PREDICTIVE MODELS FOR EVALUATING CONCRETE COMPRESSIVE STRENGTH IN EXISTING BUILDINGS

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ABSTRACT :

An accurate assessment of the concrete compressive strength is a fundamental step towards evaluation of existing rc structures under gravity and seismic loads. The results obtained in previous studies by the authors on current destructive and non-destructive methods, dealing with buildings located in the Italian Region of Tuscany, show that the combined Sonreb method, considering different variants found in the relevant literature, consistently provides the best prediction of strength compared to the sclerometric and to the ultrasonic methods, being characterized by an high stability. In this paper, considering the same data base of experimental data used in the previous studies, new models are proposed to improve the prediction of concrete compressive strength as obtained from the sclerometric and ultrasonic methods, also to verify their capability to reach similar reliability to that of the Sonreb method.

KEYWORDS: Existing rc structures, concrete compressive strength, destructive and non-destructive testing.

1. INTRODUCTION

The most recent issues of the Italian seismic code have significantly boosted the need for seismic assessment of a large number of existing rc buildings. One fundamental step towards seismic assessment is a suitable estimate of concrete compressive strength, which, according to the Ordinanza P.C.M. n. 3431 (2005), can be obtained by integrating results from destructive tests with those from non-destructive tests having 'proved suitability'.
This approach is confirmed by the recent D.M. 14/01/2008 "Norme Tecniche per le Costruzioni" which requires that the characterization of mechanical properties of materials in existing structures be obtained from material testing, in addition to available documentation and in situ inspections.
Estimate of concrete compressive strength through non-destructive testing (sclerometric, ultrasonic, combined Sonreb methods) relies upon suitability of correlation formulas, which relate the measures of physical quantities to the concrete strength. In this respect, it has to be noticed that current formulas have been calibrated based on concrete samples that were realized 'ad hoc', thus representative of new buildings, i.e. these calibrations are usually not accounting for peculiarities of existing buildings.
In this study, therefore, the different available methods are compared by using a data base obtained by sampling 277 rc buildings built between the years '50 and '90; furthermore, reliability of different methods, destructive and non-destructive, is defined and new models are proposed for the estimation of concrete cubic compressive strength. The results provided by the new models are then compared to those obtained from well known models and it is proved that these new models make sclerometric and ultrasonic testing to achieve a degree of accuracy similar to that characterizing the combined Sonreb method.

2. ANALYZED SAMPLE

The data used in this paper refer to 277 existing rc public buildings, primarily school buildings, located in the most seismic areas of Tuscany: Amiata 6%, Casentino 9%, Valtiberina 16%, Lunigiana 21%, Garfagnana 21%

and Mugello 27%. These data were obtained from the Regional Seismic Department of Tuscany.
The sample was grouped according to the decade of construction, in order to obtain more homogeneous sample groups in terms of construction practices and technical codes. Most buildings, beyond 90%, were built between the ’60s and the ’80s, as shown in Figure 1.

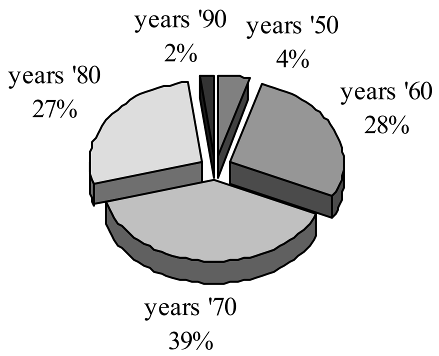


Figure 1 Distribution of building sample as a function of the construction decade

By grouping buildings according to their construction decade, it has been found (D'Ambrisi et al. 2007) that the average concrete cubic compressive strength of the sample built in the ‘50s is about 13 MPa, while it increases up to over 30 MPa for buildings constructed in the ‘80s.

3. ASSESSMENT OF CONCRETE COMPRESSIVE STRENGTH

For the determination of concrete cubic compressive strength from cylindric specimens the following four expressions were chosen among those available in the technical literature: British Standard (1983), Concrete Society (1976), Braga F. et al. (1992) and Cestelli Guidi M. and Morelli G. (1981).
Below, the average strength $R_{c,cub.ave}$ obtained by the above-mentioned four expressions is investigated, as their values do not differ significantly. It should be noticed that the above expressions have been calibrated for fresh concrete, 28 days after casting; therefore, their calibration does not refer directly to concrete from existing buildings, that can be characterized by remarkable effects of aging, such as carbonation.
Table 1 shows, for each decade of construction, the most significant statistical characteristics of concrete compressive strength $R_{c,cub.ave}$.
Regarding the sclerometric method, the formulas chosen for obtaining $R_{c,\,cub}$ from the rebound index I_r are those developed by: Schmidt E. (1951), Schmidt E. (1960), Pascale G. (1993) and Del Monte E. et al. (2004). In this paper, five new expressions were validated: one of them refers to the entire sample of 860 data Eqn. 3.1 and the other four refer to each decade: the '50s Eqn. 3.2, the '60s Eqn. 3.3, the '70s Eqn. 3.4 and the ‘80s Eqn. 3.5:

$$R_{c,cub} = 5{,}1698 \cdot e^{0{,}0341 \cdot I_r} \quad \text{[MPa]} \tag{3.1}$$

$$R_{c,cub} = 5{,}0398 \cdot e^{0{,}0254 \cdot I} \quad \text{[MPa]} \tag{3.2}$$

$$R_{c,cub} = 7{,}0427 \cdot e^{0{,}0225 \cdot I} \quad \text{[MPa]} \tag{3.3}$$

$$R_{c,cub} = 6{,}6614 \cdot e^{0{,}0273 \cdot I_r} \quad \text{[MPa]} \tag{3.4}$$

$$R_{c,cub} = 9{,}5529 \cdot e^{0{,}0265 \cdot I_r} \quad \text{[MPa]} \tag{3.5}$$

In Figures 2 and 3 the correlation between the rebound index and $R_{c,cub.ave}$ is shown. Additionally, the four models resulting from literature formulas, the new model herein calibrated over the entire data base, i.e. Eqn. 3.1, and the new models referred to each decade are presented.

It can be seen that the four literature models tend to overestimate the concrete compressive strength while the models calibrated in this paper: Eqn. 3.1, Eqn. 3.2, Eqn. 3.3, Eqn. 3.4 and Eqn. 3.5, lead to better predictions of $R_{c,cub}$.

Table 1 Principal statistical characteristics of $R_{c,cub\ ave}$: (a) years ’50, (b) years ’60, (c) years ’70, (d) years ’80

R c,cub ave (MPa)	
Average	13.25
Standard error	0.75
Median	12.26
Standard deviation	5.99
Min	5.68
Max	43.56
Level of significance (95,0%)	1.50

(a)

R c,cub ave (MPa)	
Average	18.09
Standard error	0.44
Median	16.72
Standard deviation	8.24
Min	4.55
Max	48.34
Level of significance (95,0%)	0.86

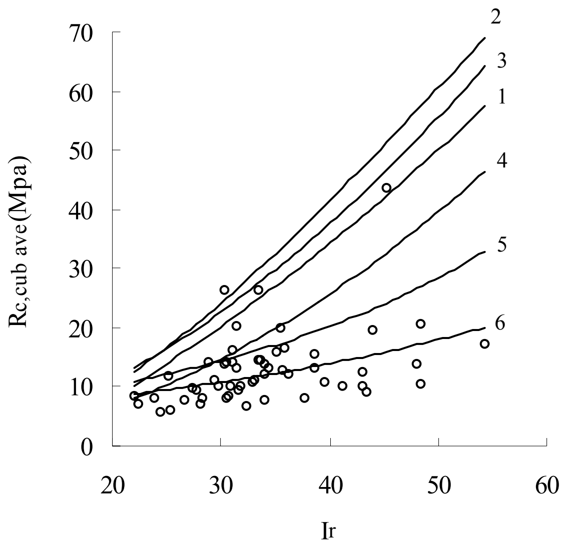
(b)

R c,cub ave (MPa)	
Average	22.47
Standard error	0.54
Median	20.45
Standard deviation	10.39
Min	5.00
Max	60.24
Level of significance (95,0%)	1.07

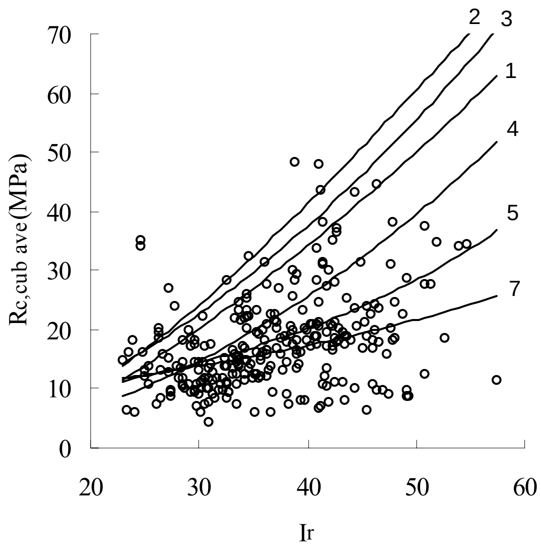
(c)

R c,cub ave (MPa)	
Average	30.92
Standard error	0.79
Median	28.67
Standard deviation	11.55
Min	9.67
Max	66.70
Level of significance (95,0%)	1.55

(d)



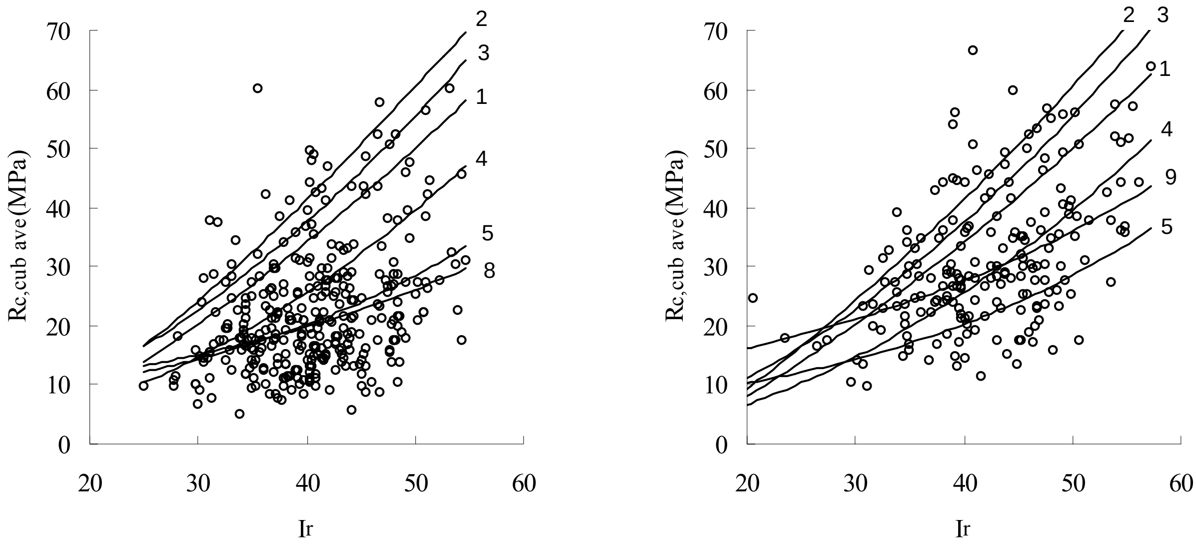
(a)



(b)

1 – Schmidt (1951) 2 – Schmidt (1960) 3 – Pascale (1993) 4 – Del Monte et al. (2004)
5 – Eqn. 3.1 6 – Eqn. 3.2 7 – Eqn. 3.3

Figure 2 Comparison among sclerometric models: (a) years ’50, (b) years ’60



(a) (b)

1 – Schmidt (1951) 2 – Schmidt (1960) 3 – Pascale (1993) 4 – Del Monte et al. (2004)
5 – Eqn. 3.1 8 – Eqn. 3.4 9 – Eqn. 3.5

Figure 3 Comparison among sclerometric models: (a) years '70, (b) years '80

The data base has been treated similarly regarding the ultrasonic method. The literature formulas chosen to predict the $R_{c,cub}$ are: Belgian Standards (1976), Cestelli Guidi M. and Morelli G. (1981), Popovics S. (1986), Ciampoli M. and Napoli P. (1993) and Del Monte E. et al. (2004).
Even in this case five new exponential models have been calibrated to correlate $R_{c,cub}$ with the velocity of the ultrasonic pulse, measured on the element before being subjected to coring, V_{us1}: one refers to all available data Eqn. 3.6; the others to each decade: the '50s Eqn. 3.7, the '60s Eqn. 3.8, the '70s Eqn. 3.9 and the '80s Eqn. 3.10.

$$R_{c,cub} = 2{,}9010 \cdot e^{0{,}0006 \cdot V_{us1}} \quad \text{[MPa]} \tag{3.6}$$

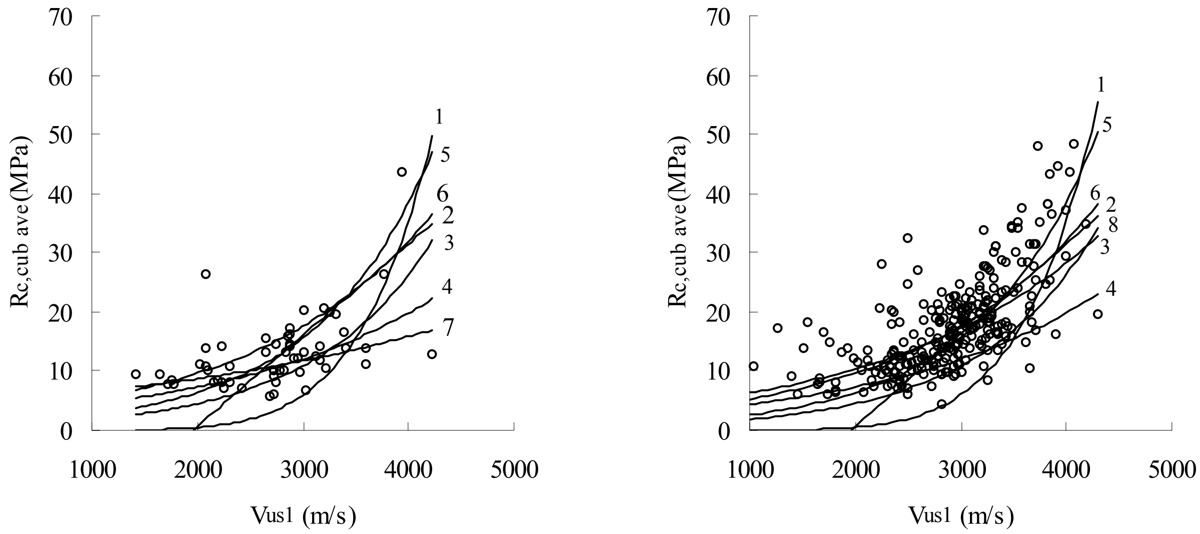
$$R_{c,cub} = 4{,}7704 \cdot e^{0{,}0003 \cdot V_{us1}} \quad \text{[MPa]} \tag{3.7}$$

$$R_{c,cub} = 3{,}8281 \cdot e^{0{,}0005 \cdot V_{us1}} \quad \text{[MPa]} \tag{3.8}$$

$$R_{c,cub} = 3{,}2360 \cdot e^{0{,}0006 \cdot V_{us1}} \quad \text{[MPa]} \tag{3.9}$$

$$R_{c,cub} = 3{,}7537 \cdot e^{0{,}0006 \cdot V_{us1}} \quad \text{[MPa]} \tag{3.10}$$

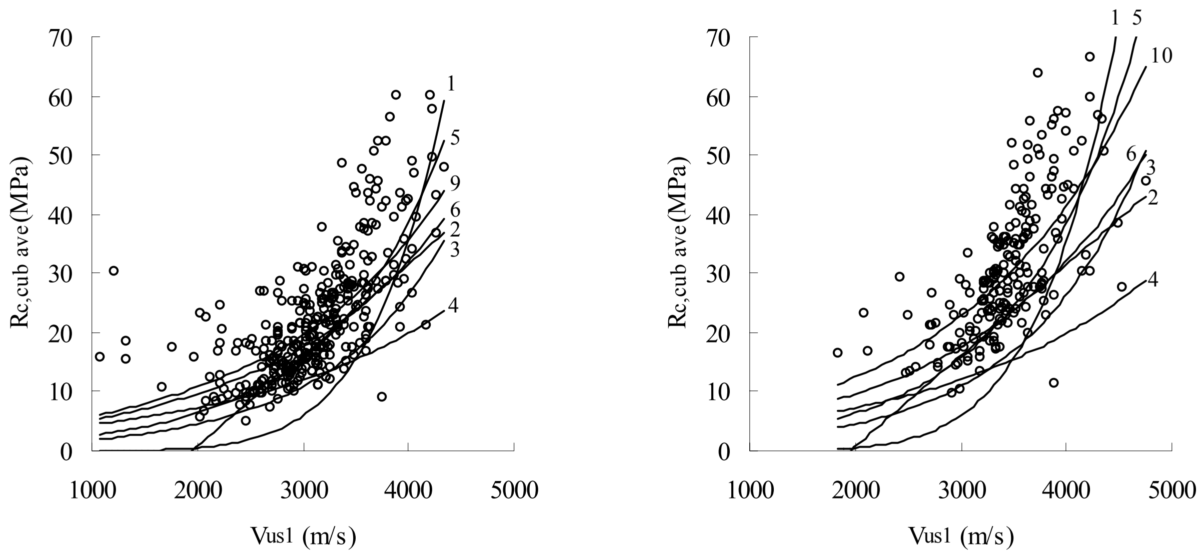
Figures 4 and 5 show the results obtained with the above ultrasonic models and the correlation between velocity of the ultrasonic pulse and the average cubic compression strength. On this dispersion chart the literature models Belgian Standards (1976), Cestelli Guidi M. and Morelli G. (1981), Popovics S. (1986), Ciampoli M. and Napoli P. (1993) and Del Monte E. et al. (2004) have been also represented, for the sake of comparison. It is evident that correlation models Eqn. 3.6, Eqn. 3.7, Eqn. 3.8, Eqn. 3.9 and Eqn. 3.10 provide better results than current models in the technical literature.
For the combined method Sonreb (sclerometric + ultrasonic methods), only existing models, i.e. those from Giachetti R. and Lacquaniti L. (1980), Gašparik J. (1992), Di Leo A. and Pascale G. (1994), Arioğlu E. and Köylüoğlu O. (1996) and Del Monte E. et al. (2004), have been considered to check their reliability.



(a) (b)

1 – Belgian Standards (1976)
2 – Cestelli Guidi and Morelli (1981)
3 – Popovics (1986)
4 – Ciampoli and Napoli (1993)
5 – Del Monte et al. (2004)
6 – Eqn. 3.6
7 – Eqn. 3.7
8 – Eqn. 3.8

Figure 4 Comparison of ultrasonic models: (a) years ’50, (b) years ’60



(a) (b)

1 – Belgian Standards (1976)
2 – Cestelli Guidi and Morelli (1981)
3 – Popovics (1986)
4 – Ciampoli and Napoli (1993)
5 – Del Monte et al. (2004)
6 – Eqn. 3.6
9 – Eqn. 3.9
10 – Eqn. 3.10

Figure 5 Comparison of ultrasonic models: (a) years ’70, (b) years ’80

To gain further insight into reliability of the examined non-destructive methods, as well as of the proposed correlation models, to predict cubic compressive strength, the mean errors, non-dimensionalized to the average strength of the corresponding decades (denoted as 'mean relative error'), are shown in Figures 6, 7 and 8.
Regarding the sclerometric method (Figure. 6), it emerges that it is unsuitable when existing models are used to correlate the rebound index to the concrete compressive strength, as the mean relative error may reach even a value of 1.40 with the Schmidt E. (1960) formulation when applied to buildings of the '50s. With the models calibrated in this paper, mean relative error reduces significantly, up to 0.25 for the buildings of the'80s, a value similar to that obtained with the Sonreb method (Figure 8).

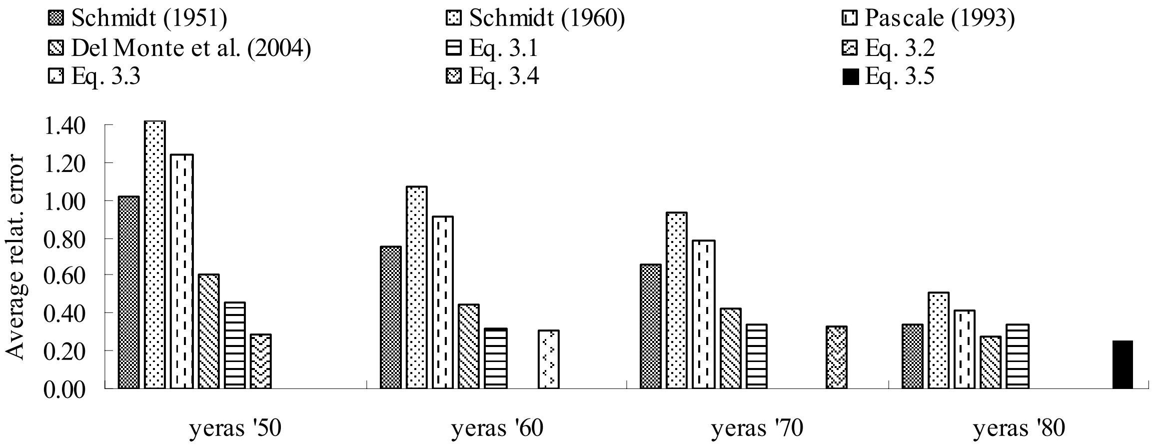


Figure 6 Sclerometric method: comparison of mean relative error for the different formulations under investigation

The ultrasonic method, though generally presenting values of the mean relative error lower than those found for the sclerometric method, still is characterized by a rather poor reliability, as mean relative errors may reach a value of 0.65 for the model subscribed by the Belgian Standards (1976) when applied to buildings of the '50s (Figure 7). With the model proposed herein, Eqn. 3.10, a remarkable improvement is obtained since mean relative error reduces up to 0.22 for the buildings of the'80s, a value again similar to that achieved with the Sonreb method.

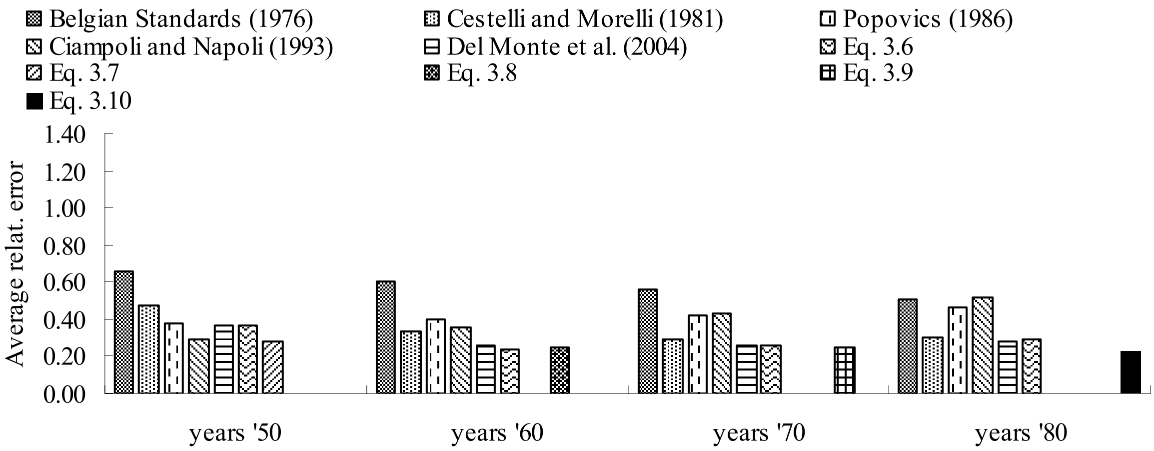


Figure 7. Ultrasonic method: comparison of mean relative error for the different formulations under investigation

As expected, the Sonreb method achieves the lowest errors, which never exceed 0.45 with the expression by Arioğlu E. and Köylüoğlu O. (1996), as shown in Figure 8. Such method is also very stable as the adopted model varies, since values differ slightly within each decade. With the formulations of Gašparik J. (1992), Di Leo A. and Pascale G. (1994) and Del Monte E. et al. (2004) the best correlations are obtained, as the mean relative error reduces up to 0.21 for the '80s (Figure 8). As previously underlined, only the exponential models proposed herein for the sclerometric and the ultrasonic methods achieve a similar reliability.

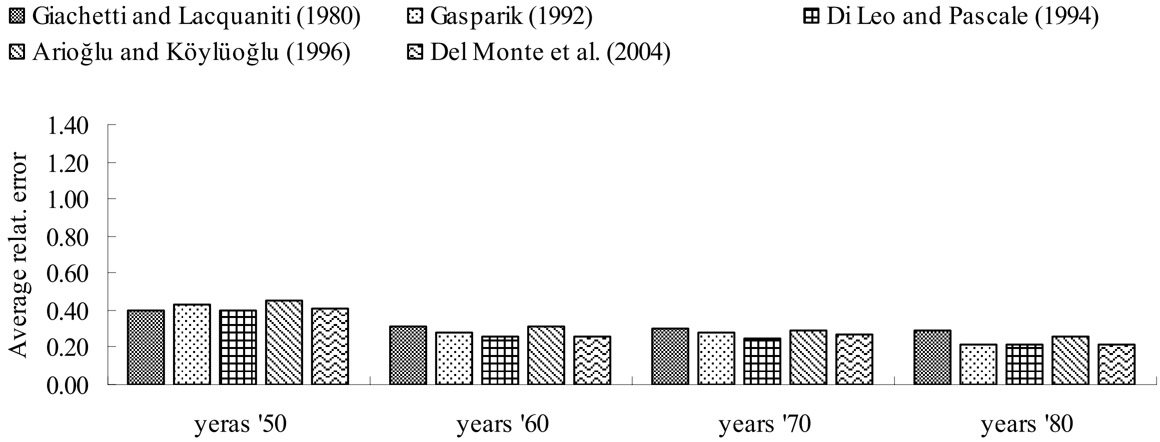


Figure 8 Sonreb method: comparison of mean relative error for the different formulations under investigation

4. CONCLUSIONS

In this paper a data-base of 860 cores from beams and columns belonging to 277 existing rc buildings has been analyzed to calibrate new models for correlating sclerometric and ultrasonic tests to concrete compressive strength. The available data have been grouped according to the building decade of construction in order to improve data interpretation.

When using current predictive models, taken from the relevant literature, it has been found that sclerometric and ultrasonic methods are not suitable as their reliability is much lower than that of the combined Sonreb method, which generally presents a mean relative error of about 0.21. In particular, models based on the sclerometric method are totally unreliable since the corresponding mean relative error may reach even a value of 1.40; models based on the ultrasonic method are characterized by low reliability, as the mean relative error ranges from 0.65 to 0.22.

With the predictive exponential models presented in this paper, the sclerometric and the ultrasonic methods can be used almost as reliably as the combined Sonreb method, which is universally considered the most suitable one.

5. ACKNOWLEDGEMENTS

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