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ORIGINAL ARTICLE

Testing of concrete by rebound method: Leeb versus Schmidt hammers

Konstantin Kovler · Fengzhe Wang · Boris Muravin

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Abstract Hardness is considered as an important property of concrete; it can be used to estimate compressive strength of concrete in situ. The classic Schmidt rebound hammer is the most popular nondestructive method to measure concrete surface hardness, while the Leeb rebound hammer has been extensively studied in geological and metallographic fields over decades, and its use for testing concrete is almost not known. The national and international standards for the measurement of hardness are reviewed. Concrete made different *w*/*c* ratios (0.33, 0.4 and 0.5) were tested by both methods. The simple linear correlation between rebound numbers (both Schmidt and Leeb) and concrete compressive strength are proposed. Schmidt rebound number was differently correlated with compressive strength for concretes with different *w*/*c* ratios, while the Leeb rebound numbers were more consistent and could be applied in predicting concrete compressive strength within 10% error for all *w*/*c* ratios. It was also concluded that Schmidt test can be considered as a semi-destructive method, because of significant strength reduction (in average by 10.5 MPa) that was observed after application of Schmidt hammer impact on specimens, while the Leeb rebound test procedure did not result in any damage of concrete. This difference can be explained by the dramatic difference in impact energy of the two hammers (2207 and 11 N·mm - for Schmidt rebound hammers of *N*-type and Leeb hammers of *D*-type, respectively). Moreover, the classic Schmidt rebound hammer is not recommended to be used on the concrete specimens, which are aimed for compressive tests at early age (less than 3 days) or when expected compressive strength is less than 7 MPa. These constraints do not apply to lower impact Leeb rebound devices, which can be considered as perfectly invasive (non-destructive). At the same time, as expected, Leeb rebound test is sensitive to the surface conditions, such as carbonation and surface moisture.

Keywords Concrete · Nondestructive tests · Schmidt rebound hammer · Leeb rebound hammer · Compressive strength · Hardness

K. Kovler (✉) · F. Wang
Faculty of Civil and Environmental Engineering, Technion - Israel Institute of Technology, Haifa, Israel
e-mail: cvrkost@technion.ac.il

F. Wang
e-mail: wangfz@campus.technion.ac.il

B. Muravin
Integrity Diagnostics Ltd., Netanya, Israel
e-mail: boris@ndt.co.il

1 Introduction

A quantitative assessment of concrete properties plays a predominant role in design of modern reinforced concrete structures. Compressive strength of concrete is considered the most important property. However, standardized compressive strength is not always being available to be executed in real time in situ. Meanwhile, the hardness, technically, is considered as the resistance of the material against the penetration of a specific and typically harder indenter. With the developments of nondestructive testing (NDT) methods, like rebound hardness tests, the measurements can be performed directly on the structure and then the mechanical properties of concrete can be estimated from the measured values.

In 1950s, a Swiss engineer, Ernst Schmidt, developed a spring impact hammer using a rebound principle [1, 2], and this device is also referred as the Swiss hammer. The final rebound value can be read directly on the display of the testing device. The basic purpose of Schmidt rebound hammer tests is usually to find a correlation between Schmidt rebound value (*S*-value) and compressive strength to estimate the strength of concrete with an acceptable confidence level. Many studies have been carried out to investigate the parameters interfering the results by Schmidt rebound number [3–7]. The Schmidt hammer provides a comparatively quick, mobile and easy executable measurement of surface hardness and it is still the most widespread used in situ apparatus.

At the same time, there is another dynamic hardness test method and instrument, known as Leeb rebound hammer. The Leeb rebound hardness test method was developed in 1975 by Leeb [8] at Proceq SA to provide a portable hardness test for metallic materials. However, Leeb rebound hammer is not used for testing concrete, although it is widely used in geological and metallographic fields over decades. In our opinion, each type of rebound hammer test/instrument has the own advantages and disadvantages. In view of this, the authors tried to understand what are possible explanations (if any) that concrete practitioners, both engineers and researchers, are unaware of the Leeb rebound hammer.

The Leeb rebound hammer fires an impact body containing a permanent magnet and a very hard spherical tungsten-carbide indenter towards the surface of the tested material (Fig. 1). A mass is accelerated by a spring toward the surface of a test object and impinges on it at a defined velocity, and the rebound of the impact body leads to a deformity of the upper surface, which results in a loss of kinetic energy. As a small permanent magnet within the impact body generates an induction voltage during its passage through a coil, the velocities before impact and rebound are both measured, while the voltage recorded is proportional to the velocity of the impact body. Then, the loss of energy during impact is determined by the measuring these velocities and used to calculate the Leeb hardness value (Fig. 2).

The Leeb Hardness (*L*-value), HL, is a direct measure of the hardness, which is defined as follows:

$$\mathrm{HL} = 1000 V_{\mathrm{r}}/V_0 \tag{1}$$

where V_0 is impact velocity, and V_{r} is rebound velocity. At the beginning, the Leeb hardness number (HL) was not well-known among the engineering community and always was converted into traditional hardness numbers like Brinell (HB), Rockwell (HR), and Vickers (HV), which were widely used to assess material quality. Since the significance and reliability of Leeb rebound hammer tests have been extensively studied on testing natural rocks and metallic materials over past decades [7, 9–20], it can be an alternative (and perhaps competing in some cases) method to estimate concrete quality, elastic and strength properties. However, to the best of our knowledge, only one paper described the use of this method for testing concrete has been published so far—by Szilágyi et al. [25]. Unfortunately, the concrete engineering and research community is unaware about a potential, pros and cons of the Leeb rebound method, and the procedure for testing concrete is still not established. The goal of the current paper is to study a possibility of using Leeb rebound hammer method for testing concrete and understand its advantages and limitations, in comparison with the well-known method of Schmidt rebound hammer.

2 Influence of different factors on rebound numbers

2.1 Empirical correlations with compressive strength

Empirical correlations, either linear, power or exponential functions, have been established between concrete or rock compressive strengths and Schmidt hammer numbers in many publications [21–29]. Malhotra and Carino [30] reported that the accuracy of the compressive strength estimation (as the relative

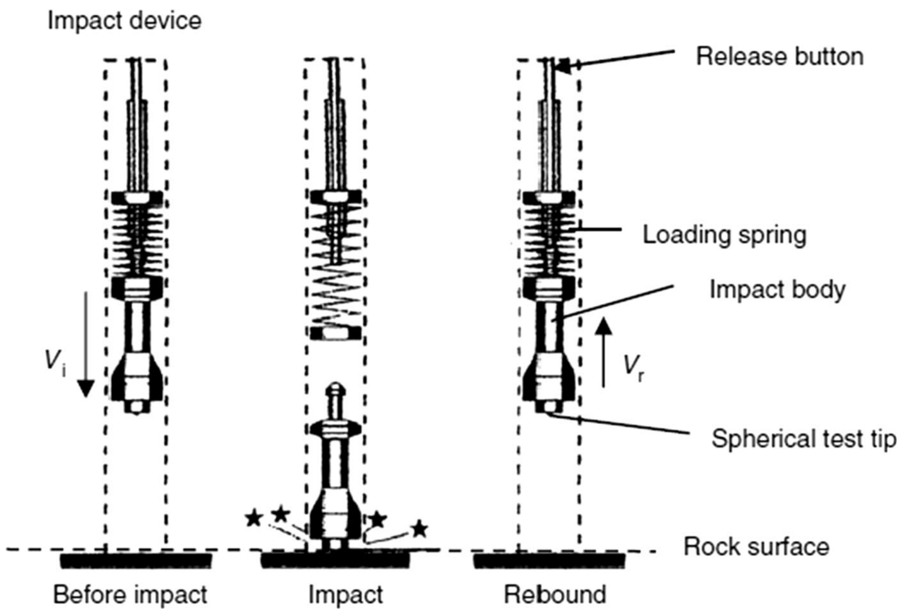

Fig. 1 Operating schematic of Leeb rebound hammer impact device [9]

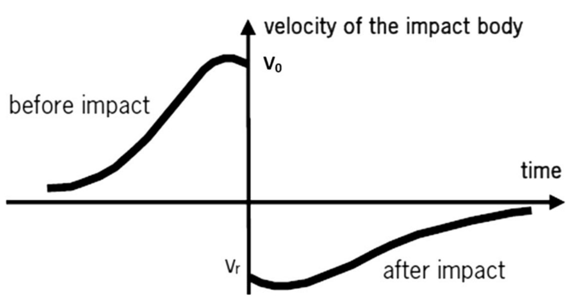

Fig. 2 The definition of Leeb hardness, HL

error in the strength estimation) using the rebound hammer was in the range between 60% and 70%. This error is relatively large, because the accuracy of the method depends on many factors, such as the variability of the concrete, concrete age, moisture, temperature etc. For the Leeb hammer test, Verwaal and Mulder [11] reported a reasonable simple linear relation between uniaxial compressive strength (UCS) of rock and Leeb number. Kawasaki et al. [14] presented linear correlations between *L*-value and UCS for sandstone, green schist, shale, hornfels and granite core samples. oki and Matsukura [16] also proposed an optimum correlation to estimate UCS by taking into account both the Leeb hardness value and rock porosity.

2.2 Effect of the specimen/block size

For either Schmidt hammer or Leeb hammer test, sufficient number of impacts/readings are the priority factor for ensuring reliability of the hardness measurements. In fact, a larger test area is required in Schmidt hammer testing, due to the relatively large impact tip in Schmidt hammer compared to Leeb rebound hammer. Demirdag et al. [6] indicated that block size is critical to Schmidt rebound numbers, which increase with the block size and concluded that the optimum dimension of cubic sample is 110 mm. In contrast, Viles et al. [7] in the study based on in situ measurements found that the Leeb rebound values do not depend on the rock block size. Yılmaz [17] also did not find an evidence that the specimen size has any significant effect on the results of the Leeb hammer test.

2.3 Effect of the surface layer properties

In general, rebound hammer tests are strongly influenced by the characteristics of the tested material layer adjacent to the surface. The thickness of the layer, which influences the rebound value, depends on the amount of impact energy, the impact area, and the elastic and strength properties of the material. Hack and Huisman [4] reported that Schmidt values are affected by the underlying material with depths up to several centimeters, and by the discontinuities, which lie within the radius of influence. Moreover, surface irregularities (always fragmented), as well as potential micro-cracking, grain crushing and pore collapse, which may be generated under the strong impact of Schmidt plunger tip (2207 N mm, *N*-type), result in dissipation of the impact energy and bias of the results. Statistical accuracy increases with the number of readings (measurements), but paradoxically decreases with the degree of surface damage due to additional Schmidt hammer tests. Moreover, Adyin and Basu also [31] claim that the Schmidt hammer impact can induce micro-cracks in the tested material and therefore significantly decrease its UCS, especially in the case of weak rocks. Consequently, using the same specimen in Schmidt hammer and compressive strength tests, can result in erroneous correlation of strength versus *S*-value. This drawback of Schmidt hammer test may limit its application. In contrast, because of the small impact energy of the Leeb hammer (11 N mm, *D*-type), which is only 1/200 of the *N*-type Schmidt rebound hammer, the Leeb hammer seems avoids the problem of surface damage and seems to be suitable for measuring hardness of a very thin layer near the surface.

The Leeb test is of low energy and mobilizes a small portion of the surface of a sample. Theoretically, this may be a limitation to the applicability of the test to concrete, because such test is expected to be more sensitive to the influence of the properties of surface layer and therefore may provide inaccurate estimates of the actual strength of a specimen. Aggregates close to the surface may potentially introduce more variability in the results. Indeed, it may be interesting to study the effect of the distance of aggregates from the sample surface in future. At the same time, it would be rather difficult to simulate such effect, because this distance is hardly defined by the known testing methods, and for this purpose the method of measuring this distance must be developed first.

2.4 Effect of moisture

Moisture of the material can influence the results of rebound hammer tests. Summer and Nel [5] found that influence of rock moisture content on Schmidt rebound number varies with the rock type, e.g. for quartzite block the Schmidt numbers at 60% saturation were by around 7% lower than the Schmidt rebound values obtained when the rock was dry; the Clarens sandstone showed a more significant decrease (exceeding 17%) in the rebound numbers after the dry rock was water-saturated. In addition, the significant influence of surface moisture on the Leeb hammer readings were reported by Viles et al. [7].

2.5 Influence of repeated impacts

Considering the compacting effect after ten repeated impacts on the same spot, Yılmaz [17] proposed a new Leeb hammer testing methodology, which involves a hardness parameter, so called hybrid dynamic hardness (HDH)—a combination of the surface rebound hardness and deformation ratio of a rock material. Aoki and Matsukura [16] reported that the Leeb number of rock gradually increases with the increasing number of impacts (at the same point) and finally converges to a constant value. We assume that this effect is a result of the compacting of the same hit area.

2.6 Rebound hammer tests in concrete and rock of different strength

Applicability of rebound hammer tests in the materials of different strength can be different. Let us consider a possible influence of strength on the rebound numbers for both rock and concrete. In the rock classification suggested by Bieniawski [32], the rocks with a UCS less than 25 MPa are considered very weak, 25–50 MPa—weak, 50–100 MPa—medium strong, 100–250 MPa—strong, and finally the rocks stronger than 250 MPa are categorized as very strong ones. In parallel, concrete is also divided into three main categories by its compressive strength: low-, normal- and high-strength concrete.

Momber [33] presented the deformation and fracture of rock when loaded with spherical indenter generated applied contact forces between 0.1 and 2.45 kN, with indenter sizes of 1.0 and 5.0 mm, respectively. He found that the depression radius on the soft rock is linearly increased with the indenter radius, causing radial cracking and strength degradation in the near surface regions. The 2007 revised recommendation of the International Society for Rock Mechanics and Rock Engineering (ISRM) suggests [34] that Schmidt hammer test is generally nondestructive for rock sample with UCS of at least 80 MPa. At the same time, the recommendation of ASTM

(American Society of Testing Materials) [35] states that Schmidt rebound hammer is of limited use for testing both very soft rock and very hard rock, which are defined as having UCS less than approximately 1 MPa or greater than 100 MPa, respectively.

As far as concrete is concerned, the ASTM standard C805/C805m-13a [36] does not address such limitation for Schmidt hammer test on concrete—perhaps, because most of concrete (in both structural and non-structural applications) has compressive strength in between 1 and 100 MPa.

2.7 Rebound hammer tests in standardization

A considerable progress in the development of NDT methods for testing concrete is well-reflected in standards and guidelines recently published. Many NDT methods, like the rebound hammer test, have been standardized by ASTM International, the British Standards Institute (BSI), European Committee for Standardization (CEN) and the International Standards Organization (ISO), etc. Various national standards and organization recommendations for measurement of Schmidt and Leeb rebound numbers on various materials (harden concrete, rock and metal) are partly listed in Tables 1 and 2, respectively. Table 1 lists the standards regulating uses of Schmidt hammer method for testing concrete and rock, while Table 2 addresses uses of Leeb hammer method for testing metals. Compared to the progress in geological and metallographic fields, the awareness of concrete research and engineering community, practical experience and, consequently, standardization of Leeb rebound method for testing concrete is still relatively blank.

Table 2 Standards for the determination of Leeb rebound number on metallic materials

Country (A–Z)	Designation	Year
China	GB/T 17394.1-2014	2014
European Union	EN ISO 16859-1:2015	2015
Germany	DIN 50156-1:2007-07	2007
International	ISO 16859-1:2015	2015
United Kingdom	13/30263150 DC[a]	2013
USA	ASTM A956-12	2012

[a]Replaced by BS EN ISO 16859-1:2015

Table 1 Standards for the determination of rebound number on concrete or rock

Country (A–Z)	Designation	Year
Brazil	ABNT NBR 13317:2012	2012
China	JGJ/T23-2001	2001
Denmark	DS 423.30:1984[a]	1984
European Union	EN 12504-2:2012	2012
France	NF P18-417:1989[a]	1989
Germany	DIN 1048-2:1991[a]	1991
India	BIS IS 13311: Part 2-1992	2008
International	ISO 1920-7:2004	2004
ISRM	ISRM suggested method (2007 revised)[b]	2009
Italy	UNI 9189-88[a]	1988
Japan	JIS A 1155:2012	2012
Korea	KS F 2730-2008	2008
Norway	NS 3677:1987[a]	1987
Netherlands	NEN 5978:1990[a]	1990
RILEM	NDT 3	1984
United Kingdom	BS 1881-202:1986[a]	1986
USA	ASTM C805/C805M-13a;	2013
	ASTM D5873-14	2014
Vietnam	TCVN 9334:2012	2012
Singapore	SS 78-B2:1992[c]	1992

[a]Replaced by EN 12504-2:2012

[b]ISRM Suggested method for determination of the Schmidt hammer rebound hardness: Revised version

[c]Withdrawn and can refer to EN 12504-2:2012

Different methods of measuring Schmidt rebound value have been suggested by various standards and technical reports. Schmidt hammer test is most commonly performed following the ISRM Suggested method, ASTM C805/805m-13a and EN 12504-02:2012 standards [34, 36, 37]. The recommended Schmidt hammer test requirements for testing concrete and rock are summarized below:

(1) Specimen size:

- ASTM: Concrete members to be tested shall be at least 100 mm thick with at least 150 mm test area.
- EN: Concrete elements to be tested shall be at least 100 mm thick.
- ISRM: Block specimens should be at least 100 mm thick at the point of impact.

(2) Measurement distance:

- ASTM: The distances between impact points shall be at least 25 mm, and the distance between impact points and edges of the member shall be at least 50 mm.
- EN: Distance between two impact points shall be more than 25 mm and at least 25 mm from an edge.
- ISRM: Impacts separated by at least a plunger diameter (to be adjusted according to the extent of impact crater and radial cracks).

(3) Number of impacts (readings):

- ASTM: Record ten readings from each test area.
- EN: Select minimum of nine valid readings for a test location.
- ISRM: It is recommended to gather 20 rebound values and choose 10 subsequent readings when those numbers differ only by four units.

(4) Reading validity:

- ASTM: Discard the entire set of readings if more than 2 readings differ from the average by 6 units.
- EN: Discard the entire set of readings if more than 20% of all the readings differ from the median by more than 30%.
- ISRM: no reading should be discarded, and the mean, median, mode and range of the readings should be presented to fully express the variations in the surface hardness.

(5) Tested surface:

- ASTM: Heavily textured, soft, or surfaces with loose mortar shall be ground flat with the abrasive stone. Smooth-formed or troweled surfaces are preferred. Free surface water shall be removed before testing.
- EN: The same with the requirement in ASTM C805/805m-13a.
- ISRM: Test surfaces, especially under the plunger tip (impact points), should be smooth and free of dust and particles. Fine sandpaper can be used to smooth the surfaces of cores and block specimens. Cores and blocks should be air dried or saturated before testing.

(6) Specimen fixation:

- ASTM: Concrete elements (> 100 mm thick) should be fixed within a structure. Smaller elements or specimens must be rigidly supported.
- EN: The same requirement as in ASTM C805/805m-13a.
- ISRM: Specimens should be securely clamped to a steel base located on firm, flat ground. Core specimens should be placed in a V-shaped machined slot.

From the analysis of the existing standards it can be clearly seen that the standardization on testing of both concrete and rock using Schmidt rebound is well-established, while the standards for testing concrete with Leeb rebound hammer are absent—in our opinion, because of unawareness of the concrete research and engineering community on the Leeb rebound method and its potential. At the same time, the question raises why not to learn and utilize the knowledge gained in the field of application of Leeb rebound method for testing rock and metals, where a massive research has been conducted and, as a result of this research activity, the standardization is well-established.

3 Experimental

3.1 Materials and specimens

Portland-limestone cement CEM II 42.5N/B-LL was used in this study and concrete mixtures were designed in accordance with ACI 211.1-91 [38]. The concrete mixture proportions varied to three different *w*/*c* ratios 0.33, 0.40 and 0.50, respectively. The targeted slump was 125 mm and the mixture proportions used in this research are shown in Table 3, where maximum size of coarse aggregate used in mixture was 9.5 mm. For each *w*/*c* ratio, 18 concrete samples were cast as 100-mm cubes. This size suits well the optimum dimension of cubic sample critical to Schmidt rebound numbers [6], especially considering the maximum size of coarse aggregate.

All concrete specimens were moist cured under standard temperature (20 ± 3 °C) at first 28 days in laboratory, and followed by air-dry curing at laboratory temperatures until age of testing.

All compressive strength tests and rebound hammer tests were conducted on 100-mm concrete cubes at 3, 7 and 28 days. Three twin specimens were tested for compressive strength at water-saturated surface-dry conditions (these conditions are defined as the conditions in which all of the pore space within the specimen is full of water, but no water is present on the surface), and the measurement results were averaged.

3.2 Experimental methods

The original Schmidt hammer (*N*-type) and Leeb hammer (*D*-type) were selected as testing apparatus in this study. Three twin cube samples were tested for each *w*/*c* ratio series. The four flat molded specimen surfaces (100 mm × 100 mm) were chosen as test areas for impacts. Twelve and twenty-five readings were collected at laboratory temperature (20 ± 3 °C) for each sample in Schmidt hammer and Leeb hammer tests, respectively. In Schmidt hammer tests, the cube specimens were clamped on the platform of the compressive strength test machine, and the load of 2.5 ± 0.5 kN was applied on concrete specimens, whereas for conducting Leeb rebound hammer tests, a simple flat and firm ground only was needed as a support. The standard compressive strength testing was carried out on concrete cubes, at the age of 28 days, following the standard procedure in accordance with BS EN 12390-3:2009 [39]. The original Leeb hardness (HL) was chosen as a unit in Leeb rebound test.

4 Results and discussion

Standard compressive strength tests were carried out to determine the compressive strength at 3, 7 and 28 days using 100-mm cube specimens. The strengths of concrete cubes at 28 days ranged from 30 to 60 MPa. The concrete made of *w*/*c* = 0.5 showed the mean strength exceeding 55 MPa at 28 days and therefore can be considered as high-strength concrete, while the compositions cast at higher *w*/*c* ratios represent normal-strength concrete. Table 4 summarizes the test results of rebound hammer and compressive strength. In order to investigate the effects of Schmidt hammer test on concrete mechanical properties, two types of concrete compressive strengths were measured, that of the original (virgin) concrete and that of the concrete, which had been tested by Schmidt hammer prior to compressive strength testing.

By comparing the compressive strengths of concrete specimens before and after conducting Schmidt hammer tests, the influence of the Schmidt hammer

Table 3 Mixture proportions and concrete slump

w/*c*	Cement (kg/m^3)	Water (kg/m^3)	Coarse aggregate (dolomite gravel) (kg/m^3)	Fine aggregate (quartz sand) (kg/m^3)	Superplasticizer (%)[a]	Slump (mm)
0.33	509	176	858	796	1.2	125
0.4	475	197	858	769	0.8	135
0.5	452	233	858	694	0	130

[a]By mass of cement

Table 4 Results of rebound hammer and compressive strength tests on 100-mm cubes

w/c	Age (days)	Compressive strength (MPa)			Schmidt rebound number		Leeb rebound number (HL)	
		Without prior Schmidt hammer test (SD)	With prior Schmidt hammer test (SD)	Strength drop	Mean	SD	Mean	SD
0.33	3	44.59 (0.60)	33.79 (1.41)	10.80	18.40	1.70	293.20	2.22
	7	52.88 (1.72)	43.79 (2.55)	9.09	24.70	1.36	356.00	1.87
	28	57.46 (1.39)	45.88 (2.80)	11.58	30.50	1.69	365.23	1.95
0.4	3	28.59 (2.07)	15.91 (2.04)	12.68	17.20	1.01	183.00	4.6
	7	34.10 (2.39)	27.75 (1.83)	6.35	21.28	0.78	238.30	5.14
	28	39.59 (0.67)	32.81 (2.63)	6.78	25.67	0.79	303.97	4.91
0.5	3	15.25 (2.34)	0 (failure)	15.25	14.89	0.94	162.80	2.18
	7	22.38 (2.29)	11.94 (1.91)	10.44	14.44	0.57	203.30	2.38
	28	35.20 (2.50)	24.13 (3.64)	11.07	21.30	2.37	252.90	1.82

SD standard deviation

test on the compressive strength of concrete is observed. This damage is a function of two main factors, size of the specimens and initial compressive strength depending on water/cement ratio.

A trial to test small-size specimens of the 40 × 40 mm cross-section made of the same concrete compositions with the same Schmidt hammer revealed severe cracking in the vicinity of the impact. This damage well supports the standard requirements for a minimum specimen size (100 mm in our case).

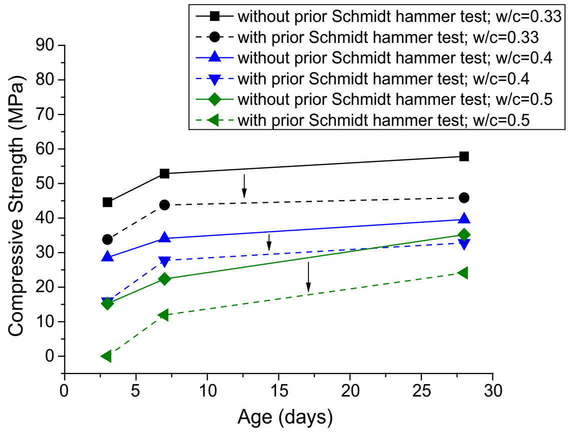

Fig. 3 The effect of Schmidt hammer test impact on compressive strength of concrete specimens made with different *w/c* ratios

Schmidt rebound test shows clearly that because of the strong impact energy, this type of test is actually partially destructive one. The impact by Schmidt rebound hammer may indeed damage the specimen and consequently misidentify the mechanical properties of those concretes in which cracking or critical damage exist. Figure 3 clearly demonstrates that all the values of compressive strength measured on the standard 100-mm cubes drop as a direct result of the previous Schmidt hammer tests carried out on the same specimens. Due to the significant impact energy generated, Schmidt hammer left clearly seen signs of local surface damage in the form of rounded blemishes-depressions, or even severely damaged the tested specimen. A non-negligible decrease of compressive strength is observed, especially, on early-age concrete specimens. For example, after conducting Schmidt hammer testing on 100-mm concrete cubes, made at the highest *w/c* of 0.5 and tested at 3 days age, the visible flaws and crushed particles were found on the testing surfaces. This damage can lead to completely loss of concrete compressive strength, as it happened with this series. It can be seen that the macro damage and micro-cracking due to the previous Schmidt hammer test reduced final concrete compressive strength of 100-mm cube specimens by approximately 20%. That is why the regular Schmidt rebound hammer test cannot be recommended for using on early age concrete (with age less than 3 days) or with expected compressive strength less than 7 MPa. At the same time, a special Schmidt hammer with less impact force can be applied to test concrete with compressive strength lower than 1 MPa. Nevertheless, testing concrete with compressive strength between 1 and 7 MPa with Schmidt hammers is a problem.

It is interesting also to mention that relative strength reduction was higher in the weaker concrete, while the absolute reduction in strength was quite significant for all the *w*/*c* concrete mixes: 10.5 MPa in average, varying from 6.4 to 15.2 MPa (Fig. 3).

Figure 4 shows the correlation between Schmidt rebound number and concrete compressive strength. The higher uncertainty concerning the Schmidt value of the weak concrete (made with the highest *w*/*c* ratio of 0.5 and tested at early age) is observed. The Schmidt numbers for 3 and 7 days concrete in the *w*/*c* = 0.5 series were rather close. In this sense, the Schmidt hammer of this type does not seem very much suitable to test hardness of relatively weak concrete. For testing soft concrete, another type of Schmidt hammer, of so-called pendulum type, is more appropriate.

Figure 4 shows also that the patterns of the curves of different *w*/*c* ratios are different. They can be divided onto two groups, for high-strength made at *w*/*c* of 0.33, and for normal-strength concrete made at *w*/*c* of 0.4 and 0.5. At the same time, for concretes with similar compositions, empirical relations between hardness and compressive strength are expected to follow a close path. This was not a case with Schmidt numbers.

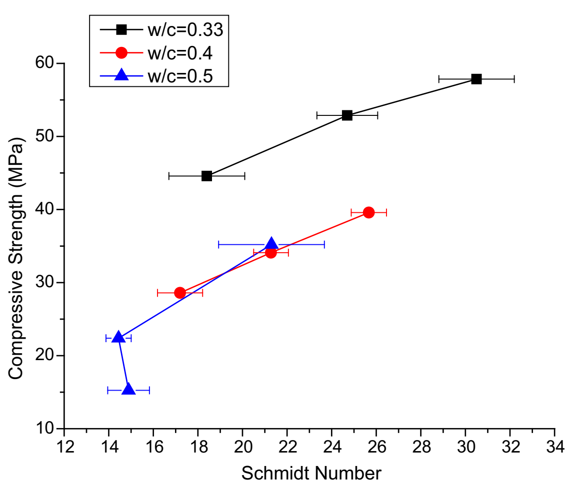

Fig. 4 Correlation between Schmidt hardness value and compressive strength for the tested concrete compositions

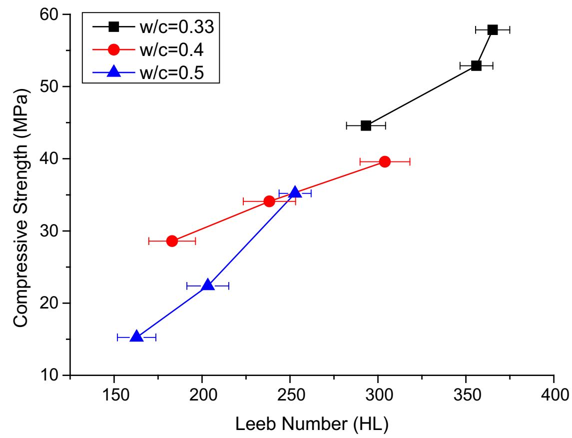

Fig. 5 Correlation between Leeb hardness value and compressive strength for the tested concrete compositions

Figure 5 shows the correlation between Leeb rebound numbers and concrete compressive strength. In contrast to Fig. 4 showing the correlation between Schmidt number and strength, the dependence between the Leeb rebound number and compressive strength for concrete made with various *w*/*c* ratios was more consistent (i.e. can be approximated by the same linear curve), while the data scatter seem to be slightly affected by the *w*/*c* ratio.

For the statistical analysis the regression dependences of the results of hammer tests versus the results of compressive strength obtained on “virgin” samples, it means before the hammer tests, were analyzed.

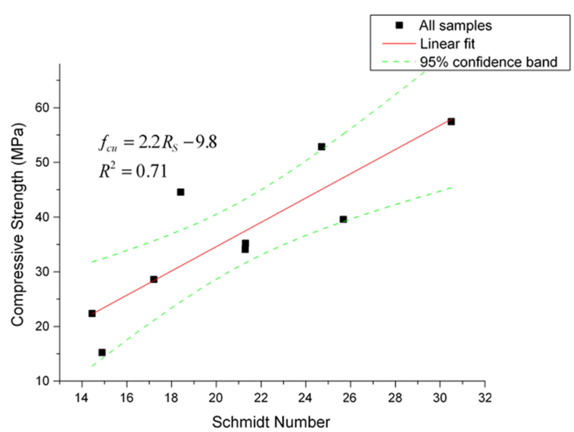

Fig. 6 Simple linear fitting of the relationship between Schmidt hardness value and compressive strength for the tested concrete compositions

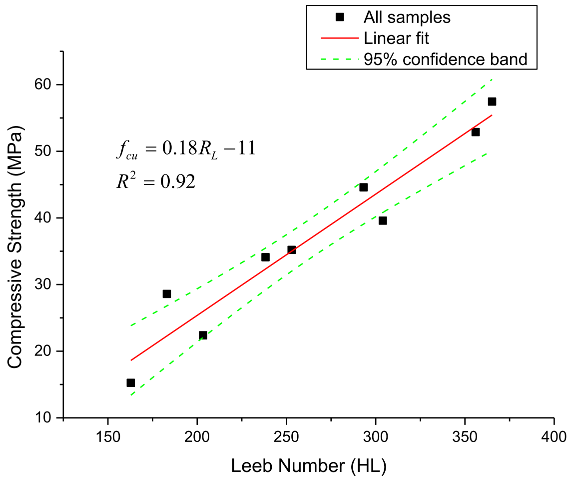

Fig. 7 Simple linear fitting of the relationship between Leeb hardness value and compressive strength for the tested concrete compositions

The following simple linear dependences are proposed between the rebound number numbers and compressive strength of the tested concrete compositions, including the confidential intervals for the predicted compressive strength (Figs. 6, 7):

$$f_{cu} = 2.2R_S - 9.8; \quad R^2 = 0.71 \tag{2}$$

$$f_{cu} = 0.18R_L - 11; \quad R^2 = 0.92 \tag{3}$$

where f_{cu} is concrete compressive strength at 28 days, MPa, R_S is Schmidt rebound number and R_L is Leeb rebound number.

Table 5 shows the analysis of measured compressive strength and that predicted with a help of Schmidt and Leeb numbers. Generally, it can be seen that Leeb rebound numbers estimate compressive strength values more accurately—with about 10% bias from the original compressive strength value, while Schmidt numbers have an error of 15%.

While the influence of moisture on the Schmidt rebound number is well described in the literature, the influence of surface moisture on the *L*-value is not known. In general, the surface moisture was expected to influence the results of Leeb hammer tests, because any loss of that low impact energy generated by apparatus during testing could affect the final rebound results. Therefore, an additional series of cubes of the same compositions was tested in order to study a possible influence of surface moisture on the Leeb rebound number. These cubes were tested at the mature age (of 1 year). The concrete specimens were divided onto two parts, one part from each *w*/*c* ratio was tested wet immediately after immersion in water, and another part was tested in air-dry surface conditions. We assumed that to a certain extent, the water film on concrete surface of the first type of the specimens could absorb the impact energy during

Table 5 Comparison of measured and predicted compressive strength by means of Schmidt and Leeb numbers

w/*c*	Strength (MPa)	Schmidt rebound number $f_{cu} = 2.2R_S - 9.8$			Leeb rebound number $f_{cu} = 0.18R_L - 11$		
		R_S	Predicted strength (MPa)	Bias in strength prediction (%)	R_L	Predicted strength (MPa)	Bias in strength prediction (%)
0.33	44.6	18.40	30.68	− 31.2	293.20	41.78	− 6.3
	52.9	24.70	44.54	− 15.8	356.00	53.08	+ 0.4
	57.5	30.50	57.30	− 0.3	365.23	54.74	− 4.7
0.4	28.6	17.20	28.04	− 1.9	183.00	21.94	− 23.3
	34.1	21.28	37.02	+ 8.6	238.30	31.89	− 6.5
	39.6	25.67	46.67	+ 17.9	303.97	43.71	+ 10.4
0.5	15.2	14.89	22.96	+ 50.5	162.80	18.30	+ 20.0
	22.4	14.44	21.97	− 1.8	203.30	25.59	+ 14.4
	35.2	21.30	37.06	+ 5.3	252.90	34.52	− 1.9
Average absolute bias				14.8			9.8

Table 6 Leeb rebound numbers for concrete tested at different surface moisture conditions

Group	w/c	Leeb rebound value (HL)		Difference (%)
		Air-dry surface	Wet surface	
1	0.33	485.4	463.9	4.43
2		474.0	463.9	2.13
3	0.4	475.1	423.6	10.84
4		444.8	433.4	2.56
5	0.5	432.1	405.9	6.06
6		432.1	413.2	4.37
Average				5.07

rebounding, and reduce the rebound velocity. Table 6 shows an insignificant decrease of the Leeb number in the cubes with wet surface, by approximately 5%. It is interesting that similarly, for Schmidt rebound hammer test, dry concrete surfaces give usually higher rebound numbers than the specimens with wet surfaces (ASTM C805/805m-13a [36]). Although the effect of surface moisture on the results of Leeb rebound test is limited, it seems that testing concrete always with dry surface would avoid any uncertainty caused by this effect and be beneficial in the future standard procedures of quality control.

Finally, the results of Schmidt and Leeb rebound tests of concrete made at different *w/c* ratios and tested at different ages, at 3–28 days and in a very mature age of 1.5 years, were analyzed. The correlation between Leeb and Schmidt rebound numbers clearly shows a shifting of the dependence to the right (Fig. 8). The only reasonable explanation of this phenomenon would be surface carbonation. Indeed, the higher sensitivity of Leeb rebound test to the properties of the thin exterior layer of concrete, together with understanding that this layer can be completely carbonated during the long aging of the material in the air, can explain these results.

In other words, the Leeb rebound number is more affected by the surface carbonation of concrete. Crawford [40] reported that the Schmidt rebound numbers for carbonated concrete can be up to 50% higher than those obtained on a non-carbonated concrete surface. The same statement is found in the RILEM report (2012) [41]. In our experiments, the Leeb rebound numbers of old concretes were around 60–80% higher than those of younger concretes. The increase of the Leeb rebound numbers with aging is more pronounced for the weaker concrete compositions made at higher *w/c* ratios, because of faster carbonation rates in more porous systems.

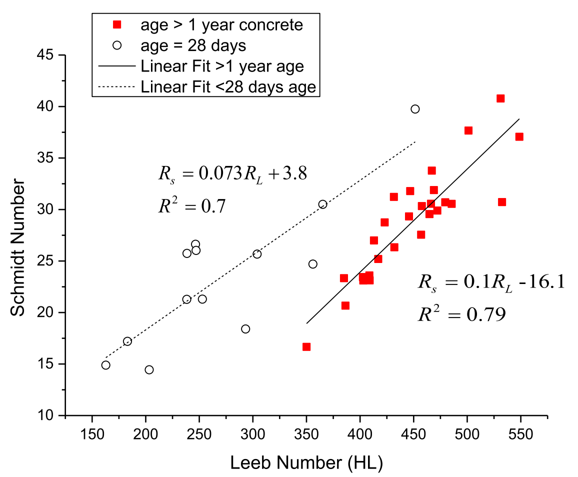

Fig. 8 Leeb versus Schmidt rebound numbers of concrete compositions tested at the ages of 3–28 days and 1.5 years

5 Conclusions

This paper has studied the use of most commonly used nondestructive method, Schmidt rebound hammer, to determine the hardness of concrete mixes varied to three *w/c* ratios, 0.33, 0.4 and 0.5, and estimate their compressive strength. The different technique, Leeb rebound hammer test, known in testing rock and metallic materials, was applied for testing the same concrete compositions in parallel. The correlations between Schmidt, Leeb rebound hammer numbers and compressive strength were obtained. The factors influenced hardness value were discussed, and the following conclusions could be drawn:

(1) Schmidt rebound hammer is considered as one of the most popular non-destructive methods of testing concrete, while Leeb rebound test is not used in quality control of concrete—concrete practitioners are unaware of the potential (as well as limitations) of the Leeb hammer test, the situation is opposite to geological and metallographic fields, where the standardization is well-established and application of Leeb rebound method for testing rock and metals is well-known and considered as a routine practice.
(2) Schmidt rebound hammer provides an information on material hardness from deeper surface layer, while Leeb rebound number seems to be informative of very thin surface layer of concrete.
(3) The compressive strength of concrete specimens made at different *w*/*c* ratios and tested in the ages of 3…28 days varied from 15.2 to 57.5 MPa, while Schmidt hammer (*N*-type) test reduced the strength of the same specimens in average by 10.5 MPa. This reduction is rather significant. The fragmented surface irregularities, potential micro-cracking, grain crushing and pore collapse can be found on concrete samples due to the strong impact energy (2207 N mm) generated by hammer spring. In view of this, Schmidt hammer test can be considered, as semi-destructive method. Moreover, the same specimens tested first using Schmidt rebound hammer and then by compressive strength should not be used for calibration purposes of building the correlation between rebound number and strength.
(4) The classic Schmidt rebound hammer is not recommended for testing early age (< 3 days) or low-strength (< 7 MPa) Concrete. However, such constraints do not necessarily apply to the Leeb rebound devices having low impact energy.
(5) Both Schmidt and Leeb rebound numbers can be easily translated into compressive strength using simple linear relationships.
(6) The correlations between *S*-value and compressive strength show significantly different patterns for normal-strength concretes and high-strength concretes. The predictions of compressive strengths differ from the original experimental results by $\sim$ 15%.
(7) Compared to the Schmidt hammer test, the linear regression of the *L*-value obtained using Leeb hammer and concrete compressive strength seems to be more reliable and more suitable for practical use in predicting concrete compressive strength. It helps to estimate the strength with about 10% error for all *w*/*c* ratios. However, it is still believed that the data scatter is affected by *w*/*c* ratio, while further investigation is needed to confirm this conclusion.
(8) As expected, Leeb rebound hammer value is affected by the specimen surface conditions. In particular, *L*-value is sensitive to the surface moisture due to its small impact energy (11 N mm, *D*-type). The *L*-values obtained on the specimens with wet surface are lower by $\sim$ 5% than those of the air-dry surface specimens. The explanation can be a dissipation of impact energy absorbed by water film present on the concrete surface. To avoid an influence of the surface moisture on Leeb rebound numbers, it is worth to remove water film covering the concrete surface during the test (it means to test concrete in SSD conditions), or even better—to dry the surface of concrete before the test—for example, using a hot fan. At the same time, the influence of surface moisture is not significant, and, in our opinion, can be neglected in practice, considering a typical statistical scatter of the rebound number, which is much larger.
9) Finally, the Leeb rebound numbers are more affected by aging, than the Schmidt rebound numbers—especially, in more porous concrete. This finding was expected, because the Leeb test is sensitive to mechanical properties of the thinner surface layer, which is exposed to carbonation reaction with carbon dioxide from the air. This reaction is faster in more permeable concrete made of lower *w*/*c* ratios.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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