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Research Article

Rebound Hammer Test: An Investigation into Its Reliability in Applications on Concrete Structures

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The issue of concrete strength often arises in civil engineering practice, either due to quality control of new constructions or due to the assessment of existing structures. To this aim, one of the most widely spread techniques is the rebound hammer (Schmidt hammer) test, for which calibration is still related to the original Schmidt curve dating back to the early 50's. In spite of the large amount of research work performed in the last decades, the uncertainties of the rebound test are still not clearly quantified and open to further insight. This paper presents and discusses a wide research campaign on laboratory specimens and on third-party specimens delivered to the Laboratory for Building Materials of the University of Genoa, Italy, for standard quality controls. While it is well known that moisture content, surface finishing, and concrete maturity strongly affect the test result, the effect of the stress state has not yet been studied and is found in this research to be a further parameter affecting the test reliability. The final outcome of all the uncertainties is variability in estimated concrete strength as large as ±70%; additionally, some issues are discussed on the intrinsic uncertainty of this test. As already demonstrated by many authors, the results of this research also show that a universal calibration curve to be used for any concrete, in any condition, conceptually does not exist.

1. Introduction

The estimation of concrete quality is needed both for quality controls of new buildings and for the assessment of existing structures, mainly when being retrofitted to the standards of the modern seismic codes. Among the NDT procedures, the rebound (Schmidt hammer) test is largely used in common engineering practice because of its simplicity and the low price of the equipment. The reliability of the test is still substantially unknown, thus opening the way to a research field that is still active.

The procedures based on surface hardness date back more than 130 years [1], but only at the beginning of the 50's [2, 3], Schmidt proposed its use for estimating concrete strength, gaining immediate attention from both the scientific [4–6], among the others, and the professional world [7].

In the first years, the aim was to find a universal calibration curve, relying on that the contribution of different factors affecting the test, such as concrete maturity and hardening conditions, moisture, surface finishing, concrete composition, aggregate type, and hardness, could be a minor and negligible issue. Figure 1 shows some of the early calibration curves [3–6], from which it is clear that the possibility of setting up a unique calibration curve was in doubt from the very beginning.

Recent works, in the last two decades [8–10], among the others, separated the effects of different parameters, showing that the results are rather strongly affected either by the concrete type (aggregate size, water/cement ratio, admixtures, etc.) or by the conditions (moisture, concrete maturity, curing conditions, surface carbonation, etc.). The calibration curves obtained so far [11] (Figure 2) summarize the wide dispersion of the up-to-date research on the Schmidt hammer.

The most recent results of scientific research made clear of one of the early ideas: the rebound hammer cannot be

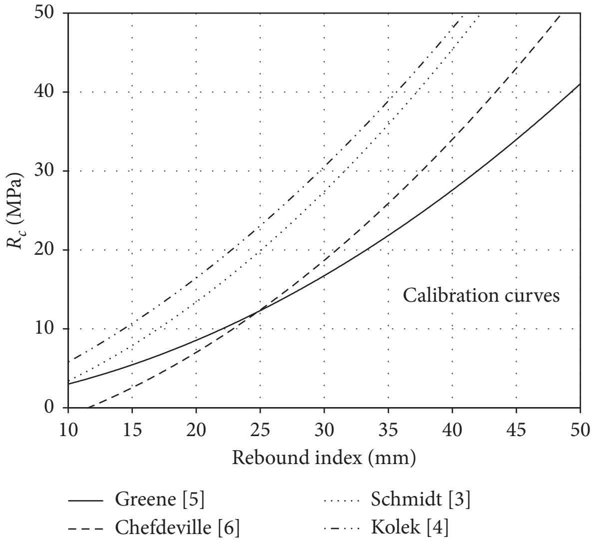


Figure 1: Calibration curves for the rebound hammer from [3–6].

used as an absolute measure of concrete strength and might provide some information only if it is calibrated on the specific concrete type it is used on [12, 13].

A similar approach can be found in several codes [14–25] where severe limits to the use of the Schmidt hammer can be found. As an example, [23] limited the rebound methods to (i) assessing the in-place uniformity of concrete; (ii) finding regions in a structure of poor quality or deteriorated concrete; and (iii) estimating in-place strength if a correlation is developed. It has to be noted that the estimation of concrete strength is allowed provided a detailed correlation is developed for the specific concrete.

Due to the serious concerns on the reliability of the calibration curves for Schmidt hammer test, [26, 27], among the others, and according to the aforementioned codes, the test should not make use of the calibration curve provided along with the equipment, i.e., a curve that is not calibrated on the specific concrete it is applied to. An alternative approach [28] should make use of multivariate functions assuming the hydration degree, type and amount of cement and aggregates, water-to-cement ratio, and environmental and testing conditions as (at least 7) independent variables. Even though scientifically sound, such an approach is hardly applicable in common engineering practice due to both practical complexity and a substantial lack of knowledge regarding the independent variables.

Unluckily, these conclusions did not yet enter common structural engineering practice. Besides, it has to be noted that a majority of the producers of rebound hammers still provide the equipment with the original Schmidt curve [3], which has been calibrated on the Swiss concretes produced in the late 40’s.

In this paper, the possibility of calibrating the rebound hammer (type *N*) test is discussed relying on a series of laboratory and field tests, gathering the experience of the Laboratory of Building Materials of the University of Genoa, Italy [29]. Several parameters are taken into account: moisture content, concrete maturity, distance from the free edges, dimension and mass of the structural element, and stress state. This latter “parameter”, which pertains to the structure and not the material, has never been considered for the calibration of the test and is taken into account in no code. As the discussion shows, this could be one of the major sources of error and an uncontrollable bias in the test.

Calibration is performed either on concrete specimens specifically built for the research (ideal conditions) or on concrete cubes delivered to the laboratory for quality controls (from commercial production). In addition, 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.

The outcomes are not encouraging since an absolute calibration for the Schmidt hammer test turns out to be almost impossible. See [11, 28, 29] for a deep review on this issue. A discussion on some specific issues on concrete hardening, on the surface and subsurface defects that develop during concrete hardening, and on the effect of the structural element on the test provides some reasons for explaining the outcomes enforcing what has been found from many different points in the last decades. Since the surface and subsurface defects are not included in laboratory tests, but are quite common in building practice, this paper shows that the common approach to surface hardness tests, which cannot take into account several parameters affecting concrete quality, has to face a very large variability of test data.

2. The Experimental Campaign

A series of 4 concrete mixes has been produced with different water/cement ratios but with approx. constant density; in the case of free edges, a 5th concrete mix has been used (Table 1).

The specimens used in the experimental campaign are as follows:

(i) 100×200 mm cylinders and $150 \times 150 \times 150$ mm cubes, both used to identify the concrete strength and the latter also for test calibration

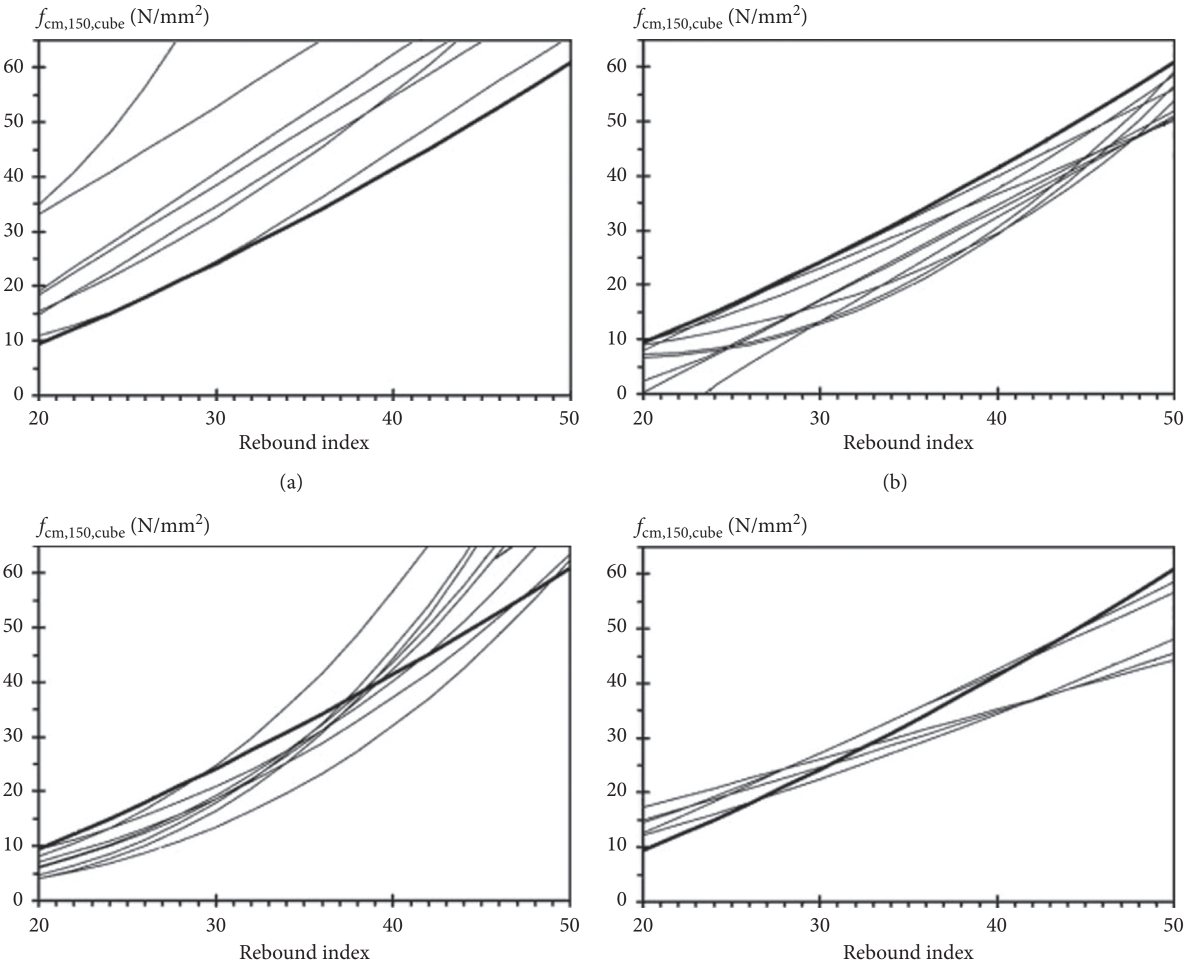
(ii) $250 \times 250 \times 500$ mm prisms aiming at representing a column

(iii) $320 \times 800 \times 1200$ mm specimens, as elements with large mass (Figure 3)

Figure 4 shows the hardening curves of the concrete mixes (Table 1) cured in standard conditions (in water at an average temperature of 20°C ± 2°C); exponent s of equation (1) provided by EC2 [28, 30] is given as the best fitting values (EC2-type curves) for the 7, 14, and 28 days of tests (Table 1).

$$R_c(t) = R_{c,28} e^{s(1-\sqrt{28/t})}. \quad (1)$$

In Figure 4, the C55_EC2 curve adopts, exactly, the value for s provided by EC2 ($s = 0.35$) showing that the actual strength gain ratio could be higher than what is predicted by EC2. For the three lower classes, the difference between the best fitting curves and the EC2 approach is hardly noticeable.



(a)

(b)

(c)

(d)

Figure 2: Calibration curves for the rebound hammer that can be found in the literature [11]. Calibration curves: (a) all above; (b) all below; (c) from below to above; (d) from above to below the original Schmidt calibration curve.

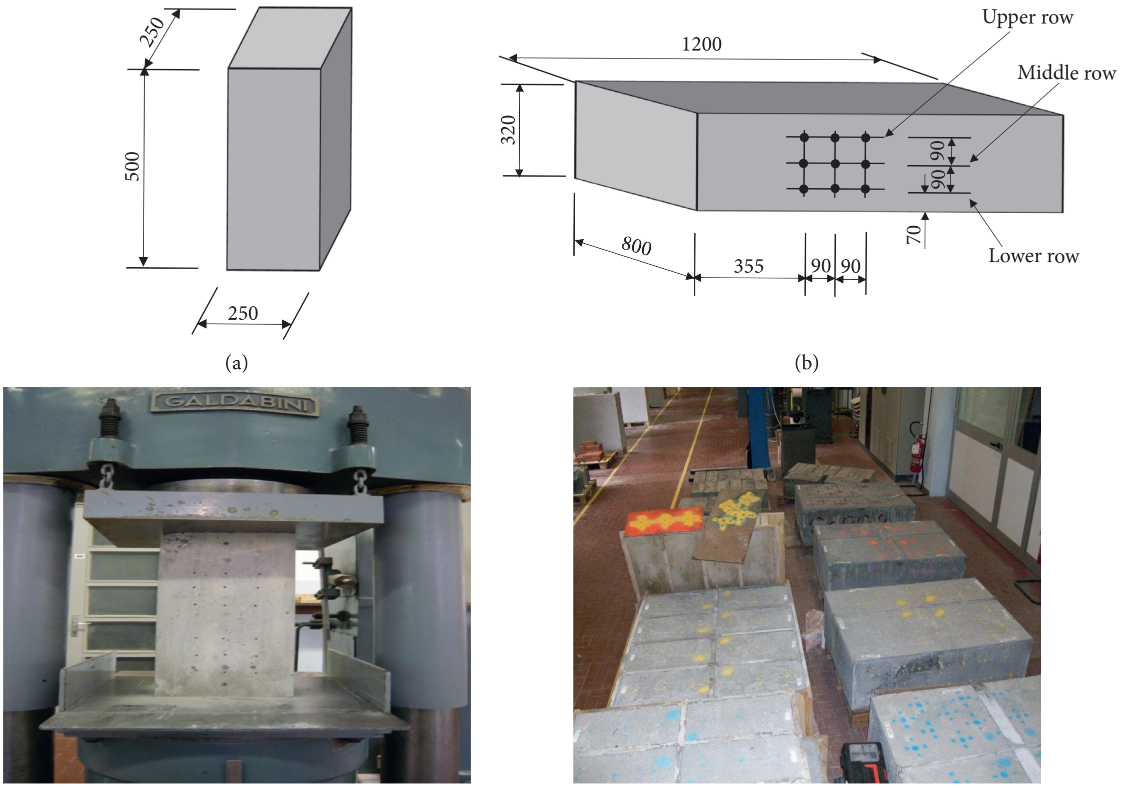
Table 1: Concrete mix characteristics. See equation (1) for the meaning of the symbols.

Mix type	Aggregates (% in weight) C 0/4	C 3/6	Nat. 6/12	Pl. (l)	Water (l)	Cem. content (kN)	Cem. type (R)	$f_{c,28}$	$R_{c,28}$	$(f/R)_{28}$	Pl. (l)	$R_{c,\mathrm{testing}}$	Dens (kN/m^3)	s-best fitting	s-EC2
C10	40.2	26.9	32.9	1.9	255	1.93	32.5	7.7	8.3	0.93	C10	17.7	22.0	0.80	0.35
C25	43.2	21.9	34.9	3.6	204	3.06	32.5	23.0	26.0	0.88	C25	16.5	22.9	0.45	0.35
C30	41.5	23.0	34.2	4.0	167	3.72	32.5	13.3	15.1	0.88	C30	41.1	22.4	0.48	0.35
C40	40.2	24.9	34.9	4.5	193	3.73	32.5	28.7	32.2	0.89	C40	48.1	22.8	0.40	0.35
C55	38.2	36.9	24.9	5.3	178	4.41	42.5	47.5	51.2	0.93	C55	73	24.6	0.30	0.35

C: crushed aggregate; Nat.: natural aggregate; Pl: plasticizer/superplasticizer.

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

In Table 1, concrete is addressed by means of the standardized 28-day strength, but the tests have been performed at approximately 12 months after pouring so that the material strength in the diagrams refers to the strength at the moment of testing and not to the reference 28-days strength, from which severe differences arise sometimes. The names of the concrete types refer to the aimed strength classes, but in some cases, the actual strength was strongly different from the initial goal. Therefore, the names of the concrete types do not refer to their actual strength.



(a) (b)

(c) (d)

Figure 3: Specimens used for calibration. Geometry of (a) the prisms and (b) the large prisms; crosses indicate the locations of the tests; (c) prism inside the press to preload the specimen; (d) large prism in the laboratory.

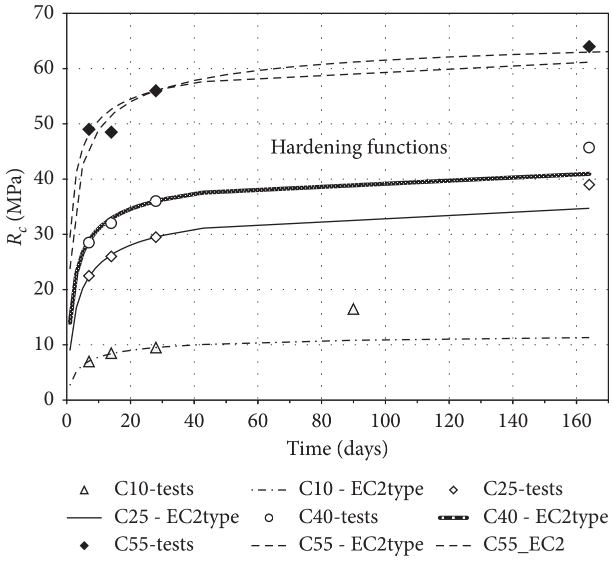


Figure 4: Hardening curves of the concrete mixes.

3. Test Results

The first goal of the experimental campaign aims at identifying the effect of some relevant parameters on the test results:

(i) Free edges (Figure 3(b)) on large prisms—Figure 5

(ii) Moisture (dry vs. saturated) on cubes—Figure 6

(iii) Uniform compressive stress state in compressed and confined (stirrups) prisms, representing the stress state in a column—Figure 7

(iv) Mass of the tested element, comparing the results of the tests on different specimens either as standalone or compressed in a press—Figure 8

Figure 6 refers to saturated cubes, kept in water for not less than 6 hours and then just wiped with fabric, and dry ones, kept in a dry environment (inside the laboratory, heated) for 4 months with resulting average moisture content in the range 1.5–1.8% (in weight).

Figure 7 shows an unexpected result for high-strength (72 MPa) concrete, in which rebound seems to be less (on the average) than the value measured for lower classes. This is an unexpected outcome that asks for further insight, being related to an unusual concrete for which the technical and scientific literature provide poor data.

In all the figures, circles, crosses, squares, and triangles represent experimental points (each one being the average of 18 measurements in different locations) associated to a concrete class. The concrete strength is the average value measured from standard cubes with C.o.V. never higher than 6%.

The diagrams are obtained as best fitting curves (exponential) for the test data through the origin. In general, it

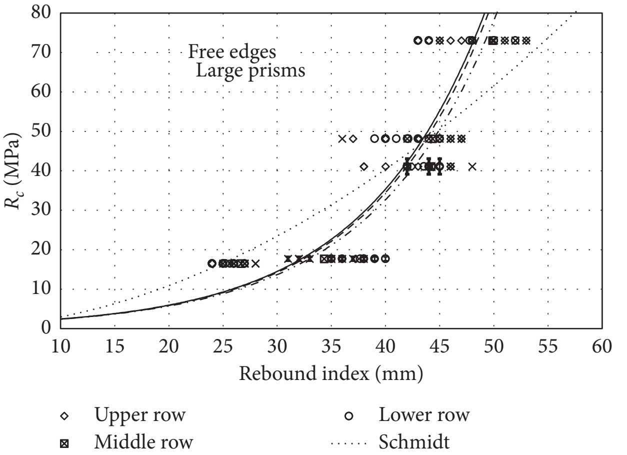


Figure 5: Calibration curve for different distances of the test location from free edges. Dash-dotted line: in the middle of the element; continuous and dashed line: close to the free edges; dotted bold line: Schmidt curve. Calibration curve: $R_c = e^{aRI}$; RI = rebound index; $a \in [0.87, 0.89]$; $R^2 \in [0.66, 0.84]$. Inside any dataset, C.o.V. ≤ 9%.

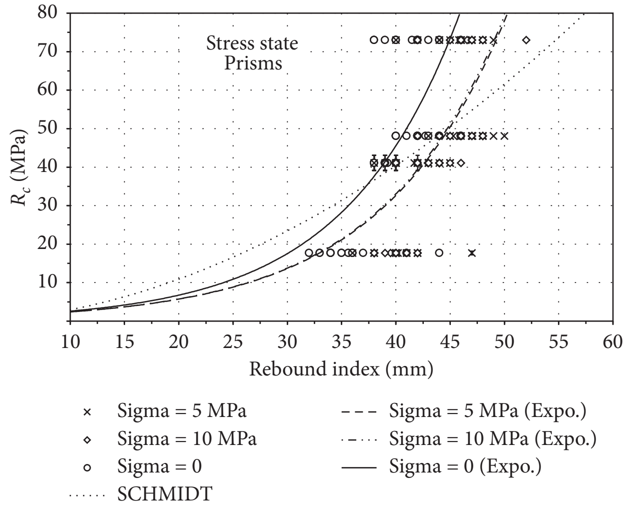


Figure 7: Calibration curve for different stress states. Average compressive stress: dashed line: 5 MPa; dash-dotted line: 10 MPa; continuous line: 0 MPa; dotted bold: Schmidt curve. Calibration curve: $R_c = e^{aRI}$; RI = rebound index; $a \in [0.088, 0.096]$; $R^2 \cong 0.67$. Inside any dataset, C.o.V. ≤ 9% for vanishing stress; C.o.V. ≤ 6% for compressed prisms (5 and 10 MPa).

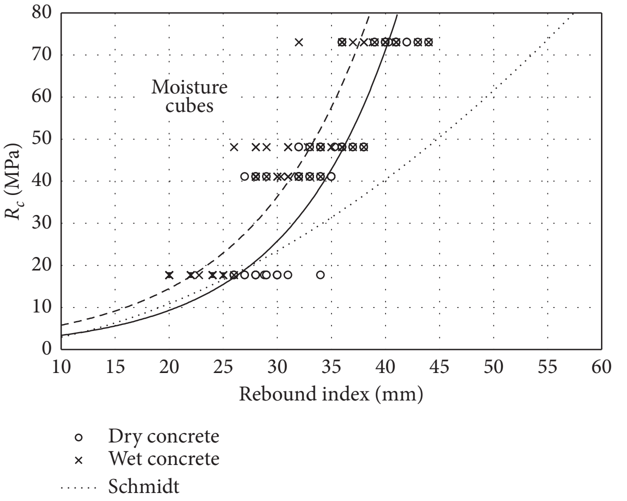


Figure 6: Calibration curve for dry and saturated cubes. Continuous line: dry cubes; dashed line: saturated cubes; dotted bold: Schmidt curve. Calibration curve: $R_c = e^{aRI}$; RI = rebound index; $a \in [0.11, 0.12]$; $R^2 = 0.91$. Inside any dataset, C.o.V. ≤ 9%, dry; C.o.V. ≤ 12%, saturated.

can be observed that the experimental data are rather dispersed, which implies that the R^2 value for the best fitting curves is always rather low, in between 0.6 and 0.9. The C.o.V. of the datasets, which is a measure of the root mean square error, is limited below 12% for laboratory specimens (below 6% in several cases) and rises above 15% for specimens taken from building sites. These figures refer to the dataset of the tests on a specific specimen; tests on different specimens of the same concrete may show the same dispersion. The wide dispersion of the data, outlined in Figures 5–8, arises from the significant variability of the average values. The C.o.V. for a specimen is relatively low, mainly if compared to the common practice.

It has to be noted that, in laboratory tests, the calibration of the Schmidt hammer (type *N*) on a standard anvil was performed every 50 hits, i.e., several times per day, while in common practice, such an instrument control is seldom performed so that we can argue that data dispersion in common practice might be due, to some extent, to imperfect calibration of the hammers.

In all the figures, the rebound index is given the dimensions of mm even though it is often addressed without a unit. Such a choice is aimed at recalling the mechanical meaning of the rebound index: not a virtual "index" indirectly related to the mechanical problem but a direct physical measure of a mechanical property (surface hardness).

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

(i) Distance from the free edges (Figure 5) has almost no effect on the rebound index since a 70 mm distance from the free edges is large if compared to the impact area and to the aggregate size; such a conclusion is not surprising since the test is performed on a very restricted area in comparison to the distance from the specimen edges

(ii) Moisture content may affect the strength estimate even more than 50%; this is to be taken into account when using the rebound hammer on wet structures

(iii) Stress state, specimen mass, and boundary conditions (i.e., the effectiveness of its connection to other structures) play a relevant effect on the strength estimate that may also be larger than the moisture content

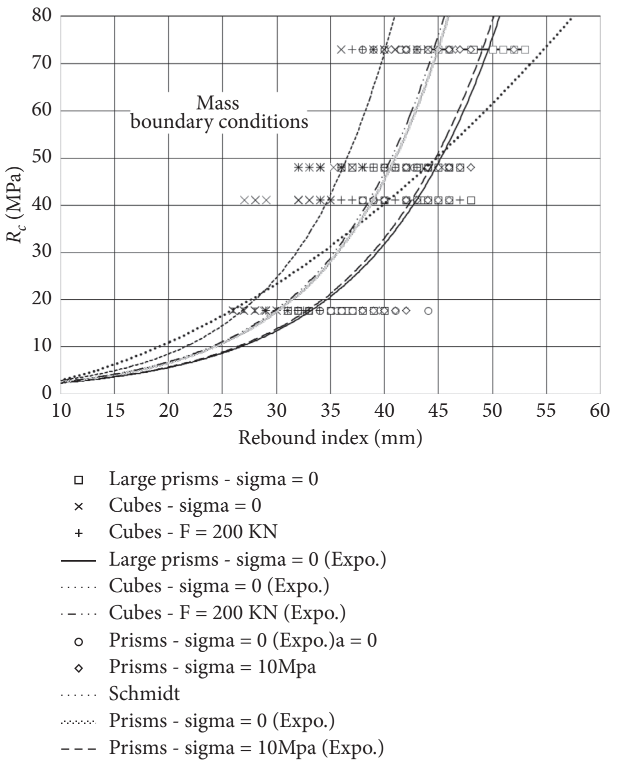


Figure 8: Calibration curves for different specimen mass and stress state. Dotted bold line: Schmidt curve. Calibration curve: $R_c = e^{a\mathrm{RI}}$; RI = rebound index; $a \in [0.088, 0.110]$; $R^2 \cong [0.66, 0.93]$. Inside any dataset, C.o.V. $\leq 9\%$ for vanishing stress; C.o.V. $\leq 10\%$ for compressed prisms (5 and 10 MPa, 200 kN).

Even though the effect of stress state is already known for rocks [31], it has never been fully investigated in concrete, for which it seems of great relevance, too, because (i) the stress state affects the results by 30–35%; (ii) it relates the structure to the material properties, which is an undesired feature of a test aiming at identifying the material.

It has to be noted that data dispersion is a relevant feature of the rebound tests: the calibration data used in the previous figures show that the uncertainty of the test is high so that the actual use of the calibration curves is doubtful. 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 producing specific specimens with different strengths 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 maturity are highly controlled until the test; this is not exactly what happens in civil engineering practice.

In this section, Figure 9 shows the effect of concrete maturity on the rebound index referring to a large database collected in the last two years in the Laboratory for Building Materials of the University of Genoa. The specimens were all 150 × 150 × 150 mm cubes either delivered to the laboratory for standard quality testing or moulded by the laboratory during its usual quality controls in the building sites. For these specimens, which are cured in standard conditions, data of 7 and 28 days could be obtained with good precision, while third-party specimens are often older than 100 days since the 28-day limit is seldom respected; besides, these latter specimens have been cured in uncontrolled conditions since they are usually delivered to the laboratory when the structure is completed and not within 48 hours from moulding. As Figure 9 shows, concrete maturity plays a relevant role: a 30 mm rebound index would account for a compressive strength ranging from 32 MPa for 7-day-old cubes to 57 MPa for more than 100-day-old cubes, which is almost 85% more. Since the same rebound index applies to concrete with different strengths, we can say that concrete maturity affects the rebound index not only through concrete strength but also through some other parameter, such as the surface hardness, which also changes as concrete maturity increases. All the tests summarized in Figure 9 show a negligible carbonation of the external surfaces, all being cubes kept in controlled conditions (not in open air) before testing.

Such an outcome is not surprising in itself and quantifies what could be, in practical applications, the overall effect of the independent variables on the test for the concrete quality assessment [29]. The error introduced only by the curing conditions is thus systematic, i.e., it affects the mean value, the parameter that is used for estimating concrete strength.

4.2. Field Tests. In existing structures, concrete becomes a general term to identify a class of materials originated from the mix of gravel, sand, cement, and water and cured under very different environmental conditions. It is not unusual that the concrete poured in the mid-summer may experience temperatures as high as 70–75°C in Europe or more in hotter areas. When the structures are built in winter, concrete temperature might be close to the ice limit, thus slowing down concrete hardening. This requires very careful application of the calibration curve, deduced in some controlled conditions, to real materials.

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. The cylindrical-to-cubic strength ratio could be assumed to be equal to 0.83.

Figure 10 shows different possible "calibration curves" for the same set of field data compared to the original Schmidt curve; more than 30 points can be found in the figure because in several cases, the tested structure showed more than one concrete type due, for example, to expansion of the building (i.e., an added floor over the original roof) after its construction. It can be observed that none of the curves fit the cloud of field data, which shows that a universal curve for concrete cannot

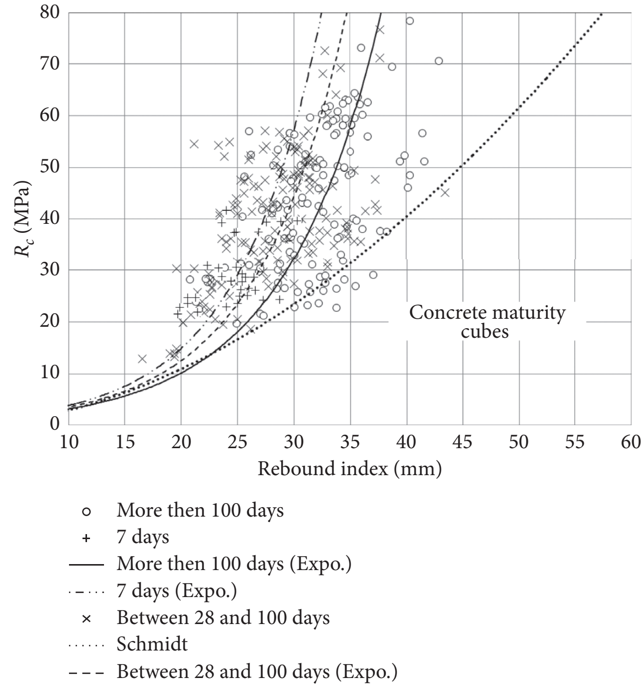


Figure 9: Calibration curve for different concrete ages after casting (standard curing conditions). Calibration curve: $R_c = e^{a\mathrm{RI}}$; RI = rebound index; $a \in [0.12,\ 0.14]$; $R^2 \cong [0.61,\ 0.81]$. Inside any dataset, C.o.V. ≅ 13% for <100-day cubes; C.o.V. ≅ 22% for cubes∈ [28, 100] days; C.o.V. ≅ 11% for 7-day cubes.

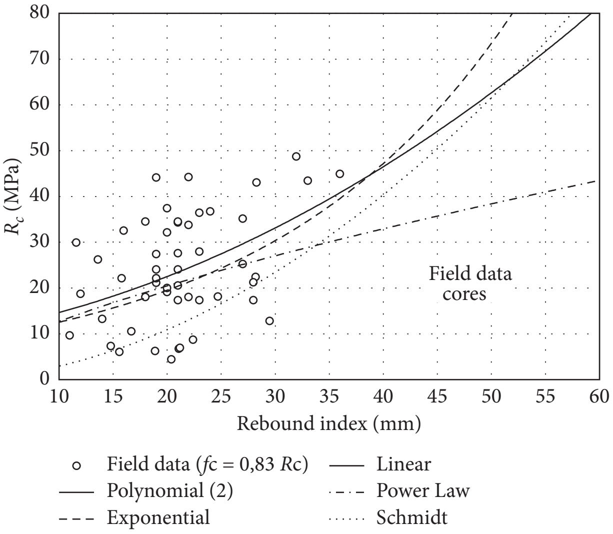


Figure 10: Different calibration curves and field data.

exist, as already assumed by scientific research [26, 27, 32] and by code provisions [24].

This result can be explained noting that the cubic and cylindrical specimens used for quality tests are cured in conditions that are anyway more controlled and not so extreme as the actual structure. In situ tests apply to structures that are left in uncontrolled environmental conditions that, as already discussed, in winter and, more frequently, in summer, may be extreme. This introduced another systematic error that makes the "calibration specimens" quite different from the concrete of the real structure.

5. Comparisons

Figure 11 shows the calibration curves obtained for dry and saturated cubes at different stress levels (vanishing stress, 20%, 40%, and 60% of their compressive strength) along with the original Schmidt curve. It can be observed that the two parameters considered in Figure 11, stress state and moisture, may account for a difference in the estimated concrete strength as large as 100% for RI = 30 mm and 150% for RI = 35 mm. These figures show that the stress state is a parameter that cannot be neglected in the interpretation of rebound hammer tests.

Figure 6 shows a relevant difference in the calibration curves for dry and saturated concrete. This result is already known, and the differences quantified in Figure 6 are coherent with what has been already estimated in [33].

Figures 7, in which the stress state is not related to the material compressive strength, and 11 show that the most relevant effect of the stress state is for limited stresses, substantially in the range 0 to 5 MPa, while the effect over 5 MPa can be hardly recognized. Such a conclusion is coherent with the outcomes of [32], which also showed that the calibration curves for in-between 0 and 5 MPa can be deduced by linear interpolation.

The results found in this research are in rather good agreement with some literature data. It has to be noted that, in the early research on rebound tests, calibration curves were either linear or very close to linear curves, see also Figure 1, since the strength range under consideration was quite restricted and the difference between linear and nonlinear curves was practically negligible. Extending the strength range on which the calibration curve is required, due to the increase in strength of the concrete commonly used in the construction field, calibration curves need to be extended. As a result, the linear approximation can no longer be acceptable, and nonlinear curves need to be addressed [34]. In this paper, it has been confirmed that calibration curves are nonlinear and that any of the parameters affecting the test result leads to a nonlinear calibration curve.

In all the cases, it has to be noted that the calibration curves are the best fitting diagrams of very dispersed experimental data so that the confidence of the curves is not less than 35–40%. The outcome of this circumstance will be discussed in the final section of the paper.

6. Some Observations on the Rebound Mechanism

It is well known and repeated in all the Schmidt hammer manuals that the concrete surface has to be smoothed down (with the grinding stone provided with the equipment) before performing the test. This is enough to make the surface plane, but it is not enough to get rid of one of the features of concrete structures: in the outer part of the elements, concrete has no

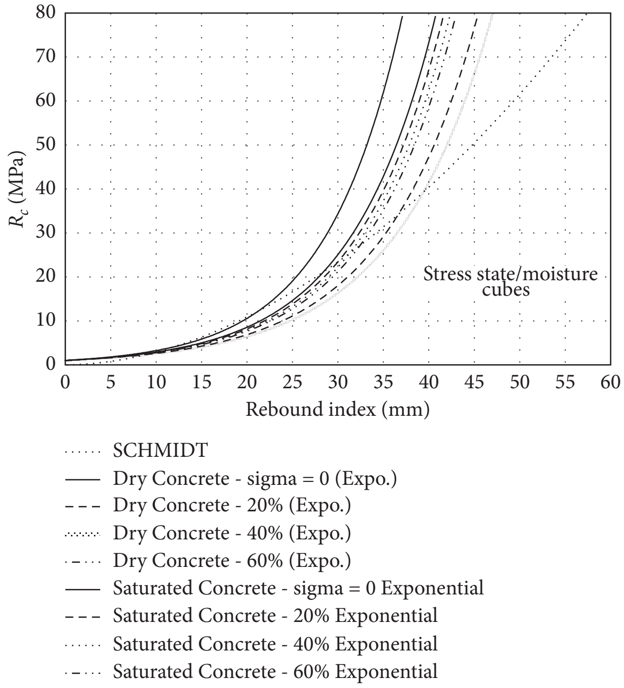


Figure 11: Calibration curves for moisture content and loading conditions (% of the ultimate load). Calibration curve: $R_c = e^{a\mathrm{RI}}$; RI = rebound index; $a \in [0.094, 0.120]$; $R^2 \cong [0.62, 0.97]$.

large aggregates but only fine ones (Figure 12). This means that the rebound hammer, which measures the surface hardness of concrete, actually puts the plunger on a material that resembles more of cement mortar than concrete.

Another phenomenon affecting concrete compaction during the casting phase is bleeding, consisting of a flow towards the upper surface of a mixture of water and cement. Since the outer layer of concrete elements is different, also displaying different densities, the effect of bleeding is that of gathering water lenses at a short distance from the surface (Figure 13). Besides, a similar phenomenon can also be found close to the subvertical surfaces of the aggregates, Figure 14, which also shows the different composition and consistency of the outer concrete layers.

These circumstances give partial explanation of the data dispersion that is always found when using rebound methods. In fact, these circumstances are one of the most severe drawbacks of this kind of test methods since they show that the tested surface is rather different from the inner core of concrete, which is the part of the material the structural engineer looks at when assessing a structure.

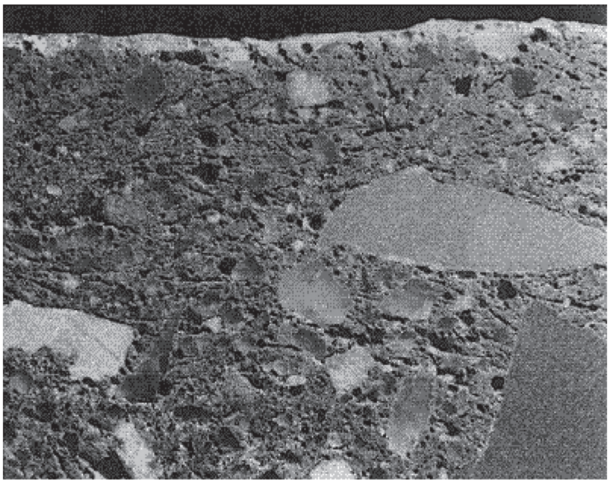


Figure 12: Outer layer of a concrete element: aggregates remain 5–10 mm approx. far from the surface. 5x photo.

Another drawback of the Schmidt hammer test is that its results are not only affected by the material but also by the structure the test is performed on. Figure 15 shows two kinds of structures that have similar performances with respect to rebound tests. Due to the limited thickness of the stairs of Figure 15(a) and the reduced redundancy of the precast flight of stairs of Figure 15(b), both structures are subjected to clear perceptible vibrations when hit by the plunger in the locations and directions shown in Figure 15 by the arrows. In these cases, a part of the impact energy provided by the plunger is transferred to the structure as kinetic energy, resulting in low values of the rebound index that are not due to the material surface. According to the experience of the Laboratory, these values are 20-to-30% of the value obtained for the same concrete on massive specimens.

Even though these tricky cases can be avoided by proper practice, the interaction of the structural element with material properties is an undesired feature of rebound procedures that cannot be corrected, also introducing multivariate functions [28].

Other misleading circumstances that cannot be easily discovered are related to high porosity of concrete close (but internal) to the surface and to the presence of either large aggregates (rare) or reinforcing bars close to the surface.

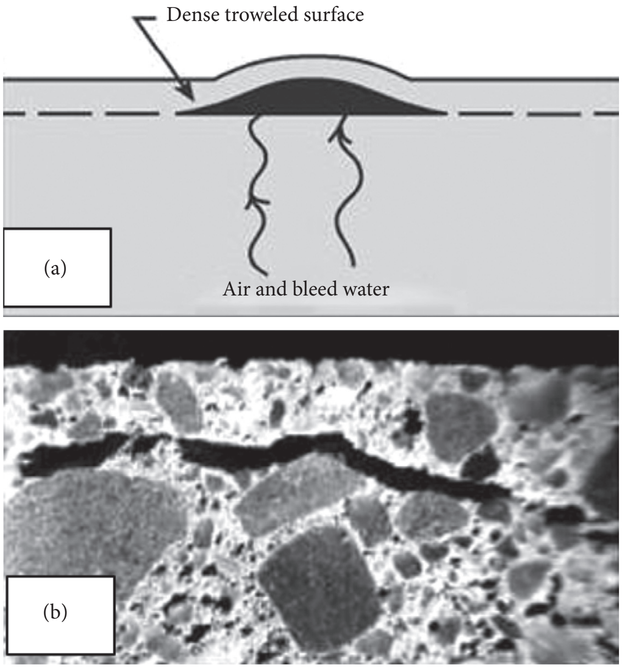


Figure 13: Effect of bleeding below the upper layer of concrete: (a) schematic draft; (b) 5x photo.

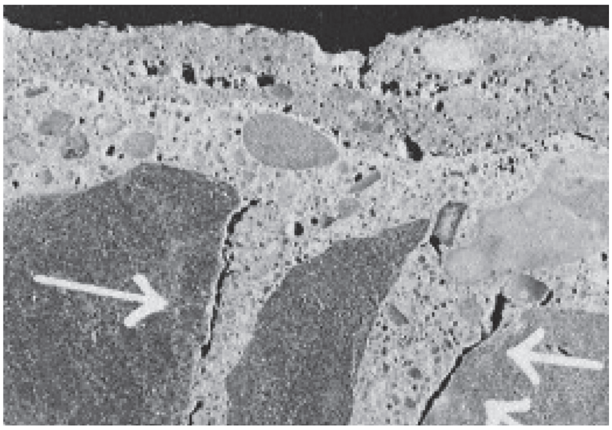


Figure 14: Effect of bleeding close to subvertical surfaces (5x).

(a)

(b)

Figure 15: (a) Thin and (b) precast r.c. structures (stairs in this case).

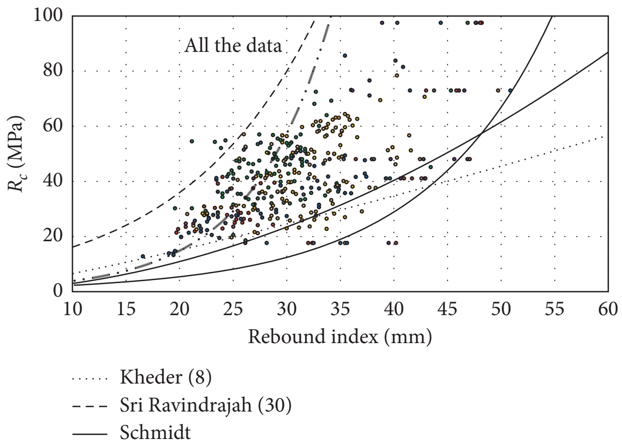


Figure 16: The whole set of experimental data compared to the calibration curves of this paper, the Schmidt curve, and the curves obtained in [8, 30].

7. Discussion and Conclusions

Figure 16 shows a summarizing plot in which the whole set of experimental data of this paper is compared to the calibration curves obtained in the paper (upper and lower curves, grey lines) and the calibration curves found in the literature [8, 35] that are on the outer boundaries of the cloud of 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.

The large scattering of experimental data has been obtained taking into account not only concrete specimens cast 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, carefully cast in the laboratory for research purposes, but also on a large number of concretes. These differ not only in their strength but also in the aggregate mix, the aggregate type, the cement type, pouring and curing conditions, etc., representing the “real” materials the test is intended for. This introduced in the experimental campaign other parameters, affecting the rebound test, as highlighted by the dispersion of the values represented in Figure 16.

This is the direct consequence of the intrinsic features of the rebound hammer test:

(i) Very limited area hit by the plunger, which makes the test strongly affected by all the parameters, affecting local properties of the material

(ii) Irregularities of concrete mix close to the surface that cannot be removed, smoothing down the surface by means of grinding

(iii) Interaction of the plunger with local irregularities (voids, aggregates, and bars)

The large scattering of the test data substantially represents what happens if the multivariate functions introduced in [28] are not taken into proper consideration. Because of the use of multivariate functions of independent variables that are unknown in engineering practice, a crucial question is given: is the rebound hammer somehow significant in estimating the concrete strength? Figure 16 provides part of the answer, suggesting that the rebound test may be considered as a really rough tool for the estimation of concrete strength. Since this has not been understood yet in engineering practice, general calibration curves should not be provided by the producers of the Schmidt hammers.

The approach suggested by some code ([24] and its national versions) and by recent research (see [34] for a comprehensive overview) is somehow similar. In order to use the rebound test to assess concrete strength, one should adopt a predefined shape of the calibration curve suggested by the codes and perform a specific calibration campaign on the concrete under consideration (i.e., shift the given curve so as to best fit the experimental data). In this way, no universal calibration is assumed, but a universal form of the curve is set, that is, according to [24], slightly nonlinear for low-strength concrete (<8 MPa) and linear for high-strength concrete (from 8 to 50 MPa). Such a curve does not fit many of the experimental results, such as the ones of this paper, if it is extended over 50 MPa, and also is not completely satisfying in the range 35–50 MPa, according to the data obtained in this research. Similar results have been obtained in [29].

In conclusion, the reliability of the rebound hammer test has been investigated in this paper. This test is very widespread in practice because it is a simple, nondestructive, fast, and cheap technique, but not enough attention is paid on its reliability.

Use of simple, noninvasive, and inexpensive methodologies to characterize materials and for their degradation monitoring is a crucial issue in civil engineering. Nondestructive tests are the ones that best fit these features, even though their reliability is not always in the priority list of professional engineers. While the Schmidt hammer, that is one of the simplest NDT methods, strictly pertains to concrete and rocks, noninvasive techniques were proposed and widely applied in many other fields, such as in geophysics and geotechnical investigations [36–38]. Due to the ease in these tests and many circumstances that may introduce a bias into the results, the accuracy and reliability of these techniques must be properly discussed. It is precisely on reliability of the Schmidt hammer that the research illustrated in this paper has focused.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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