How many cores are needed to assess on site concrete strength with non-destructive techniques ?

Breysse Denys[1], Romao Xavier[2], Alwash Maitham[1,3], Balayssac Jean-Paul[4], Sbartaï Zoubir Mehdi[1]

[1] *Université Bordeaux, I2M-UMR CNRS 5295, d.breysse@i2m.u-bordeaux1.fr*

[2] *University of Porto, xnr@fe.up.pt*

[3] *University of Babel, Iran, maitham_alwash@yahoo.com*

[4] *LMDC, INSA-Université Paul Sabatier, Toulouse, balayssac@insa-toulouse.fr*

ABSTRACT. *The RILEM Technical Committee (TC-ISC 249) was devoted to the writing of practical guidelines for the reliable estimation of concrete strength in existing structures using non-destructive techniques. This work accounted for recent research findings and used both real datasets from existing structures and synthetic datasets, enabling a systematic analysis of the influence of key variables. Three target levels of assessment (Estimation Quality Level – EQL) have been defined for which recommendations specify all useful steps (among which the quantification of the measurement quality). They also provide practicable information for the everyday engineering practice, as for example the prescription of a minimum number of cores required to fulfil each target EQL, i.e. the tolerance interval on the estimated parameter.*

RÉSUMÉ. *Le Comité Technique de la RILEM (TC-ISC 249) s'est consacré à la rédaction de recommandations opérationnelles pour une estimation fiable de la résistance en place du béton des ouvrages par méthodes non destructives. Ce comité a exploité les avancées récentes faites par les chercheurs de ce domaine. Le travail, s'appuyant sur des jeux de données issues d'ouvrages réels et des jeux de données synthétiques, ont permis d'identifier le rôle des facteurs qui contribuent le plus à la qualité des estimations. Trois niveaux d'exigence (EQL) ont été définis pour lesquels les recommandations précisent les tâches indispensables (en particulier l'évaluation de la qualité des mesures). Elles fournissent des informations pratiques telles que le nombre de carottes à prélever pour identifier les paramètres du modèle de conversion entre mesures ND et résistance, en respectant l'intervalle d'incertitudes correspondant à chaque EQL.*

KEYWORDS : *concrete strength, core sampling, non-destructive evaluation, precision, risk*

MOTS-CLES : *carottage, échantillonnage, évaluation non destructive, précision, résistance du béton, risque*

1. Recommendations for a consistent approach for assessing the on-site concrete strength

Concrete strength assessment in existing buildings using non-destructive techniques (NDT) remains a challenging issue. The RILEM Technical Committee TC-ISC 249 (In-situ strength evaluation of concrete) was created to develop and validate a methodology that would guarantee the quality and the reliability of such an assessment. This committee has identified the most controversial issues and the necessary key points to analyze them and produced recommendations that can be useful for engineers facing this question. The fundamental aspects of the recommendations can be summarized through the flowchart of Figure 1 which covers all the steps of the investigation and assessment program. All steps are described, with emphasis on a series of key issues (grey boxes with bold contour) that include:

- The definition of the target Estimation Quality Level (EQL) that establishes target tolerance intervals on three quantities: mean strength, standard deviation of strength, local strength values. The RILEM TC has defined three different EQL 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). At the first level, EQL1, estimating the mean strength is the unique challenge, with a tolerance interval of +/- 15% around its true value. For the two other levels, the three targets are considered, with more ambitious objectives for EQL3 than for EQL2.

- The assessment of the Test Result Precision (TRP) which is quantified through the within-test-repeatability (WTR), either in terms of standard deviation or of coefficient of variation. The WTR values derives from the physical processes involved in the test method, the sensitivity to fluctuations of influencing parameters (like environmental conditions), the quality of the device and the experience of the investigator. A meta-analysis by (Pessiki, 2003) has provided, for instance, COV_{rep} values 0.4 % and 1.9 % for ultrasonic pulse velocity (UPV) measurements. For all common NDT techniques, three levels of Test Result Precision (TRP), respectively TRP1, TRP2 and TRP3, have been defined (Table 2) in order to lead, after converting the NDT test results into strength values, to an identical uncertainty interval on strength irrespective of the NDT type.

- The use of conditional coring, which defines the location of cores after an efficient first screening of the structure using NDTs. By following this option, the distribution of concrete strengths obtained from the extracted cores is expected to be similar to that of the whole structure. Conditional coring can provide the same quality of assessment with a reduced number of cores and it is more profitable when the number of cores is smaller.

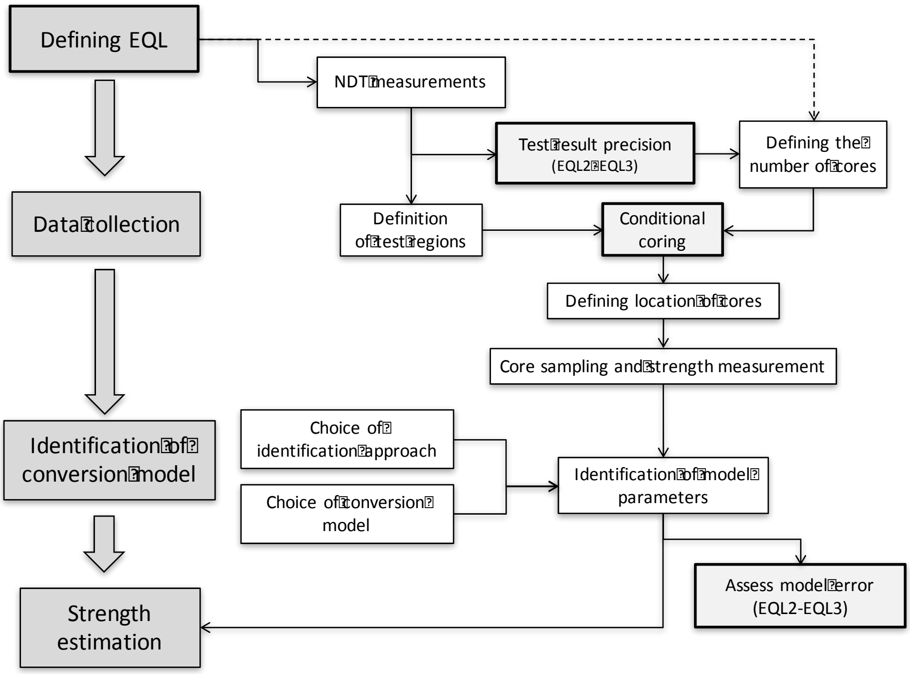

Figure 1. *Flowchart for a consistent concrete strength assessment approach.*

Table 1. R*elation between the estimation quality levels (EQL) and the target tolerance intervals on strength assessment (abstract of the original table)*

Estimated property	EQL1	EQL2	EQL3
Mean value of local strengths	±15%	±15%	±10%
Standard deviation of local strengths	not addressed	4 MPa	2 MPa
Root mean square error on local strength		6 MPa	4.5 MPa

Table 2. *Definition of the three TRP classes (COV = coefficient of variation)*

Coefficient of variation COV_{rep}	TRP1 high precision	TRP2 medium precision	TRP3 poor precision
For Rebound Hammer RH	$COV_{rep} \leq$ 3 %	3 % < $COV_{rep} \leq$ 7 %	COV_{rep} > 7%
For Ultrasonic Pulse Velocity UPV	$COV_{rep} \leq$ 1%	1 % < $COV_{rep} \leq$ 3 %	COV_{rep} > 3 %

2. How many cores are needed?

The number of cores required for reaching the prescribed targets is a complex issue, since many factors influence the quality of the estimate. These factors have been analyzed in detail by Alwash et al [ALW 15], where the risk curve concept was also developed. Using synthetic simulations, the investigation and assessment process was reproduced for a variety of contexts and, by varying the values of the most influencing factors, the distribution of final strength estimates around the true values was quantified [ALW 17]. The next step was to quantify the risk of missing the prescribed targets defined for each EQL. Finally, all simulation results were post-processed in order to identify empirical multi-variable risk functions with the following format:

$$R = a\,(N_c)^b\,(\varepsilon_{NDT})^c\,(f_{c\,mean})^d\,(sd(f_c))^e \qquad (1)$$

where R is the risk, N_c is the number of cores, ε_{NDT} is the WTR, $f_{c\,mean}$ is the mean concrete strength, $sd(f_c)$ is the strength standard deviation, and a, b, c, d and e are fitted parameters. These functions were defined for each of the three possible targets and the various tolerance intervals defined in Table 1. Examples of these functions are provided in Figure 2 for a concrete category with $f_{c\,mean}$ = 30 MPa and $cv(f_c)$ = 20%, for the three TRP levels and for NDT measurements defined by RH or UPV.

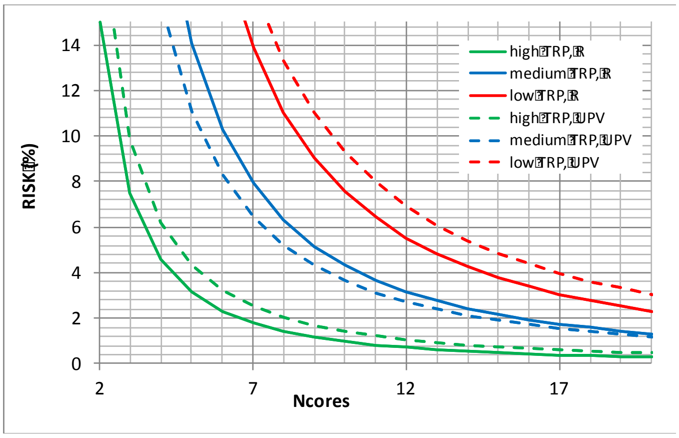

Figure 2. *Risk model curves for a target on f_c at +/-10%, risk is given in %.*

As expected, there is a clear decrease of the risk when N_c increases. However, it can be seen that TRP has also a major effect: the required number of cores to reach a 5% risk is respectively 4 for R (and 5 for UPV) for high precision TRP, 7 for R (and 9 for UPV) for medium precision TRP and 13 for R (and 15 for UPV) for low precision TRP. One can also see the closeness of the curves for RH and UPV, hence justifying the intervals defined in Table 2, since these intervals effectively lead to similar performances irrespective of the type of NDT.

However, the curves in Figure 2 are only valid for a given concrete category (i.e. a pair of mean strength and standard deviation) and it was difficult to provide results adapted for everyday engineering practice. Thus, an additional post-processing step was performed in order to build tables providing a minimum number of cores for various concrete categories once TRP and WTR are known (these are the two first key steps of the flowchart of Figure 1).

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 3a-b and 4.

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 values 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 readers. For more details, extensive text extensive information will be provided in 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

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 3a-b. *Prescribed number of cores for EQL1 (a-left) and EQL2 (b-right) for medium TRP (rebound hammer test results). These numbers are 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 4. *Prescribed number of cores for EQL1 for poor TRP (rebound hammer test results). These numbers are only illustrative, and cannot be taken at face value.*

The two tables of Figure 3 correspond to the case of medium TRP (i.e. TRP 2 in Table 2) for respectively EQL1 (on left) and EQL2 (on right). Figure 4 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 done:

(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 4 (poor TRP) are significantly larger than those in Figure 3a.

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

The RILEM Technical Committee TC-ISC 249 was created in order to consider how recent research advances in NDT for concrete structures could be transferred to the everyday practice of engineers. A consistent approach of the investigation of existing concrete structures has been defined and recommendations will be published soon. These recommendations cover all stages of the investigation and assessment while pointing the major issues and mandatory tasks for reaching reliable concrete strength estimates. Practicable information for everyday practice are also provided, through a recommended minimum number of cores adapted to each specific context.

Acknowledgements
The authors thank all members of RILEM TC ISC 249 for their ideas and their contribution to the RILEM guidelines.

4. References

[ALW 15] AL WASH M., BREYSSE D., SBARTAI Z.M., Non-destructive strength evaluation of concrete : analysis of some key factors using synthetic simulations, *Constr. Build. Mat.*, 99, 235-245, 2015.

[ALW 17] ALWASH M., BREYSSE D., SBARTAI Z.M., Using Monte-Carlo simulations to evaluate the efficiency of different strategies for nondestructive assessment of concrete strength, *Materials and Structures*, 50, 1, 2017.

[PES 03] PESSIKI S.P. (chair), In-place methods to estimate concrete strengths, ACI 228.1R-03 report, 2003.