Construction and Building Materials 121 (2016) 576–587

Contents lists available at ScienceDirect

Construction and Building Materials

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

Criteria for identifying concrete homogeneous areas for the estimation of in-situ strength in RC buildings

Angelo Masi, Leonardo Chiauzzi *, Vincenzo Manfredi

School of Engineering, University of Basilicata, Potenza, Italy

HIGHLIGHTS

- The estimation of in-situ concrete strength in existing RC structures is crucial.
- The reliability of the most usual NDT and DT methods is discussed.
- Suggestions for sampling and evaluation of test results are provided.
- Possible improvements to current structural codes are proposed.
- An application to a real RC building structure is reported.

ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form 11 April 2016
Accepted 8 June 2016

Keywords:
Existing RC buildings
Structural assessment
Seismic code
In-situ concrete strength
Homogeneous areas

ABSTRACT

The investigation of the structural characteristics (geometry, structural details, materials quality, etc.) is a crucial step in the assessment of existing reinforced concrete (RC) constructions especially after earthquakes, fire or explosions, increase of live loads, etc. Specifically, the investigation of materials quality can also be required for new constructions in the case of non-conformity of the strength obtained from standard test specimens. Therefore the knowledge of the in-situ mechanical properties of constituent materials (concrete and steel) is a key issue in the evaluation of structural capacity. In order to achieve this goal, destructive (DT; e.g., cores) and non-destructive (NDT; e.g., ultrasonic, rebound) test methods are often adopted, either alone or combined. However, insufficient indications are provided in the current European and Italian codes to permit an effective use of these methods, individually or in combination, during in-situ investigation campaigns. To remedy this, this paper proposes some possible improvements to the current standards paying special attention to the identification of the concrete areas with homogeneous properties within the structure using non-destructive tests (rebound index and direct ultrasonic velocity tests). It also, using a duly selected number of destructive test values (i.e., cores), establishes a multivariate relation between NDT and DT data for each homogeneous area, thus also permitting the estimation of concrete strength in the other points where only NDT tests are provided. Suggestions for the application of the proposed procedure, are provided in the report of a real case.

1. Introduction

The knowledge of in-situ material properties is the first step in the assessment process of existing structures and, where needed, in the design of the consequent strengthening intervention. For this reason, there is an increasing need to put sufficiently reliable and inexpensive estimation methods of in-situ material properties at the disposal of technicians and other involved stakeholders.

The first and foremost aspect in the estimation of material properties of reinforced concrete (RC) structures is the determination of in-situ concrete strength, particularly the compressive strength.

The variability of the mechanical properties of concrete within a whole structure can be quite high, as a result of its intrinsic non-homogeneity due to both casting and curing, as well as to some events (e.g., environmental degradation, accidental events) which the structure can be subjected to during its lifetime. Some methods of investigating and processing in-situ data are currently available for the estimation of estimate mechanical properties and, particularly the compressive strength of concrete, mainly based on field works and experimental studies conducted around the world

* Corresponding author.
E-mail address: leonardochiauzzi@hotmail.it (L. Chiauzzi).

http://dx.doi.org/10.1016/j.conbuildmat.2016.06.017
0950-0618/

(e.g. [1], in Europe [2,3], in the United States [4–9], in Italy). With reference to the assessment and retrofitting of existing RC buildings, many design codes (e.g. [10–14]), give rules for the estimation of in-situ concrete strength and its use in the safety verifications of structural members. Specifically, the European [12] and Italian [13,14] codes prescribe that the estimation of in-situ strength has to be mainly based on cores drilled from the structure (destructive test, DT). However, non-destructive tests (NDTs) can effectively supplement coring thus permitting a more economical and representative evaluation of the concrete properties throughout the whole structure under examination. The critical step is to establish reliable relationships between NDT results and actual concrete strength. The approach suggested in most standards and guidelines is to correlate the results of in-situ NDTs carried out at selected locations with the strength of the corresponding cores and, as a result, derive additional strength values from NDT results using the established correlation. Thus, NDTs can significantly reduce the amount of coring needed to appropriately evaluate the concrete strength throughout the entire structure.

In-situ investigations are usually carried out on limited areas of the structure under study and not many destructive and non-destructive test points can be selected to estimate concrete strength. Among the variables affecting the planning of an in-situ survey campaign, the budget requirements and, with regard to core drilling, the need to minimize possible negative effects on the structural capacity during and after the tests [15] have an important role in limiting the extension of the investigation. On the other hand, the number and extension of tests needs to be adequate to obtain a reliable assessment in compliance with the code provisions.

To sum up, an investigation process based on DTs in conjunction with NDTs should follow alternative paths aimed at minimizing the number of DTs while providing an effective solution from both the economical and technical point of view. To this end, performing NDTs and DTs in series rather than in parallel can provide a more effective solution. In other words, NDTs can be preliminarily performed to diffusely "explore" the concrete in the structure, taking into account their ability when used to define the material properties in relative (homogeneity verification). Afterwards, the lowest possible number of DTs can be performed in a targeted manner guided by the identification of the concrete portions where the mechanical properties can be considered sufficiently homogeneous, taking advantage of the processing of NDT results. In such a way the distribution of coring points can be suitably allocated throughout the structure, thus avoiding the necessity to perform an excessive number of cores in some areas of the structure under examination, to the possible detriment of other areas where property variability could require a more accurate survey. Many good practices to select the position of testing points on which extract the cores starting from an analysis of a preliminary campaign of non-destructive measurements are available in literature, particularly using the ultrasonic test ([16,17]) or through a suitable combination between rebound and ultrasonic methods [8].

Particularly in [8] a preliminary execution of NDTs is suggested in order to identify homogeneous areas in terms of concrete properties, thus effectively addressing locations of DTs while limiting their number. On the basis of this idea, the paper provides some suggestions concerning planning of in-situ investigation, number and type of test, location for sampling, etc., based on the expertise derived from several in-situ or laboratory investigations on existing RC structures.

2. Concrete strength estimation: structural code provisions and test methods

The structural evaluation of existing structures, both as built and after a possible intervention, has typically a different degree of uncertainty with respect to the design of new structures. Different sets of material and structural safety factors are therefore required, as well as different analysis procedures, depending on the completeness and reliability of the information at hand. To this purpose, some design codes (e.g. [12–14]) require that a knowledge level (KL) be defined in order to choose the admissible type of analysis and, above all, the appropriate confidence factor (CF) value to be used in the structural evaluation. KL depends on the geometry, structural details and mechanical properties of the constituent materials. Once the mean strength values of the materials through proper in-situ and laboratory tests has been estimated, the CF adjusts these values in order to reflect the confidence in the attained knowledge, thus providing design strength values that should be on the safe side [18]. Three knowledge levels are defined in both the European [12] and Italian Codes [13,14]: limited, normal and full knowledge.

With respect to the material properties, a certain knowledge level can be obtained complementing test results with information derived from the standards at the time of construction, or provided by original design specifications or test reports. When the test results do not confirm such information a higher level of testing is required (e.g. from limited to extended). With regard to cast-in-place concrete, whose properties depend on the current practice of the period and the type of construction, an additional investigation is needed if there is a large discrepancy in the results.

Regarding the use of non-destructive test methods, the European code [12] specifies that: "Use of non-destructive test methods (e.g., Schmidt hammer test, etc.) should be considered; however such tests should not be used in isolation, but only in conjunction with destructive tests (i.e. tests on material samples extracted from the structure)". In the same way, the Italian code [13,14] states that NDTs always need to be used in conjunction with core tests suggesting that some DTs (no more than 50%) can be replaced by a larger number (at least three times) of NDTs, carried out in isolation or in combination, and calibrated with the results of DTs. Also FEMA 356 standards [19] states that "Quantification of concrete strength via ultrasonic or other non-destructive test methods shall not be substituted for core sampling and laboratory testing", further specifying that NDTs "do not yield accurate strength values directly".

The number of material samples (cores) per floor that have to be taken depends on the level of testing. For ordinary situations, the recommended minimum values suggested by [12] are reported in Table 1 and refer to each floor and each type of primary structural element.

In the same way, the EN 13791 standards [20] propose that the number of cores to be taken from one test region (i.e., one o several elements assumed or known to be from the same population, then contained within the same homogeneous area) shall be determined on the basis of the volume of concrete involved and the purpose for the testing of cores [21]. In the Italian code [13,14], the same requirements are recommended, with an added specification which relates the minimum number of cores to the in-plan dimension of the structure: the minimum number refers to floor area up to 300 m^2 and, when the floor area is larger than 300 m^2, it needs to be proportionally increased. Furthermore, to effectively apply

Table 1
Recommended minimum requirements (i.e., minimum number of cores) for different levels of testing given in [12].

Level of testing	For each floor and type of primary element (beam, column, wall)
Limited	One core
Extended	Two cores
Comprehensive	Three cores