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Calibration and Reliability of the Rebound (Schmidt) Hammer Test

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Abstract One of the most widely spread techniques to estimate the compressive strength of concrete is the rebound hammer test, also known as Schmidt Hammer test. In spite of a large number of scientific works trying to calibrate the test, to identify the parameters affecting its results and to estimate its reliability, the original Schmidt curve is still provided by the producers along with the hammer and is used in Structural Engineering Applications. This paper discussed an extensive research, and application, of this technique to a large number of cubes provided by the Laboratory for Building Materials of the University of Genoa, Italy, showing that several phenomena strongly affect the test: moisture content, maturity, stress state among the others. Strength estimates may differ as much as 70% if these parameters are not taken into account. Besides, several in situ investigations on existing buildings were affected by a large dispersion of data, so that we should conclude that the Rebound Hammer is unable of giving a reliable estimate of the concrete strength. This is probably due to the very limited area of the material on which the test is performed that allows also small local inhomogeneity to affect quite strongly the test. Therefore, the rebound hammer seems to be useless in the estimation of concrete compressive strength, being only a rough tool for estimating material homogeneity inside a specific concrete type.

Keywords Concrete, Compressive Strength, Non Destructive Testing, Rebound Hammer, Reliability

1. Introduction

In Civil Engineering practice, the estimation of concrete quality is needed both for quality controls of new buildings and for rapid surveys of existing structures. Among the NDT and MDT procedures, the Schmidt, or rebound, Hammer test is largely the most commonly used worldwide. The reason for such a success is not the reliability of the tests, that may be easily showed to be less than 30%, but the simplicity of the procedure, the low price of the equipment and its easy of use.

The strength estimation of concrete on the basis of its surface hardness dates back more than 100 years [1]. Nevertheless, a simple and low cost procedure was proposed only at the beginning of the 50's [2 and 3] gaining immediate attention from either the scientific [4 and 5] and professional world. The worldwide use of the procedure [6] soon raised some doubt on the reliability of the test so that a vast number of research projects have been developed trying to better calibrate the Schmidt Hammer test, either dating back from the 60s' till recent years. A comprehensive bibliography can be found in [7].

In the first years, calibration has been performed on a large number of specimens cured in standard conditions but without separating the contribution of the different factors affecting the test, such as concrete maturity and hardening conditions, moisture, surface finishing, concrete composition, aggregate type and hardness, etc. The fundamental assumption was that these parameters only slightly affect the strength estimate. Only recent works, in the last two decades [8-10], separated the effects of different parameters. Figure 1 summarizes the up-to-date knowledge, displaying the calibration curves that can be found in literature.

The most recent results of scientific research show that the Rebound Hammer might provide some information on concrete quality provided that it is calibrated on the specific concrete type it is used on [11 and 12]. Unluckily, these conclusions did not yet enter common Civil Engineering practice.

In this paper, the calibration of the Rebound Hammer is studied by means of a series of laboratory and field tests gathering the experience of the Laboratory of Building Materials of the University of Genoa, Italy. Several parameters are taken into account: surface finishing, moisture content, concrete maturity, distance from the free edges, dimension and mass of the structural element, stress state. Calibration is performed either on concrete specimens specifically built for the research (ideal conditions) and on concrete cubes delivered to the laboratory for quality controls (actual commercial production). Also field data, from existing structures of different types and age, are considered in order to allow a rational estimation of the test reliability by comparison of the available data.

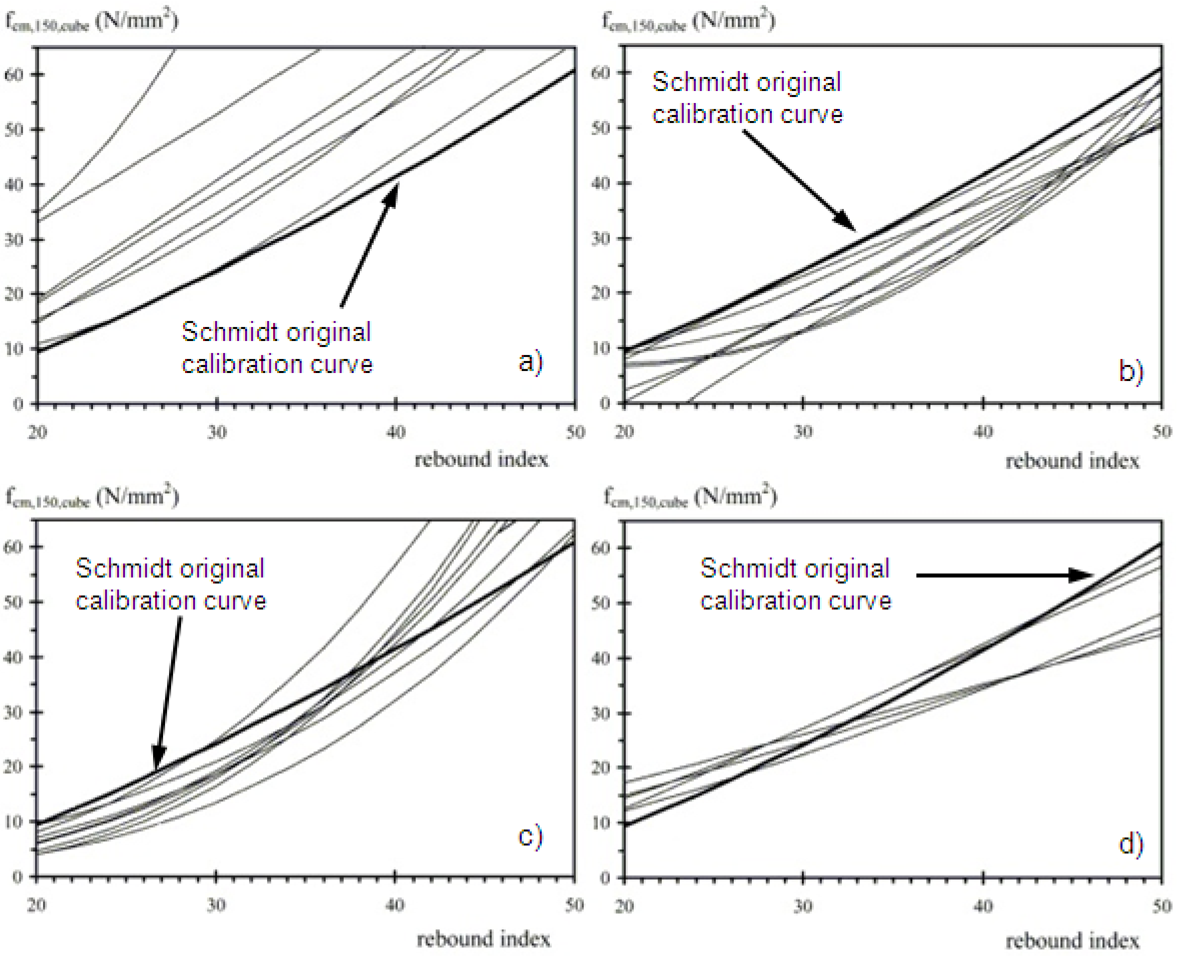


Figure 1. Calibration curves for the Rebound Hammer that can be found in literature [7]. Calibration curves: a) all above; b) all below; c) from below to above; d) from above to below the original Schmidt calibration curve.

2. The Experimental Campaign

It is well known that the rebound hammer test consists of the calibrated impact of a mass against the surface of concrete mass through a ϕ=20mm plunger. Due to the reduced dimension of the impact area, smaller than the maximum size of the aggregates, the test strongly depends on local inhomogeneity of the material: hidden aggregates at short distance from the impact area, voids due to improper mix, water content and finishing of the surface, concrete maturity, etc. are some examples, figure 2. There are some other parameters, not related to the material itself but to the tested structural element, such as the stress state, the mass of the element, the distance of the impact area from free edges that had not yet been studied, figure 3. In this paper, a large experimental campaign has been carried out to investigate the effect of these parameters on the test outcomes.

To this aim, a series of 5 concrete mix has been produced, table 1, with different water/cement ratio but with approx. constant density. The specimens used in the experimental campaign are:

- 100x200mm cylinders and 150x150x150mm cubes (*cubes* in what follows), both used to identify the concrete strength and the latter also for the test calibration;
- 250x250x500mm prisms (*prisms*) aiming at representing a column;
- 320x800x1200mm (*large prisms*) specimens, as elements with large mass;
- 6000mm in span, 1000mm wide and 200mm thick bended plates (*plates*), figure 4.

Figure 5 shows the hardening curves of the concrete mix cured in standard conditions (in water at average temperature of 20°C ±2°C); the exponent s of the exponential law provided by EC2 [13], Eq. (1), is given as the best-fitting value, table 1.

$$R_c\left(t\right)=R_{c,28}e^{s\left(1-\sqrt{\frac{28}{t}}\right)}, \qquad (1).$$

It is worthwhile noting that the forecasts provided by Eq. (1), grounded on the 7, 14 and 28 days data, for which the theoretical estimate is rather good, underestimate by approx. 10% the actual strength measured at 164 days.

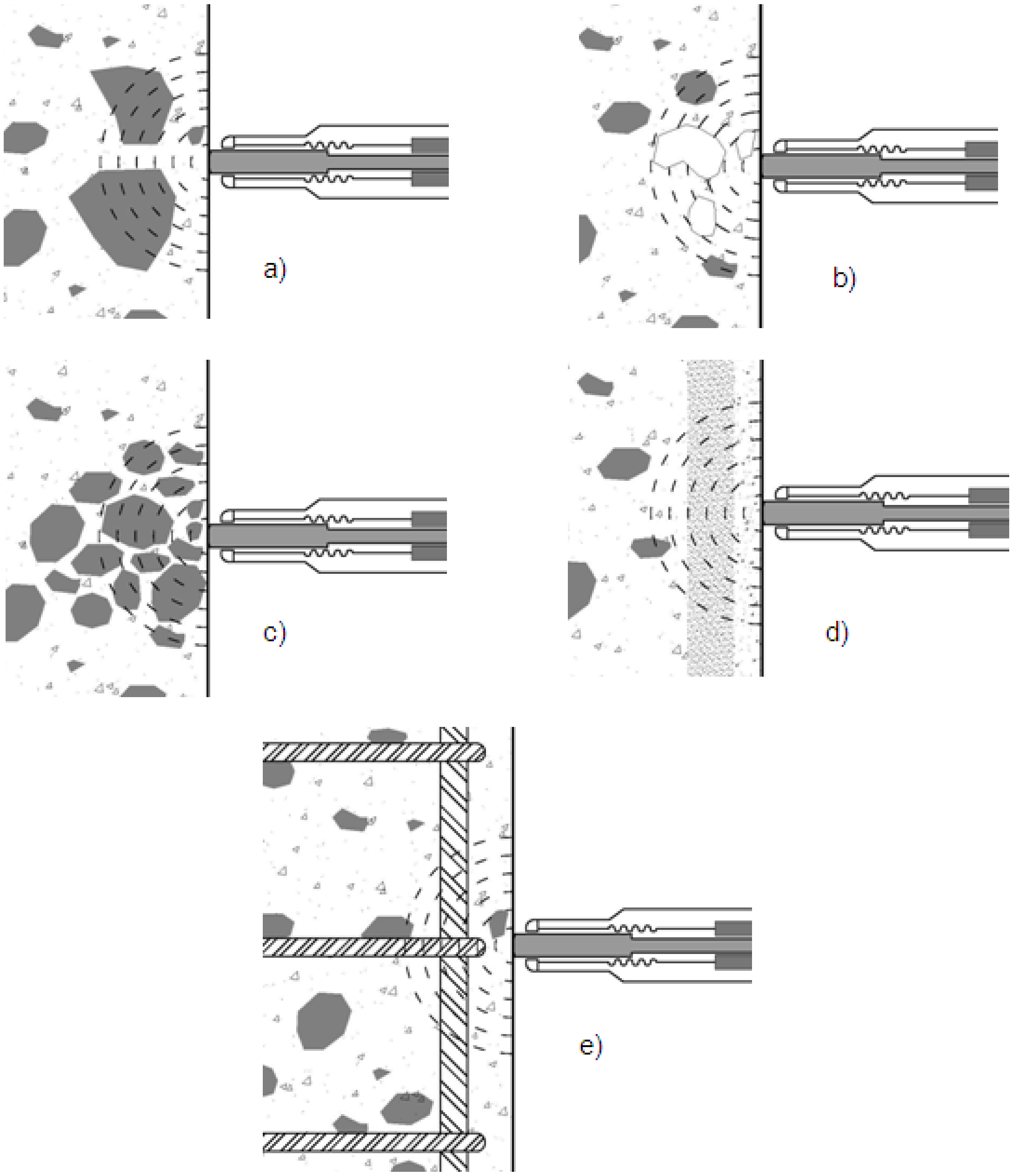


Figure 2. Local inhomogeneity affecting the rebound test: a) large gravels; b) voids; c) gravel aggregate; d) bleeding; e) reinforcing bars close to the surface.

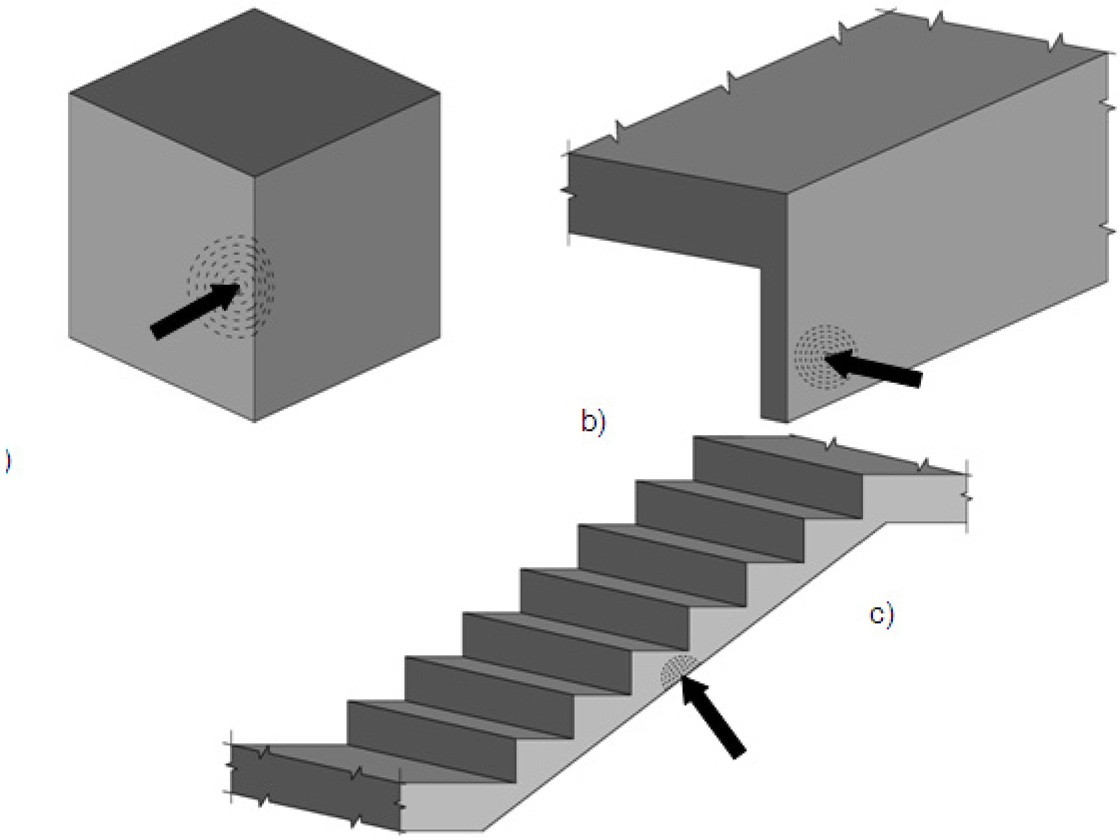


Figure 3. Structural parameters that may affect the rebound test; impact position: a) close to a free edge; b) and c) to deformable and vibrating structures.

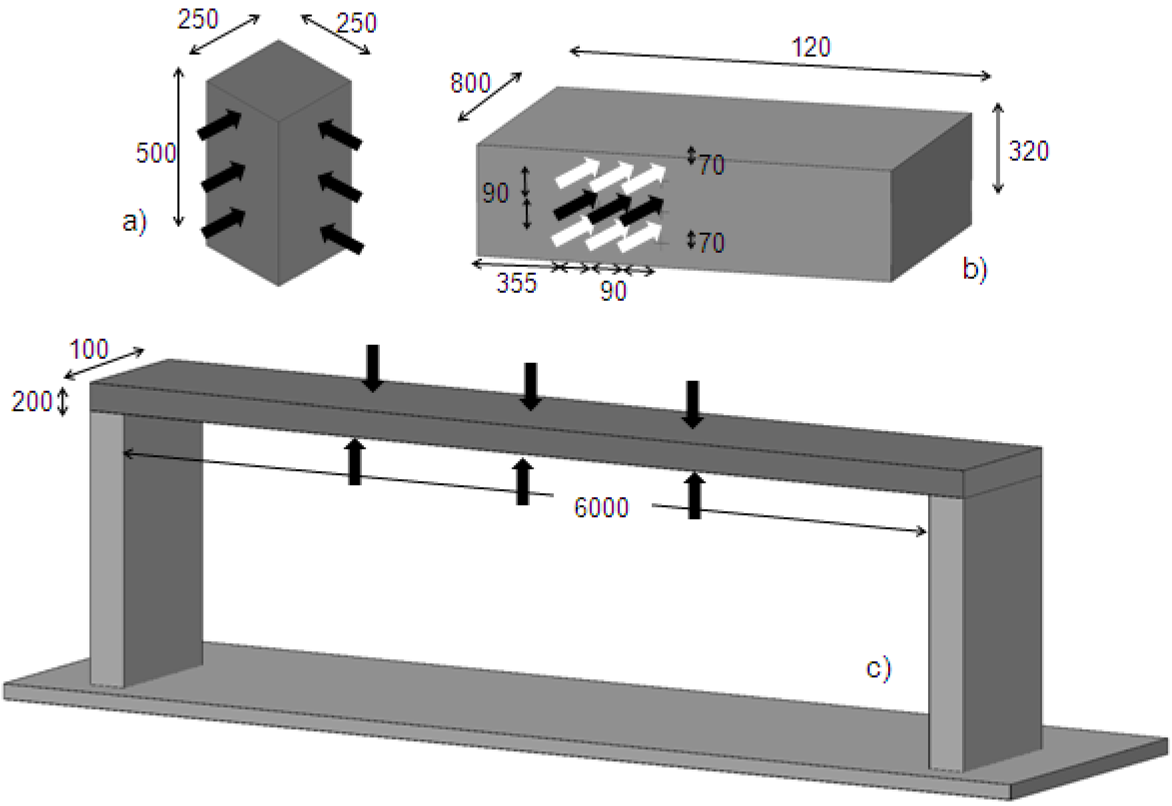


Figure 4. Specimens used for calibration. Arrows indicate the locations of the tests

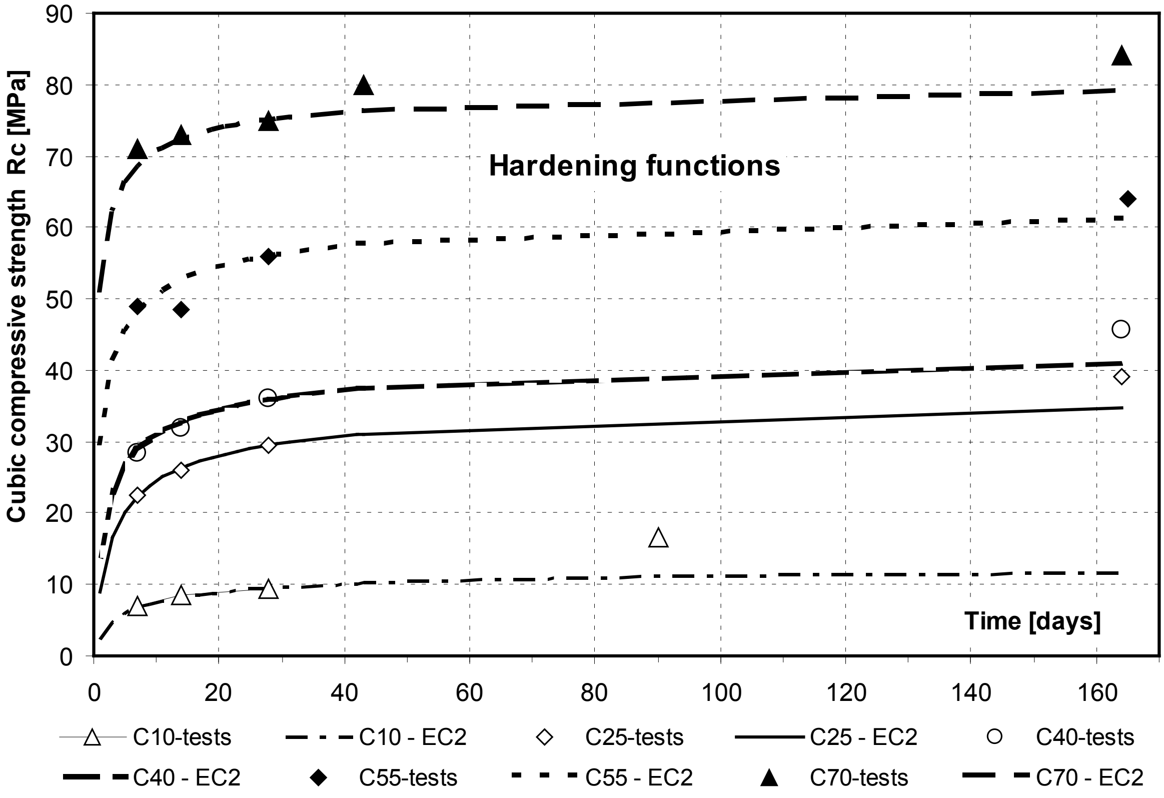


Figure 5. Hardening curves of the concrete mixes.

Table 1. Concrete mix characteristics.

Mix type	**Aggregates [% in weight]**				***Pl.* [l]**	**Water [l]**	**Cement type II 32.5[kN]**	**W/C**	$f_{c,28}$	$R_{c,28}$	$(f/R)_{28}$	**Dens [kN/m^3]**	**s**
	C 0/4	**C 3/6**	***Nat* 6/12**	**C 11-22**									
C10	40.2	26.9	32.9	/	1.9	2.55	1.93	1.32	7.7	8.3	0.93	22.7	0.296
C25	43.2	21.9	34.9	/	3.6	2.04	3.06	0.67	23.0	26.0	0.88	22.5	0.277
C40	40.2	24.9	34.9	/	4.5	1.93	3.73	0.52	28.7	32.2	0.89	22.5	0.220
C55	38.2	36.9	24.9	/	5.3	1.78	4.41	0.40	47.5	51.2	0.93	22.7	0.150
C70	38.1	26.9	/	34.9	10.1	1.77	5.07	0.35	62.6	74.8	0.84	24.2	0.090

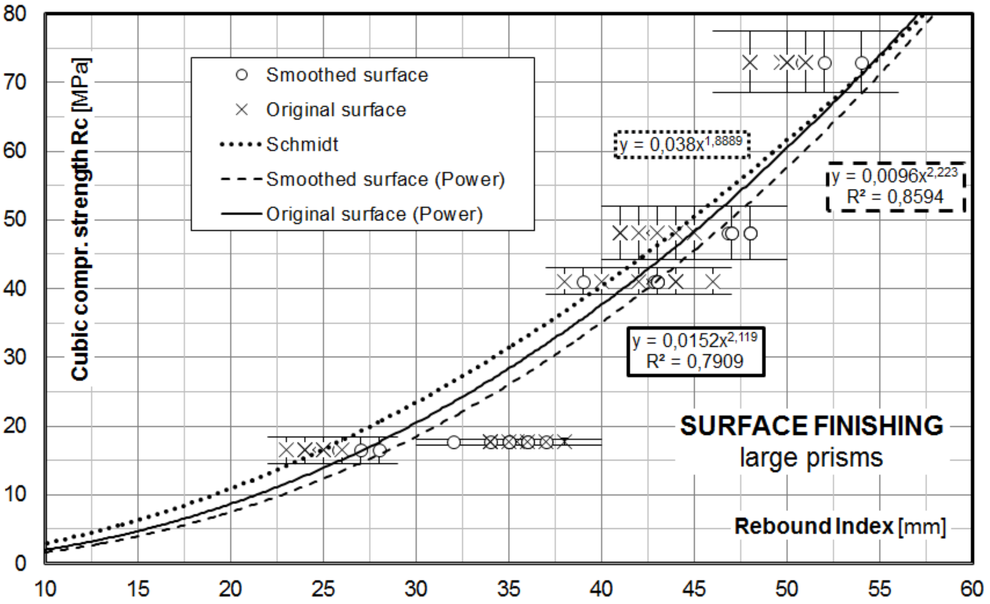
Legenda: *C*: crushed - *Nat.*: natural - *Pl*: Plasticizer / Superplasticizer

3. Test results

The experimental campaign aims at identifying the effect of the following parameters:

- surface finishing and free edges (Figure 4.b), on large prisms – Figures 6 and 7;
- moisture (dry vs. saturated) on cubes – Figure 8;
- uniform compressive stress state in compressed and confined (stirrups) prisms, representing the stress state in a column – Figure 9;
- mass of the tested element, comparing the results of the tests on the different specimens either as standalone and compressed in a press – Figures 10 and 11;

In all the figures, the band containing the experimental data represent the variability of the compressive strength measured on reference cubes. The diagrams are obtained as best fitting curves for the test data passing through the origin. In general, it can be observed that the experimental data are rather disperse, which implies that the R^2 value for the best fitting curves is always rather low.



(continuous line: original surface; dashed line: smoothed surface; dotted bold: Schmidt curve).

Figure 6. Calibration curve for different surface finishing

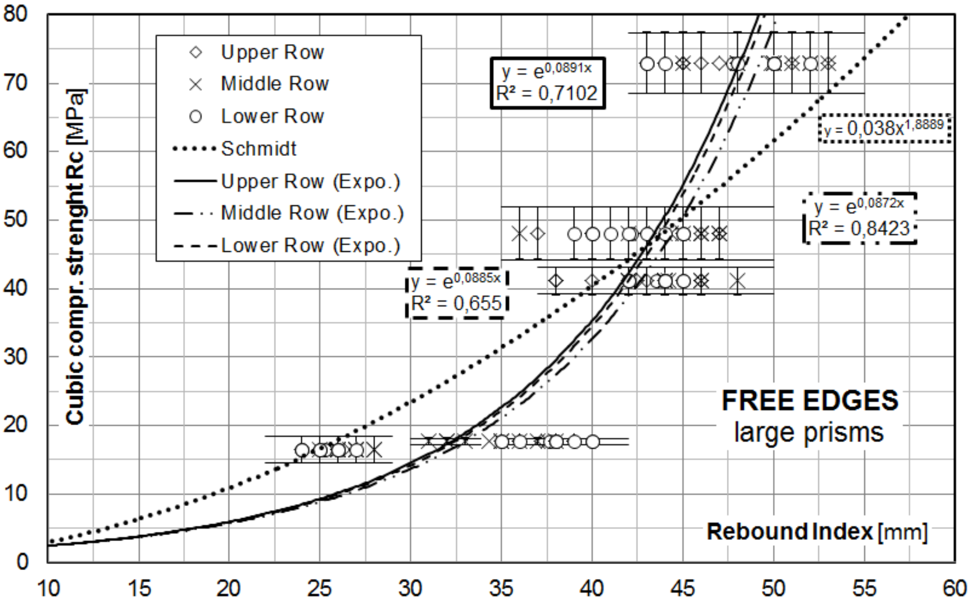
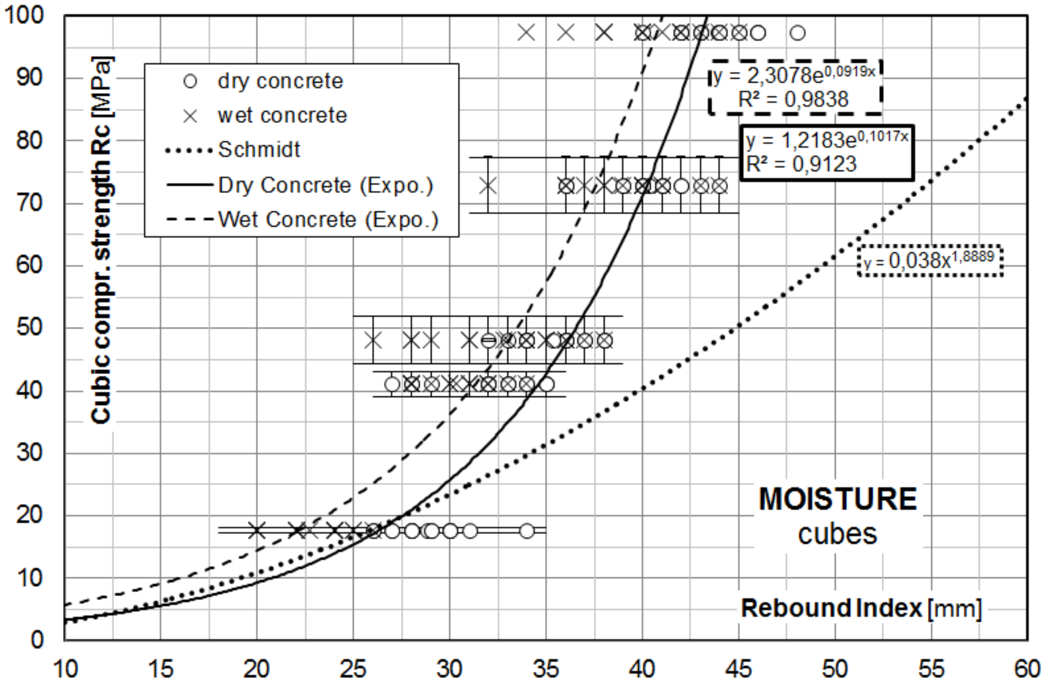


Figure 7. Calibration curve for different distance of the test location from free edges. (dash-dotted line: in the middle of the element; continuous & dashed line: close to the free edges; dotted bold line: Schmidt curve).



(continuous line: dry cubes; dashed line: saturated cubes; dotted bold: Schmidt curve).

Figure 8. Calibration curve for different moisture contents: dry and saturated cubes.

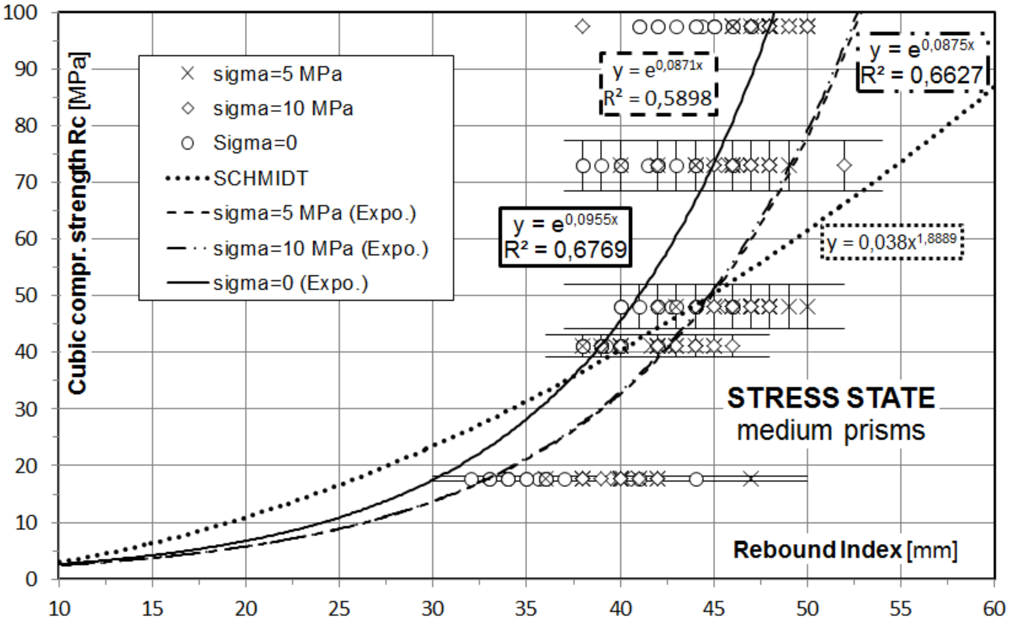


Figure 9. Calibration curve for different stress states. (average compressive stress: dashed line 5MPa; dash-dotted line 10MPa; continuous line 0MPa; dotted bold: Schmidt curve).

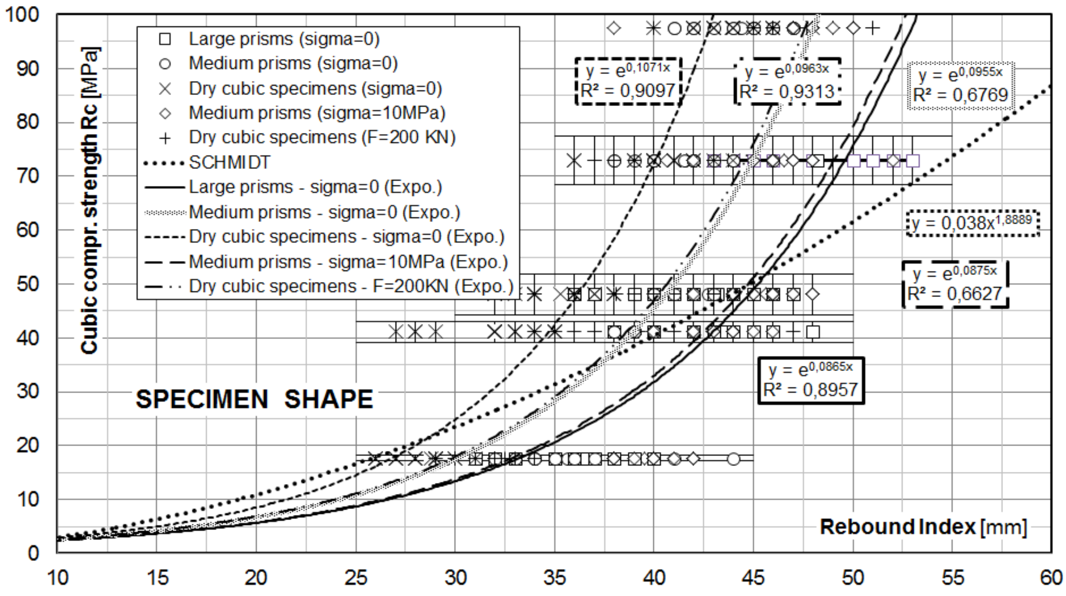


Figure 10. Calibration curve for dimensions and stress states of the specimens. (dashed line: dry cubes - continuous line: saturated cubes. Cubes loaded at: dashed lines: 20% of l.c.c; dotted lines: 40% of l.c.c.; dash-dotted lines: 60% of l.c.c.; dotted bold line: Schmidt curve).

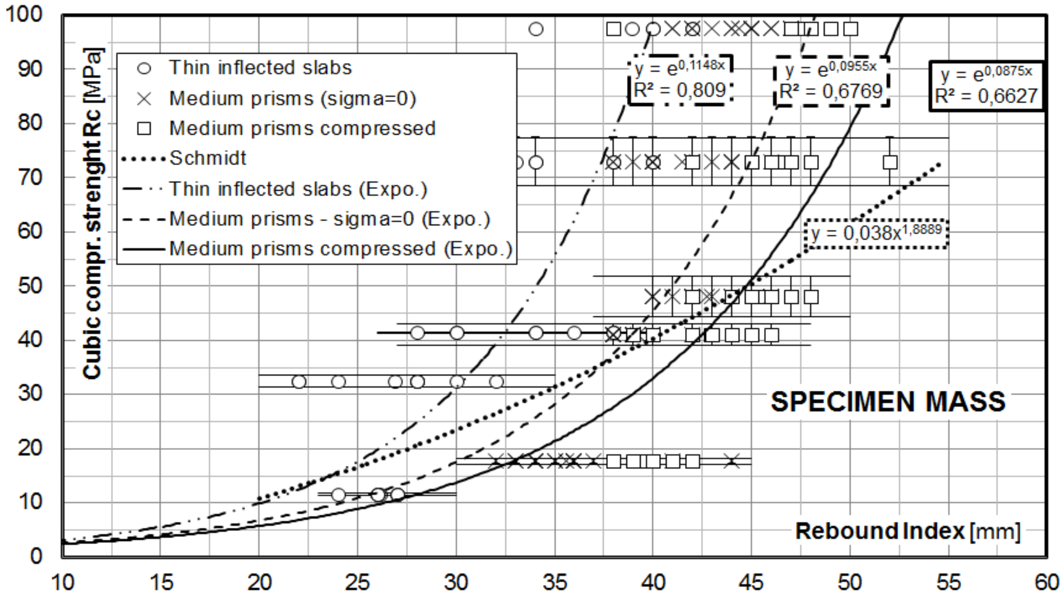


Figure 11. Calibration curves for different specimens mass and stress state (dotted bold line: Schmidt curve).

Taking into account all the parameters affecting the test, we can observe that the effect of:

- surface finishing is hardly noticeable, which is due to an "original" surface that was already substantially smooth being the specimens casted in plane formworks and being the concrete pouring very accurate;

- distance from the free edges has almost no effect on the rebound index since a 70mm distance from the free edges is large if compared to the impact area and to the aggregate size;

- moisture content may change the strength estimate also more than 50%, which is a well-known feature to be taken into account when using the rebound hammer on wet structures;

- stress state, specimen shape and mass play a relevant effect on the strength estimate that may be also larger than the moisture content.

This latter result is rather new since it is related to geometric (free edges, specimen shape) and mechanical (stress state) characteristics of the structure. Besides these aspects, the data dispersion is another relevant feature of rebound tests: the calibration data used in the previous figures show that the uncertainty of the test is incredibly high. Further discussion is provided in the next sections.

4. Other Experimental Data

4.1 Third Party Cubes

The typical procedure for calibrating a test is that of producing specific specimens with different strength but with the same concrete type (aggregate size and type), as in the previous section. This leads to tests that are affected by a specific bias: concrete variability, not only in the mix but also in the aggregate types, is as limited as possible and both the concrete age and its maturation conditions are highly controlled till the test day, which is not exactly what happens in Civil Engineering practice.

In this section, Figure 12 shows the effect of concrete maturity on the rebound index based on a large data base collected in the last two years in the Laboratory for Building Materials of the University of Genoa. The specimens were all 150x150x150mm cubes either delivered to the Laboratory for standard quality testing and moulded by the Laboratory during its usual quality controls in the building sites. In the latter cases, 7 and 28 days data could be obtained with good precision, while third party specimens are often older than 100 days since the 28 days limit is seldom respected. These circumstances allow to discuss the effect of concrete maturity on rebound tests, which turns out to be quite important: a 30mm rebound index would account for a compressive strength ranging from 32 MPa for 7 days old cubes to 57 MPa for more than 100 days old cubes, which almost 85% more. This shows that concrete maturity is one of the main parameters affecting the rebound test.

4.2. Field Tests

One of the applications of the Rebound Hammer is in existing structures. In these cases, concrete becomes a general term to identify a huge variety of materials originated from the mix of gravel, sand, cement and water. Some examples could make clear this latter rather strong statement.

Italy suffered economic sanctions by the League of Nations as a consequence of the war in Abyssinia (1935) during the last ‘30s of the last century. This made a serious shortage of cement that affected the building companies, so that concrete strength, in those years, ranges from 5 to 15 MPa, being strength higher than 15MPa only an extraordinary exception.

During the early 50’s, Italy started reconstruction after the WWII damages (in many cities more than half of the buildings had been destroyed). Due to shortage of cement and gasoline and to the critical conditions of railways and roads, which made transports very difficult, several structures have been built using low cement quantities ($\approx 2\text{kN/m}^3$) and high water/cement ratios (larger than 0.7), river gravels and sea sand. The outcome is something similar to concrete of the last ‘30s.

These examples show that any calibration of any test procedure should be very carefully applied to this kind of materials. In this section a comparison of what would be expected if the calibration curves of the previous sections were used on existing buildings is discussed.

In the last five years, the Laboratory for Building Materials of the University of Genoa carried out more than 30 wide testing campaigns on existing buildings on behalf of private third parties. In these cases, no cubic or cylindrical strength could be obtained from moulded specimens, so that the “actual strength” had to be deduced from cores drilled from the structures. This procedure is a rather tricky phase since the damage produced to drilled cores make these specimens different from moulded cylinders. Besides, in these cases, the cylindrical-to-cubic strength ratio could not be considered constant and equal to 0.83, as table 1 shows.

In the following, we assume a correction factor, for obtaining the cubic strength from the core strength, linearly ranging from 0.93 for C10 concrete to 0.83 for C70 concrete. This is a somehow arbitrary assumption that is needed to estimate a concrete “actual” cubic strength that is more reliable than what we would obtain from the standard and constant cylindrical-to-cubic strength ratio = 0.83.

Figure 13 shows the comparison of the field data with different possible calibration curves and with the standard Schmidt curve. It can be observed (R^2 value) that none of the curves fit the cloud of field data. Figure 14 compares the field data to the Schmidt classical curve and to the proper curve obtained in this paper. It can be seen that the forecasts of the Schmidt Hammer are almost useless if compared to the “actual” data.

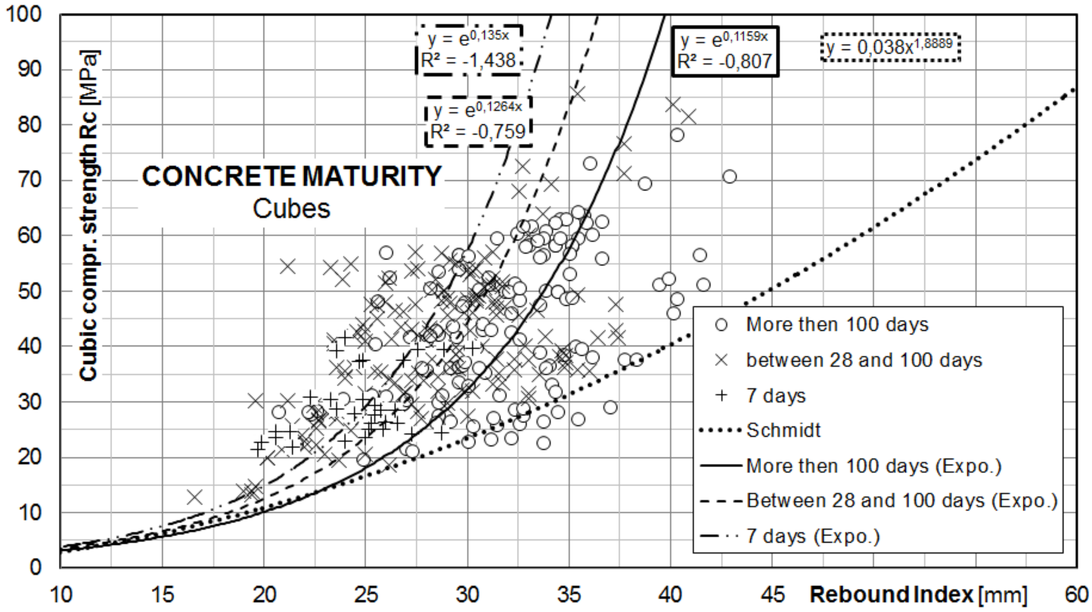


Figure 12. Calibration curve for different concrete age after casting (standard curing conditions).

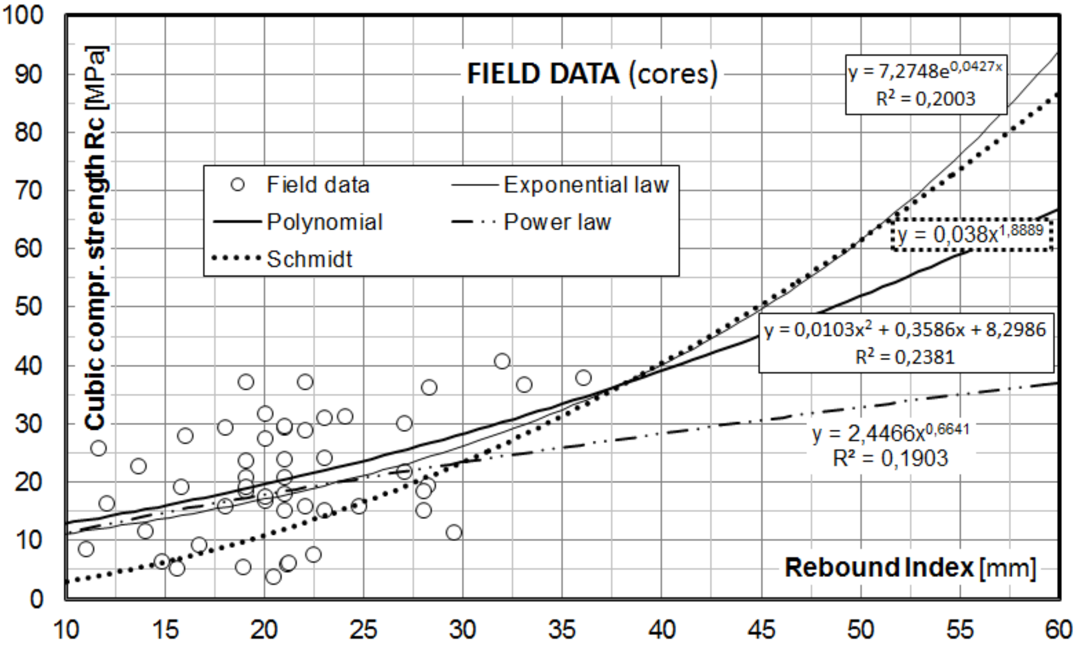


Figure 13. Different calibration curves and field data.

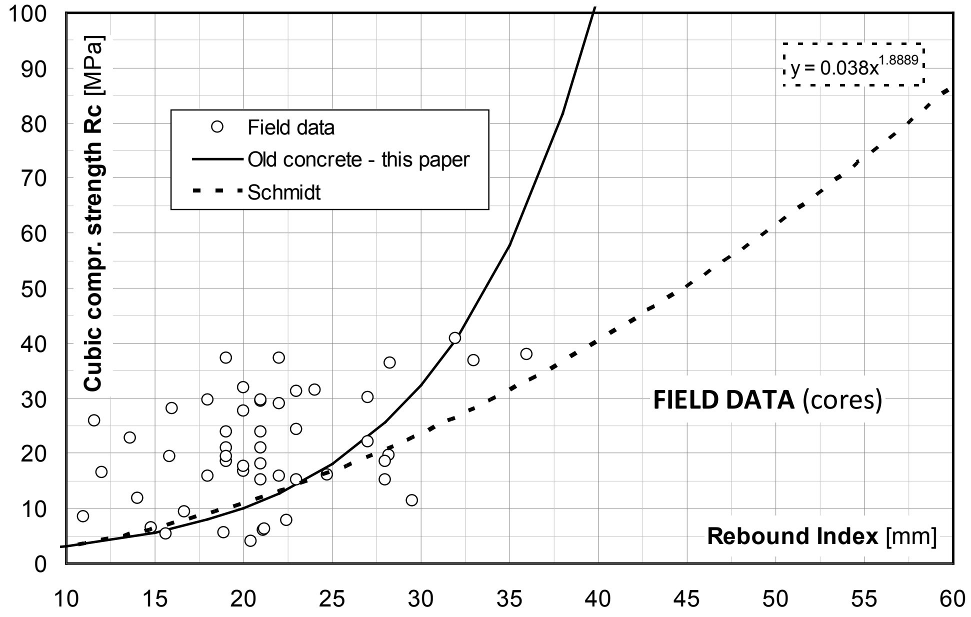


Figure 14. Calibration curve for old concrete and field data. Comparison with the Schmidt curve.

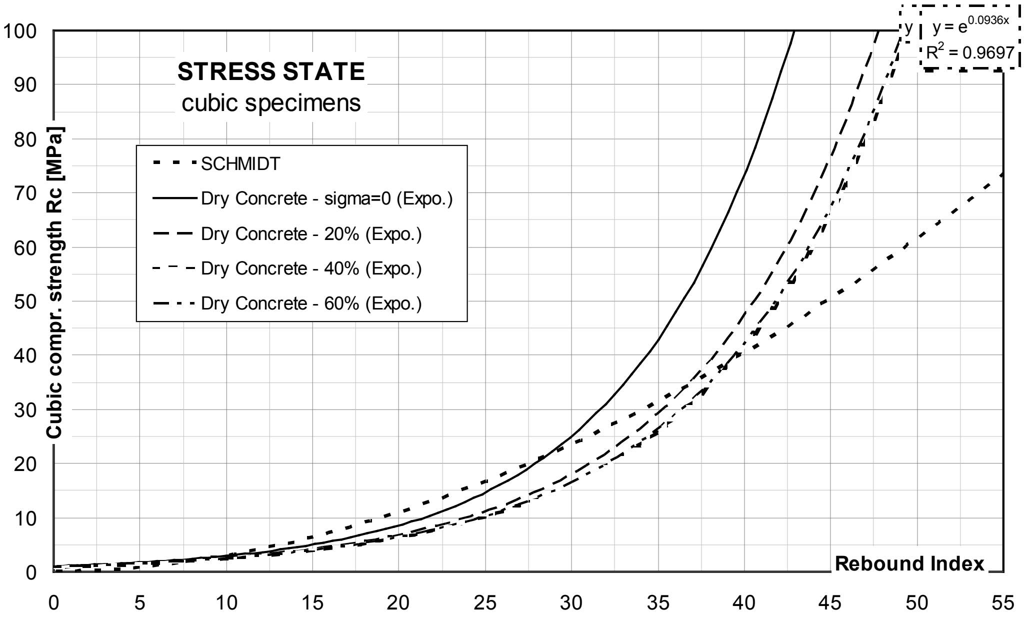


Figure 15. Effect of compressive stress state on the rebound index for dry cubes

5. Comparisons

Figure 15 shows the diagrams of figure 10 only to outline the effect of the stress state (compressive uniform).It can be observed that the stress state may account for a difference in the estimated concrete strength in-between 40% (IR=30mm) to 75% (IR=45mm). These figures show that the stress state is a parameter that cannot be neglected in the interpretation of rebound hammer tests.

Figure 16 has been obtained adding to figure 15 the calibration curves related to saturated cubes. The curves (grey lines) are clearly shifted leftwards, and introduce a further 60-70% increase in the strength estimate. The effect of the stress state and the effect of moisture result in strength estimation that are more than twice the estimate that would be obtained if these parameters were neglected.

This observation can be justified considering that the rebound hammer test is performed in a small area, so that all the parameters that may affect the mechanical behaviour of the material, also locally, play a fundamental role on the final estimate.

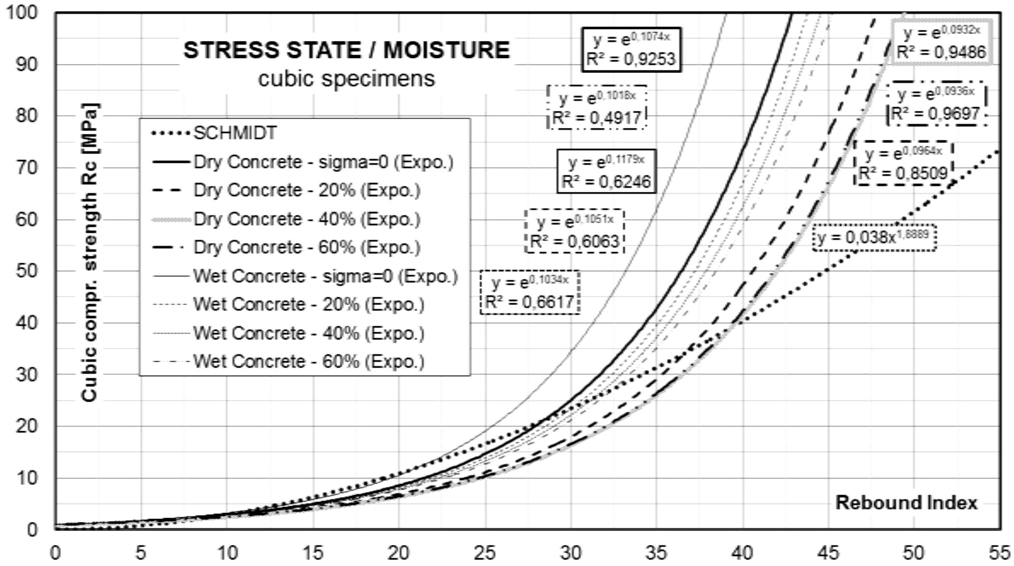


Figure 16. Calibration curves for moisture content and loading conditions (% of ultimate load).

6. Discussion and Conclusions

Figure 17 shows a summarizing plot in which the whole set of experimental data of this paper is compared to the calibration curves obtained in this paper. Figures 13 and 14 provide other similar drawings. To this aim, we remind that the R^2 coefficient of the calibration curves is very low in all the cases due to the high scattering of the test data.

At first glance we see that the test data are collected in some sort of cloud covering almost half of the diagram area. This is the direct consequence of the intrinsic features of the rebound hammer test: the very limited area in which it is performed makes the test to be strongly affected by all the parameters affecting either global and local properties of the material.

Such a large scattering of experimental data has been obtained taking into account not only concrete specimens casted specifically for this research, but also the cubes that the Laboratory of Building Materials of the University of Genoa tested in the last 2 years. In this way, the calibration curves could rely not only on a specific type of concrete, but on a large number of concretes, differing not only in their strength but also in the aggregate mix, in the aggregate type, in cement type, curing conditions, etc. In this way, laboratory tests have been integrated (separately in the previous sections, altogether in figure 17) by standard concrete production coming from the same geographic area. This introduced in the experimental campaign other parameters that the dispersion of figure 17 shows to affect the rebound test.

The large scattering of the calibration curves, also showed in Figure 1, that is the result of a huge scattering of experimental data, rises a crucial question: is the rebound hammer somehow significant in estimating the concrete strength? Figure 17 provides only a negative answer, suggesting that it might be considered a very rough tool for comparing the quality of concrete surface by comparison with data obtained by means of different and more reliable tools, but not a tool for estimating directly the concrete strength.

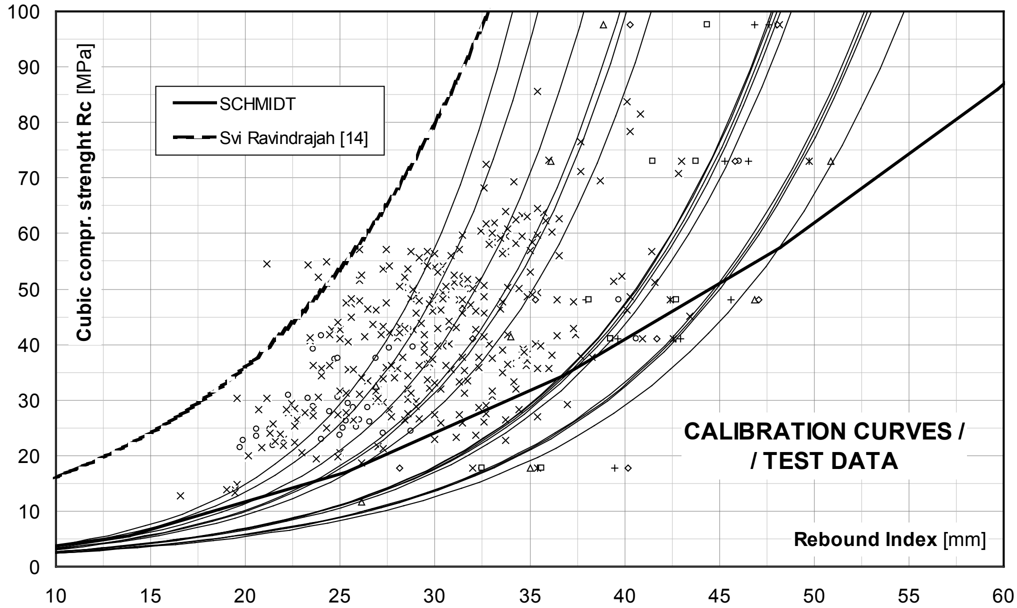


Figure 17. The whole set of experimental data compared to the calibration curves of this paper, the Schmidt curve and the curve obtained in [14]

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