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UCS field estimation of intact rock using the Schmidt hammer: A new empirical approach

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Abstract. In the present work we discuss the results of a number of Schmidt hammer tests (total number of impacts N > 2,400) that were performed *in situ* on rock outcrops of different lithology (marl, calcareous marl, limestone, sandstone, quartz sandstone and rhyolite) that occur in Italy. Firstly, a specific field procedure to choose the reference value of the rebound index adopted to calculate UCS of intact rock is suggested. A relationship between L and N hammer rebound index values (R_L and R_N, respectively) is subsequently assessed. Considering the experimental datasets provided by a Schmidt hammer construction company and other research available in literature, a new exponential equation for the correlation between R_L and UCS of intact rock has been derived. Considering the here-proposed R_L–R_N relationship, a new exponential correlation between R_N and UCS has also been defined. The newly proposed procedure and relationships were successfully utilised to determine the intact rock strength of different rocks. The calculated UCS values are very similar when using both types of Schmidt hammer (L and N) and are generally in line with previous determinations from experimental data available in literature.

1. Introduction

In common practice of rock engineering, the Schmidt hammer is widely used to obtain an indirect estimation of the intact rock strength, specifically of its uniaxial compressive strength (UCS) [1–4]. UCS can be easily calculated by means of empirical equations that correlate the Schmidt hammer rebound index (R) with the intact rock strength. Many empirical equations are available in literature, for both L- and N-type hammers. These empirical equations were established on the basis of hammer tests that were performed on various types of rocks [3, 5–10]. The indirect estimation of the intact rock strength on using the Schmidt hammer was found to be strongly influenced by some basic issues concerning the specific test conditions [7–12]. Among these issues, the differences between field and laboratory testing, the specific test procedures and the assessment of the reference rebound value to calculate UCS have widely been discussed in literature and represent key features when using the Schmidt hammer in rock mechanics practice. Notably, most research investigates the intact rock properties on the basis of laboratory tests carried out on rock specimens. However, laboratory testing on rock specimens requires specific apparatus and specimen preparation [2, 4, 13] that may result in complex, expensive and time-consuming procedures. On the contrary, research published on *in situ* Schmidt hammer tests is fairly limited. Nevertheless, the Schmidt hammer is more commonly used by engineers and geologists to obtain a quick estimation of the intact rock strength directly on the field, where conditions are rather different when compared with those designed in the laboratory.

Various procedures of recording Schmidt hammer rebound indexes have been proposed by different authors, which are substantially based on either “single impacts” or “continuous impacts” at one point. In common engineering practice, the most adopted procedures are those suggested by ISRM [2], recently revised by Aydin [13], and ASTM [4], which are based on single impacts at one point. However, some authors demonstrated that test procedures based on continuous impacts at one point provide a more reliable and accurate estimation of UCS than single impacts tests [8, 9, 11, 12]. Moreover, no universally accepted indication exists in literature for the determination of the reference value of the rebound index to calculate the intact rock strength, in particular for field applications. ISRM recommends selecting the average of the upper ten readings from 20 single impacts [2], whereas ASTM suggests discarding readings differing from the average of ten readings by more than seven units and determining the average of the remaining readings [4]. Hucka [11] and Poole and Farmer [12] suggested selecting the peak rebound value from 10 and 5 continuous impacts at one point, respectively, whereas Goktan and Gunes [8] recommended excluding outliers from 15–20 continuous impacts at one point by Chauvenet’s criterion and averaging the remaining readings.

The aforementioned issues demonstrate that Schmidt hammer test procedures necessitate deeper investigation in order to gain comprehensive knowledge concerning the use of this device for intact rock characterisation, in particular for field applications. In this paper, we present the results of a number of Schmidt hammer tests that were performed *in situ* on rock outcrops occurring in Italy of six different lithologies, using both L-type and N-type hammers (total number of impacts > 2,400). A new procedure for recording Schmidt hammer rebound indexes will be proposed, along with the assessment of the reference value of the hammer rebound to correlate with the intact rock strength. Moreover, new empirical equations that correlate the reference rebound indexes for both L-type (R_L) and N-type (R_N) hammers will be established, based on a R_L–R_N relationship. The main aim of this paper is to rationalise the large number of Schmidt hammer tests by developing a standard test procedure that proves to be valid for particular field applications.

2. Rock types and field test procedure

The Schmidt hammer tests carried out for this study were performed *in situ* on exposed surfaces of rock masses occurring in Italy and characterised by different lithology, as follows:

- Marl, outcropping in the Rosandra valley (Trieste, NE Italy);
- Calcareous marl, outcropping in the Rosandra valley (figure 1a);
- Sandstone, outcropping at Castiglione dei Pepoli (Bologna, Central Italy) (figure 1b);
- Quartz sandstone, outcropping in the Rosandra valley;
- Limestone, outcropping on the failure scar of a shallow rockslide in the Rosandra valley (figure 1c);
- Rhyolite, outcropping at Galzignano Terme (Padova, NE Italy) (figure 1d);

The Schmidt hammer tests were carried out with both L-type and N-type hammers in order to investigate the relationship between the rebound index values R_L and R_N. The field tests were carried out in dry conditions and on smooth and planar surfaces over the area covered by the hammer plunger and far from edges or fractures of the rock. The impact points tested with the N-type hammer are separated by at least a plunger diameter from the corresponding points of impact tested with the L-type hammer, but not far from the latter in order to better appreciate the correlation between R_L and R_N. The measured rebound indexes were normalised according to Basu and Aydin [14] in order to obtain correct values that refer to the reference horizontal impact direction of the hammer. The field test procedure adopted to record the Schmidt hammer rebound index values has been assessed on the basis of the findings of Hucka [11], Poole and Farmer [12] and Goktan and Gunes [8] and, particularly, considering some key geomechanical aspects. In fact, joint surfaces outcropping on exposed rock masses that are commonly tested with the Schmidt hammer on the field can be characterised by highly variable degrees of weathering. Joint surface weathering is responsible for a decrease in the mechanical properties of the rock at shallow depths (of a millimetre or sub-millimetre thickness). This means that the joint wall strength is, in any case, lower than the strength of the intact rock. Therefore, Schmidt hammer field test procedures based on single impacts at one point [2, 4] are highly sensitive to the weathering degree of the tested surface and are better related to the joint wall strength rather than to the strength of the intact rock. On the contrary, continuous impacts at one point cause a progressive compaction of the rock over the area covered by the plunger, thus providing local responses that are better related to the intact rock properties, as also highlighted by Buyuksagis and Goktan [9]. However, it should also be noted that excessive compaction can cause an alteration (or strengthening) of the rock or may result in localised microcracking and this should be kept in mind when choosing the most reliable rebound index value to correlate with the intact rock strength.

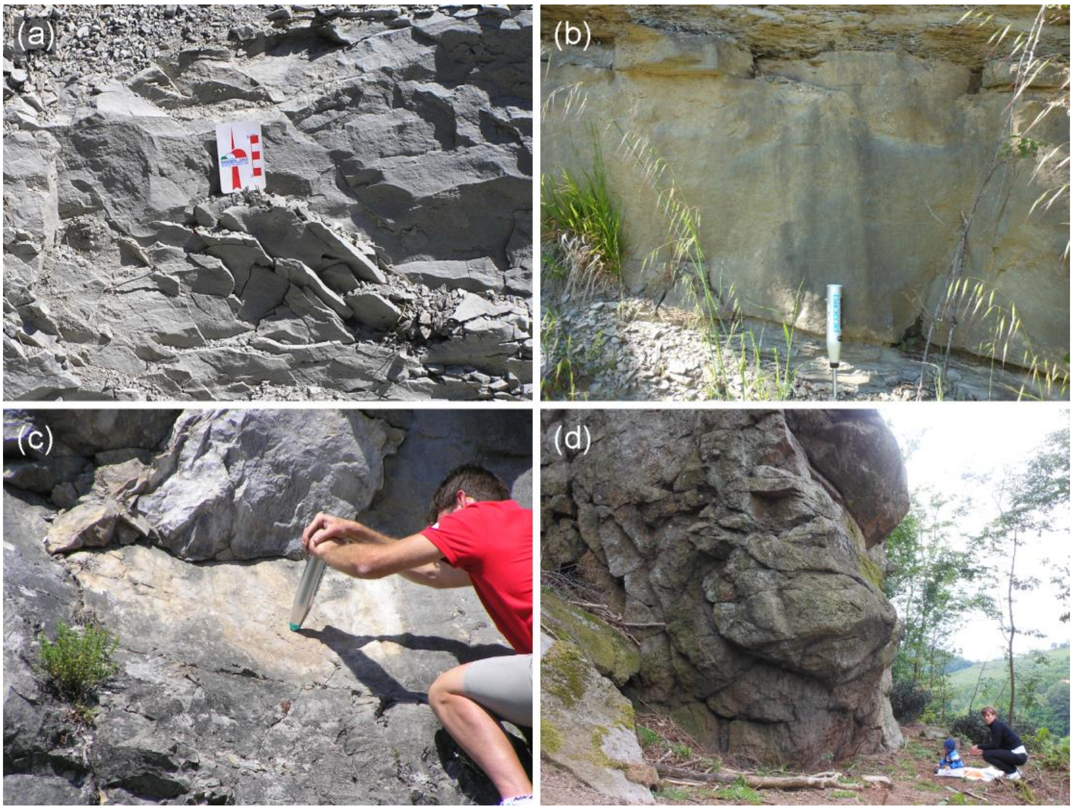

Figure 1. Some rock outcrops tested with the Schmidt hammer and made up of: (a) calcareous marl, (b) sandstone, (c) limestone, and (d) rhyolite.

Considering the previously discussed issues, the field procedure adopted for the Schmidt hammer tests performed for this study is based on continuous impacts at one point. In particular, 20 multiple impacts have been executed at 10–12 different points for a single tested surface and for both L-type and N-type hammers. For each single test, a number of at least 200 rebound index values has been collected and, for each hammer type, a number of impacts N > 1,200 has been performed, with an overall amount of impacts of N > 2,400. This large dataset can provide a robust statistical sample that allows for a reliable analysis of the average properties of the intact rock. In this light, we did not exclude the extreme values of the rebound index distribution in order to keep the results objective and only erroneous readings clearly caused by the improper functioning of the hammer were discarded. In fact, discarding a large number of the low rebound values as recommend by ISRM [2] may result in an erroneous assessment of the rock strength since low numbers might be the response of an inherently weak portion of the rock surface and not merely the effect of test deficiencies. It must also be pointed out that, when considering the typical normal distribution of the rebound values, a large amount of data inherently reduces the misleading effect of including possible erroneous readings in the analysis.

3. Rebound index distributions

The response of the rock to the continuous hammer impacts at one point is different among the tested lithologies and clearly depends on the characteristics of the rock matrix. Figure 2 shows the trends of the rebound index values of some representative sequences of 20 continuous impacts at one point (for both L-type and N-type hammers) related to two rock types that are characterised by opposite behaviours (marl and rhyolite). For weaker materials like the marl, the compaction effect as the number of impacts increases causes a progressive increase in the value of the rebound index (i.e. a strengthening of the rock) until, after a certain number of impacts, the value of R suddenly drops as a result of microcracking of the rock surface (figure 2). After this drop, the hardening effect starts again with a new increase in the value of R. This particular behaviour, which results in a rather high standard deviation of the rebound index (±4.7 and ±3.1 for R_L and R_N, respectively), was observed for a variable number of cycles during the entire sequence of 20 continuous impacts at one point (typically 2–4 cycles). On the contrary, for stronger materials like the rhyolite, no strengthening–microcracking cycle was observed and the values of R were found to have a more constant trend over the 20 continuous impacts (figure 2). The very low standard deviation of the rebound index (±1.3) is below the sensitivity of the Schmidt hammer device (±2.0). In addition, all the tests performed show that, for each sequence of continuous impacts, the value of R related to the first impact is lower than the values of the following 2–4 impacts, proving a certain weathering of the tested surface.

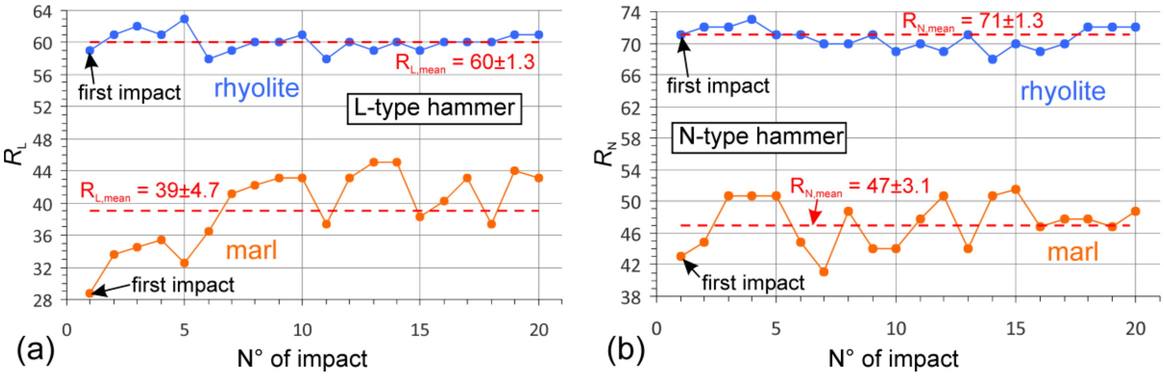

Figure 2. Trends of the rebound index values over the 20 continuous impacts at one point for: (a) L-type hammer and (b) N-type hammer.

The values of R_L and R_N obtained from the Schmidt hammer tests are displayed in the histograms of relative frequency of figure 3, for each tested rock type. The distributions of the rebound indexes can be approximated with asymmetrical normal distributions in which the bell curves exhibit a negatively skewed pattern with a longer left tail on the graph. The left tails of the asymmetric distributions are mainly correlated with the first impacts of the sequences performed as continuous impacts at one point. As a result of the asymmetric distribution, the mode corresponds, in most cases, with R values that are higher than those associated with the mean and the median. As expected, the overall average values of the rebound index measured on the various tested rocks are higher for the harder rocks (figure 3e, f) and lower for the weaker rocks (figure 3a, b). The dispersion of the rebound indexes measured on the different rock types is strongly dependant on the lithology, since the widest range was found to be that of the marl (figure 3a), whereas the tightest range is that of the rhyolite (figure 3f). This means that harder rocks are intrinsically characterised by a lower variability in the Schmidt hardness, whereas the porous microstructure of the weaker rocks is largely affected by weathering as well as by the compaction effect caused by the impact energy, as previously shown (figure 2). The distributions of the hammer rebound indexes of the six tested rock types can help in defining the reference value of the rebound index to correlate with the intact rock. This reference value should be assessed on the basis of two important aspects. Firstly, the lowest values of the distributions are related to the first impacts and, as a consequence, they are influenced by the weathering of the rock surfaces tested on the field. These low values tend to decrease the overall average of the rebound index distribution. This means that the rebound index value that better represents the intact rock strength should be higher than the average value of the distribution. Subsequently, the highest values of the distributions are influenced by the compaction effect caused by the hammer impact energy during the continuous impacts at one point. These high values tend to overestimate the hardness of the rock and are not representative of the actual strength of the intact rock. As a consequence, the reference rebound index for the intact rock should be lower than the peak values of the distributions. It should also be noted that, for all the distributions analysed, the 75° percentile corresponds with the mode or another close peak of relative frequency (figure 3). The large dataset related to the different rocks tested on the field shows that the 75° percentile of the rebound index distribution can be considered as a reference value that, on both statistical and geomechanical basis, well represents the intact rock hardness.

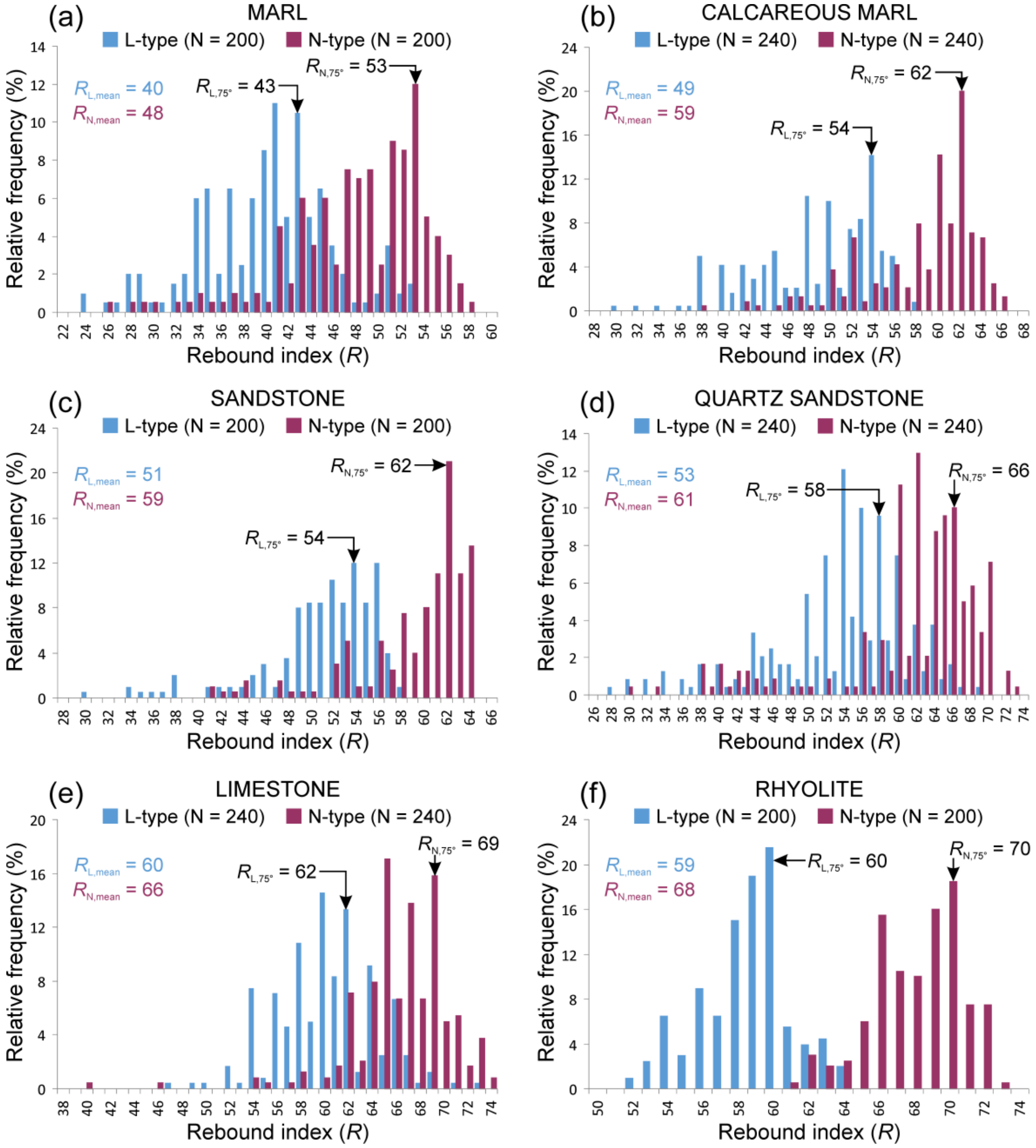

Figure 3. Distributions of the overall rebound index values (R_L and R_N) measured on: (a) marl, (b) calcareous marl, (c) sandstone, (d) quartz sandstone, (e) limestone, and (f) rhyolite.

The use of both L-type and N-type hammers on each tested rock type allowed us to establish a R_L–R_N relationship on the basis of the average values of the measured rebound indexes. The best fitting correlation was found to be linear, with a correlation coefficient of $R^2 = 0.97$ (figure 4a). The average rebound index values vary in the ranges $R_L = 40$–60 and $R_N = 48$–68. These ranges are rather narrow if compared with the highly variable hardness of rocks that are commonly tested with the Schmidt hammer. As a consequence, the previous relationship has been expanded considering additional R_L–R_N points characterised by lower rebound index values, which are provided by the manufacturer as a result of Schmidt hammer tests on concrete specimens. Moreover, another reference point has been added, which is represented by the R_L–R_N values related to the verification anvil, as provided by the manufacturer. The new relationship has a correlation coefficient of $R^2 = 0.99$ (figure 4b).

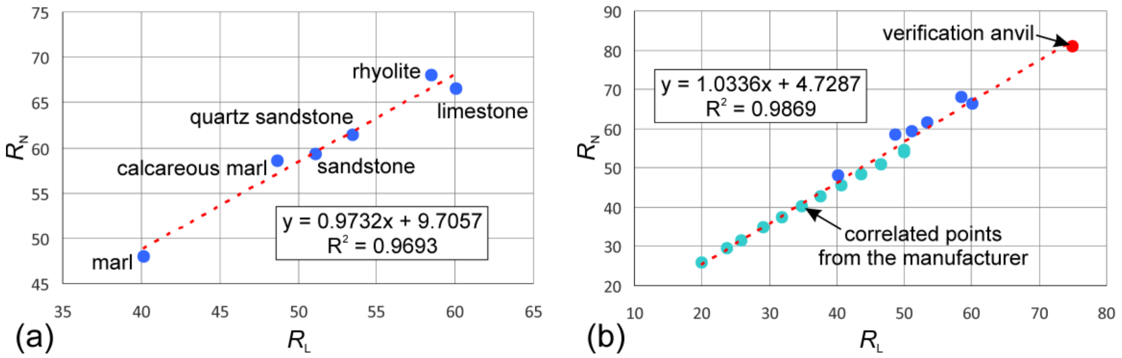

Figure 4. Relationship between R_L and R_N for: (a) the six tested rock types and (b) a number of points also including some tests performed by the manufacturer and on the verification anvil.

4. New empirical equations to calculate UCS

The compressive strength of a material tested with the Schmidt hammer can be easily estimated from the measured rebound index value by means of some correlation charts that are provided by the device manufacturers and that are directly displayed on the side of the hammer. These correlation charts are based on a large number of tests that were performed on concrete specimens. Despite this large dataset, the correlation curves are only valid for a restricted range of the rebound index, that is in the range $R = 20$–55. For higher values of R that can be obtained from measurements on hard rocks, the empirical equation proposed by Aydin and Basu [7] for the L-type hammer is widely adopted by engineers and geologists. The latter is based on Schmidt hammer tests performed in the laboratory on granite specimens and was found to be quite accurate in estimating UCS of the intact rock. In the present study, we are proposing a new empirical equation for the L-type hammer that is simply based on the conjunction of the correlation curves provided by both the manufacturer of the hammer and Aydin and Basu [7]. This procedure has allowed us to take comprehensively into account the large dataset provided by the manufacturer as well as some measurements obtained from hard rocks characterised by higher values of R. The new empirical equation for the L-type hammer has an exponential form (figure 5) and is as follows:

$$\sigma = 6.507\exp(0.0464R_L) \qquad R^2 = 0.9861 \tag{1}$$

It must be noted that the high correlation coefficient is due to the large number of points included in the dataset of the manufacturer. Moreover, the newly proposed correlation curve shows a good approximation of UCS for values of the rebound index up to $R_L = 65$. For $R_L > 65$ a slight deviation from the points of the correlation curve provided by Aydin and Basu can be noted (up to 20–30 MPa, figure 5). This means that, in this critical field of the rebound index value for the L-type hammer, the proposed empirical equation should be used with care. However, values of the reference rebound index greater than $R_L = 65$ frequently characterise very hard rocks (in particular, hard igneous rock), whereas typical values of UCS for sedimentary rocks can be well estimated through equation (1).

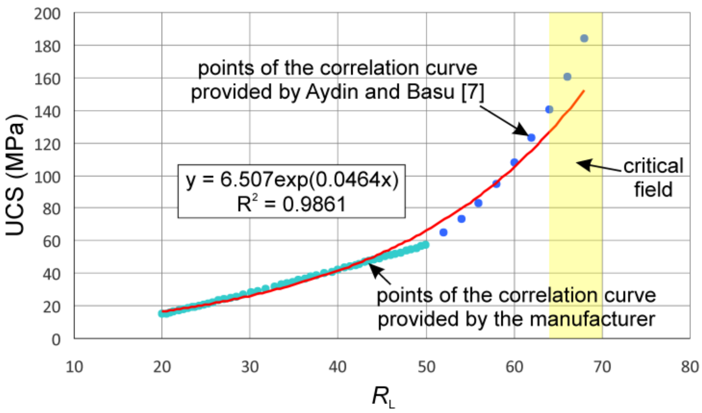

Figure 5. Correlation curve proposed for the L-type hammer between R_L and UCS.

The relationship between the R_N values and UCS has been simply obtained from equation (1) by considering the previously established R_L–R_N relationship (figure 4b). The new empirical equation for the N-type hammer is as follows:

$$\sigma = 5.2251\exp(0.0449 R_N) \tag{2}$$

The UCS values for the different tested rock types were calculated through equations (1) and (2) for the L-type and N-type hammers, considering the 75° percentile of the rebound index distributions as reference value correlated with the intact rock strength, as shown in the previous section (table 1).

Table 1. Calculated values of UCS for the different rocks tested on the field with both L-type and N-type hammers.

Rock type	$R_{L,75°}$	$UCS_{L,75°}$ (MPa)	$R_{N,75°}$	$UCS_{N,75°}$ (MPa)
Marl	43	48	53	56
Calcareous marl	54	80	62	85
Sandstone	54	80	62	85
Quartz sandstone	58	96	66	101
Limestone	62	116	69	116
Rhyolite	60	105	70	121

The calculated values of UCS are fairly in line for both the empirical equations adopted (for L-type and N-type hammers) and are also consistent with typical values of the intact rock strength for the specific rocks that have been tested on the field [15]. As a result, the field test procedure and the new empirical equations that have been proposed to estimate the intact rock strength using the Schmidt hammer on the field seem to be valid and accurate.

5. Conclusions

Many attempts have been made in literature to define an empirical correlation between the intact rock strength and the rebound index value obtained from Schmidt hammer tests. Most of the test procedures and empirical relationships have been assessed on the basis of laboratory tests on rock specimens. On the contrary, very little research has been forwarded on the use of this device in field applications. While suggested methods and calculation procedures have been assessed to perform Schmidt hammer tests in the laboratory and to evaluate the joint compressive strength (JCS), no reference exists yet about the specific procedure required to estimate the uniaxial compressive strength (UCS) of the intact rock from field tests. Notably, the Schmidt hammer is more commonly used by engineers and geologists *in situ*, in order to gain a quick estimation of the rock properties. This study contributes to defining a specific test procedure as well as assessing two new empirical equations (for L-type and N-type hammers) to estimate the intact rock strength from Schmidt hammer tests performed *in situ*.

Firstly, it is important to highlight the strong differences in the test procedure required to estimate JCS rather than UCS *in situ*. For the evaluation of the joint wall strength, only the first hammer impacts should be considered, since they reflect the actual weathering of the tested surface. On the other hand, the field test procedure to estimate the intact rock strength is based on continuous impacts at one point and requires the acquisition of at least N = 200 measurements of the rebound index for each tested rock surface (20 impacts × 10 measurement points). This is necessary to gain a robust statistic sample and to properly assess the reference value of the rebound index to correlate with the intact rock strength. The reference rebound index that better correlates with the intact rock was found to be the 75° percentile of the rebound index distribution. The empirical equations proposed in this study have been constructed on the basis of both the correlation curves provided by the manufacturer of the hammer and other empirical equations available in literature. The newly proposed relationships provide a reliable estimation of the intact rock strength of six types of rocks tested on the field with the Schmidt hammer, proving the validity and accuracy of the here proposed field test procedure.

References

[1] Deere D U and Miller R P 1966 Engineering Classification and Index Properties for Intact Rock *Air Force Weapons Laboratory Technical Report AFWL-TR-65-116* (Urbana, Illinois: University of Illinois) 327 pp

[2] ISRM 1978 Suggested methods for determining hardness and abrasiveness of rocks *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* **15** 89–97

[3] Cargill J S and Shakoor A 1990 Evaluation of empirical methods for measuring the uniaxial compressive strength of rock *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* **27** 495–503

[4] ASTM 2014 Standard test method for determination of rock hardness by rebound hammer method *ASTM International Designation: D5873–14* (West Conshohocken, PA: ASTM International)

[5] Sheorey P R, Barat D, Das M N, Mukherjee K P and Singh B 1984 Schmidt hammer rebound data for estimation of large scale in situ coal strength *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* **21** 39–42

[6] Katz O, Reches Z and Roegiers J-C 2000 Evaluation of mechanical properties using a Schmidt hammer *Int. J. Rock Mech. Min. Sci.* **37** 723–28

[7] Aydin A and Basu A 2005 The Schmidt hammer in rock material characterization *Engineering Geology* **81** 1–14

[8] Goktan R M and Gunes N 2005 A comparative study of Schmidt hammer testing procedures with reference to rock cutting machine performance prediction *Int. J. Rock Mech. Min. Sci.* **42** 466–72

[9] Buyuksagis I S and Goktan R M 2007 The effect of Schmidt hammer type on unaxial compressive strength prediction of rock *Int. J. Rock Mech. Min. Sci.* **44** 299–307

[10] Karaman K and Kesimal A 2015 A comparative study of Schmidt hammer test methods for estimating the uniaxial compressive strength of rocks *Bull. Eng. Geol. Environ.* **74** 507–20

[11] Hucka V 1965 A rapid method of determining the strength of rocks in situ *Int. J. Rock Mech. Min. Sci.* **2** 127–34

[12] Poole R W and Farmer I W 1980 Consistency and repeatability of Schmidt hammer rebound data during field testing *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* **17** 167–71

[13] Aydin A 2009 ISRM Suggested method for determination of the Schmidt hammer rebound hardness: Revised version *Int. J. Rock Mech. Min. Sci.* **46** 627–34

[14] Basu A and Aydin A 2004 A method for normalization of Schmidt hammer rebound values *Int. J. Rock Mech. Min. Sci.* **41** 1211–14

[15] Hoek E 2007 Practical rock engineering *http://www.rocscience.com/educational/hoeks_corner* Accessed January 2021