# IMPROVED SONREB METHOD FOR THE ASSESSMENT OF CARBONATED CONCRETE

MARCO BRECCOLOTTI, *marco.breccolotti@unipg.it*
MASSIMO FEDERICO BONFIGLI
ANNIBALE LUIGI MATERAZZI
Department of Civil and Environmental Engineering, Perugia, Italy

**Abstract:** The safety evaluation of existing RC buildings strictly depends on the accurate evaluation of the concrete compressive strength. The most consistent way to determine this property is by means of testing on concrete cores extracted from the actual structures. However, non-destructive testings like the SonReb method would be preferred because they do not damage structures, but they are not as reliable as destructive ones. In particular, it is well known in the literature that one of the most important issues encountered using the SonReb method on existing structures is the effect of carbonation of concrete surface. Infact it alters the concrete physico-mechanical characteristics, producing rebound index measures that are no more a good depiction of the effective inner concrete properties. In this work, Authors have developed an improvement of the SonReb method by taking into account, as an additional input parameter, the thickness of the carbonated concrete layer. Using experimental data obtained from existing structures they have shown how this method resulted in a significantly improved accuracy against other traditional NDTs.

**Keywords:** NDT, SonReb, concrete, carbonation, rebound index, I-SonReb.

## 1. Introduction

SonReb method is one of the most used NDT method for in-place assessment of concrete compressive strength in existings structures. It consists in combining ultrasonic pulse velocities and rebound index measurements by means of an empirical correlation equation, calibrated using destructive tests, in order to evaluate the material strength. The rebound index belongs to the surface hardness methods but has been modified to take into account the properties of concrete. In fact, the R index is the ratio between the distances traveled after and before the impact by the impacting mass, expressed in percent. Concretes having low strength dissipate more energy by crushing and thus producing a smaller rebound distance. Conversely, concretes with higher strength behave more elastically, giving back more energy to the impacting mass. The ultrasonic pulse velocity method, instead, is based on the relationship between the elastic modulus and the pulse velocity inside an isotropic homogeneus material and on the indirect correlation between concrete strength and stiffness.

The combination of both techniques is useful to partially counterbalance their drawbacks: rebound hammer measurements are significantly affected by the conditions of the outer layer of concrete, ultrasonic measurements are instead affected by the presence of reinforcement or of a hidden internal cracking. One of the most used form for the SonReb correlation expression is given in Eq.1:

$$f_c = a_1 \cdot R^{a_2} \cdot V^{a_3} \tag{1}$$

where: R and V are the measured rebound index and ultrasonic pulse velocity, respectively.

It is well known [1] [2] however that the phenomena of surface carbonation increases the measured values of the rebound index. In fact, carbonation is a chemical process that increases both the material strength and stiffness. This usually results in an overestimation of actual concrete strength that hugely decreases the accuracy of traditional rebound hammer and SonReb methods in presence of carbonation. Moreover this phenomenon is most of the times present in old reinforced concrete structures, the ones for which a load bearing evaluation is usually required. In the present paper Authors have investigated the influence of carbonation thickness on measured rebound index by means of a first exploratory finite element analisys of the impact phenomena, and then, based on the obtained results, they have defined an improved SonReb method that has been validated using data coming from real-world structures.

## 2. Numerical investigation of the influence of carbonation on rebound hammer measurements

As a first step, a numerical analysis has been carried out [3] to evaluate how the presence of a carbonated concrete surface of a given thickness alters the measured rebound index from the one that would have been obtained in absence of carbonation. Numerical modeling is particularly useful since it allows Authors to ignore all the other sources of uncertainities usually involved in NDTs tests that could have resulted in difficulties while catching the fundamentals of the investigated phenomenon.

The finite element analysis has been performed using the Abaqus environment with an explicit integration scheme. Since the rebound index directly depends on the ratio between the velocities of the plunger before and after the impact, the analysis consisted in observing how the rebound speed of the impacting plunger changes when the carbonated surface thickness changes. The constitutive model adopted to model the concrete behavior is the Concrete Damaged Plasticity (CDP), which is suitable to describe both the ratio-dependent and inelastic behavior of concrete even under triaxial states of stress. Only a given concrete strength, 24MPa, was investigated given the difficulties in obtaining the physical and mechanical data needed to properly describe both the non-carbonated and carbonated concretes. Nevertheless, it is Authors'opinion that the general conclusions drawn for a specific concrete can easily be transferred to concretes of different strengths.

The geometry of the model consists in an axisymmetrical solid of radius 100 mm and height 200 mm. The specimen is splitted into three parts corresponding to the following three different materials: non-carbonated concrete in the inner core, carbonated concrete in the outer surface of thickness $x_c$ and a layer of partially carbonated concrete in between the previous two materials having the same thickness $x_c$ of the outer one. Chang and Chen [4] experimentally investigated the existence of this latter zone that has about the same thickness of the fully carbonated layer. The property of these different materials were obtained from the literature [4] [5] [6]. For the CDP parameters Authors have performed a sensitivity analysis to evaluate wheter the velocity after rebound was influenced by them or not. In the first case the parameters have been calibrated using experimental rebound hammer measurements on non-carbonated concretes. Figure 1 and Figure 2 illustrate typical outputs in terms of vertical normal stresses distribution.

Authors have defined the coefficient of correction $k(x_c)$ the ratio between the rebound index in absence of carbonation and the one in presence of a concrete surface of thickness $x_c$

$$k_c(x_c) = \frac{Q(0)}{Q(x_c)} \tag{2}$$

where: Q is the rebound index which is defined as the ratio of the post and pre-impact speeds of the plunger.

The results of the numerical investigations are plotted in Figure 3, along with other data found in the literature [7] [8] that confirms the validity of the findings.

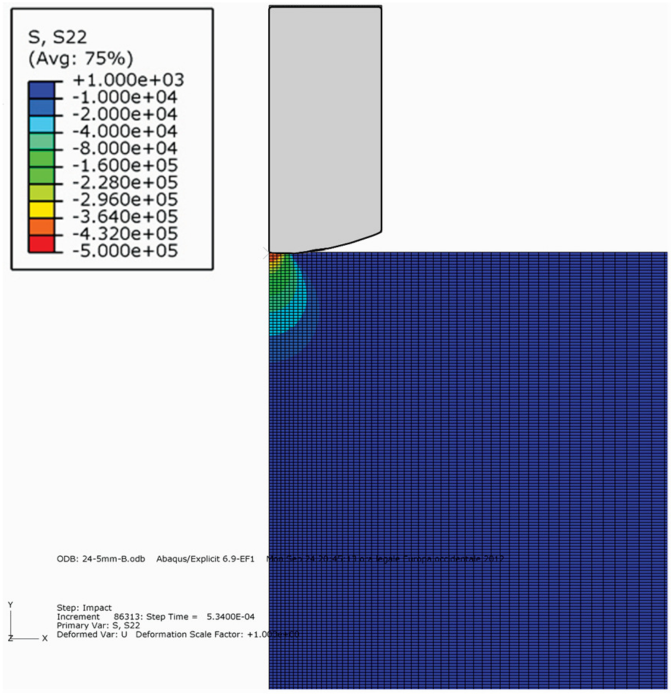


Fig. 1. Typical distribution of vertical normal stresses in concrete during the rebound hammer impact obtained by means of FE analysis. Stresses at the beginning of the contact

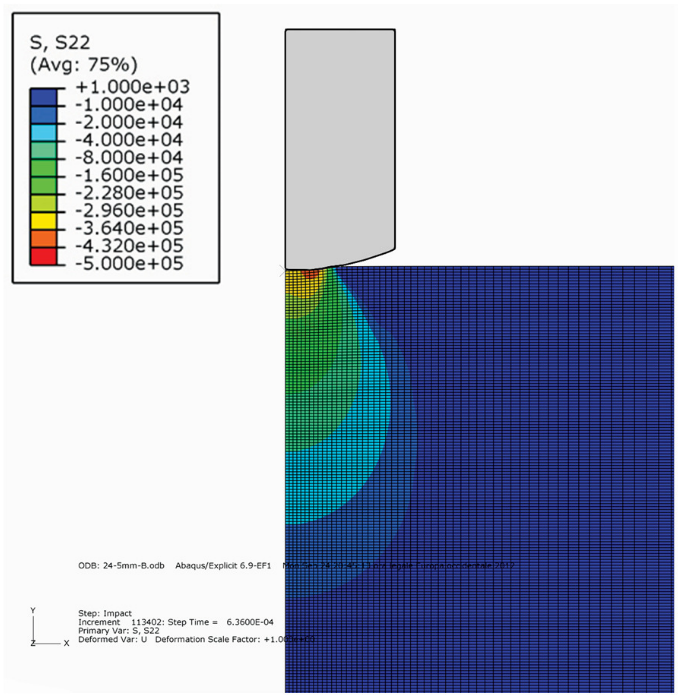


Fig. 2. Typical distribution of vertical normal stresses in concrete during the rebound hammer impact obtained by means of FE analysis. Stresses at the beginning of the rebound

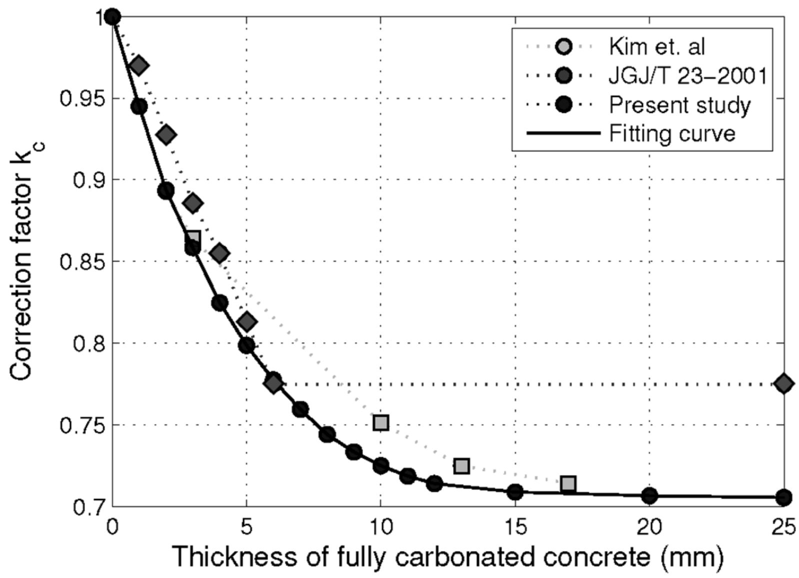


Fig. 3. Comparison between experimental and numerical values of $k_c$

From this data a general expression for the coefficient of correction $k(x_c)$ has been derived:

$$k_c(x_c) = 1 - e^{b_1} + e^{b_1 \cdot e^{x_c / b_2}} \quad (3)$$

where, for the specific concrete being investigated, it results $b_1 = -1.2$ and $b_2 = 7.5$.

Eq. 3 can be used to model the way in which carbonation affects the rebound index. As for the classic SonReb correlation expression, Eq. 3 still needs to be calibrated against experimental data collected from the same concrete being investigated. Infact, if a proper evaluation of parameters of Eq. 3 is obtained by using destructive tests than the measured rebound numbers in presence of carbonation could be used, along with actual carbonated surface thickness $x_c$, to obtain the ones that would have been measured in absence of carbonation, that better represents the properties of the inner, non carbonated, concrete.

## 3. Investigation of carbonation influence on ultrasonic pulse velocities measurements.

Before the definition of an improved SonReb method that can be used in presence of carbonation, the influence of this latter on UPV measurements needs to be clarified. In a homogeneous and isotropic material, like concrete in this work is assumed to be, a compression wave travels with a velocity V given by:

$$V = \sqrt{\frac{(1-\nu_d)\, E_d}{(1+\nu_d)\,(1-2\,\nu_d)\rho}} \quad (4)$$

where: $\nu_d$ and $\rho_d$ are the concrete dynamic Poisson's ratio and the dynamic elastic modulus of the material.

Since carbonation alters both the elastic modulus and the density of concrete, it is necessary to evaluate the significance of this phenomenon in altering the UPV measurements. This explorative study is performed analyzing the problem for the same concrete analyzed in the previous section. It's Author's opinion that the general conclusions drawn will be valid for every ordinary concrete. An overview of the property of the investigated materials is given in Table 1. It should be pointed out that the value of $\nu_d$ in Eq. 4 has an almost negligible influence on the UPV measurements (less than 3%) if it belongs to the usual range [0.1, 0.2], so its accurate evaluation is not needed for the sake of this investigation. For $\nu_d$ a value equal to 0.15 has been assumed. The dynamic elastic modulus have been obtained from the static one by adopting, the provision of the British Standard BS 8110-2.

The following assumptions have been made:

1) The ultrasonic emitter and receiver probes are located in front of each other, at a distance S equals to the specimen width (direct transmission layout).
2) Under the fully carbonated layer there is another one of partial carbonation of the same thickness $x_c$ of the fully carbonated one.
3) The faces of the specimen are parallel and so are the surfaces that sperarates the non-carbonated layer from the partially carbonated one and the latter from the outer, fully carbonated surface.

The performed investigations allowed to point out the theoretical values of the coefficient of correction $k_v(S, x_{c,tot})$ defined as:

$$k_v = \frac{V(0)}{V(S, x_c)} \tag{5}$$

Under these assumptions, if the sum of the fully carbonated layers on the opposite surfaces is called $x_{c,tot}$ and the travelling speeds inside the non-carbonated concrete, the partially carbonated concrete and the fully carbonated one are respectively called $V_0$, $V_{pc}$ and $V_{fc}$ then the following expression for $k_v$ is obtained:

$$k_v\,(S, x_c) = \begin{cases} \dfrac{V_0\ x_{c,tot}}{S}\left(\dfrac{1}{V_{fc}} + \dfrac{1}{V_{fc}} - \dfrac{2}{V_0}\right) + 1 & if\quad x_{c,tot} \le \dfrac{S}{2} \\ \dfrac{V_0\ x_{c,tot}}{S}\left(\dfrac{1}{V_{fc}} - \dfrac{1}{V_{fc}}\right) + - \dfrac{V_0}{V_{pc}} & if\quad \dfrac{S}{2} \le x_{c,tot} \le S \end{cases} \tag{6}$$

The values of the parameter $k_v$ for values of S in the range [0-500 mm] are plotted in Figure 4 for different carbonated depths.

The *case a* and *case b* are referred respectively to the first and second branch of Eq. 6. It can be noticed how the theoretical influence of carbonation on UPV measurements is always under 9%. The striped region on the upper left corner represents the most frequently occourring conditions during in-situ evaluation. In this situation, the correction is even lower than 3%. The results allowed Authors to conclude that influence of carbonation on UPV measures is negligible and that it can be ignored.

Table 1. Physical and mechanical properties of the investigated concrete (from [4] [5] [6])

| **Concrete Type** | **Density (kg/m$^3$)** | **Static El. Modulus (MPa)** | **Static Poisson's Ratio** |
|---|---|---|---|
| Non-carb. concr | 2300 | 17967 | 0.15 |
| Part. carb. concr | 2325 | 20617 | 0.15 |
| Fully carb. concr. | 2400 | 26946 | 0.15 |

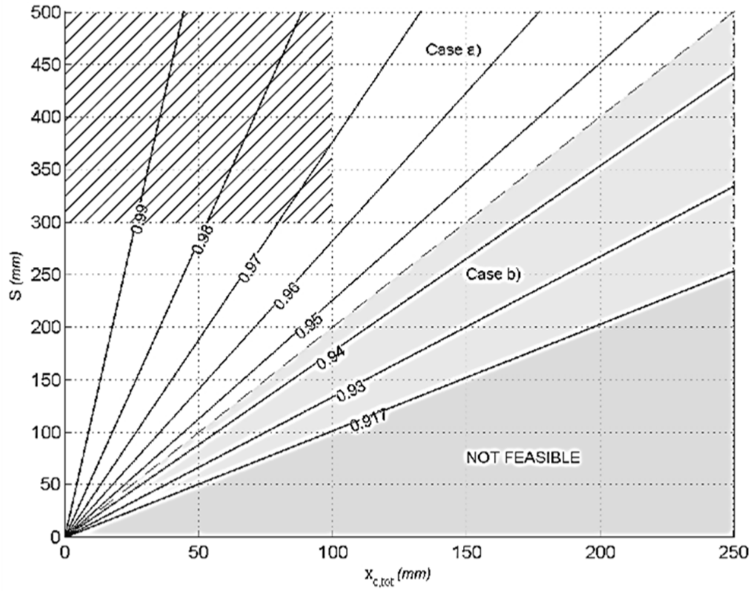


Fig. 4. Theoretical values of $k_V$ for different values of S and $x_{c,tot}$

## 4. Definition of an improved SonReb method

After the influence of carbonation over both rebound index and ultrasonic measurements has been investigated, it is possible to proceed to develop an improved SonReb method to being used in presence of carbonation.

By combining Eq. 1 with Eq. 2 and Eq. 3 the following new correlation expression is obtained:

$$f_c = a_1 \cdot \left[ R \cdot (1 - e^{b_1} + e^{b_1 \cdot e^{x_c / b_2}}) \right]^{a_2} \cdot V^{a_3} \tag{7}$$

The proposed improved SonReb (I-SonReb) method, based on Eq.7, consists in the following steps:

1) Choose a suitable number of places in the structure where to drill cores to calibrate the coefficients of Eq.7. It is advisable to choose sampling locations with different carbonation conditions, if possible.
2) Measure the rebound index R, ultrasonic pulse velocity V in positions identified in the previous step following the rules provided by appropriate international standards.
3) Extract cores and measure the thickness of carbonated layer by mean of a pheonlphtalein solution.
4) Test cores to evaluate the compressive strength of concrete $f_c$.
5) Find the coefficients of Eq.7 by non-linear fitting of the data set.
6) Perform an extended test campaign on the structure measuring for each sampling point the rebound index R, the ultrasonic pulse velocity V, the carbonation thickness $x_c$.
7) Use the correlation expression calibrated during step 5 to evaluate the concrete strength based on NDT data coming from step 6.

Authors have validated the proposed method by comparing its result with those obtained using traditional NDTs on datasets coming from real world structures. Each record of a dataset is composed by 4 measured values: the rebound hammer index, the ultrasonic pulse velocity, the carbonation thickness and the compressive strength obtained by compressive tests on concrete cores.

*Dataset 1*

This set of data comes from the measurements performed in 2013 on RC columns of a ten floor building located in Rome. The collected data were used to fit Eq.1, Eq.7 along with the following equations:

$$f_c = a_1 \cdot R^{a_2} \tag{8}$$

$$f_c = a_1 \cdot V^{a_3} \tag{9}$$

that correspond to the rebound hammer method and UPV method, respectively. The comparison has been performed in terms of the coefficient of determination $R^2$ that is a synthetic parameter commonly used to evaluate the goodness of fit. The results clearly shows that by using Eq. 7, which keeps into consideration as an additional data the concrete carbonation thickness, the goodness of fit in terms of $R^2$ is significantly better than the one achieved using the traditional rebound hammer, UPV or combined SonReb methods. Table 2 summarizes the results of the fitting of these 4 expressions.

Table 2. Results of fittings using dataset 1

| Correlation formula | $a_1$ | $a_2$ | $a_3$ | $b_1$ | $b_2$ | $R^2$ |
|---|---|---|---|---|---|---|
| $f_c = a_1 \cdot R^{a_2}$ | 0.16 | 1.47 | | | | 0.356 |
| $f_c = a_1 \cdot V^{a_3}$ | $1.12 \cdot 10^{-5}$ | | 1.83 | | | 0.457 |
| $f_c = a_1 \cdot R^{a_2} \cdot V^{a_3}$ | $9.04 \cdot 10^{-6}$ | 1.04 | 1.38 | | | 0.598 |
| $f_c = a_1 \cdot \left[ R \cdot (1 - e^{b_1} + e^{b_1 \cdot e^{x_c / b_2}}) \right]^{a_2} \cdot V^{a_3}$ | $3.38 \cdot 10^{-5}$ | 1.36 | 1.08 | -1.79 | 20.82 | 0.713 |

Table 3. Results of fittings using dataset 2

| Correlation formula | $a_1$ | $a_2$ | $a_3$ | $b_1$ | $b_2$ | $R^2$ |
|---|---|---|---|---|---|---|
| $f_c = a_1 \cdot R^{a_2}$ | 0.047 | 1.79 | | | | 0.304 |
| $f_c = a_1 \cdot V^{a_3}$ | $5.75 \cdot 10^{-4}$ | | 1.34 | | | 0.178 |
| $f_c = a_1 \cdot R^{a_2} \cdot V^{a_3}$ | $7.87 \cdot 10^{-8}$ | 2.04 | 1.48 | | | 0.635 |
| $f_c = a_1 \cdot \left[ R \cdot (1 - e^{b_1} + e^{b_1 \cdot e^{x_c / b_2}}) \right]^{a_2} \cdot V^{a_3}$ | $5.06 \cdot 10^{-6}$ | 1.29 | 1.36 | -0.84 | 47.17 | 0.813 |

*Dataset 2*

The second set of data comes from the measurements performed in 2011 on several piers and capbeams of a viaduct. The analysis is the same of that carried out on dataset 1, and the results are summarized in Table 3. The results confirm the trend that was observed also in dataset 1. The goodness of fitting is greatly improved by passing from the traditional SonReb method ($R^2$ = 0.635) to the proposed I-SonReb method ($R^2$ = 0.813) and overall the error in estimating the actual concrete strength is significantly reduced.

## 5. Conclusions

In this paper Authors have proposed an improvement of the traditional SonReb method to increase the accuracy of concrete strength extimation by means of NDTs in presence of carbonation, a very likely condition in old structures. First it has been carried out a numerical investigation on the influence of carbonation on rebound index, obtaining a general expression of a corrective coefficient to be applied to the measured rebound index values. Afterwards Authors have investigated the opportunity of correcting UPV values, concluding that the error introduced by carbonation is negligible and thus ignoring it. Finally, an improved SonReb method has been defined and applied to two datasets coming from existing structures. The results have shown a significant improvement in estimating concrete strength using the proposed method with respect to the traditional SonReb, UPV and rebound hammer methods.

## 6. Aknowledgments

Authors would like to thank MOST S.r.l. for providing the experimental data used in this research project.

## References

1. Amasaki S. Estimation of strength of concrete structures by the rebound hammer, CAJ Proceedings of Cement and Concrete, nr 45/1991.
2. Malhotra V, Carino N. J., Handbook on Nondestructive Testing of Concrete, Second Edition, CRC Press, 2003.
3. Breccolotti M., Bonfigli M.F., Materazzi A.L. Influence of carbonation depth on concrete strength evaluation carried out using the SonReb method, NDT&E International, nr 59/2013
4. Chang C.F., Chen J.W. The experimental investigation of concrete carbonation depth, Cement and Concrete Research, nr 36/2006.
5. Chang C.F., Chen J.W. Strength and elastic modulus of carbonated concrete, Materials Journal, nr 102/2005.
6. Jerga J. Physico-mechanical properties of carbonated concrete, Construction and Building Materials, nr 18/2004.
7. Kim J-K et al. Effect of carbonation on the rebound number and compressive strength of concrete, Cement and Concrete Composites, nr 31/2009.
8. JGJ: JGJ T23/2001: Technical specification for inspection of concrete compressive strength by rebound method, Industrial Standard of the People's Republic of China, 2001.