Reliability of non destructive on site strength assessment of concrete

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RÉSUMÉ. Fiabiliser l'estimation de la résistance en compression du béton d'ouvrages existants via des techniques non destructives est un défi complexe. L'amélioration des normes et des procédures employées par les experts doit s'appuyer sur des recommandations plus formelles, se référant à des connaissances bien établies. Nous proposons ici de considérer le processus d'investigation et d'évaluation de la résistance en place du béton d'ouvrages existants comme un processus aléatoire dans lequel de nombreuses incertitudes apparaissent à différentes étapes et conditionnent la précision de l'estimation finale. Nous avons développé un outil de simulation qui permet de décrire les différentes étapes du processus, de mener une étude méthodique des facteurs influents, et de tester des options que peuvent développer les investigateurs. Les résultats de simulation ont été utilisés pour bâtir des courbes de risque pour plusieurs cibles de l'évaluation, et confirment le rôle majeur que joue la qualité (répétabilité) des mesures. Elles permettent aussi de justifier des recommandations quant au nombre de carottes nécessaire.

ABSTRACT. Improving the reliability of concrete strength estimation in existing structures with nondestructive techniques is a complex challenge. Better standards and improved engineering practice can be based on more formal recommendations that would refer to well established knowledge. We propose here to consider the onsite investigation and assessment of strength in existing concrete structures as a random process in which many uncertainties arise at various steps, which condition the uncertainty attached to final assessed strength. A simulation framework has been developed, that enables to describe all these steps and to carry on a systematic analysis of all influencing factors and of some alternative options that can be taken by the investigators. The simulation results were used to establish risk-curves for several assessment targets, which points the major role of the test result repeatability and give way to the definition of recommended number of cores.

MOTS-CLÉS : évaluation non destructive, incertitudes, répétabilité des mesures, résistance du béton, variabilité

KEY WORDS: concrete strength, nondestructive evaluation, precision, repeatability of test results, uncertainty, variability

1. The on-site evaluation of concrete strength in existing buildings: an archetypal complex problem

The estimation of concrete strength in existing buildings with nondestructive techniques (NDT) remains a challenging issue. The scientific literature contains many examples where NDT are used in order to assess the concrete strength. Some standards also exist which explain how NDT can be carried out and the limits of these techniques (ACI, 2008) or how they can be used to derive local concrete strength estimates. However, one still lacks guidelines which would tell how non destructive measurements can be gathered, processed and used in order to derive reliable information about the onsite concrete strength. The RILEM Technical Committee ISC 249 (In-situ strength of concrete) has been created to prepare such guidelines. The common concrete strength assessment process can be subdivided in three main stages, as illustrated on Figure 1: (a) data collection (including NDT measurements and core strength measurement), (b) model identification, (c) model use and concrete strength estimation. To be more precise, it can be told that any investigation strategy must consider the following items:

(a) Definition of points (number and location) where NDT measurements are carried out.

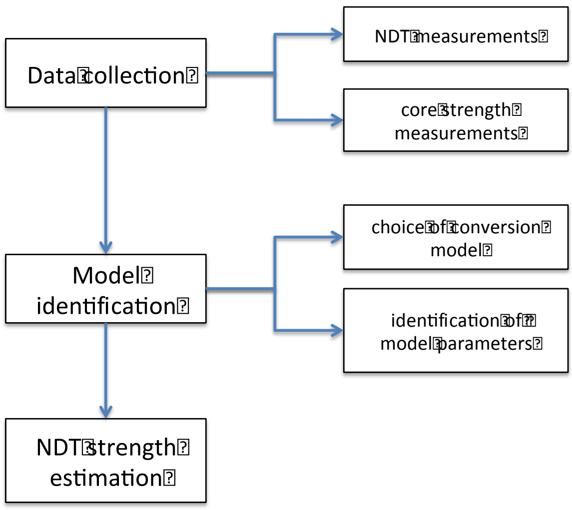
(b) Definition of points (rules for choice, number, location) where cores are to be taken. These two first decision steps interact because of constraints (cost, time…) on the whole process. An important option is the selection of core locations, which can be based on the NDT results.

(c) Identification of the conversion model.

(d) Use of the conversion model to estimate strength from NDT measurements.

(e) Evaluation of the quality of estimation.

At each of these steps, many options are possible. For instance, if one focuses on step (c), these options regard: (a) the domain to which the model will apply, i.e. the whole investigation domain or only a region of it, like only columns or a single story in a multi-story building, (b) the mathematical shape of the model (linear or nonlinear equation), (c) the way the model parameters are identified. Figure 2 represents several ways for this last step.



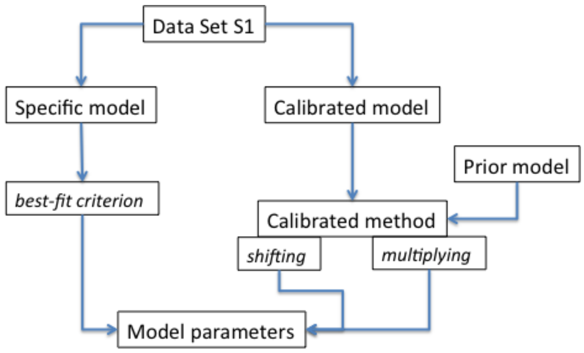


Figure 1 (left). The three main steps of the strength assessment process

Figure 2 (above). The various options regarding the identification of the conversion model parameters

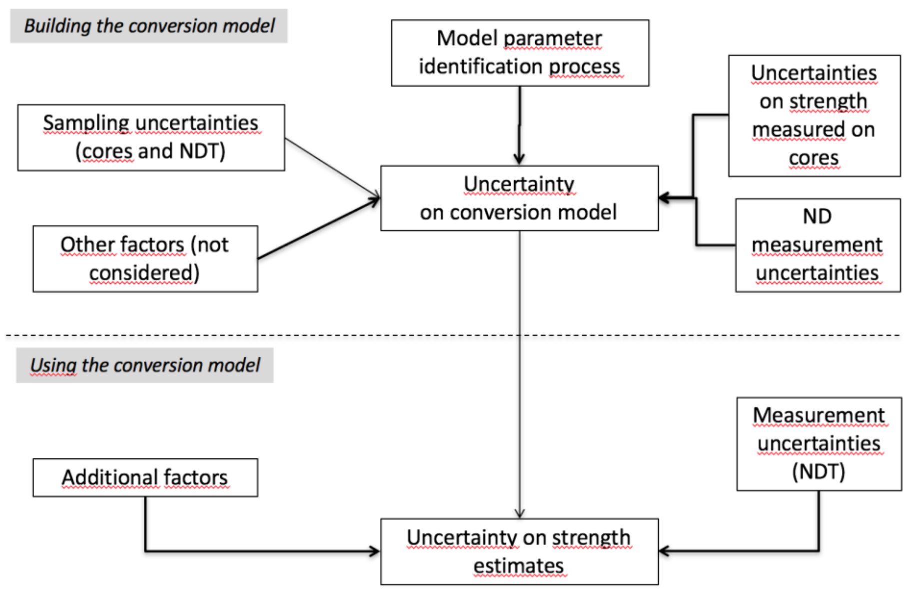


Figure 3.Uncertainties arising at all steps of the assessment strategy

The first source of complexity is therefore the large number of possible options and their interactions. But complexity also arises from uncertainties. In fact uncertainty is present at each step of the investigation and assessment process, as illustrated on the flowchart of figure 3, which is divided in two parts.

Firstly, the uncertainty attached to the identified conversion model (i.e. the uncertainty on the values of the model parameters) results from:

(a) The sampling uncertainties that come from the fact that the model is identified from a limited dataset (let us note N_{core} the number of cores, which is also the number of ($f_{c\ i}$, Tr_i) pairs where $f_{c\ i}$ is the i-th strength value measured on a core and Tr_i is the i-th nondestructive test result. To the classical problem of a finite size sample, which has known solutions, is added the fact that, depending on how core location has been selected, the core strength values can provide a more or less representative picture of the father population.

(b) The measurement uncertainties, since the $f_{c\ i}$ and Tr_i values are obtained from experimental tests and thus do not exactly correspond to the “real” value of the same property at this location. In fact, the real value cannot be known and is only approached by the measurement. Repeating the same measurement at the same location (which is possible with nondestructive tests but not for strength) would provide a different value.

(c) Any other influencing factor that can affect the measured value without being considered explicitly in the conversion model. Many such influencing factors are known for concrete, like the moisture content, the carbonation depth, the type of aggregates...

All these factors being known, the model parameter identification process has also a small influence. Different identification approaches can be used, like a fitting a specific model through the minimization of squares, or calibrating a prior curve with a drift (like in EN13791) or a multiplying factor. These different options would lead to slightly different uncertainties.

Once the conversion model has been identified, the second step is that of using it to estimate strength values from new nondestructive rest results. As shown on figure 2, one has thus new measurement errors while additional influencing factors can increase the uncertainty, for instance if the temperature is different from what it was when the first series of measurements had been carried out.

It is also possible to consider the uncertainties into four groups, according to the fact that they can be controlled or not during the investigation and assessment process:

- statistical (sampling) uncertainty, due to the limited size of the dataset on which the model is calibrated, i.e. typically the number of cores,
- measurement uncertainty, on strength measurements as well as on NDT measurements, which mostly depend on the technique itself, but also on the device, on the expertise of who takes the measurement and on the environmental context,
- factors in relation with the assessment methodology, like for instance the choice of the mathematical shape of the model, or that of selecting the location of cores. This set contains a large number of degrees of freedom and offers a large potential for improvement,
- factors in relation with the material itself, typically its average strength $f_{c,\ mean}$ and its standard deviation $sd(f_{c,})$, which have both an influence on the fitting and prediction error of the conversion model, all other parameters being fixed.

One must understand that the estimated strength which is finally derived at the end of the estimation must be regarded as a random variable, whose statistical properties (mean and standard deviation) result from all choices, uncertainties and interactions cited above. This justifies to analyze the NDT assessment process as a random process, which will enable to derive more relevant conclusions.

2. Synthetic simulations for addressing uncertainty and risk-curves development

The main objective of the investigation is to estimate the concrete strength, which can be the local strength value or the mean strength over a given domain or a series of concrete components. Of course, as it is an estimation problem, it is relevant to attach an uncertainty interval to any estimated value, which comes to introduce two additional data: the uncertainty interval and the risk level.

Therefore, instead of writing

$$f_c = f_{c\ est}$$

the relevant formulation would become

$$f_{c\ est}/(1 + x) \leq f_{c\ true} \leq f_{c\ est}/(1 - x)$$

or

$$f_{c\ est} - X \leq f_{c\ true} \leq f_{c\ est} + X$$

since the uncertainty interval can be expressed either in relative terms (+/- x%) or in absolute ones (+/- X MPa) and a risk level α must be attached in both cases, which corresponds to the α probability that the true strength value falls outside this interval. Due to the many random influences, whatever the magnitude of the accepted tolerance interval, there is always some probability that the assessed value falls outside the given uncertainty interval.

The same probabilistic formulation also works regarding the error on the estimation of local strength. This error can be quantified through its root mean square error RMSE, which measures the distance between estimated and true strength. However, since the estimation results from a random process, RMSE appears as a random parameter, which can be estimated only through statistics. Therefore, while the common writing is:

$$RMSE_{true} = RMSE_{est}$$

one gets a statistical distribution of $RMSE_{est}$, which may lead to quantify the risk that the true RMSE is over a prescribed value.

When going on site, what happens during the investigation and assessment process is therefore only ONE realization of this random process, and the derived strength properties are only ONE value drawn from a wider distribution of « possible assessed strengths ». This means that, if the same expert would come back once more on the same structure to carry on the same series of actions, the final strength he would derive would ANOTHER value drawn from the same theoretical distribution.

This statement is crucial since it prevents the derivation of any firm conclusion from the comparison of only two values, the first one derived with Options A and the second with Option B. Any relevant analysis must consider the variability of derived strength, which may be very large and try to analyze the robustness of the investigation process. This is why we had chosen to develop a framework for simulating *in silico* the whole investigation and assessment problem.

The basic idea is to reproduce within the computer all steps of the process and to simulate at best all uncertainties arising at each step. Since the simulation can be easily repeated many steps, the statistical distribution of estimated properties is easy to derive. An additional advantage is that the « reference » values are fully known and the error can thus be quantified (this is more complex in real case studies, where the predictive error can only be checked on an additional dataset or through cross-checking procedures). Figure 4 illustrates the principles of these synthetic simulations, which had been used for the first time in (Breysse et al, 2014) to analyze the reasons for uncertainties in the identification of the conversion model parameters.

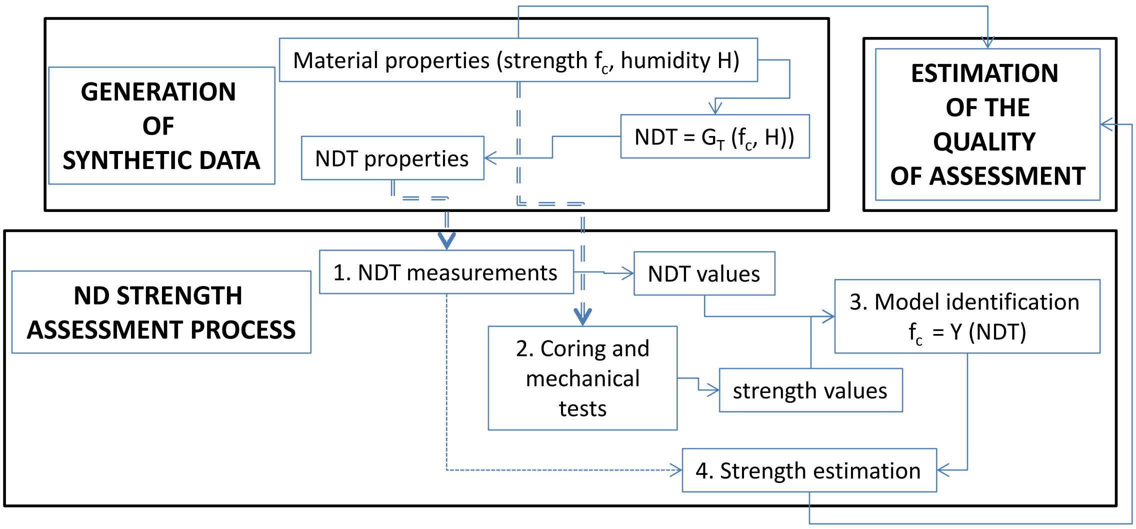


Figure 4.Principles of synthetic simulations for carrying ND strength assessment of concrete.

On figure 4, one can distinguish three blocks that correspond to three subdomains in the synthetic world:

- World 1 - Generation of synthetic data using a synthetic model that serves to generate “true” material properties and “true” measurements values. The intrinsic variability of material properties is simulated there.
- World2 - ND strength assessment process, which corresponds to the first stage on Figure 1 and to the universe of the NDT practitioner: information is taken through ND measurements and cores, which all induce some epistemic uncertainties. Then a model is identified, with some additional epistemic uncertainties (as described in the upper part of figure 3). This model will be used for strength estimation.
- World 3 - Estimation of the quality of assessment, corresponding to the lower part of figure 3. Here assessed value (in World 2) and real values (in World 1) are compared. By working in this world, thanks to Monte-Carlo simulations, we get the distribution of assessed properties, corresponding to the many repetitions of the same process.

Of course, in order to avoid any speculation, the governing laws of World 1 must be as close as possible to those of the real world. A specific attention has been paid to this issue, and the governing laws used have been described at length in (Breysse et al, 2014), (AlWash et al, 2015). Monte-Carlo simulations carried out with these principles have been used to analyze the specific contribution of the most important influencing parameters (AlWash et al, 2017a) and to compare the efficiency of different investigation programs promoted by experts in an international benchmark (AlWash et al, 2017a), (Breysse et al, 2017).

As explained above, any assessment induces an uncertainty interval and a risk attached to this interval. It is the reason why we have also developed the concept of risk curves, in order to highlight how the risk value can change when some of the most influencing parameters change. These parameters are the number of cores N_{core}, the magnitude of the NDT measurement error, and the two main statistical properties of concrete, i.e. mean strength f_{cmean} and strength standard deviation $sd(f_c)$. Risk-curves plot risk against N_{core} for a given investigation and assessment strategy (AlWash et al, 2017b).

3. From risk curves to the definition of required number of cores

The number of cores and the magnitude of the measurement error (which can be assessed through the within-test-repeatability WTR) are the two most influencing factors explaining the reliability of the concrete properties. We have thus carried out a first series of simulations in order to quantify their influence.

In these simulations, we have considered the following data:

- a Gaussian distribution of concrete properties, with mean strength $f_{c\ mean}$, and concrete strength coefficient of variation $cv(f_c)$. 25 combinations of concrete properties were simulated, with $f_{c\ mean}$ ranging from 10 MPa to 50 MPa and $cv(f_c)$ ranging from 10% to 30%,
- nondestructive measurements that can be done with the rebound hammer technique (R) or with ultrasonic pulse velocity (UPV) which can be used separately of combined,
- three possible WTR respectively corresponding to high precision (TRP1), medium precision (TRP2) and low precision (TRP3). These three precision levels respectively correspond to a standard deviation of WTR equal to 1, 2 and 4 units for Rebound, and 50 m/s, 100 m/s and 200 m/s for UPV test results,
- a core number N_c varying between 2 and 20.

The variety of possibilities regarding the conversion model identification (fig. 2), including an innovative bi-objective approach that has been recently developed, multiplies the number of options. Therefore, once a dataset has been made available, Monte-Carlo simulations of this post-processing stage result in a series of conversion models, each of them having its own performance level. For the sake of simplicity, we will consider here only the results obtained with linear mono-variate and bi variate models, that write:

$f_{c\ est} = a\ R + b$ and $f_{c\ est} = a\ V + b$ for monovariate models

and $f_{c\ est} = a\ R + b\ V + C$ for bivariate model.

In all cases, the model parameters have been obtained here through a simple regression and minization of r^2.

Figure 5 and Figure 6 respectively provide the results obtained with the processing of UPV measurements for mean strength assessment with a +/- 10% uncertainty interval (fig. 5) and 5%-risk RMSE (i.e. value of RMSE corresponding to the lower 5% percentile, which has only a 5% risk to be exceeded, fig. 6) in the specific case of a concrete with f_{cmean} = 30 MPa and $sd(f_c)$ = 4.5 MPa (i.e. COV (f_c) = 15%). On each figure, three curves are drawn, corresponding to three levels of WTR. Both figures show similar patterns with a clear regular convergence as the number of cores increases and a clear difference between the TRP levels, with better results (lower risk) when the nondestructive test results have a better repeatability (i.e. TRP1).

The main difference is that curves converges towards zero for mean strength assessment while the residual error of local strength converges towards an horizontal plateau whose elevation depends on TRP : it amounts respectively 2.6 MPa, 4.0 MPa and 5.2 MPa for the three quality of NDT measurements. This means that, at best (with the more precise measurement), for this concrete and this assessment strategy (type of model, method of identification of the model parameters...), the residual error on local strength is 2.6 MPa. One can note that while this value is about 60% of the concrete strength standard deviation, that obtained with TRP3 measurements is larger than the concrete standard deviation. This means that, NDT measurements can in one case (TRP1) give way to the patterns of concrete spatial variability while these patterns will be masked in the other cases behind the effect of measurement noise.

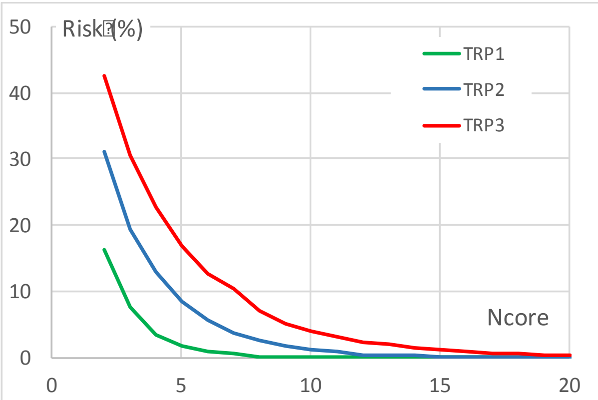


Figure 5. Risk curves for mean strength assessment

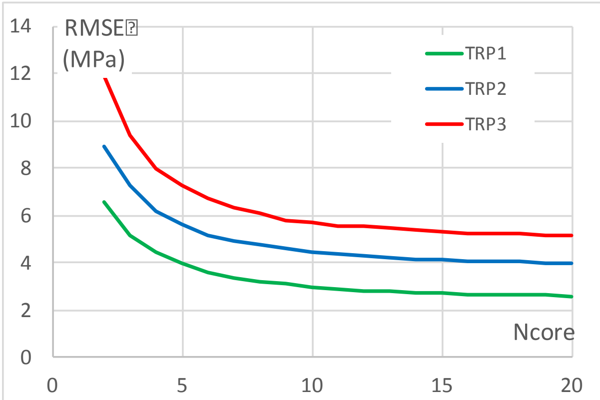


Figure 6. Risk curves for 5%-risk RMSE

Regarding the mean strength assessment, curves also enable to derive the risk corresponding to a given number of cores or, reversely, to estimate how many cores are required in order to get a given risk. For instance, 3, 5 and 8 cores are respectively requested to reach a 10%-risk, with TRP1, TRP2 and TRP3 respectively. This confirms the high interest of checking the within-test-repeatability, since having TRP1 would save mane cores without increasing the uncertainty on strength assessment.

4. Expected improvement for engineering practice

Figure 6 provides the risk curves for strength assessment of concrete with a +/- 10% uncertainty interval for five different concretes. The same concrete than above (f_{cmean} = 30 MPa, COV (f_c) = 15%) has been kept while the four others correspond to combinations of low and high strengths (10 and 50 MPa) and small and large variability (10% and 20%). The properties of concrete (mean, COV) are given in the legend. For the same relative uncertainty (+/-10%) on the target mean strength, it appears that the risk increases as the mean strength decreases (red curves) and as the COV increases (dotted curves). This two effects can superimpose, like on the red dotted curve, i.e. (10, 20%) concrete, or compensate, like on the (50, 10%) concrete whose risk curve is very close from that of the original (30, 15%) concrete curve. These influences show that much care is needed if one wants to justify the required number of cores for an accepted risk on the assessed strength : this number depends on the four influencing parameters : number of cores, WTR of test results, mean strength and variability of concrete. While the first two can be chosen or controlled during the investigation, the other two do not depend on the investigator who has at best some prior information about them.

From the results of a large series of simulations, we have developed an empirical model describing how this required number of cores depends of these influencing parameters. This model is not detailed here, but Table 1 illustrates how the information can be synthesized, here in the specific case of TRP2 UPV test results. The significant effects of both mean strength and concrete strength variability are clearly visible.

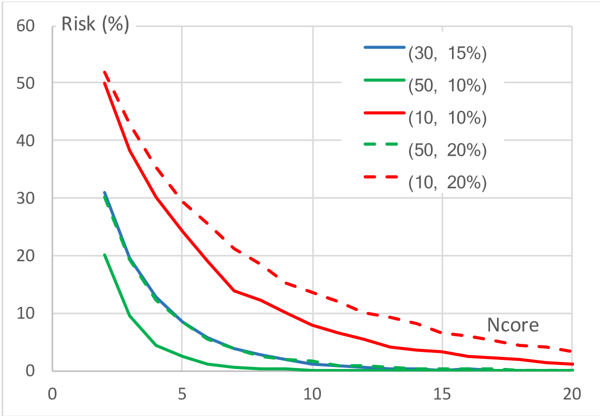


Figure 6. Risk curves for mean strength assessment for 5 different concretes (mean, COV)

Table 1. Required number of cores for assessing mean strength at +/-10+% with 10% risk, as a function of mean strength (in MPa) and coefficient of variation of concrete (in %)

TRP medium	COV				
fc mean	10	15	20	25	30
10	7	9	11	13	15
15	5	7	9	10	12
20	5	6	7	9	10
25	4	5	6	8	9
30	4	5	6	7	8
35	3	4	5	6	7
40	3	4	5	6	7
45	3	4	5	5	6
50	3	4	4	5	6

Another issue that has been analyzed through synthetic simulations is the interest of an innovative option can can be taken during the in-situ investigation, that of conditional coring. This idea has been originally promoted by [LUP 08] and simply consists in defining the location of cores after a first screening of the structures with NDT in such a way that the expected distribution of concrete strengths within the set of N_{core} cores is similar to that on the whole structure. This option, which avoids a random selection, is expected to provide the same quality of assessment with a reduced number of cores. It is easy to quantify its possible added-value with simulations while checking it in practice would be very challenging.

Conditional coring does not induce any additional cost, and only requires that NDT test results have been made available before the time of taking cores. A possibility for defining the core location is to rank all NDT test results and to choose core locations in order to correctly cover the whole range of values given by the statistical distribution of the NDT test results: if N_{core} cores have to be taken from a set of N_{NDT} locations where nondestructive test results have been obtained (with $N_{NDT} >> N_{core}$), it suffices to subdivide the whole NDT set into N_{core} subsets of size N_{NDT}/N_{core} and to take one core in each subset. Figure 7 provides RMSE risk curves for the local error for a concrete whose strength is assumed to follow a Gaussian distribution with $f_{c\ mean}$ = 30 MPa and sd(f_c) = 9 MPa and rebound measurements. The six curves respectively correspond to predefined (or random) coring (curves, PC) and conditional coring (marks, CC). The three colors respectively refer to TRP1 (green), TRP2 (blue) and TRP3 (red).

The first important feature is the major effect of TRP level which has been noted previously. If one focuses on what conditional coring may bring, it is relevant to compare PC (curves) and CC (marks) in the same situation. It is easy to see that CC improves the performances (i.e. reduces the risk for a given N_{core} value or reduces the required N_{core} number for a given risk) in all cases. For instance, if we consider TRP2 nondestructive test results (blue curves), respective value of 6 MPa and 4.5 MPa are reached with only 2 and 8 cores for conditional coring against 6 and 12 for random coring. This confirms the high interest of conditional coring: this option, which has no cost, can save cores for reaching a prescribed target or reduce the uncertainty if the number of cores is given. Its interest is particularly significant when the number of cores is small.

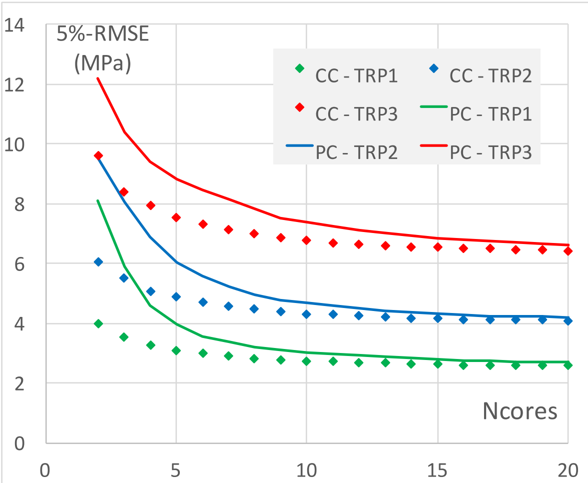


Figure 7. Risk curves for 5%-RMSE

5. Conclusions

The issue of nondestructive assessment of concrete properties in insitu conditions has been revisited in this paper. While common approaches are unable to establish a quantified relationship between the resources used (type and number of tests, models...) and the quality of the strength assessment, we have promoted a completely different approach, which is driven by uncertainties. Uncertainties on the final strength assessment result from the existence and interactions between the many uncertainties that arise at the various stages of the investigation and assessment program, and that are related to the measurements or to modelling errors.

We have developed a simulation framework which combines the simulation of the material features and that of the investigation and assessment process. The randomness of the assessment process has been considered at all relevant stages, which enabled an in-depth analysis of all significant factors that contribute to the quality of the final assessment. This assessment has also been revisited. It has been expressed in terms of risk of missing a prescribed target (mean strength) to which an uncertainty interval is attached. Synthetic simulations also give access to the mean error on local strength assessment.

We have shown in this paper how such a framework has been used to justify the identification of risk curves which quantify how many cores are required in a given situation to reach the prescribed target. The same tools have been widely used to analyze other features of the investigation program, as the conditional coring whose interest has been confirmed. Many other results have been obtained, not detailed here, for instance regarding the influence of the conversion models used, the assessment of concrete standard deviation or the interest of combining several nondestructive techniques, which remains a matter of debate between experts. These many results will be used in Guidelines and Recommendations that are being prepared by RILEM TC-ISC 249.

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