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Nail penetration test for determining the uniaxial compressive strength of rock

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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

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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$^{\circledR}$ (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 second was applied. To avoid possible disturbance and/or internal destruction, sample coring was done before the application of the nail penetration test on intact rock blocks.

3.2. *Schmidt hammer rebound test*

The most popular two standards chosen for the SRH applications are the ISRM [28] and ASTM [29]. ISRM recommends the use of L-type hammer on rocks with UCS ranging from 20 to 150 MPa and averaging the upper 50% of at least 20 impacts. On the other hand, ASTM does not specify any hammer type and recommends applying at least 10 impacts for rocks with UCS ranging from 1 to 100 MPa. According to ASTM, the rebound numbers diverting more than seven units from the average should be discarded and the remaining numbers be averaged. Both standards require impact applications be separated at least one plunger diameter.

The impact energies of L- and N-type Schmidt rebound hammers are 0.735 and 2.207 N m, respectively. The guidelines regarding the choice of hammer type in standards are not clear. Sheorey et al. [30] pointed out that the N-type should be used for rocks with UCS > 20 MPa. Gokceoglu and Aksoy [4] indicated that an N-type hammer produces more accurate and reliable estimates of rock strength in the range of approximately 20–290 MPa. Del Porto and Hurlimann [31] reported that the N-type SRH underestimates the UCS of weak rocks (UCS < 20 MPa) and the L-type results in slightly more precise values for weak rocks. This observation concurs with that of [30]. Ayday and Goktan [32] found good correlations between L-type and N-type Schmidt hammer rebound values. An extensive literature review [20] reveals that both types were employed to predict the strength of various rock types. They reported that the N-type performs better since the higher impact energy represents the intact rock strength more reliably. They also showed that R_N and R_L, the rebound numbers of N- and L-type SRH, respectively, correlate very well (r=0.99).

There has been a great deal of studies relating the UCS, tangent modulus, and rebound values for various rocks in the form of empirical relationships. These relationships were developed for both single rock types and a mixture of rock types. A comprehensive list of such relationships can be found in [1,20,33,34]. The list provided by [20] comprises relationships including and excluding the density of rocks.

The ASTM standard [35] was employed for Schmidt hammer applications. In order to avoid the orientation corrections, the hammer was held downward at a right angle to the rock surface. At least one plunger diameter distance was kept between impacts. Both L- and N-type SRH were used to measure the hardness of intact rock blocks. Ten single impacts were taken with each hammer on each rock specimen. Since the test surface should be free from cracks to a depth of at least 6 cm, implying that the penetration depth of the impact wave may exceed this depth and the NX size cores do not comply with this requirement [20], no attempt was made to measure the hardness of cores drilled from large blocks. Schmidt hammer rebound tests were carried out, as in the case of extracting uniaxial strength test cores prior to the application of nail penetration tests.

3.3. *Point load test*

Broch and Franklin [36] indicated that this test method applies to hard rock (UCS > 15 MPa). In this test, the concentrated load is applied through coaxial, truncated conical platens. The failure load is used to calculate the point load strength index and to estimate the UCS. The diametral, axial, and block tests are the choices depending on the availability of rock cores with sufficient length.

As with the SRH, there are a great deal of published empirical relationships between point load index and UCS. Kahraman [1] provided a comprehensive list of such relationships. The general procedure for the conversion from point load strength to USC is to determine a coefficient factor using the linear relationship between the results of two test types. Broch and Franklin [36] reported that the UCS is about 24 times the point load index. Bienawski [37] proposed this coefficient to be roughly 23. The ISRM [38] suggested this value be between 20 and 25. Sonmez and Osman [39] showed that this number has a wide range from 5 to 55. According to Yilmaz and Sendir [22], this range is even wider, from 6 to 105. As can be seen from these studies, there is no unique relationship between the point load strength and the UCS. This means that, multiplying the point load strength by mostly 24, the point load strength provides only a crude estimate for the uniaxial compression of intact rocks.

The axial and block tests were carried out on cores and blocks drilled and saw-cut from the intact rock blocks. The cores for the axial tests were prepared so that the height of the sample ranged between $D/3$ and D. Likewise, the block samples were cut so that the height was between $W/3$ and W, where W is the dimension representing the width and length, and is equal to or >50 mm. Ten axial- or block-test specimens were prepared for each rock type. Some of the rock blocks yielded only several test specimens. All tests were performed on air-dried samples. Great care was applied so that the specimen failures conformed to the standards and the tests that did not comply with this principle were discarded. Either coring of specimens for the axial test or the cutting of rectangular samples was done so the visible bedding planes, if any, remain parallel to the loading surfaces. At the end, the mean value of point load index ($I_{s(50)}$) was calculated as the mean of remaining values after discarding the two highest and lowest values, having performed the necessary corrections in the case of rectangular samples.

3.4. *Nail penetration test*

The literature review revealed that the concrete nailer has never been applied to rocks. The hypothesis for this investigation is that there should be a relationship between nail penetration depth and the intact rock strength. That is, the weaker the rock, the deeper the nail penetration should be, and vice versa.

The nailer can be held in any position. It should be at nearly a right angle to the rock surface (Fig. 1). Shots deviating significantly from perpendicularity may cause chiseling of the rock surface and errors in true penetration length. When visible discontinuities such as bedding planes existed, not violating the intact rock principle, the nailer was positioned perpendicular to the planes of weakness. The nailer was used both in the field and laboratory. The purpose of its use in the field was to collect rock blocks representative of all penetration depths. The laboratory applications were carried out such that the shot points were sufficiently far from the edges of blocks to prevent disintegration. Five shots were performed on each rock block. The clearance between shotpoints was roughly adjusted so the possible weakness planes (usually not detected visually) created by nails do not interfere with each other. The length of the nail outside the rock was measured by a digital caliper (sensitivity is 0.01 mm) and the penetration depth was obtained after deducting this length from the total length of the nail. The average of five shots was rounded to the nearest one-tenth.

Regarding the repeatability of the proposed method, a series of nail penetration tests were conducted on large blocks of andesite and ignimbrite with machine-flat surfaces. Thirty-nine shots made on the andesite block gave the mean, minimum, and maximum values of 21.98, 20.03, and 25.16 mm, respectively. The

Table 1
The results of laboratory tests.

No.	Rock type	Unconfined compression strength		Schmidt rebound test[a]		Point load test		NPT d (mm)
		σ_c (MPa)[a]	ρ (g/cm^3)	R_L	R_N	Type[b]	$I_{s(50)}$ (MPa)[a]	
1	Gypsum	17.8/18.6/18.2/2	2.3	14.0/20.0/17.0/10	17.0/23.0/20.2/10	B	1.5/2.1/1.9/10	37.5
2	Gypsum	15.9/16.4/16.1/2	2.3	13.0/17.0/14.6/10	15.0/23.0/17.4/10	A	1.1/1.7/1.5/10	42.9
3	Sandstone	16.1/16.8/16.4/2	2.3	18.0/26.0/22.6/10	20.0/30.0/23.9/10	A	1.2/1.6/1.4/10	37.2
4	Sandstone	4.4/5.0/4.7/2	1.6	11.0/13.0/11.0/10	12.0/17.0/13.7/10	A	0.7/0.8/0.7/10	60.0
5	Andesite	43.5/51.4/47.5/2	2.1	38.0/48.0/42.2/10	40.0/48.0/44.3/10	A	4.0/4.6/4.2/10	15.9
6	Andesite	51.0/58.9/54.9/2	2.0	40.0/48.0/44.6/10	42.0/50.0/46.6/10	A	3.5/3.8/3.6/10	19.3
7	Sandstone	25.0/25.8/25.5/2	2.1	20.0/28.0/24.8/10	22.0/32.0/25.6/10	A	1.7/1.9/1.8/10	32.7
8	Sandstone	19.3/23.3/21.3/2	2.1	20.0/28.0/24.0/10	22.0/27.0/26.0/10	A	1.5/1.8/1.7/10	28.7
9	Ignimbrite	15.4/15.5/15.4/2	1.8	18.0/26.0/22.3/10	22.0/29.0/26.0/10	A	1.3/1.7/1.5/10	40.5
10	Ignimbrite	12.6/13.8/13.2/2	1.6	16.0/23.0/19.2/10	19.0/24.0/22.2/10	A	0.9/1.2/1.1/10	37.9
11	Ignimbrite	6.8/9.2/7.9/3	1.5	17.0/24.0/20.1/10	18.0/24.0/22.1/10	A	1.1/1.2/1.1/10	45.3
12	Ignimbrite	9.4/10.0/9.7/2	1.5	18.0/26.0/22.3/10	18.0/26.0/22.7/10	A	1.3/1.4/1.3/10	49.5
13	Ignimbrite	11.2/13.1/12.3/3	1.6	20.0/26.0/22.8/10	22.0/27.0/23.8/10	A	1.0/1.5/1.4/10	41.1
14	Tuff	4.1/4.2/4.1/2	1.5	12.0/16.0713.9/10	14.0/20.0/16.0/10	B	0.5/1.2/0.8/10	47.8
15	Tuff	5.6/5.8/5.7/2	1.5	12.0/16.0/14.4/10	12.0/19.0/15.1/10	B	0.5/0.8/0.7/10	52.4
16	Tuff	17.4/18.5/18.0/2	1.5	21.0/28.0/24.2/10	22.0/29.0/26.0/10	B	1.2/1.4/1.3/10	44.6
17	Andesite	70.5/74.9/72.7/2	2.2	48.0/54.0/51.5/10	45.0/59.0/52.1/10	B	3.4/3.6/3.5/10	12.1
18	Andesite	33.6/38.7/36.2/2	2.0	38.0/44.0/40.2/10	38.0/46.0/43.2/10	B	2.5/3.2/2.9/10	19.3
19	Andesite	32.2/39.9/36.1/3	2.1	46.0/54.0/49.8/10	48.0/56.0/52.1/10	A	2.2/2.2.5/2.4/10	19.9
20	Andesite	59.7/83.5/71.6/2	2.3	42.0/48.0/45.3/10	42.0/50.0/48.2/10	A	3.9/4.8/4.4/10	16.0
21	Andesite	73.9/74.9/74.4/2	2.3	48.0/56.0/52.0/10	50.0/60.0/54.4/10	A	4.0/5.1/4.5/10	15.0
22	Andesite	65.5/79.6/72.6/2	2.3	36.0/49.0/43.6/10	40.0/45.0/43.2/10	A	4.2/4.8/4.6/10	12.5
23	Andesite	18.9/19.3/19.1/2	2.1	24.0/30.0/27.3/10	23.0/38.0/34.5/10	B	1.0/1.5/1.3/10	38.2
24	Gypsum	4.8/7.5/6.4/3	2.3	18.0/22.0/19.4/10	18.0/26.0/22.6/10	A	1.1/1.6/1.3/10	45.2
25	Gypsum	7.1/7.2/7.1/2	2.2	20.0/24.0/22.4/10	20.0/26.0/24.2/10	B	1.3/1.5/1.4/10	42.2
26	Gypsum	14.5/15.6/15.1/2	2.2	20.0/30.0/24.0/10	26.0/34.0/30.6/10	A	1.5/1.6/1.5/10	36.5
27	Gypsum	14.7/14.8/14.8/2	2.2	18.0/24.0/21.3/10	18.0/26.0/22.0/10	B	1.3/1.6/1.5/10	38.3
28	Gypsum	11.9/12.2/12.1/2	2.2	17.0/22.0/19.5/10	17.0/24.0/21.6/10	A	1.3/1.7/1.5/10	43.5
29	Gypsum	26.4/26.6/26.5/2	2.2	19.0/28.0/22.1/10	19.0/28.0/23.3/10	A	1.7/2.0/1.8/10	35.4
30	Ignimbrite	3.3/4.2/3.8/2	1.3	14.0/22.0/17.6/10	16.0/22.0/19.9/10	B	0.5/0.8/0.6/10	55.6
31	Ignimbrite	2.8/3.7/3.3/3	1.3	14.0/18.0/16.0/10	17.0/22.0 /19.5/10	B	0.6/0.8/0.7/10	53.0
32	Ignimbrite	5.0/5.3/5.2/2	1.3	18.0/24.0/20.2/10	20.0/24.0/22.4/10	B	0.7/1.0/0.8/10	52.1
33	Ignimbrite	11.9/12.4/12.2/2	1.8	22.0/32.0/26.4/10	31.0/36.0/32.1/10	B	1.0/1.6/1.3/10	35.4
34	Ignimbrite	8.8/14.9/11.7/3	1.7	19.0/26.0/22.4710	27.0/34.0/29.9/10	B	0.9/1.2/1.1/10	35.6
35	Ignimbrite	9.2/9.3/9.3/2	1.7	20.0/28.0/23.2/10	20.0/31.0/25.5/10	B	0.8/1.2/0.9/10	49.4
36	Ignimbrite	7.9/14.1/11.0/2	1.5	18.0/32.0/24.6/10	19.0/27.0/23.8/10	B	1.1/1.3/1.2/10	33.8
37	Tuff	2.7/3.0/2.9/2	1.2	11.0/13.0/11.9/10	12.0/14.0/13.0/10	B	0.3/0.6/0.5/10	60.0
38	Tuff	4.3/5.2/4.8/3	1.3	16.0/24.0/20.6/10	18.0/24.0/21.1/10	B	1.0/1.5/1.3/10	51.4
39	Ignimbrite	7.9/12.3/10.1/3	1.6	18.0/26.0/21.4/10	18.0/26.0/23.8/10	B	1.6/2.0/1.8/10	33.1
40	Tuff	3.3/3.7/3.5/2	1.2	19.0/24.0/19.7/10	18.0/24.0/21.4/10	B	0.8/1.1/0.9/10	59.0
41	Ignimbrite	11.1/15.3/13.5/3	1.6	22.0/30.0/25.9/10	24.0/35.0/29.5/10	B	1.5/2.1/1.8/10	30.5
42	Ignimbrite	22.8/27.6/25.6/3	1.7	29.0/34.0/27.9/10	25.0/34.0/28.9/10	B	1.9/2.4/2.1/10	30.0
43	Ignimbrite	23.2/23.5/23.4/2	1.7	24.0/28.0/25.6/10	22.0/34.0/27.1/10	B	2.0/2.6/2.2/10	26.4
44	Ignimbrite	14.3/14.7/14.5/3	1.7	24.0/34.0/28.7/10	24.0/30.0/29.4/10	B	1.8/2.0/1.9/10	30.7
45	Sandstone	62.5/79.0/70.7/2	2.5	36.0/46.0/41.2/10	42.0/48.0/44.8/10	A	4.8/5.2/5.0/10	10.7
46	Sandstone	49.3/52.5/50.9/3	2.4	34.0/44.0/39.8/10	38.0/48.0/42.1/10	A	3.4/3.7/3.6/10	15.0
47	Andesite	82.4/86.4/84.4/2	2.2	48.0/45.0/50.1/10	48.0/54.0/51.0/10	A	5.5/6.4/5.9/10	9.4
48	Anhidrite	5.0/6.0/5.5/2	2.1	11.0/12.0/11.5/10	11.0/14.0/12.4/10	B	0.8/079/0.8/10	50.0
49	Andesite	58.8/75.8/67.3/2	2.2	46.0/54.0/49.2/10	52.0/56.0/54.0/10	A	4.6/5.7/5.2/10	12.0
50	Ignimbrite	30.9/37.5/34.4/3	1.7	40.0/46.0/42.9/10	36.0/49.0/43.6/10	A	2.1/2.5/2.3/10	26.3
51	Ignimbrite	43.6/57.9/51.8/3	2.1	40.0/48.0/45.2/10	48.0/54.0/52.7/10	A	3.3/3.5/3.4/10	21.9
52	Ignimbrite	18.3/20.7/18.8/3	1.3	28.0/32.0/30.1/10	28.0/34.0/31.7/10	A	1.2/1.3/1.3/10	36.2
53	Ignimbrite	25.6/31.6/29.2/3	1.7	34.0/40.0/36.7/10	32.0//42.0/38.0/10	A	2.2/2.4/2.3/10	32.6
54	Ignimbrite	24.5/27.6/26.4/3	1.8	32.0/44.0/37.4/10	38.0/48.0/42.8/10	A	2.1/3.0/2.6/10	25.6
55	Ignimbrite	42.9/52.2/47.6/3	1.8	40.0/48.0/45.0/10	48.0/54.0/49.5/10	A	2.7/3.1/2.9/10	23.3
56	Marble	52.4/57.1/55.2/3	2.6	46.0/52.0/48.8/10	49.0/59.0/52.0/10	A	3.1/3.8/3.4/10	12.2
57	Marble	54.7/58.6/56.1/3	2.6	44.0/50.0/46.3/10	48.0/58.0/52.6/10	A	3.1/3.8/3.4/10	13.3
58	Andesite	42.4/52.1/47.3/2	2.2	32.0/36.0/33.6/10	23.0/38.0/34.5/10	A	2.6/3.3/3.0/10	22.2
59	Limestone	71.7/117.9/85.4/3	2.4	50.0/56.0/52.8/10	56.0/60.0/57.5/10	A	4.0/5.2/4.7/10	7.7
60	Limestone	103.3/110.5/106.4/3	2.5	50.0/58.0/53.2/10	54.0/64.0/59.0/10	A	4.6/6.5/5.3/10	6.7
61	Limestone	88.5/97.2/92.9/3	2.4	52.0/58.0/54.4/10	52.0/62.0/58.4/10	A	4.8/7.2/5.9/10	5.9
62	Limestone	47.0/57.5/52.1/3	2.4	38.0/44.0/40.6/10	42.0/50.0/45.3/10	A	3.1/4.2/3.5/10	21.9
63	Limestone	105.2/118.3/111.7/3	2.5	52.0/58.0/55.6/10	56.0/64.0/59.7/10	A	5.3/6.5/5.9/10	5.2
64	Limestone	54.4/57.8/56.1/2	2.4	36.0/48.0/41.6/10	38.0/48.0/44.8/10	A	3.4/4.1/3.6/10	16.9
65	Limestone	40.7/57.5/51.8/3	2.5	36.0/44.0/39.6/10	38.0/46.0/43.5/10	A	3.6/4.4/3.9/10	22.3

[a] Numbers separated by slash from left to right are the minimum, maximum, mean values and the number of tests done.
[b] A: axial test; B: block test; *d*: nail penetration depth.

standard deviation was 1.26 mm. Fifty shots on the ignimbrite block yielded the mean, minimum, and maximum values of 34.24, 32.22, and 35.46 mm, respectively. The standard deviation for this group of measurements was 0.86 mm. Those two series of tests demonstrate that the proposed method is repeatable for the gas-nailer employed in the investigation. We used only one gas-nailer in this investigation. Therefore, we have no idea if other gas-nailers with the same energy level would give similar results. This should be explored in further studies.

4. Experimental results

The results of all five test methods (i.e., UCS, PLT, SRH-L, SRH-N, and NPT) are presented in Table 1. In order to determine the best empirical correlations between the NPT and UCS, $I_{s(50)}$, and rebound numbers for L- and N-type of hammers, regression curves for different test procedures were drawn in Figs. 2–5. The regression coefficients (R^2) between the nail penetration depth (d) and UCS, $I_{s(50)}$, and rebound numbers for L- and N-type of hammers are found to be 0.92, 0.92, 0.86, and 0.85, respectively. The regression coefficients between the nail penetration depth and the rebound numbers for two types of the SRH are in close agreement since the regression coefficient between R_L and R_N is very high (R^2=0.98) (Fig. 6).

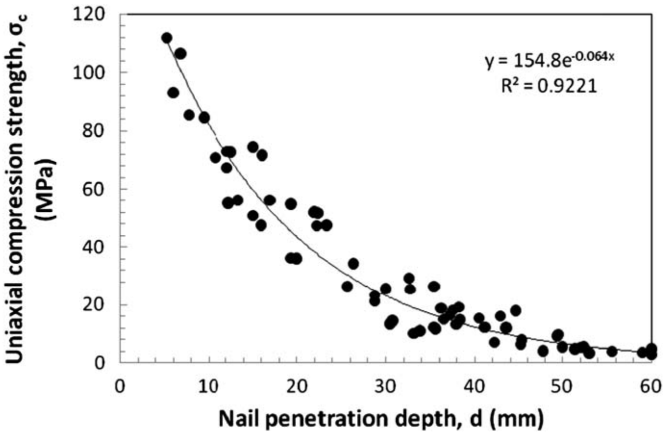

Fig. 2. Relationship between the UCS and the nail penetration depth.

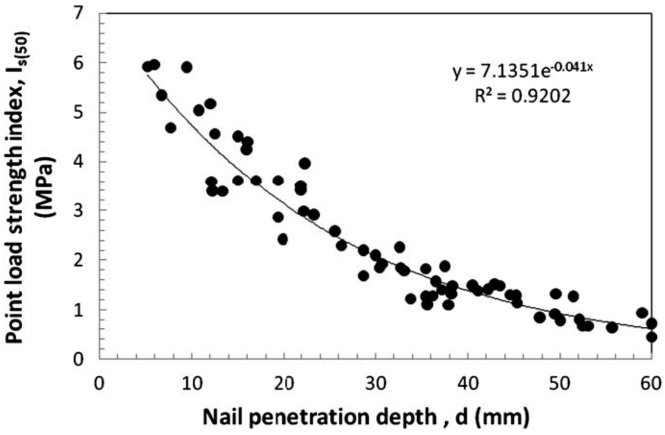

Fig. 3. Relationship between the $I_{s(50)}$ and the nail penetration depth.

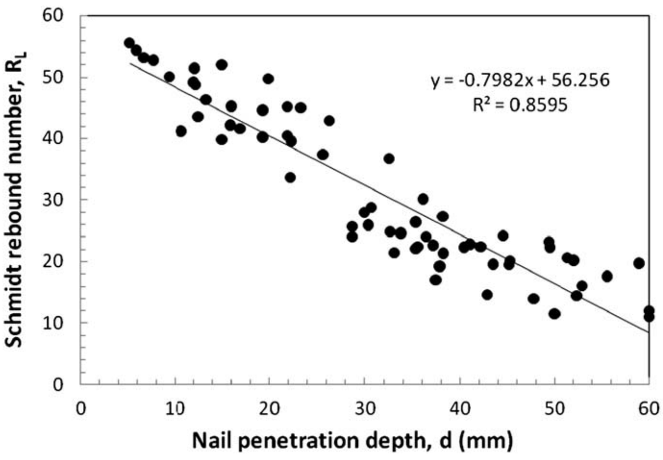

Fig. 4. Relationship between the R_L and the nail penetration depth.

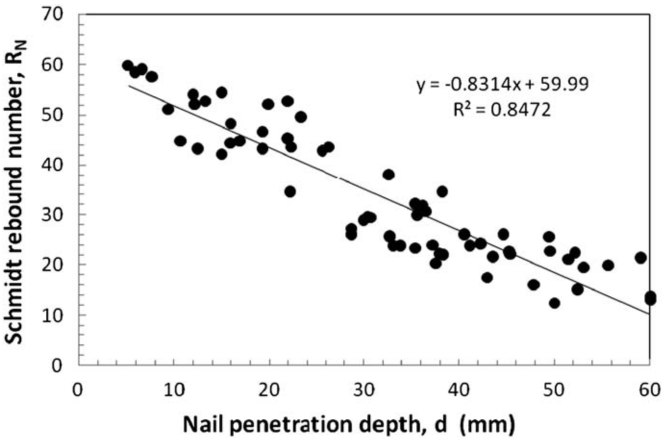

Fig. 5. Relationship between the R_N and the nail penetration depth.

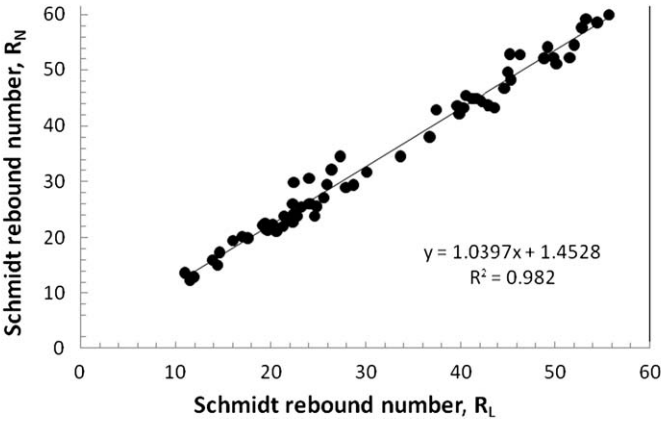

Fig. 6. Relationship between R_N and R_L.

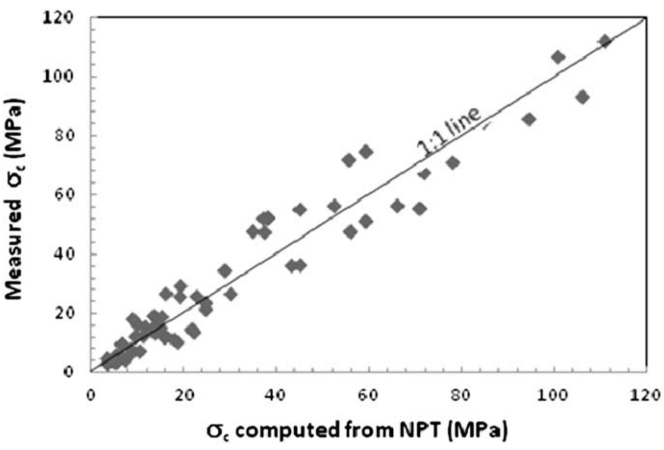

Fig. 7. Comparison between the measured UCS and the UCS computed from the NPT.

As can be seen from Fig. 2, the empirical relationship between the nail penetration depth (d) and the UCS is

$$\sigma_c = 154\exp(-0.064d) \tag{1}$$

New graphs were plotted to demonstrate that the NPT is superior to both the PLT and SRH in estimating the UCS indirectly. The UCS values measured were compared with the computed UCS values using Eq. (1) in Fig. 7. It can be asserted that the reliability of the NPT to estimate the UCS is very high. The $I_{s(50)}$ values obtained from the PLT were converted to UCS values by multiplying by 24. A comparison between the measured UCS values and the computed UCS values from the PLT (Fig. 8) reveals that the PLT significantly underestimates the UCS. Likewise, the rebound numbers from the L-type SRH were converted to UCS values using the empirical relationship by [40]

$$\sigma_c = 9.97\exp(0.02R_L\rho) \tag{2}$$

The estimates of UCS using the rebound numbers were compared to the UCS values measured in Fig. 9. While the UCS estimates by R_L values appear to be better than those of the PLT, the SRH also underestimates the UCS in general. The overall conclusion from those comparisons is that the NPT appears to provide somewhat better estimates for the UCS than either the PLT or SRH.

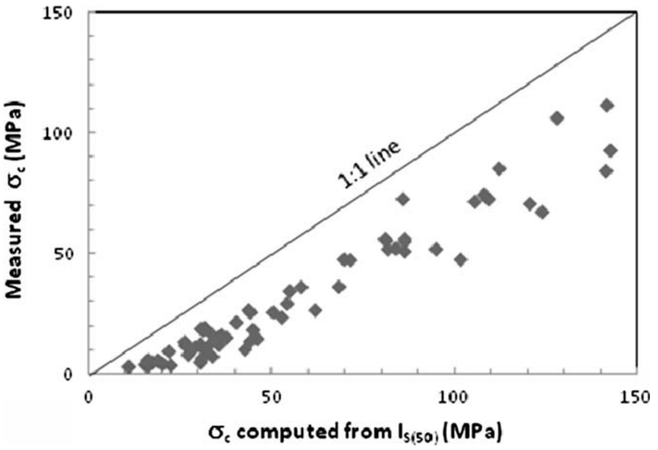

Fig. 8. Comparison between the measured UCS and the UCS computed from the $I_{s(50)}$.

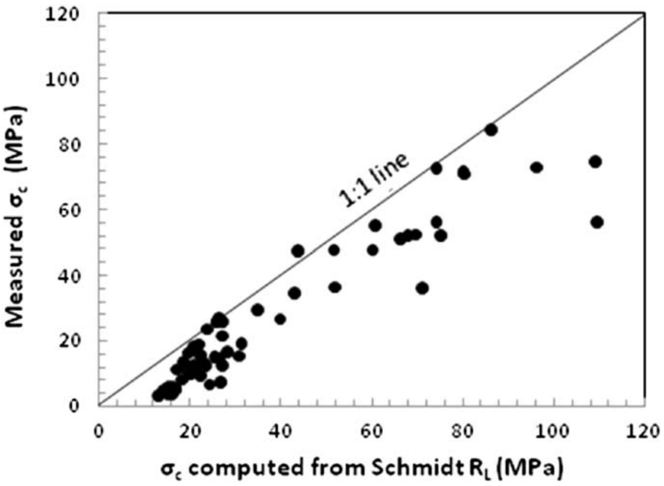

Fig. 9. Comparison between the measured UCS and the UCS computed from the R_L.

5. Conclusions

A new index testing tool is proposed to estimate indirectly the compressive strength of intact rocks. The major equipment used to carry out this test has the main advantages of portability, robustness, quickness, low cost, and non-destructiveness, depending on the use. The reliability and accuracy of the nail penetration test to assess the compressive strength indirectly and quantitatively seem to be higher than those of the Schmidt rebound hammer and point load tests. In addition to the substitution with the SRH and PLT in many applications requiring the determination of the UCS, the major areas where the proposed equipment would be considered more helpful include the classification of weathering grades, classification of compressive strength, and the alternative use in rock mass rating, in place of the uniaxial compression or the point load tests. The proposed method has also a potential to be standard index test for intact rocks.

The application of the gasnailer on rocks is a new subject. Some of the restrictions for the Schmidt rebound hammer such as the improper functioning of the instrument, surface irregularities of the rock, weathering state of the tested rock, existence of nearby discontinuities, rock surface moisture content, test specimen size, spacing between impacts, orientation of the nailer, type of the nailer, available impact energy, and application on non-homogeneous rocks may also be valid for the nail penetration test. Those issues need to be addressed further.

Because the point load test involves a very speculative factor as the conversion coefficient, the nail penetration test is superior to the point load test in providing the UCS more reliably.

The destructiveness of the proposed testing tool depends upon whether it is used in the field or in the laboratory. Unless the rock block is not extracted from its place, the destruction is unlikely because of the confinement. However, applications on rock blocks smaller than a certain size (by experience, usually larger than approximately 1 dm^3 in volume) or near the edges would lead to destruction. The NPT tests we carried out in the laboratory aim to establish an empirical relationship between the nail penetration depth and the USC. We propose this tool should be used in mainly in situ rock strength evaluations.

The results obtained in this investigation and the proposed testing method along with the classification schemes developed are valid only for the commercial nailer used in this study. The other commercially available nailers are expected to give different results unless they have similar features such as the impact energy and the type of concrete nails.

The tool employed in the investigation covers a relatively wide range of uniaxial compression strengths. UCS of very weak to moderately strong rocks can be estimated with an appreciable degree of accuracy. While the tool's ability is restricted to approximately 100 MPa of USC, further research is recommended to include the determination of uniaxial strength of strong to very strong rocks by developing a nailer with the adjustable impact energy levels.

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