Experimental Evaluation of Drilling Damage on the Strength of Cores Extracted from RC Buildings

A. Masi, A. Digrisolo, and G. Santarsiero

***Abstract*—**Concrete strength evaluated from compression tests on cores is affected by several factors causing differences from the in-situ strength at the location from which the core specimen was extracted. Among the factors, there is the damage possibly occurring during the drilling phase that generally leads to underestimate the actual in-situ strength. In order to quantify this effect, in this study two wide datasets have been examined, including: (i) about 500 core specimens extracted from Reinforced Concrete existing structures, and (ii) about 600 cube specimens taken during the construction of new structures in the framework of routine acceptance control. The two experimental datasets have been compared in terms of compression strength and specific weight values, accounting for the main factors affecting a concrete property, that is type and amount of cement, aggregates' grading, type and maximum size of aggregates, water/cement ratio, placing and curing modality, concrete age. The results show that the magnitude of the strength reduction due to drilling damage is strongly affected by the actual properties of concrete, being inversely proportional to its strength. Therefore, the application of a single value of the correction coefficient, as generally suggested in the technical literature and in structural codes, appears inappropriate. A set of values of the drilling damage coefficient is suggested as a function of the strength obtained from compressive tests on cores.

***Keywords*—**RC Buildings, Assessment, In-situ concrete strength, Core testing, Drilling damage.

I. Introduction

VULNERABILITY assessment of Reinforced Concrete (RC) existing buildings has a key role in the process of determining and reducing the impact of earthquakes. In fact, a great deal of RC buildings, now placed in seismic zones, have been designed and constructed before seismic codes were in force or using old unsatisfactory seismic design approaches.

Part 3 of Eurocode 8, Assessment and retrofitting of buildings [1], has been developed with reference to this context, with the main objective to provide criteria for the evaluation of the seismic performance of existing individual building structures and, consequently, to set forth criteria for the design of the possible retrofitting measures.

In RC structures, the compressive strength of concrete can have a crucial role on the seismic performance and is usually difficult to estimate. Reliable procedures to take into account the factors influencing the estimation of in-situ concrete strength, particularly in case of poor quality concrete, are required. Several studies are currently in progress to this end where different kinds of approach are adopted to estimate the concrete strength and the role of the main influencing factors.

In-situ concrete strength can be estimated through destructive or non-destructive testing methods, or through a combination of both methods. The most widespread methods for RC structures include core testing among destructive tests, rebound number and ultrasonic pulse velocity among non-destructive tests.

According to various codes, (e.g. in Europe [1] and, in Italy, [2]) estimation of in-situ concrete strength has to be mainly based on cores drilled from the structure.

Specifications to use core testing are given in several standards (e.g. in Europe [3]). Although core testing is the most direct method to estimate concrete strength in a structure, it has to be taken into account that there are some differences between the strength measured on core specimens and the actual in-situ strength. The main factors determining such differences are the size and geometry of the core specimens, the coring direction, the presence of reinforcing bars or other inclusions, the effect of drilling damage.

To this purpose, a relationship to convert the strength of a core specimen f_{core} into the equivalent in-situ value f_c is given in [4]:

$$f_c = (C_{H/D} \cdot C_{dia} \cdot C_{st} \cdot C_{dam}) \cdot f_{core} \quad (1)$$

where:

- $C_{H/D}$ = correction for height/diameter ratio H/D different from 2 due to restraint from the compression test machine platens the strength decreases for ratios H/D >1 [5], therefore, in accordance with [6],it is assumed $C_{H/D} = 2/(1.5 + D/H)$ that provides $C_{H/D}$ equal to 1 and 0.8 for H/D, respectively, equal to 2 and 1;
- C_{dia} = correction for diameter of core D, to be taken equal to 1.06, 1.00 and 0.98 for D, respectively, equal to 50, 100 and 150 mm, as suggested in [7];
- C_{st} = correction for the presence of reinforcing bars, equal to 1 for no bars, and varying between 1.03 for small diameter bars (Φ10) and 1.13 for large diameter bars (Φ 20);
- C_{dam} = correction for damage due to drilling.

The correction coefficient C_{dam} asks for a particular attention: whereas a constant value equal to 1.06 is suggested in [7], in the technical literature (e.g. [8]) also C_{dam} = 1.10 is proposed, provided that the extraction is carefully carried out

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by experienced operators. However, taking into account that the lower the original concrete quality the larger the drilling damage, in [4] it is suggested to put C_{dam} =1.20 for f_{core}< 20 MPa, and C_{dam} =1.10 for f_{core}> 20 MPa.

To better analyze the possible reduction amount of core specimen strength due to drilling damage, thus providing more accurate values of the correction coefficient C_{dam}, two wide experimental databases have been examined and compared in the present study.

The first DB includes test results from over 500 core specimens taken from existing structures, while the second one includes about 600 cube specimens taken during the construction of new structures in the framework of routine acceptance control. All tests were carried out at the Laboratory of Structures of the University of Basilicata, Italy.

The properties of the specimens contained in the two DBs have been compared in terms of concrete strength and specific weight, accounting for the role of other important factors that can influence concrete strength. Specifically, the considered factors are: (i) type and amount of cement, (ii) grading, type and maximum size of aggregates, (iii) water/cement ratio, (iv) placing and curing procedures, (v) concrete age.

II. Experimental Data

The present study is based on two DBs made up of experimental tests on concrete specimens, either cubes or cores.

The cube specimens are relevant to standard acceptance test carried out during the construction of new concrete structures. It is worth noting that specimens with cubic shape are generally used in Italy to this end. Specifically, all the results of the experimental tests carried out at the Laboratory of Structures of the University of Basilicata during 1990 have been considered in the study. With the objective of studying only the concrete used in ordinary RC constructions, experimental tests concerning high strength concrete, such as those relevant to pre-stressed structures, have been excluded, thus achieving a sample globally made up of 594 cubes. In particular, all tests with f_c> 50 MPa have been excluded.

The core specimens taken from existing structures are relevant to experimental investigations performed in the time period 1989-2003, thus achieving a sample globally made up of 515 cores. Their age is very variable but clearly cores are generally far older than cubes.

Analysis of data is based on two physical properties available for all specimens, that is:

- concrete strength f_c (cylindrical value, when needed derived from the correspondent cubic value);
- specific weight (SW).

The core strengths directly obtained from the compression tests have been converted into the equivalent value f_c referred to cylindrical specimens having a ratio H/D =2 using the coefficient $C_{H/D}$ provided in [1].

With respect to cube specimens, standard test results are provided in terms of cubic strength R_c, therefore to be appropriately compared with the strength value of cores, they have been converted into the equivalent cylindrical value through the expression f_c =0.83 R_c. The age of the cube specimens has been assigned considering the difference between the test and placing date as reported in the laboratory acceptance test reports.

In Table I some simple statistics of the f_c and SW values relevant to the two DBs of cubes and cores are reported, namely minimum, maximum, mean value, standard deviation and coefficient of variation (CV) of the test results.

TABLE I
Minimum, Maximum, Mean Value, Standard Deviation and Coefficient of Variation of Strength and Specific Weight Values on Core and Cube Specimens

	CORES		CUBES	
	f_c (MPa)	SW (kN/m^3)	f_c (MPa)	SW (kN/m^3)
Mean	21.96	22.98	25.04	23.53
Standard Dev.	13.85	1.15	9.61	0.82
CV (%)	63.07	5.00	38.38	3.48
Minimum	2.55	19.26	4.76	20.53
Maximum	100.40	27.23	64.91	26.00

In Figs. 1 and 2 the relationships between the SW and f_c values for the sample of cores and cubes, respectively, are shown.

Besides, in Figs. 1 and 2 the best SW-f_c correlations are displayed along with the correlation coefficient R. A significant dispersion can be seen, especially for the cube specimens (R =0.51), because both samples belong to data sets quite dispersed in terms of type and amount of cement, type and grading of aggregates, water/cement ratio, age. Additionally, with respect to cube specimens, it should be considered that in some cases concrete had a limited curing age, therefore its strength was still in the increasing phase.

In order to obtain less scattered SW-f_c relationships a data filtering operation has been done by removing the pairs SW-f_c having too large scatter (outliers) with respect to the best fit regression of each dataset.

The filtering operation has been carried out as follows:

1. an interval delimited by the curves (1-k) f_c(SW) and (1+k) f_c(SW), obtained offsetting the best correlation curve f_c(SW) with the coefficients 1-k and 1+k, has been defined;
2. all the pairs SW-f_c falling outside this interval, being considered too far away from the average, have been removed;
3. for the new dataset, purified of data outside the interval, the correlation SW-f_c has been re-evaluated;
4. steps 1-3 have been repeated for values of k in the range 0.1-0.5 thus selecting the values providing the best correlation.

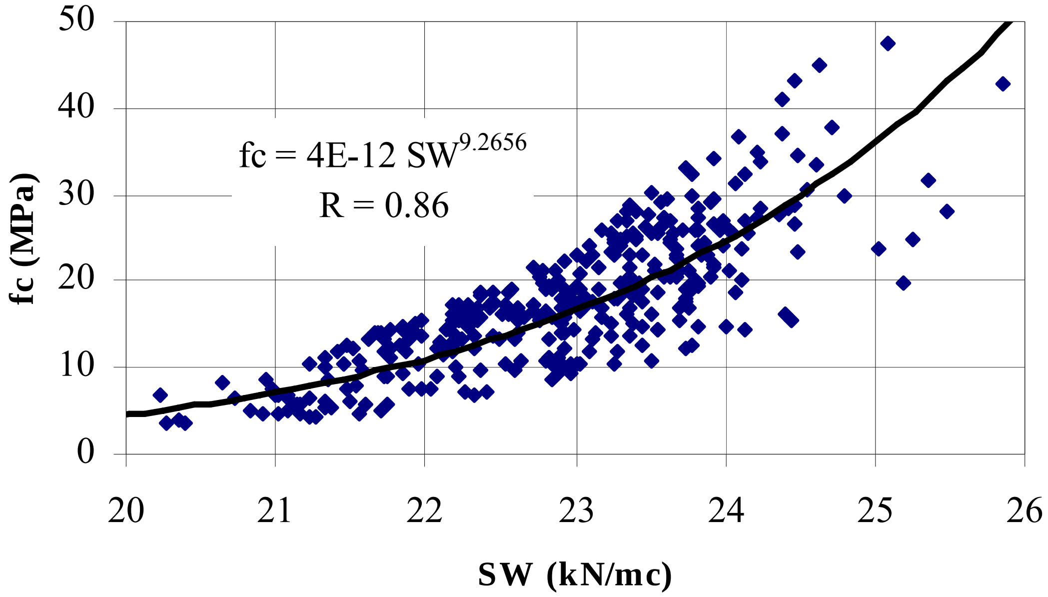

Fig. 1 Relationship between the SW and f_c values for the sample of core specimens

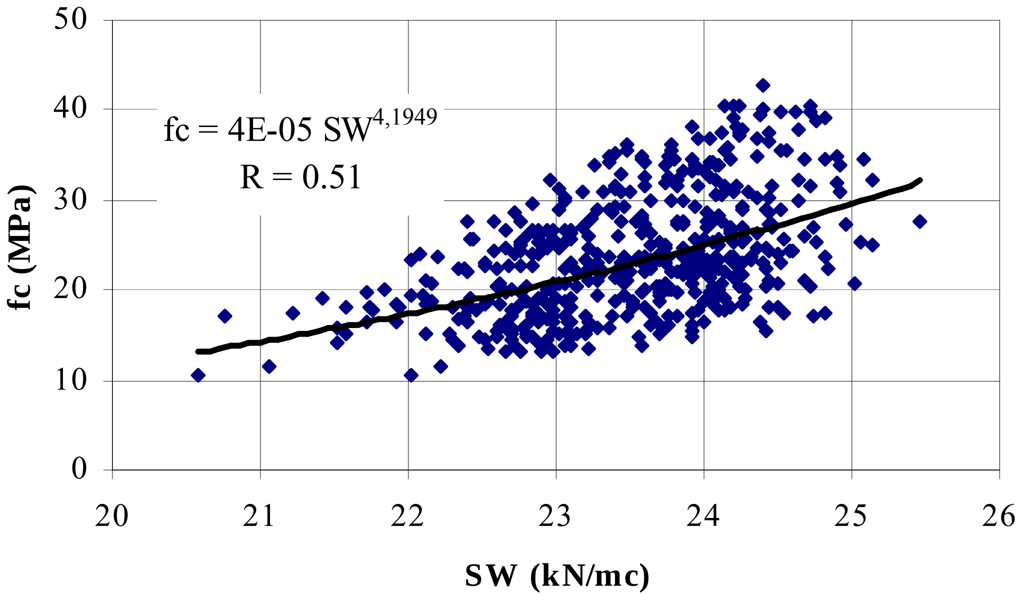

Fig. 2 Relationship between the SW and f_c values for the sample of cube specimens

Performing the above described procedure, whose intermediate results are not reported for sake of brevity, it was found that:

- the best correlation SW-f_c for the cores is obtained considering the whole dataset, without removing any specimen;
- for the cubes, the correlation slightly increases from R=0.51 to R=0.52eliminating some outliers.

As a matter of fact the correlation relevant to core specimens was already good (R=0.86), contrarily to what happens for the sample of results from cubes. For this reason, the role of ageing on concrete strength variation has been considered by removing all data from cubes with age less than 90 days (Fig. 3) that is considering that in concrete with age less than 90 days not negligible strength increments can be expected. As a result, a significant improvement of the correlation has been obtained (R=0.61, see Fig. 3).

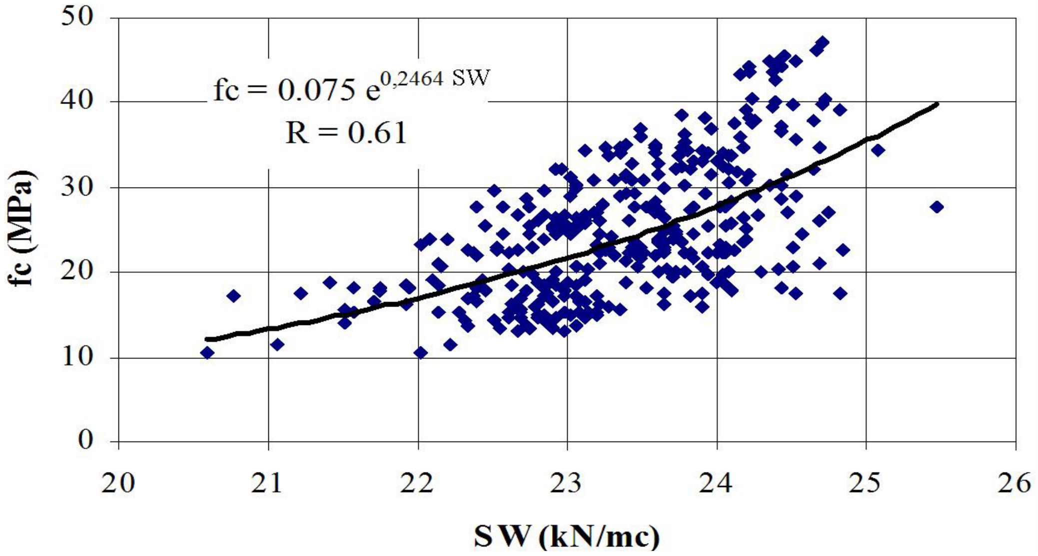

Fig. 3 Relationships between the SW and fc values for the sample of cubeswith curing age higher than 90 days

In Fig. 4 the best fit SW-f_c regressions for the two datasets of cores and cubes are displayed and compared, having the following expressions:

- CORES

$$f_c = 4 \cdot 10^{-12} \cdot SW^{9.266} \qquad R = 0.86 \qquad (2)$$

- CUBES

$$f_c = 0.075 \cdot e^{0.246 SW} \qquad R = 0.61 \qquad (3)$$

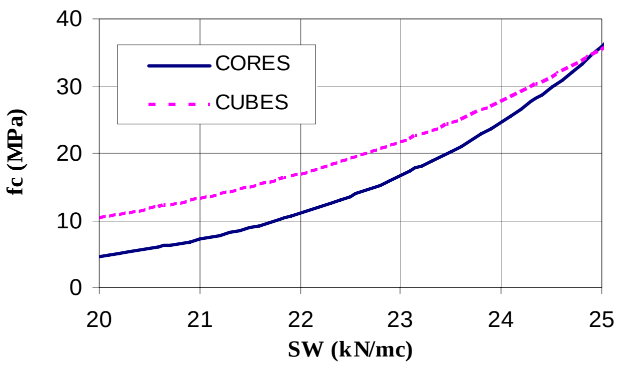

Fig. 4 SW-f_c regression lines for the two datasets of cores and cubes that provide the best correlations

The analysis of curves plotted in Fig. 4 shows that, making a comparison with equal SW values, the strength of cubes is always larger than that of cores. The difference decreases with increasing SW values and tends to be zero for the higher values of the specific weight that is SW around 25kN/m^3.

Such a difference can derive from several reasons that will be carefully examined in the following section, among others there is the role of drilling damage affecting (i.e. reducing) concrete strength obtained from core specimens.

III. Evaluation of the Drilling Damage Coefficient

Concrete strength is dependent on many factors. Bearing in mind objective and methodology of the present study, among the main influencing factors it is crucial to consider those ones that have some influence on the specific weight too, separating them from the factors that have negligible influence on the SW values.

In Table II the main factors that influence the final strength of concrete [9] are reported and, for each of them, the possibility that they can influence the SW values is pointed out in the third column (Role on SW: Yes/No).

TABLE II
Main Factors Influencing Strength and Specific Weight of Concrete

	Influencing factors	Role on SW	CUBES	CORES	α_i
1	Aggregate grading	Yes			1
2	Aggregate type	Yes			1
3	W/C ratio	Yes			1
4	Placing modality	Yes			1
5	Cement type	No	325-425	325	1-1.06
6	Cement amount (kg)	No	250-350	200-250	1-1.15
7	Aggregate max size	No			1
8	Curing modality	No	standard	in-situ	1-1.10
9	Age	No			1[(§)]

[(§)] it is assumed α_9=1 because the contribution of age was already accounted for by considering cube specimens with age > 90 days.

In the following it is assumed that the contribution of the factors that influence both SW and f_c, namely grading and type of aggregates, water/cement ratio and placing procedure (compactness), is already accounted for in the relationships SW-f_c displayed in Fig. 4. In other words, the effect of possible differences of these factors between cube and core concrete is already considered.

This effect is not included for those factors that have no influence on the SW values, whose differences between cubes and core concrete contribute to determine the detected difference between core and cube strength. Analyzing the contribution of these factors the specific effect of drilling damage can be highlighted.

To this purpose, it has to be considered that the concrete of cores is generally older than that one of cubes, with differences ranging from years to decades. Therefore, differences concerning concrete composition as well as curing modality and age can be expected as a consequence of the evolution of the usual practice during different construction periods. The main factors that can determine the difference between the concrete of core and cube specimens, without influencing SW, along with their quantitative effect on strength, are listed in the following:

a) Type of Cement: The cement used for cores is usually at most of class 325 (i.e. the cement paste shall have compressive strength at 28 days not lower than 32.5 MPa), while for cubes classes 325 and 425 can be expected. Passing from a cement of class 325 to one of class 425 the concrete strength can increase of about 6% [9].
b) Amount of Cement: As a consequence of the different construction periods which cores and cubes date back to, it can be assumed that the amount of cement used in the concrete of cores was lower than in that of cubes. Based on the usual practice of the periods, the average amount of cement in the cores can be estimated to be 200-250kg/m^3, while in the cubes it ranges between 250 and 350kg/m^3. This difference can cause a strength variation around 15% [9].
c) Maximum Size of Aggregates: The effect of this parameter can be included in the strength loss due to drilling damage because the larger is the maximum size of aggregates, the larger can be the damage to the drilled specimens [8].
d) Curing Modality: The curing of cores takes place in-situ, while the curing of cube specimens is carried out applying standard procedures (appropriate formworks, exposure of specimens to specified conditions of moisture and temperature, etc.). According to some authors [8] the strength difference is on the order of 10%.
e) Curing Age: The set of cores is generally made-up of very old specimens, while the set of cubes is made-up of specimens having an age of few months. Concrete strength increases over time, therefore differences between the two sets can be expected. However, taking into account that the cubes with age less than 90 days have been excluded, the remaining cubes have an age that allows considering already occurred most of the strength increment. For this reason, the role of this factor on core-cube difference has been neglected assuming the related coefficient $\alpha_9 = 1$.

In the last column of Table II the correction coefficients α_i related to the different factors influencing the concrete strength are reported. These coefficients can increase the cube strength with respect to core strength, then the following relationship between the strength of cores and cubes can be written as follows:

$$f_{cube} = \alpha_{tot} \cdot f_{core} \quad (4)$$

where:

$\alpha_{tot} = \alpha_1 \cdot \alpha_2 \cdot ... \cdot \alpha_9$.

Considering the α_i values reported in Table II, the limits of the interval of α_{tot} are $\alpha_{min} = 1$ and $\alpha_{max} = 1.34$.

In order to point out the effect of drilling damage a correction of the cubes' strength is needed to make it comparable to that of cores, thus calculating modified cube strength as follows:

$$f_{cube,mod} = (f_{cube}/\alpha_{tot}) \quad (5)$$

where it is assumed that the maximum variation is attained for a specific weight of 20kN/m^3, and that the variation between α_{min} and α_{max} is linear.

In the diagram in Fig. 5 the modified curve relevant to cubes is reported: the cubes' curve is lower than that reported in Fig. 4 although remains above that of cores. Since all the main factors that can determine differences between the compressive strength of cubes and cores have been taken into account, the remaining difference between the two curves in Fig. 5 can be ascribed to the strength loss caused by deterioration suffered during service life and drilling damage, both being able to reduce core strength.

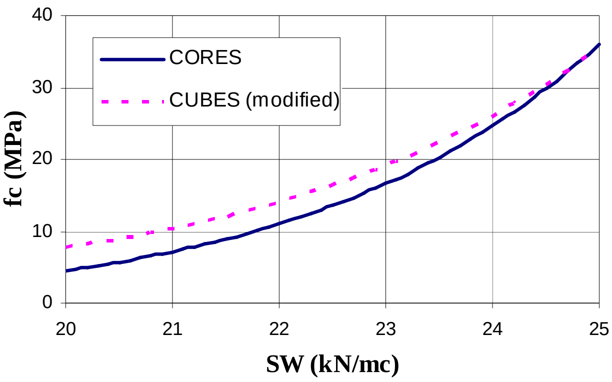

Fig. 5 SW-f_c regression lines for the two datasets of cores and cubes (modified) that provide the best correlations

It is worth noting that the first reducing effect is generally not required when assessing structural capacity that is based on the current in-situ concrete strength, thus including degradation over time. On the contrary, the effect of drilling damage needs to be evaluated to correctly estimate the current in-situ strength when using core specimens. However, to identify the contribution of drilling damage in determining the differences displayed in Fig. 5, the complementary contribution of deterioration should be estimated.

As can be expected, Fig. 5 shows that the reducing effect is significant in the initial part of the curves (low f_c and SW values, therefore poor quality concrete) and, then, the reducing effect rapidly decreases while f_c and SW increase.

Based on the curves displayed in Fig. 5, in Table III the ranges of the drilling damage coefficient C_{dam} along with the suggested values for various strength intervals are reported.

TABLE III
MIN-MAX DIFFERENCE BETWEEN CUBE AND CORE STRENGTH AND SUGGESTED VALUES FOR THE CORRECTION COEFFICIENT OF DRILLING DAMAGE

f_{core}(MPa)	$f_{cube,mod}$ / f_{core}	C_{dam}(suggested)
f_{core}< 10	1.3 - 1.7	1.3
10 <f_{core}< 20	1.15 - 1.3	1.2
20 <f_{core}< 30	1.05 - 1.15	1.1
f_{core}> 30	1.0 - 1.05	1.0

As can be seen in Table III, for strength values less than 10 MPa, ($f_{cube,mod}$/f_{core}) ratios in the range 1.3-1.7 have been obtained. These values appear really large especially if compared with the correction coefficient of drilling damage suggested in [7], that is C_{dam}=1.06. Such high values of the ratio ($f_{cube,mod}$/f_{core}) lead one to think that the cores having very low SW values (i.e. less than 21kN/m^3) can be subjected to both large degradation over time and high damage sustained during drilling, as a consequence of the original poor concrete quality. Further, core strength reduction might be worsened by incorrect extraction operations. In the case doubts arise that cores were not taken correctly, it becomes mandatory to take additional cores, otherwise a precautionary value C_{dam}=1.3 can be suggested.

For the specimens with strength values between 10 and 20 MPa, ($f_{cube,mod}$/f_{core}) ratios are in the range 1.15-1.3. Also in this case C_{dam} values far higher than the coefficient proposed in [7] are found, but close to the value suggested in [10], where a value of C_{dam}=1.2 is proposed when the concrete strength is less than 20MPa. In this case the suggested value is equal to 1.2.

Specimens whose strength values are between 20 and 30 MPa show ratios ranging in the interval 1.05-1.15, not so different from what suggested in [10] and equal to the C_{dam} value proposed in [11] where a correction coefficient equal to 1.1 is proposed for strength values higher than 20 MPa. Hence, the suggested value is C_{dam}=1.1.

Finally, for specimens with strength higher than 30MPa the ratio ($f_{cube,mod}$/f_{core}) is between 1 and 1.05. For these specimens, in case of a correct drilling procedure, damage can be considered negligible thus suggesting to apply no correction coefficient, i.e. C_{dam}=1.

IV. CONCLUDING REMARKS

Core testing is currently considered the most accurate technique for estimating the concrete strength of existing structures, used in isolation or along with non destructive tests. Core strength, however, can result different from the in-situ strength of the concrete at the location from which the core specimen was extracted, due to several causes. Among others, the difference can be caused by the damage that can occur during the extraction phase, thus determining an underestimation of the real in-situ strength.

In the technical literature and in some structural codes suggestions to estimate the damage that can occur during the extraction of cores are provided. However, to the best knowledge of the authors these suggestions appear not sufficiently supported by experimental data. For this reason, in the paper a wide database of test results made up of about 500 cores extracted from existing structures and about 600 cubes obtained during the casting of concrete for new structures, has been collected and analyzed.

The two datasets have been analyzed with respect to the compression strength f_c (either cubes, f_{cube}, or cores, f_{core}) and the specific weight SW of the specimens, accounting for the contribution of the factors that can significantly affect concrete strength. These factors include type and the amount of cement, aggregates' grading, type and maximum size of aggregates, water/cement ratio, placing and curing procedures, and concrete age.

After the determination of the best correlations SW-f_c for the two datasets, their comparison showed that- considering equal SW values -the strength of cubes is always higher than the strength of cores, even though the difference tends to zero for high SW values. The main factors determining this difference have been identified recognizing, among them, the damage sustained by cores during drilling. After, the effect of each factor has been estimated, thus permitting the contribution due to drilling damage to be pointed out.

The results show that the magnitude of the strength reduction due to drilling damage is strongly affected by the concrete strength itself. Therefore, the application of a single value of the correction coefficient, as generally suggested in the technical literature and in structural codes, appear inappropriate. On the contrary, the adoption of a correction coefficient inversely proportional to the original core strength appears more correct.

In the paper, a set of values of the drilling damage coefficient is suggested as a function of the strength obtained from compressive tests on cores. Correction coefficients are higher than those provided by literature for low strength values (and, then, for low specific weight values), while are practically coincident for high strength values. Further experimental activities, currently in progress, will allow to better evaluate the effect of drilling damage, with the final objective of obtaining a continuous function of the related correction coefficient.

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