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Assessment of concrete degradation in existing structures: a practical procedure

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Abstract. In the assessment of existing RC buildings, the reliable appraisal of the compressive strength of in-situ concrete is a fundamental step. Unfortunately, the data that can be obtained by the available testing methods are typically affected by a high level of uncertainty. Moreover, in order to derive indications about the degradation and ageing of the materials by on site tests, it is necessary to have the proper terms of comparison, that is to say, to know the reference data measured during the construction phases, that are often unavailable when the building is old. In the cases when such a comparison can be done, the in situ strength values typically turn out to be lower than the reference strength values (tests performed on taken samples during the construction). At this point, it is crucial to discern and quantify the specific effect induced by different factors: ageing of the materials; poor quality of the placement, consolidation or cure of the concrete during the construction phases; damage due to drilling. This paper presents a procedure for correlating the destructive compressive tests and non-destructive tests (ultrasonic pulse velocity tests) with the data documenting the compressive strength tested during the construction phases. The research work is aimed at identifying the factors that induce the difference between the in-situ strength and cubes taken from the concrete casting, and providing, so, useful information for the assessment procedure of the building.

Keywords: existing RC buildings; in-situ strength of concrete; compressive strength; seismic assessment; core drilling; structural safety; compaction degree; concrete; ultrasonic pulse velocity method; concrete degradation

1. Introduction

In the last few years, Italian (PCM 2003, C.S.LL.PP. 2008, C.S.LL.PP. 2009) and international (ACI 228 1998, CEN 2005a, CEN 2005b, FEMA 274 1997) technical standards have introduced significant new elements about the seismic assessment of existing buildings. In breaking with the previous regulatory issue is that the execution of experimental tests for the mechanical characterization of in-situ materials is now mandatory, and is actually a founding base of the final judgement, that will bind the whole design of retrofitting interventions. Considering the case of existing RC buildings and the related protocols for the preliminary knowledge, a crucial role is

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played by the investigation of the concrete quality.

The mechanical properties, and in particular the compressive strength, have a decisive influence on the resistance of the structural elements, on the overall structural behaviour and on the durability performance.

As widely reported in the literature, in existing buildings it is quite common to notice a high variability of the concrete quality, not only from one floor to another, but also at the same level or even within the same structural element. Such a randomness is due to various factors, among which, for example, the duration of the exposure to degrading agents or, as in the case of beam elements, the load conditions for anthropic actions and the consequent stress state the stress state for vertical loads (Masi and Vona 2009, Halstead 1969, Bloem 1965). Another factor of uncertainty is related to placing, consolidation, and curing practices that, in older constructions, were often improper and poor (e.g., absence of consolidation by vibration). This can induce a significant strength variation along the height of vertical elements.

According to Italian Ministerial Circular n. 617 of 2 February 2009 (*see §C8A.1.B.3*), measure of the mechanical properties must be performed evaluated by means of destructive tests (DT), consisting "*in the extraction of samples and execution of compression tests up to failure*". These can be integrated with non-destructive tests (NDT) provided that the results are calibrated with data obtained by DT. The standards point out that NDT methods cannot completely replace destructive tests, but can be used to support them in view of the structural investigation, that could not be realistically performed with only a destructive approach. In the literature, there are several studies that propose procedures based on the simultaneous use of destructive and non destructive methods in order to extend the results of DT (Dolce *et al.* 2006, Mikulic *et al.* 1992, Qasrawi 2000, Malhotra 1976). In addition it must be said that often the in-situ strength arising from compression tests are characterized by an evident dispersion of numerical data. When it becomes too large should be made proper corrections. An solution could be to extend the width of the sampling by resorting to data provided by non-destructive tests (instead of increasing the number of drilled cores). This finding is confirmed by the results collected by the authors on several school buildings on regional scale (Fiore *et al.* 2013). It is also worth observing that the in-situ compressive strength of concrete ($R_{c,situ}$) provided by the interpretation of testing on concrete cores is usually lower than the strength (R_{CU}) measured on cast specimen (cubic or cylinder samples) in standard conditions. In particular, the Italian Building Code (C.S.LL.PP. 2008), following the indications of European and International standards (ACI 228 1998, CEN 2005a), considers this situation providing the acceptance criteria of the in-situ concrete strength, specifying that: "*the average value of the in-situ strength (which is defined as the structural resistance) is generally lower than the average values provided by strength test results from standard-cured cast specimens (which is defined as the potential resistance)*", and that "*an acceptable average value of the structural strength should be not lower than 85% of the design value*".

The variation of in-situ concrete strength in structures depends on two main factors: the care and control exercised during the execution (placing, consolidation and curing practices), and the deterioration of the material (Collepardi 2010, Uva *et al.* 2014). The first factor can be usually appraised by comparing the compaction degree of drilled cores and concrete specimens. The second factor is more difficult to determine, but is particularly important, since it allows not only to assess the actual structural condition, but also to foresee the residual life of the building. The possibility of effectively appraising the concrete degradation by means of suitable procedures is also important for the possible implications and relapses that the judgement about the efficiency of the materials involves. In fact, when the in-situ strength is found to significantly disagree with the original design value, indicating that a relevant decay and degradation of the materials has occurred, according to the present Italian standards (C.S.LL.PP. 2008) it is mandatory to perform the safety assessment of the structure than to non-seismic loads (C.S.LL.PP. 2008 - *§ 8.3*). If the safety check is negative "*immediate and mandatory provisions*" must be adopted (C.S.LL.PP. 2009).

In a previous work of the authors (Uva *et al.* 2013) a methodology has been proposed for appraising the effects of the deterioration of the concrete by means of a non-dimensional parameter (called "C_{DD}") dependent on the compaction degree g_c. The aforementioned study was based on the numerical processing of data deriving only from drilled cores. Concrete cores are usually of lower number than to the set of NDT experimental tests generally used in combination with destructive ones to define the mechanical properties of on-site concrete. In order to extend the sampling, in the present paper it is proposed an extension of the previous methodology which allows to exploit also the results of the ND tests. Among these, in the present work, it was chosen to make use of data provided by Ultrasonic Pulse Velocity method, since this method is considered the most suited for the appraisal of the homogeneity of in-situ concrete and is conceptually coherent with the measurement of "compaction degree" of concrete. So, the results provided by destructive testing (cores) and by ultrasonic testing have been combined, following the principles that are usually adopted in the professional practice, where the ultrasonic tests are systematically used to correctly target the program of DTs. Even if ultrasonic measures don't allow to assess of the mechanical features of in-situ concrete, they are a very reliable method for identifying the structural parts that are characterized by homogeneous concrete properties.

In the paper, after presenting the overall state of the art about core drilling and ultrasonic tests, the methodology originally proposed by the authors is summarized, and the proposed extension is then discussed. Finally, the proposed procedure is demonstrated on two case studies (one existing and one new RC building), for the processing and interpretations of test data deriving from drilled concrete cores and ultrasonic tests.

2. Overview of the state of the art

2.1 Core drilling

Core drilling is the most commonly used destructive method for in-situ investigations in RC buildings, since it allows to determine the strength of concrete cores according to a procedure that is very similar to the standard test method for compressive strength of concrete cast specimens. The procedure of drilling cores consists in the extraction of cylindrical specimens ("cores") by means a drilling apparatus rigidly anchored to the member and equipped with a diamond-impregnated drill attached to the core barrel.

The whole procedure is regulated by specific Standards - UNI EN 12390-1, UNI EN 12390-3, UNI EN 12504-1 (2009). The drilling phase is very delicate: the drilling apparatus should be rigidly anchored to the member to avoid wobble, which could damage the cross section of the core.

With regard to the test procedure and to the numerical elaboration of the results, a fundamental reference is represented by the American Standards ACI 214.4R-03 (1998), ASTM C42-90 (1992), and by the British Standards B.S. n.1881 (1983). In these documents, it is defined the "*reference*" value for the core strength, which should be measured on a standard specimen characterized by the following slenderness

$$\lambda = \frac{H}{D} = \frac{200mm}{100mm} = 2 \tag{1}$$

where *H* and *D* respectively are the height and the diameter of the cylindrical core.

Actually, it is also possible to use specimens having a non standard slenderness, provided that the corresponding strength ($f_{c,nst}$) is properly corrected, deriving the strength of the "equivalent" standard specimen ($f_{c,st}$), as follows

$$f_{c,st} = F_{H/D} F_{dia} F_r f_{c,nst} \tag{2}$$

The coefficients $F_{H/D}$, F_{dia} and F_r are introduced in order to correct the strength value, respectively, with regard to the variation of λ, D and to the presence of embedded reinforcements.

In the 1927 edition of ASTM C42 was already known that the parameter λ has a significant influence on the ultimate strength of a core specimen. Actually, in the presence of a slenderness close to 1, the collapse load is very high, thanks to the reduced lateral dilation occurring during the test (Newman and Lachance 1964), whereas for standard slenderness ratios ($\lambda=2$) the loading carrying capacity is much smaller (ASTM C42-90 1992), and the dispersion of the results is also very limited (Murdock and Kesler 1957). Core specimens with a small diameter are also often used in this field, because they are easy to handle, store, and allow to limit invasive drilling on structural elements, thanks to the small diameter of the perforation (Bartlett and MacGregor 1994a). Besides, in the case of thin structural members, this is the only way to obtain a standard slenderness ratio λ=2 even with a small height of the core (e.g., λ=150 mm/75 mm or λ=100 mm/50 mm). In the technical literature, the issue of the representativeness of small diameter cores with respect to the strength $f_{c,nst}$ has been widely investigated, but a variety of conflicting opinions is actually present. According to some authors, the dimension of the diameter has no influence on the compressive strength of the specimen (Meininger 1968, Lewis 1976), whereas in other research studies it has been demonstrated that the strength measured on small cores is lower than the one referred to standard diameters (D=100 mm) (Campbell and Tobin 1967). Since 1992, the ASTM C42 has established that only standard diameters can be adopted.

In the case in which reinforcement pieces are embedded in the drilled core, the value of the strength should be corrected by a factor F_r, which varies according to the number of embedded rebars. A research study performed by Loo *et al*. (1989) has shown that the effects induced by the embedded steel bars can be neglected (F_r=1) for cores of small diameter.

Another important aspect to be considered is the curing practice, which has important relapses on the final value of the strength (Bartlett and MacGregor 1994c). A common practice is to immerse the samples in water for at least 40 hours before performing the compressive test, with the aim to obtain an uniform moisture degree for all the specimens. In a first version of the Standards ASTM C42 (dating back to 1927), specific correction coefficients were proposed in order to account for the variation of the moisture degree. Several experimental research studies have then definitely demonstrated that compressive strength is considerably different when specimens are immersed in water before the test: Bloem (1968), Meininger *et al*. (1977) have shown, for example, that the compressive tests performed on cores cured by air drying provide values 10-20% higher than those carried out on soaked cores. The actual value of *in-situ* strength of concrete, at last, is different than the standard strength according to the following relationship

$$f_{c,situ} = F_{mc} F_d f_{c,st} \tag{3}$$

where the coefficients F_{mc} and F_d, take account, respectively, for the curing practices and for the damage due to drilling during the extraction (they are usually called "passive" factors).

The American Standards ACI 214.4R-03, in according to the standards ASTM C42-90 and Fema 274, proposed a correction coefficient for the damage due to drilling constant and equal to *1.06*. This numerical value guarantees a good matching with experimental tests by the relationship (measured in inches) of Bartlett and MacGregor (1994a)

$$F_d = \left(1 - \frac{0.2265}{D}\right)^{-1} \tag{4}$$

Bloem (1968) has tested a set of cores extracted from concrete slabs and a set of standard cylindrical specimens. He showed that the average strength of the first set is 1.074 times higher than the second set. In a similar research study, instead, Campbell and Tobin (1967) compared the set of drilled cores with diameter D=150 mm and the standard set of cylindrical specimens. They obtained the average cylinder strength 1.045 times the average core strength, which again is in close agreement with the value of 1.039 predicted using the Eq. (4). Both the researches showed results near to value of 1.06 suggested by the standards.

In the previous parts it has been highlighted that the in-situ concrete strength is highly variable depending on a number of different factors, which can be related to intrinsic features of the drilled cores (slenderness ratio, diameter, presence of inclusions, etc.), or can be induced by external elements (preparation and curing of the specimens, disturbance due to drilling). The effects of these factors are taken into account through coefficients contained in the Eqs. (2)-(3). Several formulations have been proposed in the literature in order to correct the strength of concrete core (f_{core}) on the basis of all mentioned factors

In the present research work, and in particular in the case study discussed in *§* 4, we will refer to the formulation proposed by Masi and Chiauzzi (2013), which has a conceptual framework similar to FEMA 274 and based on the indications provided by the research studies of Bartlett &MacGregor (1994a, 1994b), that is here summarized

$$R_{c,situ} = \left(C_{H/D} C_{dia} C_r C_d f_{core}\right) \frac{1}{0.83} \tag{5}$$

for assessment the in-situ concrete strength ($R_{c,situ}$) with the following meaning of the correction coefficients:

• $C_{H/D}$ corrects the results if the slenderness λ is different from 2

$$C_{H/D} = \frac{2}{\left(1.5 + \frac{D}{H}\right)} \tag{6}$$

• C_{dia} takes into account of the diameter D of the core and its effects on the strength value. It is equivalent to the parameter F_{dia} provided in Fema274 and it assumes values 1.06, 1.00 and 0.98, respectively, for diameters of 50 mm, 100 mm and 150 mm;

• C_r takes into account of the possible presence of reinforcement bars into the core sample. It is equal to 1 if no bar is present, whereas varies from 1.03 for small diameters (ϕ10) to 1.13 for large diameters (ϕ20);

• C_d takes into account of the disturbance induced by drilling. The author suggests to assume a value equal to 1.20 for f_{core}<20 MPa and 1.10 for f_{core}>20 MPa (Collepardi 2010).

2.2 Ultrasonic pulse velocity method

The Ultrasonic Pulse Velocity (UPV) method is very reliable for assessing the homogeneity of

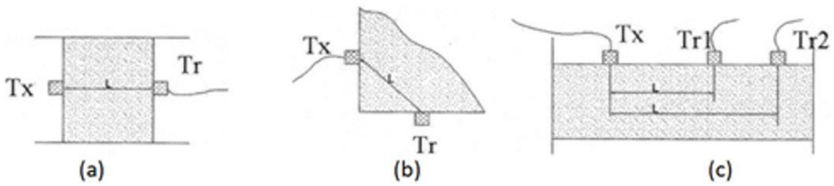

Fig. 1 Different arrangements of the transducers in the Ultrasonic Pulse Velocity method. (a) direct transmission. (b) semi-direct transmission. (c) indirect transmission.

the in-situ concrete and appraise the possible presence of internal cracking. The use of ultrasonic measures as a Non Destructive Method is regulated by ACI 228 (1998), ASTM C597 (2002), UNI EN 12504-4 (2009).

The method consists in placing one or more pairs of transducers at a given distance on the surfaces of the structural element and measuring the time taken by the ultrasonic pulse to pass from the transmitter to the receiver, in order to derive the velocity of propagation of the impulse through the material (V_{us}). The measure can be made in different ways, depending on the relative position of the transducers (see Fig. 1): direct transmission (Fig 1(a), the two transducers are placed on opposite faces); semi-direct transmission (Fig. 1(b), the two transducers are placed on adjacent faces); indirect transmission (Fig. 1(c)), the two transducers are placed on the same face). The higher reliability is provided by the “direct” test set-up.

The factors that most influence the measurements are (Trtnik *et al.* 2009, Sturrup *et al.* 1984):

• *size of the aggregates*: the presence of large diameters in the granulometry of the concrete mixture increases the pulse velocity although the concrete strength is constant;

• *water / cement ratio (a/c)*: for lower values of *a/c* the compressive strength $for\ asse_{,situ}$ significantly increases, whereas the velocity V_{us} remains substantially constant;

• *age of the concrete*: in the ideal situation strength increases with time, whereas the ultrasonic pulse velocity is inversely proportional to the age;

• *moisture content*: it has been experimentally shown that the pulse velocity increases with the moisture content (ASTM C 597-022 2002);

• *actual stress state of the structural element*: for stresses greater than 50% the collapse values, the pulse velocity becomes lower, because of the triggering of internal micro-cracking;

• *presence of reinforcements*: considering that the pulse velocity within the steel is approximately 40% higher than that of concrete, in strongly reinforced elements, the apparent velocity V_{us} can be much greater than the real one.

As for core drilling, also for the ultrasonic pulse velocity method different formulations have been proposed in the literature for determining the in-situ concrete strength ($R_{c,situ}$) from the value of the ultrasonic pulse velocity V_{us}. The present research work does not provide the direct assessment of in-situ strength of concrete on the basis of V_{us} (actually, a proposal for the correlation of ultrasonic pulse velocity and compaction degree, aimed at the appraisal of the degradation of in-situ concrete, will be presented). It should be noted that many manufacturers have developed correlation curves of the type $R_{c,situ}=R_{c,situ}(V_{us})$, which are provided as a complement of the ultrasonic devices. Anyway, these kind of diagrams, that are obtained for very specific types of concrete, are only an approximate indication of an “ideal” trend of the concrete strength as a function of the ultrasonic pulse velocity, and do not have any general validity.

3. Methodology for assessing the reliability of the measures of in-situ strength of concrete

3.1 The compaction degree g_c

In buildings built with ordinary concrete (excluding self-compacting concrete) the “structural resistance” (i.e., the strength determined on drilled cores) is always lower than the strength obtained from cubic or cylindrical specimens of the concrete casting. This means that, by denoting with R_{CU} the mechanical strength of a cubic specimen and with R_{CI} the mechanical strength of a cylindrical specimen, the following relation will hold

$$0.83R_{CU} = R_{CI} \geq f_{core} \tag{7}$$

The difference can be ascribed, first of all, to the various factors related to the extraction operations (as described in § 2.1), but above all to the imperfect compaction reached by the in-situ concrete, whereas the specimens which are prepared during the concrete casting for quality control are fully compacted. The correlation between R_{CI} and f_{core} is strictly dependant on the care taken during the execution phases of the RC elements (placing, consolidation, and curing practices), that can be quantified by the “*degree of compaction”* g_c (Collepardi 2010)

$$g_c = \frac{m_V}{m_{VO}} \tag{8}$$

where m_{V0} is the density of the cast specimen and m_V the density of the drilled core.

If during the execution phases of a generic structure the concrete has been compacted with the same care of the concrete of the cast specimens, the compaction degree will have a unit value: g_c=1. If the compaction of the in-situ concrete is not so effective as that of the cast specimen, the density m_V will be lower than m_{V0}, and it will result g_c<1. In his research studies, Collepardi has carried out several experimental tests on different classes of concrete mixtures, obtaining the correlation between g_c and the percentage loss of the mechanical strength (ΔR_g) that is observed for the real structure, if compared with the corresponding cast specimen

$$\Delta R_{\text{g}} = \frac{R_{CI} - f_{core}}{R_{CI}} 100 \cong \frac{R_{CU} - R_{c,situ}}{R_{CU}} 100 \cong (1 - g_c)500 \tag{9}$$

The third member of Eq. (9) represents a linear relationship between ΔR_g and g_c (Fig. 2), and is valid in the range 0.90<g_c<1. In the figure, the shaded rectangle points out the field corresponding to the usual structural concrete classes.

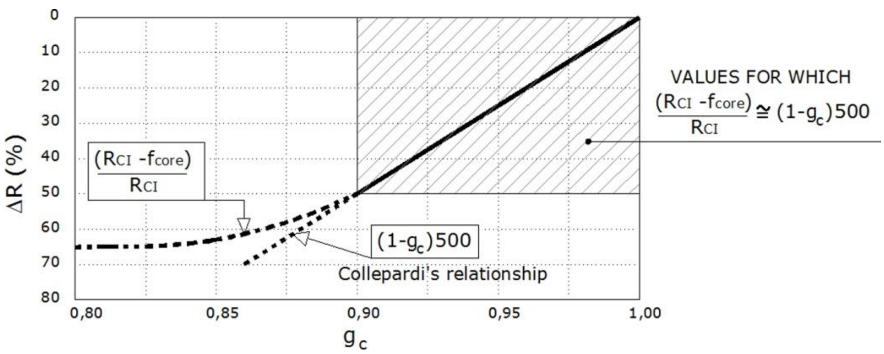

Fig. 2 Influence of the compaction degree g_c over the strength reduction R_g

The following paragraph presents a summary of a specific methodology developed by the authors in a previous research work (Uva *et al.* 2013), in which the percentage decrease of the mechanical strength (ΔR_g) of the cores (related to the combined effect of ageing and alteration due to drilling and manipulation) was evaluated as a function of the compaction degree g_c.

3.2 A methodology for the appraisal of degradation and disturbance effects induced by drilling

Let us suppose that for a given structure a population of samples constituted by concrete cores and cubic specimens prepared during the execution phases is available. Then, the methodology is based on the following assumptions:

"*In the ideal situation in which the variations related to age and different curing conditions are negligible, and supposing that no damage has occurred in the extraction of the cores (C_d=F_d=1), the value of $R_{c,situ}$ derived as a function of f_{core} (by any of the usually accepted formulations) will usually show a divergence from the ideal correlation (§ 3.1 - Fig. 2) that describes how the structural strength varies with the decrease of compaction. Such a disagreement is the effect of the concrete degradation and of the damage actually suffered by the samples during the extraction*".

In order to obtain the value of $R_{c,situ}$ to be used in the numerical application presented in § 4, the formulation proposed by Masi and Chiauzzi (2013) has been adopted. On the basis of Eq. (9), thence, for the generic set of samples the percentage variation of the strength $\Delta R_{gDR}(\%)$ from the ideal correlation $\Delta R_g(\%)$ is given by

$$\Delta R_{gDR}^{(i)}(\%) = \frac{R_{CU}^{max} - R_{c,situ}^{(i)}}{R_{CU}^{max}} 100 \tag{10}$$

where, for the set of the *n* strength values (including *K* cores and *P* cast cubes):

- R_{CU}^{max} is the maximum of the strength values of the *P* cubes;
- $R_{c,situ}^{(i)}$ is the in-situ strength of the *i-th* core;

In Fig. 3 the graphical representation of the methodology is shown, with the following meaning of symbols:

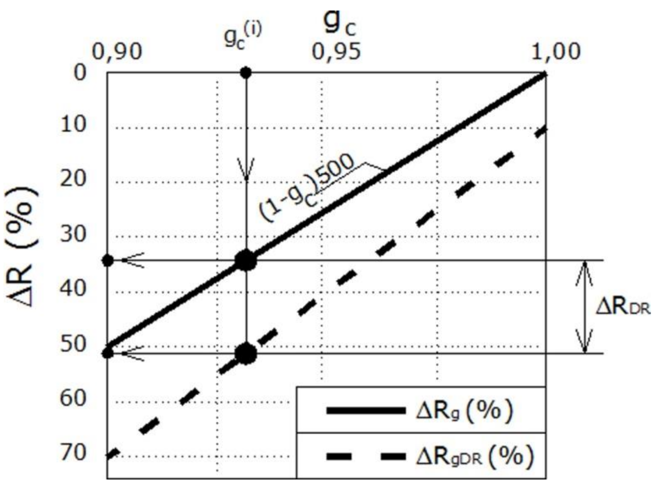

Fig. 3 Graphical representation of the methodology (Uva *et al.* 2013).

• ΔR_g is the linear trend of the strength reduction related to the compaction degree of the concrete, obtained by applying Eq. (9) on the whole set of samples;

• ΔR_{gDR} is the linear trend of the overall strength reduction related to the compaction, the degradation of concrete, the disturbance induced by drilling and manipulation. The numerical value is obtained by Eq. (10), by neglecting in the calculation of $R_{c,situ}$ the effects of drilling on the concrete cores (C_d=f_d=1).

The procedure can be applied only to the samples characterized by a value of the compaction degree comprised within the range 0.90<g_c<1, interval in which the function ΔR_g is linear in g_c. The specimens characterized by g_c<0.90 shall be excluded by the sampling in order to apply the described methodology. On the other hand, it is worth observing that values of the compaction degree lower than 0.90 correspond to a reduction of the in-situ strength higher than 50%, if compared to the values of the cubes. Such an anomalous reduction of the strength, apart from any other consideration about the applicability of the proposed methodology, is surely the clear sign of a very poor quality of the execution, or of a severe alteration and damage of the materials. For the generic value of compaction degree $g_c^{(i)}$ can be determined the reduction of the in-situ strength due to the degradation of the material, the placing, the consolidation and curing practices (ΔR_{gD}). The numerical value can be obtained by Eq. (10) in which the disturbance effects are included in the calculation of $R_{c,situ}$ (C_d or f_d >1). Trend of ΔR_{gD} is intermediate between trends of ΔR_g and ΔR_{gDR} .

4. A proposal for the correlation of ultrasonic pulse velocity and compaction degree for appraisal of the degradation of in-situ concrete

It will be now presented an extension of the procedure discussed in the previous paragraph. This extension provides the inclusion of the results of UPV tests, and, therefore, it will be first of all necessary to properly integrate the database. More in detail, considering a generic set *"C"* of samples, composed by *P* cast cubes, *K* cores, *U* ultrasonic tests executed on the structural elements, the extended procedure is based on the following assumptions:
"*Let us consider an ideal situation in which the curing conditions and age are the same both for the cast specimens and for the drilled cores. Let us then consider the set - RC -* composed by all in-situ strength values (*derived as a function of f_{core} by means of any of the usually accepted formulations, including the effects of disturbance C_d and F_d>1 and correlating the ultrasonic pulse velocities with the information related to core tests). A difference ΔR_D (=ΔR_{gD}–ΔR_g) will result with respect to the ideal correlation ΔR_g* (§ 3.1 - Fig. 2) *that describes how the structural strength varies with the decrease of compaction. Such a disagreement is the effect of the degradation of the concrete and of the damage actually suffered by the samples during the extraction*".
More in detail, for the elements of the subsets "*P*", "*K*", "*U*" belonging to the set "*C*", the following data are required:

• *Subset "P"*: strength values (R_{CU}) and volume masses (m_{V0}) of the *P* cubic specimens prepared during the construction phases;

• *Subset "K"*: strength values (f_{core}), ultrasonic velocities (V_{core}) and volume masses of the *K* drilled cores;

• *Subset "U"*: ultrasonic velocities (V_{us}) measured on the structural elements by UPV method.

Below the basic steps of the procedure:

<u>Step N.1</u>: Evaluation of the compaction degree $g_c^{(i)}$ for each element of the subset "*K*".

$$g_c^{(i)} = \frac{m_V^{(i)}}{m_{V0}^{max}} \tag{11}$$

where m_{V0}^{max} indicates the maximum of the volume masses of the "*P*" samples.

Step N.2: Evaluation of the in-situ concrete strength ($R_{c,situ}$) of each element of the subset "*K*".

The in-situ concrete strength is calculated as a function of f_{core}, according to any of the usually accepted formulations (for example, ACI 228 1998, Masi and Chiauzzi 2013, Fema 274 1997). In the present proposal, it was chosen to consider, in the elaboration of f_{core}, the effects of the disturbance due to the drilling and manipulation of the cores. For these reasons, it was adopted the formulation expressed by Eq. (5). In addition, some hypotheses about the initial conditions of the drilled cores have been made. In particular, homogeneous dimensional characteristics have been assumed for all the cores (diameter d=100 mm; slenderness λ=2d), supposing that there are no embedded reinforcements. Under these conditions, the correction factors provided by Eq. (5) ($C_{H/D}$, C_{dia}; C_r) are all equal to 1, and $R_{c,situ}$, that is exclusively influenced by the disturbance due to drilling and manipulation of the samples, can be expressed by the following simplified relationship

$$R_{c,situ}^{(i)} = C_d f_{core} \frac{1}{0.83} \tag{12}$$

Step N.3: Numerical Correlation between destructive tests and UPV tests with exponential regression.

It is necessary to define some analytical relationships for estimating the values of the compaction degree ($g_{c,us}$) and of the strength ($R_{c,us}$) in correspondence of each value of the ultrasonic pulse velocity obtained from the tests. This has been made by defining the correlation between destructive tests and UPV tests performed on the concrete cores, through an exponential regression, according to the following expressions

$$GC = a_1 {b_1}^{VC} \tag{13}$$

$$RCS = a_2 {b_2}^{VC} \tag{14}$$

where:

- GC={$g_c^{(1)}$;... ...; $g_c^{(k)}$} is the set composed by the compaction degree values of the cores;
- RCS={$R_{c,situ}^{(1)}$;... ...;$R_{c,situ}^{(k)}$} is the set composed by the in-situ strength values (calculated by processing f_{core});
- VC={$V_{core}^{(1)}$;... ...; $V_{core}^{(k)}$} is the set composed by the ultrasonic pulse velocities measured on the cores.

Step N.4: Evaluation of compaction degrees and concrete strength for elements of the subset "U".

The extension of the original procedure (described in § 3.2), in order to increase the initial sampling with data derived by non destructive UPV tests, involves the correlation of the basic information about the cores (g_c, $R_{c,situ}$) with the pulse velocity V_{core}. At this point, by using the dimensionless parameters of the exponential regression (a_i , b_i) calculated by Eqs. (13) and (14), for each velocity V_{us} of the subset "*U*", $g_{c,us}$ and $R_{c,us}$ are determined

$$GCU = a_1 {b_1}^{VU} \tag{15}$$

$$RCU = a_2 {b_2}^{VU} \tag{16}$$

where:

• $GCU=\{g_c^{(1)};\ldots\ \ldots;\ g_c^{(U)}\}$ is the set including the cores' compaction degree values associated to the ultrasonic pulse velocities measured on the structural elements;

• $RCU=\{R_{c,us}^{(1)};\ldots\ \ldots;R_{c,us}^{(U)}\}$ is the set including the in-situ strength values associated to the ultrasonic pulse velocities measured on the structural elements;

• $VU=\{V_{us}^{(1)};\ldots\ \ldots;\ V_{us}^{(U)}\}$ is the set including all the ultrasonic pulse velocities measured on the structural elements (subset "U");

Step N. 5: Assessment of the percentage reductions of the concrete strength due, respectively, to compaction degree (ΔRG) and the combined effects of compaction degree and degradation ($\Delta RGD=\{(\Delta R_{gD}^{(1)};\ \ldots\ \ldots;\ (\Delta R_{gD}^{(k+U)}\}$).

ΔRG is determined by applying Eq. (9). ΔRGD is obtained by applying, for each i-th element belonging the set "$K+U$", the following formulation, that represents the extension of Eq. (10) defined in § 3.2

$$\Delta RGD(\%) = \frac{R_{CU}^{max} - RC}{R_{CU}^{max}} 100 \tag{17}$$

with,

• $RC=\{R_{c,us}^{(1)};\ \ldots\ \ldots;R_{c,us}^{(U)};\ R_{c,situ}^{(1)};\ \ldots\ \ldots;R_{c,situ}^{(k)}\}$ is the set including the strength values calculated by Eq. (16);

• R_{CU}^{max} , already defined in Eq. (10), is the maximum of the strength values of the P cubes;

The strength loss of the in-situ concrete, if compared to the cast samples, is finally provided by the following expression

$$\Delta RD(\%) = \Delta RGD(\%) - \Delta RG(\%) \tag{18}$$

with ΔRG (%) is the percentage loss of the mechanical concrete strength evaluated by linear relationship between ΔR_g and g_c (Fig. 2 and Eq. (9)).

The graphical outline reported in Fig. 4 can certainly help in understanding the entire procedure and its sequence of steps.

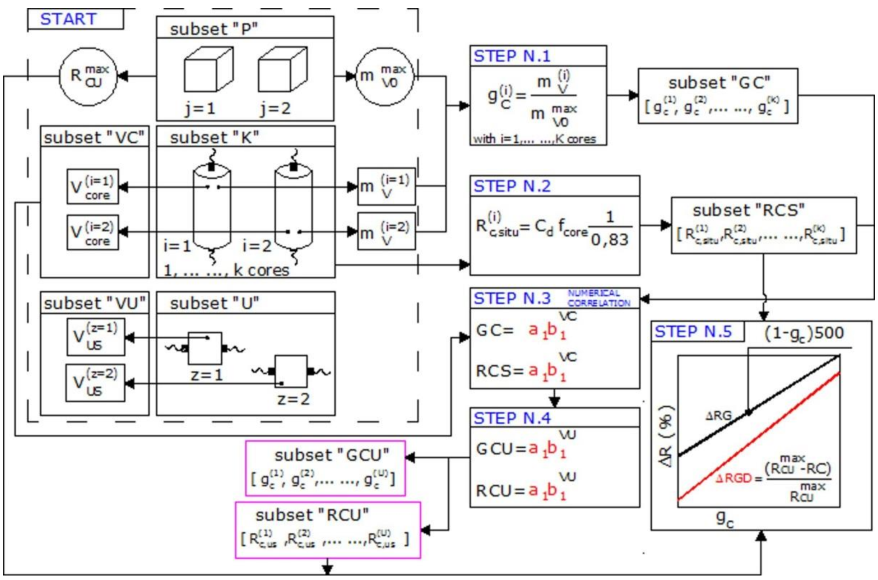

Fig. 4 Graphical representation of the methodology proposed in this work

5. Two case studies

The procedure described in § 4 has been applied on two case studies (respectively consisting in an existing RC building and a new construction) for which an extended sampling was available, including concrete cores drilled from the structural elements, cast cubic specimens prepared during the execution phases and Ultrasonic Pulse Velocity tests. In the following paragraphs, the 2 case studies will be denoted as "*Case study #* 1" and "*Case study #* 2".

5.1 Case study #1

The first case study is an existing strategic RC building dated back to the second half of '80s, for which the experimental investigation about the quality of concrete had been carried out. The database includes the original quality inspection certificates of the concrete (results of the compressive tests for 8 cubic specimens - 150 mm×150 mm). Information is then completed by the results of destructive tests (5 samples extracted by core drilling) and by the results of UPV tests (15 ultrasonic measures). The data set used as the basis for the application of the proposed procedure is summarized in Table 1.

Consistently with the assumptions of the methodology, all the concrete cores had no embedded reinforcement; their slenderness was λ=2, and the curing conditions were the same of the cast cubic specimens (150 mm×150 mm*)*. The measurement of the ultrasonic pulse velocity on the structural elements was made by direct transmission (Fig. 1(a)). For the calculation of the different values of the compaction degree, according to Eq. (11), the reference max volume mass is that of the sample *P8*.

The processing of the values f_{core} has been made by applying Eq. (12) in two distinct situations: with or without considering the alteration induced by the drilling operations (hereafter, the two

Table 1 Database of the Case study #1.

Cores				Cast cubes		UPV	
Label	f_{core} [MPa]	g_c	V_{core} [m/s]	Label	R_c [Mpa]	Label	V_{us} [m/s]
K1	11.96	0.969	3862	P1	30.50	U1	3808
K2	15.75	0.961	3873	P2	33.00	U2	3770
K3	11.31	0.958	3473	P3	35.50	U3	3655
K4	13.30	0.919	3417	P4	37.00	U4	3780
K5	22.28	0.958	3818	P5	30.00	U5	3724
				P6	29.00	U6	3330
				P7	34.00	U7	3267
				P8	30.50	U8	3340
						U9	2609
						U10	3209
						U11	3623
						U12	3613
						U13	3474
						U14	3716
						U15	3429

Table 2 Case study #1: set of values of the compaction degree (GCU) and set of values of in-situ strength RCU ^{r} and RCU ^{nr} correlated to the ultrasonic tests.

Label	GCU	RCU ^{r} [MPa]	RCU ^{nr} [MPa]
U1	0.961	21.83	18.63
U2	0.958	21.41	18.24
U3	0.951	20.19	17.09
U4	0.959	21.52	18.34
U5	0.955	20.90	17.76
U6	0.930	17.08	14.19
U7	0.926	16.54	13.69
U8	0.930	17.16	14.27
U9	0.884	11.78	9.40
U10	0.922	16.05	13.24
U11	0.949	19.85	16.77
U12	0.922	16.08	13.27
U13	0.939	18.39	15.41
U14	0.955	20.83	17.69
U15	0.936	17.97	15.01

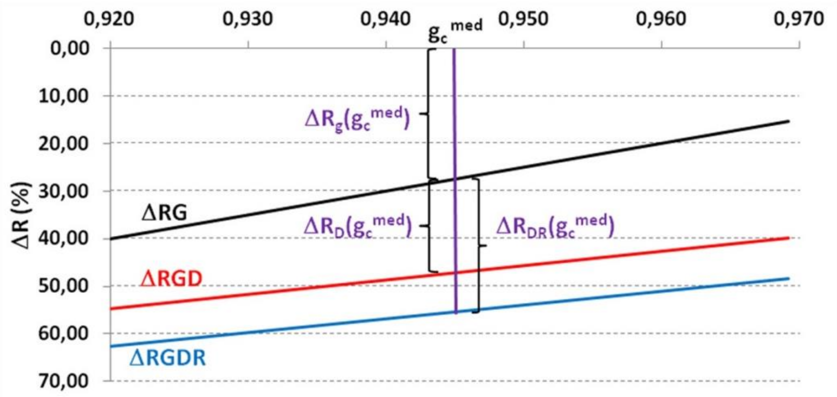

Fig. 5 *Case study #1*: Percentage reduction of the structural strength of in-situ concrete with respect to the strength of cast cubes, as a function of the compaction degree g_c. Comparison among strength loss ΔRG related to imperfect compaction (black line), strength loss ΔRGD related to imperfect compaction and degradation (red line), strength loss $\Delta RGDR$ related to imperfect compaction, degradation and disturbance due to drilling (blue line)

cases will be referred to with the superscripts "*r*" and "*nr*"). With regard to the ultrasonic pulse velocities V_{us}, they have been correlated with the values of the compaction degree and with the in-situ compressive strength values of the *K* concrete cores. The corresponding results (compaction degree $g_{c,us}^{(i)}$, strength values with or without disturbance due to drilling - $R_{c,us}^{(i),r}$ and $R_{c,us}^{(i),nr}$), obtained according to Eq. (15) and Eq. (16) (see the procedure described in § 4), are presented in Table 2.

In correspondence of the ultrasonic pulse velocity measured on the sample U9, the compaction degree assumed the value $g_{c,us}^{(9)}<0.90$, which, according to the acceptance criteria imposed by the

Table 3 Case study #1: values of R_g(%), R_D(%) and R_{DR}(%) corresponding to a minimum, medium and maximum compaction degree

g_c		$R_g^{(i)}$ (%)	$R_D^{(i)}$ (%)	$R_{DR}^{(i)}$ (%)
min.	0.919	40.45	14.62	22.43
med.	0.945	27.43	19.80	27.98
max.	0.969	15.40	24.58	33.09

methodology (§ 3.2), is not acceptable and was then excluded by the sampling. At this point, Eq. (17) has been applied in the two cases of presence/absence of disturbance due to extraction (i.e., the values of $R_{c,situ}$ corresponding to the K concrete cores have been respectively calculated by assuming C_d>1 and C_d=1). In Fig. 5, for the case study#1, the graphical representation of the proposed methodology is shown.

Considering that it was initially supposed that the two set of samples (drilled cores/cubic specimens) were homogeneous and equivalently cured, the differences encountered can be ascribed to two different causes (which can occur separately or in combination). The first cause is related to the possible deterioration undergone (by the materials during the service life of the structure, the second is related to the damage due to the drilling and manipulation of the samples. By referring to the indications provided by (Masi and Chiauzzi 2013) about the disturbance induced by the extraction of the cores (see § 2.1) the strength loss related to the combined presence of imperfect compaction and degradation is represented in Fig. 5 by the line ΔRGD. In the presence of disturbance effects due to drilling, as it could be expected, the relationship is provided by the blue line $\Delta RGDR$.

The percentage reductions graphically shown in the figure (in which are marked reductions in correspondence with the medium compaction degree g_c^{med}) are also summarized in Table 3: $\Delta R_g^{(i)}$ is the i-th strength loss related to imperfect compaction, $\Delta R_D^{(i)}$ is i-th the further loss related to degradation, $\Delta R_{DR}^{(i)}$ is i-th the strength loss related to the combined effect of degradation and disturbance due to drilling.

It should be remarked that ΔR_D is proportional to the compaction degree g_c, whereas the strength loss ΔR_g related to the imperfect compaction, as expected, is inversely proportional to g_c. Consequently, higher values of the strength loss related to degradation are encountered in correspondence of the better quality of the execution. It can be seen that ΔR_D increases of about 10% passing from the minimum to the maximum compaction degree.

The disturbance effects due to drilling (ΔR_R), expressed as

$$\Delta R_R(\%) = \Delta R_{DR}(\%) - \Delta R_D(\%) \tag{19}$$

have a percentage incidence of 7.81%, 8.18% and 8.51% in correspondence of the minimum, medium and maximum compaction degree. On average, in the Case study #1, drilling operations have induced on the cores a percentage strength reduction equal to 8.16%, with respect to the strength of the cast specimens.

5.2 Case study #2

The data of the second case study are relative to a new RC construction (a strategic building). Because of some problems arisen about the quality controls during the construction phases, in

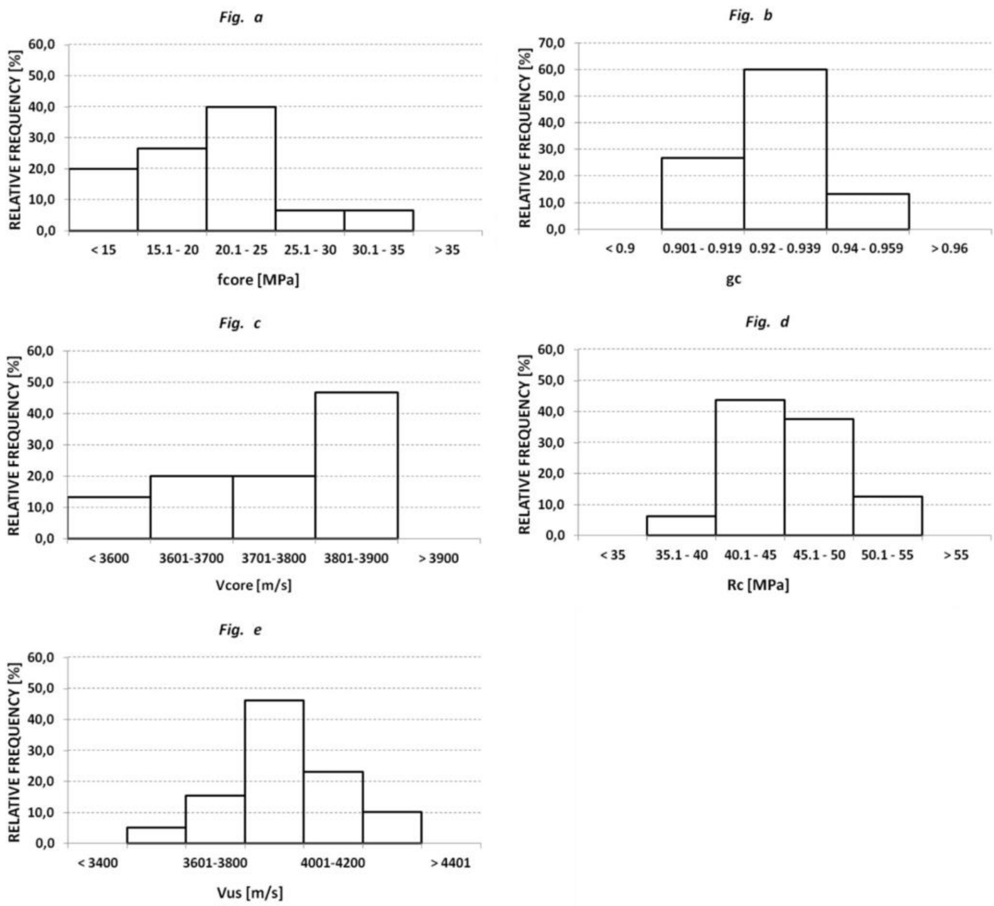

Fig. 6 Database of the case study #2 in terms of Relative Frequencies. (a-b-c) The data of cores. (d) The data of cast cubes. (e) The data of UPV

addition to the cubic specimens (150 mm×150 mm), a wide program of destructive and non destructive tests (including Ultrasonic Pulse Velocity) was carried out on the structural elements. It should be remarked that in this case, considering the two short time interval between quality inspections and core drilling, the two types of samples – cast concrete cubes and drilled concrete cores – are homogeneous and have the same age. In analogy with the previous case, the cores have no embedded reinforcements, the slenderness ratio is $\lambda=2$, and they were kept in environmental conditions comparable to those of the extraction. While, in contrast to the case study #1, since the data are very numerous, each variable is represented by the distribution of relative frequencies (Fig. 6).

For the correct application of the methodology, as for the Case study #1, the cores having a compaction degree <0.9 have been discarded. As for the first case study, the processing of the values f_{core} has been made by applying Eq. (12) in two distinct situations: with or without considering the alteration induced by the drilling operations. With regard to the set of ultrasonic pulse velocities *VU*, the exponential regression has been made according to Eqs. (15)-(16), obtaining the values of the compaction degree *GCU* and of the strength $RCU^{\ r}$ and $RCU^{\ nr}$

(respectively expressed in terms of relative frequency in Figs. 7(a)-(b)-(c). Eq. (17) has been applied in the two cases of presence/absence of disturbance due to extraction (i.e., the values of $R_{c,situ}$ corresponding to the concrete cores has been calculated by respectively assuming $C_d>1$ and $C_d=1$).

In Fig. 8, for the case study #2, the graphical representation of the proposed methodology is shown.

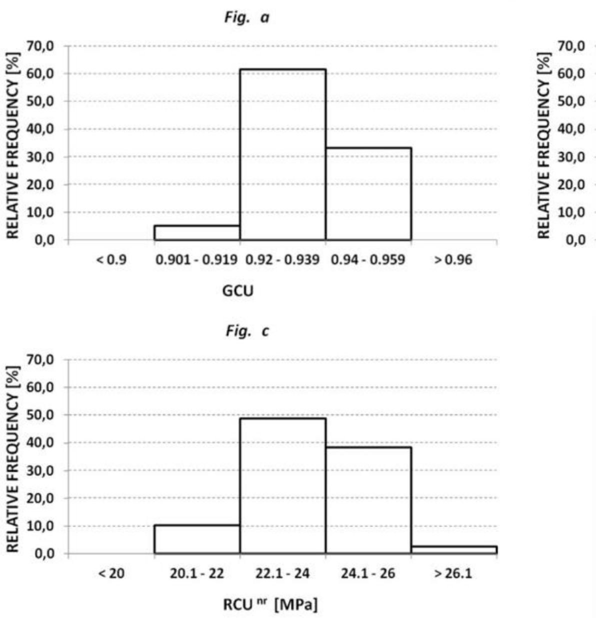

Fig. 7 Case study #2: values of the compaction degree (GCU) and values of in-situ strength RCU^{r} and RCU^{nr} correlated to the ultrasonic tests

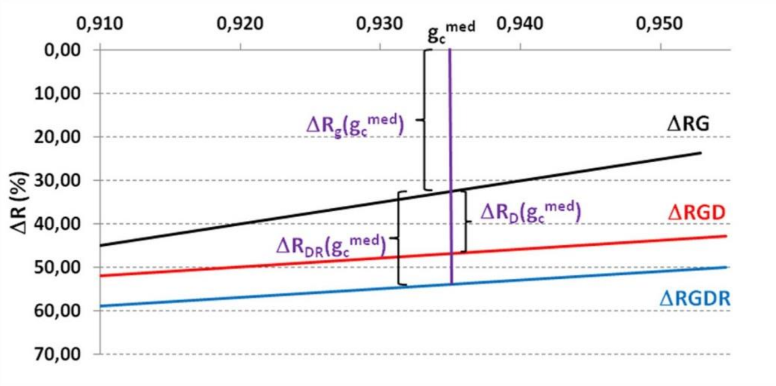

Fig. 8 *Case study #2*: Percentage reduction of the structural strength of in-situ concrete with respect to the strength of cast cubes, as a function of the compaction degree g_c. Comparison among strength loss ΔRG related to imperfect compaction (black line), strength loss ΔRGD related to imperfect compaction and degradation (red line), strength loss $\Delta RGDR$ related to imperfect compaction, degradation and disturbance due to drilling (blue line)

Table 4 Case study #2: values of ΔR_g(%), ΔR_D(%) and ΔR_{DR}(%) corresponding to a minimum, medium and maximum compaction degree

g_c		$\Delta R_g^{(i)}$ (%)	$\Delta R_D^{(i)}$ (%)	$\Delta R_{DR}^{(i)}$ (%)
min.	0.910	45.05	6.93	13.95
med.	0.935	32.61	14.22	21.40
max	0.955	22.68	20.04	27.34

Table 5 Comparison between the values of the percentage strength loss ΔR_D evaluated according to the procedure proposed in Uva *et al.* (2013) and to the extended procedure presented in the paper (§ 4)

	Sampling #1			Sampling #2		
	ΔR_D (Uva *et al.* 2013)	ΔR_D [§ 4]	Δ	ΔR_D (Uva *et al.* 2013	ΔR_D [§ 4]	Δ
$g_{c,min}$ (%)	8.77	14.62	+ 5.85	7.10	6.93	- 0.17
$g_{c,med}$ (%)	19.73	19.80	+ 0.07	11.08	14.22	+ 3.14
$g_{c,max}$ (%)	26.78	24.58	- 2.20	13.90	20.04	+ 6.14
	E_m (%) (Uva *et al.* 2013)	E_m (%) [§ 4]	ΔE_m (%)	E_m (%) (Uva *et al.* 2013)	E_m (%) [§ 4]	ΔE_m (%)
E_m (%)	25.10	9.25	- 15.85	19. 98	6.97	- 13.01

The percentage reductions related to the different effects are summarized in Table 4: $\Delta R_g^{(i)}$ is *i*-th the strength loss related to imperfect compaction, $\Delta R_D^{(i)}$ is *i*-th the further loss related to degradation, $\Delta R_{DR}^{(i)}$ is *i-th* the strength loss related to the combined effect of degradation and disturbance due to drilling.

The disturbance effects due to drilling (ΔR_R - Eq. (19)) have a percentage incidence of 7.02%, 7.18% and 7.30% in correspondence, respectively, of the minimum, medium and maximum compaction degree. On average, in the Case study #2, drilling operations have induced on the cores a percentage strength reduction equal to 7.16%, with respect to the strength of the cast specimens.

6. Some remarks about the results

In Table 5, for the two case studies (§ 5.1 e § 5.2), the results in terms of ΔR_D obtained by applying the original methodology proposed by the authors in Uva *et al.* (2013), and summarized in § 3.2, are compared with those provided by the extended procedure illustrated in the present paper (§ 4). In the same table, it is reported the average percentage difference E_m(%) between the estimate $\Delta RGD(\%)$ calculated by Eq. (17) in the two above mentioned cases.

The results reported in the table clearly show that the correlation between destructive and non destructive tests has not introduced any substantial modification to the original framework of the methodology presented in Uva *et al.* (2013) and § 3.2. In fact, the results have not been altered by the use of the data of the ultrasonic test, making it even more reliably the degree of compaction as a parameter for checking the in-situ strength of concrete. The most remarkable difference is represented by the increase of the strength loss due to the degradation for the Case study *#2*, which is anyway quite moderate: 6.14%.

Table 6 Suggested values of the disturbance coefficient C_d according to Masi and Chiauzzi (2013)

f_{core} [MPa]	C_d
f_{core}<10	1.3<C_d<1.7
10<f_{core}<20	1.15<C_d<1.3
20<f_{core}<30	1.05<C_d<1.15
f_{core}>30	1.0<C_d<1.05

It is worth noting, anyway, that the differences found for ΔR_D are strictly dependent on the numerical value assumed for the correction coefficient C_d (see Eq. (12)), which modifies the strength f_{core} in order to account for the disturbance due to drilling. In their research work, Masi and Chiauzzi (2013) assumed C_d=1.2 if f_{core}<20 MPa and C_d=1.1 if f_{core}>20 MPa. Some recent research study about of the parameter C_d have shown that the values traditionally assumed were quite low. The same Masi, in a recent research work of 2006, has evaluated the coefficient C_d by statistically processing a database of more than 500 cores coming from existing RC buildings, and suggested the scheme presented in Table 6 for the correct choice of C_d.

The values presented in Table 6 are actually characterized by a relevant variability, which would affect the results obtained by the proposed procedure. For example, in the case of the Case study #2, the strength loss related to the deterioration of the materials (6.93%<ΔR_D<20.04%) is much greater than expected (for example, in correspondence with the maximum degree of compaction compared to the case #1 there is a difference of only 4.5%), considering that the cores were extracted after a very short time after the construction, and thence it is reasonable to assume that no ageing effects has occurred. The reason for this excessive level of the strength loss induced by deterioration, therefore, can only be ascribed to the uncertainty related to the coefficient C_d. By increasing the numerical value of C_d, as indicated by Masi *et al.* (2013), the strength degradation ΔR_D would decrease, and the distance between the lines ΔR_g and ΔR_{gD} in Fig. 8 would correspondently reduce. Anyway, this doesn't affect the general reliability of the methodology that, as it could be reasonably expected, has shown that the strength loss related to the deterioration, is lower (even if only slightly) in the case of the Sampling *#2*(new building).

The most interesting conclusion that can be derived by the critical discussion of the results is that the incorporation of ND tests in the sampling is particularly useful in order to validate the appraisal of the degradation of in-situ concrete. In fact, the average percentage error E_m(%) obtained on the wider population of samples (E_m(%)=9.25%; E_m(%)=6.97% for the Case study #1 and *#2* respectively) is much smaller than the one provided by the original procedure of Uva et al. (2013), in which the population of samples, besides the cast specimens, is only composed by the drilled cores (the reduction of the error is equal to 15.85% for the Case study #1 and to 13.01% for the Case study #2). These considerations are translated graphically into a approaching of the red line to the black line (see Figs. 5 and 8) using the proposed procedure instead of one based on the sample consisting by only cast cubes and concrete cores.

7. Conclusions

In evaluating the structural safety of existing buildings, a fundamental step is represented by the knowledge of the mechanical properties of the structural materials. The judgement about the reliability of the materials is often the main factor that affects the final result of the assessment.

After the experimental investigations, it is then important to properly correlate the results of DTs (in the case of concrete, compressive tests on drilled core) and NDTs by applying a proper correlation procedure. Among the non-destructive tests is appropriate to take those aimed at evaluating the homogeneity of the concrete for locating any phenomena of material degradation. After identifying the homogeneous classes of the in-situ concrete and the corresponding strength, a fundamental step is the comparison with the quality inspection tests (cast concrete specimens) performed during the construction. This comparison will typically point out that the value of in-situ strength is lower than the one measured on the cast specimens. The reasons can be different: a degradation process related to ageing and aggressive environmental conditions; bad quality of the execution (placing, consolidation and curing practice); disturbance suffered by the drilled cores during the extraction. It is very important to correctly identify the causes, in order to adopt a suitable and effective rehabilitation strategy.

The procedure illustrated in the present paper, which is the extension of e previous work of the authors (Uva *et al.*, 2013), has the objective of investigating the differences between the cores' strength and the cast cubes' strength exploiting the information provided by destructive and non destructive tests. More in detail, if the following data are available:

- Cast cubes prepared during the construction phases;
- Concrete cores extracted by the structural elements;
- UPV tests performed on the structural elements

it is possible to evaluate the amount of strength loss (ΔR_D) that has to be ascribed to the time deterioration of the concrete.

The estimate is performed by using an exponential correlation between the ultrasonic pulse velocity, the compaction degree, and the in-situ strength. The methodology has been applied on two case studies (an existing and a new building). The results obtained have shown that the strength loss determined by the degradation is about *20%* for the existing building, and about *15%* for the new one. The extension of the procedure by the incorporation of UPV tests has confirmed the reliability of the methodology, ie there is an additional reduction of resistance than to the one induced by an imperfect compaction degree. However by using a wider database, thank to the information obtained by ultrasonic tests, allows a reduction of the average percentage error $E_m(\%)$ of about *15%*. It should then be remarked that the additional data related to UPV tests required by the procedure are usually easily available. In fact, in the current practice, during the investigation programs on existing buildings, destructive tests, which are very invasive and expensive, are typically limited in number, and completed by an extensive set of ND tests, which are more rapid, easy and cheap.

The proposed methodology, thence, is a valid tool for supporting the vulnerability assessment of existing buildings, by providing a significant characterization – which is not simply a numerical evaluation – of the in-situ concrete. In fact, the procedure allows to determine if the homogeneous classes of concrete are the representation of a material more or less degraded. It also allows to know how much influence the effects of material degradation and disturbance caused by drilling operations on the strength value which must be used in the safety assessment.

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