimated after ten repetitions. **V2** comes from the internal slab variability (due to the concrete fabric, to boundary effects, to the non-homogeneity in water content...). It is

estimated by moving the sensors within each specimen and evaluated after ten points of measurements. **V3** comes from the mix variability. It is evaluated by comparing the average measurements obtained on the eight specimens of each mix. **V3a** comes from the mix lack of repeatability. It is evaluated by comparing the measurements on specimens originating from a twinned reference mix, with w/c = 0.45. **V4** corresponds the to the overall contrast between all mixes and specimens. It is evaluated by comparing the average values for each mix.

4.2. BUILDING AND QUALIFYING RELEVANT OBSERVABLE QUANTITIES AND MODELS

When one aims at material condition assessment, the relevancy of a given ND technique depends on:

- The accuracy of the technique: thus V1 has to be as low as possible.
- The exactness of the technique: thus values obtained of similar specimens have to be the same, thus V3a has to be as low as possible.
- The sensitivity of the technique to what is looked for, thus the contrast V4 has to be as large as possible.

Based on these findings, a first step has consisted, for each observable, in quantifying of variances and in building synthetic indexes, which have been named:

- The “quality index”, which is larger when V1, V2 are small with regard with V3.
- The “relevancy index”, which is larger when the technique is more sensitive to the material property.

Thus, the “quality index” mostly qualifies the techniques when the “relevancy index” qualified its ability to find the results that are expected. All measurements are processed, and these two indexes are quantified for all observable quantities, enabling to sort out what are the most efficient for a given purpose (at this stage, for assessing water content and porosity, which are both known to be very influent on strength and modulus).

Before using and combining two (or several techniques), a further step must be done, that of analyzing and quantifying the relations between indicators and observable quantities. At this stage, linear regressions can be tested for all relations (or non linear ones if they seem more adapted from literature survey, as it is the case for instance for resistance measurements which are know to depend on porosity and water content following a power law). Figure 11a and b illustrates what is obtained for the relation between ultrasonic wave velocity (observable) and porosity (indicator). The Fig. 11a plots only average values for

all mixes while Fig. 11b plots all individual values on specimens. The linear regressions give:

$$V\ (m/s) = 5332 - 65.4\ p\ (\%) \qquad r^2 = 0.72$$
$$V\ (m/s) = 5272 - 61.0\ p\ (\%) \qquad r^2 = 0.64$$

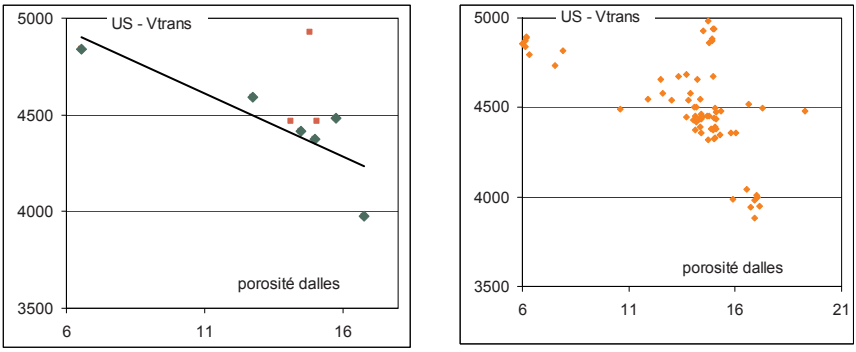


Figure 11a, b. Correlations between ultrasonic wave velocity and concrete porosity

The difference between the two graphs clearly shows the influence of V3 variability, whose result a small « cloud » of points around the average point for each mix. It has the consequence of decreasing the quality of the regression equation, thus the quality of the assessment if one wants to predict the porosity from the velocity measurement.

An additional interesting remark can be done, since on the first graph, the green points correspond to mixes in which only w/c has been varied, when the three small red points correspond to additional mixes, for which the aggregate has been changed (either in size, or in shape, or in nature). It can be seen that a point widely departs from the general relation. It corresponds to a mix in which siliceous aggregates have been used instead of limestone, like in all other mixes. It can be clearly seen that the regression equation cannot predict accurately the properties in this situation, since the velocity is 500 m/s larger than for the basic mixes. This points fundamental limits on all strategy aiming at using NDT for material quantitative assessment if the relations between indicators and observable quantities have not been identified and validated on similar materials. A last step is the selection of series of observable quantities whose combination will be helpful regarding a given purpose. This point will be addressed below.

5. Combination of Techniques for an Improved Reliability of Assessment: Strength Assessment Case Study

5.1. WHY COMBINATION OF TECHNIQUES HAS SOME LIMITS? STRENGTH ASSESSMENT WITH THE SONREB EXAMPLE

5.1.1. *Framework of Simulations*

We will here privilege a synthetic approach, using random simulations, to better understand on what basis lays the use of combination of techniques. The demonstration is based on the use of simulations in which we will simulate physical material properties and non-destructive properties of specimens. These measurements will allow building statistical laws that will be used in a second step to assess the material properties. The principles of the simulations are the following ones:

(a) The material is physically described through two properties: porosity p and saturation rate, which are varying at each point in the structure, with the following assumptions:
   – Porosity assumed to be Gaussian (p_m, s(p)), where s(p) is the standard.
   – Saturation assumed to be uniformly distributed (S_{rm} +/– ΔS_{rm}).

(b) The NDT measurement provide two physical properties: ultrasonic wave propagation velocity V and rebound hammer measurement R, whose "true" value is supposed to be a deterministic function of the [p, S] set. However, since the measurement are not perfect, the measured value of the non destructive parameter is not the real value, the magnitude of the difference depending on the quality of the technique, which is taken as a parameter. The measured values (V_{meas} and R_{meas}) are computed by multiplying the true values by a factor (1 + ε()) where the error ε() is a Gaussian variable (mean zero, standard deviation s(ε()) given, depending on the quality of the technique).

(c) The mechanical properties (E, f_c) can also be assessed from laboratory tests, thus the true values differ from the assessed ones. Their measured values (E_{meas} and $f_{c\ meas}$) are computed by multiplying the true values by a factor (1 + ε()) where the error ε is a Gaussian variable (mean zero, standard deviation s(ε()) given, depending on the quality of the test measurement).

(d) Empirical correlations can be drawn from the measured values of V and R on one hand and those of E and f_c the other hand. It will be focused in the following on the strength parameter, but the same logic prevails for E.

To summarize, the input data for simulations are:

- The range of variation porosity and saturation rate, which corresponds in the reality to material variability
- The level of quality of NDT measurement, given by the error values ε(R) and ε(V)
- The level of quality of mechanical measurement, given by the error values ε(E) and εf_c
- The model functions between material properties and NDT properties:

$$(R, V) = f_{th}(p, S) \tag{7}$$

- The model functions between material and mechanical properties:

$$(E, f_c) = g_{th}(p, S) \tag{8}$$

The real relations between mechanical properties and NDT properties thus writes:

$$(E, f_c) = h_{th}(R, V) = h_{th} = g_{th} \times f_{th}^{-1}(R, V) \tag{9}$$

but it cannot be known because of several reasons:

- The measured values differ from true ones, due to various error measurements.
- The exact functions and ar unknown and can only be approached via empirical correlations on measurement results.

5.1.2. *Simulation of the SonReb Method and Influent Factors*

Monte-Carlo simulations are performed, aiming at modulus and strength assessment. The general idea is to randomly generate a set of varying material properties (p, S). Each (p, S) set induces both mechanical properties (through Eq. 8) and NDT properties (through Eq. 7). These properties are estimated with NDT tests (with some errors ε(V) and ε(R)) and with mechanical tests (with some errors ε(E) and $\varepsilon(f_c)$). For each simulation, one obtains then a set of measured values (p_{meas}, S_{meas}, E_{meas}, $f_{c\,meas}$).

Considering the series of Monte-Carlo simulations, one obtains a series of such sets from which empirical correlations can be identified, for instance using linear regressions.

In practice, this strategy is independent of models used for Eqs. (7) and (8). However these "physical" models have been chosen such as to fulfill some requirements: physical consistency, agreement with what is observed in reality in terms of sensitivity and range of variation of the properties. To do that, experimental information given in (Soshiroda et al., 2006) and obtained by some of the authors in the extensive ANR-SENSO experimental program have been used. The models are given in Table 5. The consistency of the whole set of

simulation has been checked by analyzing the range of variations of true properties and that of measured properties, as well as on the empirical correlations that can be drawn from them. We will study below how the strength assessment depends on the quality (or lack of quality) of the NDT measurement. The quality of all measurements is quantified by the magnitude of the measurement error which is varied from 10^{-3} to 0.20, which covers a wide range of usual techniques. Some results of the SENSO program have been used there.

TABLE 5. Models used for simulations

UPV (m/s)	$V = V_o\,(1 - \alpha_1\,p)\,(1 - \alpha_2/3\,S + \alpha_2 S^2)$	V_o = 5,600 m/s, $\alpha_1 = 0.1$, $\alpha_2 = 0.05$
Rebound hammer measurement R	$R = 10 + R_o\,(1 - \alpha_3\,p)^3\,(1 - \alpha_4\,S)$	$R_o = 60$, $\alpha_3 = 1.5$, $\alpha_4 = 0.1$
Young's modulus E (GPa)	$E = E_o\,(1 - p)^3\,(1 - p\,S)$	E_o = 55 GPa
Compressive strength f_c	$f_c = f_{co}\,(1 - p)^7\,(1 - \alpha_5\,S)$	f_{co} =140 MPa $\alpha_5 = 0.5$

5.1.2. *Illustration of Effects of Noise on Correlations Between Measurements*

In these simulations, the average material properties are assumed to be p = 13% and S = 80% with a standard deviation of 2% for porosity and a range of +/− 5% for saturation rate. The relation between NDT properties and mechanical properties can be approached with linear regressions, as shown on Fig. 12a and b. These figures show that, even if the real relations are not linear (because of models used in Eqs. 7–8), the quality of fit for true values is good in the experimental range of variation of the parameters. It also shows that the quality of fit is lower for measured values, because of measurement errors. These graphs have been obtained with: $s(\varepsilon(R)) = 5\%$, $s(\varepsilon(V_p)) = 0.5\%$, $s(\varepsilon(f_c)) = 5\%$).

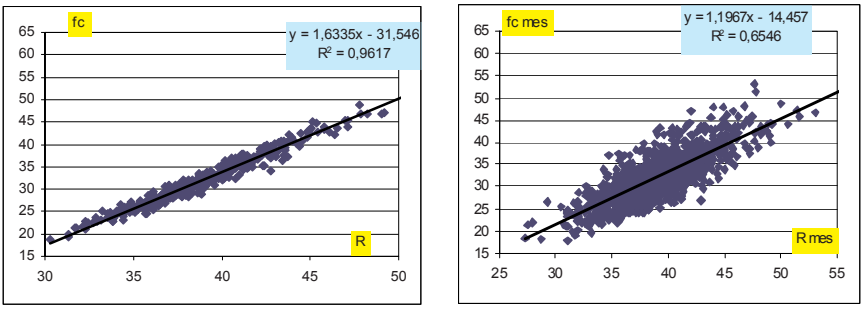


Figure 12a, b. Correlations between Rebound and strength: true values (*left*) and measured values (*right*)

The quality of fit regularly decreases when the quality of the sources of information decreases. It can be either because of one of the NDT quality or

because of the destructive test quality. The direct consequence is that the "cloud" is larger and that the regression which will be used for calibration will be less reliable.

5.1.3. *Simulation of the SonReb Method: Calibration and Strength Assessment*

The regressions obtained between R and f_c (see Fig. 12a and b) or between V and f_c can be used to assess the in-situ strength. The idea is on a first step (calibration stage) to identify these correlations, obtained via sampling on some cores (thus one has both measured values or R (or V) and f_c) and, on a second step, to assess from the NDT measurement only. The best is to perform the calibration on the structure under study, but calibration curves can be used if this is not possible. Here, the calibration stage is simulated.

5.1.4. *Calibration Stage*

From the set of measurements, one can write:

$$f_c = f_{c\,ref} + k_V (V - V_{ref}) + k_R (R - R_{ref}) \tag{10}$$

where the *ref* index refers to "reference", for instance an average value on the specimen population. The k_V and k_R coefficients respectively quantify the sensitivity of strength to any change in V or R. The quality of these equations depends on the quality of the destructive tests themselves, since the measured value of f_c is also noisy.

5.1.5. *Assessment Stage*

Thus, assuming that, the measured values on the specimen are V_p and R, the reference values are known to be respectively $f_{c\,ref}$, V_{ref} and R_{ref}, one can deduce estimation for f_c which accounts for corrections after non-destructive measurements:

$$f_{c\,est} = f_{c\,meas} + k_V (V - V_{ref}) + k_R (R - R_{ref}) \tag{11}$$

By simulations, it is possible to study how these corrections (single correction from V or R or combined correction) are able to improve the estimation of real values. The Fig. 16 shows how f_c is related with V_p and R in two cases (good quality of f_c measurement, poor quality of f_c measurement). As see from the shape of clouds, the quality of the regression is better when the f_c measurement is more accurate.

The level of quality of the technique being given, k_V and k_R values are easily identified (for instance $k_R = 1.1685$ in the left side case and $k_R = 1.1993$ in the right side case) and the assessment can be performed as soon as new value of R are provided. These regressions show that a gain of ten points on the

R scale corresponds to a gain of about 11 or 12 MPa in strength. Since our models have been fitted to real experimental data, this is consistent with what is observed in practice.

5.1.6. *Some Results: Efficiency and Limits of Combination*

We will compare the quality of the strength assessment in three cases:

– Case (a) – the strength assessment comes from the rebound measurement only:

$$f_{c\,est} = f_{c\,meas} + k_R\,(R - R_{ref}) \qquad (12)$$

– Case (b) – the strength assessment is given by the UPV measurement only:

$$f_{c\,est} = f_{c\,meas} + k_V\,(V - V_{ref}) \qquad (13)$$

– Case (c) – both UPV measurement and rebound measurement contribute to the strength assessment:

$$f_{c\,est} = f_{c\,meas} + k_V\,(V - V_{ref}) + k_R\,(R - R_{ref}) \qquad (14)$$

This last case formally corresponds to the SonReb protocol and SonReb charts. Figure 13 enables to compare the *true* values (truth can be known since it is not real world but a synthetic world!) to the assessed ones in the case (c). Figure 14 synthesizes all results when the quality of the two NDT techniques is simultaneously varied. It plots how the correlation coefficient between true and assessed values of strength varies when the error on R increases (from near 0 – very good to 20% – very bad) for three values of error on V (0.1%, 2%, 4%) that respectively correspond to a very good, average and bad quality of the technique.

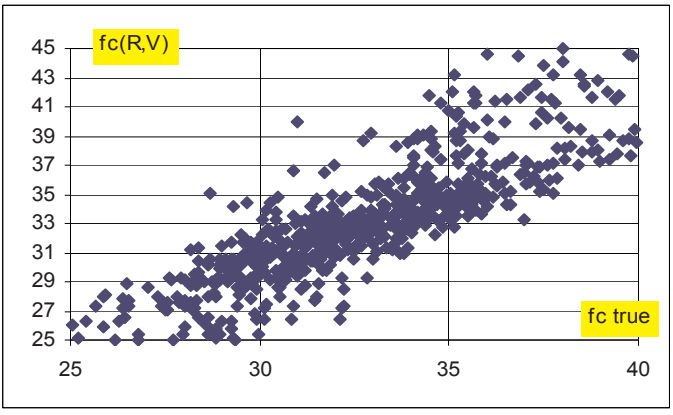


Figure 13. Comparison of true and assessed strength values for case (c) (s(ε(V) = 0.5%, s(ε(R) = 3%, s(f_c(R) = 2%)

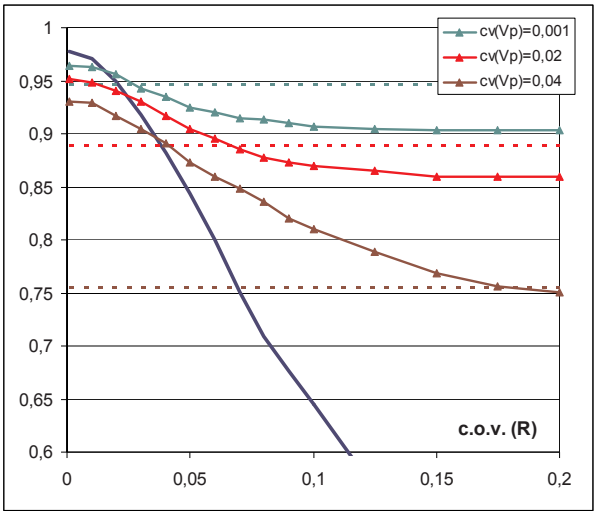


Figure 14. Variation of the quality of strength assessment correlation coefficient between true and assessed values) for varying quality of NDT techniques, with and without combination

Three sets of curves are plotted. The blue bold curve corresponds to the case (a) measurement. It shows that the quality of assessment regularly decreases with the quality of the rebound measurement. The three horizontal lines correspond to case (b) for the three levels of quality of V measurements. They logically show that the quality of strength assessment varies from being good when the error on V is small to being bad when this error is large. The three last curves correspond to the combination (case (c)).

Analyzing these curve is much interesting. If we take for instance the curve corresponding to c.o.v.(V) = 2%, three domains can be seen. On the left part (small c.o.v.(R)) the case (a) gives the best result, since the corresponding curve is the higher. On the right part (high c.o.v.(R)), it is the case (b) which provides the best strength assessment. Between the two (here for 3% < c.o.v.(R) < 6%), the best strength assessment is provided by case (c), i.e. by the combination of techniques. The same can be seen for the other values of c.o.v.(V), even if the boundaries of optimal domains change. SENSO results have shown that we can assume c.o.v.(R) = 3–4% and c.o.v.(V) = 2%, which corresponds to the domain in which the combination really brings something. This confirms the potential interest of this combination.

This conclusion can be generalized, telling that, if any NDT is very accurate, assessing the strength on its simple basis is the best solution, but the combination has an added-value in an intermediate domain, when both techniques are of an average quality. For instance, when c.o.v.(R) = 0.04 and c.o.v.(V) = 0.2, the correlation coefficient jumps from 0.89 (for cases (a) and (b)) to 0.93 (case (c)).

5.2. WHAT CAN BRING THE COMBINATION OF SEVERAL NDT? STIFFNESS ASSESSMENT EXAMPLE

Since UPV measurements are very easy to handle they have been often combined to a secondary technique for material assessment. One interesting idea is to combine them with another technique that is also sensitive to water content. Capacitive measurements (Sirieix et al., 2007), GPR measurements (Saisi et al., 2001; Laurens et al., 2003), IR thermography (Sirieix et al., 2007; Kandemir-Yucel et al., 2007) or electrical resistivity (Sirieix et al., 2007; Breysse et al., 2008b) have been commonly used. However a more formal approach appears to be necessary. This is one of the objective of the SENSO research project on concrete.

The statistical analysis of the measurements when varying the concrete composition and the saturation rate made us capable of selecting the more interesting observable quantities (See Section 4) and of drawing multiple regression laws between properties and NDT measurements. For instance, regarding water content and porosity, the following relations have been derived:

$$Y1 = 1128 + 4.87\ Sr + 26.4\ Esat \quad (15)$$
$$Y2 = 2644 + 8.77\ Sr + 39.1\ Esat \quad (16)$$
$$Y3 = 1.94 - 0.015\ Sr + 0.053\ Esat \quad (17)$$
$$Y4 = 0.541 - 0.0016\ Sr + 0.0014\ Esat \quad (18)$$
$$Y5 = 0.956 + 0.00379\ Sr - 0.0032\ Esat \quad (19)$$

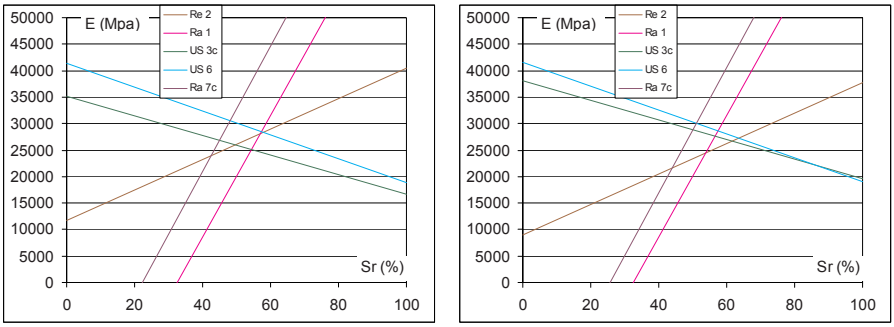
where Sr and Esat are respectively the saturation rate (in %) and the saturated Young's modulus (in GPa) and Y1 to Y5 are NDT observable quantities: Y1 is the group velocity of surface waves (in m/s), Y2 is the UPV of compression waves (in m/s), Y3 is the log of electrical resistance (in Ω.m), Y4 is the magnitude of a radar signal and Y5 is the time of arrival (in ms) of a radar signal;

We have also identified the degree of variability of each measurement, due to the intrinsic material heterogeneity and to the non-perfect repeatability of the measurement (corresponding to the **V3** variance). It can be expressed in terms of signal variance or standard deviation. For instance, for the same five observables, the standard deviations are respectively: sd (Y1) = 41.2; sd (Y2) = 11.5; sd (Y3) = 0.11; sd (Y4) = 0.025; sd (Y5) = 0.020

The smaller is the standard deviation, the more accurate the estimation of {Sr, Esat} will be when using the (15–19) equations for inversion.

Figures 15a and b plot in the Sr-Esat plane the regression line corresponding to the measured value with the five observable quantities Y1-Y5 for two specimens (two slabs) made of the same concrete and kept in the same conditions. If both the measurements and the (statistical regression) models were perfect, all lines would cross in a unique point. If the material was homogeneous, the two graphs

would be identical. Any difference is thus due to one these three explanations: measurements are not perfect, the linear regression model is an approximation, the material is not homogeneous.



Figures 15 a, b. Use of linear regression model to identify the {Sr, Esat} values for two concrete specimens on two specimens of the same mix

The complementarities of the techniques involved here can be clearly seen through the fact that lines do not follow the same directions. If the two sonic techniques (Y1/US3c and Y2/US6) give parallel lines, the two radar measurements (Y4/Ra1 and Y5/Ra7c) gives two parallel lines very different and the last technique, electric resistance (Y3/Re2) has a very different slope. The more slopes are different, the better the techniques will bring added-value to each other. The diagram plots the results corresponding to five observable quantities (which have been selected from a larger set, since a lot of info has been obtained during the SENSO experimental program), but the method works as soon as two observable quantities are available. Nevertheless, the diagnostic is not perfect, since all lines do not cross in a unique point. To give some basis for comparison, the measured value of Sr, estimated by weighing the slabs is between 47% and 54% and the Young's modulus, measured on cylinders is about 27 GPa. The Sr value seems to be slightly overestimated, but the stiffness is accurately estimated. In addition, the knowledge of the standard deviation for each measurement provides an information about the level of accuracy of the estimate (a slightly different value of the measurement would correspond to a slight displacement of the line in the Esat-Sr diagram). For instance, if one considers the resistance measurement Y3, with sd(Y3) = 0.11, this leads to an uncertainty of about +/− 0.11/0.015 = +/− 6% on Sr and of about +/− 0.11/0.053 = +/− 2 GPa on Esat.

6. Conclusions

We have tried in this paper to review some challenges and some recent research results showing that the high potential of NDT for assessing material condition, including engineering parameters. This discussion was based on a combination of:

- Real on-site measurements, with many sources of noise, due to environmental conditions and the complex history of structure
- Laboratory measurements in which these parameters are controlled
- Synthetic simulations, to better understand what happens and the weight of each factor

We have shown that the important influence of environmental factors (like temperature and humidity) has to be controlled and can even be eliminated, such as to analyze the measurements as if they would have been obtained in "reference conditions".

The high influence of material variability (including cover depth) on the measurements has been confirmed, preventing any reliable statement if one is not able of making the part between the noise of the technique and this material variability. We have shown that it is possible to quantify its influence on measurements, thus to eliminate it if it is measured by a secondary technique.

We have also given the first results of a very ambitious program tending to give a more comprehensive view on the key question of combination of techniques while using NDT. The selection of the more appropriate techniques is possible, on the basis of their intrinsic quality, of their sensitivity to what is looked for and of their complementarities. It has also been shown that in some cases, the use of a second technique brings no additional information and if thus counterproductive.

Of course, all these open tracks remain to be deepened, with the aim of providing experts a more formal methodology for structural condition investigation. The time when it will be able to feed computational models of reliable data on existing structures has not yet come, but it surely will do.

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