Scientific Research Publishing

Geomaterials, 2018, 8, 15-25
http://www.scirp.org/journal/gm
ISSN Online: 2161-7546
ISSN Print: 2161-7538

Estimate of Uniaxial Compressive Strength of Hydrothermally Altered Soft Rocks Based on Strength Index Tests

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How to cite this paper: Kohno, M. and Maeda, H. (2018) Estimate of Uniaxial Compressive Strength of Hydrothermally Altered Soft Rocks Based on Strength Index Tests. *Geomaterials*, **8**, 15-25.
https://doi.org/10.4236/gm.2018.82002

Received: April 12, 2018
Accepted: April 27, 2018
Published: April 30, 2018

Abstract

The purpose of this study was to clarify the relationships between results of index tests and uniaxial compressive strength (UCS) in hydrothermally altered soft rocks of the Upper Miocene, which are typical of the soft rock found in northeastern Hokkaido, Japan. Index tests were performed using point load testing machine and needle penetrometer with irregular lump specimens under forced-dry, forced-wet, and natural-moist states. The relationships between irregular lump point load strength (IPLS) index and UCS, and needle penetration (NP) index and UCS were "UCS = approximately 19 IPLS index" and "UCS = 0.848 (NP index)$^{0.619}$", respectively, in soft rocks with a UCS below 25 MPa. These relationships could be applied to on-site tests of rocks with natural moisture content. The UCS could be calculated from IPLS and NP tests on soft rocks only when UCS was below 25 MPa, using the equations obtained as a result of this study.

Keywords

Uniaxial Compressive Strength (UCS), Irregular Lump Point Load Strength (IPLS) Index, Needle Penetration (NP) Index, Empirical Equation, Hydrothermally Altered Rocks

1. Introduction

The strength of rocks is generally evaluated based on uniaxial compressive strength (UCS). However, rock core pieces for UCS tests cannot always be obtained from outcrops of faulted, jointed, or heavily crushed rock masses. In these cases, the point load strength (PLS) or needle penetration (NP) test is a convenient and effective alternative to the UCS test because it can be done promptly using onsite testing equipment with various shaped small rock specimens taken from outcrops or floats. Provided that UCS can be estimated from a PLS or NP value, PLS and NP tests are more convenient and cheaper.

Many researchers have already studied the relationship between the PLS index and UCS. The representative relationships between the PLS index and UCS are shown in **Table 1**. In these relationships, the maximum values of UCS ranged from 150 to 350 MPa (**Table 1**). Furthermore, the number of points on soft rocks (UCS = 25 MPa or less) was less than the number of points on hard rocks (UCS = 25 MPa or more). Therefore, it could not be considered that these studies have clarified the relationship between the PLS index and UCS of soft rocks. Relationship between the PLS index and UCS of soft rocks was determined by Tsiambaos and Sabatakakis [12] (2004; UCS = 13 PLS, Maximum value of UCS is 50 MPa), Basu and Aydin [13] (2006; UCS = 18 PLS, Maximum value of UCS is 200 MPa), Agustawijaya [14] (2007; UCS = 13.4 PLS, Maximum value of UCS is 12 MPa), and Kohno and Maeda [15] (2012; UCS = 16.4 PLS, Maximum value of UCS is 25 MPa). Recently, Wong *et al.* (2017) [16] have studied the UCS and PLS index of volcanic irregular lumps.

Smaller samples are difficult to obtain even for PLS tests. In this case, the NP test is convenient and effective. Recently, relationship between the NP index and UCS of rocks was determined by Park *et al.* (2011) [17], Ngan-Tillard *et al.* (2011, 2012) [18] [19], Ulusay and Erguler (2012) [20], Azadan and Ahangari (2014) [21], Ulusay *et al.* (2014) [22], and Kahraman *et al.* (2017) [23]. The most popular UCS–NP equation was proposed by Okada *et al.* (1985) [24]. However, this equation mainly used cement material specimens, and there are very few reports about the relationship between the NP index and UCS of soft rocks.

The purpose of this study was to investigate the relationship between the PLS index and UCS of hydrothermally altered soft rocks, which are typically found in

Table 1. Typical examples of equations correlating uniaxial compressive strength to the point load strength.

References	Equations	Maximum value of UCS (MPa)
D'Andrea *et al.* (1964) [1]	UCS = 15.3 PLS + 16.3	350
Broch and Franklin (1972) [2]	UCS = 23.7 PLS	250
Bieniawski (1974; 1975) [3] [4]	UCS = 23 PLS	350
Brook (1977; 1980) [5] [6]	UCS = 12.5 PLS	300
Hassani *et al.* (1980) [7]	UCS = 29 PLS	200
ISRM Commission (1985) [8]; Brook (1985) [9]	UCS = 20···25 PLS	250
Hikita and Kikuchi (1988) [10]	UCS = 12.3···15.0 PLS	200
Kahraman (2001) [11]	UCS = 23.62 PLS − 2.69	150
Kahraman (2001) [11]	UCS = 8.41 PLS + 9.51	150

northeastern Hokkaido, Japan (**Figure 1**), using irregular lump PLS (IPLS) test specimens. In addition, we obtained the relationship between the NP index and UCS. It is expected that the results can provide a practical method that will be useful for evaluation of landslide hazards, for landslide hazard mapping, rock classification, and other applications.

2. Rock Samples

Rock samples, which were collected primarily from the earth's surface in ancient hydrothermal fields in northeastern Hokkaido, Japan, were hydrothermally altered volcaniclastic rocks, including fine tuff, medium tuff, pumice tuff, lapilli tuff, welded tuff, dacite, tuffaceous mudstone, tuffaceous sandstone, and tuffaceous conglomerate. The modes of occurrence of these hydrothermally altered rocks were examined in the field, and the hydrothermal alteration minerals in the rocks were identified primarily by X-ray powder diffraction (XRD) tests.

3. Methods and Equipment

3.1. Irregular Lump Point Load Strength Test

The IPLS test was conducted in accordance with ISRM Commission (1985) [8]. In the IPLS tests, the specimens were loaded to failure by application of a concentrated load through a pair of spherically truncated, conical platens. The testing machine consisted of conical loading platens, a loading frame, dial gauge, manual control handle, load cell, and load measuring system (**Figure 2**). The loading speed was set so that each specimen failed within 10 - 60 s. This was achieved using a manual control handle by loading each specimen continuously at a constant (as much as possible) loading speed up to approximately 100 N/s of load increase. The size-corrected IPLS index of a rock specimen was defined as the value of PLS that would have been measured by a diametral PLS test with diameter $D = 50$ mm ($D_e^2 = 2500$ mm^2, where D_e is the equivalent core diameter). The IPLS index can be represented by the formula:

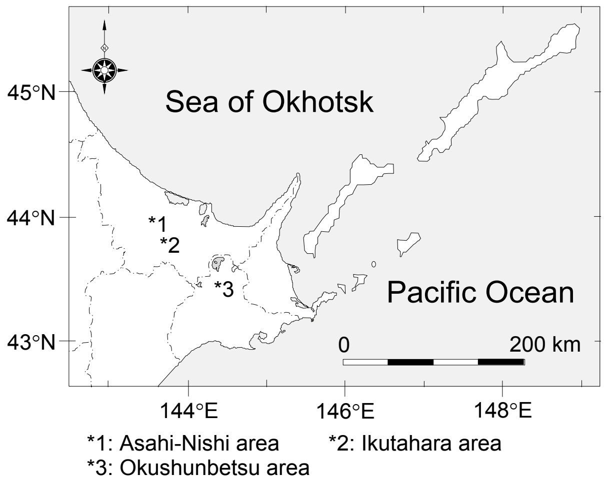

Figure 1. Location of the sampling sites in northeastern Hokkaido, Japan.

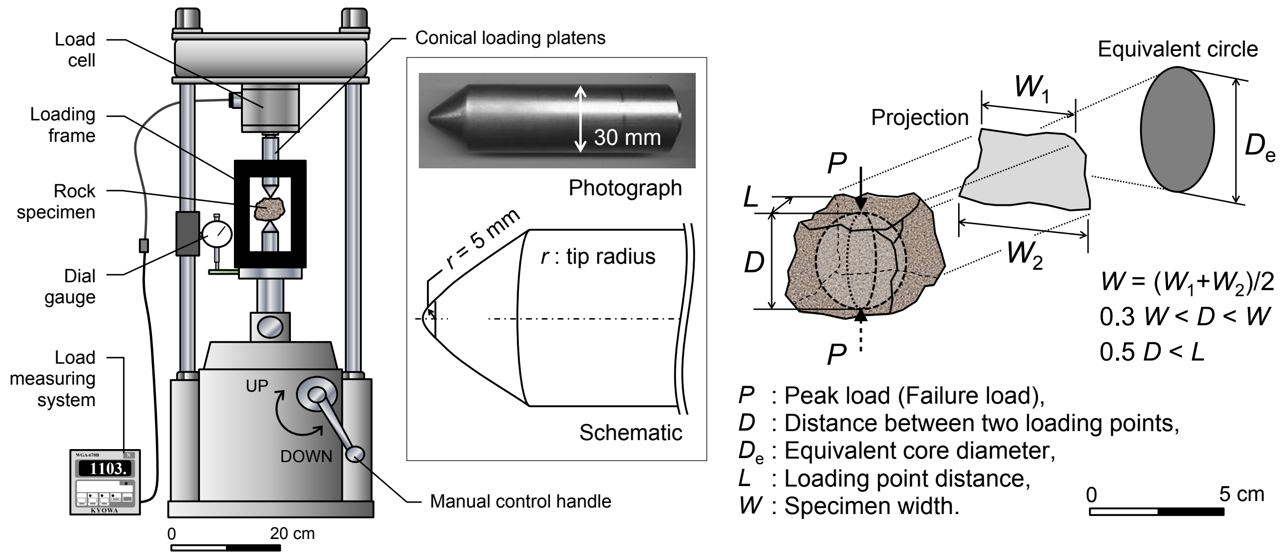

Figure 2. Point load strength testing machine, shape of rock specimen, load configuration, and conditional expression for irregular lump point load strength test.

$$I_{s(50)} = F \frac{P}{D_e^2} \tag{1}$$

where F is the size correction factor, P is the peak load (failure load), and D_e is the equivalent core diameter. D_e is the diameter of a circle with an area equal to the minimum area of the cross sections containing the two loading points, and can be represented by the formula:

$$D_e^2 = \frac{4WD'}{\pi} \tag{2}$$

where D_e is the equivalent core diameter, W is the specimen width, and D' is the distance between the two loading platens at the time of failure. The ISRM Commission (1985) [8] stipulated that if significant penetration of the conical platens occurs during the test, such as when testing soft rocks, the value of D' should be the final value of the distance between the two loading platens. Therefore, in this study, the PLS was calculated using the distance between the two loading platens at the time of failure:

$$D' = D - \alpha \tag{3}$$

where D' is the distance between the two loading platens at the time of failure, D is the distance between the two loading platens, and is the penetration distance of the conical platens. The distance between the two loading platens and the penetration distance of the conical platens were measured using slide calipers and a dial gauge (analog type), respectively. F can be represented by the formula:

$$F = \left(\frac{D_e}{50}\right)^{0.45} \tag{4}$$

where F is the size correction factor, and D_e is the equivalent core diameter.

In this study, irregular lump specimens were used for the IPLS tests (**Figure 2**). The IPLS test specimen sizes satisfied the conditional expression of $0.3W < D < W$ and $0.5D < L$ (ISRM Commission (1985) [8]; **Figure 2**).

3.2. Needle Penetration Test

The NP test was conducted in accordance to the methods proposed by Okada *et al.* (1985) [24] The needle penetrometer (**Figure 3**) consisted of the penetration needle, load indication ring, penetration and load scales, chuck, spindle, and penetration indication cap. The NP index can be represented by the formula:

$$\text{NP index} = \frac{P}{a} \tag{5}$$

where P is the penetration load, and a is the penetration depth.

3.3. Specimen Moisture Content and Number of Specimens

The IPLS, NP, and UCS tests in this study were performed using a laboratory testing machine with specimens in forced-dry, forced-wet, and natural-moist states. The forced-dry and forced-wet states included absolutely dry and fully water-saturated specimens, respectively. The specimens were dried in an electric oven at a temperature below 60˚C for 4 days or more to achieve a constant mass and were saturated with water for 15 days or more to achieve a constant mass, respectively (Kohno *et al.* (2010) [25]).

A total of 9 different rock types were sampled, and the total number of rock specimens tested was 2413 for the IPLS test, 180 for the NP test, and 262 for the UCS test (**Table 2**). The number of specimens in **Table 2** does not include invalid test specimens.

4. Results and Considerations

Data points in the **Figures 4(a)-(d)** and **Figure 5** is the average value of specimens, and numbers of the points is same numbers of sampling sites.

4.1. Relationship between IPLS Index and Uniaxial Compressive Strength

The relationships between the IPLS index and UCS in soft rocks with a UCS below 25 MPa are shown in **Figure 4**. Such samples that do not satisfy the number

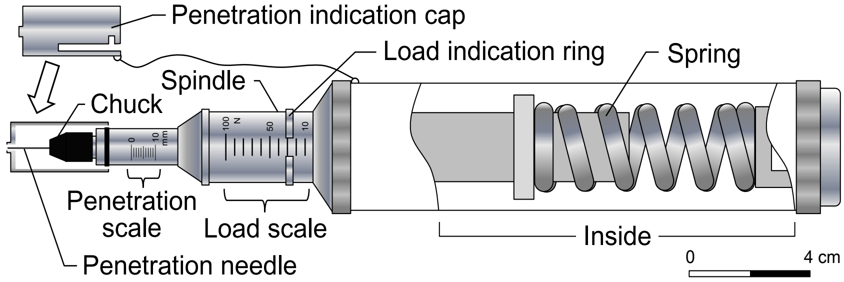

Figure 3. Needle penetrometer.

Table 2. Numbers of specimens and sampling sites.

Rock type	Irregular lump point load strength test		
	Forced-dry state	Forced-wet state	Natural-moist state
f Tf	302 (12)	426 (19)	401 (10)
m Tf	25 (1)	22 (1)	-
pm Tf	195 (6)	129 (6)	81 (2)
lap Tf	28 (1)	102 (3)	66 (2)
weld Tf	76 (3)	66 (3)	50 (1)
tfMs	-	15 (1)	46 (1)
tfSs	117 (3)	96 (3)	100 (2)
tf Cg	10 (1)	12 (2)	-
Dac	23 (1)	25 (1)	-
Rock type	**Needle penetration test**		
	Forced-dry state	**Forced-wet state**	**Natural-moist state**
f Tf	-	-	100 (10)
m Tf	-	-	-
pm Tf	-	-	20 (2)
lap Tf	-	-	20 (2)
weld Tf	-	-	10 (1)
tfMs	-	-	10 (1)
tfSs	-	-	20 (2)
tf Cg	-	-	-
Dac	-	-	-
Rock type	**Uniaxial compressive strength test**		
	Forced-dry state	**Forced-wet state**	**Natural-moist state**
f Tf	35 (12)	63 (19)	-
m Tf	1 (1)	1 (1)	-
pm Tf	34 (6)	32 (6)	-
lap Tf	1 (1)	10 (3)	-
weld Tf	16 (3)	16 (3)	-
tfMs	-	3 (1)	-
tfSs	19 (3)	17 (3)	-
tf Cg	2 (1)	2 (2)	-
Dac	5 (1)	5 (1)	-

fTf: Fine tuff, m Tf: Medium tuff, pm Tf: Pumice tuff, lap Tf: Lapilli tuff, weld Tf: Welded tuff, tfMs: Tuffaceous mudstone, tfSs: Tuffaceous sandstone, tf Cg: Tuffaceous conglomerate, Dac: Dacite.
( ): Numbers of sampling sites.

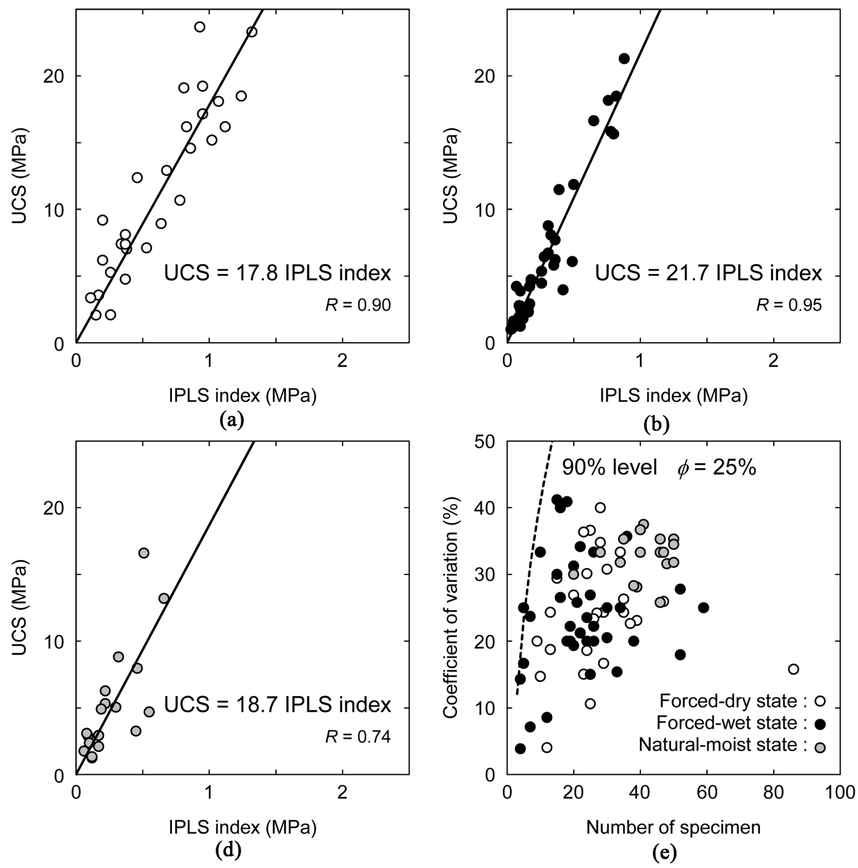

Figure 4. Relationship between irregular lump point load strength index and uniaxial compressive strength in the forced-dry state (a), forced-wet state (b), forced-dry and forced-wet states (c), natural-moist state (d), and relationship between number of irregular lump point load strength test specimens and coefficients of variation (e).

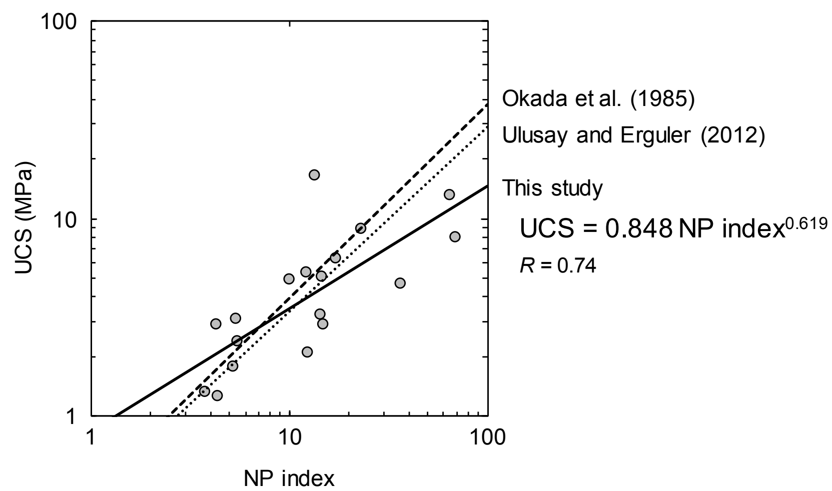

Figure 5. Relationship between needle penetration index and uniaxial compressive strength in the natural-moist state.

of specimens required for the coefficient of variation or those that have only one specimen were eliminated in IPLS and UCS tests, respectively; they were not included in the analysis. The correlations between the IPLS index and UCS in the forced-dry and forced-wet states were linear. The line drawn through the data points is the best fit, determined by the method of least squares regression. The equations and correlation coefficients for the forced-dry state were

UCS = 17.8 × (IPLS index), and $R = 0.90$ (Figure 4(a)), respectively.

And those for the forced-wet state were

UCS = 21.7 × (IPLS index), and $R = 0.95$ (Figure 4(b)), respectively.

Here, R is the correlation coefficient. The correlation coefficients for the forced-dry and forced-wet states were 0.90 and 0.95, respectively, indicating a strong correlation. We attempted to combine the forced-dry and forced-wet states. The equation and correlation coefficient for the line were

UCS = 18.9 × (PLS index), and $R = 0.93$ (Figure 4(c)), respectively.

Where R is the correlation coefficient. The scatter in the data points was lesser at low strengths, and slightly higher at higher strengths (Figure 4(c)). The relationship was established by combining those for the forced-dry and forced-wet states, and a strong correlation between them was observed as well. In soft rocks, the relationships between the IPLS index and UCS in the "forced-dry and forced-wet states (Figure 4(c))" and "natural-moist state (Figure 4(d))" were similar. Therefore, it can be concluded that it is also possible to apply the relationship to onsite tests of soft rocks in the natural-moist state, which is intermediate between the forced-dry and forced-wet states. The UCS under natural-moist state in this study was estimated based on water content of specimen.

4.2. Relationship between NP Index and UCS

The relationships between the NP index and UCS in soft rocks with a UCS below 25 MPa are shown in Figure 5. The equation and correlation coefficients for the natural-moist state are

UCS = 0.848 × (NP index)$^{0.619}$, and $R = 0.74$ (Figure 5), respectively,

Where R is the correlation coefficient. On comparing this equation to that proposed by Okada *et al.* (1985 [24]; logUCS = 0.978 log (NP index) + 1.599) and Ulusay and Erguler (2012 [20]; UCS = 0.4 (NP index)$^{0.929}$), there were differences observed in slope of the graph. One of the reasons why the equation in this study and that proposed by Okada *et al.* (1985) [24] and Ulusay and Erguler (2012) [20] differed was that the rock sample was a hydrothermally altered soft rock with a UCS below 25 MPa. Therefore, we need to choose either the equation proposed in this study (soft rocks) or that proposed by Okada *et al.* (1985) [24] and Ulusay and Erguler (2012) [20] (hard rocks). Thereby, we can obtain a more accurate value of UCS.

4.3. Variation in the Tests

The discrepancies in the IPLS and UCS tests were calculated using a coefficient of variation:

$$C_v = \frac{S}{x} \times 100(\%) \tag{6}$$

where C_v is the coefficient of variation, S is the standard deviation, and x is the average of the IPLS (or UCS) test results. The coefficient of variation can be used to determine the number of specimens required for IPLS testing. The number of specimens required to obtain results within $\phi = 25\%$ of the average value over a one-sided confidence interval at a 90% level of confidence was 5, 7, and 10 for a C_v of 20%, 30%, and 40%, respectively (dashed line in **Figure 4(e)**). The relationships between the number of IPLS test specimens and the coefficient of variation are shown in **Figure 4(e)**. A sufficient number of specimens were used for most of the IPLS tests. The coefficient of variation for most UCS specimens was less than 25%, ensuring that precise measurements were obtained for these tests. Therefore, the IPLS and UCS testing methods established in this study were highly precise. On the other hand, the coefficient of variation for most NP specimens was less than 20%.

5. Conclusions

The following is a summary of our findings related to the UCS estimates of hydrothermally altered soft rocks from northeastern Hokkaido, Japan, based on our IPLS test and NP test results.

1) The relationships between the IPLS index and UCS and the NP index and UCS were "UCS = approximately 19 × (IPLS index)" and "UCS = 0.848 × (NP index)$^{0.619}$", respectively in soft rocks with UCS below 25 MPa.

2) In soft rocks, the relationships between the IPLS index and UCS in the "forced-dry and forced-wet states" and "natural-moist state" were similar. Therefore, it can be concluded that it is also possible to apply the relationship to onsite tests of soft rocks in the natural-moist state, which is intermediate between the forced-dry and forced-wet states.

3) We need to choose either the equation proposed in this study (soft rocks) or that proposed Okada *et al.* (1985) [24] and Ulusay and Erguler (2012) [20] (hard rocks). Thereby, we can obtain a more accurate value of UCS.

4) The number of tested specimens satisfied the accuracy requirements based on the coefficient of variation. The IPLS was strongly correlated with the UCS. Therefore, the relationships between IPLS and UCS established in this study were highly precise.

5) The IPLS and NP tests were convenient and effective because they could be performed promptly using onsite and laboratory testing equipment for various shaped small rock specimens taken from outcrops or floats.

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