Construction and Building Materials 151 (2017) 916–924

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Estimating in situ concrete strength combining direct and indirect measures via cross validation procedure

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HIGHLIGHTS

- UPV and compressive tests on microcores for indirect concrete strength estimation.
- Linear regression and cross-validation (CV) as a new procedure for strength estimation.
- Iterative CV procedure (CVP) is effective in evaluating the prediction error.
- Better reliability of the proposed CVP compared to UNI13791 standard procedure.
- CVP allows using a significantly lower number of cores than EN 13791 standard.

ARTICLE INFO

Article history:
Received 12 January 2017
Received in revised form 13 June 2017
Accepted 21 June 2017

Keywords:
Compressive strength
Concrete
Non destructive tests (NDT)
Microcoring
Cross-validation analysis

ABSTRACT

This paper proposes a new approach, based on the cross validation analysis of data, to establish reliable models for estimating the in situ compressive strength of concrete from the results of indirect tests, including Ultrasonic Pulse Velocity test and compressive test on microcores. The method was validated on a database obtained from an extensive diagnostic campaign performed on an existing building. The reliability of the proposed method was evaluated along with the results obtained by means of the Alternative 1 approach of EN 13791 standard by comparing the mean and the characteristic values of the estimated uniaxial compressive strengths issued from the two methods with the real ones obtained directly from the cores.

Compared to the standard approach, the proposed method resulted in a better reliability in estimating the in situ compressive strength, even with a lower number of cores used to obtain the relationships.

1. Introduction

On site concrete strength assessment is a key challenge in many situations, such as: quality control during building construction, that is to establish if employed materials complies with the design requirements; design of repair and/or strengthening measurements; evaluation of residual mechanical properties after the effect of aging or damage on existing structures. The strength assessment is usually carried out by means of destructive tests, namely uniaxial compressive strength (UCS) test on cores extracted from the structure, according to specific technical standard [1]. The core extraction from the structure is expensive, invasive, time consuming and in some situations hard to be performed. Consequently, the cores are usually extracted in a small number, which does not allow the full mapping of the concrete strength levels in the building under investigation.

The use of non-destructive tests or semi-destructive tests (N/SDT) offers a promising alternative to destructive tests (DT), since many N/SDT parameters are sensitive to material strength variations. Several non-destructive and semi-destructive methods are available for evaluating concrete compressive strength and their reliability depends on the degree of correlation between the values of the measured N/SDT parameters and UCS. In principle, manufacturers of devices usually give empirical relationships for their own testing system. Such relationships are not suitable for every kind of concrete and they need to be calibrated for the different mixtures [2]. Each developed model is calibrated for a specific dataset, so that none of them is able to predict the concrete strength with enough accuracy in order to use the assessed value for structural computations [3]. The conclusion is that in practice, it is not

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http://dx.doi.org/10.1016/j.conbuildmat.2017.06.141
0950-0618/

possible to obtain a unique regression function between N/SDT parameters and UCS [4].

The main questioned problem is to account properly for the uncertainty that exists in evaluating in place test results. The quality of the assessment, in fact, depends on the quality of the measurement, the existence of uncontrolled factors, the number of data used for regression analysis and the range of UCS variations [3,5–7].

The approach suggested in most standards and guidelines [8,9] consists of determining a specific relationship (model) between each N/SDT and UCS, for each case study. This requires a sufficient number of direct (UCS on standard cores) and indirect (non-destructive and semi-destructive) tests to be carried out at the same points (test location) of the structures.

The existing model identification approaches can be classified in two main categories: regression approaches, which identify a specific model by using a limited dataset of core strengths and indirect test results, and calibration approaches in which a prior model is modified to obtain the best agreement with an experimental dataset [10]. The EN 13791 standard includes these two approaches, namely: Alternative 1 (A1), which is a regression approach, and Alternative 2 (A2), which is a calibration approach. The efficiency of Alternative 2 is influenced by the choice of the prior model and it has been demonstrated that it is lower than that of Alternative 1 when an high number of cores is available [4,11]. On the other hand, A1 has been criticized for three main reasons [12,13]: high number of cores needed for calibration; incomplete information about the procedure; use of tolerance intervals for establishing the models. Thus, no procedure has yet been agreed upon for the assessment of UCS based on the results of indirect in place tests.

Several works trying to overcome the above mentioned standard limitations and improve correlations have been presented in the literature. Most of them combine several parameters in order to reduce the influence of the measure uncertainties on the models, by using a multivariable analysis [14] as well as advanced statistical techniques such as Bayesian inference analysis [15] and artificial intelligence techniques [16,17]. Some works also investigate the influence of the number of coring points on the reliability of the models [14,18].

In the present paper, we develop a new approach (hereafter indicated as Cross Validation Procedure – CVP) for obtaining reliable correlations between DT and N/SDT aimed at estimating the mean value ($f_{m,is}$) and the characteristic value ($f_{ck,is}$) of the *in-situ* UCS, starting from indirect test results. The method moves from a linear regression analysis of data by means of the least square method, to find a first model between N/SDT and DT results. Then the standard deviation of the prediction errors is accurately estimated by means of a Cross Validation iterative procedure, and it is used to correct the initial model.

The analysis was applied on an existing database and it concerned data obtained from UCS test on cores and from two indirect tests, namely ultrasonic pulse velocity test (UPV) on cores and compressive strength test on microcores (UCS_m). The former is one of the most widely used non-destructive methods to assess UCS [19]. UCS_m is a moderately invasive test, as it requires the extraction of small diameter cores (35 mm diameter) from the structure. Compared with other moderately destructive tests, e.g. the pull out, UCS_m offers the significant advantage of the measurement of the same property investigated, namely the UCS, along with low intrusion [20]. Some linear correlations among compressive strengths measured on cubes and microcores have been established in laboratory conditions [2,20–22] and the present study gives new insights on the possibility of correlation for materials on site.

The reliability of the proposed method in estimating in situ UCS starting from the results of the UPV and UCS_m tests, was evaluated in respect to the A1 approach reported in the standard [8], on the basis of the RMSE and by comparing the estimated values of $f_{m,is}$ and $f_{ck,is}$ with those obtained directly from the cores.

Establishing a minimum number of cores, necessary to have a good UCS estimation from the indirect test results is an important step toward the applicability of the proposed method and this aspect was investigated, too.

2. Assessing the in situ compressive strength according to EN 13791 standard

2.1. The direct method

The direct method refers to the assessment of $f_{ck,is}$ from results of uniaxial compressive strength tests performed on the cores extracted from the structure. According to EN 13791 [8], two different approaches (Approach A and B) may be followed depending on the number of available cores. This standard states that for a specific test region (TR) the UCS assessment shall be based on three cores, at least. TR is defined as "*one or several structural elements, or precast concrete components assumed or known to be from the same population. A test region contains several test locations.*" Test location (TL) is defined as "*a limited area selected for measurements used to estimate one test result, which is to be used in the estimation of in-situ compressive strength*".

The Approach A may be applied when at least 15 cores are available while Approach B is allowed when a number of cores between 3 and 14 is available. In both the approaches the mean value ($f_{m(n),is}$)and the standard deviation (s_n) of in situ UCS results are calculated, according to the procedures reported in 7.3.2 and7.3.3 paragraphs of the Standard [8].

2.2. The indirect method

The indirect method is applied when tests other than compressive strength test on cores (indirect tests) are used to assess in situ UCS. An indirect tests measure a different property than UCS, thus it is necessary to find a relationship (Model) between the results of indirect tests and the compressive strength test on cores. To this purpose EN 13791 proposes two approaches: Alternative 1 (A1) and Alternative 2 (A2). A1 is used when at least 18 core test results are available to establish the Model, while A2 is used when a limited number of cores is available. The Model is valid for a single TR. Once the relationship is established by means of one of the two approaches, EN 13791 prescribes that the assessment of $f_{ck,is}$ for each test region shall be based on at least 15 indirect test results, different from those used to find the Model. $f_{ck,is}$ is then calculated as the lower value between:

$$f_{ck,is} = f_{m(n),is} - 1.48s \tag{1}$$

and

$$f_{ck,is} = f_{is,lowest} + 4 \tag{2}$$

where s is the higher value between the standard deviation of the UCS estimated by the Model and 3 MPa.

Establishing the Model according to the A1 approach described in EN 13791 standard includes some steps. Firstly, a linear regression analysis should be performed on the data pairs obtained in the testing program, considering direct test results (y) as a function of indirect test results (x). The EN 13791 prescribes to compute the tolerance limits (TL) of y, for each individual indirect test observation (x_i). It also recommends to determine "*the relationship as the*