Int J Earth Sci (Geol Rundsch) (2011) 100:189–195
DOI 10.1007/s00531-009-0506-5

ORIGINAL PAPER

A correlation between Schmidt hammer rebound numbers with impact strength index, slake durability index and P-wave velocity

P. K. Sharma · Manoj Khandelwal · T. N. Singh

Received: 14 September 2009 / Accepted: 12 December 2009 / Published online: 19 January 2010
© Springer-Verlag 2010

Abstract The main objective of this study was to establish statistical relationship between Schmidt hammer rebound numbers with impact strength index (ISI), slake durability index (SDI) and P-wave velocity. These are important properties to characterize a rock mass and are being widely used in geological and geotechnical engineering. Due to its importance, Schmidt hammer rebound number is considered as one of the most important property for the determination of other properties, like ISI, SDI and P-wave velocity. Determination of these properties in the laboratory is time consuming and tedious as well as requiring expertise, whereas Schmidt hammer rebound number can be easily obtained on site which in addition is non-destructive. So, in this study, an attempt has been made to determine these index properties in the laboratory and each index property was correlated with Schmidt hammer rebound values. Empirical equations have been developed to predict ISI, SDI and P-wave velocity using rebound values. It was found that Schmidt hammer rebound number shows linear relation with ISI and SDI, whereas exponential relation with P-wave velocity. To check the sensitivity of empirical relations, Student's *t* test was done to verify the correlation between rebound values and other rock index properties.

Keywords Schmidt hammer rebound number · Impact strength index · Slake durability index · P-wave velocity · *t* test

P. K. Sharma · T. N. Singh
Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

M. Khandelwal (✉)
Department of Mining Engineering, College of Technology and Engineering, Maharana Pratap University of Agriculture and Technology, Udaipur 313001, India
e-mail: mkhandelwal1@gmail.com

Present Address:
P. K. Sharma
Geological Survey of India, Jaipur 302004, India

Introduction

The Schmidt hammer test method is today routinely used to estimate the strength and the quality of rock. The Schmidt hammer provides a quick and inexpensive measure of surface hardness which is widely used for estimating the mechanical properties of rock material (Kahraman 2001). Such fast, non-destructive and in situ evaluations of rock mechanical parameters reduce the time and expenses for sample collection vis-à-vis tedious and time-consuming laboratory testing.

The Schmidt hammer was developed for non-destructive testing of concrete hardness (Schmidt 1951), and later used to estimate rock strength (Cargill and Shakoor 1990). It has a spring-loaded mass that is released against a plunger when the hammer is pressed onto a fresh rock surface. The plunger impacts the surface and the mass recoils; the rebound value of the mass is measured by a sliding pointer that indicates the rebound of the hammer on a graduated scale. The principle of the test is based on the absorption of part of the spring-released energy through plastic deformation of the rock surface, while the remaining elastic energy causes the actual rebound of the hammer. The distance traveled by the mass, expressed as a percentage of the initial extension of the spring, is called the rebound number (Kolaiti and Papadopoulus 1993). Such fast, non-destructive and in situ evaluations of rock mechanical properties reduce the time and expenses for sample collection and laboratory testing.

Durability is an important engineering parameter for all the litho-types pertaining to the weak rock group. But as mentioned by Franklin and Chandra (1972), the term durability may be used in a rock engineering context to mean resistance to weakening and disintegration resulting from a standard cycle of drying and wetting.

Durability is an important rock characteristic controlling the stability of surface and underground excavations as well as the evolution and stability of both artificial and natural slopes. Also, in tunnels and caverns, and slopes, the presence of slaking or swelling rock must be anticipated to reduce the failure and mud flow specially in the seismically active regions, where rock mass have swelling and squeezing characteristics. It may also cause surface sloughing and gradual retreat of the face to slope failures resulting from the loss of strength with time. A simple index test of tendency of rock to weather and degrade is the slake durability test (ISRM 1981).

The slake durability index (SDI) test is a measure of the resistance of a rock sample to weakening and disintegration resulting from a standard cycle of drying and wetting (Franklin and Chandra 1972). Weathering can induce a rapid change of rock material and its response from initial rock like properties to soil like properties. The sensitivity of a rock type and the rate of occurrence of such a change are often described through a durability parameter.

Impact strength index (ISI) is useful tool to extract information about crushing behavior of rock particularly when desired rock samples are not available for testing. It provides quickly strength properties of rock in the field as well as laboratory.

Ultrasonic P-wave velocity of a rock is useful to determine the elastic properties, and rock mechanical properties for reservoir subsidence and casing industries.

ISI, SDI and P-wave velocity are very crucial for any underground excavations, drilling, blasting, slope stability, embankments and many other civil and mining day-to-day operations (Sharma and Singh 2008). The strength properties always require careful test setup and specimen preparation and thus index tests are useful only if the properties are reproducible from laboratory to other properties and can be measured inexpensively. So, in this paper, an attempt has been made to obtain these properties from Schmidt hammer rebound number, which is a very simple and scientific test in actual field conditions as well as nondestructive.

Various researchers (Osborn 1959; Krishnamurthy and Udas 1981; McCarrol 1991; Sjoberg and Broadbent 1991) have correlated the Schmidt hammer rebound numbers with degree of weathering of rocks including igneous rocks like gabbro, granite.

Miller (1965) produced a general and crude correlation chart for Schmidt hammer, relating rock density, compressive strength and rebound number, applicable to all rock types. Deere and Miller (1966) suggested another correlation chart for Schmidt hammer, relating rock density, tangent modulus and rebound number. Ege et al. (1970) applied the rock test hammer technique in engineering geological field investigations to volcanic rocks. Aufmuth (1973) obtained high correlation coefficient between Schmidt hardness (*N*) with unconfined compressive strength (UCS) and Young's modulus with taking into the consideration of rock density, on the samples from different lithological units. Kidybinski (1980) suggested an empirical equation to calculate unconfined compressive strength from Schmidt number. The International Society for Rock Mechanics (ISRM 1981) suggests the use of the Schmidt hammer as a routine test apparatus for determining the discontinuity wall strength in rock masses. Singh et al. (1983), Shorey et al. (1984) and Haramy and De Marco (1985) obtained very strong correlation between unconfined compressive strength and Schmidt number for different lithological units. Ghose and Chakraborti (1986) proposed an empirical relation between UCS and *N* for Indian coal measure rocks. O'Rourke (1989) obtained correlation with regression coefficient of 0.60 from the samples of sandstone, siltstone, limestone and anhydrite.

The detailed petrographic study of various rock types used in present study has been dealt by Krishnamurthy and Udas (1981); Osborn (1959) and Singh et al. (2005). The rocks used in the present study and their mineralogical compositions are given in Table 1.

In these rocks feldspar minerals have been found altered to clay minerals like Kaolinite, Halloysite and Smectite as reported by Krishnamurthy and Udas (1981) and Osborn (1959). However, in sandstone clay minerals are present as matrix filling the pore spaces between the grains (Singh et al. 2005).

This study aims to express the relationships between Schmidt hammer rebound numbers with ISI, SDI and P-wave velocity of different rocks by empirical equations. Empirical expressions of these relationships will make it

Table 1 Rock types with their respective compositions

Rock type	Composition
Granite	Quartz + orthoclase + plagioclase + minor amount of hornblende
Basalt	Plagioclase in ground mass, phenocryst of ankaramite, augite
Andesite	Plagioclase + augite + olivine
Sandstone	Quartz + feldspar, small amount of micaceous minerals
Quartzite	Mainly quartz

possible to determine these properties by using the Schmidt hammer rebound number, which is used as an index for a quick strength characterization due to its rapidity and easiness in execution, portability and low cost. It is thus hoped that this paper will serve civil, geotechnical and rock engineers in making practical decisions at the stage of the preliminary site investigation works using the Schmidt hammer test.

Laboratory investigation

The aim is to find out the relation of Schmidt rebound number with ISI, SDI and P-wave velocity. To achieve this research goal, different rock types were collected from the different localities of India taking care of representation of variety of strength. Moreover, Schmidt hammer tests were performed on intact rock mass to find out the rebound numbers. Representative rock mass samples were also collected from the site to carry out other tests in the laboratory. During sample collection, each block was inspected for macroscopic defects so that it would provide test specimen free from fractures and joints. Tests were performed with an N-type hammer having impact energy of 2.207 Nm. All tests were performed with the hammer held vertically downwards and at right angles to the horizontal rock faces. To get Schmidt hammer rebound number, initially ten readings were taken and then the mean of five higher values were used for the analysis.

The impact strength test was first developed by Protodyakonov, and then it was used by Evans and Pomeroy (1966) for the classification of coal seams in the former USSR and UK. The test was then modified by Paone et al. (1969), Tandanand and Unger (1975) and Rabia and Brook (1980). Tandanand and Unger (1975) obtained simple relation between strength coefficient and compressive strength. Rabia and Brook (1980) used the modified test apparatus to determine the rock impact hardness number and developed an empirical equation for predicting drilling rates for both DTH and drifter drills. Hobbs (1964) applied this test to various rocks and established the following equation:

$$\mathrm{UCS} = 53 \times \mathrm{ISI} - 2509 \qquad (1)$$

where, UCS is the uniaxial compressive strength (kgf/cm^2) and ISI is the ISI.

To carry out this test, fragments of rocks were impacted 20 times by a 1.81 kg plunger falling from 12 in. height. The amount of fines below 1/8 in. is used as the strength index. The results of impact strength test of different rocks are given in Table 1.

The main purpose of 'slake durability test' is to evaluate the water resistance of rock samples. The slake durability of rocks is closely related to their mineralogical composition and its relation to water. This test measures the resistance of a rock sample to weakening and disintegration resulting from a standard cycle of drying and wetting. Test was carried out according to standards suggested by International Society for Rock Mechanics (ISRM 1979). A sample comprising nine rock lumps of a particular rock roughly spherical in shape, each weighing 50 ± 10 g for a total weight of 500 ± 50 g had been taken and placed in a perforated drum to dry until a constant weight was obtained in an oven at 105°C for 4–5 h. For the slake durability test, the drum was mounted on the trough and was coupled to the motor. The trough was then filled with water to a level of 20 mm below the drum axis and to maintain the temperature at 25°C. The drum had been rotated at 20 rpm for a period of 10 min and the drum was removed from the trough and placed in an oven and dried out at a temperature of 105°C for 4 h to drain out the remaining moisture in the samples. During the test, the finer products of slaking pass through the mesh and into the water bath. The slake durability index (SDI) is the percentage ratio of final to initial dry weights of rock in the drum (Singh et al. 2004).

$$\text{Slake durability index (SDI)} = (C - E)/(A - E) \times 100\%, \qquad (2)$$

where,

A Initial weight of sample + drum (kg)
C Weight of sample + drum after second cycle of rotation (kg), and
E Weight of empty drum.

For each rock, five test sets were carried out for two cycles and the average values are reported in Table 2.

The velocity of ultrasonic pulses traveling in a solid material depends on the density and elastic properties of that material. The quality of some materials is sometimes related to their elastic stiffness so that measurement of ultrasonic pulse velocity in such materials can often be used to indicate their quality as well as to determine elastic properties. To determine the P-wave velocity of different rocks, rock blocks were cored in laboratory for NX size core recovery. The instrument used in this study was portable ultrasonic non-destructive digital indicating tester (PUNDIT). The average results of P-wave velocity of different rocks are given in Table 2.

Results and discussions

In order to describe, the relationships between Schmidt hammer rebound number with ISI, SDI and P-wave velocity of the tested rocks, regression analysis was done. The equation of the best fit line and the coefficient of determination (R^2) were determined for each test results.

Table 2 Results of different rocks properties

Rock type	Rock class	P-wave velocity (m/s)	Impact strength index	Schmidt hammer rebound number	Slake durability index
Sandstone (highly weathered)-1	Sedimentary	2,129.1	79.1	28	96.28
Sandstone (highly weathered)-2	Sedimentary	2,132.7	80.8	27	97.22
Sandstone (highly weathered)-3	Sedimentary	2,134.4	81.2	27	96.11
Sandstone (highly weathered)-4	Sedimentary	2,135.2	81.8	28	96.44
Sandstone (highly weathered)-5	Sedimentary	2,152.7	82.6	29	96.23
Sandstone (highly weathered)-6	Sedimentary	2,153.2	82.8	29	96.12
Sandstone (highly weathered)-7	Sedimentary	2,156.3	83.1	29	96.23
Sandstone (highly weathered)-8	Sedimentary	2,120	80.1	30	97.35
Sandstone (highly weathered)-9	Sedimentary	2,053.5	82.4	27	97.33
Sandstone (moderately weathered)-1	Sedimentary	2,296.9	85.2	30	97.59
Sandstone (moderately weathered)-2	Sedimentary	2,282.2	84.2	31	97.54
Sandstone (moderately weathered)-3	Sedimentary	2,289.8	84.6	32	97.56
Sandstone (moderately weathered)-4	Sedimentary	2,288.7	83.5	31	97.52
Sandstone (moderately weathered)-5	Sedimentary	2,298.2	84.2	33	97.45
Sandstone (moderately weathered)-6	Sedimentary	2,310.3	84.6	34	97.51
Siltstone-1	Sedimentary	2,321.8	85.2	34	97.60
Siltstone-2	Sedimentary	2,278.8	83.8	33	97.51
Siltstone-3	Sedimentary	2,345.9	85.3	30	97.42
Siltstone-4	Sedimentary	2,190.2	82.2	32	97.56
Siltstone-5	Sedimentary	2,188.9	82.0	32	97.51
Siltstone-6	Sedimentary	2,180.3	85.1	33	97.44
Conglomerate-1	Sedimentary	2,218.2	84.1	36	97.23
Conglomerate-2	Sedimentary	2,183.4	85.9	34	97.03
Conglomerate-3	Sedimentary	2,142.8	84.9	31	97.56
Conglomerate-4	Sedimentary	2,240.1	86.4	34	97.65
Sandstone-1	Sedimentary	2,465.3	86.3	34	97.12
Sandstone-2	Sedimentary	2,212.1	84.9	37	97.42
Schist-1	Metamorphic	2,428.8	87.5	39	97.41
Schist-2	Metamorphic	2,517.6	90.5	41	97.36
Schist-3	Metamorphic	2,554.7	89.2	42	97.51
Quartzite-1	Metamorphic	3,798.07	93.5	56	98.36
Quartzite-2	Metamorphic	3,623.4	92.4	54	98.28
Quartzite-3	Metamorphic	3,562.8	93.5	53	98.19
Gneiss-1	Metamorphic	3,559.2	93.8	54	98.22
Gneiss-2	Metamorphic	3,595.05	94.1	53	98.25
Gneiss-3	Metamorphic	3,550	93.8	57	98.21
Gneiss-4	Metamorphic	3,594.4	92.1	55	98.17
Granite (coarse grained)-1	Igneous	4,964	98.9	62	98.35
Granite (coarse grained)-2	Igneous	4,970.2	98.2	61	98.36
Granite (coarse grained)-3	Igneous	4,976.8	98.1	62	98.39
Granite (medium grained)-1	Igneous	4,985.6	97.9	63	98.44
Granite (medium grained)-2	Igneous	4,992	98.1	63	98.51
Granite (medium grained)-3	Igneous	4,980.2	97.8	60	98.42
Basalt-1	Igneous	5,753	98.6	65	98.92
Basalt-2	Igneous	5,530.2	96.9	63	98.98
Basalt-3	Igneous	5,421.6	95.9	65	98.78
Andesite-1	Igneous	5,426.2	96.9	62	98.67
Andesite-2	Igneous	5,422.4	96.2	61	98.62

Table 2 continued

Rock type	Rock class	P-wave velocity (m/s)	Impact strength index	Schmidt hammer rebound number	Slake durability index
Andesite-3	Igneous	5,431.6	97.0	63	98.99
Andesite-4	Igneous	5,434.4	97.2	64	99.01
Andesite-5	Igneous	5,512.2	97.6	62	98.97

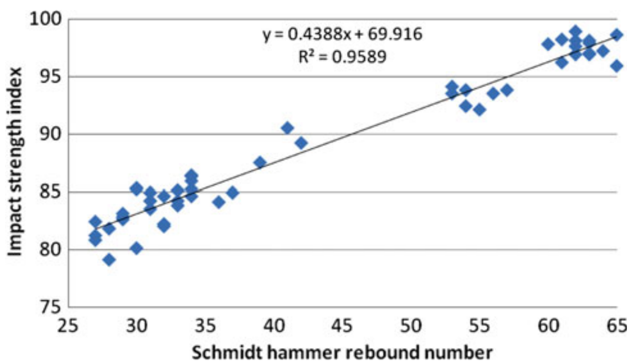

Fig. 1 Schmidt hammer rebound number versus impact strength index

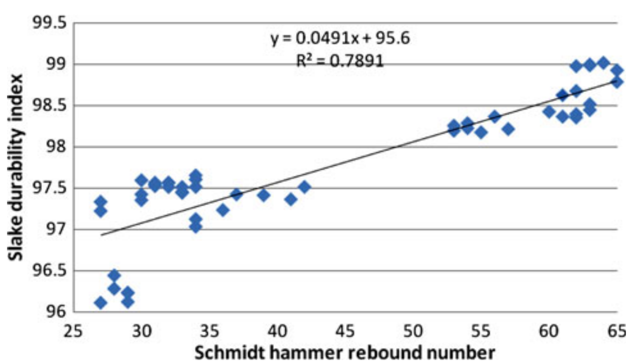

Fig. 2 Schmidt hammer rebound number versus slake durability index

The plot of the Schmidt hammer rebound number as a function of ISI is shown in Fig. 1. There is linear relation between Schmidt hammer rebound number and ISI for all rock types. A strong coefficient of determination ($R^2 = 0.9589$) was found between Schmidt hammer rebound number and the ISI for all rock types. The equation of this relation is as follows:

$$\mathrm{ISI} = 0.4388 \times \mathrm{RR} + 69.916, \quad (3)$$

where, RR and ISI are Schmidt hammers rebound number and ISI, respectively.

Similarly, linear relationship has also been observed between Schmidt hammer rebound number and slake durability for all rock types. Coefficient of determination ($R^2 = 0.7891$) was found between them for all tested rock types (Fig. 2). The equation of this relation is as follows:

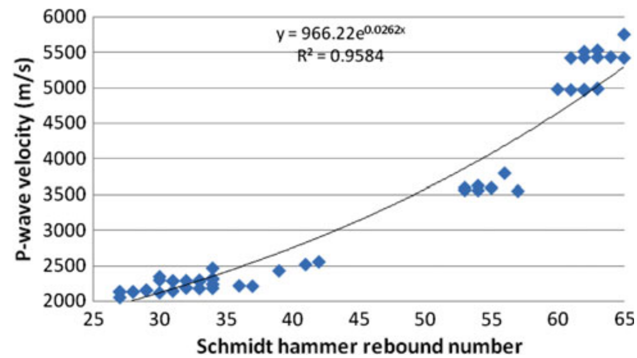

Fig. 3 Schmidt hammer rebound number versus P-wave velocity

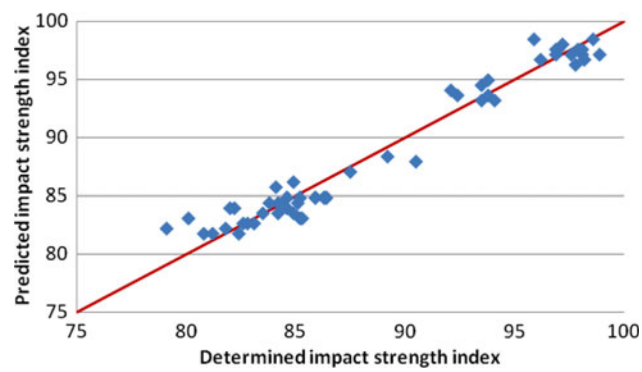

Fig. 4 Observed impact strength versus predicted impact strength index

$$\mathrm{SDI} = 0.0491 \times \mathrm{RR} + 95.6, \quad (4)$$

where, SDI is slake durability index.

For Schmidt hammer rebound number and P-wave velocity, curve also shows an exponential relation (Fig. 3). A very higher coefficient of determination ($R^2 = 0.9584$) was found between Schmidt hammer rebound number and P-wave velocity for all rocks. The equation of relation is as given below.

$$P_v = 966.22\, e^{0.0262\mathrm{RR}}, \quad (5)$$

where, RR is Schmidt hammer rebound number.

It can be seen from the Figs. 1, 2, 3 that in all the three cases the best-fitted relation were found to be best represented by linear regression curves for ISI and SDI, whereas exponential for P-wave velocity. However, it is only

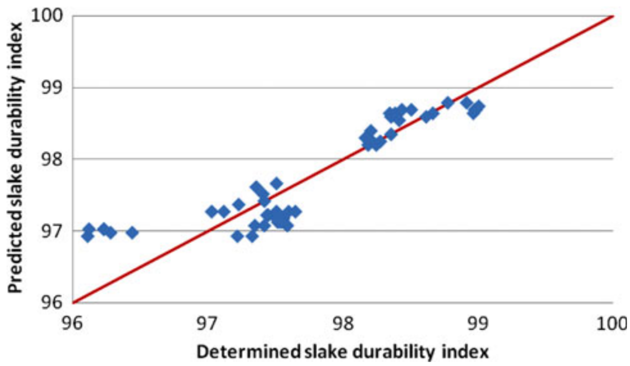

Fig. 5 Observed slake durability versus predicted slake durability index

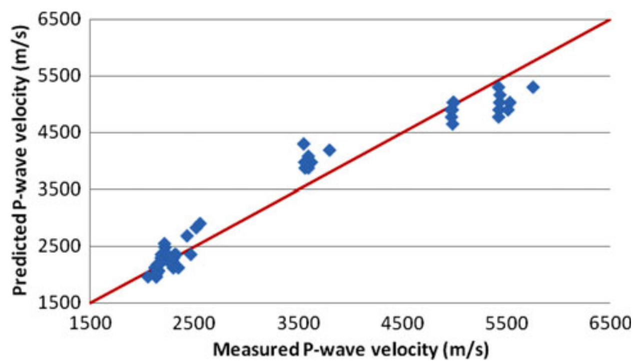

Fig. 6 Observed P-wave velocity versus predicted P-wave velocity

applicable under the rebound number range 25–70. For the lower rebound number these equations may give some misleading results. So, extrapolation should not be used to validate the results from empirical equations.

The empirical methods used in this study were evaluated by comparing their results with each other. Data from each test were used in the respective empirical equation to calculate other properties. The predicted values of ISI, SDI and P-wave velocity values were then plotted against the measured values for all tested rocks, respectively, on 1:1 line (Figs. 4, 5, 6). Point lying on the slope line indicates an exact estimation. It is clear from the Figs. 4, 5, 6 that rebound number is one of the reliable methods for estimating ISI, SDI and P-wave velocity to avoid cumbersome and time-consuming laboratory test methods.

Statistical analysis of the *t* test

The relationship between Schmidt hammer rebound number values with other tests like P-wave velocity, ISI and SDI of the tested rock types, Student's *t* test has been performed.

The formula for the *t* test is a ratio in which the numerator is just the difference between the two means or averages and the denominator is a measure of the variability or dispersion of the scores. The numerator of the formula is easy to compute by finding the difference between the means. The denominator is called the standard error of the difference which is computed by the calculating the variance for each group and dividing it by the number of people in that group. These two values are then added and their square root is taken.

The final formula for the *t* test is

$$t = \frac{\ddot{x}_{\mathrm{T}} - \ddot{x}\mathrm{C}}{\sqrt{\left(\frac{\mathrm{Var}_{\mathrm{T}}}{n_{\mathrm{T}}} + \frac{\mathrm{Var}_{C}}{n_{\mathrm{C}}}\right)}}.$$

The *t* value is positive if the first mean is larger than the second and negative if it is lower. Once the *t* value is computed, it is then compared with the tabulated value. If the computed value is larger than the tabulated one, then it indicates strong and significant correlation. To test the significance, one needs to set a risk level (called the alpha level). In most cases, the "rule of thumb" is to set the alpha level at 0.05, i.e., 95% confidence interval. Table 3 shows the calculated and tabulated values of *t* test.

In all the three cases, calculated value is much higher than the tabulated value, hence they all have significantly strong correlation among themselves and this may be used for prediction of these parameters using Schmidt hammer rebound number for other rock types also.

Conclusions

The study indicates that the ISI, SDI and P-wave velocity of igneous, sedimentary and metamorphic rocks types can be estimated from their Schmidt hammer rebound number values by using simple mathematical relations. ISI and SDI showed linear relationship with Schmidt hammer rebound

Table 3 Tabulated results of the *t* test

Rock tests	*t* test	
	Calculated value	Tabulated value
1. P-wave velocity and rebound number	17.16321703	1.98
2. Impact strength index and rebound number	20.68929522	1.98
3. Slake durability index and rebound number	26.96384334	1.98

number, whereas, P-wave velocity showed exponential relation. The mathematical expressions are as follows:

$$\mathrm{ISI} = 0.4388\mathrm{RR} + 69.916 \left(R^2 = 0.9589\right).$$

$$\mathrm{SDI} = 0.0491\mathrm{RR} + 95.6 \left(R^2 = 0.7891\right).$$

$$P_v = 966.22\,\mathrm{e}^{0.0262\mathrm{RR}} \left(R^2 = 0.9584\right).$$

A strong coefficient of determination was found between Schmidt hammer rebound number with ISI, SDI and P-wave velocity of the tested different rocks. This was also verified by Student's *t* test, which showed higher calculated values for each relation, rather than tabulated values. Hence, they all have significantly strong correlation among themselves and the proposed correlation equations can be used for determination of P-wave velocity, ISI and SDI by simple Schmidt hammer rebound number.

This study reveals that ISI, SDI and P-wave velocity can be estimated by determining rebound values with the given empirical equations under the range of 25–70 without any extrapolation.

These equations are practical, simple and accurate enough to apply for use in general practice to obtain important index properties of the different rocks for design and planning of excavation with greater safety and stability.

References

Aufmuth RE (1973) A systematic determination of engineering criteria for rocks. Bull Assoc Eng Geol 11:235–245

Cargill JS, Shakoor A (1990) Evaluation of empirical methods for measuring the uniaxial compressive strength of rock. Int J Rock Mech Min Sci Geomech Abstr 27:495–503

Deere DU, Miller RP (1966) Engineering classification and index properties for intact rocks. Tech Report Air Force Weapons Lab, New Mexico, No. AFNL-TR, 65–116

Ege JR, Miller DR, Danilchik W (1970) Schmidt hammer test method for field determination of physical properties of zeolitized tuff. E. S. Geological Survey Open-file report 1490. USGS, pp 40

Evans I, Pomeroy CD (1966) The strength, fracture and workability of coal. Pergamon Press, London

Franklin JA, Chandra R (1972) The slake durability test. Int J Rock Mech Min Sci 9:325–341

Ghose AK, Chakraborti S (1986) Empirical strength indices of Indian coals-an investigation. In: Proceedings of 27th US Symp on Rock Mechanics. Balkema, Rotterdam, pp 59–61

Haramy KY, De Marco MJ (1985) Use of Schmidt hammer for rock and coal testing. In: 26th US Symp on Rock Mechanics, 26–28 June, Rapid City, Balkema, Rotterdam, pp 549–555

Hobbs DW (1964) Rock compressive strength. Colliery Eng 41:287–292

ISRM (1981) Suggested methods for determining hardness and abrasiveness of rocks, Part 3. Commission on standardization of laboratory and field tests, pp 101–102

Kahraman S (2001) A correlation between P-wave velocity, number of joints and Schmidt hammer rebound number. Int J Rock Mech Min Sci 38:729–733

Kidybinski A (1980) Bursting liability indices of coal. Int J Rock Mech Min Sci Geomech Abstr 17:167–171

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

Krishnamurthy P, Udas GR (1981) Regional geo-chemical characters of the Deccan Trap lavas and their genetic implications. In: Subbarao KV, Sukheswala RN (eds) Deccan volcanism. Mem Geol Soc Ind 3:394–418

McCarrol D (1991) Schmidt hammer, weathering and rock surface roughness. Earth Surf Process Land 16(5):477–480

Miller RP (1965) Engineering classification and index properties for intact rock. PhD Thesis, University of Illinois

O'Rourke JE (1989) Rock index properties for geo-engineering in underground development. Min Eng pp 106–110

Osborn EF (1959) Role of oxygen pressure in crystallization and differentiation of basaltic magma. Am J Sci 257:609–647

Paone J, Madson D, Bruce WE (1969) Drillability studies: laboratory percussive drilling. USBM RI, 7300

Rabia H, Brook W (1980) An empirical equation for drill performance prediction. In: Proceedings of the 21st US symposium on rock mechanics. Univ Missouri-Rolla, pp 103

RM IS (1979) Suggested method for determining water content, porosity, density, absorption and related properties and swelling and slake durability index properties. Int J Rock Mech Min Sci Geomech Abstr 16:141–156

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

Sharma PK, Singh TN (2008) A correlation between P-wave velocity, impact strength index, slake durability index and uniaxial compressive strength. Bull Eng Geol Environ 67:17–22

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

Singh RN, Hassani FP, Elkington PAS (1983) The application of strength and deformation index testing to the stability assessment of coal measures excavations. In: Proc 24th US Symp on Rock Mech, Texas A&M Univ, AEG, Balkema, Rotterdam, pp 599–609

Singh TN, Verma AK, Singh V, Sahu A (2004) Slake durability study of shaley rock and its predictions. Env Geol 47:246–252

Singh TN, Sarkar K, Bali R (2005) A geotechnical investigation of rocks of Amiyan landslide area, Kumaun Himalaya, Uttaranchal. Min Eng J 6(7):21–26

Sjoberg R, Broadbent N (1991) Measurement and calibration of weathering, using the Schmidt hammer on wave washed moraines on the upper Norrland Coast, Sweden. Earth Surf Process Land 16(1):57–64

Tandanand S, Unger HF (1975) Drillability determination: a drillability index of percussive drills. USBM RI, 8073