# Reliability of non destructive on site strength estimation of concrete


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# Improving the reliability of on-site concrete strength estimation with non-destructive techniques

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## Abstract

The non-destructive assessment of concrete strength in existing structures is a complex issue. While many standards exist addressing the way non-destructive measurements must be carried out, few exist for the strength assessment itself. Many questions remain unanswered, like for instance the reliability of the strength estimation, the possibility of estimating the concrete variability, or the advantages of combining several non-destructive techniques. These problems have been tackled by a recent RILEM committee (TC ISC 249) whose Guidelines and Recommendations are to be released soon. This paper details their main innovations and how they are expected to improve the engineering practice and the reliability of strength estimation in existing structures.

**Keywords:** concrete structures, non-destructive techniques, on-site measurements, strength assessment

## 1 Introduction

The non-destructive assessment of concrete strength in existing structures is a complex issue. While on one hand, many studies and research programs have been carried out in order to develop tools and models for assessing concrete strength, on the other hand, one still lacks any validated methodology that guarantees the quality and efficiency of this process.

Several non-destructive techniques (NDTs) have been promoted (rebound hammer [1], ultrasonic wave velocity measurement [2], pull-out [3-4], etc.) and a large variety of conversion models (i.e. empirical relationships providing a strength estimate once the NDT result is obtained) have been proposed. However, no agreement exists on what can be done in real situations in order: (a) to estimate concrete strength, (b) to know the quality of this assessment. Many case studies have developed an investigation methodology for existing structures and established specific conversion models using a variety of NDTs (e.g. see [5-8]) but they usually fail to draw more general conclusions that could be applied as general rules of good practice.

Some other disputable practice in research are that:

- many efforts are devoted to finding a better conversion model, notwithstanding the fact that it is widely known that a universal conversion model is an illusion;
- the quality of conversion models is most often checked using the model calibration set, an approach unable to provide meaningful information about the real predictive capacity of the models;
- many heuristic "black-box" conversion models are developed, based for instance on neural networks or methods based on fuzzy logic. However, the practical interest of such models for engineers is debatable since they cannot apply for new datasets.

Thus, significant effort is still wasted without providing significant inputs for best engineering practices. Simultaneously, interesting methodological innovations have been proposed but were unable to be widely disseminated until now. This is the case, for instance, of the analysis of various scales of heterogeneity in an existing building [9-10]) or of the added value than can be derived from conditional coring, which involves selecting the location of concrete cores on the basis of prior NDT results, as initially promoted by [11] and [12].

Strength assessment however remains a key issue when buildings have to be retrofitted or when their structural safety is questioned. Therefore, a RILEM Technical Committee (TC-ISC 249) was created to study this important issue and to propose a relevant assessment methodology. Such proposal accounts for:

- the fact that existing Standards, while opening the possibility of non-destructive strength assessment of existing structures, usually require such a large number of cores that it cannot provide a practicable option from an economical point of view [13-14],
- the fact that, in most cases, the final assessment of concrete properties remains limited to an estimate of a strength value (which can be a mean strength or a local strength) but that nothing is known about the uncertainty interval of this estimate,
- the need for a consistent approach, covering all steps of the assessment, from the data collection to the strength assessment,
- the possibility of addressing additional issues, such as estimating concrete variability which plays a major role in safety analyses of existing structures,
- the need to provide recommendations regarding a controversial issue: the possibility of combining several non-destructive techniques to obtain a more reliable assessment. This idea has been promoted by RILEM twenty-five years ago [15], but there is still a debate about the added value it can bring or not [16-17].

## 2 Effect of uncertainties during the strength estimation process

Significant research efforts have only been recently devoted to the fundamental issues of the non-destructive concrete strength assessment [18-19] and to a more systematic analysis of the all degrees of freedom of the non-destructive investigation and assessment process. The following three main steps can be defined for this process:

- The data collection stage, covering both non-destructive and destructive measurements, which includes the definition of the type of tests, the number of measurements, their location, etc...
- The conversion model identification stage, which covers both the choice of the mathematical shape of the empirical model and the choice of the identification process for the model parameters,
- The strength assessment stage, which must also cover the estimation of the uncertainty of this assessment.

Given the importance of controlling the uncertainty on the final strength assessment, one must be aware that it is influenced by several sources of uncertainty that can arise at any stage of the process, as shown by the flowchart in

Figure 1 which is divided in two parts. It is also possible to divide the uncertainties into four groups, according to the possibility of controlling them 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 depends on the technique itself, but also on the device, on the expertise of who takes the measurement and on the environmental context. This uncertainty has an influence during both the conversion model identification stage and the strength assessment stage,
- factors related to the assessment methodology, like for instance the choice of the mathematical shape of the model, or the method that is used to select the location of cores. This set contains a large number of degrees of freedom and offers a large potential for improvement,
- factors related to 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 the prediction error of the conversion model, all other parameters being fixed.

## 3 Changing the paradigm: controlling the uncertainty on the strength estimation

Due to uncertainties, the challenge of strength estimation can no longer be that of capturing the true strength, and must be replaced with that of controlling the final uncertainty on the estimated strength. Instead of having $f_{c,\ est}$ = X MPa, the final result should be written as:

$$p\ (X - \Delta X < f_{c,\ est} < X + \Delta X) = 1 - \alpha \qquad (1)$$

where $\Delta X$ is the accepted value for half the tolerance interval and $(1 - \alpha)$ is the accepted risk of making a wrong estimation. Of course, these two parameters are strongly related, since the larger the $\alpha$ value, the larger the $\Delta X$. Equation 1 corresponds to a paradigm change. The purpose is no longer about getting the true strength value. Instead, it is about being "reasonably certain" that the assessment process, seen as a full and consistent process, leads, in the end, to an estimate that is compatible with a predefined target tolerance interval associated with an acceptable risk of a wrong prediction.

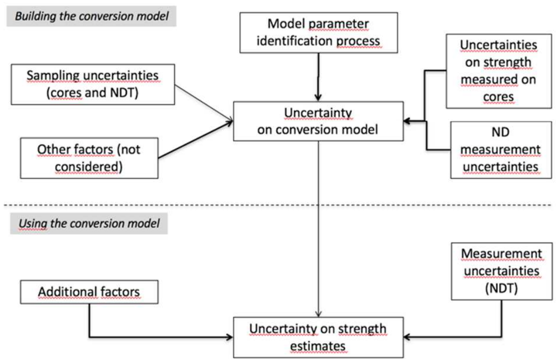


*Figure 1. Uncertainties arising in the different stages of the strength estimation process*

As uncertainties are driving parameters governing the quality / reliability of the strength estimation, it is necessary to establish the relationships between the magnitude of these uncertainties, the tolerance interval and the risk on the final assessment. These relationships are very complex, because of the variety of uncertainties (see fig. 1) and the complexity of their interactions.

Even though the research that was carried out on these issues cannot be detailed herein, exchanges between experts, comparisons between the efficiency of several investigation strategies [20] and a series of numerical simulations, both on true datasets and on synthetic datasets [12], made it possible to identify the key tasks that have a major influence on the final uncertainty. Furthermore, this research also established the recommended number of cores that guarantees, in a given situation and with a certain accepted risk level, that the prescribed target is reached. This number of cores is highly dependent on the context, and it can be significantly lower than what is commonly prescribed in existing guidelines [13].

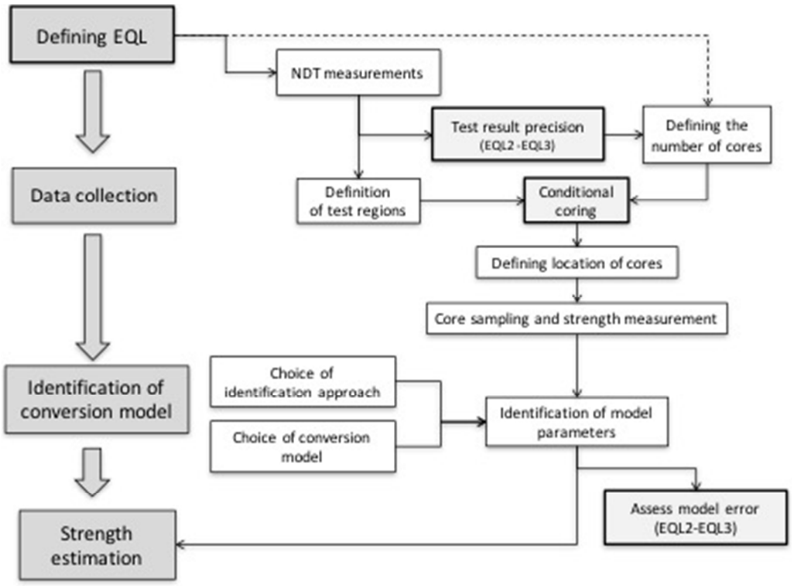


*Figure 2. Detailed steps of the recommended concrete strength assessment process*

## 4 Key steps in the assessment process

The flowchart of figure 2 describes how the strength assessment process must be organized, and defines it as a consistent series of tasks. This flowchart establishes the reasoning process that underlines the soon to be published RILEM recommendations. The four shaded boxes with a bold contour correspond to the most important tasks, which are usually missing in engineering practice. These tasks are essential in order to guarantee a reliable strength assessment.

These four key tasks are:

- The definition of EQL (Estimation Quality Level) which has to be chosen at the start of the investigation. Three possible EQLs are proposed, that correspond to target precisions (tolerance intervals) associated to several objectives of the assessment: mean strength, strength variability or prediction error on local strength values. Therefore, the investigator must define what are the objectives of the assessment.
- NDT Test Result Precision (TRP) is a major issue, since the measurement uncertainties are a major governing factor of the final estimated strength.
- Conditional coring is a task proposed to avoid a predefinition of the core locations (some cores are required in order to correlate concrete strength and NDT results and to identify the conversion model). This technique defines the location of cores after an efficient first screening of the structure using NDTs. For instance if one wants to take N cores and has the value of the NDT test results at N' locations (N' being usually much larger than N), it is possible to choose locations such as the distribution of NDT test results on set N mimics the distribution of NDT test results on the larger set N'. This simple process guarantees that some cores will be taken in lower strength areas as well as in higher strength areas. The consequence is that, N being given, the uncertainty of the identified conversion model is smaller than that obtained through random selection of the core locations (as happens for predefined locations). This technique has more advantages when the number of cores is reduced (less than 10), but it requires that NDT test results provide a reliable information (i.e. high TRP).
- Checking the final estimation error is also important. Although the conversion model is identified (calibrated) using a given dataset, it is applied to other datasets. In many cases, investigators limit their checking by analyzing the

fitting error that provides the quality of fit on the calibration set. This error underestimates the real prediction error, when the same model is applied to new data. An extreme case of this situation can be seen when the number of parameters to be fitted using the conversion model is equal to the number of cores. In such situation, the calibrated model perfectly fits all the data, but this perfect fit provides no information about its predictive ability, which is the real topic of interest. Several procedures can be used in order to estimate the prediction error, using cross-checking tests, which are not detailed here.

To illustrate some of the issues, the two first concepts (EQL and TRP) and their influence on the assessment process are detailed in the following sections.

## 5 Definition of the Estimation Quality Level (EQL)

Since the paradigm has been changed, it comes now to define (a) a target, (b) a tolerance interval, (c) and an accepted risk level. One must understand that this strength estimation process is seen as a random process (due to the random character of sampling and to measurement errors) and that it is impossible to enforce a zero level of risk.

*Table 1: relation between estimation quality levels (EQL) and the target tolerance intervals on strength assessment (simplified version)*

| Estimated property | EQL1 | EQL2 | EQL3 |
|---|---|---|---|
| Mean | ±15% | ±15% | ±10% |
| Stdev | not addressed | 4 MPa | 2 MPa |
| RMSE | not addressed | 6 MPa | 4.5 MPa |

The RILEM TC has defined three different EQLs that correspond to progressively more severe requirements for the assessment, as described in Table 1 (the original table from the recommendations has been simplified here for the sake of clarity). In this table, three targets are considered, which are respectively the mean strength, the strength standard deviation Stdev (concrete variability) and the mean error on the local strength value RMSE. At the first level EQL1, estimating the mean strength is the unique challenge, with a tolerance interval of +/- 15% around its true value. At the two other levels, the three targets are considered, with more ambitious objectives for EQL3 than for EQL2.

## 6 Assessing the Test Result Precision (TRP)

The number of cores (statistical uncertainty) and the measurement errors are the two factors that contribute the most to the final uncertainty on the strength estimate. A large measurement error prevents an accurate estimation of the conversion model parameters (upper part in Figure 1) and, once the conversion model is known, also prevents a reliable strength estimation (lower part in Figure 2).

No matter the type of NDT that is performed (rebound measurements (RH), ultrasonic pulse velocity (UPV) measurements, pull-out...), the quality of their test results can be easily quantified by estimating the within-test-repeatability (WTR) which can be expressed in terms of a standard deviation or a coefficient of variation of test results. The WTR values derives from the physics involved in the test, the sensitivity to fluctuations of influencing parameters (like environmental conditions), the quality of the device and the experience of the investigator. A meta-analysis [21] has provided, for instance, $COV_{rep}$ values 0.4 % and 1.9 % for UPV measurements.

We have defined, for all common NDT techniques, three levels of Test Result Precision (TRP), respectively TRP1, TRP2 and TRP3. A higher TRP corresponds to a higher WTR value, i.e. to a larger value of the standard deviation of test results. The intervals corresponding to each TRP class were defined so as to lead, after conversion of the NDT test results into strength values, to an identical uncertainty interval on strength irrespective of the NDT type.

Table 2 indicates the thresholds defining the three TRP classes for RH and UPV. Thus, a medium precision TRP would lead to the same uncertainty on the estimated strength irrespective of the type of NDT (i.e. RH or UPV). However, it must be pointed out that commonly available UPV test results are able to be compatible with the TRP1 or TRP2 classes, if one accepts the values cited in [21], while typical RH test results will be compatible with the TRP2 or TRP3 classes.

*Table 2. Definition of the three TRP classes ($COV_{rep}$ = coefficient of variation for WTR, in %)*

| COV | TRP1 high precision | TRP2 medium precision | TRP3 poor precision |
|---|---|---|---|
| rebound (RH) | $COV_{rep} \leq 3$ | $3 < COV_{rep} \leq 7$ | $COV_{rep} > 7$ |
| ultras. pulse velocity (UPV) | $COV_{rep} \leq 1$ | $1 < COV_{rep} \leq 3$ | $COV_{rep} > 3$ |

## 7 Quantifying the effect of governing factors on the assessment precision

The objectives of the assessment (in terms of targets and precision) are defined through the EQL, and the quality of the input data is defined through the TRP. To be able to define the investigation process and the number of cores that are necessary to obtain the target final precision, a precise analysis of the relationships between all governing factors and the final precision is required. The reader is referred to [22] for additional details on how this analysis was carried out and how prescriptions regarding the recommended number of cores were derived.

These analyses combined a semi-quantitative approach and a quantitative one. The former was mainly based on comparisons between several possibilities of sharing a given amount of resources proposed by various experts. Their results were compared in terms of accuracy and some results were derived regarding the contribution of the most influencing factors [20]. A more systematic analysis was then carried out in a second stage based on synthetic simulations.

The basic idea is to reproduce *in silico* all the steps of the assessment process and to simulate as best as possible all the uncertainties that arise at each step. Since the simulation can be easily repeated many times, the statistical distribution of estimated properties can then be derived. An additional advantage is that the « reference » values are fully known and the error of the assessment process can thus be quantified.

We have also developed the concept of risk curves, in order to highlight how the risk value $\alpha$ (of obtaining an estimated strength outside the target tolerance interval) can change when some of the more 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. the mean strength $f_{cmean}$ and the strength standard deviation $sd(f_c)$. Figure 3 illustrates how the risk value is determined: when a given investigation strategy is repeated many times through Monte Carlo simulations (i.e. the same concrete strength distribution, the same type of NDT results, the same number and quality of NDT measurements, the same method for deriving a conversion model), one can build a distribution of estimated strengths, since the random character of sampling (choice of core location) and of measurement errors provide a different result each time. The cumulative distribution of the estimated parameter (e.g. the mean strength) is plotted in fig. 3. If the tolerance interval is given (here –U1 and +U2 from the true value), it is easy to assess the ratio of correct estimates (i.e. that fall within the prescribed limits) and thus the complementary risk ($Rs1 + Rs2 = \alpha$).

The variation of this risk for different values of the number of cores (i.e. the sample size used for calibrating the conversion model) is easily analyzed and these relations are named risk curves [23]. Figure 4 illustrates how this risk value decreases when the number of cores increases and when the precision of the NDT test results increases from TRP3 to TRP1. The effect of the NDT test result WTR appears to be crucial, since more repeatable test results enable to drastically reduce the number of cores for the same target. A systematic analysis of all most influencing factors was undertaken, provi-ding risk values for all combinations of possibilities.

## 8 Prescribing the number of cores

Once the tolerance interval (i.e. the EQL) and the accepted risk are given, fig. 4 also shows that it is possible to quantify how many cores are needed, in a given context (i.e. type of concrete, quality of NDT test results) to be in agreement with the target. For instance, if the risk level is taken as 5%, the same target can be reached with respectively 4, 7 and 10 cores for TRP1, TRP2 and TRP3.

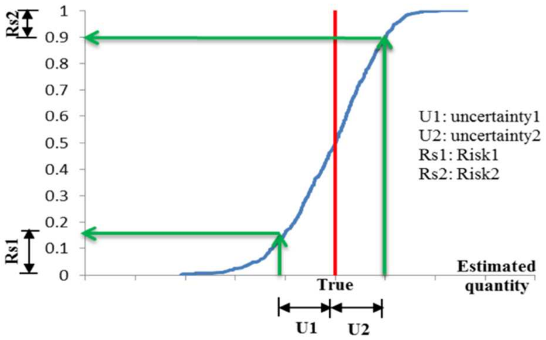


*Figure 3. Estimating risk from the many simulations of the same strategy*

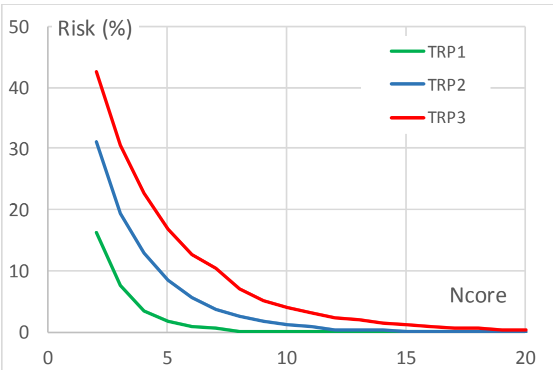


*Figure 4. How the risk associated to the assessment of mean strength depends on the number of cores and on the TRP level*

The simulation results were synthesized in a final step to provide, in a simple format, practical prescriptions regarding the minimum number of cores for each specific context. The context is defined by the concrete category (mean strength and variability), by the quality of measurements (TRP level) and by a series of options made during the investigation and assessment stages (choice of core location, type of conversion model, method chosen for identifying its parameters, i.e. for fitting the model, etc.). To be easier to handle, this information was summarized in tables like those of Figures 5-7.

The numbers in these tables are only indicative, since they correspond to specifications that were not fully detailed in this paper: the target precision on concrete variability is absolute (respectively 2 and 4 MPa at EQL1 and EQL2), while the target precision on local strength value is relative (respectively 20% and 15% of the mean strength at EQL1 and EQL2). These numbers cannot be taken at face value to be used in a different context and interested people must refer to the extensive text of the RILEM recommendations.

| Medium TRP | | | | | |
|---|---|---|---|---|---|
| fc mean | cv | | | | |
| | 10 | 15 | 20 | 25 | 30 |
| 10 | 4 | 5 | 6 | 6 | 7 |
| 15 | 3 | 4 | 4 | 5 | 5 |
| 20 | 3 | 3 | 4 | 4 | 4 |
| 25 | 2 | 3 | 4 | 4 | 4 |
| 30 | 2 | 3 | 4 | 4 | 4 |
| 35 | 2 | 2 | 4 | 4 | 4 |
| 40 | 2 | 2 | 4 | 4 | 4 |
| 45 | 2 | 2 | 4 | 4 | 4 |
| 50 | 2 | 2 | 4 | 4 | 4 |

*Figure 5. Prescribed number of cores for EQL1 for medium TRP (RH test results). <u>These numbers are only illustrative, and cannot be taken at face value</u>.*

| Medium TRP | | | | | |
|---|---|---|---|---|---|
| fc mean | cv | | | | |
| | 10 | 15 | 20 | 25 | 30 |
| 10 | 13 | 17 | 20 | 24 | 27 |
| 15 | 8 | 10 | 12 | 14 | 16 |
| 20 | 5 | 7 | 8 | 9 | 11 |
| 25 | 4 | 5 | 6 | 7 | 8 |
| 30 | 3 | 4 | 5 | 6 | 6 |
| 35 | 3 | 4 | 5 | 5 | 5 |
| 40 | 4 | 4 | 5 | 5 | 5 |
| 45 | 4 | 5 | 5 | 5 | 5 |
| 50 | 5 | 5 | 5 | 6 | 6 |

*Figure 6. Prescribed number of cores for EQL2 for medium TRP (RH test results). <u>These numbers are</u>*

*only illustrative, and cannot be taken at face value.*

| Poor TRP | | | | | |
|---|---|---|---|---|---|
| fc mean | cv | | | | |
| | 10 | 15 | 20 | 25 | 30 |
| 10 | 7 | 8 | 9 | 10 | 11 |
| 15 | 6 | 6 | 7 | 7 | 8 |
| 20 | 6 | 6 | 6 | 6 | 7 |
| 25 | 6 | 6 | 6 | 6 | 6 |
| 30 | 6 | 6 | 6 | 6 | 6 |
| 35 | 6 | 6 | 6 | 6 | 6 |
| 40 | 6 | 6 | 6 | 6 | 6 |
| 45 | 6 | 6 | 6 | 6 | 6 |
| 50 | 6 | 6 | 6 | 6 | 6 |

*Figure 7. Prescribed number of cores for EQL1 for poor TRP (RH test results). These numbers are only illustrative, and cannot be taken at face value.*

The two tables in Figures 5-6 correspond to the case of medium TRP (i.e. TRP 2 in Table 2) for respectively EQL1 (Fig. 5) and EQL2 (Fig. 6). Figure 7 corresponds to the case of poor TRP (i.e. TRP 3 in Table 2) for EQL1. Despite the fact that these numbers are only illustrative, two interesting comments can be made:

(a) The prescribed number of cores is no longer a constant but depends on the severity of the assessment targets, on the quality of the NDT measurements (TRP) and on the concrete properties. Therefore, the same number can be relevant in one case and not in another.
(b) The major influence of TRP is confirmed, since numbers in Figure 7 (poor TRP) are significantly larger than those in Figure 5.

## 9 Conclusions

The intent of this paper is to explain how some recent methodological research advances in the field of NDT application to concrete structures were synthesized by a common work of experts. This collaborative research has enabled a detailed analysis of the influence of all common factors that influence the quality of the estimated concrete strength.

Thanks to some benchmarks and with the additional use of synthetic simulations, it has been possible to:

(a) propose a consistent framework for both the investigation stage and the assessment stage (see flowchart of fig. 2),

(b) point out major issues, like the mandatory evaluation of NDT measurements repeatability,

(c) provide practical information, including values for the prescribed numbers of cores that will ensure different levels of precision of the estimated concrete strength.

These research advancements will soon be published by RILEM and we are firmly convinced they will contribute to a more efficient and less controversial use of non-destructive techniques for the on-site estimation of concrete strength.

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