Available online at www.sciencedirect.com

SCIENCE DIRECT

Engineering Geology 81 (2005) 1–14

ENGINEERING GEOLOGY

www.elsevier.com/locate/enggeo

The Schmidt hammer in rock material characterization

A. Aydin *, A. Basu

Department of Earth Sciences, The University of Hong Kong, Pokfulam Rd., Hong Kong, China

Received 24 February 2005; received in revised form 9 June 2005; accepted 20 June 2005
Available online 22 August 2005

Abstract

The Schmidt hammer provides a quick and inexpensive measure of surface hardness that is widely used for estimating the mechanical properties of rock material. However, a number of issues such as hammer type, normalization of rebound values, specimen dimensions, surface smoothness, weathering and moisture content, and testing, data reduction and analysis procedures continue to influence the consistency and reliability of the Schmidt hammer test results. This paper presents: a) a critical review of these basic issues; and b) the results of tests conducted on granitic rocks of various weathering grades in the light of the conclusions of this review. It was found that a very good correlation exists between L and N hammer rebound values and that both hammers are fairly sensitive to the physical properties, particularly to dry density though less so to effective and total porosities. The N hammer, producing a lesser scatter in the data, proved to be more efficient than the L hammer in predicting uniaxial compressive strength and Young's modulus. The exponential form of the correlation curves was found to reflect microstructural changes during the course of weathering and the differences in the probing scales or mechanisms in the means of measuring these mechanical properties, and could be generalized to other crystalline igneous rocks. The possibility of predicting weathering grades from rebound values was also explored. The changes in the rebound values during multiple impacts at a given point produced a better indication of the weathering grade than a single impact value. It was concluded that increasing the impact energy and plunger tip diameter should significantly reduce the scatter in coarse-grained weathered rocks and hence improve the reliability of the Schmidt hammer as a rock material characterization tool.

Keywords: Schmidt hammer; Rebound value; Uniaxial compressive strength; Young's modulus; Weathering grade; Igneous rocks

1. Introduction

The Schmidt hammer, developed in the late 1940s as an index apparatus for non-destructive testing of concrete in situ, has been used in rock mechanics practice since the early 1960s, mainly for estimating the uniaxial compressive strength (UCS) and Young's modulus (E_t) of rock materials. Considering its long history and widespread use, the standard methods for the Schmidt hammer test (ISRM, 1978a; ASTM, 2001) might be expected to ensure consistent and reliable values and reproducible correlations for a given rock type. Much of the published work has focused on improving data gathering procedures and developing new correlations

* Corresponding author. Tel.: +852 22415474; fax: +852 25176912.
E-mail address: aaydin@hku.hk (A. Aydin).

0013-7952/$ - see front matter
doi:10.1016/j.enggeo.2005.06.006

for different rock types. However, a number of issues such as hammer type, normalization of rebound values, specimen dimensions, surface smoothness, weathering and moisture content, and testing, data reduction and analysis procedures continue to undermine the reliability of the Schmidt hammer. This paper first presents a critical review of these issues and then experimentally demonstrates how the insights gained from this review identified ways of reducing scatter, thereby improving the reliability of the Schmidt hammer as a rock material characterization tool.

2. Basic issues in Schmidt hammer tests

2.1. Operational principle

When the Schmidt hammer (consisting of a spring-loaded piston) is pressed orthogonally against a surface, the piston is automatically released onto the plunger. Part of the impact energy of the piston is consumed largely by absorption (work done in plastic deformation of rock material under the plunger tip) and transformation (into heat and sound). The remaining energy represents the impact penetration resistance (or hardness) of the surface and enables the piston rebound. The harder the surface, the shorter the penetration *time* (i.e., smaller impulse) or *depth* (i.e., lesser work or energy loss), and hence the greater the rebound (i.e., smaller momentum change). The distance traveled by the piston after rebound (expressed as a percentage of the initial extension of the key-spring) is called the rebound value (R), which is considered to be an index of surface hardness. The details of operational aspects of the Schmidt hammer can be found in Basu and Aydin (2004).

2.2. Hammer type

The standard L-and N-type Schmidt hammers are built to generate different levels of impact energy: 0.735 and 2.207 Nm, respectively. Provided that the hammer impact results in uniform compaction (i.e., without crushing of discrete grains, skeletal collapse, or extensive cracking and chipping off):

a) ratios of rebound values measured on different (homogeneous) surfaces at two different energy levels should be constant; and
b) higher impact energy (corresponding to probing a larger volume of material by a deeper and wider penetration) should reduce scatter in rebound values obtained at different points on a heterogeneous surface (e.g., of a coarse-grained rock in which scale of heterogeneity is comparable with the plunger tip or the material volume sustaining the impact).

It is therefore not clear why ISRM (1978a) only endorsed the use of the L hammer for testing rocks, while ASTM (2001) did not specify the hammer type. Ayday and Goktan (1992) have demonstrated that reliable correlations could be developed between the rebound values of the L-and N-type hammers.

While both hammer types were used for testing rocks of a large range of the uniaxial compressive strength (UCS), ISRM and ASTM recommended a significantly narrower range of UCS (1–100 MPa, respectively). Shorey et al. (1984) indicated that the N hammer should be used for rocks with UCS values more than 20 MPa. Li et al. (2000) showed theoretically that on homogeneous weak rocks (UCS $<$ 10 MPa) no rebound should occur, due to strong plasticity, whereas on extremely strong rocks (UCS $>$ 300 MPa) the rate of rebound value increase should slow down (suggesting near complete recovery of impact energy).

2.3. Normalization of rebound values

Schmidt hammer rebound values obtained along non-horizontal impact directions are influenced by gravitational forces to varying degrees. In order to nullify these effects, non-horizontal rebound values must be normalized with reference to the horizontal direction. Both ISRM (1978a) and ASTM (2001) stipulated that the rebound values should be normalized using the correction curves provided by the manufacturer. Barton and Choubey (1977) proposed a correction chart for the L hammer based on data furnished by the manufacturer, which was later adopted by ISRM (1978b). Kolaiti and Papadopoulos (1993) detected an inconsistency in this correction method. The corrections provided by the Schmidt hammer manufacturers are derived empirically for a certain material (mostly concrete) with a relatively narrow range of mechanical properties, and are often limited to two or four impact directions (±45° and ±90°). Basu and Aydin (2004) proposed an analytical formulation for normalization of the Schmidt hammer rebound values and experimentally verified its applicability to a wide range of rock materials. This normalization method can be used for any type of Schmidt hammer fired in any direction, and is proven to be more accurate than empirical methods.

2.4. Specimen requirements

Day and Goudie (1977) demonstrated that the test points should be away from the boundaries to avoid abnormally low values due to strong dissipation of impact energy. ISRM (1978a) stipulated that block specimens should have an edge length of at least 6 cm, while ASTM (2001) recommended an edge length of at least 15 cm. Both standards specify that core specimens should be of NX size (54.7 mm) or larger in diameter. It was also recommended that the test surface should be free from cracks to a depth of at least 6 cm (implying that the penetration of the impact wave may exceed this depth). Obviously NX cores do not comply with this requirement. In any case, larger blocks/cores should always be preferred, to avoid a significant dissipation of impact energy at the rock specimen–steel base interface.

The degree of surface smoothness of the specimens also significantly affects the rebound values (Hucka, 1965). Surface irregularities or asperities are often crushed before the plunger tip reaches down the main surface, resulting in an additional loss of impact energy. Katz et al. (2000) noted that the magnitude and repeatability of the hammer readings increase depending on the degree of polishing.

2.5. Weathering and moisture content

Weathering of igneous rocks under humid tropical conditions produces microstructural changes, starting with discoloration, microfracturing and loosening of grain boundaries, continuing with chemical alteration and leaching of constituent minerals, and ending with collapse of relict (skeletal) structure (Aydin and Duzgoren-Aydin, 2002). Because the six-fold weathering classification scheme is based on subjective criteria, identifying and assigning weathering grades objectively and quantitatively by index tests have obvious advantages, and a large number of studies have been devoted to investigating the possibility of developing a practical (sensitive and consistent) scale to achieve this goal (Aydin and Duzgoren-Aydin, 2002). In this context, the Schmidt hammer (arguably the most typical mechanical index) has attracted considerable attention in recent years (e.g., Dearman and Irfan, 1978; Saito, 1981; Hencher and Martin, 1982; Karpuz and Pasamehmetoglu, 1997). Williams and Robinson (1983) concluded that even slight weathering is capable of reducing rebound values significantly. Microstructural changes are especially complex in polymineralic rocks, because of the different weathering susceptibilities of common rock forming minerals such as quartz and feldspars. Therefore, scatter in rebound values is expected to increase with weathering especially in coarse-grained igneous rocks due to the comparable size of standard plunger tip. This in turn produces considerable overlaps among the rebound value ranges of adjacent weathering grades.

Sumner and Nel (2002) indicated that the influence of moisture on rebound values varies according to the rock type. Therefore, the internal moisture content should be taken into consideration particularly in comparing the in situ states of weathering. Rebound values generally decrease non-linearly with increasing moisture content. On the contrary, Ballantyne et al. (1990) surmised that the presence of incompressible water in surface voids might actually increase the rebound values. This may only occur if the void is effectively enclosed to permit dissipation of pore water pressure induced during instantaneous loading and a hydraulic microfracture is not generated in the process.

2.6. Test requirements

It is essential to ensure that the hammer axis is perpendicular to the test surface to minimize variations that would arise from oblique impact (or eccentric contact of the plunger tip). When testing a laboratory specimen, a geometric mismatch at the specimen–support interface and the use of a base softer than the specimen may lead to a significant loss of impact energy. To account for these effects, both ISRM (1978a) and ASTM (2001) stipulated that specimens should be securely clamped to a steel base with a minimum weight of 20 kg and that cylindrical (core) specimens should be placed along a machined slot (with an arc-shaped cross-section of the same radius) or a V-block. The steel base needs to be heavier for the N hammer, and an arc-shaped groove should be preferred to a V-block (which leaves the specimen unsupported directly below the impact points and may facilitate flexural cracking of weak rocks, particularly with the N hammer). It should be noted that in situ testing may produce a wider scatter due to roughness of natural surfaces, lack of control for the existence of cracks below the surface, and variations in moisture content.

2.7. Data gathering and reduction

Rules have yet to be established for determining the number of impact points necessary to capture hardness variations (at the microstructural scale) over a specimen surface and for reducing the corresponding rebound value readings to a representative value. This reduction process is carried out by removing the lowest readings attributed to the presence of hidden cracks and averaging the others. ISRM (1978a) recommended averaging the upper 50% of at least 20 single impact readings, after eliminating any reading from points that show signs of cracking. ASTM (2001) suggested taking at least 10 single impact readings, discarding those differing from the average by more than 7 units, and averaging those left. Both standards require that the impact points be separated by at least one plunger diameter. Shorey et al. (1984), on the other hand, preferred lower mean values because they correlated better with UCS. Amaral et al. (1999) indicated that it is important to understand the variations in the readings because they are strictly related to the material heterogeneity and therefore, all values should be taken into account.

Hucka (1965) and Poole and Farmer (1980) observed that the peak values of repeated impacts (ten and five impacts, respectively) at individual points are more consistent than first or single impact values. This can be attributed to the apparent hardening upon multiple impacts due to compaction, particularly in weathered rocks. Thus the peak rebound value represents an altered state of rock material surface, which could lead to erroneous predictions UCS and E_t. However, rebound value trends during a few repeated impacts may be used as an index of the weathering grade or the structural integrity of rock materials in general.

2.8. Correlation with uniaxial compressive strength

As the Schmidt hammer is considered to be a non-destructive tool, Xu et al. (1990) used the same specimens to determine their corresponding UCS values and thus to establish a direct correlation between rebound value and UCS. However, particularly in the case of weak rocks, use of the same specimen for both tests can be very misleading, as hammering will induce microcracks inside the specimen and significantly lower its UCS. On the other hand, when different specimens are used, their microstructural equivalence should be ensured by careful microscopic examination.

Previous studies have charted a large number of empirical relationships between rebound values and UCS and tangent modulus (E_t) of various rocks (Table 1). These relationships are expressed by power, exponential or linear functions (as grouped in Table 1). In a number of these functions, rebound value (the main independent variable) is multiplied with dry density (introduced as a second variable) in an effort to improve the correlations. In doing so, the carefully derived average rebound value of each specimen is magnified/reduced relative to other specimens. This attempt defies the notion of index testing and ignores the fact that:

a) where reliable density measurements are available, they will likely correlate as well with the mechanical properties as the Schmidt hammer test; and
b) dry density in the field and in weak, argillaceous and/or weathered rocks is more difficult to determine, and involves approximate procedures and larger sampling variability.

On the other hand, multiplying rebound value with dry density (i.e., a local property with a bulk property) may help reduce the influence of surface deterioration and/or small-scale variations (of asperities, minerals, cracks, etc), which could dominate Schmidt hammer results for certain specimens. All in all, use of additional variables (e.g., density, porosity, ultrasonic velocity) should be avoided in establishing empirical correlations for practical use unless their roles are

Table 1
Relations of rebound value with uniaxial compressive strength and Young's modulus

References	Proposed correlations*	r	Validity range		
			Rock type	σ_{UCS}	R
Aufmuth (1973)	$\sigma_{UCS}=0.33*(R_L*\rho)^{1.35}$	0.80	25 different lithologies	12–362	10–54
	$E_t=4911.84*(R_L*\rho)^{1.06}$	0.75			
Kahraman (1996: in Yilmaz and Sendir, 2002)	$\sigma_{UCS}=0.00045*(R_N*\rho)^{2.46}$	0.96	10 different lithologies	–	–
Gokceoglu (1996: in Yilmaz and Sendir, 2002)	$\sigma_{UCS}=0.0001*R^{3.27}$	0.84	Marl	–	–
Yasar and Erdogan (2004)	$\sigma_{UCS}=0.000004*R_L^{4.29}$	0.89	Carbonates, sandstone, basalt	40–112	45–55
Dearman and Irfan (1978)	$\sigma_{UCS}=0.00016*R_L^{3.47}$	–	Granite	11–266	23–62
	$E_t=1.89*R_L-60.55$	0.93	(Grade I to IV)		
Xu et al. (1990)	$\sigma_{UCS}=2.98*e^{(0.06*R_L}$	0.95	Mica-schist	9–56	17–53
	$E_t=1.77*e^{(0.07*R_L)}$	0.96			
	$\sigma_{UCS}=2.99*e^{(0.06*R_L)}$	0.91	Prasinite	8–145	21–64
	$E_t=2.71*e^{(0.04*R_L)}$	0.91			
	$\sigma_{UCS}=2.98*e^{(0.063*R_L)}$	0.94	Serpentinite	–	–
	$E_t=2.57*e^{(0.03*R_L)}$	0.88			
	$\sigma_{UCS}=3.78*e^{(0.05*R_L)}$	0.93	Gabro	–	–
	$E_t=1.75*e^{(0.05*R_L)}$	0.95			
	$\sigma_{UCS}=1.26*e^{(0.52*R_L*\rho)}$	0.92	Mudstone	–	–
	$E_t=0.07*e^{(0.31*R_L*\rho)}$	0.89			
Deere and Miller (1966)	$\sigma_{UCS}=9.97*e^{(0.02*R_L*\rho)}$	0.94	28 different lithologies	22–358	23–59
	$E_t=0.19*R_L*\rho^2-7.87$	0.88			
Beverly et al. (1979: in Xu et al., 1990)	$\sigma_{UCS}=12.74*e^{(0.02*R_L*\rho)}$		20 different lithologies	38–218	–
	$E_t=0.19*R_L*\rho^2-12.71$				
Cargill and Shakoor (1990)	$\sigma^{UCS}=3.32*e^{(0.04*R_L*\rho)}$	0.93	Sandstones		
	$\sigma_{UCS}=18.17*e^{(0.02*R_L*\rho)}$	0.98	Carbonates	35–271	27–49
Kahraman (2001)	$\sigma_{UCS}=6.97*e^{(0.01*R_N*\rho)}$	0.78	Carbonates	4–153	15–70
This study	$\sigma_{UCS}=1.45*e^{(0.07*R_L)}$	0.92	Granite	6–196	20–65
	$E_t=1.04*e^{(0.06*R_L)}$	0.91	(Grade I to IV)		23–76
	$\sigma_{UCS}=0.92*e^{(0.07*R_N)}$	0.94			
	$E_t=0.72*e^{(0.05*R_N)}$	0.92			
Yilmaz and Sendir (2002)	$\sigma_{UCS}=2.27*e^{(0.06*R_L)}$	0.91			
	$E_t=3.15*e^{(0.05*RL)}$	0.95	Gypsum	15–30	30–44
Katz et al. (2000)	$\sigma_{UCS}=2.21*e^{(0.07*R_N)}$	0.96	Limestone, sandstone	11–259	24–73
	$E_t=0.00013*R_N^{3.09}$	0.99	Syenite, granite		
Kidybinski (1980)	$\sigma_{UCS}=0.52*e^{(0.05*R+\rho)}$		Coal, shale, mudstone, siltstone, sandstone	–	–
Shorey et al. (1984)	$\sigma_{UCS}=0.40*R_N-3.60$	0.94	Coal	3–13	15–40
Haramy and DeMarco (1985)	$\sigma_{UCS}=0.99*R_L-0.38$	0.70	Coal	7–46	12–44
Ghose and Chakraborti (1986)	$\sigma_{UCS}=0.88*R_L-12.11$	0.87	Coal	13–41	28–53
Singh et al. (1983)	$\sigma_{UCS}=2.00*R_L$	0.86	Sandstone, siltstone, mudstone, seatearth	12–73	10–35
O' Rourke (1989)	$\sigma_{UCS}=4.85*R_L-76.18$	0.77	Sandstone, siltstone, limestone, anhydride	14–215	19–52
Sachpazis (1990)	$\sigma_{UCS}=4.29*R_L-67.52$	0.96	33 different carbonates	22–311	16–60
	$E_t=1.94*R_L-33.93$	0.88			
Tugrul and Zarif (1999)	$\sigma_{UCS}=8.36*R_L-416.00$	0.87	Granite	109–193	64–72

Abbreviations:
σ_{UCS}: UCS (MPa); E_t: tangent Young's modulus (GPa) at 50% of σ_{UCS}; ρ: density (gm/cm^3); R_L and R_N: rebound values for L and N hammers; r: regression coefficient.

* Note that some of the above relations were modified from their original forms into one of the general expressions (power/exponential/linear) with common SI units for individual variables.

complementary and significant and can be clearly explained.

3. Specimens and methods

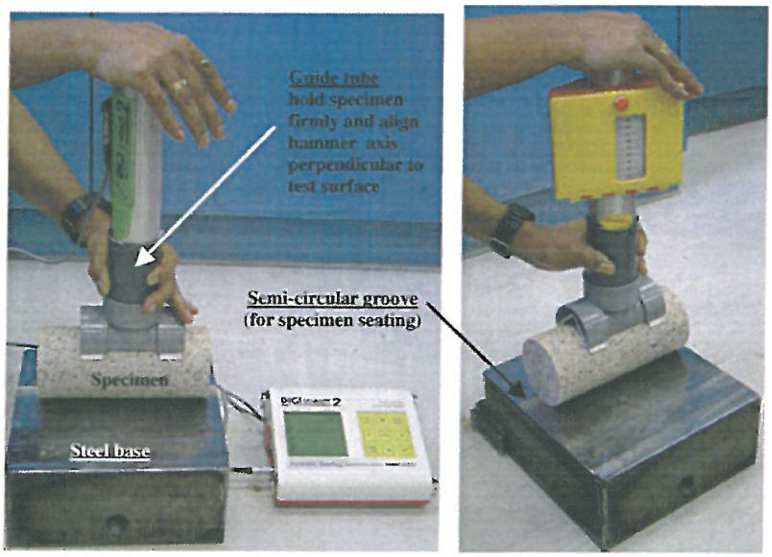
In this study, a total of 40 granitic (compositionally monzogranite) core specimens (>NX diameter) of various degrees of weathering from Hong Kong were tested by the standard (L and N type) Proceq© Schmidt hammers. The accuracy and stability in rebound value readings of the hammers were verified by repeated impacts on the manufacturers' calibration anvil before, during and after the investigation. Air-dried core specimens (length–diameter ratio ≈ 2 : 1) were placed along an arc-shaped groove on the surface of a steel slab (weight: 45 kg; width: 23.2 cm; length: 25.2 cm; thickness: 10.3 cm) (Fig. 1). A guide tube was fabricated to help hold the specimen firmly against the base and orient the firing direction vertically downward and orthogonal to the test surface (Fig. 1).

On each specimen, single impact readings at 10 different points were recorded for each hammer. The specimen surfaces were reasonably smooth and free of visible cracks and each impact point was separated by at least two plunger diameters. No reading was discarded unless the impact produced visible cracks and/or chips on the test surface. For both hammers, all rebound values were normalized with reference to the horizontal impact direction (Basu and Aydin, 2004). The means and variances of these single impact values are given in Table 2.

4. Results and analysis

Rebound values of the N hammer (R_N) were consistently higher than those of the L hammer (R_L), as expected (Table 2). Results revealed a very good correlation between R_N and R_L (Fig. 2) despite a wide range of weathering grades of the specimens. Scatter in the data was always wider for the L hammer (Table 2) reflecting increasing sensitivity to rock heterogeneity with lower impact energy.

Dry density (ρ_{dry}), effective porosity (n_e), and total porosity (n_t) of equivalent specimens were determined (Table 2) to correlate with the corresponding rebound values. For n_e, specimens were immersed into water in a vacuum of less than 800 Pa for 1 h and then dried to a constant mass at 105 °C. The water displacement method was adopted to measure the bulk volume of



ND hammer **LR hammer**

Fig. 1. Schmidt hammer test set up in the laboratory.

Table 2
Rebound values, physical properties, uniaxial compressive strengths and Young's moduli

Sp. No.	R_L		R_N		ρ_{dry} (gm/cm^3)	n_e (%)	n_t (%)	UCS (MPa)	E_t (GPa)
	Mean	Var.	Mean	Var.					
1	64.67	1.57	75.75	0.21	2.69	0.98	1.33	196.45	53.19
2	62.83	0.80	74.79	0.14	2.68	1.63	3.75	160.20	51.70
3	62.60	1.46	74.02	0.40	2.63	1.17	1.71	157.22	51.05
4	61.75	1.50	71.96	0.41	2.65	1.99	6.15	155.70	47.33
5	61.42	1.60	71.89	0.65	2.57	3.13	7.33	148.36	50.00
6	65.76	1.29	75.97	0.21	2.66	0.98	1.31	136.15	45.57
7	61.84	1.78	72.40	0.75	2.59	1.12	2.04	133.55	46.70
8	61.84	1.77	70.97	0.86	2.62	2.10	1.82	123.25	45.65
9	62.13	1.66	72.57	0.72	2.63	1.00	5.66	139.45	47.62
10	60.43	1.82	70.00	1.17	2.62	1.42	2.37	121.40	43.30
11	60.24	1.81	69.89	1.22	2.58	1.66	2.49	116.30	42.90
12	60.48	2.10	69.94	1.17	2.57	2.86	3.86	106.34	31.79
13	61.40	2.60	72.20	1.34	2.65	1.83	5.06	88.20	28.36
14	59.53	2.40	67.94	1.43	2.62	1.84	9.05	83.13	21.92
15	58.02	2.44	71.20	1.39	2.49	3.92	7.54	68.21	25.32
16	52.74	2.76	61.84	1.64	2.59	2.87	8.74	59.36	24.24
17	49.15	3.60	58.14	2.06	2.57	3.13	10.91	53.19	18.93
18	43.29	2.29	56.78	1.69	2.57	3.03	9.00	45.67	16.92
19	42.45	5.69	51.64	4.76	2.42	6.66	18.23	32.16	7.02
20	39.94	6.45	51.76	5.17	2.36	7.57	16.88	31.14	16.26
21	48.86	17.81	55.20	13.66	2.47	5.93	7.58	26.83	12.20
22	35.01	15.69	45.23	8.54	2.46	6.37	18.29	24.35	15.82
23	34.91	15.60	43.97	8.00	2.42	8.23	19.21	22.96	6.99
24	33.43	17.72	42.89	9.62	2.41	9.08	14.08	22.32	5.22
25	43.99	14.12	52.45	11.04	2.52	6.58	7.35	14.70	13.18
26	43.65	14.76	52.07	12.16	2.52	9.88	14.23	13.66	6.06
27	36.39	11.85	43.80	7.95	2.37	8.59	13.87	13.61	8.37
28	34.24	22.36	43.04	18.51	2.40	6.01	9.95	18.84	8.77
29	32.24	16.04	42.61	13.20	2.26	15.74	19.71	17.30	10.00
30	35.67	18.71	43.69	14.65	2.32	11.42	13.77	7.64	5.38
31	33.00	18.00	42.49	14.56	2.24	13.49	17.77	23.15	6.49
32	34.00	21.07	42.83	19.22	2.28	13.57	15.63	19.70	6.41
33	34.91	23.55	44.27	19.58	2.36	10.26	21.04	25.14	11.83
34	32.28	20.46	41.75	18.15	2.35	9.23	16.09	22.16	9.01
35	34.39	17.92	43.38	15.74	2.34	9.63	12.99	11.67	8.30
36	20.00	30.25	23.00	25.40	2.13	18.15	18.94	6.32	4.46
37	50.33	9.06	59.53	4.50	2.55	4.24	5.60	33.86	13.89
38	51.46	7.52	60.18	4.28	2.56	4.36	9.17	41.73	14.28
39	48.48	11.89	57.01	5.95	2.47	5.52	5.96	25.38	12.35
40	46.69	13.69	53.87	6.94	2.46	5.91	6.98	22.66	8.81

Abbreviations:
var.: variance; ρ_{dry}: dry density; n_e: effective porosity under vacuum; n_t: total porosity.

wax-coated weathered samples and the volume of their fine powdered equivalents. Fig. 2 indicates that both hammers were fairly sensitive to the physical properties, particularly to ρ_{dry} though less so to n_e and n_t.

UCS and E_t of equivalent air-dried specimens (length–diameter ratio ≈ 2 : 1) were determined to establish their relationships with both R_N and R_L (Table 2). R_N correlated better with both UCS and E_t (Fig. 3), probably because of a larger probing capacity that suppresses minor local variations (as evidenced by the smaller scatter in the N hammer data). Distinct changes in the slope of the correlation curves (Fig. 3) showed that R, UCS and E_t decreased

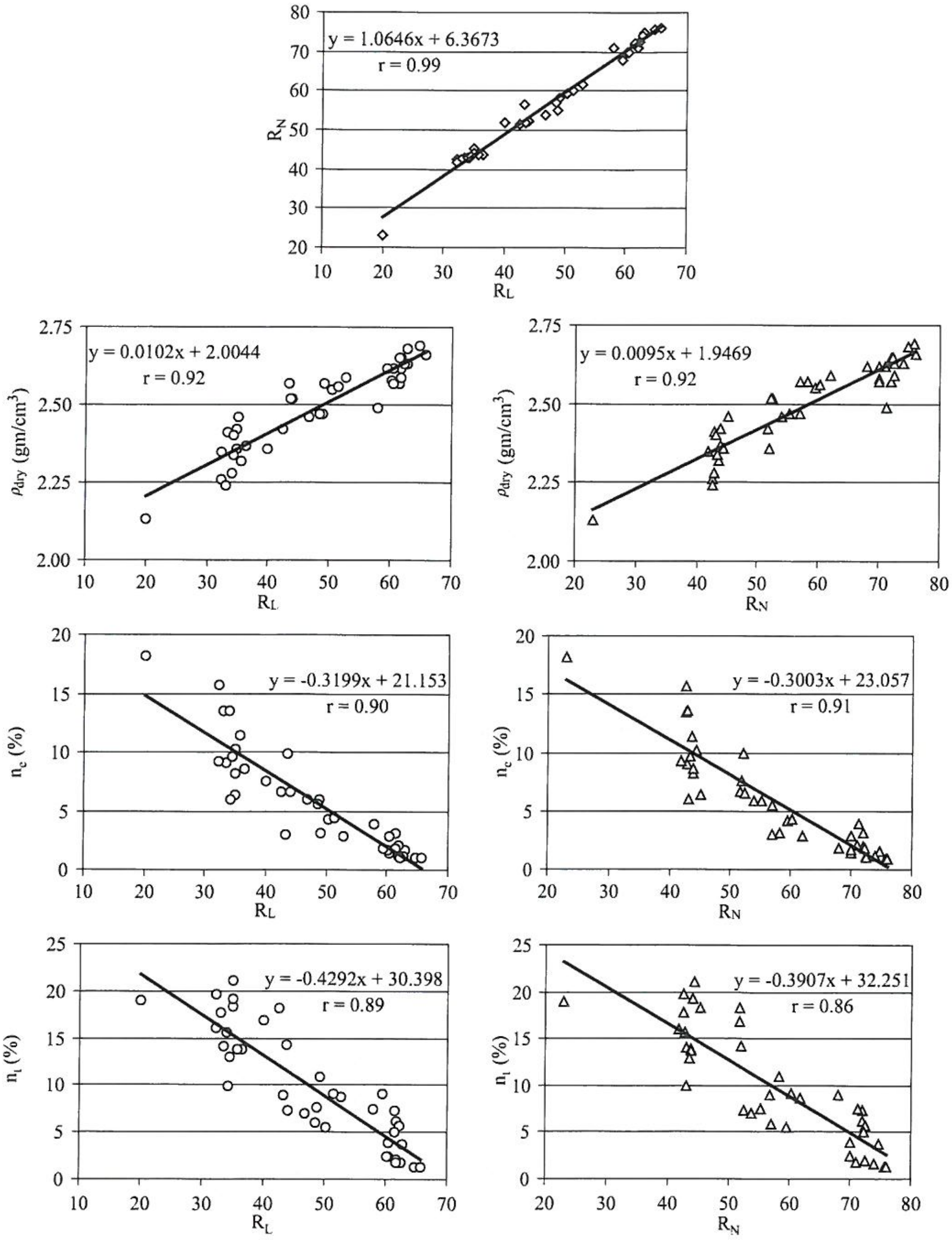


Fig. 2. Relations between L and N hammer rebound values and their correlations with physical properties.

at different rates during different stages of weathering. To further examine the nature of R vs. UCS and E_t correlations (Fig. 3), each specimen was assigned a weathering grade (WG), subsequently adjusted/confirmed by petrographic examination (Table 3), and a superimposed plot of WG vs. UCS, E_t, R_N and R_L values was prepared (Fig. 4, excluding specimens Nos. 37–40). This plot revealed remarkably different weathering response patterns for R and UCS or E_t. In fresh crystalline igneous rocks UCS and E_t are very

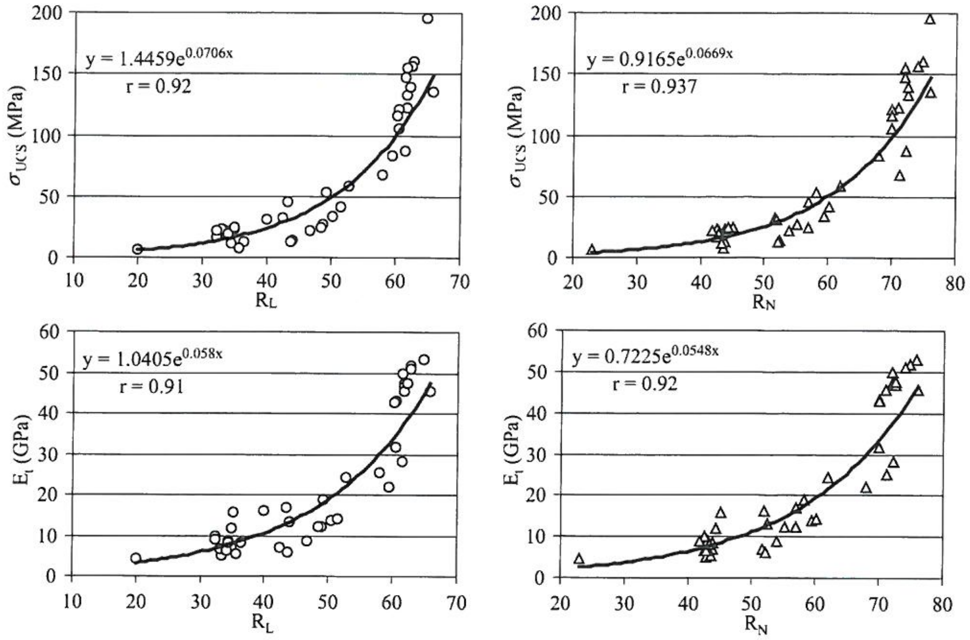


Fig. 3. Correlations of rebound values with uniaxial compressive strengths and tangent Young's moduli.

sensitive to the presence and orientations of microcracks (as failure and deformation in strongly bonded materials occur by the coalescence of existing and loading-induced microcracks). Thus initial sharp drops in UCS and E_t can be attributed to a sudden increase in the intensity of existing flaws with the onset of weathering (represented by Grades I–II and II). As weathering advances (represented by Grades III to IV), the skeletal structure (grains and intergranular contacts or bonding) weakens. This process slows down the rate of change in strength and deformation, and hence to a reduction of R at a similar rate as UCS and E_t (Fig. 4). In other words, the smallest scale at which deformation/strength probing is representative of the standard bulk scale is reduced to size of a few grains.

To sum up, the exponential form of R vs. UCS and E_t correlation curves (Fig. 3) is a consequence of microstructural changes during the course of weathering and the differences in the probing scales or mechanisms of a) deformation (E_t) and failure (UCS) of the whole specimen under uniaxial loading and b) penetration of a small diameter plunger and compaction by the relatively small impact of a Schmidt hammer. In line with this analysis, UCS and E_t of crystalline igneous rocks at any degree of weathering (Grade I to IV) can be predicted from one of the following pairs of generalized expressions:

$$\sigma_{\mathrm{UCS}} = a^{*}\mathrm{e}^{(b^{*}R)} \quad \& \quad E_t = c^{*}\mathrm{e}^{(d^{*}R)}$$

$$\sigma_{\mathrm{UCS}} = a^{*}R^{b} \quad \& \quad E_t = c^{*}R^{d}$$

where a, b, c and d are positive constants based on the rock type.

It should be noted that there are similar (exponential and power) correlations (Table 1) derived for random mixtures of fresh rocks (argillaceous, clastic, carbonate, foliated, etc.), each of which has its own unique microstructure (and strength range) and should respond to both uniaxial and impact loadings entirely differently. In other words, there is no sufficient rationale behind such "universal relationships". On the other hand, there are also a number of linear relationships mostly obtained for a single (e.g., coal) or similar (e.g., sedimentary) rock type(s) with relatively narrow UCS ranges (Table 1). While this may be reasonable in some cases, the data sets (where available) do not always warrant these trends.

Table 3
Weathering grades, grain sizes and rebound values

Sp. No.	WG	d_g (mm)	Range R_L Mean	Range R_L Var.	Range R_N Mean	Range R_N Var.	Mutiple impacts R_L	Mutiple impacts R_N	$R_{L2}-R_{L1}$	$R_{N2}-R_{N1}$
1	I	3.56					66.13,67.08,67.08,67.08	75.50,76.91,77.38,77.38	0.95	1.41
2	I	3.48					62.36,63.31,63.31,64.25	74.55,75.97,75.97,76.44	0.95	1.42
3	I	3.73					62.36,63.31,63.31,63.31	74.55,76.44,76.44,77.38	0.95	1.89
4	I	4.14					63.31,64.25,64.25,64.25	69.84,71.53,71.72,71.72	0.94	1.69
5	I	3.30					62.36,63.31,64.25,64.25	72.67,74.55,74.55,74.55	0.95	1.88
6	I	3.43	60.24–	0.80–	69.89–	0.14–	67.55,68.49,68.49,68.49	75.50,76.91,77.38,77.38	0.94	1.41
7	I	3.30	65.76	1.82	75.97	1.22	60.48,61.42,61.42,61.42	72.67,74.08,74.55,74.55	0.94	1.41
8	I	3.68					60.48,61.42,61.42,61.42	69.84,71.72,71.72,72.67	0.94	1.88
9	I	3.72					61.42,62.36,63.31,63.31	73.61,75.12,75.50,75.50	0.94	1.51
10	I	3.67					61.42,63.31,63.31,64.25	69.84,72.29,72.48,72.67	1.89	2.45
11	I	3.70					60.48,61.42,62.36,62.36	68.89,70.97,71.72,71.72	0.94	2.08
12	I–II	3.73					59.53,62.36,63.31,63.31	69.84,73.61,73.61,73.61	2.83	3.77
13	I–II	3.40	59.53–	2.10–	67.94–	1.34–	62.36,65.19,65.19,65.19	70.78,74.08,74.08,74.36	2.83	3.3
14	I–II	3.79	61.40	2.60	72.20	1.43	62.69,66.29,66.61,66.80	67.00,70.69,71.72,71.72	3.60	3.69
15	II	3.87					58.59,62.83,62.83,62.83	69.36,73.80,73.80,74.20	4.24	4.44
16	II	4.08					51.98,55.76,55.76,55.76	60.39,64.36,65.12,65.12	3.78	3.97
17	II	4.08	39.94–	2.29–	51.64–	1.39–	51.04,54.82,54.82,55.76	58.50,62.75,62.75,63.23	3.78	4.25
18	II	4.08	58.02	6.45	71.20	5.17	41.57,46.31,46.31,47.25	55.67,60.58,60.58,61.34	4.74	4.91
19	II	3.98					44.41,48.20,48.20,48.20	51.31,55.85,56.61,56.61	3.79	4.54
20	II	3.95					40.62,44.89,45.36,45.36	50.93,55.29,55.29,55.48	4.27	4.36
21	III	4.12					50.09,55.29,55.76,55.76	56.61,62.66,62.66,63.23	5.20	6.05
22	III	4.14					33.00,38.72,39.67,39.67	43.35,49.99,50.93,47.14	5.72	6.64
23	III	4.13	33.43–	11.85–	42.89–	7.95–	35.86,41.57,41.57,42.52	42.40,49.04,49.04,48.09	5.71	6.64
24	III	3.99	48.86	17.81	55.20	13.66	34.91,41.57,41.57,41.57	42.40,49.99,49.99,49.99	6.66	7.59
25	III	3.81					45.36,51.04,51.04,51.04	50.93,56.61,56.61,57.56	5.68	5.68
26	III	3.88					43.46,49.15,49.15,50.09	50.93,57.56,58.50,58.50	5.69	6.63
27	III	3.98					34.91,42.52,43.46,43.46	43.35,51.50,51.88,48.09	7.61	8.15
28	III--IV	3.60					35.86,41.57,41.57,42.52	45.25,52.83,53.77,51.88	5.71	7.58
29	III–IV	4.02					31.09,41.57,42.52,42.52	41.64,51.88,52.35,49.04	10.48	10.24
30	III–IV	3.91					34.91,41.57,41.57,41.57	45.25,52.83,52.83,51.88	6.66	7.58
31	III–IV	3.98	32.24–	16.04–	41.75–	13.20–	32.05,38.72,38.72,39.67	43.35,51.88,52.83,49.99	6.67	8.53
32	III–IV	3.66	35.67	23.55	44.27	19.58	35.86,43.46,43.46,43.46	41.45,49.51,49.51,49.99	7.60	8.06
33	III–IV	3.96					34.91,40.62,41.57,41.57	45.25,52.64,52.64,51.88	5.71	7.39
34	III–IV	4.17					31.09,42.52,42.52,43.46	41.45,53.77,53.77,48.66	11.43	12.32
35	III–IV	3.77					33.96,40.62,40.62,40.62	42.40,50.18,50.74,50.74	6.66	7.78
36	IV	4.20	20	30.3	23	25.4	20.44,34.91,24.35,23.38	23.24,38.4,no rebound	14.47	15.16
37	III–IV	2.41	50.33–	7.52–	59.53–	4.28–	51.04,56.70,56.70,57.65	61.34,67.95,68.89,69.84	5.66	6.61
38	III–IV	2.45	51.46	9.06	60.18	4.50	51.98,57.18,57.65,58.59	60.39,66.06,66.06,67.95	5.20	5.67
39	IV	2.32	46.69–	11.89–	53.87–	5.95–	50.09,57.18,56.70,57.65	58.5,66.53,67.00,64.17	7.09	8.03
40	IV	2.37	48.48	13.69	57.01	6.94	50.09,57.65,58.59,58.59	54.72,62.47,63.23,63.23	7.56	7.75

Abbreviations:
WG: weathering grade; d_g: average grain size; R_{2-1}: difference between 2nd and 1st rebound values.

4.1. Predicting weathering grades

As indicated above, visually assigned weathering grades were adjusted/confirmed by careful petrographical examinations. For each group of specimens representing one of the identified weathering grades, the ranges of means and variances of the single impact rebound values obtained by both L and N hammers were listed in Table 3, which reveal considerable overlaps (particularly of the ranges) at the grade boundaries. As suggested earlier, the rate of increase in rebound values during a few multiple impacts at the

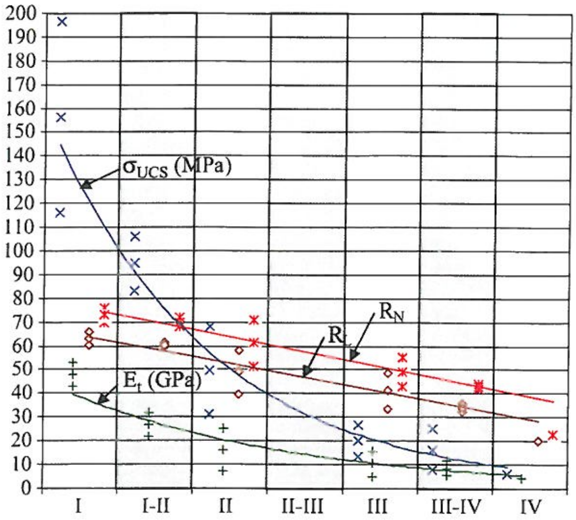


Fig. 4. Rate of change in uniaxial compressive strength, Young's modulus and rebound value with changes in weathering grades.

same point may be a good indicator of the weathering grade. To investigate this possibility, the points at which single impact rebound values were within ±2 of the mean value (of a given specimen by a particular hammer) were chosen as multiple impact sites. Rebound values from a total of three consecutive impacts were shown in Table 3 together with the first single impact rebound value. In general, the second impacts produced the strongest increases, while the subsequent impacts only produced minor increases (and occasionally minor decreases indicating collapse or cracking beyond the original zone of compaction) (Table 3). The magnitudes of these changes plotted against the weathering grades for both hammer types (Fig. 5) revealed a much clearer indication of weathering grades with overlaps only between Grades III and III–IV (except for specimen nos. 37–40).

4.2. Influence of grain size

The average grain size of each specimen was determined with the help of the image analysis software analySIS© in order to investigate the influence of grain size on rebound values (Table 3). Although specimens Nos. 37–40 were compositionally similar to the others, they were much finer grained and displayed higher mean rebound values, lower scatter and smaller increases in R due to multiple impacts than their coarser grained equivalents. Specimens (of a given rock type) with significant grain size differences should therefore be evaluated separately, particularly when the data is to be used for identification of weathering grades.

4.3. Modification of Schmidt hammer

In finer grained rocks, the plunger tip interacts with more grains, and minimizes the influence of grain strength heterogeneity relative to the scale of probing area/volume (evident from lower variance in rebound values of specimens nos. 37–40, Table 3). This implies that a slight increase in the impact energy and the plunger tip diameter (keeping the impact force per unit area the same as for a standard N hammer) may further reduce the scatter in the rebound values in coarse-grained rocks.

5. Conclusions

Various aspects of Schmidt hammer testing and analysis procedures continue to influence its consistency and reliability as an index tool in rock material characterization, including prediction of UCS, E_t and quantitative classification of weathering grades. These issues, namely selection of hammer type, normalization of rebound values, specimen dimension, surface

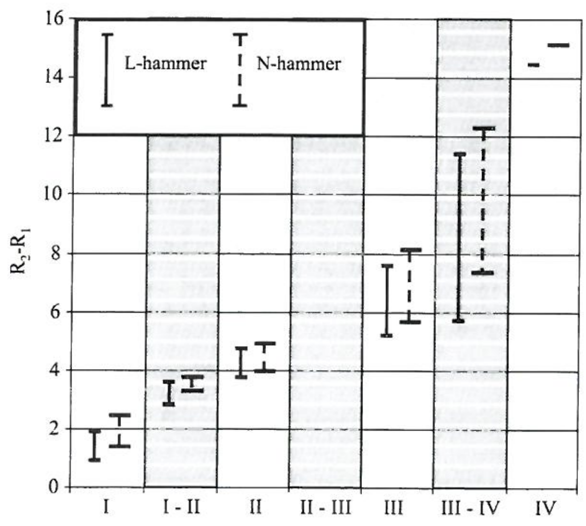


Fig. 5. Variations in rebound value differences during the first two subsequent impacts with weathering grades.

smoothness, weathering and moisture content, and testing, data reduction and analysis procedures, were critically reviewed. The main points are highlighted below:

a) rebound value is a measure of the resistance of a surface to impact penetration of a plunger tip (of a given shape and diameter);
b) the appropriate hammer type and corresponding UCS range are probably dictated by the lithological (or more precisely microstructural) characteristics that control the extent of impact damage, and thus the magnitude and rate of change of rebound values;
c) larger than NX cores should always be preferred to avoid a significant dissipation of impact energy at the interface between rock specimens and a heavy steel base;
d) although the standards stipulate the use of only the higher range of rebound values, it is important to understand the source of variations, and not to discard any reading unless there are visible cracks and/or chips on/around the corresponding impact point;
e) the peak rebound value of repeated impacts at a point represents an altered state of rock material surface, and leads to erroneous prediction of UCS and E_t;
f) rebound value variations during a few repeated impacts may be used as an index of weathering grade or structural integrity of rock materials in general;
g) investigations to establish relationships between rebound value and mechanical properties should use different specimens to avoid possibility of hammering-induced microcracks and should ensure the microstructural equivalence of the specimen pairs by careful microscopic examination; and
h) the use of additional variables (e.g., density, porosity, ultrasonic velocity) should be avoided in establishing empirical relationships for practical use, unless their roles are complementary and significant and can be clearly explained.

In this study, both N and L hammers were used in order to evaluate their relative efficiencies in characterizing granitic rocks of various weathering grades (Grade I to IV) from Hong Kong. The use of large diameter cores (mostly 84 mm), a heavy (40 kg) and thick (10.3 cm) steel slab as a base and a specially fabricated guide tube should have minimized errors and variability in rebound values. It was found that a very good correlation exists between the L and N hammers, and that both hammers could be used effectively, although the L hammer showed a higher sensitivity to rock heterogeneity with a larger scatter in the data. Both hammers were fairly sensitive to the physical properties, particularly to ρ_{dry} though less so to n_e and n_t. The rebound values of both hammers strongly correlated with the UCS and E_t values, while the N hammer performed better, suggesting that higher impact energy helps predict intact rock behavior more reliably.

The exponential form of R vs. UCS and E_t correlation curves is a natural consequence of microstructural changes during the course of weathering of granitic rocks and the differences in the probing scales or mechanisms of a) deformation (E_t) and failure (UCS) of the whole specimen under uniaxial loading and b) penetration of a small diameter plunger and compaction by the relatively small impact of a Schmidt hammer. Assuming similar style and sequence of microstructural changes in igneous crystalline rocks, UCS and E_t of such rocks at any degree of weathering (Grade I to IV) can be predicted from one of the following pairs of generalized expressions:

$$\sigma_{UCS} = a^* e^{(b^* R)} \quad \& \quad E_t = c^* e^{(d^* R)}$$

$$\sigma_{UCS} = a^* R^b \quad \& \quad E_t = c^* R^d$$

where a, b, c and d are positive constants based on the rock type.

An investigation was also conducted to explore the possibility of predicting weathering grades from rebound values. It was observed that changes in the rebound values during a few multiple impacts at a given point produced a better indication of the weathering grade than a single impact value. The magnitude of drop in rebound values during the first two impacts plotted against the weathering grades revealed a much clearer indication of weathering grades with overlaps only between Grades III and III–IV. This approach may however need some modifications when adapted to other rocks types.

Grain size plays an important role in the magnitude and scatter of rebound values. Therefore, specimens of the same rock type and significantly different grain sizes should be evaluated separately, particularly when relating the rebound values with weathering grades. The finer the grain size, the smaller the scatter in the data. This implies that a slight increase in impact energy and plunger diameter (keeping the impact force per unit area same as for N hammer) may further reduce the scatter in the rebound values and improve the reliability of Schmidt hammer applications in rock characterization.

Acknowledgements

The work was financially supported by the Research and Conference Grants Committee of The University of Hong Kong. The authors gratefully acknowledge the technical assistance provided by Mr Alan Kwok of the Department of Earth Sciences.

References

Amaral, P.M., Rosa, L.G., Fernandes, J.C., 1999. Determination of Schmidt rebound hardness consistency in granite. Int. J. Rock Mech. Min. Sci. 36, 833–837.

ASTM, 2001. Standard test method for determination of rock hardness by rebound hammer method. ASTM Stand. 04.09 (D 5873-00).

Aufmuth, R.E., 1973. A systematic determination of engineering criteria for rocks. Bull. Assoc. Eng. Geol. 11, 235–245.

Ayday, C., Goktan, R.M., 1992. Correlations between L and N-type Schmidt hammer rebound values obtained during field testing. Eurock '92. Thomas Telford, London, pp. 47–50.

Aydin, A., Duzgoren-Aydin, N.S., 2002. Indices for scaling and predicting weathering-induced changes in rock properties. Environ. Eng. Geosci. VIII, 121–135.

Ballantyne, C.K., Black, N.M., Finlay, D.P., 1990. Use of the Schmidt test hammer to detect enhanced boulder weathering under late-lying snowpatches. Earth Surf. Processes Landf. 15, 471–474.

Barton, N., Choubey, V., 1977. The shear strength of rock joints in theory and practice. Rock Mech. 10, 1–54.

Basu, A., Aydin, A., 2004. A method for normalization of Schmidt hammer rebound values. Int. J. Rock Mech. Min. Sci. 41, 1211–1214.

Cargill, J.S., Shakoor, A., 1990. Evaluation of empirical methods for measuring the uniaxial compressive strength. Int. J. Rock Mech. Min. Sci. 27, 495–503.

Day, M.J., Goudie, A.S., 1977. Field assessment of rock hardness using the Schmidt test hammer. Br. Geomorphol. Res. Group Tech. Bull. 18, 19–29.

Dearman, W.R., Irfan, T.Y., 1978. Assessment of the degree of weathering in granite using petrographic and physical index tests. Proc. Int. Symp. on Deterioration and Protection of Stone Monuments. Unesco, Paris, pp. 1–35. Paper 2.3.

Deere, D.U., Miller, R.P., 1966. Engineering classification and index properties for intact rocks. Tech Report. Air Force Weapons Lab., New Mexico, No. AFNL-TR, pp. 65-116. Kirtland.

Ghose, A.K., Chakraborti, S., 1986. Empirical strength indices of Indian coals—an investigation. Proc. 27th US Symp. on Rock Mech. Balkema, Rotterdam, pp. 59–61.

Haramy, K.Y., DeMarco, M.J., 1985. Use of Schmidt hammer for rock and coal testing. Proc. 26th US Symp. on Rock Mech. 26–28 June, Rapid City. Balkema, Rotterdam, pp. 549–555.

Hencher, S.R., Martin, R.P., 1982. The description and classification of weathered rocks in Hong Kong for engineering purposes. Proc. 7th Southeast Asian Geotechnical Conference, Hong Kong, pp. 125–142.

Hucka, V.A., 1965. A rapid method for determining the strength of rocks in situ. Int. J. Rock Mech. Min. Sci., Geomech. Abstr. 2, 127–134.

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

ISRM, 1978b. Suggested methods for the quantitative description of discontinuities in rock masses. Int. J. Rock Mech. Min. Sci., Geomech. Abstr. 15, 319–368.

Kahraman, S., 2001. Evaluation of simple methods for assessing the uniaxial compressive strength of rock. Int. J. Rock Mech. Min. Sci. 38, 981–994.

Karpuz, C., Pasamehmetoglu, A.G., 1997. Field characterization of weathered Ankara andesites. Eng. Geol. 46, 1–17.

Katz, O., Reches, Z., Roegiers, J.-C., 2000. Evaluation of mechanical rock properties using a Schmidt Hammer. Int. J. Rock Mech. Min. Sci. 37, 723–728.

Kidybinski, A., 1980. Method of investigation, estimation and classification of roofs in the USA for the selection of suitable mechanized support for long walls. Project No. 14-01-0001-1450. Central Mining Institute, Katowice, Poland. 25 pp.

Kolaiti, E., Papadopoulos, Z., 1993. Evaluation of Schmidt rebound hammer testing: a critical approach. Bull. Int. Assoc. Eng. Geol. 48, 69–76.

Li, X., Rupert, G., Summers, D.A., Santi, P., Liu, D., 2000. Analysis of impact hammer rebound to estimate rock drillability. Rock Mech. Rock Eng. 33, 1–13.

O' Rourke, J.E., 1989. Rock index properties for geoengineering in underground development. Min. Eng., 106–110.

Poole, R.W., Farmer, I.W., 1980. Consistency and repeatability of Schmidt hammer rebound data during field testing. Int J. Rock Mech. Min. Sci., Geomech. Abstr. 17, 167–171.

Sachpazis, C.I., 1990. Correlating Schmidt hardness with compressive strength and Young's modulus of carbonate rocks. Bull. Int. Assoc. Eng. Geol. 42, 75–83.

Saito, T., 1981. Variation of physical properties of igneous rocks in weathering. Proc. Int. Symp. on Weak Rock, Tokyo, pp. 191–196.

Shorey, P.R., Barat, D., Das, M.N., Mukherjee, K.P., 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.

Singh, R.N., Hassani, F.P., Elkington, P.A. S., 1983. The application of strength and deformation index testing to the stability assessment of coal measures excavations. Proc. 24th US Symp. On Rock Mech. Texas A and M Univ. AEG, Balkema, Rotterdam, pp. 599–609.

Sumner, P., Nel, W., 2002. The effect of rock moisture on Schmidt hammer rebound: tests on rock samples from Marion Island and South Africa. Earth Surf. Processes Landf. 27, 1137–1142.

Tugrul, A., Zarif, I.H., 1999. Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey. Eng. Geol. 51, 303–317.

Williams, R.B.G., Robinson, D.A., 1983. The effect of surface texture on the determination of the surface hardness of rock using the Schmidt hammer. Earth Surf. Processes Landf. 8, 289–292.

Xu, S., Grasso, P., Mahtab, A., 1990. Use of Schmidt hammer for estimating mechanical properties of weak rock. Proc. 6th International IAEG Congress, vol. 1. Balkema, Rotterdam, pp. 511–519.

Yasar, E., Erdogan, Y., 2004. Estimation of rock physiomechanical properties using hardness methods. Eng. Geol. 71, 281–288.

Yilmaz, I., Sendir, H., 2002. Correlation of Schmidt hardness with unconfined compressive strength and Young's modulus in gypsum from Sivas (Turkey). Eng. Geol. 66, 211–219.