Jurnal Teknologi

Full paper

Estimating Uniaxial Compressive Strength of Tropically Weathered Sedimentary Rock Using Indirect Tests

Maybelle Liang,* Edy Tonnizam Mohamad, Ma Chau Khun, Mohd Nur Asmawisham Alel

Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia

*Corresponding author: maybelle_liang@hotmail.com

Article history

Received: 17 August 2014
Received in revised form:
17 November 2014
Accepted: 24 December 2014

Graphical abstract

Abstract

Uniaxial compressive strength (UCS) of intact rock is particularly important in rock mechanic studies, especially for those involving civil and mining projects. However, the determination of UCS using direct test is generally expensive, time consuming and almost impossible in preparation of samples for highly weathered sedimentary rocks. In view of this, indirect tests are comparatively cheap, simpler, faster and more convenient to perform either in laboratory or at site. This paper aims to develop an estimation procedure in determining the UCS values of such weak weathered rocks. Among the indirect tests present herein are point load index, Schmidt Rebound hammer, Brazilian tensile test and slake durability test. Unfortunately, it was found that the accuracy of each single test varies with weathering states. Hence, a recommended procedure using combined indirect tests in determining UCS of weak sedimentary rocks is presented herein.

Keywords: Sedimentary rock, Point load index, Schmidt Rebound hammer, Brazilian test, Slake durability, weathering

Abstrak

Kekuatan mampatan sepaksi (KMS) bahan batuan adalah amat penting dalam kajian mekanik batuan, terutamanya yang melibatkan projek-projek awam dan perlombongan. Namun demikan, penentuan KMS melalui ujian secara langsung adalah agak berkos tinggi, memakan masa dan proses penyediaan sampel batuan sedimen terluluhawa adalah amat sukar untuk dilakukan. Memandangkan situasi-situasi yang dinyatakan, ujian-ujian kekuatan tidak langsung adalah lebih murah, ringkas, cepat dan mudah untuk dilaksanakan sama ada di dalam makmal atau di tapak kajian. Kertas ini bertujuan untuk membangunkan satu prosedur anggaran untuk menentukan nilai KMS batuan-batuan terluluhawa. Antara ujian kekuatan tidak langsung yang diambilkira ialah ujian beban titik, tukul pantulan Schmidt, ujian ketegangan Brazilian, dan ujian pemeroian. Adalah didapati bahawa ketepatan setiap ujian tersebut adalah tidak tentu bagi setiap keadaan luluhawa batu yang berlainan. Maka, satu prosedur cadangan yang menggabungkan ujian-ujian tidak langsung tersebut dalam menentukan KMS batuan sedimen lemah akan dibentangkan di bawah.

Kata kunci: Batuan sedimen, kajian mampatan sepaksi, tukul pantulan Schmidt, ujian ketegangan Brazilian, ujian pemeroian, keluluhawaan

1.0 INTRODUCTION

Intact rock strength is particularly important in rock mechanics engineering. The strength of rock is the most important input parameter used in the engineering projects such as excavation, mining and slope stability. Uniaxial Compressive Strength (UCS) test is inevitably the most reliable means to determine the rock strength. However, it is almost impossible to prepare the UCS samples for weathered weak sedimentary rock.[1,2,3] Besides, it is also the most expensive and time-consuming practice since it involves the transportation of the samples to laboratory and its testing is based on strict laboratory procedures.

Hence, it is particularly important and necessary to conduct indirect tests to estimate the UCS value of such rocks.

In this paper, the results of various indirect tests performed to determine their suitability in estimating the intact rock strength are presented. The indirect tests used in this study are Point load test, Schmidt Rebound hammer test, Brazilian test and slake durability test. As a matter of fact, many researchers have studied the relationship between indirect tests and UCS values. For point load test (PLT), the relationship between point load index and UCS for hard rock has long been introduced. The most frequently cited correlations between Point load index (*Is*) and UCS are UCS = 24*Is* ,[4] UCS = 22.7 *Is* ,[5] and UCS = 20-25*Is*.[6,7] Unfortunately, the above mentioned empirical equations were dedicated for hard rocks and correlations for weathered sedimentary rock which is weak in nature are yet to establish.

On the other hand, past researchers also proposed empirical equations for evaluating the rock strength based on Rebound hammer value (*R*). The philosophy behind is the Schmidt hardness and the UCS are closely related. Miller suggested a correlation tables which reflects the relationships between unit weight,[8] UCS and rebound values. This table was enhanced by Deere and Miller incorporated the rock density,[9] Young's modulus and rebound values. Kindybinski proposed an empirical formula,[10] making use of *R* values for estimating the rock strength. Ghose and Chakrabarti have suggested an empirical relationship between Schmidt rebound values and UCS for Indian coals.[11] Sachpazis developed a formula relating the UCS and young's modulus.[12] Aggistalis et al. compared the point load index, *R* values and *E* of gabbros and basalts, and an empirical formula was proposed for these rocks.[13] Katz et al. compared *R* with the UCS, *E* and rock density of different types of rocks.[14] Kilic and Teymen proposed an empirical formula between Schmidt harness and UCS for igneous rock.[15] It was established that the Schmidt Rebound value, *R* can be correlated with the rock strength based on these extensive literature review. However, the correlations for weathered sedimentary rocks have not yet been established and the direct application for these existing empirical formulas is being questioned due to large varieties of rock properties in weathered sedimentary rock. Table 1 shows the proposed correlation between the Schmidt hammer values and UCS.

Studies have also shown that compressive strength can be related to tensile strength of rock samples. The accuracy of the correlation is highly dependent on the ratio between compressive strength and tensile strength of the rock material.[16,17] Kahraman et al. conducted a research on UCS and Indirect Tensile Strength (ITS) of different type of rocks.[18] Based on their studies, a linear correlation was proposed. Farah showed in her study that the correlation of UCS with ITS is better compared to *Is*.[19] Altindag and Guney found strong correlation between UCS and ITS for wide range of rock typses.[20] Din and Rafigh found this correlation can also be extended to limestone in Pakistan.[21] Table 2 shows the correlations between UCS and ITS.

Comparatively, there are only few studies relating the UCS with durability of rock. Eigenbrod found in his study that UCS reduction correlated well with decreased durability.[22] Unfortunately, no correlations were developed for UCS and slake durability strength (SDS). Bonelly,[23] and Cargill and Shakoor,[24] tried to develop the correlation between UCS and SDS. Bonelli concentrated on sandstones,[23] whereas Cargill and Shakoor focused on carbonate and granitic rocks.[24] They concluded that SDS would be useful when a wide range of values could be obtained particularly for weak or highly weathered rocks.

Table 1 Correlation between *R* and UCS

Researcher	Equations	R^2	Rock type
Deere and miller (1966)	$UCS = 10^{(0.00014\gamma R+31.6)}$	0.94	Three based rock types
Kidybinski (1980)	$UCS = 0.447exp\,[0.045(R + 3.5) + \gamma]$	0.72	Rock coal
Ghose and Chakraborti (1986)	$UCS = 0.88R – 12.11$	0.77	Coal
Sachpazis (1990)	$R = 0.2329UCS + 15.7244$	0.81	33 Lithological units
Aggitalis (1996)	$UCS = 1.31R – 2.52$	0.55	Gabbro and basalt
Kilic and Teymen (2008)	$UCS = 0.0137\ R^{2.2721}$	0.97	19 different rock types

R^2: regression coefficient, R: Schmidt values, UCS: Uniaxial compressive strength (MPa), γ: density of rock (g/cm^3)

Table 2 Correlation between ITS and UCS

Researcher	Equations	R	Rock type
Kahraman et al. (2012)	$UCS = 10.61 \times ITS$	0.5	Varies
Farah (2011)	$UCS = 5.11 \times ITS – 133.86$	0.68	Limestone
Altindag and Guney (2010)	$UCS = 12.38\times ITS^{1.0725}$	0.89	Varies rock type

R: regression coefficient, ITS: Indirect Tensile STrength, UCS: Uniaxial compressive strength (MPa)

2.0 GEOLOGY OF STUDIED AREA

This study aims to investigate the properties of tropically weathered sedimentary rock in Nusajaya, Jurong Formation. The samples were collected from three separate sites namely SiLC 1, SiLC 2 and Legoland. The rock mass in these sites were mainly composed of shale and immature sandstone, with very little siltstone, conglomerate and volcanic layers. In accord with the regional strike, this feature swings from north-northwest direction in the north to west-northwest in the south. The ridge is composed mainly of argillaceous rocks and has been subjected to considerable dissection.

Figure 1 Geological map of studied sites

2.1 Properties of Weathered Sandstone and Shale

Tropic country has sunny flux all the year (22-32°C), high moisture content in air and underground, high quantity of rain (> 1200 mm) and underground water of 28 °C.[25]
With these characteristics, climate has great influence to exegetic process especially to chemical weathering where high intensity of rain and high temperature will accelerate the weathering process.

Several studies have been done to further understand the geotechnical properties of weathered sedimentary rock in Peninsular Malaysia.[26,27] The results show that material properties of rock deteriorate from the fresher material as more intense weathering took place. The weathered rock has lesser strength due to the presence of micro fractures and the loosening of the bonding between grains.[28] The weathering effect can take place up to 100 m down from the ground surface in tropical areas.

Generally, sedimentary rock mass consists of more than a type of rock and always forms alternate laminated because of natural forming process and also exposed to tectonic effect and pressure.

3.0 LABORATORY TEST PROCEDURE

Rock strength test is used to verify the resistance of rock against loading. The rock strength test can be classified as direct or indirect based on comparison between the outputs of the test with the desired testing properties. For instance, the output of point load test is point-load index but 'indirectly' used to estimate UCS value. UCS test is direct test as its output can be read as UCS value 'directly.' The summary of each test carried out is shown in Table 3.

3.1 Uniaxial Compressive Strength Test

UCT is used for estimating the compressive strength of rock specimens under uniaxial loading. The compressive strength of rock sample is obtained through loading rock specimens under either load-controlled condition or strain-Controlled condition depends on the accuracy requirement in stress-strain curve. Generally, both of them can produce accurate UCS values but the latter is more accurate in determining complete stress-strain curve. The testing of UCS sample is illustrated in Figure 2(a). In this study, a total of 29 and 9 UCS samples were prepared for sandstone and shale respectively.

Table 3 Summary of tests performed

Type of test	Standard	No. of Samples	
		sandstone	Shale
UCT	ISRM (1985)	29	9
PLT	ISRM (1985)	190	100
Schmidt Hammer Test	ASTM (2005)	290	170
ITS	ISRM (1981)	34	12
Slake Durability Test	ISRM (1981)	320	100

3.2 Point Load Index Test

The point load test has been used in geotechnical analysis of over thirty years. The test involves the compressing of a rock sample between conical steel platens until failure occurs. The apparatus for this test consists of a rigid frame, two point load platens, a hydraulically activated ram with pressure gauge to measure the applied load. The point load test is illustrated in Figure 2(b).

The ISRM established the basic procedures for testing and calculation of the *Is*.[29] The point load allows the determination of the uncorrected point load strength which is *Is* and to be corrected to the standard equivalent diameter (De) of 50 mm. if the core being tested is around 50 mm in diameter, correction is not needed. The procedure for size correction can be obtained graphically or mathematically as outlined by ISRM.[29] The value for corrected point load index, I_{S50} is determined by the following equation:

$$\sigma_t = \frac{0.636P}{Dt} \quad (2)$$

$$I_{S50} = \frac{P}{De^2} \quad (1$$

where *P* is the failure load. As pointed out by Hoek,[30] the mechanics of PLT has tendency to cause the rock to fail in tension. He found that the accuracy of PLT in predicting UCS has mainly depends on the ratio between the UCS and tensile strength. For most brittle rocks, this ratio is approximately 10 but for weak rocks, the ratio drops drastically to approximately 5. This implies that the *Is* might be not accurate for weak sedimentary rock. In this study, a total of 290 samples were tested, with 190 sandstone samples and the remaining are shale samples.

3.2 Schmidt Rebound Hammer Test

In this study, the L-type Schmidt hammer was used to measure Rebound value, *R*. The tests included conducting rebound hammer test in-situ of each panel on the abovementioned sites. At each point about 20 cm x 20 cm surface of the rock was prepared by peeling off using hammer and performing about 10 tests on each panel. Among the numbers obtained, 7 closest values were selected and the average value was considered as Schmidt number for that particular point.

where *P* is the load at failure, *D* is the diameter of the test specimen and *t* is the thickness of specimen.

3.3 Slake Durability Test

The slake durability test was originally developed by Franklin and Chandra,[33] recommended by ISRM.[32] It measures the percentage of dry weight of material retained in a steel mesh drum after rotation in a trough of water. Gamble encouraged the adoption of a second cycle after drying.[34] The slake test was originally developed to provide an indication of material behaviour during the stresses of alternate wetting and drying, which to some degree simulates the effects of weathering.

In using this method, 10-rock lumps were chosen with a mass-40-60 g to give a total sample mass of 450- 550g. The maximum grain size did not exceed 3 mm. The lumps are roughly spherical in shape and rounded corners during preparation. The lump is placed in a clean drum and is dried to constant mass at a temperature of 105°C

The procedure was following ASTM standards.[31]

3.4 Brazilian Test

There are many difficulties in performing a direct uniaxial tensile test on rock. Thus, Indirect Tensile test (ITS) or Brazilian test, has been proposed. The test involves of loading a rock cylinder diametrically between two platens. The diametric loading of a small rock disc is performed by Universal Testing Machine (UTM), which complies to ISRM requirements for the indirect testing of tensile strength.[32] The test method consists of loading the disc until failure occurs along its diametric axis. The disc is prepared from 48 mm diameter core samples with a thickness to diameter ratio of 1:2. In order to ensure uniaxial failure and hence the validity of the test, the failure of the disc should initiate at the center of the specimen. Due to the induction of high shear stresses at the point of contact, it is recommended that this test is only done on specimens with high shear to tensile stress ratio. The measurement of the tensile strength by the ITS give reproducible results. This is due to the smaller the size of specimen required for the test, a smaller initial sample is required. However, the necessity for machining and grinding make the preparation time is particularly inconvenient. The tensile strength of the specimen can be calculated using the following expression:

and requires 2 to 6 hours in an oven. The mass A of the drum plus sample is recorded. The sample is then tested after cooling.

The lid was replaced, the drum mounted in the trough and coupled to the motor. The trough was filled with slaking fluid, usually tap water at 20°C, to a level 10 mm below the drum axis, and the drum rotated for 200 revolutions during a period of 10 minutes to an accuracy of 0.5 minutes. The drum was then removed from the trough, the lid removed from the drum, and the drum plus retained portion of the sample dried to a constant mass at 105°C. The mass B of the drum plus retained portion of the sample is recorded after cooling. The steps were repeated and the mass C of the drum plus retained portion of the sample was recorded. The drum is cleaned and its mass, D was recorded. The slake durability index (second cycle) was calculated as the percentage ratio of final to initial dry mass samples masses as follows:

$$I_{d2} = \frac{C-D}{A-D} \times 100 \quad (3)$$

The second cycle slake durability index, calculated in Equation 3 is used in this paper. However, the samples with second cycle indexes ranging from 0 to 10 percent are further characterized by their first cycle slake durability indexes as follow:

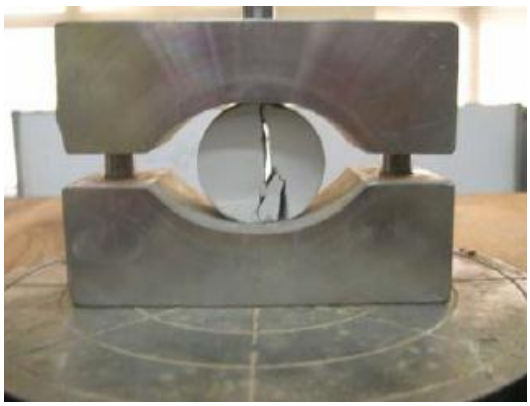
$$I_{d1} = \frac{B-D}{A-D} \times 100 \quad (4)$$

where Id_1 and Id_2 are slake durability index for first cycle and second cycle respectively.

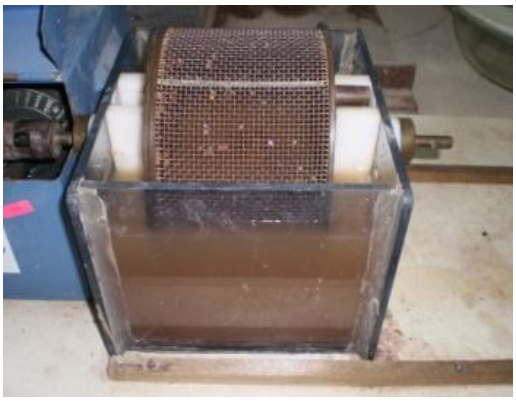
(a) UCS samples are ready to be tested

(b) PLT on irregular samples

(c) Surface hardness test using rebound hammer



(d) Indirect tensile test or Brazilian test



(e) Slake durability test on weak samples

Figure 2 Laboratory rock strength test

■4.0 RESULT AND ANALYSIS

4.1 Estimating ICS using I_{S50}

Figure 3 shows the correlation made between Is50 and UCS. Figure 3(a) and 3(b) present the correlation for sandstone and shale respectively. It should be noted that no fresh rock samples were discovered at study sites, hence no data for this particular weathering state is presented. Meanwhile for shale, only moderately weathered, highly weathered and completely weathered states were presented due to the similar reasons as stated above.

Based on close observation, it was found that the Is50 is best represented UCS for sandstone as the R^2 based on linear regression is 0.9239 indicating high correlation for sandstone compared to 0.7723 only for shale. This is mainly due to the assumption made for UCS values for highly weathered shale as no UCS sample can be prepared. In this study, it is assumed that the UCS value for highly weathered shale is zero. However, the correlation for moderately weathered shale also can be seen scattered. This is mainly due to Shale has denser lamination structure compared with Sandstone and the loading tip can easily initiate the cracking between the lamination. It was observed in the test that when the orientation of lamination is almost parallel to the loading tip, even very small load can break the sample. As the investigation on the effects of orientation of lamination to PLT value is beyond the scope of this study, detail discussion will not be made herein. Hence, it is recommended that PLT can be used to estimate UCS strength for sandstone from slightly weathered state rock to completely weathered state rock. The use of PLT to estimate shale is not recommended.

4.2 Estimating UCS using *R*

Figure 4 shows the correlation between rebound hammer value, *R* and Is50. Theoretically, the compressive strength of a rock material can be represented by surface hardness, but the results from the linear regression shown counter-intuitive.

As can be seen in Figure 4, both *R* values for sandstone and shale do not correlate well with UCS. The linear regression R^2 values for sandstone and shale is 0.5954 and 0.9122 respectively showing non-correlation. The high R^2 value for shale is due UCS value and *R* value for highly and completely weathered shales returned to zero. However, as can be seen in PLT test, shale from these weathering zones present very small compressive strength. Hence it is assumed that rebound hammer test is too insensitive to be used to test highly weathered and completely weathered shale. Higher scatter can be observed with the increase of weathering states for sandstone mainly due to the insensitivity of the rebound hammer. Hence, it is not recommended to use *R* value to estimate the UCS value for weathered weak sedimentary rocks.

4.3 Estimating UCS using ITS

Figure 5 shows the correlation between ITS and UCS. As discussed previously, the accuracy of the correlation between ITS and UCS depends on the ratio of compressive and tensile strength of the rock material. Figure 5 confirms that ITS is appropriate to be used in estimating UCS vale for sandstone and sufficiently adequate for moderately weathered shale as the ITS and UCS shows constant linear relationship. In fact, this finding has been widely reported elsewhere where UCS can be proportionately represented by ITS[16-21]. However, due to the difficulties in sample preparation, it is also not recommended to use ITS for samples with higher weathering state.

4.4 Estimating UCS using Slake Durability Index

Figure 6 shows the correlation between slake durability index and UCS values. It should be noted that all the slake durability index here were obtained based on second cycle values except completely weathered sandstone and highly weathered cum completely weathered shale using first cycle values. This is due to the latters are too weak to perform second cycle.

For sandstone, the slake durability index is well correlated with UCS except for slightly weathered sandstone. This might be due to 1 cycles tests have negligible effect on this type of material hence led to inaccurate results. On the other hand, the correlation between slake durability index of first cycle and UCS is agreeable for shale, although small scatter can be found for moderately weathered shale. It also can be seen that slake durability index is more appropriate to be used for weak rock compared to strong rock. Hence, it is recommended that the slake durability index can be used to estimate UCS values for both sandstone and shale with weathering states beyond slightly weathered state.

■5.0 PROPOSED TEST PROCEDURES

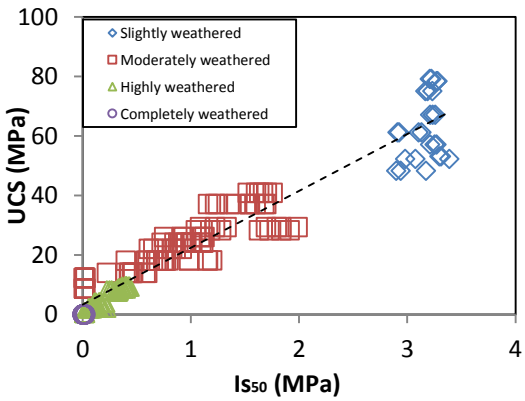
Table 4 lists the summary of indirect tests which are appropriate to be used for estimating UCS of sandstone and shale with different weathering states. The shaded box indicates the tests suitable to be used for this particular weathering state by considering the possibility in sample preparing and good correlation. Table 5 lists the empirical correlation equations which can be used to estimate UCS values based on linear regression analysis.

For estimating UCS values for tropically weathered sedimentary rocks in Nusajaya, Malaysia, it is recommended that one should refer to Table 4 for suitability for the indirect test selection. Different indirect tests should be selected for different types of rock as well as different states of weathering. After the selection of indirect tests to be used, the UCS values can be estimated by referring to Table 5. The empirical equations proposed herein are not exactly accurate in estimating UCS values for tropically weathered sedimentary rocks but sufficient adequate to give an insight for preliminary design.

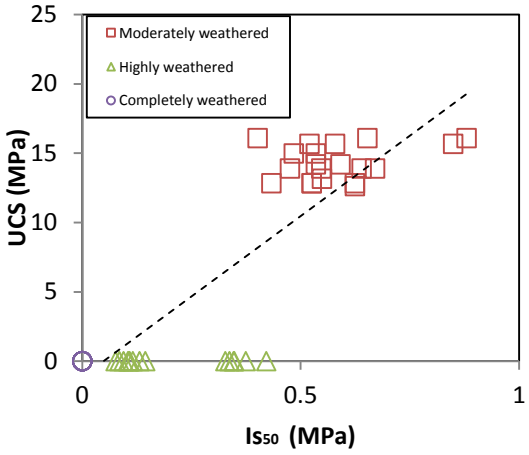
■6.0 CONCLUSIONS

Four different types of indirect tests have been conducted to justify their suitability in estimating UCS values of tropically weathered sedimentary rocks. Based on tests carried out, it was found that majority of the indirect test values decrease with increasing weathering states. Hence, it can be concluded that material strength generally deteriorates with increase of weathering states. However, some of the indirect tests carried out herein are too insensitive such as Rebound hammer test which showed large inaccuracies in estimating UCS values for tropically weathered sedimentary rocks. The use of PLT in estimating UCS values for sandstones is promising but less effective for shale. For Brazilian test, it was found that good correlation can be found for ITS and UCS. The slake durability test suggested good correlation with UCS for very weak material. The accuracy is not pronounced for stronger rocks.

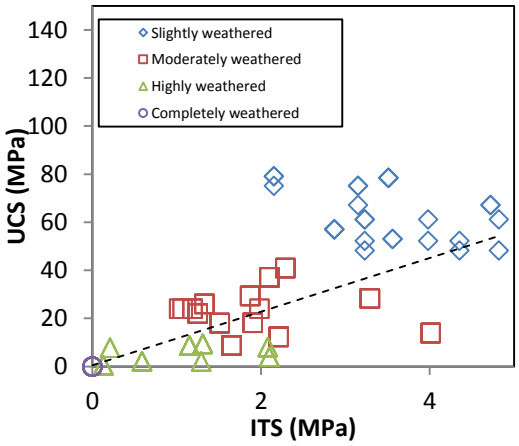
Based on the analysis carried out herein, the suitability of each indirect test was proposed for each different rock types with corresponding weathering states. The empirical equations for each indirect test to predict UCS values of tropically weathered sedimentary rocks are then proposed. It is clearly shown in this study that no single testing method can be used to predict the UCS values for all weathering grades.



(a) Sandstone

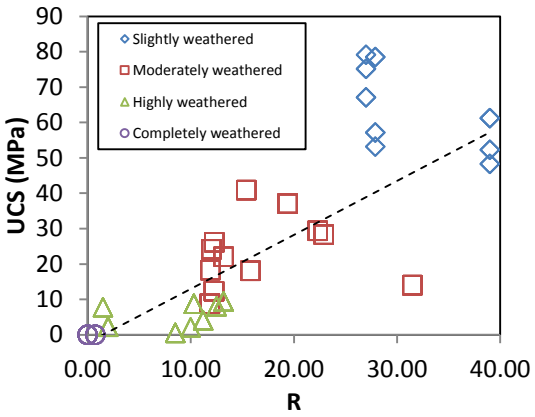


(b) Shale

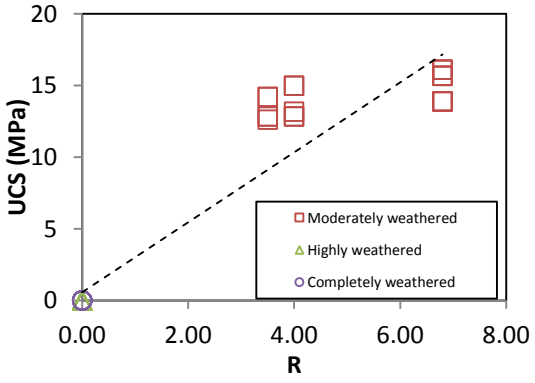


(a) Sandstone

Figure 3 Correlation between Is50 and UCS

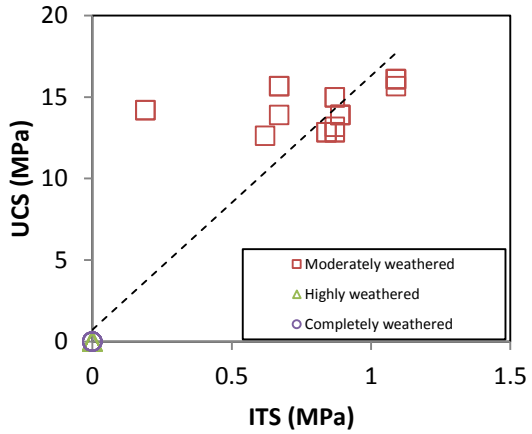


(a) Sandstone



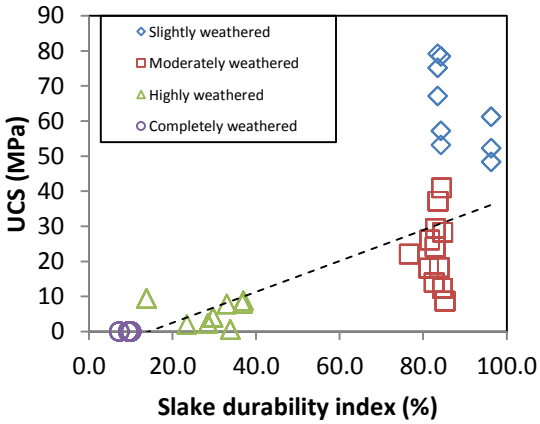
(b) Shale

Figure 4 Correlation between *R* and UCS

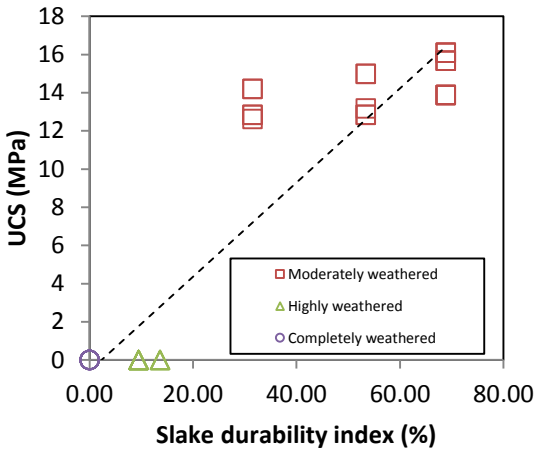


(b) Shale

Figure 5 Correlation between ITS and UCS



(a) Sandstone



(b) Shale

Figure 6 Correlation between Id to UCS

Table 4 Suitability of indirect tests in estimating UCS

(a)Sandstone

Weathering states (Sandstone)				
Testing	Slightly	Moderately	Highly	Completely
PLT				
R				
ITS				
Id_2				

(b)Shale

Weathering states (Shale)				
Testing	Slightly	Moderately	Highly	Completely
PLT				
R				
ITS				
Id_1				

Table 5 Empirical equations for estimation of UCS

(a)Sandstone

Weathering states (Sandstone)			
Testing	Equation		R^2
PLT	$UCS = 19.122Is_{50} + 3.2906$	(5)	0.9239
Id	$UCS = 0.3\ Id_2 - 2.87$	(6)	0.6214

(b)Shale

Weathering states (Sandstone)			
Testing	Equation		R^2
ITS	$UCS = 15.588ITS + 0.7169$	(7)	0.9239
Id	$UCS = 0.2466Id_1 - 0.5707$	(8)	0.8749

References

[1] Romana, M. 1999. Correlation between Unconfined Compressive and Point-load (Miller tests) Strengths for Different Rock Classes. *9th ISRM Congress*. 1. Balkema, Paris. 673–676.

[2] Kahraman, S., Fener, M., and Kozman, E. 2012. Predicting the Compressive and Tensile Strength of Rocks from Indentation Hardness Index. *Journal of the Southern African Institute of Mining and Metallurgy*. 112(5): 331–339.

[3] Ceryan, N., Okkan, U., and Kesimal., A. 2012. Prediction of Unconfined Compressive Strength of Carbonate Rocks using Artificial Neural Networks. *Environ Earth Sci*. DOI: 10.1007/s12665-012-1783-z.

[4] Broch, E., and Franklin, J.A. 1972. The Point Load Strength Test. *International Journal of Rock Mechanic and Mining*. 9: 669–697.

[5] Bieniawski, Z.T. 1975. The Point Load Test in Geotechnical Practice. *Engineering Geology*. 9: 1–11.

[6] Brook, N. 1985. The Equivalent Core Diameter Method of Size and Shape Correction in Point Load Testing. *International Journal of Rock Mech. Min.Sci. & Geomech. Abstr*. 22: 61–70.

[7] ISRM. 1985. Suggested Method for Determining Point Load Strength. ISRM Commission on Testing Methods, Working Group on Revision of The Point Load Test Method. *International J. Rock. Mech. Min. Sci & Geomech. Abst*r. 22: 51–60.

[8] Miller, RP. 1965. *Engineering Classification and Index Properties for Intact Rock*. PhD thesis, University of Illinois.

[9] Deere, DU. and Miller, RP. 1966. *Engineering Classification and Index Properties for Intact Rocks*. Tech Rep Air Force Weapons Lab, New Mexico, no AFNL-TR. 65–116.

[10] Kindybinski, A. 1980. *Bursting Liability Indices of Coal*. Int. J. Rock Mech. *Min. Sci. Geomech. Abstr*. 17: 167–161.

[11] Ghose, A.K. and Chakraborti, S. 1986. Empirical Strength Indices of Indian Coals – *An Investigation. Proceedings of 27th US symposium on rock mechanics*. Balkema, Rotherdam, 59–61.

[12] Sachpazis, C.I. 1990. Correlating Schmidt Hammer Rebound Number with Compressive Strength and Young's Modulus of Carbonate Rocks. *Bull Int. Assoc. Eng. Geol*. 42:75–83.

[13] Aggistalis, G., Alivizatos, A., Stamoulis, D. and Stournaras, G. 1996. Correlating Uniaxial Compressive Strength with Schmidt Hammer Rebound Number, Point Load Index, Young's Modulus, And Mineralogy of Gabbros and Basalts (Northern Greece). *Bull Eng. Geol*. 54: 3–11.

[14] Katz, O., Reches, Z. and Roegiers, J.C. 2000. Evaluation of Mechanical Rock Properties Using Schmidt Hammer. *Int. J. Rock Mech. Min. Sci*. 37: 723–728.

[15] Kilic, A. and Teymen, A. 2008. Determination of Mechanical Properties of Rocks Using Simple Methods. *Bull Eng. Geol. Environment*. 67: 237–244.

[16] Sheorey, P. R. 1997 *Empirical Rock Failure Criteria*. Rotterdam: A.A. Balkema. 176p.

[17] Romana, M. 1999. Correlation between Unconfined Compressive and Point-Load (Miller tests) Strengths for Different Rock Classes. *In: 9th ISRM Congress*. 1: 673–676. Balkema, Paris.

[18] Kahraman, S., Fener, M., & Kozman, E. 2012. Predicting the Compressive and Tensile Strength of Rocks from Indentation Hardness Index. *Journal of the Southern African*

[19] Farah, R. 2011 *Correlations between Index Properties and Unconfined Compressive Strength of Weathered Ocala Limestone*. UNF Theses and Dissertations. Paper 142

[20] Altindag, R., and Guney, A. 2010 Predicting the Relationships between Brittleness and Mechanical Properties (UCS, TS and SH) of Rocks. *Scientific Research and Essays*. 5(16): 2107–2118.

[21] Din, F., and Rafiq, M. 1997. *Correlation between Compressive Strength and Tensile Strength/ Index Strength of Some Rocks of North- west Frontier Province (Limestone and Granite)*. Geological Bulletin, University of Peshawar. 30: 183.

[22] Eigenbrod, K.D. 1972. *Progressive Failure in Overconsolidated Clays and Mudstones*. Ph.D Dissertation, University of Alberta, Edmonton, Alberta, Canada.

[23] Bonelli R. 1989. *.Relationship Between Engineering Properties And Petrographic Characteristics Of Selected Sandstones*. M.S. Thesis,Department of Geology, Kent State University, Ohio

[24] Cargill JS, Shakoor A. Evaluation of Empirical Methods for Measuring the Uniaxial Compressive Strength of Rock. *J. Rock Mech. Min. Sci*.

[25] Cargill JS, Shakoor A. 1990. Evaluation of Empirical Methods for Measuring the Uniaxial Compressive Strength of Rock. *J. Rock Mech. Min. Sci. Geomech. Abstr*. 27(6): 495–503
[26] Thomas, M.F. 1994 *Geomorphology in the Tropics- A Study of Weathering and Denudation in Low Latitudes*. Chicester, John Wiley & Sons.
[27] Ibrahim Komoo. 1995. *Geologi Kejuruteraan- Perspektif Rantau Tropika Lembap*. Syarahan Perdana, Universiti Kebangsaan Malaysia
[28] E.T. Mohamad, R. Saad, M. Md. Noor, F. Md. Isa, A.N. Mazlan. 2010. Excavatability Assessment of Weathered Sedimentary Rock Mass Using Seismic Velocity Method. *The 4th Asian Physics Symposium*. Bandung, Indonesia.
[29] Fookes, P.G., Gourley, C.S. and Ohikere, C. 1988. Rock Weathering in Engineering Time. Quart. *Journal Engineering Geology*. 4: 139–185.
[30] ISRM. International Society of Rock Mechanics. Commission on Testing Methods. 1985. Suggested Method for Determining Point Load Strength. *International Journal Of Rock Mechanics, Mineral Sciences And Geo-Mechanics*. *Abstract* 22: 51–60
[31] Hoek E. 1977. Rock Mechanics Laboratory Testing in the Context of a Consulting Engineering Organization. *Int. J.Rock Mech. Min. Sci. and Geomech, Abstract*. 14: 93–101.
[32] ASTM. 2005. *Standard Test Method for Determination of Rock Hardness by Rebound Hammer Method*.D 873–05.
[33] ISRM. 1981. Rock Characterization, Testing and Monitoring. *ISRM Suggested Methods*. Editor E.T. Brown. Pergamon press
[34] Franklin, J.A., and Chandra, R. 1972. The slake durability test: International *Journal of Rock Mechanics and Mining Science*. 9: 325–341.
[35] Gamble., J.C. 1971, *Durability-Plasticity Classification of Shales and Oter Argillaceous Rocks*: Unpublished PhD Thesis, University of Illinois Urbana, Chmapaign, IL 161