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Nondestructive evaluation of concrete strength: An historical review and a new perspective by combining NDT methods

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ABSTRACT

This paper analyzes why and how nondestructive testing (NDT) measurements can be used in order to assess on site strength of concrete. It is based on (a) an in-depth critical review of existing models, (b) an analysis of experimental data gathered by many authors in laboratory studies as well as on site, (c) the development and analysis of synthetic simulations designed in order to reproduce the main patterns exhibited with real data while better controlling influencing parameters. The key factors influencing the quality of strength estimate are identified. Two NDT techniques (UPV and rebound) are prioritized and many empirical strength-NDT models are analyzed. It is shown that the measurement error has a much larger influence on the quality of estimate than the model error. The key issue of calibration is addressed and a proposal is made in the case of the SonReb combined approach. It is based on the use of a prior double power law model, with only one parameter to identify. The analysis of real datasets from laboratory studies and from real size buildings show that one can reach a root mean square error (RMSE) on strength of about 4 MPa. Synthetic simulations are developed in order to better understand the role played by the strength range and the measurement error. They show that the number of calibration cores can be significantly reduced without deteriorating the quality of assessment. It is also shown that the optimal calibration approach depends on the number of cores.

1. Introduction – the challenge of non-destructive strength assessment

Strength assessment of existing buildings is a key challenge for structural engineers who need to feed structural computations with material data. Such assessment is required in various contexts: (a) when some damage has developed through time, (b) when new requirements have to be addressed, because of changes in regulations or in the loads to be supported, (c) when the material condition must be checked because of some suspicion e.g. when the concrete in control cast cylinders may differ from the concrete in the building itself! In any case, nondestructive testing (NDT) techniques offer an interesting approach, since they give access to material properties while remaining rapid and of moderate cost. The quality of estimation is a key issue since it can impact the decisions regarding maintenance [106]. However, NDT techniques are sensitive first to physical properties and provide only an indirect way towards material mechanical performances [32]. Quantifying a mechanical property like strength is the highest level of requirement for assessment (lower ones being detecting or ranking), since values are expected, even with some range of uncertainties [11].

Much research has been devoted to the development of NDT or of data processing for a better assessment of building materials. Some authors have tried to synthesize the abilities of NDT with respect to given problems [20,114,15] or to define the most promising paths for developments [87]. It is usually agreed that the quality of assessment is limited due to sources of uncertainties arising at various levels and caused: by the testing method, by systematic interferences with the environment, by random interferences (due to material intrinsic variability), by human factor influence and by data interpretation, including errors in the model between what is measured and what is looked for [49,10]. The difficulty to correlate the values of physical NDT measurements with the mechanical properties has been pointed out for a long time.

NDT is currently used in combination with destructive tests (cores) or semi-destructive tests which provide more direct information [53]. Rebound measurement and ultrasonic pulse velocity (UPV) are among the most widely used NDT methods regarding concrete strength assessment [74] and a recent European standard provides a formal solution on how concrete strength can be estimated from in situ testing [36]. However this standard requires at least 15 cores from the site to be used in order to establish a

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calibration curve. This requirement increases the cost of NDT investigation and limits its practical use. The development and validation of a methodology that would lead with an acceptable level of confidence to a reliable strength assessment remains a key issue. A main point is that of "calibration", i.e. that of building and using a reliable relationship between NDT values and strength.

The difficulties encountered with calibration lead to the development of "combined approaches" since a second measurement can enable correction of the influence of some uncontrolled factor(s) on a first measurement. Combined methods were developed first by RILEM (Technical Committees 7 and 43) based on seminal works from Facaoaru [41]. Among the large number of possible combinations the SonReb combination which combines UPV measurements and rebound hammer measurements is the most widely known and used. Since its first developments (thanks to RILEM) in Rumania and Eastern Europe, it has spread in many other countries [22,27,103] and was standardized in China in 2005 [24]. The correlation between NDT measurements and strength is established on a standard concrete mixture. Five influence coefficients are introduced to account for the effect of influencing factors. This limits the practical use of the method. The main advantages of SonReb method remain its easiness and low cost. It can be used on any type of structure and concrete, measurements do not require a high level of expertise and large area can be investigated at a relative high speed.

A common statement is that while neither UPV nor rebound are, when used individually, appropriate to predict an accurate estimation for concrete strength, the use of combined methods produces more trustworthy results that are closer to the true values when compared to the use of the above methods individually. Such a statement is however somehow optimistic since the combined approach leads to contrasted results. It was even said that they have only provided marginal improvements [91]. A large number of relationships have been proposed in order to estimate the strength from a couple of (UPV, rebound) values. It appears that there is not a unique relationship and that calibration remains a key issue, as it is the case for individual methods [14].

However research remains very active, aiming at developing and validating combined approaches. This can be explained by an increasing need for evaluating the condition of existing buildings. It is the case for instance of the seismic retrofitting of public buildings in Italy, where standards were recently modified [17]. According to the Ordinanza P.C.M. n. 3431 [89], a suitable assessment of concrete compressive strength can be obtained by integrating results from destructive tests with those from non-destructive tests having "proved suitability".

This approach is confirmed by the recent D.M. 14/01/2008 "Norme Tecniche per le Costruzioni" which requires that the characterization of mechanical properties of materials in existing structures be obtained from material testing, in addition to available documentation and in situ inspections. Estimate of concrete compressive strength through non-destructive testing (rebound, ultrasonic, combined Sonreb methods) relies upon suitability of correlation formulas. However current formulas have usually been calibrated based on concrete samples that were realized *ad hoc*, thus representative of new concretes and new buildings, i.e. these calibrations are usually not accounting for peculiarities of existing buildings [30]. It is also stated that they are not valid for concrete of poor quality [17].

The general panorama remains complex and confusing. It is difficult:

(a) to draw conclusions on the practical added-value of NDT methods (alone and/or in combination for quantitative on-site strength assessment,
(b) to explain why NDT assessment appears to be effective in some situations and noneffective in other situations,
(c) to understand what could be rules of "good practice" for achieving acceptable results regarding strength assessment.

The purpose of this synthetic paper is to answer these questions. It is based on an extensive literature review in the field of nondestructive strength assessment, concerning both laboratory studies and on site investigations. After an analysis of the involved physical phenomena and of the commonly accepted results, we will try to understand why this problem is complex and why apparently contradictory conclusions have been reached. Advantages and weaknesses of the methods will be analyzed, always keeping in mind that the real aim is on-site assessment and that some patterns, like carbonation, which have no influence in laboratory studies at early age may play a very important role on site, when investigating a 30-year old building. Most of the paper will be focused on UPV and rebound measurements (used individually or in combination – SonReb), when other techniques and combinations could have been discussed (in the following, *V* and *R* respectively denotes the measured values of UPV and rebound). This choice has been made for three reasons: (a) focusing on the most commonly used NDT methods while avoiding a too lengthy paper, (b) the fundamental issues addressed would have been similar for other NDT methods, (c) the main conclusions and proposal would have been similar for other NDT methods. Some other NDT methods will be briefly discussed in order to show the general character of some statements.

Synthetic simulations will be used in order to reproduce the context of NDT and its main patterns. They will highlight the respective weights of the quality of measurements, and of the model error. Two possible approaches for calibration will be compared and a synthetic proposal on how to calibrate NDT results will be undertaken. To conclude, the issue of assessment at the building scale will be shortly addressed, mainly based on recent Italian works [76].

This paper is restricted to the estimation of "average properties", keeping apart some other issues like that of "characteristic strength" assessment which deserves further considerations, combining statistics and analysis of variability. The reader interested in this specific issue is invited to report to recent papers or books [46,80,108].

2. A review of uncertainty and variability in NDT measurements

We will first review why UPV and rebound measurement can provide an efficient means to estimate concrete strength. The quality of estimation may be affected by some errors and uncertainties. Two main causes of uncertainties will be discussed: (a) factors other than strength that may influence the NDT measurement and thus the NDT-strength relationship, (b) the NDT measurement variability and its roots.

Variability can be analyzed at several scales [12]:

– at a very local scale, when measurements are repeated while keeping sensors at a given location the measurement process is not fully repeatable, because of some randomness in the measurement device or data processing and because of the fluctuation of some external influencing factors (e.g. temperature or air humidity),
– at a local scale, when measurements are repeated while moving sensors in a small area where the material is assumed to keep the same properties, some additional variability is induced by: (a) the lack of repeatability of the measurement, e.g. the exact distance between emitter and receiver may fluctuate, (b) the short range material variability, due to its heterogeneity, e.g. the fact that the sensor may be near an aggregate in one case and on cement paste in another case,