Reliable assessment on in-situ concrete strength with non destructive techniques

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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 les avancées scientifiques récentes. Un Comité Technique de la RILEM (TC-ISC 249) se consacre à la rédaction de recommandations opérationnelles. Ses travaux s'appuient sur des résultats multiples, issus de l'exploitation de jeux de données sur ouvrages réels, de simulations synthétiques et de benchmarks entre experts. Les recommandations définissent un processus organisé de recueil et de traitement des informations issues de l'ouvrage et en soulignent les phases-clés qui permettent de garantir la fiabilité de l'estimation finale des propriétés. L'ensemble de la démarche s'inscrit dans une logique d'adaptation de la qualité du résultat à l'ampleur des moyens mobilisés. On propose ainsi, pour la première fois, une démarche à l'issue de laquelle l'évaluateur sera apte à fournir non seulement une estimation de la résistance moyenne et de sa variabilité mais aussi leur degré de précision.*

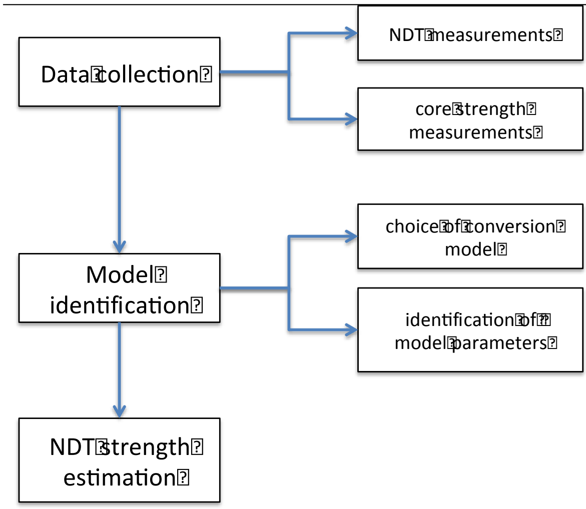
ABSTRACT. *Improving the reliability of concrete strength estimation in existing structures with non destructive techniques is a complex challenge. Better standards and improved enginering practice must be based on recent scientific progress. A RILEM Technical Committee (TC-ISC 249) is devoted to the writing of practical guidelines. Its works are based on a series of recent results, derivedas well from data processing on real structures, as from synthetic simulations and from benchmarking between experts. These guidelines promote an organized process of data gathering and processing. They also point at key-steps which enable to guarantee the reliability of concrete strength final estimates. The whole process is based on a logic of consistency between the quality of the final estimates and the resources used. A consistent method is proposed which will lead, for the first time, to both estimating the concrete properties (mean, standard deviation) and the precision of this estimation.*

MOTS-CLÉS : *évaluation non destructive, incertitudes, précision, résistance du béton, traitement de données, variabilité*

KEY WORDS: *concrete strength, data processing, non destructive evaluation, precision, uncertainty, variability*

1. Common practice for on-site evaluation of concrete strength in existing buildings

While estimating the concrete strength in existing buildings appears to be simple, it remains a challenging issue. This is even more true when the basic idea is to promote the use of non destructive techniques (NDT)for improving the concrete estimation. 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 [ACI08] 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 on site concrete strength. The RILEM Technical Committee ISC 249 (In-situ strength of concrete) has been created todevelop 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. The quality of the final assessment depends on many factors that can influence each of these steps, among which the number of cores, the way their location is decided, the type of conversion model, the method followed to identify its parameters… This problem is very complex, because of many interactions between all these factors, and nobody can really tell what is the confidence level of the final statement. Limited information and errors at all stages influence the assessment process. Reversely, if one level of confidence (or range of uncertainties) is looked for, nobody knows what must be done in order to guarantee that it will be reached.



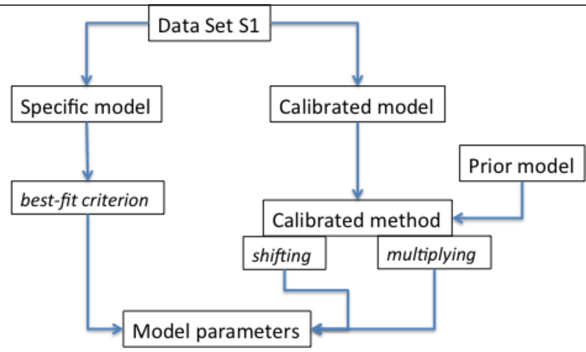


Figure 1 (left). *The three main steps of the strength assessment process*

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

To be more precise, it can be told that any investigation strategy must consider the following items:

(a) Definition of points (i.e. 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 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.

2. Recent advances for a better understanding of the concrete strength evaluation

In the last ten years, considerable efforts have been done to better understand, through several research projects, including academic research [ALW 15] and on site investigation with a variety of approaches [BAL 12], how the concrete properties of existing structures can be assessed. The RILEM TC has chosen to fill the gap between these research results and day-to-day engineering practice, which requires to be able of deriving general conclusions from the analysis of facts or findings that have been obtained in a more specific context. To do so, TC members have based their collective effort on several approaches : (a) processing of real data, obtained in the laboratory or on real structures, (b) meta-analysis of engineering practice, i.e. comparison between alternative approaches for gathering data or analysing the same dataset, (c) numerical simulations, in order to reproduce*in silico* what happens in true life, where uncertainty has a significant influence, and where results must be considered from a probabilistic point of view. Thanks to the development of a specific simulation framework [ALW 15] it was possible to analyze real datasets as well as synthetic ones, in a variety of situations.Many important findings have resulted from these efforts:

- the analysis of influencing factors regarding the conversion model quality (the conversion model is the f_c(NDT) function thanks to which strength can be estimated from the value of NDT test results). As shown on Figure 3, its quality, linked to the reliability of the model parameters, depends on: (a) the number of cores, which gives the size of the dataset used for identifying the model parameters, (b) the uncertainty level on all types of test results, destructive and non destructive, (c) the real concrete strength variability, since the model parameters are more stable if the dataset cover a wider domain, (d) the assessment methodology, which covers the choice of the model type and that of the option for model parameter identification among those described at Figure 2. All these factors have been analysed through synthetic simulations, in order to quantify their influence, for instance on the stability of strength assessment. For instance, how the number of cores NC influences the uncertainty of mean strength estimates has been studied in a variety of contexts [ALW 15, ALI 17].

- the main role of the quality of measurement was soon identified and specific attention had been paid to it. Whatever thenature of test results, their quality can be quantified through the within-test repeatability (WTR), and it was decided to define three levels of « test result precision » (TRP). The WTR values corresponding to each TRP where quantified for common ND techniques, based on what has been obtained on site in a variety of works [BAL 12]. Indicative values of WTR for rebound and ultrasonic pulse velocity are provided at Table 1.

- a specific attention was also devoted to the assessment of concrete variability. Mean strength is a common target while concrete variability is both much less studied and much more difficult to quantify accurately. The efficiency of several approaches was analyzed on the basis of expert benchmarks where common approaches were compared [BRE 17]. It was shown that all options described at Figure 2 fail to accurately estimate the concrete variability and an innovative approach, named « bi-objective approach » was developed. The bi-objective approach aims at identifying the conversion model parameters in such a way that they minimize both the error on mean strength estimation and on the concrete variability estimation. This approach has proved to be very efficient while it only needs a simple change during the model identification stage (see Figure 1), without requiring any additional measurement [ALW 16]. It is however recommended only for low or medium precision TRP.

- to more accurately quantify the reliability of assessment, we have also analyzed how, for a fixed tolerance on the estimated strength (this is valid for mean strength as well as for strength variability), the probability of getting an estimation which is within the accepted tolerance varies according to influencing factors. These influencing factors are mainly those already mentioned at Figure 1. It was then possible to derive « risk curves » which quantify the risk of a wrong estimate (i.e. outside the tolerance interval) in a variety of contexts. Figure 4 shows such curves for two levels of TRP in a situation where the target is the concrete average strength with a ±10% tolerance,the concrete has a 50 MPa true mean strength and a COV = 20% and a specific linear conversion model is used. Such risk curves can be used for instance to define the minimum number of cores once the tolerance interval is given and the quality of measurements is known.

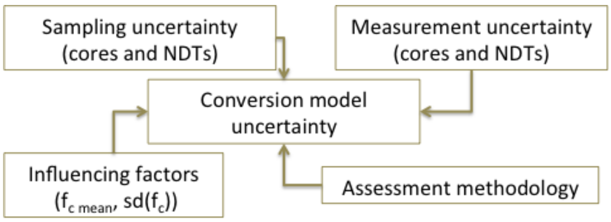


Figure 3 (above). *Influencing factors regarding the uncertainty on the conversion model*

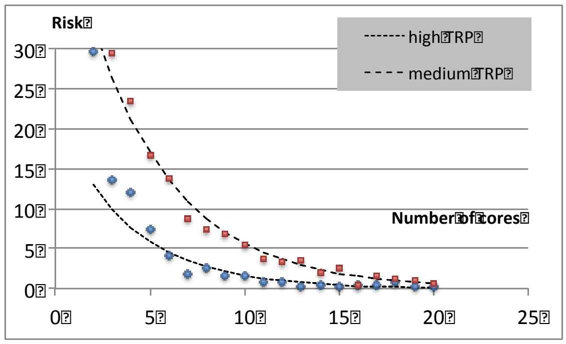


Figure 4 (right). *The various options regarding the identification of the conversion model parameters*

Table 1: *Indicative order of magnitude of TRP (COV = coefficient of variation)*

	high precision	medium precision	poor precision
Rebound number	COV < 3 %	3 % ≤ COV < 7 %	COV ≥ 7%
Ultrasonic pulse velocity	COV < 1 %	1 % ≤ COV < 3 %	COV ≥ 3 %

Among the other recent scientific issues that have been discussed and analyzed, one can also cite:

- a proper estimation of the quality of estimation, where it has been shown that the prediction error is a valid quantity while the (more commonly used) fitting error would lead to wrong conclusions[ALW 15];

- the analysis of conditional coring, that has been promoted by some experts[BRE 17], which comes to define 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 cores is similar to that on the whole structure. This option may provide the same quality of assessment with a reduced number of cores;

- the definition of test regions, that are defined as being areas of the structure where the concrete is “homogeneous” and can be described through a unique and specific conversion model [MAS 16];

- the analysis of combining two NDT which had been promoted for a long time by some experts, without reaching any consensus regarding its efficiency in practice. The better understanding of how uncertainties propagate along the estimations process has explained why no consensus existed between research results, since the combinations had appeared efficient in some cases and unefficient in others.

3. Conclusion : new guidelines for a reliable assessment of concrete strength

Based on all these recent results and collective expertise developed along very rich discussion, the RILEM TC has been able to define a consistent methodology which is summarized in the flowchart of Figure 5. It can be compared to that of Figure 1, since it directly highlights how and where recent scientific progress will result in an improvement in engineering practice. All items discussed in the previous section are visible in this flowchart. A last innovation is that the strategy is based on the Estimation Quality Level (EQL) concept that corresponds to a target quality regarding assessment. Three EQLs are defined, each of them corresponding to a target tolerance interval that is supposed to be obtained on three quantities: mean strength, standard deviation of strength, local strength. Depending on the EQL, the guidelines will define what are the mandatory tasks and the required means, typically regarding the quality of non destructive test results (TRP). Our opinion is that these guidelines will provide for the first time a firm basis for non destructive strength assessment of concrete, and will contribute to a wider use of NDT in civil engineering.

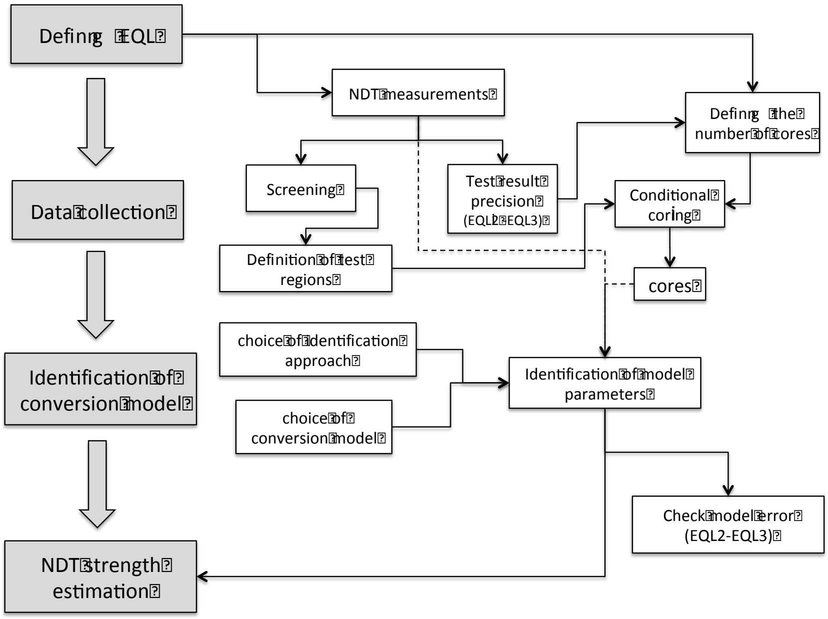


Figure 5. *Flowchart for a consistent strength assessment approach.*

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