Rock Mech Rock Eng (2009) 42:931–938
DOI 10.1007/s00603-008-0001-5

TECHNICAL NOTE

A Comparison of Different Indirect Techniques to Evaluate Volcanic Intact Rock Strength

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Received: 7 May 2007 / Accepted: 25 March 2008 / Published online: 2 July 2008

1 Introduction

Quantifying the strength of volcanic rocks in remote areas of difficult access is a challenging task. Volcanic areas generally present an outstanding variety of rock types, in a relatively random pattern, ranging from very strong, coherent, welded rocks to weak, interlocked vesicular pyroclastic units. The strength of volcanic rock masses can be approached, in a way similar to other materials, as a combination of the study of the strength of the rock matrix and the structure and quality of the rock mass.

The difficulty in assessing volcanic rocks in remote areas lies in the relative inaccessibility of many outcrops, which prevents traditional geotechnical sampling and testing campaigns being used, or borehole investigations being carried out. Also, due to their genesis, many volcanic rocks contain rock type-unit-specific fractures and rock mass structures which differ from most other rock types. This can make it difficult to decide on the criteria which ensure that the samples tested are representative of the intact rock. To overcome this problem, the intact rock or rock matrix is defined here following Hoek and Brown's (1997) observation that there is a "critical sample size" below which the strength is constant. To avoid biasses in problematic volcanic rocks, only samples below the critical sample size, but large enough to be tested, have been considered to be representative of the rock matrix.

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The small number of published intact rock strength measurements of volcanic rocks are generally from strong, coherent materials and, therefore, only give an upper limit for rock strength (e.g. Schultz 1995). Altered or vesicular rocks, or rock units comprising aggregates of small fragments, which compose a significant volume of most volcanic edifices, have rarely been tested, as there is a lack of guidance on the procedures to be followed.

The general objective of this technical note is to compare and assess different viable direct and indirect methods for obtaining intact rock strength parameters in remote volcanic areas. In particular we compare the efficiency of different Schmidt hammers, and the trends of unit weight with strength values from Schmidt hammers, point load tests and uniaxial compression tests.

All samples and tests have been carried out on the sub-aerial post-shield volcanic materials of the central area of the island of Tenerife, in the North Atlantic Ocean. Volcanic activity in this area has been characterised by the cyclic building of silica-under-saturated, evolved edifices, all of which ended in caldera-forming eruptions.

2 Methods for Quantifying Intact Rock Strength Parameters

Ideally, the matrix of volcanic rocks should be tested in uniaxial compression under laboratory conditions in which the axial strain, strain rate and load can be controlled and measured, and uniaxial compressive strength (σ_{ci}), Young's modulus and Poisson's ratio can be calculated directly. However, several cores are needed to carry out this test and extracting and carrying such samples from remote areas across volcanic terrain can be very difficult. In addition, the fragmented nature of some volcanic rocks does not allow this. For these reasons, only a small number of uniaxial compression tests were performed and alternative indirect testing methods had to adopted; the Schmidt hammer and the point load test.

2.1 The Schmidt Hammer

The Schmidt hammer is a light hand-held device which consists of a spring-loaded mass inside a piston that is released when the hammer is pressed orthogonally onto a surface. The rebound height of the mass (R) is recorded on a linear scale and gives an indication of the strength of the material being tested. There are two types of Schmidt hammers (L- and N-type), with different impact energies (0.735 and 2.207 Nm, respectively). The results of the tests are given as the rebound height R_L and R_N for the L- and N-type Schmidt hammers, respectively. There are no clear guidelines on the choice of hammer type. The International Society for Rock Mechanics (ISRM; 1987) only endorses the L-type Schmidt hammer, while the American Society for Testing and Materials (ASTM; 2001) does not specify the type used. Aydin and Basu (2005) suggest that both hammers should give the same values and that the N-type should give less scattered results. Although the Schmidt hammer was initially designed to test concrete (Schmidt 1951), it is widely used on natural rock.

The aim of the present work with the Schmidt hammer is to determine whether it is valid to use the results from Schmidt hammer tests to estimate the uniaxial compressive strength of volcanic rocks and to determine whether either, or possibly both, hammers can be used for such materials. Thirty-four locations were visited and the rock matrices of fresh and altered lavas, welded pyroclastics and autoclastic breccias were tested with both Schmidt hammers, with 20 readings recorded for each material at each location. Testing was performed in situ following the ISRM (1987) and ASTM (2001). Care was taken to ensure that the material tested was well-cemented and "elastic" and that its surfaces were relatively smooth in relation to the size of the impact plunger (~20-mm diameter). Tests were performed away from discontinuities following guidance from Day and Goudie (1997) to avoid the dissipation of energy, and values obtained from tests carried out at oblique angles to the horizontal were corrected following the findings of Basu and Aydin (2004).

Previous workers report that Schmidt hammer rebound values can be correlated with uniaxial compressive strength and Young's modulus following an extensive number of published empirical correlations which range from simple linear (e.g. Dinçer et al. 2004) to complex non-linear relationships (e.g. Kahraman 2001). Some of these studies consider unit weight in the calculation (e.g. Deere and Miller 1966) and some do not (e.g. Xu et al. 1990). Dinçer et al. (2004), Kahraman (2001) and Fener et al. (2005) provide comprehensive lists of those correlations.

2.2 The Point Load Test

The point load test provides strength measurements of irregular fragments of rocks or of rock cores, with all rock dimensions being greater than 50 mm. This test is performed on samples extracted from their natural emplacement, and can be either carried out in the laboratory or in the field. For the test, the sample is placed between two conical platens which move towards each other on application of a hydraulic pressure. A steadily increasing load is applied to the sample, which fails by the development of tensile cracks parallel to the axis of loading. Pressure values at failure are then normalised to a standard 50 mm core size and, from this, strength values are given in terms of the point load index ($I_{s(50)}$).

One hundred and fifteen samples of scoria and 37 of autoclastic breccia clasts (taken to be representative of the rock matrix) were tested in point load tests following the ISRM (1981) and ASTM (2000). As with the Schmidt hammer, there are a number of published empirical correlations between point load index and both uniaxial compressive strength and tensile strength of the material. These correlations are mostly linear and range from a factor of 16 to a factor of 24 for uniaxial compressive strength (e.g. D'Andrea et al. 1964; Broch and Franklin 1972; Read et al. 1980; ISRM 1985) and 1.25 and 3.43 for tensile strength (e.g. ISRM 1985; Mesquita Soares et al. 2002). Kahraman (2001) gives a comprehensive list of the correlations.

3 Evaluation of the Methodology

Schmidt hammer rebound values from 34 different locations and from five different geotechnical units (fresh lavas, altered lavas, fresh welded pyroclastics, autoclastic breccias and calibration anvil) have been collected. An error analysis for both

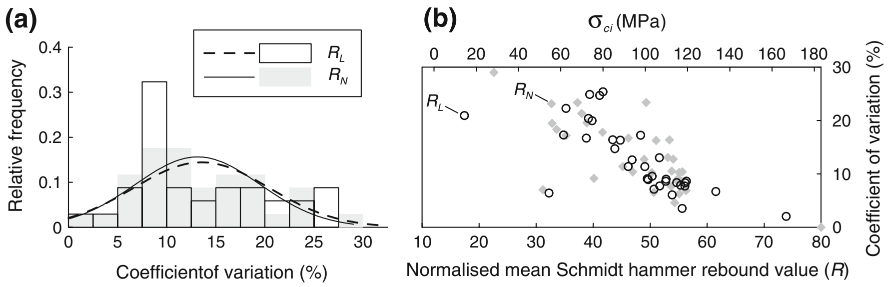

Fig. 1 Comparison of the standard error from both Schmidt hammers' rebound values from Tenerife. **a** Very similar distribution of the normalised error for both hammers. **b** The error in both cases decreases for increasing strength values and more precise results are given by the L-type Schmidt hammer (R_L) for the stronger materials in the range tested than the N-type Schmidt hammer (R_N). Uniaxial compressive strength values (σ_{ci}) calculated following Dinçer et al. (2004)

Schmidt hammer tests shows they both have very similar coefficient of variation distributions (Fig. 1a) and that, in both cases, the errors decrease linearly for increasingly stronger rocks (Fig. 1b).

Only 20 measurements were recorded per sample, and, statistically, this is not very significant. However, further analysis shows that the difference between the arithmetic and geometric means at each location (0.45 and 0.4 for R_N and R_L, respectively) are more than an order of magnitude smaller than the mean standard deviations (5.8 and 5.2, respectively). In other words, the uncertainty associated with Schmidt hammer values, and the relatively small number of measurements carried out, could mask possible skewness in the distribution of the results.

Standard normality tests (Kolmogorov–Smirnov) show that the measured values for each locality are normally distributed. Both Schmidt hammers give less scattered results for stronger materials, with R_L giving slightly better results for materials with high uniaxial compressive strength ($\sigma_{ci} > 90$ MPa) (Fig. 1b). It has been noted that the N-type Schmidt hammer underestimated the uniaxial compressive strength of weak rocks ($\sigma_{ci} < 20$ MPa), as it crushed discrete grains and caused cracking of the sample. A similar outcome was reached by Sheorey et al. (1984).

The rebound values given by both Schmidt hammers for the same material at 34 locations give the following correlation:

$$R_N = 1.0642R_L + 2.5687 \quad R^2 = 0.85$$

which agrees with that proposed by Aydin and Basu (2005) (Fig. 2). The higher correlation of 0.99 achieved by Aydin and Basu (2005) is attributed to the reduction in surface roughness by mechanically polishing their samples prior to testing.

The R_N values provide a good linear correlation between unit weight of the material (γ, in kN/m^3) and rebound value (Fig. 3a), given by:

$$R_N = 2.64\gamma - 16.33 \quad R^2 = 0.98$$

The R_L values, on the other hand, are less sensitive to variations in unit weight ($R^2 = 0.85$) (Fig. 3a).

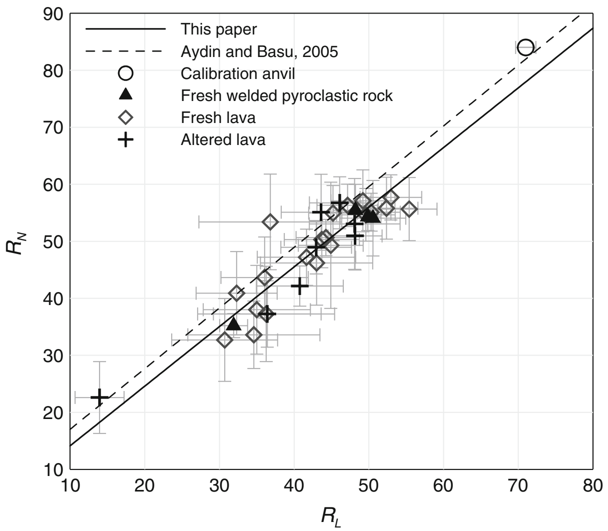

Fig. 2 Linear relationship between N-type (R_N) and L-type (R_L) Schmidt hammer data from Tenerife compared to the correlation proposed by Aydin and Basu (2005)

Point load tests give a very broad scatter of results which, surprisingly, show no meaningful relation to unit weight (Fig. 3b). Even when the results are presented for discrete units (Fig. 4), the scatter and poor relation with unit weight are clear. Unit weight values are normally distributed for clasts of the same unit (Fig. 4a, b), but point load index values result in a highly skewed distribution, which suggests that most clasts are equally weak, with only a few samples, from a range of unit weights, showing significant strength.

Uniaxial compression test results show less scatter in the results and a clear logarithmic increase of uniaxial compressive strength with increasing unit weight (Fig. 3c), given by:

$$\sigma_{ci} = 0.626e^{0.178\gamma} \quad R^2 = 0.93$$

A final comparison of the three different methodologies (Table 1) suggests that, if only a few samples are used in uniaxial compression tests, Schmidt hammer measurements can give results which are twice as precise. It also shows that point load tests give the broadest scatter in values.

4 Conclusions

When used to test the intact rock strength of a wide range of volcanic rocks in situ, rebound values from the two Schmidt hammers (L- and N-type) show a good linear correlation between them. Error analyses show that, for both hammers, the errors are higher for weaker materials and that the R_L values tend to be slightly more precise than the R_N values for very weak ($\sigma_{ci} < 20$ MPa) and for relatively strong to very strong rocks ($\sigma_{ci} > 90$ MPa). Strength values from point load tests on vesicular

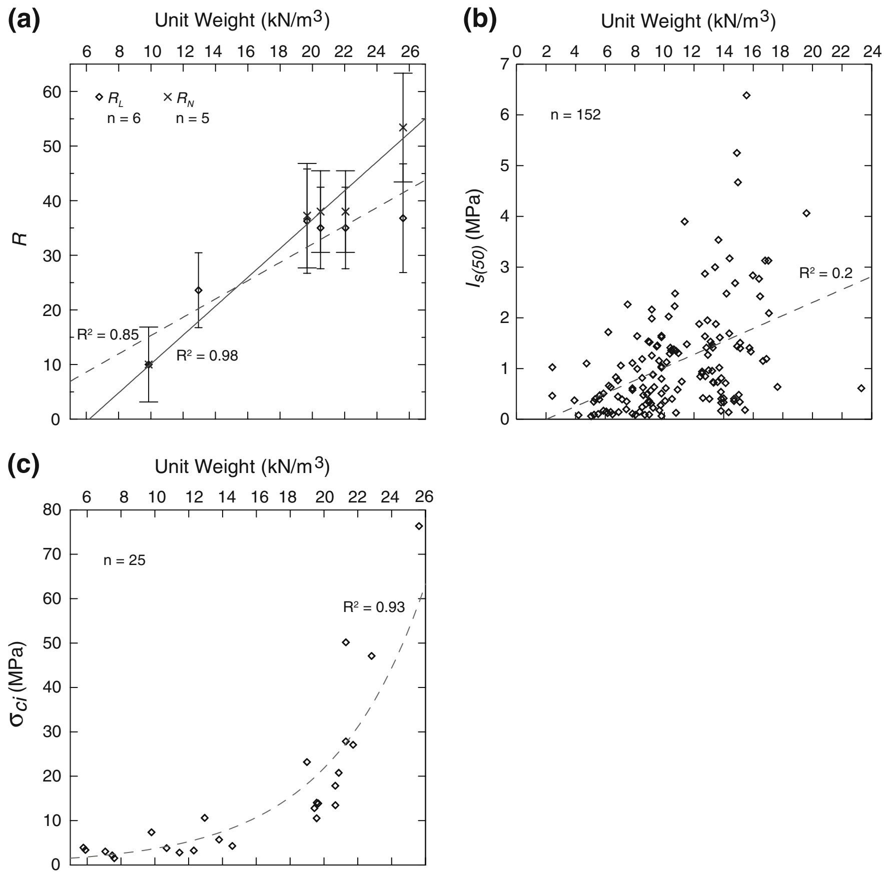

Fig. 3 Strength value variations with unit weight for three different methods. **a** Schmidt hammer rebound correlations (R) show that L-type values (R_L) are more sensitive to variations in material density than N-type values (R_N). **b** Point load index values ($I_{s(50)}$) show no significant trend with increasing unit weight. On the other hand, **c** uniaxial compressive test values show a good logarithmic trend

volcanic rocks show great scatter and fail to give a relation with unit weight. Uniaxial compression test results show little scatter and a good logarithmic relation with unit weight.

Results from this study show that, if only few samples can be tested, Schmidt hammers can give results similar in quality to uniaxial compression tests. However, care must be taken when comparing uniaxial compression strength values obtained from different indirect techniques, as these values are heavily dependent upon the correlation factors chosen.

Schmidt hammers are light to carry and multiple tests can be quickly performed on the same material. This, coupled with the acceptable precision ranges achieved, makes them a very useful tool for obtaining estimates of uniaxial compressive strength of rocks in remote areas. However, the good quality of the results obtained

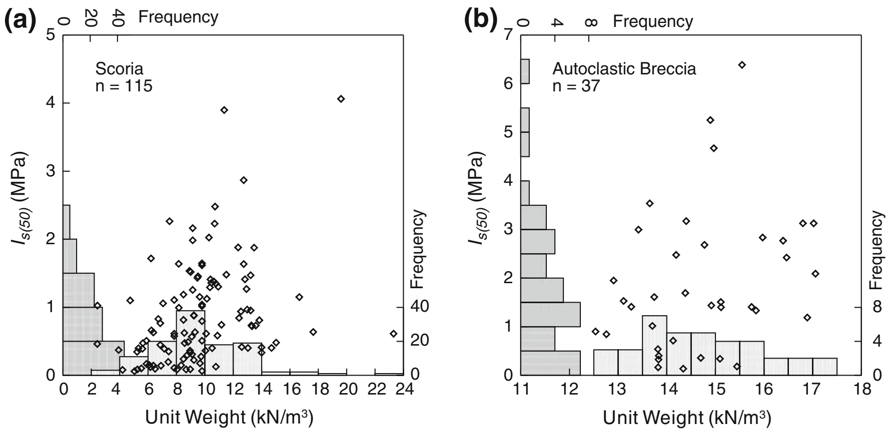

Fig. 4 Relationship between point load index values ($I_{s(50)}$) and unit weight for **a** scoria and **b** autoclastic breccia units. Each graph shows the numerical value in each case, as well as the frequency distribution

Table 1 Comparison of the coefficient of variation given by the different methodologies for one unit of autoclastic breccias

Method	Samples	σ_{ci} geometric mean	σ_{ci} 95% confidence limits	Coefficient of variation (%)
SH (R_L)	6	29.9[a]	21.2–42.3[a]	10.2
PLT	37	28.8[b]	10.8–76.8[b]	29.2
UCS	2	16.9	8.7–32.9	23.6

SH (R_L) = L-type Schmidt hammer; PLT = point load test; UCS = uniaxial compressive test

[a] Values correlated following Dinçer et al. (2004)

[b] Values correlated following the ISRM (1981)

suggests that they could also be used for preliminary assessment in other, more accessible environments.

Acknowledgements This research was partly supported by Cartográfica de Canarias S.A. (GRAFCAN). Helpful comments from Harry Pinkerton greatly improved an earlier version of the manuscript. Luís Hernández and the Regional Ministry of Works of the Government of the Canary Islands are gratefully acknowledged for facilitating laboratory and field equipment in Tenerife.

References

American Society for Testing and Materials (ASTM) (2000) Standard test method for determination of the point load strength index of rock. ASTM 04.08 (D5731-02)

American Society for Testing and Materials (ASTM) (2001) Standard test method for determination of rock hardness by rebound hammer method. ASTM 04.09 (D5873-00)

Aydin A, Basu A (2005) The Schmidt hammer in rock material characterization. Eng Geol 81(1):1–14

Basu A, Aydin A (2004) A method for normalization of Schmidt hammer rebound values. Int J Rock Mech Min Sci 41(7):1211–1214

Broch E, Franklin JA (1972) The point load strength test. Int J Rock Mech Min Sci 9(6):669–697

D'Andrea DV, Fisher RL, Fogelson DE (1964) Prediction of compression strength from other rock properties. Colo Sch Mines Q 59(4B):623–640

Day MJ, Goudie AS (1997) Field assessment of rock hardness using the Schmidt Test Hammer. Br Geomorphol Res Group Tech Bull 18:19–29

Deere DU, Miller RP (1966) Engineering classification and index properties for intact rock. Air Force Weapons Laboratory, technical report no. AFWL-TR 65-116, Kirtland Base, New Mexico

Dinçer I, Acar A, Çobanoğlu I, Uras Y (2004) Correlation between Schmidt hardness, uniaxial compressive strength and Young's modulus for andesites, basalts and tuffs. Bull Eng Geol Environ 63(2):141–148

Fener M, Kahraman S, Bilgil A, Gunaydin O (2005) A comparative evaluation of indirect methods to estimate the compressive strength of rocks. Rock Mech Rock Eng 38(4):329–343

Hoek E, Brown ET (1997) Practical estimates of rock mass strength. Int J Rock Mech Min Sci 34(8):1165–1186

International Society for Rock Mechanics (ISRM) (1981) Rock characterization, testing and monitoring. ISRM suggested methods. Pergamon Press, New York

International Society for Rock Mechanics (ISRM) (1985) Suggested method for determining point-load strength. Int J Rock Mech Min Sci 22:53–60

International Society for Rock Mechanics (ISRM) (1987) Suggested methods for determining hardness and abrasiveness of rocks. Int J Rock Mech Min Sci Geomech Abstr 15:89–97

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

Mesquita Soares S, Dinis de Gama C, Reis e Sousa M (2002) Geomechanical properties of basalts from the volcanic complex of Lisbon—some interesting correlations. In: Dinis da Gama C, Ribeiro e Sousa L (eds) Proceedings of the Workshop on Volcanic Rocks, ISRM International Symposium on Rock Engineering for Mountainous Regions, Eurock 2002, Funchal, Madeira, November 2002, pp 73–80

Read JRL, Thornten PN, Regan WM (1980) A rational approach to the point load test. In: Proceedings of the 3rd Australian-New Zealand Geomechanics Conference, Wellington, New Zealand, pp 2-35–2-39

Schmidt E (1951) A non-destructive concrete tester. Concrete 59(8):34–35

Schultz RA (1995) Limits on strength and deformation properties of jointed basaltic rock masses. Rock Mech Rock Eng 28(1):1–15

Sheorey PR, Barat D, Das MN, Mukherjee KP, Singh B (1984) Schmidt hammer rebound data for estimation of large-scale in situ coal strength. Int J Rock Mech Min Sci 21(1):39–42

Xu S, Grasso P, Mahtab A (1990) Use of Schmidt hammer for estimating mechanical properties of weak rock. In: Price DG (ed) Proceedings of the 6th International Congress of the International Association Engineering Geology (IAEG), Balkema, Rotterdam, The Netherlands, August 1990, pp 511–519