Amélioration de la méthodologie d'évaluation non destructive de la résistance mécanique du béton dans les structures existantes

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RÉSUMÉ. *Les méthodes de contrôle non-destructif (CND) telles que le rebond (R) sont largement utilisées avec les techniques destructives (ex : prélèvements) pour évaluer la résistance mécanique du béton sur les bâtiments existants. Le choix d'une stratégie efficace pour estimer la résistance mécanique du béton d'un bâtiment est un enjeu important. En effet, le gestionnaire d'ouvrages a besoin de cette information pour évaluer correctement l'état de ce bâtiment et prendre les décisions adéquates (échéances de maintenance, re-calcul de la capacité portante, durabilité de l'ouvrage, sécurité, etc.). Cette étude vise à fournir les étapes principales pour la mise en œuvre d'une stratégie efficace permettant une évaluation plus fiable de la résistance mécanique des bétons in situ. En raison du nombre limité de données expérimentales en notre possession, nous avons effectué des simulations synthétiques pseudo-aléatoires permettant de contrôler un maximum de paramètres. L'avantage d'une telle approche est qu'elle permet de construire une base de données synthétiques pour simuler différentes configurations et d'estimer l'erreur de prédiction et par conséquent d'évaluer la qualité de la stratégie.*

ABSTRACT. *Non-destructive techniques (NDT) like rebound hammer (RH) are widely used in conjunction with destructive techniques (DT cores tests) for assessing the concrete strength in existing buildings. The selection of an efficient strategy to estimate the concrete strength of a building is a real challenge for the manager of structural maintenance to take decision about the condition of this building (evaluation of structural capacity, durability evaluation, saftey, etc.). The Present work aims to provide some outlines about the efficient strategy that can produce a confidence value of the concrete strength. Since the ability of the data sets from an experimental work for deepening the analysis of a problem having a lot off degrees of freedom like our problem is limited, therefore the synthetic simulation approach is adopted. One of the advantages of using this approach is that several strategies can be simulated enable the calculation of the prediction error and consequently evaluate the quality of the strategy.*

MOTS-CLÉS: *résistance mécanique du béton, Rebond, stratégie efficace, CND, simulation synthétique.*

KEY WORDS: *Concrete strength, Rebound hammer, efficient strategy, NDT techniques, synthetic simulation.*

1. Introduction

In the real practice, the structural engineer always needs to carry on tests in existing structures in order to make the right decision about the condition of the structure. The testing of existing structures is usually related to an assessment of structural integrity. When the assessment is based only on destructive testing (DT) by taking cores for compressive tests, the cost of coring and testing may only allow a relatively small number of tests to be carried out on a large structure, which may be misleading [IAEA 02]. Thus non-destructive techniques (NDT) are used for the assessment of concrete strength of existing buildings in conjunction with destructive tests. Many guidelines and specifications are available [IAEA 02, EN 07], which indicate the increasingly use of this combination of (DT) with (NDT) in real practice. Non-destructive techniques are cheaper than destructive test however their relation with concrete strength is indirect and it is affected by many influencing factors. Thus the real challenge is to find an efficient strategy that can estimate a robust value of concrete strength of an existing building.

In this paper, for a fixed budget of investigation, several strategies for assessing concrete strength are studied in order to provide some outlines about the characteristics of the efficient strategy. These strategies represent different combinations of coring tests and rebound hammer tests (R). They include the effects of following factors: the effect of number of measurements (DT & NDT), the effect of the way of selecting core locations (randomly & conditionally) and the effect of the method used for identifying the assessing model. For each strategy the prediction error is calculated and it is used as an indication of the degree of efficiency of this strategy.

A synthetic simulation approach has been proposed by [BRE 12, 13] in order to deepen the analysis of this issue. Since the ability of experimental data sets for deepening the analysis remains limited, this approach is adopted in the present study.

2. Synthetic Simulation Approach

The basic idea of this approach is to simulate statistically the problem of concrete strength evaluation using NDT techniques within the computer by creating a synthetic building with all values of DT and NDT measurements. Then an assessment strategy is used to estimate the concrete strengths in this building and calculate the corresponding errors.

The first step is the generation of concrete properties: true strength of concrete f_c is generated by assuming a Gaussian distribution $N(f_{cm}, s(f_c))$ while a truncated Gaussian distribution, $N(S_{rm}, s(S_r))$ with $S_r \leq 100\%$, is used to generate the values for the degree of saturation S_r which appears as an uncontrolled factor.

True values for the rebound number R (rebound hammer technique) which represent the NDT measurements are produced using relationships established after an in-depth literature review on the physics involved, Eq.1, proposed by [BRE 12] :

$$R = R_{ref}(f_c/f_{cref})^{1/cf}(S_r/S_{rref})^{1/cs} \quad [1]$$

where the reference values (ref index) are arbitrary values introduced in order to normalize the equations, and have no influence on the results. The exponents quantify the sensitivity of R to strength variations and humidity variations. The reference values are R_{ref}=40, S_{rref}=85% and f_{cref}=40 MPa. The exponent values have been carefully chosen, in order to accurately describe what is observed in practice. The strength sensitivity exponent cf has been taken equal to 2.10. The humidity sensitivity exponent cs has been taken equal to -3.33 [BRE 12].

As it is the case in real world, measurement errors ε_{fc} and ε_R are added to the generated true values of f_c and R respectively. The magnitudes of these errors are obtained by assuming a Gaussian distribution N(0, $s(f_{cl})$ or $s(R_l)$) with zero average value and a standard deviation, $s(f_{cl})$ or $s(R_l)$, based on the variability of measurements at a local scale. Table 1 gives these values of standard deviation for different quality levels.

Using the data set of generated strengths and NDT measurements, an assessment strategy is applied in order to identify a model, then to use it in the estimation of strength from NDT values. The quality of assessment is determined by calculating the errors RMSE (Root Mean Squared Error) between true and estimated strengths. Then the simulation is repeated in order to get statistical information about the stability and reliability of the process.

In order to create the synthetic world and perform the simulation process a computer program is developed using VBA software. The flowchart of Figure 1 illustrates how the process works.

Table 1. *The values of standard deviation s(f_{cl})and s(R_l) for different quality levels of measurements [BRE 12].*

Measurements quality level	s(f_{cl}) MPa	s(R_l)
High	1	1
Average	1.5	2
Low	2	4

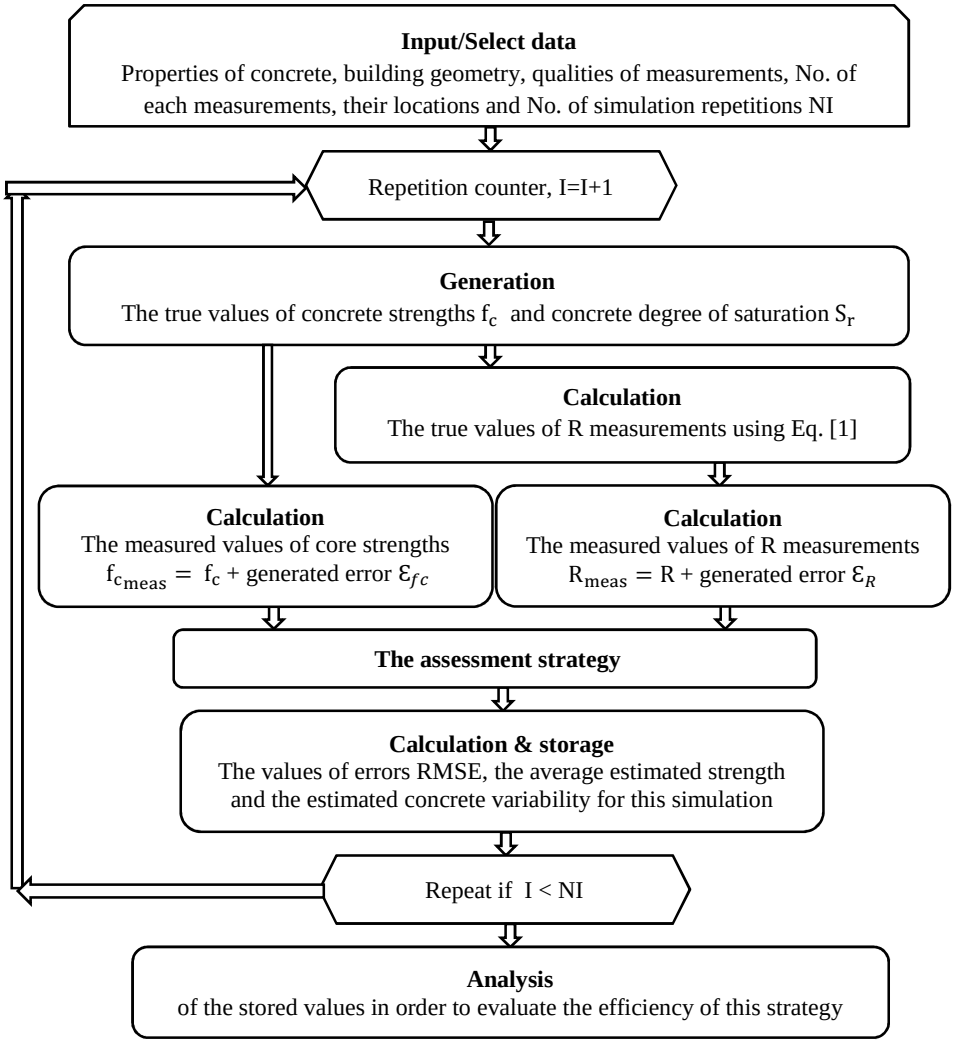


Figure 1. *Flowchart of the synthetic simulation approach.*

3. Assessment strategy

In order to analyze the problem, we define the strategy as consisting in two main parts: the first one is the ***investigation program*** i.e. the number of each type of measurements (DT and NDT), their locations in the building and the way of selection of these locations. Two ways are proposed for selecting the core points: randomly or conditionally (i.e. cores selection depends on the NDT measurements according to a specific condition). In this study, the condition is to subdivide the NDT values into a number of groups equal to the number of cores NC then to take the median point of each group to be the core point. The second part of the strategy is the ***assessment methodology*** which concerns with the model used to calculate the concrete strengths at different points in the building where only the NDT measurements exist. In practice, there are three types of approaches for producing a model: the use of a prior model produced by other researchers without any

calibration, the use of a prior model with calibration and the identification of a specific model using the regression analysis.

In the present work, two calibration methods are adopted: multiplying factor and shifting.

3.1. Calibration with multiplying factor method

First, the mean value of cores strengths $f_{c\,meas\,m.}$ is calculated, then the prior model is used to calculate the estimated strength values $f_{c\,est}$ (before calibration) at core points and as a result the mean value of these strengths is obtained. Using the two calculated mean values, the calibration factor K_{cal} is derived, Eq.2:

$$K_{cal} = f_{c\,meas\,m.}/f_{c\,est\,m.} \quad [2]$$

Finally, the calibrated model is produced, Eq.3, and it is used to calculate the estimated strengths at NDT points:

$$M_{cal}(NDT) = K_{cal} * M_{prior}(NDT) \quad [3]$$

3.2. Shifting factor method

In this method, each value of core strength, $f_{c\,meas\,i}$, is used with the corresponding value of estimated strength, $f_{c\,est\,i}$ (provided by using the prior model), to calculate the shifting factor, $\Delta f_{c\,cal.}$, Eq.4:

$$\Delta f_{c\,cal.} = (\sum_{i=1}^{NC}(f_{c\,meas\,i} - f_{c\,est\,i}))/NC \quad [4]$$

Then the calibrated model is obtained as given in Eq.5:

$$M_{cal}(NDT) = M_{prior}(NDT) + \Delta f_{c\,cal.} \quad [5]$$

4. Description of the study

The objective is to analyze the effects of the elements of assessment strategy in order to produce some recommendations about the efficient strategy. Simulations are carried on by varying some elements and analyzing how RMSE on assessed strengths varies. The varying factors are the number of cores NC, the number of points for rebound hammer measurements NR, the ways of selecting the locations of core points and the way of identifying the assessment model (prior with or without calibration, specific).

For this study, some parameters remain fixed in all simulations:

- Generated concrete has the following true values: mean strength f_{cm} = 25 MPa, strength variability s(fc) = 2 MPa, mean degree of saturation S_{rm} =75% and its variability s(S_r)= 2.25%.
- Average quality for all measurements (cores and rebound hammer).
- Number of simulation repetitions NI = 100, in order to obtain relevant statistical information.
- The investigation budget is fixed to 100 cost units (CU). The cost of techniques depends on the quality of measurements as proposed in Table 2.

For cost of 100 CU and according to Table 2 (values for average quality) we calculate the possible combinations of DT and NDT tests and these values are presented in Table 3.

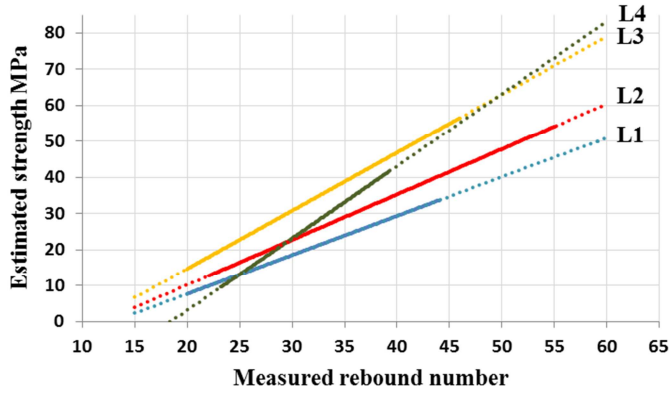
Table 2. *The values of the unit costs (CU) for DT and NDT tests.*

Measurements quality level	Drilling one core and compressive test	Rebound, one value represents the average of 10 measurements
High	14	1.4
Average	10	1
Low	7	0.7

Table 3. *The possible combinations of DT and NDT measurements for investigation cost of 100 CU and measurements with average quality.*

No. of cores NC	0	1	2	3	4	5	6
No. of rebound measurements NR	100	90	80	70	60	50	40

As stated earlier for the assessment methodology, three main approaches are adopted in the present study. The first one is the use of prior model without calibration. Four different linear models are selected from literature for this purpose. Figure 2 shows these four models with the domain of strengths from which they are derived (the solid part of each line). It is necessary to indicate that all these models are derived for 150 mm cube specimens thus we modify them for core specimens by multiplying the resulted strengths by a suitable transformation factor. For the second approach two methods are applied: multiplying factor method and shifting factor method. In the third approach (regression analysis) two types of models are considered: linear and power.



L1	$f_{c\,cube} = 1.353R - 17.393$	[QAS00]
L2	$f_{c\,cube} = 1.5676R - 18.537$	[ALA13]
L3	$f_{c\,cube} = 2.0098R - 21.749$	[CIA79]
L4	$f_{c\,cube} = 2.5R - 46$	[MIK92]

Figure 2. *The linear models that are adopted as a prior models.*

5. Results and discussion

For each of the four prior models (L1, L2, L3, and L4), we use the simulation in order to calculate the errors resulted from applying the approaches of assessment methodology on each possibility of combination (DT and NDT) given in Table 3. The authors had shown in a previous contribution (ALW 14) that the prediction error (the error between the estimated strengths and true strengths at points with rebound measurements only) is always larger than the fitting error (the error between the estimated strengths and the true strengths at the points which have been used for model fitting). Thus the strategies are only compared regarding the prediction error. The prediction error values for cases of the four models are shown in Figure 3. The results presented in this figure are for the case of randomly selected cores. Analyzing the results, the following observations can be highlighted:

- For each case (L1, L2, L3, and L4) the error values produced from using the prior models without calibration are nearly constant because these curves (curves A) are independent of core number. In this case study (f_c = 25 MPa) these values vary from 3.2 MPa for model L2 to 11.4 MPa for model L3. This means that model L2 (by chance) well represents the concrete simulated in the study while model L3 is very far from it. Thus it is very risky to use ANY prior model without calibration for assessing concrete strength.

- For the four models, the values of curves of the two calibration methods (curves B1, B2) decrease as the number of cores increases. The comparison between curves B1 and B2 for each model could not give us a clear conclusion about which one is the best. For models L2, L3 and L4, the multiplying method is better than the shifting method while for model L1 it is the opposite. We can explain this observation according to the number and values of calibrated parameters in each method. In some cases the prior linear model ($f_{cest} = mR + b$) has a good slope (m) and needs only changing the value of (b) in order to represent our concrete, this is the case of model L1. In other cases (L2, and L3) both parameters (m and b) need to be calibrated in order to represent the concrete under study. However, in case L4, the model is very far from our concrete and as a result the values of both curves B1 and B2 remain large. The efficiency of calibration depends on the prior model adopted in the calibration process.

- The curves produced from regression analysis (C1 for linear model and C2 for power model) are identical in the four figures because they are independent of the prior model. It can also be noted that these curves decrease as the number of cores increases because increasing the core number stabilizes the statistical process of model parameter identification (the large the core number, the closer the sample from the whole population).. We observe that, for small number of cores NC=2, the error resulting from using linear model (curve C1) is very close to that curve of power model (curve C2) and they become

merge as NC increases. Thus, for concrete with a small variability (2 MPa in the present study) there is not great effect of the model shape.

- The comparison between the three approaches of assessment methodology (A, B and C) shows that the use of regression analysis to identify a specific model (with the assumptions of this case study) is always the best one as soon as NC ≥ 3. However if NC < 3 the use of calibration approach is preferable.

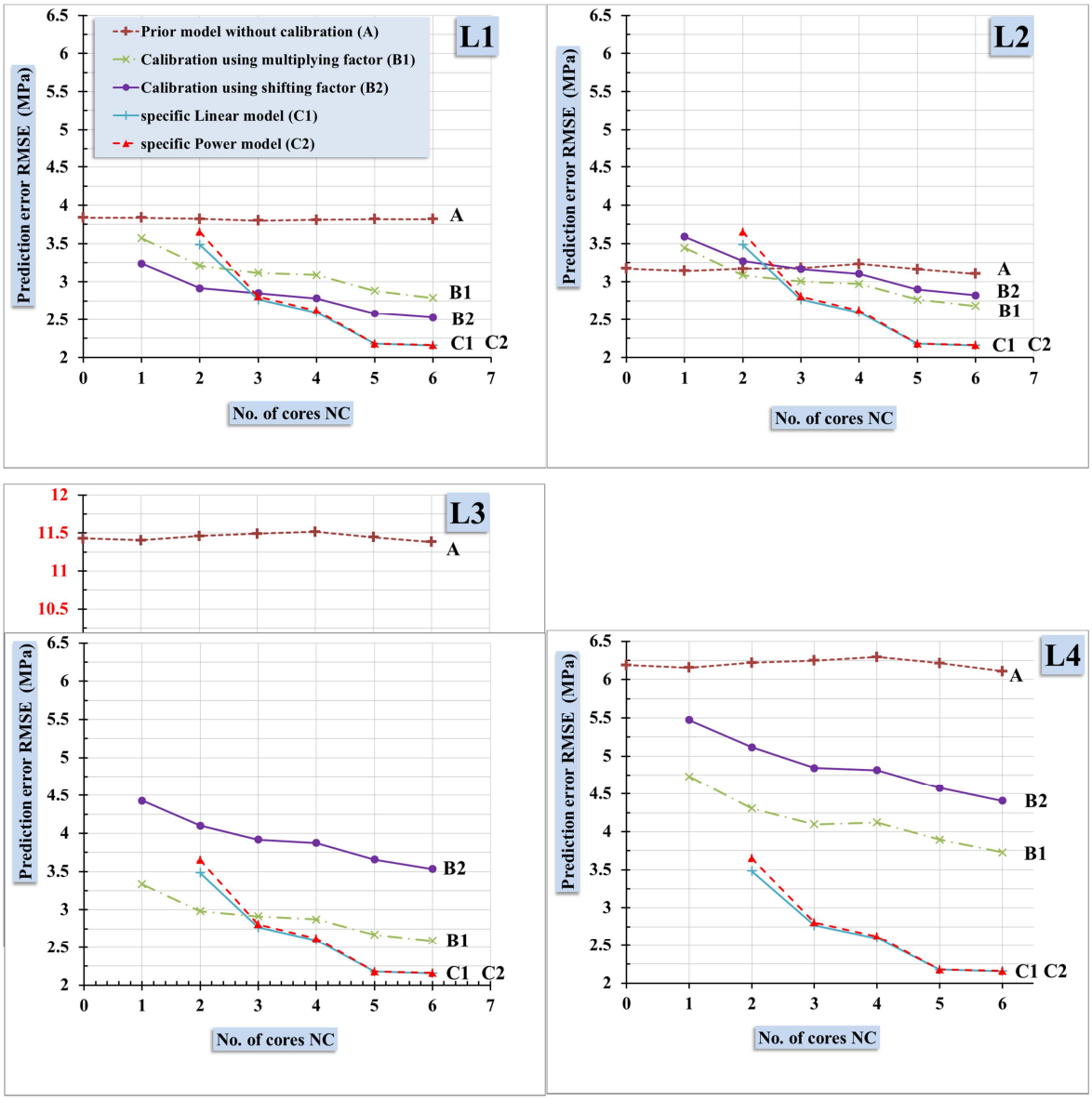


Figure 3. *Prediction errors resulted from using the approaches of assessment methodology as a function of No. of cores for each one of the four prior models.*

The previous simulations are performed using random cores locations. In order to study the effect of the way of selecting core locations on the efficiency of the strategy, the same simulations have also been carried out with conditional coring. A comparison between the errors for the two approaches is provided at Figure 4 for model L1 only. The following observations can be highlighted:

- The main consequence of conditional coring on the resulting prediction errors for the two calibration methods (multiplying factor and shifting factor) is to decrease the average values and reduce the scatter of these errors. This happens because in the conditional selection of cores, the cores strength distribution is better sampled and the calibration process is more stable. This effect is particularly visible, both on average and scatter of RMSE, when the core number is very small. This effect of

conditional cores is less visible as the number of cores increases since the sampling process, even if at random, becomes more stable.

- The other two cases (linear and power specific models) show the same type of behavior, with a larger added value of conditional coring when the number of cores is small.

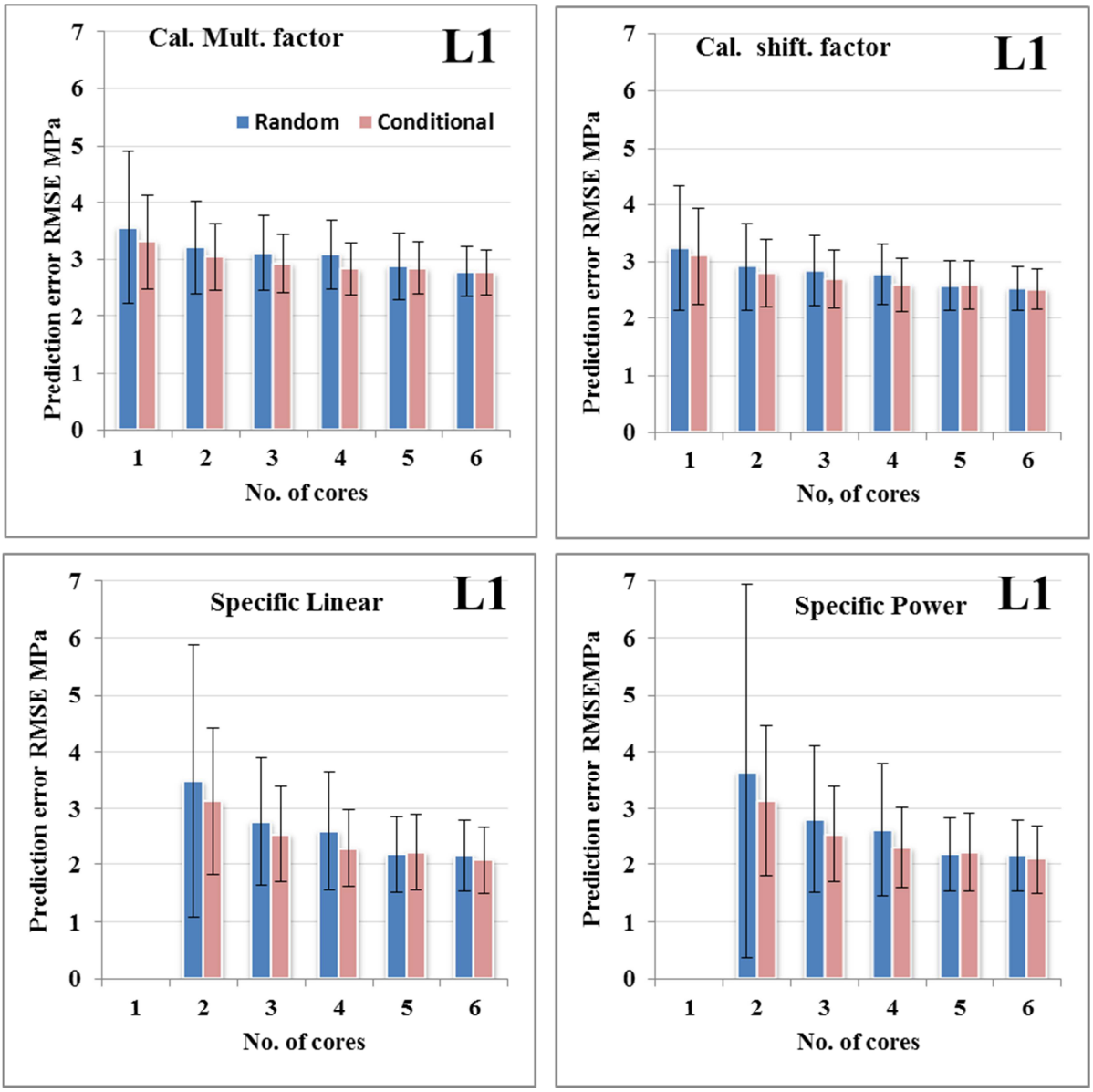


Figure 4. *Comparison between the errors resulted from using conditional cores with those resulted from using random cores for model L1.*

6. Conclusions

In order to highlight the efficiency of the strategies that can be adopted for assessing concrete strength, several elements of the assessment strategy are studied with a case study corresponding to a concrete having average strength (25 MPa) and variability (2 MPa) with a given investigation cost (100 CU) and average quality of NDT measurements. The study has been performed using the synthetic simulation approach, and the main following conclusions can be drawn:

- The synthetic simulation is a very powerful approach making it possible to study a complex problem with a lot of degrees of freedom and explain the results which NDT researchers obtain on site or in laboratory when

they make the NDT measurements. In real practice, obtained results are sometimes apparently controversial, but our approach makes it possible to explain excatly why.

- For a fixed cost of investigation (100 CU) when NC ≥ 3 the most efficient strategy is to use specific model but for NC < 3 the use of calibration method is preferable.

- For concrete with small variability there is no significant effect of the shape of the model used in the regression analysis because nonlinear effects are negligible.

- It is very dangerous to use prior model without calibration for assessing concrete strength because the efficiency of this model in the assessment of concrete strength is depends on chance only.

- Conditional coring is a very practical and cost-effective way of reducing the predictive error (both its average and scatter). This effect is particularly beneficial when the number of cores is limited (up to 4 cores).

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