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# Non-destructive assessment of both mean strength and variability of concrete: A new bi-objective approach

Maitham Alwash [a,b,*], Zoubir Mehdi Sbartaï [a], Denys Breysse [a]

[a] I2M-GCE, University of Bordeaux, UMR 5295, 33405 Talence, France
[b] Civil Eng. Dept., College of Engineering, University of Babylon, Babel, Iraq

## HIGHLIGHTS

- Bi-objective approach shows high efficiency in capturing the concrete strength variability.
- Regression approach has limited ability in capturing the concrete strength variability.
- Calibration approaches cannot be used to estimate the concrete strength variability.
- Bi-objective, regression and calibration approaches can efficiently assess the mean strength.

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## ABSTRACT

Using non-destructive techniques (NDT) like rebound hammer in combination with destructive techniques (DT) like core test is a common practice. Two approaches are widely used to produce a model for assessing the concrete strength. The first approach consists in fitting a specific model between NDT measurements and cores using the regression analysis. The second approach uses a prior model which is calibrated according to measured core strengths. The EN 13791 and ACI standards require a large number of cores to estimate mean concrete strength and concrete strength variability and consequently to calculate the characteristic strength value which depends on these two inputs. In this work, we propose a new approach for identifying the models based on NDT and DT tests in order to capture both mean strength and concrete strength variability. This approach is first illustrated by synthetic simulations which are a good way to study a problem having many degrees of freedom. The proposed approach is then tested on a real data set. In both cases, it is confirmed that the common approaches are able to estimate the mean strength but they fail, even with a large number of cores, to accurately estimate the concrete variability and hence the characteristic strength. Reversely, the new approach shows its high efficiency in capturing the concrete variability (in addition to the mean strength) with a number of cores lower than that prescribed by the standards.



## 1. Introduction

Evaluating the concrete compressive strength in existing structures is a common requirement. For example, the change in the use of a structure may require the determination of the concrete strength to accurately assess the structural capacity. There also may be a need to evaluate concrete strength after a structural failure like fire damage or environmental degradation [1]. The seismic retrofitting issue arises nowadays in several countries (like Italy and Turkey) that also emphasizes the need for an accurate in situ assessment of concrete strength in existing structures [2,3].

Destructive technique DT (core test) has many drawbacks: it is expensive, time consuming, sometimes difficult access of coring

*Abbreviations: Superscript*⁻, mean value of the variable under consideration; $s(\,)$, standard deviation of the variable under consideration; *Test location*, limited area selected for measurements used to provide one test result; $f_{ccore}$, core compressive strength, corresponding to one test location; $f_{cest}$, estimated individual strength of concrete, corresponding to one test location; $f_{c\ uncal.}$, estimated individual strength of concrete, corresponding to one test location, produced from using an uncalibrated prior model; *R*, Rebound number, test result, it is the mean of rebound hammer readings corresponding to one test location; *NC*, Number of cores; *NI*, Number of repetitions; *NR*, Number of test locations for rebound hammer measurements; *RMSE*, Root Mean Squared Error.

* Corresponding author at: I2M-GCE, University of Bordeaux, UMR 5295, 33405 Talence, France.

*E-mail address:* maitham-fadhil-abbas.alwash@u-bordeaux.fr (M. Alwash).

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machine, only representative of small volume of concrete and has some locally destructive effect on the structure [4]. To overcome these drawbacks, non-destructive techniques NDT can be combined with cores in order to provide more economical evaluation of the concrete compressive strength in the structure. The main challenge is to identify a relationship "conversion model" between the NDT test results and the concrete strength. The existing model identification approaches can be classified into two main categories: regression approaches by identifying a specific model using a limited data set of core strengths and NDT results, and calibration approaches in which a prior model is modified for best agreement with an experimental data.

In the real practice, the mean compressive strength and the characteristic compressive strength are the most common assessed values. The assessment of characteristic strength depends on the mean strength and on the standard deviation of the compressive strengths (concrete variability), thus the concrete variability is also a required value. Furthermore, the ACI 214.4R-03 [5] reported that the coefficient of variation (CV) due to in situ concrete strength variation within a structure (i.e. concrete variability/mean strength) is 13%. However Masi and Chiauzzi [6] found a CV value of 21% within one member of a structure. Masi and Vona [2] studied the concrete variability in many buildings in Italy and they observed that the probable values of CV range between 15% and 35%. Pucinotti [7] also stated that in many cases the CV reaches 35%. That is why the assessment of concrete variability within some homogenous zones (one floor for example) or the whole structure is needed in addition to mean strength value.

Using NDT methods, European Standard EN 13791 [8] allows two approaches (Alternative 1 and 2) for assessing the individual compressive strength values then the mean strength and concrete variability and as a result the characteristic strength. According to the requirements of this standard, the minimum number of cores ($NC$) is respectively 18 for Alternative 1 (regression analysis approach) and 9 for Alternative 2 (calibration approach). ACI 228.1R-03 standard [1] also requires at least 12 cores (six test locations with two cores at each location) to develop an adequate strength relationship.

In this paper, we present a new model identification approach "bi-objective" that is devoted to capture two material characteristics: the mean and standard deviation of the concrete strength values. Then the prediction capability of bi-objective approach is compared with that of the existing approaches.

The synthetic simulation [9–14] is adopted here to generate a data set (NDT test result and strength values) representative of a synthetic building. These data are used through the present study for testing and validating the proposed approach. The new approach is also applied on a real data set obtained from the scientific literature. In this paper the linear shape of conversion model is considered for all model identification approaches (calibration, regression and bi-objective).

## 2. Existing approaches for assessing the compressive strength by NDT techniques

The assessment of concrete strength always needs a conversion model establishing the relationship between the compressive strength of concrete and the test results drawn from NDT measurements. There is a consensus to say that there is no universal conversion model that could be used whatever the concrete. In practice, two groups of model identification approaches are widely used to produce a conversion model for assessing the compressive strength.

### 2.1. Regression approaches

These approaches consist in fitting a specific model between NDT measurements and compressive strength of cores using ordinary least squares method [15–17] or its modified form developed by Mandel [1,18].

### 2.2. Calibration approaches

They use a prior model (many models exist in literature or standards [8,19–24]) which is calibrated according to the measured core strengths. Two possibilities for calibration are often used in real practice: (1) multiplying factor method, and (2) shifting factor method. In this section, a brief description of each method is presented for the case of rebound hammer technique as an example. However, the same principles are also valid for any other NDT technique like for instance ultrasonic wave pulse velocity.

#### 2.2.1. Multiplying factor method (k-method)

The principle comes to update an uncalibrated prior model by a coefficient $k$ to produce a calibrated model,

$$f_{cest}(R) = k f_{c\ uncal.} \tag{1}$$

The coefficient $k$ is calculated as in the following steps:

(a) Calculate the mean value of core strengths $\bar{f}_{ccore}$,
(b) Use the uncalibrated prior model to calculate the estimated strengths at core locations then take the mean of these values, $\bar{f}_{c\ uncal.}$
(c) Calculate the calibration factor $k = \bar{f}_{ccore}/\bar{f}_{c\ uncal.}$

#### 2.2.2. Shifting factor method (Δ-method)

The concept here is to shift the uncalibrated prior model by a coefficient $\Delta$,

$$f_{cest}(R) = f_{c\ uncal.}(R) + \Delta \tag{2}$$

The coefficient $\Delta$ is calculated as in the following steps:

(a) Use the uncalibrated prior model to calculate the estimated strength at each core location $f_{c\ uncal.\ i}$ then,
(b) Calculate the shifting factor $\Delta = \sum_{i=1}^{NC}(f_{ccore\ i} - f_{c\ uncal.\ i})/NC$

where $f_{ccore\ i}$ is the compressive strength of core $i$.

## 3. The principles of bi-objective approach

From the basics of the existing approaches, it is obvious that none of these approaches has the objective to capture the concrete variability although the standards recommend some of these approaches to estimate the concrete variability because it is an essential parameter in the calculation of the characteristic strength of concrete. Thus we propose here a new "bi-objective" approach which is devoted to capture the variability of concrete strengths in addition to their mean value.

The basic idea is that any investigation program with NDT technique (rebound hammer for example) provides a data set of $NC$-pairs of ($R$, $f_{ccore}$), where the rebound measurements and core strengths are measured at the same test locations. This data set is used to identify a relationship (conversion model) between concrete strength and the rebound number test results. Usual mathematical shapes of such models have two parameters [9,25]. It is the case for the most common ones: (a) linear models $f_{cest} = aR + b$, (b) exponential models $f_{cest} = a\exp(bR)$, (c) power-law models $f_{cest} = aR^b$. Analytically, two conditions are required in order to