International Journal of Rock Mechanics & Mining Sciences 47 (2010) 265–271

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Nail penetration test for determining the uniaxial compressive strength of rock

Kamil Kayabali *, Levent Selcuk

Ankara University, Department of Geological Engineering, Ankara, Turkey

A R T I C L E   I N F O

Article history:
Received 9 March 2009
Received in revised form
23 June 2009
Accepted 23 September 2009
Available online 17 October 2009

Keywords:
Intact rock strength
Uniaxial compression test
Nail penetration test
Schmidt hammer
Point load test

A B S T R A C T

We offer a new and practical index test method, the nail penetration test (NPT), to estimate the UCS of intact rocks, to be used as alternative to the point load test (PLT) or Schmidt rebound hammer test (SRH). The major tools used in the investigation include a gasnailer with 130 J power and its nails ranging from 25 to 60 mm in length. The study material covers 65 rock blocks of gypsum, tuff, ignimbrite, andesite, sandstone, limestone, and marble. For the NPT, five nail shots were performed on each block sample and the average value was obtained. Two to three uniaxial compression tests were carried out on each specimen. Ten impacts were applied on rock blocks by using both the L- and N-types of SRH. Regarding the PLT, either 10 axial or 10 block tests was applied on each rock type.

The average nail penetration depths were correlated with the UCS, $I_{S(50)}$ and rebound number for both types of the SRH. Also, the measured UCS values were compared with those obtained from the empirical relationships using the data from the NPT, PLT, and SRH. It was found that the NPT provides better estimates for UCS than the PLT or SRH. Particularly applicable to weak to very weak rocks, the NPT is capable of indirectly estimating the UCS of intact rocks up to 100 MPa. The test is proposed for use in mainly in situ applications.

1. Introduction

Uniaxial compressive strength (UCS) is one of the most frequently used parameters in rock mechanics, and is usually determined through a uniaxial or unconfined compression test in a laboratory. While this test method appears to be relatively simple, it is time-consuming, comparably costly, and requires carefully prepared rock samples. Additional difficulties exist concerning the extraction of good quality samples, either from an outcrop in the field or from a large block in the laboratory. Weak to very weak rocks may deteriorate during coring and fail to yield good quality samples. For these reasons, the general tendency to predict the compressive strength of intact rocks is to use simpler, quicker, and less costly rock tests such as the Schmidt rebound hammer, point load test, impact strength, and sonic velocity [1].

The Schmidt rebound hammer (SRH), originally developed to measure the surface hardness of concrete [2], is a portable, compact, lightweight, cost effective, and non-destructive device extensively used in evaluating the compressive strength and modulus of elasticity. The results of this easily handled, simple, and rapid method can be converted quickly to most widely used UCS values. Some common applications of the SRH, mostly quoted from [3], include the following: determination of rock weathering [4], assessing joint separation and discontinuities [5], estimation of underground large-scale in situ strength [6], mine roof control [7,8], rock abrasivity [9], rock rippability and rock mass excavability classification [10], abrasion resistance of rock aggregates [11], penetration rate prediction of drilling machines [12,13], prediction of roadheader and tunnel boring machine performance [14], room and pillar design [15,16], evaluation of rock crushing and blasting, indirect prediction of rock mass strength, and consideration of failure strength in intact rocks and rock masses [17]. The SRH's application area includes even geomorphological studies. In this regard, [18] investigated the shore platform and marine terrace elevation changes and used SRH-based rock strengths in their interpretations.

Although this testing device offers great advantages because of its aforementioned properties, there are a number of factors affecting SRH rebound values. The factors controlling the consistency and reliability of the method are calibration and improper functioning of the instrument, surface irregularities of the rock, weathering state of the tested rock, the existence of nearby discontinuities, rock surface moisture content, testing specimen size, spacing between impacts, orientation of the hammer, the adopted test procedure, type of hammer, and available impact energy [3]. Williams and Robinson [19] reported

* Corresponding author. Tel.: +90 312 203 3341; fax: +90 312 215 0487.
E-mail address: kayabali@eng.ankara.edu.tr (K. Kayabali).

1365-1609/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijrmms.2009.09.010

that even slight weathering is capable of reducing rebound values significantly [20]. When used on moderate- to highly-weathered rocks, the rebound impact test causes denting and breaking of application surfaces [21]. Therefore, the SRH is not applicable to weak and extremely weak rocks. In this context, Li et al. [12], reported that weak rocks (UCS < 10 MPa) do not yield reliable rebound values. Also, the SRH is not applicable to non-homogeneous rocks such as conglomerate and breccias [22].

The conclusion drawn from the presentation of the background information about the SRH is that the advantages of the SRH method such as ease, low cost, portability, and repeatability are compensated by a series of factors affecting the results of its consistency and reliability.

The second most commonly used test to predict the UCS indirectly is the point load test. It was first developed in Imperial College as an aid to core logging and, after some slight modifications, has become a convenient tool for rock index tests [17]. It is both a laboratory and a field test to estimate the compressive strength of rock materials. The device can handle regular cores as well as irregular chunks >50 mm in diameter or the least dimension. The point load strength ($I_{s(50)}$) is usually converted to UCS by multiplying a certain coefficient. While this conversion is not always practicable, it is still considered to be a quick and inexpensive testing tool.

Fuenkajorn [23] proclaimed that the conventional point load test (CPL) overestimates the actual UCS, and attributed this to the curved shape of loading points. Fuenkajorn [23] modified the loader ends as flat surfaces of various diameters and concluded that the modified point load test (MPL) better predicted the actual UCS than the CPL. Bowman and Watters [24] developed a light and easy-to-operate point load test device arguing that the existing commercial point load test devices are both heavy and bulky for transporting to remote field areas. The most important constraint on the use of the point load test to estimate the actual UCS is the extremely wide range of the transformation coefficient. This issue will be addressed later in the paper.

Aoki and Matsukura [25], using the argument that the plunger impact energy of the SRH is high and therefore is not suitable for use on fragile or extremely weathered rock, proposed the use of a different tool for strength determination of rocks, the Equotip hardness tester. Although the device was developed originally for metals, it was applied later to very soft materials such as fruits. Therefore, it has a very wide range of application from as low as 0.1 MPa to several 100 MPa [25]. The device was proposed to be used in weathering studies. However, since it is a relatively new test method in rock mechanics and there have been no new insights with this technique, it is not yet certain whether the relationships between Equotip rebound values and intact rock strength are correct [26].

In addition to the testing techniques explained above, the intact rock strength can be estimated with so-called "simple means" [26]. This procedure involves utilizing hammer blows, crumbling by hand, etc. Hack and Huisman [26] provided a list of such simple means and asserted that the estimation of rock strength using "simple means" is more representative for establishing the intact rock strength of a rock mass than establishing the intact rock strength through more elaborate testing.

The aim of this investigation is to propose a new and practical test method for indirectly determining the strength of intact rocks. The major tool for the proposed technique is a gasnailer produced for concrete. A relationship between the nail penetration depth and the UCS is sought. The Schmidt hammer and point load tests are also used as aids for the relationship investigated.

Fig. 1. The concrete nailer and the nail cartridges utilized in the investigation.

2. Materials

The major tools used in this investigation include a gasnailer, Trak-It C4® (Fig. 1), and a series of concrete nails ranging from 25 to 60 mm in length. The nailgun operates with a gas cartridge exerting as high as 130-Joules power on 2.6 mm diameter pointy nails.

The rock materials used for the investigation include tuff, ignimbrite, gypsum, sandstone, marble, limestone, and somewhat weathered andesites collected mainly from the vicinity of Ankara and Central Turkey. A number of rock outcrops were visited to collect the rock blocks suitable for the investigation. The intact rock blocks free of macro-scale discontinuities and two decimeters in the smallest dimension were collected and transported to the laboratory to conduct the associated index tests. Great care was taken to pick up the rock materials so that all nail-penetration depths were represented. Very strong rocks with less than a few mm nail penetration or extremely weak rocks with the 65 mm length penetration were excluded.

3. Methods

Four testing techniques were employed in this investigation. They include the uniaxial compression test, Schmidt rebound hammer test, point load test, and nail penetration test. The details of each testing method are explained in the following subsections.

3.1. Uniaxial compression test

The ASTM D2938-95 [27] standard was applied to the cores drilled from the blocks using an NX size diamond bit. The coring direction was selected perpendicular to any visible bedding planes, particularly in gypsum. Two to three samples were cored from each intact rock block and the ends were machined flat. The length was kept in the interval between 2 and 2.5D. The core was placed between the platens (one is plain rigid while the other is spherical) of the loading frame and a stress rate of 1 MPa per