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Non-destructive strength evaluation of concrete: Analysis of some key factors using synthetic simulations

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HIGHLIGHTS

- Fitting error cannot be a real indication about the quality of concrete strength assessment by NDT.
- A misleading model is produced if we fit using cores number equal to the number of model parameters.
- To assess a fitted model, looking at: r^2, *RMSE* or $RMSE/s(f_c)$ leads to different conclusions.
- To fit a SonReb model there is a minimal number of cores above which the combination is efficient.

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ABSTRACT

Non-destructive techniques (NDT) like rebound hammer (RH) and ultrasonic pulse velocity (UPV) are widely used in conjunction with destructive techniques (core tests) for assessing the concrete strength in existing buildings. The methodology consists in fitting regression models between NDT techniques and destructive tests on a limited number of cores. The quality of the model is affected by many influencing factors such as: the number of cores, the quality of NDT measurements, the variability in concrete strength, the existence and magnitude of possible uncontrolled factors (like saturation rate) and the combination of techniques. In this paper, the effects of these factors are studied using a synthetic simulation approach in order to well understand them and consequently to develop a methodology for improving the quality of strength assessment. In order to assess the quality of fitted model and its ability to estimate strength, *RMSE* and r^2 errors are calculated and it is found that the calculation of r^2 alone may give misleading indication since r^2 is very sensitive to the scattering of the explanatory variable. Another important result of the present study is that there is a critical minimal number of cores which makes the combination efficient while for a lower number the use of single technique is preferable. This number depends on the qualities of the two techniques to be combined.

1. Introduction

In the real practice, the structural engineer always needs to carry out 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 extracting cores for compression testing, the cost of coring and testing may allow only a relatively small number of tests to be carried out on a large structure, which may be misleading [1]. Thus non-destructive techniques (NDT) are used for the assessment of concrete strength in existing building in conjunction with destructive tests. Many guidelines and specifications are available [1–4], which indicate the increasing use of NDT in real practice. The strength estimation requires a model which can be identified by establishing a statistical correlation between DT and NDT results. Many works have been published in which each author has identified his/her specific model [5–11]. State of the art papers [12,13] have recently identified a huge number of models that have been proposed by different researchers.

The ultrasonic pulse velocity and rebound hammer methods are frequently combined for a better estimation of concrete strength. This is very convenient since these two techniques are sensitive to the variations in some concrete properties in opposite directions. For instance, the increase in moisture content of concrete raises the pulse velocity but lowers the rebound number [14].

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The combination of NDT techniques was proposed firstly by RILEM (Technical committees 7 and 43) based on seminal work from Facaoaru [15]. There is a huge number of works that deal with the combination of NDT methods and provide mathematical models [16–20]. These works lead to controversial conclusions about the efficiency of combination. Some works found that "the combined use of ultrasonic pulse velocity and rebound hammer greatly improves the accuracy of the process of assessment of concrete strength especially if information about concrete mix proportions and density are available" [21], while others did not find a significant improve in the concrete assessment by combining methods [22,23].

The effectiveness of combination is studied in the present paper in order to explain the controversial results obtained by different researchers.

It is commonly agreed that none of the produced models is able to predict the concrete strength with enough accuracy for using the assessed value for further structural computations [24]. The reason is, on one hand, the influence of both measurements uncertainties and uncontrolled factors (like concrete humidity, carbonation...), and on the other hand, the lack of certainty upon the "best way" to establish the conservation model (number of cores, calibration method, the use of a single NDT method or of a combination...).

A synthetic simulation approach has been proposed [12] in order to deepen the analysis of this issue since the ability of real data sets (experimental work) for deepening the analysis remains limited. In this paper, the effects of some influencing factors such as: the number of cores which are used for the regression/calibration of the model, the quality of NDT measurements, the variability in the concrete strength, the variability in the concrete degree of saturation and the combination of NDT techniques are studied. The synthetic simulation approach is used in order to well understand these effects and consequently to improve the methodology of model development and, as a result, to improve the quality of concrete strength assessment.

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 world which mimics as closely as possible the real world, in order to make possible an in-depth analysis and a parametric study of influencing factors. While it is of course not possible to reproduce *in silico* the real world, the simulation must point what influencing factors (input data of the synthetic model) are considered, and how they influence (sign, magnitude, possible coupling effects) the physical properties measured with NDT methods (outputs of the synthetic model). In the version used in this paper, the synthetic model has been developed in order to correctly reproduce the relationships between:

- strength and moisture content considered as input data on one hand,
- ultrasonic pulse velocity and rebound value considered as output data on the other hand.

Other possible influencing factors (carbonation, cracking, aggregate type and size...) are not considered. While they may be considered in a next version of the synthetic model (a revised version, work under progress, including the influence of carbonation is presently developed by the authors for an international benchmark prepared for RILEM committee TC 249-ISC), it must be pointed that the present model does not pretend to be "the truth".

It is however the conviction of the authors that most conclusions drawn in this study have very probably a high level of generalization, that will remain to be confirmed in the future.

The detailed principles of the synthetic approach have already been published [12,24,25], to which the reader is invited to refer. In order to avoid duplication, only main patterns of the numerical process are described here.

The first step is the generation of concrete properties: true concrete strength 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 $S_r \leqslant 100\%$, is used to generate the values for the degree of saturation S_r which appears as an uncontrolled factor, see Appendix B for more numerical details.

True values (in the synthetic world) for the velocity V (ultrasonic pulse velocity technique) and the rebound number R (rebound hammer technique) which represent the NDT measurements are produced using relationships established after an in-depth literature review of available experimental results, Eqs. (1) and (2) as proposed by Breysse [24]:

$$V = V_{ref}(f_c/f_{cref})^{1/bf}(S_r/S_{rref})^{1/bs} \quad (1)$$

$$R = R_{ref}(f_c/f_{cref})^{1/cf}(S_r/S_{rref})^{1/cs} \quad (2)$$

where the reference values (*ref*) are arbitrary values introduced in order to normalize the equations, and have no influence on the general behavior. The exponents quantify the relative sensitivity of V and R to the variations in strength and humidity. The reference values are $R_{ref} = 40$, $V_{ref} = 4000$ m/s, $S_{rref} = 85\%$ 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 exponents *bf* and *cf* have respectively been taken equal to 4.90 and 2.10. The humidity sensitivity exponents *bs* and *cs* have respectively been taken equal to 7.14 and −3.33 [24]. The *bs* and *cs* values respectively correspond to an increase of 6% in V and a decrease of 12% in R as the concrete humidity changes from dry-air specimen (assumed at $S_r = 65\%$) to fully saturated condition ($S_r = 100\%$). These values are in agreement with what we have found in literature. For example for V, [26] states that the pulse velocity in saturated concrete may be up to 5% higher than in dry concrete. [27] finds an increase of 19% in V between totally dry and maximum saturated conditions i.e. 6.65% between $S_r = 65\%$ and saturated conditions. Experimental results from [21] show an increase in V of (200–400) m/s between air dry and wet conditions. Also for R, the results from [21] show a decrease of (3–4) points in R values i.e. less than 10%. [28] states that well-cured, air-dried specimens, when soaked in water and tested in the saturated surface-dried condition, show rebound readings 5 points lower than when tested dry. Czech Standard CSN 731373 after [29] indicates a 20% decrease in R.

The relationships (1) and (2) can be combined together in order to obtain an equation in the form ($f_c = f(V,R)$). One thus gets:

$$f_c = f_{cref}(1/V_{ref})^{-bsk/cs}(1/R_{ref})^k V^{-bsk/cs} R^k \quad (3)$$

$$\text{where}: k = cf * bf * cs/(cs * bf - cf * bs) \quad (4)$$

Eq. (3) provides the true (synthetic) value of strength that could be identified by: (a) measuring rebound and velocity on at least two measurement points without any measurement error, (b) choosing a double-power law conversion model. Errors on strength estimates will result from both measurement errors (the main part) and possible choice of a model having a different mathematical shape.

Eq. (3) is used to produce the iso-strength curves shown in Fig. 1a whose shape can be compared with the curves used in practice by engineers like those provided by RILEM TC-43 [15], see