The Point Load Test in Rock Material Characterization

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Abstract

Standard laboratory tests to determine uniaxial compressive strength (UCS) of rocks require machined specimens. Therefore, tests where relatively unprepared specimens can be used are often considered for predicting UCS and the point load test has long been recognized as a useful tool in this regard. Although the point load test has also been used for other purposes by researchers, its potential has not yet been fully utilized in routine rock engineering environment. This article presents a comprehensive review of the point load test in rock material characterization. Starting with the background of the test, the review focuses on different issues such as correlations of point load strength index with UCS, response of the test to rock anisotropy, estimation of fracture toughness by the test and use of the test in categorizing weathering grades. The article also recommends a few salient points for plausible improvement of the test procedure in order to obtain more reliable and reproducible test results than that achieved by following ASTM and ISRM stipulations and thus to enhance the applicability of the test in rock engineering.

Introduction

Among the various forms of strength measurements in characterizing rock materials, uniaxial compressive strength (UCS) is one of the most appreciated measurements. As the standard laboratory tests to determine UCS require machined specimens, indirect tests are often used to predict UCS. Several researchers (e.g. Brook, 1985; Cargill and Shakoor, 1990; Ghosh and Srivastava, 1991; Chau and Wong, 1996; Tugrul and Zarif, 1999; Basu and Aydin, 2006) have referred the point load test as the most competent tool in this regard. The point load strength has even been incorporated in the Geomechanics Classification of rock masses (Rock Mass Rating System after Bieniawski, 1989) as a substitute of UCS of intact material in order to rate the rock strength. However, other than predicting UCS, its potential has not been fully utilized in routine rock engineering environment. Starting with the background of the test, this article presents a critical and comprehensive review of the point load test focusing on issues such as correlations of point load strength with UCS, determination of strength anisotropy and estimation of fracture toughness by the test and use of the test in categorizing weathering grades. The article also recommends a few salient points for improvement of the test procedure.

Background

The point load test involves loading rock specimens (cylindrical, prismatic or irregular) between the conical platens (of stipulated geometry and hardness) and measuring the applied force and the distance between the platens at failure. The stress fields within the differently shaped specimens subjected to point loads are highly non-uniform. However, the stress fields along the axes of loading are broadly similar for the different shapes (Hiramatsu and Oka, 1966). The specimens fail by development of one or more extensional planes containing the line of loading.

Wijk (1978) obtained the following analytical approximations for the tensile stress at the centre of a diametrically loaded sphere and

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an axially loaded cylinder, respectively:

$$\sigma_t = -\beta_{sphere}\frac{P}{D^2} \quad (1)$$

$$\sigma_t = -\left(\beta_{plate} + \frac{2D^2\nu}{\pi W^2}\right)\frac{P}{D^2} \quad (2)$$

Where the parameter bshpere = 0.77-0.89 and bplate= 0.39-0.61 for Poisson's ratio (n) values of 0.33 and 0.10, P applied load, D distance between loading points, and W diameter of the cylinder. A similar expression was previously developed by Reichmuth (1968) for the point load tensile strength T0:

$$T_0 = K_s\frac{P_f}{D^2} + K_bP_f \quad (3)$$

Where Pf is failure load, and Ks and Kb are empirical shape and brittleness factors respectively. No size effect was evident with this analysis. Broch and Franklin (1972) reviewing the development of the test concluded that Reichmuth's formula (Eq. (3)) is complex with little practical value and could be simplified to:

$$I_s = \frac{P_f}{D^2} \quad \text{(MPa)} \quad (4)$$

Where Is is the point load strength index.

Considerable variations of Is with specimen size and shape lead Broch and Franklin (1972) to introduce a reference index Is (50) which corresponds to the Is of a diametrically loaded rock core of 50 mm diameter. Accordingly, initial Is values are reduced to Is (50) by size correction factors determined from empirical curves as a function of D. They indicated that the considerably larger shape effect should be avoided by testing specimens with specified geometries. ISRM (1985) proposed a new correction function which accounts for both size and shape effects by utilizing the concept of 'equivalent core diameter' (De). This function (known as geometric correction factor) is given by:

F=(De/50)0.45 (5)

Suggested methods by ISRM (1985) and ASTM (2001) for determining Is(50) comply completely where the index is given by:

$$I_s(50) = F \times \frac{P_f}{D_e^2} \quad (MPa)$$

Derbi and Freitas (1999) showed that the maximum tensile stress at failure, as determined by the Boussinesq equation for the diametrical point load test, is in very good agreement with the diametrical point load strength Is(50) as defined by ISRM (1985). Eq. 6 has been widely used by rock engineers to determine point load strength.

Correlation with uniaxial compressive strength

Previous studies have charted a large number of empirical relationships between point load strength and UCS (Table 1). These relationships are expressed by linear functions (Table 1). On average, UCS is 20-25 times point load strength (ISRM, 1985). However, in tests on many different rocks, the ratio or the conversion factor can vary between 11 and 29 (considering the correlation lines passing through the origin, Table 1). Especially for anisotropic rocks, the range of conversion factor could be even more (ISRM, 1985). It should be noted that a single conversion factor is neither applicable to all rock types (e.g. Chau and Wong, 1996; Basu and Aydin, 2006) nor to the full range of strength of rocks (Tsiambaos and Sabatakakis, 2004). Therefore, care should be taken while using a conversion factor for engineering purposes. It is sensible to find the reliable conversion factor for a particular rock (at comparable weathered state) with a specific geology.

Table 1: Relations of point load strength with uniaxial compressive strength.

References	Correlations	Rock type
Deer and Miller (1966)	$\sigma_{UCS} = 20.7 * I_s(50) + 29.6$	different rock types
Broch and Franklin (1972)	$\sigma_{UCS} = 24 * I_s(50)$	different rock types
Bieniawski (1975)	$\sigma_{UCS} = 24 * I_s(54)$ $\sigma_{UCS} = 21 * I_s(42)$ $\sigma_{UCS} = 18 * I_s(21.5)$	different rock types
Hassani et al. (1980)	$\sigma_{UCS} = 29 * I_s(50)$	different rock types
Read et al. (1980)	$\sigma_{UCS} = 16 * I_s(50)$ $\sigma_{UCS} = 20 * I_s(50)$	sedimentary rocks basalts
Forster (1983)	$\sigma_{UCS} = 14.5 * I_s(50)$	dolerite, sandstone, felsite
Lumb (1983)	$\sigma_{UCS} = 22 * I_s(50)$	granite, volcanics
Gunsalius and Kulhawy (1984)	$\sigma_{UCS} = 16.5 * I_s(50) + 51$	sedimentary rocks
Brook (1985)	$\sigma_{UCS} = 22 * I_s(50)$	different rock types
ISRM (1985)	$\sigma_{UCS} = 20\text{-}25 * I_s(50)$	different rock types
Singh and Eksi (1987)	$\sigma_{UCS} = 23.3 * I_s(50)$	gypsum and marl
Cargill and Shakoor (1990)	$\sigma_{UCS} = 23 * I_s(54) + 13$	14 different rock types
Ferreira and Machado (1993)	$\sigma_{UCS} = 11\text{-}24 * I_s(50)$	limestone
Chau and Wong (1996)	$\sigma_{UCS} = 12.5 * I_s(50)$	Granite, tuff
Smith (1997)	$\sigma_{UCS} = 14.3 * I_s(50)$	lime rock, sandstone
Brautigam et al. (1998)	$\sigma_{UCS} = 20.40 * I_s(50)$ $\sigma_{UCS} = 14.20 * I_s(50)$	sedimentary rocks igneous rocks
Tugrul and Zarif (1999)	$\sigma_{UCS} = 15.25 * I_s$	granitic rocks
Kahraman (2001)	$\sigma_{UCS} = 23.62 * I_s(50) - 2.69$ $\sigma_{UCS} = 8.41 * I_s(50) + 9.51$	coal measure rocks other rocks (sandstone, dolomite, limestone etc.)
Sulukcu and Ulusay (2001)	$\sigma_{UCS} = 15.31 * I_s(50)$	different rock types
Kahraman et al. (2003)	$\sigma_{UCS} = 13.1 * I_s(50)$	limestone, sandstone, dolomite, diabase, metasandstone
Palchik and Hatzor (2004)	$\sigma_{UCS} = 8\text{-}18 * I_s(50)$	porous chalk
Tsiambaos and Sabatakakis (2004)	$\sigma_{UCS} = 13 * I_s(50)$ for $I_s(50) \leq 2$ MPa, $\sigma_{UCS} = 20 * I_s(50)$ for $I_s(50) = 2\text{-}5$ MPa, $\sigma_{UCS} = 28 * I_s(50)$ for $I_s(50) > 5$ MPa	limestone, sandstone, marlstone
Basu and Aydin (2006)	$\sigma_{UCS} = 21 * I_s(50)$	granitic rocks
Kahraman and Alber (2006)	$\sigma_{UCS} = 17.91 * I_s(50) + 7.93$	shale, sandstone, limestone
Karaca et al. (2008)	$\sigma_{UCS} = 16.64 * I_s(50) + 4.35$ (for D/W = 1 in axial test) $\sigma_{UCS} = 14.27 * I_s(50) + 2.90$ (for D/W = 0.7 in axial test)	granite, marble

Determination of strength anisotropy

Broch (1983) successfully used point load test to investigate the strength anisotropy of 33 different rocks by loading the rocks parallel and perpendicular to the foliations. Both ISRM (1985) and ASTM (2001) defined the strength anisotropy index (Ia(50)) as the ratio of mean Is(50) values measured perpendicular and parallel to planes of weakness, i.e. ratio of greatest to least point load strength indices. Ia(50) assumes values close to 1.0 for quasi-isotropic rocks and higher values when the rock is anisotropic. Based on the investigation on 18 different metamorphic rocks, Tsidzi (1990) also found that the point load strength is minimum when the angle between the foliation and the loading axis is zero and is maximum when the angle is 90o.

In spite of such successful employments of the point load test in determining strength anisotropy index, a very few studies have shed light on this topic. It has been experienced by the author that performing point load test on anisotropic rocks with weakness planes at an angle with the loading direction could be troublesome as specimens often fail at a very early stage of loading along those planes depicting invalid failure modes. This might be a cause for very limited use of the test in determining or estimating strength of anisotropic rocks which eventually restricts its use also in determining strength anisotropy index.

It should be noted that calculation of Ia(50) requires strength determinations only in two specific directions (perpendicular and parallel to the weakness planes) where invalid failure modes are not frequently observed. Moreover, in case of the point load test, the same core with the help of a combination of axial and diametrical tests could provide two strength values required to calculate strength anisotropy index. This, in fact, not only reduces the hassles and cost of drilling cores in two orthogonal directions in an anisotropic rock but also provides a reliable index.

Estimation of fracture toughness

Fracture toughness, the ability of rock to resist fracturing and propagation of pre-existing cracks, is applied to rock material classification, blasting, hydraulic fracturing, mechanical fragmentation, slope analysis and many other practical problems. Numerous testing methods and specimens have been used for the determination of rock fracture toughness. ISRM (1988, 1995) suggested three testing methods (short rod specimen, chevron bend specimen and cracked chevron notched Brazilian disc methods) for determining Mode I fracture toughness (KIC). However, the use of the test for rock characterization and indexing purposes is not widespread. Lengthy process of specimen preparation, premature failure of specimens and difficulties in obtaining consistent notch dimensions to the tolerances specified could be the probable reasons for its limited use. Because of the ease of point load test involving little or no specimen preparation, a few researchers have investigated the empirical relationship between point load strength and fracture toughness. Gunsallus and Kulhawy (1984) obtained the following empirical equation: KIC = (0.0995 * Is(50)) + 1.11, where the correlation between KIC and Is(50) was not appreciable. Bearman (1999) suggested that while carrying out the experiments on rocks with some anisotropy, care should be taken to orient the test piece uniform for both the fracture toughness and point load test. Taking this into account, Bearman (1999) found extremely good correlations between KIC and Is(50) from which he produced the following equations: KIC = (29.84P)/(D)3/2 and KIC = (26.56P)/(WD)3/4 for diametrical and axial tests (or tests of irregular specimens) respectively. As Bearman (1999) considered limited rock types, researchers should explore this potentially valuable issue for wide variety of rocks.

Categorization of weathering grades

The most widely used six-fold weathering classification scheme (e.g. ANON (1995), BS5930 (1999) developed after Moye (1955)) for uniform intact rock materials (for engineering purposes) is formulated to address the need for a common but simple basis of communication with underlying messages mainly on the possible ranges of mechanical properties. Because the six-fold weathering classification scheme is based on subjective criteria, identifying and assigning weathering grades objectively and quantitatively by index tests has obvious advantages (Dearman and Irfan, 1978; Hencher and Martin, 1982; Martin, 1986 etc.). Some researchers have used point load strength for this purpose and the studies show that the general trend of degradation of point load strength over the weathering spectrum is curvilinear (Fig. 1). Gamon (1985) reported the ranges of point load strength (determined as per Broch and Franklin, 1972) for Grade II/I and Grade III granites as 3.00-14.30 MPa and 0.47-4.50 MPa respectively. Irfan (1994) indicated that for Grade I to Grade II medium-grained granites, the point load strength is generally over 5.6 MPa. Hodder and Hetherington (1991) carried out point load test on a range of samples from Grade I to Grade III greywacke. They found point load strength of 10 ± 2 MPa for Grade I and of 8 ± 3 MPa for Grade II rocks. Karpuz and Pasamehmetoglu (1997) also found overlapping of strength values in adjacent grades for andesites.

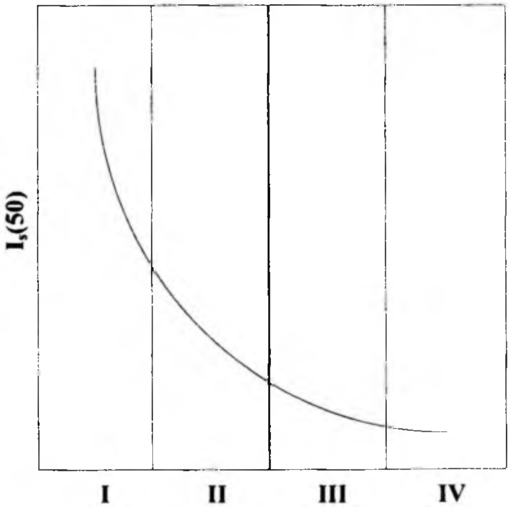

Fig. 1: General trend of point load strength with rock weathering grades.

Although the six-fold classification is adequate for general descriptions, even subdivision of the grades may be justified if a more detailed description is required; for example while relating laboratory test results with degree of decomposition. Basu and Aydin (2006) proposed a weathering classification with subdivisions of weathering grades for granitic materials based on core characteristics substantiated by a detailed petrographic study. Although the ranges of point load strength values also depicted some overlaps in adjacent weathering grades, this provided a better control in classifying weathered rocks.

Point load strength, in general, has been found to be useful in categorizing weathering grades. To discriminate grades more efficiently, it is recommended that a weathering classification must be framed by investigating rock materials of a particular type with a specific geology. The classification might have sub-grades, but must comply by and large with the six-fold classification to be consistent in communication.

Recommendations for improvement of the test method

The common standards (ISRM and ASTM) indicate that the cone penetration depth should be considered while determining Is(50) particularly for weak rocks. However, accurate measurements of cone penetration depth by Basu and Aydin (2006) with the help of a laser distance sensor attached to a point load frame revealed that deeper penetration occurs in fresher/stronger granitic rocks (Fig. 2) and when the penetration depth is considered, the scatter in the data is minimized leading to a significantly better regression coefficient and lower conversion factor for point load strength in predicting UCS. This also helps discriminate weathering grades in a more efficient manner with less overlap of strength values among different

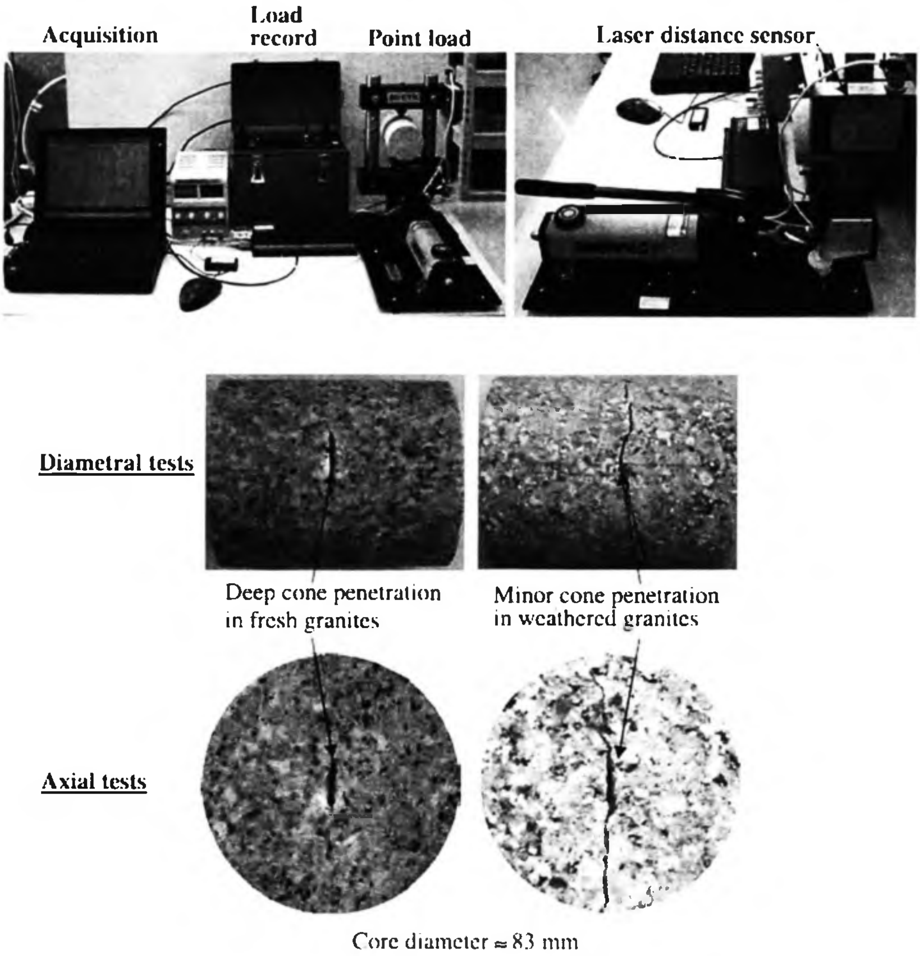

Fig. 2: Laboratory setup and failed specimens (Basu and Aydin, 2006).

grades (Basu and Aydin, 2006). It is recommended that cone penetration depth should be considered in calculating point load strength and the standards (ISRM and ASTM) must reframe/reconsider the part related to cone penetration depth in their suggested point load test method. Attempt should also be made to make use of load-deformation curves in point loading for categorizing weathering grades.

Conclusions and recommendations

The point load strength shows a linear relationship with UCS of rocks and has been referred as the most competent index in predicting UCS. Generalization of conversion factor should be avoided and it is always advisable to find out the most reliable conversion factor for a particular rock type (at equivalent stage of weathering) with a specific geology.

The point load test offers a unique opportunity to test the same core with the help of a combination of axial and diametrical tests that could provide two strength values (perpendicular and parallel to weakness planes) required to calculate strength anisotropy index. This, in fact, not only reduces the hassles and cost of drilling cores in two orthogonal directions in an anisotropic rock but also provides a reliable index.

Suggested methods by ISRM for determining fracture toughness involves lengthy process of specimen preparation, premature failure of specimens and difficulties in obtaining consistent notch dimensions to the tolerances specified. Therefore, establishing empirical relationships between fracture toughness and a rock index property could be potentially valuable in rock engineering. Bearman (1999) noticed appreciable relationship between Mode I fracture toughness and point load strength based on investigations of limited rock types. Researchers should explore this issue for a wide variety of rocks.

In general, the point load strength has been useful in categorizing weathering grades. To obtain more specific discrimination of grades, it is recommended that a weathering classification must be framed based on macroscopic characteristics substantiated by a detailed petrographic study of a particular rock type with a specific geology. The framed classification, by and large conformable to the six-fold classification, might have finer divisions.

Finally, it is recommended that cone penetration depth should be considered in calculating point load strength. The standards (ISRM and ASTM) must reframe/ reconsider the part related to cone penetration depth in their suggested point load test method. Researchers should shed light also on the nature of load-deformation curves in point loading with reference to rock weathering.

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