ISRM Suggested Method for Determination of the Schmidt Hammer Rebound Hardness: Revised Version

Adnan Aydin

1 Introduction

With its portable, simple and affordable attributes, the Schmidt hammer (SH) is an ideal index apparatus, which underlies its increasing popularity and expanding range of applications. The SH rebound hardness value (*R*) is perhaps the most frequently used index in rock mechanics practice for estimating the uniaxial compressive strength (*UCS*) and the modulus of elasticity (*E*) of intact rock both in laboratory conditions and in situ. The SH is also widely used for estimating the *UCS* of discontinuity walls and assessing the workability, excavatability and boreability of rocks by mechanical means (cutting, polishing, milling, crushing and fragmentation processes in quarrying, drilling and tunneling).

In the three decades since the earlier ISRM suggested method for conducting the SH test was published [1], researchers have sought to establish correlations between the SH rebound values (*R*) and the *UCS* and *E* for different rock types. A critical review of the basic issues was recently conducted by Aydin and Basu [2], which considered the influence of hammer type, the direction of hammer impact, specimen requirements, weathering, moisture content and testing, data gathering/reduction and analysis procedures. Understanding the operation of the apparatus and the mechanisms and modes of indentation upon hammer impact are crucial in addressing these issues, determining how the data scatter can be reduced, and settling upon an acceptable or expected degree of scatter.

With this notion, this revised suggested method aims to clarify and improve the current SH testing methodology and identifies areas where further research is needed, in particular customizing the energy level and plunger diameter and curvature to suit groups of rocks with radically different microstructures.

2 Scope

This revised suggested method focuses on the use of the SH to determine the rebound hardness of rock surfaces both in laboratory conditions and in situ with an emphasis on the use of this hardness value as an index of the *UCS* and *E* of rock materials. This revised suggested method supersedes the portion of the earlier ISRM document [1] that dealt with the SH test.

3 Apparatus

3.1 Operational Principle

The SH consists of a spring-loaded piston which is released when the plunger is pressed against a surface (Fig. 1). The impact of the piston onto the plunger transfers the energy to the material. The extent to which this energy is recovered depends on the hardness (or impact penetration/damage resistance) of the material, which is expressed as a percentage of the maximum stretched length of the key spring before the release of the piston to its length after the rebound [2].

Please send any written comments on this "ISRM Suggested Method" to Prof. Resat Ulusay, President of ISRM Commission on Testing Methods (resat@hacettepe.edu.tr).

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A. Aydin (✉)
Department of Geology and Geological Engineering,
The University of Mississippi University, Oxford,
MS 38677, USA
e-mail: aaydin@olemiss.edu

R. Ulusay (ed.), *The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007–2014*, DOI: 10.1007/978-3-319-07713-0,

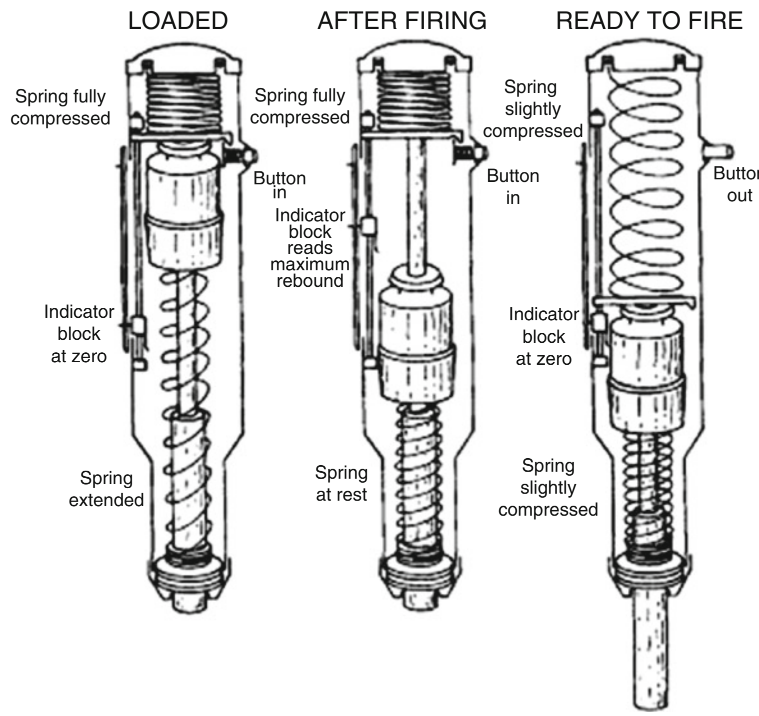

Fig. 1 Working principle of a Schmidt hammer [3]

3.2 Hammer Type, Test Range and Calibration

The earlier ISRM suggested method [1] endorsed the use of only the L-type SH. However, for a given plunger tip diameter and radius of curvature, the impact energy of the SH determines its range of applicability. Accordingly, this limitation should be kept in mind in selecting the hammer type. For instance, the standard L- and N-type hammers, with respective impact energies of 0.735 and 2.207 N m, should be used with caution when the *UCS* of the rock material or discontinuity wall is outside the range of 20−150 MPa, where sensitivity decreases and data scatter increases. The N-type hammer is less sensitive to surface irregularities, and should be preferred in field applications; while the L-type hammer has greater sensitivity in the lower range and gives better results when testing weak, porous and weathered rocks.

The use of different hammer types results in datasets which may not be readily correlated. Although the standard L- and N-type hammers were shown to have demonstrably high correlation coefficients, these correlations may not be equally convincing across the entire *UCS* range because, they are based on the assumption that both types of hammers produce similar modes of indentation at every point of impact [2]. Furthermore, higher impact energy of N-type hammer (corresponding to probing a larger volume of material by a deeper and wider penetration) should reduce scatter in rebound values compared to L-type hammers [2].

SH are supplied with calibration anvils with vertically guided impact points made of steel as hard as that of the plunger tip (usually Brinell 500 or Rockwell 52 C). It is essential to verify that the hammers maintain their standard rebound values before and after field investigations. In correlation studies, two consistent readings within the predetermined range of rebound from the anvil should be taken before and after testing each specimen. A drift in the calibrated rebound values may suggest that the key spring is losing its stiffness and should ideally be replaced. If this is not possible, a correction factor (*CF*) for the hammer should be calculated [1] and applied to all readings to account for the loss of stiffness:

$$CF = \frac{\text{specified standard value of the anvil}}{\text{average of ten readings on the anvil}} \quad (1)$$

4 Procedure

4.1 Specimen Requirements

Specimens should be intact (free of visible cracks), petrographically uniform and representative of the rock mass domain (identified from cores or exposures) being characterized. Test surfaces, especially under the plunger tip (impact points), should be smooth and free of dust and particles. In the field, a medium-grained abrasive stone can be used for local smoothing of rough surfaces in hard rock.

Fine sandpaper can be used to smooth the surfaces of cores and block specimens, especially when drilling or sawing produces visible ridges. Cores and blocks should be air dried or saturated before testing. When this is not possible, the degree of moistness of the surface and the specimen as a whole should be recorded as wet, moist or damp.

Cores should be of at least NX size (≥ 54.7 mm) for the L-type hammer and preferably T2 size (≥ 84 mm) for the N-type. Block specimens should be at least 100 mm thick at the point of impact. It is essential that impact energy is not dissipated in the form of wave scatter or cracking because the impact points are too close to the specimen boundaries. In order to provide similar degrees of confinement in all directions, impact points should be one radius away from the nearest end of core specimens and half the thickness away from block boundaries.

Length of cores and surface area of blocks should be large enough to accommodate these suggestions; for example, if a 2 cm spacing of impact points is chosen, a core length of 43.5 cm (for NX size) or a block surface area of 268 cm^2 (for 10 cm thickness) is required to gather 20 readings.

The test is generally nondestructive for rocks of at least moderate strength (>80 MPa), and the same sample can be used for the determination of the *UCS* and *E*. However, potential microcracking, grain crushing and pore collapse in friable, porous and weathered rocks necessitate use of different samples.

4.2 Test Requirements

4.2.1 Relative Direction of Impact

Unless the hammer impact direction remains roughly perpendicular to the tested surface, there is a danger of frictional sliding of the plunger tip, material removal by chipping and a partial transfer of energy to and from the hammer. It is therefore essential that the hammer be held at a right angle to the tested surface using a guide tube similar to that used by Aydin and Basu [2], to ensure that the deviation does not exceed ±5° [1]. It is suggested that a standard guide tube be manufactured and supplied with the SH.

4.2.2 Normalization of Rebound Values with Reference to Horizontal Impact Direction

The analytical normalization function defining the equivalent rebound value in the horizontal direction has been presented recently by Basu and Aydin [4]. This formulation enables testing in any direction (Fig. 2), especially for in-situ applications (e.g. testing oblique discontinuity surfaces and circular tunnel walls), provided that the direction is accurately recorded. It is suggested that a mechanical or digital angle measuring device be supplied as an attachment by the manufacturers of the Schmidt hammers.

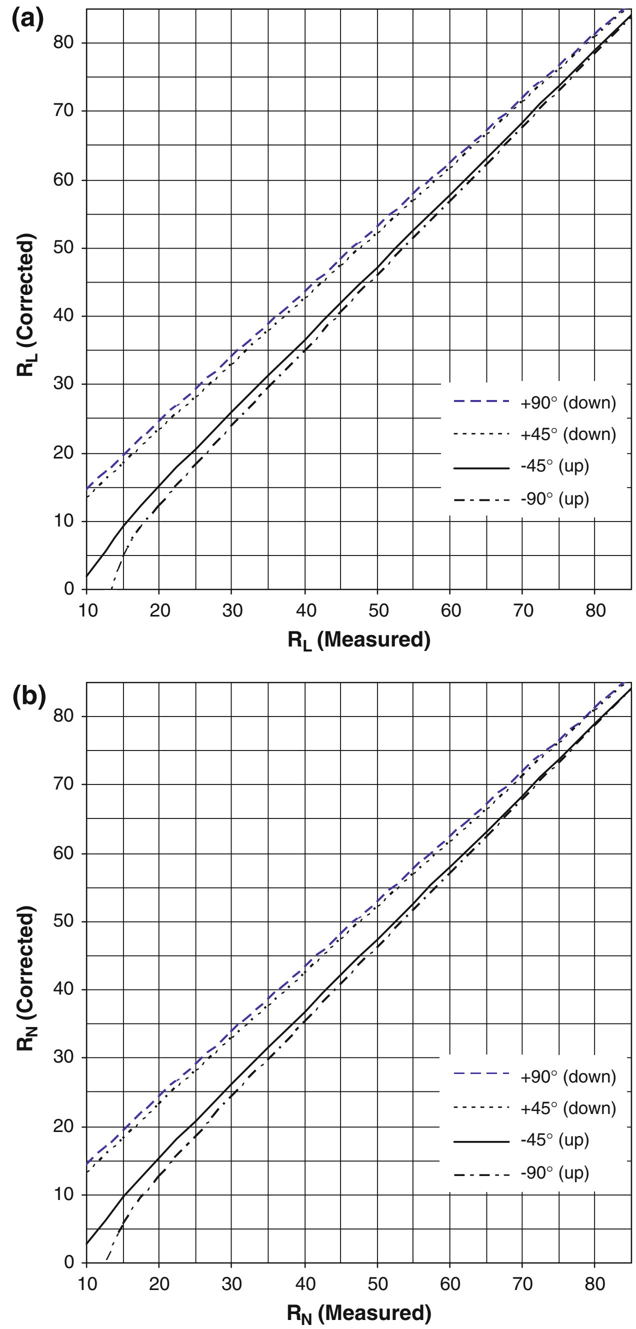

Fig. 2 Normalization of rebound values obtained by **a** L- and **b** N-type Schmidt hammers at selected angles [4] (Positive and negative angles refer to the downward and upward positions of the SH, respectively)

4.2.3 Specimen–Steel Base–Ground Interface

Specimens should be securely clamped to a steel base (with a minimum weight of 20 kg for the L-type hammer and 40 kg for the N-type hammer) located on firm, flat ground. Core specimens should be placed in an arc-shaped machined slot as shown in Fig. 3. V-shaped slots should be avoided particularly in weak rocks because the unsupported

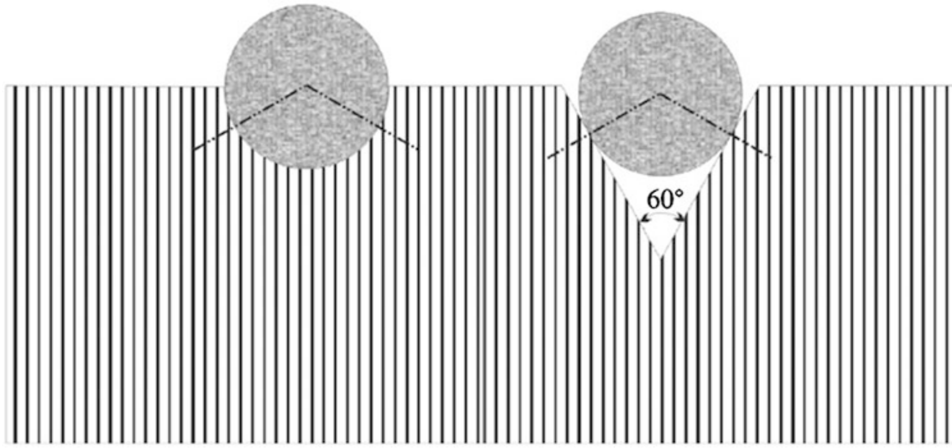

Fig. 3 Cross sections of steel-base blocks with the arc- and V-shaped machined slots in which NX size (54.7 mm) core specimens are seated. (While the use of V-shaped slots is discouraged, if used, the slots should have the specified angle to ensure identical seating positions for different diameter specimens. Also note that an arc angle of 120° is sufficient for similar lateral confinement as in V-shaped slots.)

section of the core surface falls directly below the impact point, effectively changing the loading configuration and potentially reducing rebound value.

4.3 Data Gathering and Reduction

For data gathering, 20 rebound values, as recommended by the earlier ISRM suggested method [1], should be recorded from single impacts separated by at least a plunger diameter (to be adjusted according to the extent of impact crater and radial cracks). On the other hand, the test may be stopped when any ten subsequent readings differ only by four (corresponding to SH repeatability range of ± 2).

When sufficient quantities of microstructurally uniform specimens are not available and the rock is isotropic, several sets of readings can be taken from different faces of the blocks or along any four straight lines by rotating the core axis 90° at a time. Should this be the case, the set of readings should be given in the corresponding order and any consistent reduction from the first set of measurements (e.g., due to impact-induced cracking) should be carefully monitored.

As the *UCS* and *E* values of a material are strongly influenced by the density, distribution and connectivity of its weak microstructural elements, low and high rebound readings are equally necessary to reflect the nature of heterogeneity and potential spread in the values of mechanical properties. Therefore, no reading should be discarded, and the *mean* (arithmetic average), *median* (middle value), *mode* (most repeating value) and *range* of the readings should be presented to fully express the variations in the surface hardness. Digital images of the test area before and after each impact will provide a more meaningful base for the analysis of these statistics and eliminate the need for recording detailed description of damage features such as grain crushing, pore collapse, radial and lateral cracking. An in-depth analysis of the *UCS* or *E* versus *R* correlations is presented in Appendix A.

In field applications, the operator should also record the approximate dimensions of tested blocks (the depth being the length of the block free of visible cracks or thin soft layers in the impact direction), their nature (e.g., discontinuity wall, blasted or mechanically broken block), any small scale roughnesses (asperities) of the original surface and how the impact points were smoothed.

5 Influencing Factors

5.1 Relative Strength of Coarse Grains Versus Matrix

The size and distribution of grains and the relative strength of the matrix has a considerable influence on the degree of scatter of rebound values [2]. When a surface contains grains with sizes comparable to the plunger tip diameter, the readings from these grains may significantly deviate from the average, depending on their strength relative to the matrix or dominant grain size. In such cases, impact points should be selected to obtain rebound values from individual coarse-grains and matrix separately. Averaging the rebound values of these components may result in an erroneous determination of hardness.

5.2 Weathering and Moisture Content

Microstructural changes induced by weathering result in different response mechanisms, especially in crystalline igneous rocks, and significantly different rebound values.

Differential weathering of different rock forming minerals enhances heterogeneity at grain scale, which in coarse-grained rocks results in a large scatter of rebound values. It is therefore crucial that samples are uniform in terms of overall weathering degree and detailed petrographic description.

When test samples or individual surfaces display variable degrees of weathering, the decrease in rebound value from the first to the second impact at the same point may be taken as a mechanical index of weathering, as demonstrated by Aydin and Basu [2].

Moisture content of the rock within the zone of influence of impact may considerably affect the rebound values depending on its microstructural character. Moisture facilitates inter-grain sliding and leads to softening of grains and loose skeletal bonding (plasma) holding the grains together. These mechanisms are most effective in weathered, porous, loosely cemented and/or mud rocks but may also be significant in fresh crystalline rocks with abundant intra-grain microcracks. When the purpose of the SH tests is to derive correlations between *UCS* and/or *E* and rebound values, all tests should be carried out at the same moisture content. However, low permeability rocks should preferably be tested at dry state due to the difficulty in achieving uniform saturation. It should also be noted that the influence of moisture on elastic surfaces is greatest at a depth equal to about half of the contact radius beneath the contact point where the yielding starts (refer to Appendix A for the relevant aspects of Hertzian theory).

5.3 Anisotropy

Planes of anisotropy in laminated and schistose rocks such as shale, slate, phyllite and schist control the response to impact and loading. The rebound values are strongly reduced when the impact direction is normal to such planes as they absorb impact energy whereas the *UCS* and *E* values steeply decrease at oblique angles of anisotropy. Therefore, the use of SH in such rocks is not recommended unless intact slabs thicker than 10 cm and free of such features are available. In any case, the direction of hammer impact with reference to such features should be recorded and correlations with the *UCS* and *E* should be attempted only for the same direction of loading.

5.4 Field Versus Laboratory Testing

Because of the difficulty of determining the presence of cracks and other discontinuities directly under the impact points and of clamping the blocks to a firm base in the field, the possibility of vertical deformation and vibration at such interfaces when testing laminated, exfoliated, weathered or closely fractured rocks directly on the exposed surfaces should be avoided. In rocks such as coal, shale and slate, testing over lamination walls may produce a narrow range of rebound values due to their uniform and naturally smooth nature, but also significantly low values due to these interfaces. However, in most cases, the degree of scatter will increase and the average magnitude of rebound values will decrease in field testing. On the other hand, laboratory tests suffer from limited dimensions of the core and block specimens. The influence of specimen geometry, boundary distance (defining lateral confinement) and small-scale roughness on the rebound values needs to be investigated using uniform synthetic materials of different hardness and elastic-plastic properties.

5.5 Testing Discontinuity Walls

ISRM [5] states that "The Schmidt test is one of the few tests … which takes into account the mechanical strength of the thin band of weathered wall material close to a discontinuity surface". The SH presents a unique means of estimating the *UCS* of the discontinuity walls, and thus, calculating their shear strength in situ [5]. In spite of this, testing procedures for discontinuity walls have not been well-defined due to the difficulty of assigning relative contributions of the natural discontinuity wall features to their shear strength. Small asperities (especially on freshly exposed joints), thin bands of weathering (of joints in shallow and exposed rock masses), coating and filling materials (of hydrothermal and superficial origin), and thin loose slabs (especially in shear zones and exfoliated surfaces) are common features of discontinuity walls that influence the rebound values and the shear strength in different proportions. As these features are generally non uniform across the surface, a wide range of rebound values should be expected. Determining and presenting this scatter is therefore crucial for the subsequent interpretation of the possible range of the shear strength.

In general, to preserve the loose thin layers, discontinuity walls (unlike intact rock) should not be polished. On the other hand, small asperities might cause a significant reduction in the rebound values but do not substantially contribute to the shear strength of clean freshly exposed non planar joints. Accordingly, such joint walls should be lightly polished to eliminate these small scale weak projections. It is, however, most sensible and straightforward to gather two sets of data before and after polishing the discontinuity surfaces that enables calculation of the upper and lower bound values of their shear strength. The data reduction procedure recommended for intact rock (Sect. 4.3) should be followed to obtain representative rebound values of discontinuity walls.

6 Further Improvements

Contact mechanics theory and experiments show that plunger diameter and shape significantly influence the rebound values in metals. Static indentation experiments by Momber [6] confirmed that large diameter and blunt indenters promote elastic response in rocks. Although present correlations claim significant success in predicting the *UCS* and *E,* it is essential that rock response to impact and static loading takes place in the same domain, i.e. elastic or elastoplastic. Differences in this response may be responsible for some seemingly erratic scatters (an aspect which is worth investigating with a view to determining the appropriate plunger tip radius to provide guidelines for the manufacturers).

The modulus of elasticity (E), Poisson's ratio (v) of the plunger material and the radius of curvature of the plunger tip (r) should be provided by the manufacturers to enable delineation of the contact radius (a) depth of indentation (δ) and mean pressure (p_{m}) under the contact point. These parameters in turn enable theoretical estimation of the rebound value at which the yield initiate from the ratio of work done to the impact energy (input) of a given hammer type. The tip radius (r) required for the onset of yield at a given indenter-rock system modulus (E^*) can also be estimated. As the purpose is to limit the response of rock to the elastic domain, SH should be flexibly designed to enable the piston mass and/or the stiffness or the stretch of the key spring to be changed to control the impact energy.

Field applications in particular require an angle measuring device while testing core specimens requires a standard steel base with an arc-shaped machined slot (for seating of core specimens) and clamps to secure the specimens (core or slab type specimens).

The initially smooth and hemispherical plunger tips become rough with repeated impacts and gradually lose their curvature. This deterioration modifies the initial contact area and may result in a decrease of rebound values on rock surfaces but may not cause noticeable changes in the anvil. Therefore, potential influence of plunger tip deterioration on rebound values from rock surfaces needs to be investigated.

The potential influence of specimen shape and size on rebound values has not been systematically investigated in rocks due to practically endless variations in their microstructural nature, and hence, difficulty of isolating any pattern that may exist. It is suggested that influence of specimen shape and size be investigated using uniform rock types and equivalent synthetic materials and establish correction factors if necessary.

7 Reporting of the Results

The test report should include the following information:

(a) Lithological description of the rock (preferably in the order of strength, color, texture/fabric, weathering/alteration, ROCK NAME with grain size as prefix).
(b) Geographic location and depth of sampling or *in-situ* rock faces.
(c) Date of sampling or excavation and testing, and storage conditions or climate (i.e. exposure to temperature extremes, humidity, etc.).
(d) Specimen or face number.
(e) Specimen type (core, saw-cut block, large field block, excavation face, natural exposure).
(f) Method of excavation or block production (e.g. blasting, ripping, mechanical splitting, boring)
(g) Dimensions of specimens or exposure surfaces.
(h) Sample moisture during testing (water content % or in descriptive terms such as dry, moist, damp).
(i) Hammer type (L-, N- or another type).
(j) Use and nature of clamping and steel base support.
(k) Orientation of hammer axis (impact direction) with reference to horizontal (in degrees, downward being +90° and upward −90°).
(l) Orientation of hammer axis with reference to intact rock anisotropy features (e.g. lamination, foliation, schistosity, lineation).
(m) Histogram of 20 rebound readings (normalized to horizontal impact direction and ordered in descending value), and the mean, median, mode and range statistics (the mean values should be rounded off to the nearest integer).
(n) Photographs (or description) of impact points before and after damage.

Acknowledgments The revised suggested method was based on a study supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. HKU 7143/06E). The author would like to thank Resat Ulusay for his encouragement, and Don Banks for his meticulous review of the paper.

Appendix A: *UCS* and *E* Versus Rebound Value Correlations in the Light of Indentation Mechanisms

As the number of studies proposing new correlations estimating the uniaxial compressive strength (*UCS*) and the modulus of elasticity (*E*) of intact rock based on the SH rebound hardness determination are rapidly increasing, it is important for the users of these correlations to be aware of the

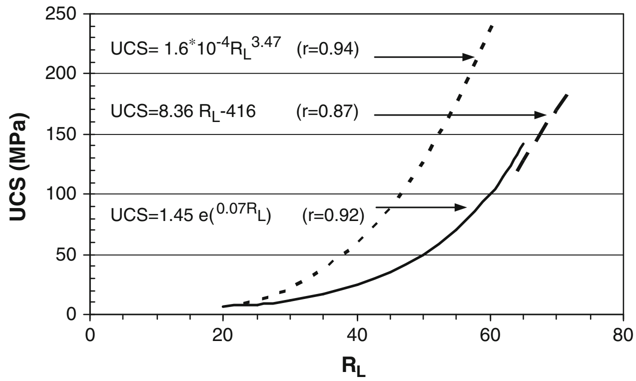

Fig. A.1 Comparison of predictions of the uniaxial compressive strength (*UCS*) of granites based on their rebound hardness values (R_L) using the L-type hammer. (*Dotted* [7]—Grade I–IV; *dashed* [8]—Grade I; *solid* [2]—Grade I–IV)

fact that high correlation coefficients presented in these studies do not necessarily guarantee better point estimates. Contrary to common assumption, the scatter in the original datasets of these correlations may be such that correlation coefficients for smaller ranges of rebound values may actually be lower than those for wider ranges. It should also be noted that the type of correlation functions varies with the range for which the correlations are established. This appendix is aimed to provide an insight into the nature of these correlations in the light of indentation mechanisms and help users to select appropriate functions and interpret them for their particular cases.

Three correlation functions (Fig. A.1) were selected from the literature to facilitate this discussion. All three functions were derived for variably weathered granites using the L-type hammer. Striking differences in these correlations (Fig. A.1) may be partly due to different testing, data gathering and reduction procedures adopted in these studies as well as different microstructures of the granites tested. For example, Hong Kong granites [2] had noticeably high microcrack densities even at fresh state resulting in lower *UCS* values than those of hydrothermally altered granites of Southwest England [7].

Interestingly, the linear correlation proposed in [8] for a wide variety of fresh to slightly weathered granitic rocks from Turkey is quite consistent with the trends of the other correlations in the same *UCS* range. Thus at the outer ends of the rock weathering spectrum (Grade I–IV) when the microstructures are relatively uniform, linear correlations may be expected. The fact that most of the linear correlations were proposed for coal [2] proves the role of microstructural consistency as well as surface smoothness in shaping these correlations.

The presence of two different linear correlation domains joined with a transitional domain suggests that indentations mechanisms change as rock microstructure is altered through weathering processes. Understanding how these mechanisms operate or how different microstructures control these mechanisms are crucial in selecting most appropriate data gathering and reduction methods and improving plunger tip shape and diameter in order to develop better correlations with well-delineated ranges of applicability.

Momber [6] applied classical Hertzian contact mechanics theory [9] to explain different modes of indentation of four rock types (granite, rhyolite, limestone and schist) by two spherical indenters (1.0 and 5.0 mm in dimater) at contact forces between 0.1 and 2.45 kN using a classical Rockwell hardness tester. He observed that elastic response (formation of an array of ring cracks or Hertzian cracks surrounding a damaged core zone) is limited to granite and rhyolite, whereas limestone and schist displayed plastic response. Indentation of limestone surface was in the form of collapse (sink-in) due to its porous structure and that of schist was in the form of pile-up (characterized by wall formation around periphery of the plunger tip, presumably due to sliding along the schistosity planes). However, according to Hertzian theory, yielding starts at a depth equal to about half of the contact radius beneath the contact point, and thus most of the deformation may be hidden in the elastic-to-plastic transition domain. Static hardness tests might also result in different indentation modes than impact tests. For example, grain crushing and fragmentation is a common occurrence under impact, especially when grains are coarse and/or weak, and plastic flow (pile-up) behavior is not observed unless the material is highly viscoelastic.

Taking such differences into account, it is now possible to interpret the nonlinear nature of most *UCS* versus *R* correlations more systematically. Looking at Fig. A.1 again, it becomes obvious that in the lower end of the weathering spectrum, where rock porosity substantially increased due to leaching and feldspar grains are at least partly weakened by pseudomorphic replacement by clay [10], indentation is mainly through the collapse of the pore space and grain crushing. In the upper end of the spectrum, the linear response is caused by the domination of an elastic-brittle response at the grain scale. The degree of scatter is also expected to be lesser in the elastic domain. In the transitional region, the response to hammer impact is mixed (elastoplastic) and the scatter is bound to be much larger than both domains.

A.1 Guidelines for the Correlations

From the preceding discussion, it becomes obvious that correlations should ideally be established for a given rock type whose response falls within a single response domain. Nonlinear correlations simply indicate significant microstructural changes in that seemingly identical rock type. This is well-illustrated in Fig. A.1 for weathering-induced microstructural changes in granite. When the aim is to derive a generic correlation function involving a large group of rock types (e.g. carbonates, mudrocks) it is essential to ensure that there are no large gaps across the entire range and all distinct microstructural varieties of each rock type are represented.

In terms of data gathering and reduction procedures, it also becomes evident that averaging single impact readings is the only rational approach. Note that data gathering procedures based on multiple (or repeated) impact at a single point alter the original microstructure of the test surface resulting in the loss of invaluable information.

The *UCS* or *E* versus *R* correlations should be established using the mean rebound value using the entire set of measurements. The structure of each rebound value data set reflects the nature of surface heterogeneity and it is not immediately obvious which microstructural element or feature (corresponding to average, median or most repeated rebound value) controls or dominates *UCS* and *E* of the corresponding rock. Therefore, median and mode (with the number of repetition) values should also be plotted along the range bars on the correlation graphs to facilitate interpretation of overall significance of the correlation and potential variability in *UCS* and *E* values of each sample.

On the other hand, the *UCS* and *E* of a given rock type are highly sensitive to slight changes in its microstructural state (e.g. degree and style of weathering, density and orientation of microcracks, grain size distribution, mineralogy). However, a systematic analysis of the potentially large variability in these basic mechanical properties is not always feasible due to the difficulties of laboratory testing (justifying the search for indirect predictions using index tests). As a result, in establishing correlations (especially those involving a mixture of rock types), only a few *UCS* or *E* values are often available to represent full range of variability in each rock type. This important limitation in constraining potential scatter in *UCS* and *E* values can be partly offset by careful evaluation of the variability in rebound values, which should be depicted on the correlation plots by range bars. The reliability of the correlation coefficient and variance can also be better evaluated in this context.

For the identification of weathering grade in granites, Aydin and Basu [2] showed that changes in rebound values between first and second impact provide the best correlation. This procedure is supported in the light of the indentation mechanisms discussed above.

In order to capture overall trends among different rock types or across the weathering spectrum of a given rock type, one of the following pairs of generalized expressions can be used to establish the *UCS* and *E* versus rebound value (R) correlations [2]:

$$UCS = ae^{bR}, \quad E_t = ce^{dR} \tag{A.1}$$

$$UCS = aR^{b}, \quad E_t = cR^{d} \tag{A.2}$$

where *a, b, c* and *d* are positive constants that depend on the rock type. However, as a final note on the validity of generalizing expressions for a mixture of rocks or for a given rock across the weathering spectrum, Aydin and Basu [2] cautioned that these correlations are valid "assuming similar style and sequence of microstructural changes". This is probably the key consideration in selecting appropriate functions for estimating point values of the *UCS* and *E,* and hence, such generalized expressions are not recommended for use in practice when more specific expressions becomes available for the corresponding rock microstructures.

It was demonstrated that when the SH tests are conducted using the recommendations outlined in this suggested method, the rebound values (*R*) obtained by using standard L- and N-type Schmidt hammers are almost perfectly correlated with a very limited scatter for the range of $R_L > 30$ or $R_N > 40$ [2]:

$$R_N = 1.0646\, R_L + 6.3673 (r = 0.99) \tag{A.3}$$

Note, however, that this relationship has been derived on granitic core samples with relatively smooth surfaces in laboratory conditions and the degree of correlation and data scatter may be expected to deteriorate in case of field applications and testing weak porous rocks due to the differences in the impact energies.

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http://www.springer.com/978-3-319-07712-3

The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014
Ulusay, R. (Ed.)
2015, XIII, 293 p. 218 illus., 53 illus. in color., Hardcover
ISBN: 978-3-319-07712-3