Mechanical Characterization of Concrete from Existing Buildings with SonReb Method

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SUMMARY:
The evaluation of the concrete compressive strength is a fundamental step for the assessment of existing reinforced concrete (RC) buildings according to the last seismic codes. This valuation can be conducted by the use of both destructive and non-destructive methods. Non-destructive methods, although being minimally invasive and easily extensible to a large number of elements, are influenced by many factors. SonReb method, combining Schmidt rebound hammer and Ultrasonic Pulse Velocity methods, allows to compensate the limits and the uncertainty typical of each method. The use of the combined methods (SonReb) increases the accuracy of the estimation of the in situ concrete compressive strength.
In this paper, a significant database of both destructives and non-destructives tests conducted on existing RC buildings located in the Italian Region of Tuscany and built between the 50's and 80's, is used to perform statistical analyses. In detail the paper evidenced the need to conduct a wide campaign of on-situ tests, useful to define the concrete compressive strength with a suitable reliability.
The results show that the uses of formulations present in the technical literature provide results different from the actual values. Conversely the results of SonReb method, calibrated with the strength of cylindrical samples (cores) extracted from a single building, are close to the actual ones.

Keywords: concrete compressive strength, destructive methods, non-destructive methods, SonReb method.

1. INTRODUCTION

After several disasters that have occurred in the last decades, both for seismic events and degradation of materials, the Italian and international building codes have been subscribing more advanced approaches towards assessment of safety of existing buildings.
In Italy, after the OPCM 3274 (2003), new initiatives to ensure the structural safety of existing buildings were started. Namely, it was required seismic assessment and, if needed, retrofit of all strategic and relevant buildings, within five years from the issue of the OPCM 3274. Amendments and additions on the evaluation of safety assessment for existing buildings, such as OPCM 3316 (2003), OPCM 3431 (2005), Norme Tecniche per le Costruzioni (2005) and Nuove Norme Tecniche per le Costruzioni (2008), have not changed substantially this approach.
This issue, at international level (FEMA 356 2000 and EC8 2004), with some variation on the definition of compressive strength, was also addressed.
The Tuscany Region, since the 90's of previous century, has undertaken a series of investigations for the prevention of seismic risk of strategic and relevant buildings constructed in areas with highest seismicity and located in the Tuscan Apennines.
The activity was launched within a regional and national program of seismic prevention, aimed mainly to assess the quality of concrete, in almost absence of specific legislation and scientific references related to existing buildings. Therefore, specific procedures of investigation and interpretation of results were developed.
In detail, a methodology of destructive (cores) and non-destructive testing was developed under the *Seismic Vulnerability of RC Buildings project* (VSCA 2004) that involves the necessity to calibrate the resistance obtained by non-destructive methods with cylindrical strength of specimens (cores) extract from same structural elements in the proximities of the non-destructive tests.
Statistical studies conducted in (D'Ambrisi et al 2007 and Cristofaro et al 2009) evidenced the extreme variability of the concrete compressive strength in the same structure. Those studies

evidenced also the poor correlation between the data obtained with the destructive tests and those obtained with non-destructive tests on the same structural element using formulations of literature.

2. CONCRETE COMPRESSIVE STRENGTH

In the valuation of the safety structural of existing RC buildings, it is necessary to estimate mechanical properties of the concrete by compressive tests carried out on cylindrical specimens extracted from structural elements. Destructive tests can be supplemented by non-destructive tests.
In this case, Italian code (NTC 2008) required the calibration of non-destructive tests on destructive ones. Moreover, 3 levels of knowledge are defined (limited knowledge, normal knowledge, full knowledge). The knowledge level defines adoptable methods of analysis as well as values of the Partial Safety Factors.

2.1 Destructive methods

Cylindrical specimens extracted from structural elements were subjected to compressive test in laboratory. In general, cylindrical strength of cores f_{core}, is about the 83% of the corresponding cubic strength R_{cub}.
In fact, many perturbative factors influence cylindrical strength of cores. In technical literature there are a series of empirical formulations that convert the f_{core} to R_{cub} and that take into account these factors as: (i) extraction directions; (ii) slenderness of specimens; (iii) concrete strength and (iv) damages caused by extraction.
The equations of wider use in the scientific field for determination of the cubic concrete compressive strength R_{cub} from the cylindrical compressive strength f_{core} are: British Standard and Concrete Society (Eqn. 2.1), Braga et al (Eqn. 2.2) and Cestelli Guidi and Morelli (Eqn. 2.3).

$$R_{cub,1} = f_{core} \cdot \frac{k_1}{1.5 + d/h} \qquad \text{[MPa]} \qquad (2.1)$$

In Eqn. 2.1, D and h are respectively the diameter and the hight of the extract core; k_1 is a coefficient that takes into account of the direction of extraction; it is 2.5 for horizontal direction and 2.3 for vertical direction.

$$R_{cub,2} = f_{core} \cdot \frac{k_2 \cdot \beta}{1.5 + d/h} \cdot \varphi \qquad \text{[MPa]} \qquad (2.2)$$

$$R_{cub,3} = f_{core} \cdot \frac{k_2}{1.5 + d/h} \cdot \varphi \qquad \text{[MPa]} \qquad (2.3)$$

In Eqns. 2.2 and 2.3, k_2 takes into account of the direction of extraction; it is 2.00 for horizontal extraction and 1.84 for vertical extraction; $\beta = 1.1$ that takes into account the damage caused by the extraction; φ is a coefficient to change from cylindrical to cubic strength; it is 1/0.83 in Eqn. 2.2 while in Eqn. 2.3 depend on the class of concrete.
In this paper only cubic strength is considered and it is obtained as mean of cubic values of three previous equations R_{cub}':

$$R_{cub}' = \left(R_{cub,1} + R_{cub,2} + R_{cub,3}\right)/3 \qquad \text{[MPa]} \qquad (2.4)$$

An equation able to providing the assessment of cubic characteristic compressive strength of on-site concrete is proposed by Pucinotti in (Pucinotti 2008).
The author adopts an approach similar to EN 13791 (2008), to obtain an accurate estimate of concrete characteristic compressive strength on-site.

2.2 Non-destructive methods

Among the non-destructive methods for the definition of the concrete compressive strength, the SonReb method (Schmidt rebound hammer + Ultrasonic Pulse Velocity) is the most used.
This is a non-invasive method and then it can extend to a large number of elements. However, they are influenced by numerous factors, such as: concrete carbonation, concrete porosity, presence of cracks in the concrete and environmental conditions (humidity and temperature) present during extraction. SonReb method allows to compensate the limits and the margins of uncertainty typical of each method considered separately.
In technical literature are available formulations that correlate SonReb results with on-site concrete compressive strength (Cristofaro 2009).
Below three of these formulations are examined: Giacchetti and Lacquaniti (Eqn. 2.5), Gašparik (Eqn. 2.6) and Di Leo and Pascale (Eqn. 2.7).

$$R_{cub} = 7.695 \cdot 10^{-11} \cdot I_r^{1.4} \cdot V_{us}^{2.6} \qquad \text{[MPa, m/s]} \qquad (2.5)$$

$$R_{cub} = 0.0286 \cdot I_r^{1.246} \cdot V_{us}^{1.85} \qquad \text{[MPa, km/s]} \qquad (2.6)$$

$$R_{cub} = 1.2 \cdot 10^{-9} \cdot I_r^{1.058} \cdot V_{us}^{2.446} \qquad \text{[MPa, m/s]} \qquad (2.7)$$

In Eqns. 2.5 - 2.7 I_r is the average value of Schmidt Rebound Hammer while V_{us} is the average value of Ultrasonic Pulse Velocity.
These equations, in most cases overestimates/underestimates the actual values of strength. For this reason it is required to validate specific expressions by a suitable correlation curve.
In the case of the SonReb method the law of correlation among compressive strength, Rebound Hammer index and ultrasonic velocity can be expressed as (Pucinotti 2005):

$$R_{cub} = a \cdot I_r^{b} \cdot V_{us}^{c} \qquad \text{[MPa, m/s]} \qquad (2.8)$$

in which the values of the constants *a* and *b* are deduced by the least-squares method.

3. STATISTICAL EVALUATION

3.1 Description of population

Statistical assessments were conducted to 745 structural elements. They belong to 89 existing RC buildings built between the 50's and 80's (Cristofaro 2009) in which both destructive and non-destructive tests were conducted.
Figure 3.1 shows, for each decade of construction, the percentage of investigated buildings, cores extracted and SonReb tests.
The most significant statistical parameters of cubic concrete strength R_{cub} obtained by the Eqns. 2.5, 2.6, 2.7 and 2.8 are shown in the Table 3.1: mean, median, standard deviation and coefficient of variation.

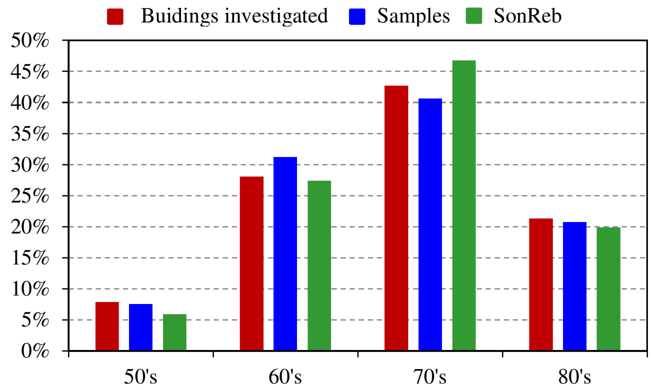

Figure 3.1. Percentage of buildings investigated, cores extracted and SonReb tests.

Table 3.1. Statistical parameters of R_{cub}' and of R_{cub} for four decades considered.

Eqns.	Decades	Mean (MPa)	Median (MPa)	Stand. Dev. (MPa)	Coef. of Var.
$R_{cub'}$ (2.4)	50's	13.83	12.23	4.54	0.33
	60's	17.07	17.44	4.32	0.25
	70's	24.12	22.95	8.24	0.34
	80's	29.55	29.28	7.66	0.26
Giacchetti, Lacquaniti (2.5)	50's	11.35	9.67	6.53	0.58
	60's	12.98	11.73	5.24	0.40
	70's	18.53	17.09	7.24	0.39
	80's	23.32	24.05	7.90	0.34
Gašparik (2.6)	50's	16.71	14.69	7.69	0.46
	60's	18.83	18.22	6.03	0.32
	70's	24.99	23.81	7.47	0.30
	80's	29.74	31.39	7.99	0.27
Di Leo, Pascale (2.7)	50's	14.89	13.15	7.34	0.49
	60's	16.89	15.27	6.03	0.36
	70's	23.08	22.12	8.12	0.35
	80's	28.59	29.08	8.56	0.30
(2.8)	50's	13.59	11.75	4.69	0.35
	60's	16.75	16.67	4.30	0.26
	70's	23.87	22.68	8.31	0.35
	80's	29.32	29.42	7.75	0.26

3.2. Statistical analysis

For each building the mean cubic compressive strength R_{cub}' is estimated by the Eqn. 2.4.
Figure 3.2 shows the correlation between R_{cub}' and R_{cub} calculated by the Eqns. 2.5, 2.6, 2.7 and 2.8 respectively (Cristofaro 2009). A careful reader can see as for buildings constructed during the 50's, 60's and '70's, compressive strengths are lower than that of buildings constructed during the 80's. In fact, while for the older buildings compressive strengths reach a maximum of 30 MPa, in the case of buildings constructed during the 80's, compressive strengths varies between 25 and 60 MPa.

Moreover, it is possible to see that the values of the R_{cub} calculated by Eqns. 2.5, 2.6, 2.7 are sometimes overestimated and sometimes underestimated, while the assessment carried out by Eqn. 2.8, calibrated to the experimental tests, is better. With the objective to compare reliability of previous formulations, we can define the percentage difference Δ % as:

$$\Delta\% = \frac{R_{cub} - R'_{cub}}{R'_{cub}} \tag{3.1}$$

In the Eqn. (3.1), $R_{SonrReb}$ represents the concrete compressive strength calculated by the Eqns. 2.5, 2.6 and 2.7 and shown in Table 3.2 where the mean percentage deviation $\Delta_{\_mean}$ % is reported.

$\Delta_{\_mean}$ % is shown in Figures 3.3a – 3.6a for the four decades considered, while Figures from 3.3b to 3.6b show the normal distributions of the mean percentage deviations for the individual decades and for the various formulations considered.

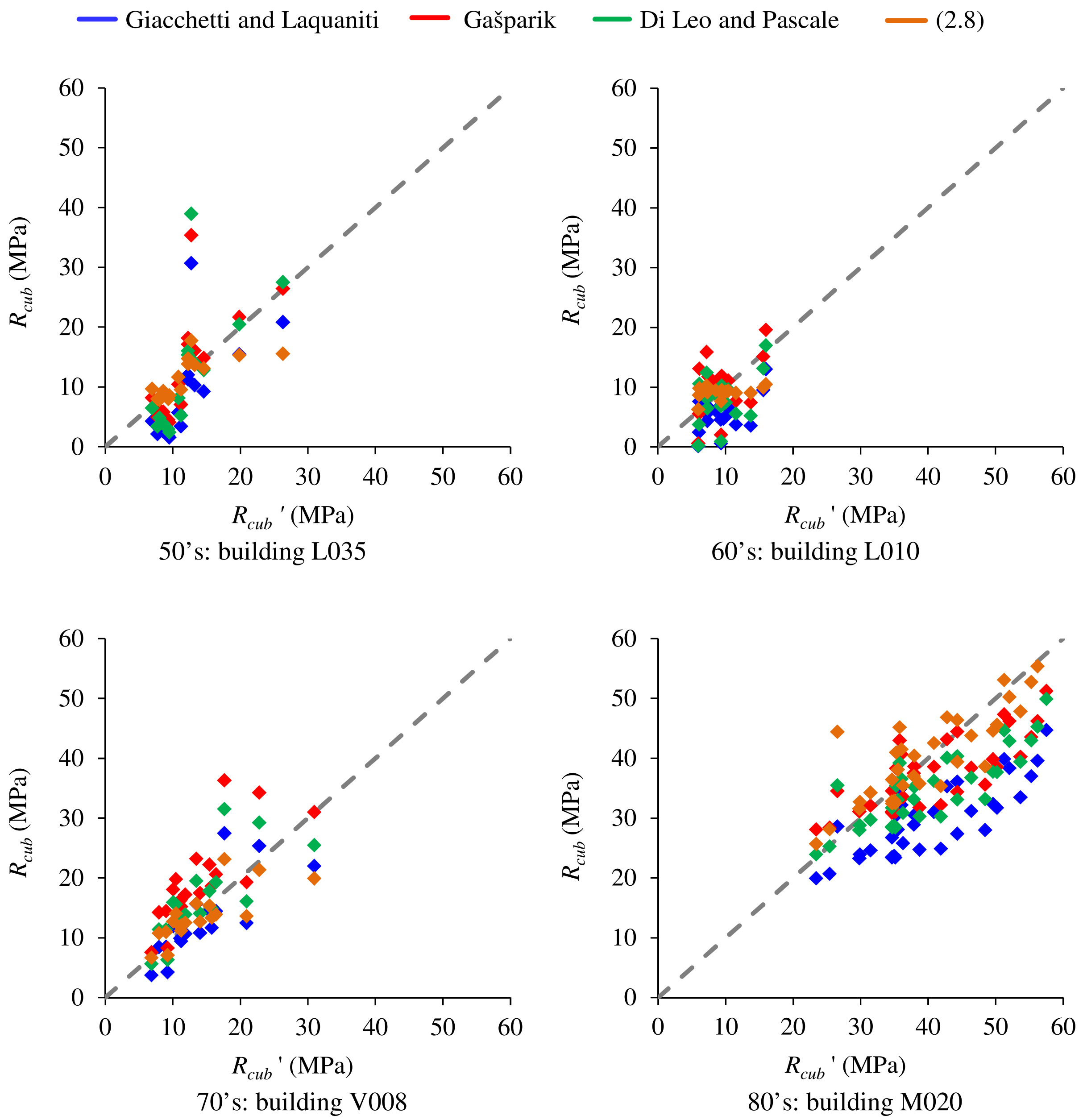

Figure 3.2. Correlation between R_{cub}' and R_{cub}.

In detail Figures 3.3a – 3.6a, show the distribution of $\Delta_{\_mean}$ %, for each Eqn. in relation with R_{cub}' of buildings constructed during all decades considered. It is evident as all the three Eqns. of literature overestimate or underestimate the actual value. In detail, the Eqn. 2.5 underestimate the actual value of compressive strength; Eqn. 2.6 overestimate it, while Eqn. 2.7 sometimes overestimate and sometimes Underestimate it. The proposed Eqn. 2.8 in all cases are close to the expected value.
The reliability of the relationships calibrated *ad hoc* is also evident from the observation of the normal distributions as shown in Figures 3.3b-3.6b. In fact, the curve obtained by the relation proposed for the all decades considered, shows a normal distribution closer and a $\Delta_{\_mean}$ % less than 2%. The other three formulations have a normal distribution larger with a greater dispersion.

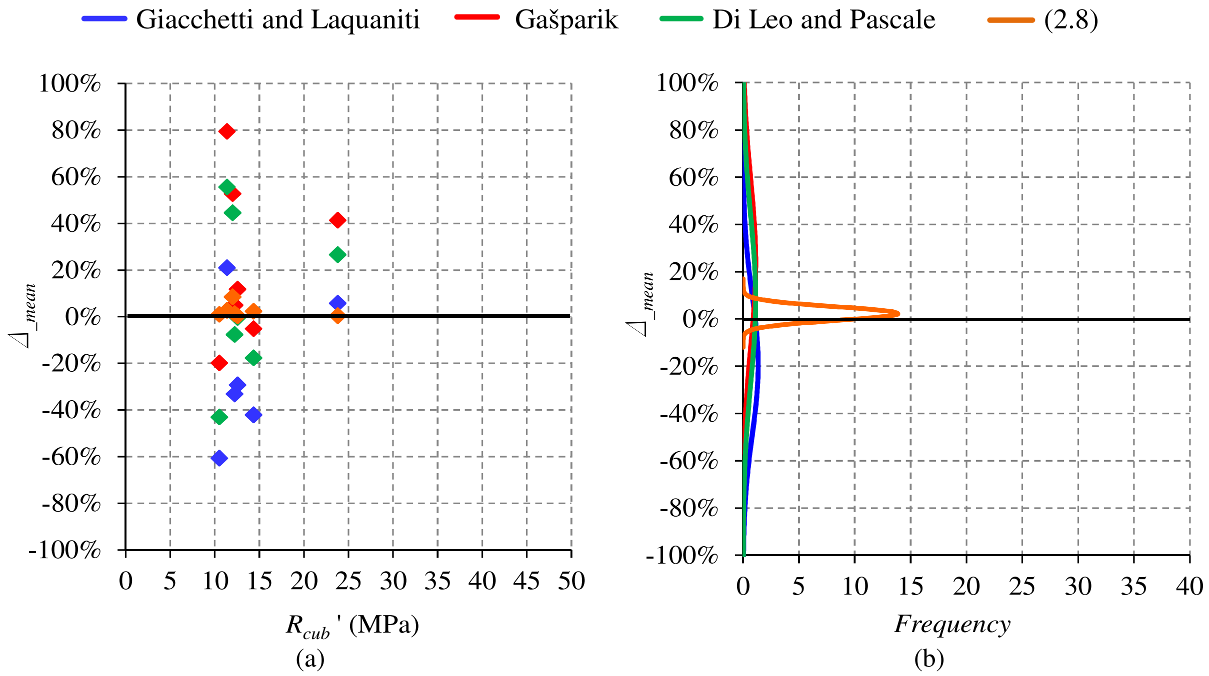

Figura 3.3. 50's: (a) mean percentage difference - (b) normal distribution.

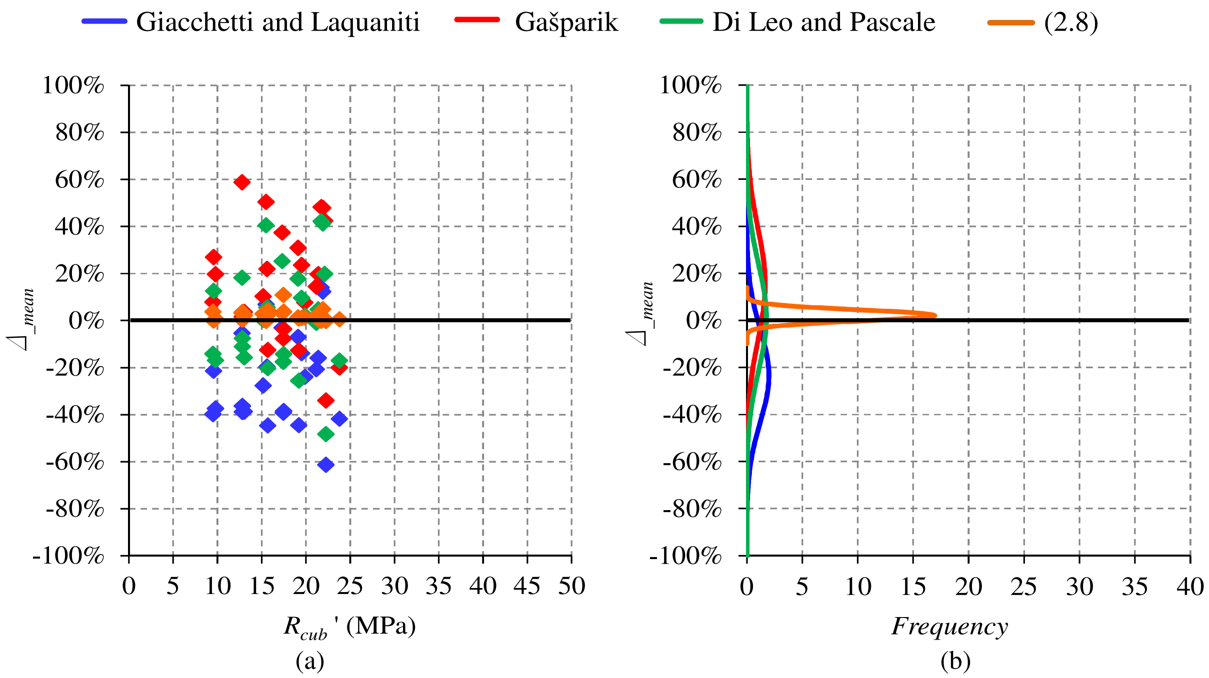

Figure 3.4. 60's: (a) mean percentage deviation – (b) normal distribution.

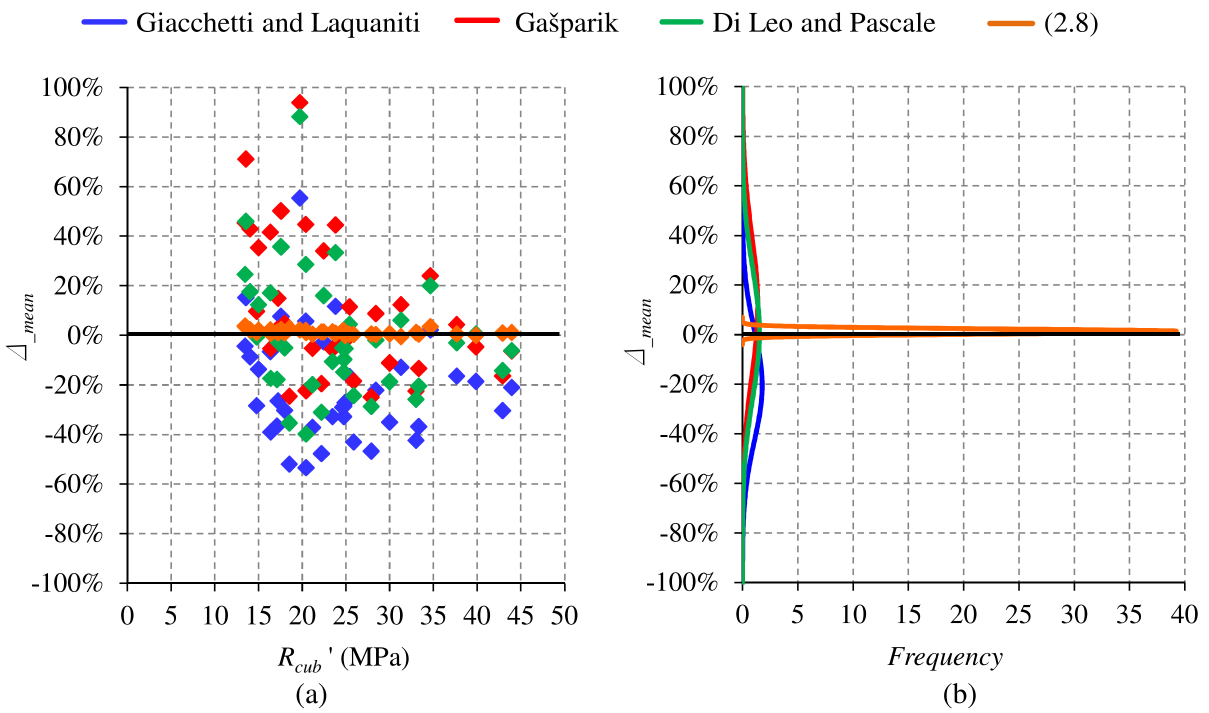

Figure 3.5. 70's: (a) mean percentage deviation – (b) normal distribution.

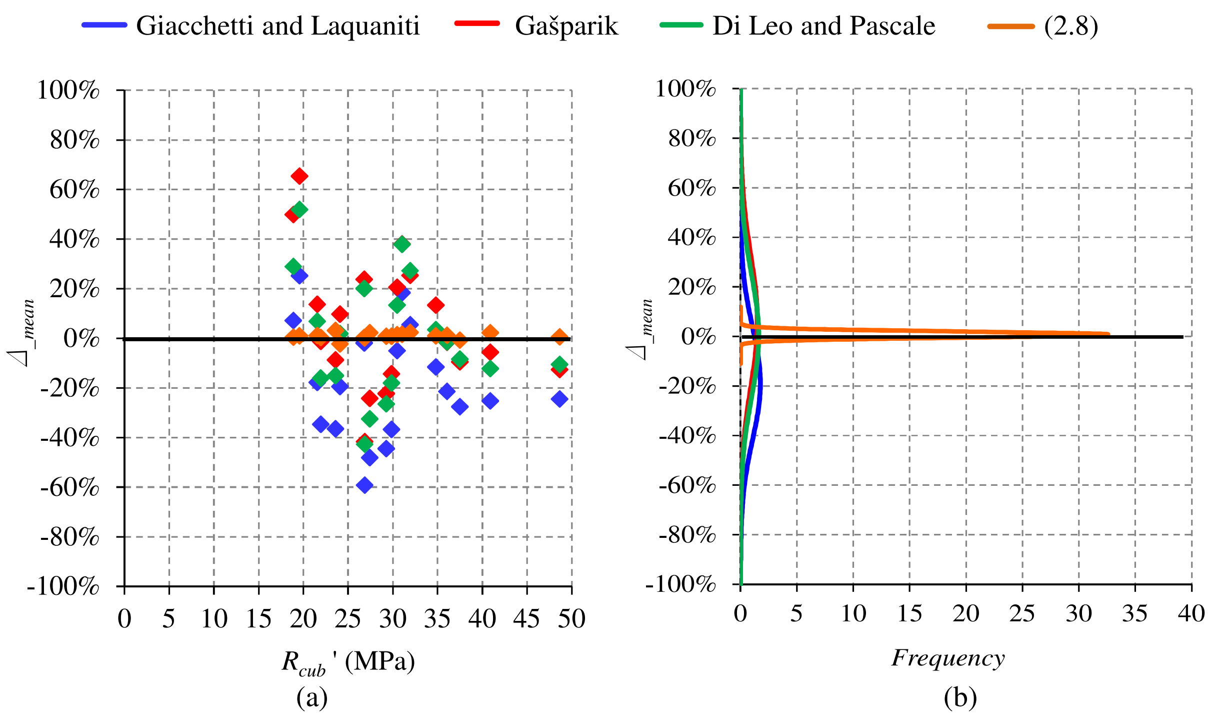

Figure 3.6. 80's: (a) mean percentage deviation – (b) normal distribution.

Table 3.2 shows, for the four decades considered, most significant statistical parameters of $\Delta_{\_mean}$ %: mean, median, standard deviation and coefficient of variation.

Table 3.2. Statistical parameters of $\Delta_{\_mean}$ % for the four decades considered.

Eqns.	Decades	Mean $\Delta_{\_mean}$ (%)	Median $\Delta_{\_mean}$ (%)	Stand. Dev. $\Delta_{\_mean}$ (%)	Coef. of Var. $\Delta_{\_mean}$ (%)
Giacchetti, Lacquaniti (2.5)	50's	-20	-29	29	151
	60's	-23	-24	20	85
	70's	-20	-27	22	110
	80's	-19	-22	23	120
Gašparik (2.6)	50's	24	12	35	150
	60's	15	14	24	157
	70's	12	3	29	>200
	80's	6	-1	27	>200
Di Leo, Pascale (2.7)	50's	8	0	35	>200
	60's	1	0	23	>200
	70's	1	-4	26	>200
	80's	0	-2	25	>200
(2.8)	50's	2	1	3	124
	60's	2	1	2	111
	70's	1	1	1	77
	80's	1	1	1	154

5. CONCLUSIONS

The evaluation of the concrete compressive strength is a fundamental step for the assessment of existing reinforced concrete RC buildings according to the most recent seismic codes. Non-destructive methods, although being minimally invasive and easily extensible to a large number of elements, are influenced by many factors.

In this paper the SonReb method was applied to perform statistical analyses using a wide database on existing RC buildings.

The comparison carried out shows how the use of known destructive methodologies (cores), associated with a non-destructive method (SonReb) allows to obtain a higher level of knowledge and a greater accuracy on the estimation of the concrete compressive strength if the relationship is calibrated *ad hoc* on the individual building. The results using the SonReb method, calibrated with the strength of cylindrical specimens (cores) extracted from a single building, are close to the actual ones.

In conclusion, the SonReb method, applied in this manner, provides a reliable assessment of the on-site concrete compressive strength which allows to obtain the required levels of knowledge. This, in turn, allows to limit the number of destructive tests needed to properly characterize concrete strength in existing buildings.

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