Sains Malaysiana 45(2)(2016): 185–193

Use of Ultrasonic Velocity Travel Time to Estimate Uniaxial Compressive Strength of Granite and Schist in Malaysia

(Penggunaan Masa Perjalanan Halaju Ultrasonik untuk Menganggarkan Kekuatan Mampatan Sepaksi Granit dan Syis di Malaysia)

GOH THIAN LAI*, ABDUL GHANI RAFEK, AILIE SOFYIANA SERASA, AZIMAH HUSSIN & LEE KHAI ERN

ABSTRACT

The uniaxial compressive strength (UCS) is one of the most common mechanical parameters required in geotechnical engineering to characterize the compressive strength of rock material. Measurements of UCS are expensive, time consuming, destructive and thus, not favorable in the presence of limited samples. Therefore, a simple yet practical application is needed for the estimation of UCS. This research presents two correlations to predict UCS values for granite and schist by using ultrasonic velocity travel time (t_p) from ultrasonic tests. The validity of the practical approach presented in this research is confirmed based on the strong correlations developed from the experimental tests conducted. For the entire data set, the correlation between UCS and ultrasonic velocity travel time was expressed as UCS = $217.2\, e^{-0.016(tp)}$ for granite and UCS = $1110.6\, e^{-0.037(tp)}$ for schist and the coefficient of determination (R^2) value for both granite and schist is 0.93. These correlations may be useful for applications related to geotechnical engineering designs.

Keywords: Empirical correlation; ultrasonic velocity travel time; uniaxial compressive strength

ABSTRAK

Kekuatan mampatan sepaksi (UCS) merupakan salah satu parameter mekanik paling lazim diperlukan dalam kejuruteraan geoteknik untuk mencirikan kekuatan mampatan bahan batuan. Pengukuran menggunakan UCS adalah mahal, tempoh yang panjang, merosakkan dan tidak sesuai jika sampel adalah terhad. Oleh yang demikian, penggunaan aplikasi yang ringkas tetapi praktikal diperlukan untuk anggaran UCS. Kajian ini membentangkan dua korelasi untuk meramalkan nilai UCS granit dan syis dengan menggunakan masa perjalanan halaju ultrasonik (t_p) daripada ujian ultrasonik. Pengesahan pendekatan praktikal yang dikemukakan dalam kajian ini disahkan berdasarkan korelasi yang baik yang dibangunkan daripada ujian eksperimen yang dijalankan. Bagi keseluruhan set data, hubung kait antara UCS dan masa perjalanan halaju ultrasonik dinyatakan sebagai UCS = $217.2\, e^{-0.016(tp)}$ untuk granit dan UCS = $1110.6\, e^{-0.037(tp)}$ untuk syis dan nilai pekali penentuan (R^2) bagi kedua-dua granit dan syis adalah 0.93. Korelasi ini mungkin berguna untuk aplikasi yang berkaitan dengan reka bentuk kejuruteraan geoteknik.

Kata kunci: Kekuatan mampatan sepaksi; korelasi empirikal; masa perjalanan halaju ultrasonik

INTRODUCTION

The uniaxial compressive strength (UCS) of rock is one of the most important mechanical parameters required in geotechnical engineering to design excavation in rock. For reasons of economics, it is never always feasible to conduct uniaxial compressive strength test as it is expensive, time consuming and destructive. Consequently, the ability to estimate UCS accurately is very important in providing the mechanical parameters needed for preliminary design and modeling.

One of the challenges in geotechnical investigation was in characterizing mechanical properties of rock materials. Researchers have been developing improved, fast and reliable techniques to measure rock characteristics indirectly over the years. An example of such techniques is ultrasonic testing which appears to be a promising technique for experimental investigation in the laboratory. Ultrasonic testing has become a favorable option and is now been practised in geotechnical engineering to characterize the physical and mechanical properties of rock material, and to predict the behavior of rock material under applied forces. It is a favorable option as it is fast, non-destructive and easy to conduct in the laboratory.

Some works have been reported on the estimation of uniaxial compressive strength (UCS) from ultrasonic velocity travel time (t_p). Horsrud (2001) and Lal (1999) established a correlation to predict UCS from ultrasonic velocity travel time for high porosity Tertiary shales in the North Sea region. Militzer (1973) established a correlation to estimate UCS of limestone and dolomite from t_p. McNally (1987) proposed a correlation from t_p to estimate UCS of fine grained, consolidated and unconsolidated sandstone in the Bowen Basin of Australia. However, none of the empirical relationships are recommended for application of granite and schist.

Since there are multiple options of empirical relationships for various lithologies in different geological settings, it is necessary to understand these empirical relationships and their range of applicability prior to utilizing them. This paper presents the results of research aimed at developing a correlation to estimate UCS value from t_p for granite and schist in Malaysia. These correlations allow for the estimation of UCS value without having to conduct UCS test in actual practice, as ultrasonic testing can be conducted easily in the laboratory. Table 1 summarizes the established relationships between UCS and t_p.

70 granite samples were collected from five localities (Figure 1). The JKR Quarry in Bukit Penggorak, Kuantan is an abandoned quarry which has long been operated. Bignell and Snelling (1977) studied the granites and dolerites in Kuantan and found that the age of granite intrusion in Bukit Penggorak is from the late Permian-early Triassic. Silk Highway is located approximately 5 km from Bandar Sungai Long and 6 km north of Semenyih town. Granites in this area were formed in the late Paleozoic era (Scrivenor 1931). Kajang Rock Quarry is located approximately 2 km from Silk Highway. According to Gobbett and Hutchison

TABLE 1. Empirical relationships between UCS and Δt_p

Reference	UCS	Lithology
Horsrud (2001)	$0.77(304.8/\Delta t_p)^{2.93}$	High porosity tertiary shales (North Sea)
Lal (1999)	$10\ (304.8/\Delta t_p\text{-}1)$	High porosity tertiary shales (North Sea)
McNally (1987)	$1200 \cdot e^{-0.036\Delta tp}$	Fine-grained sandstones (Bowen Basin, Australia)
Militzer (1973)	$(7682/\Delta t_p)^{1.82}/145$	Limestone and dolomite

Units used: UCS (MPa), Δt_p (μs/ft)

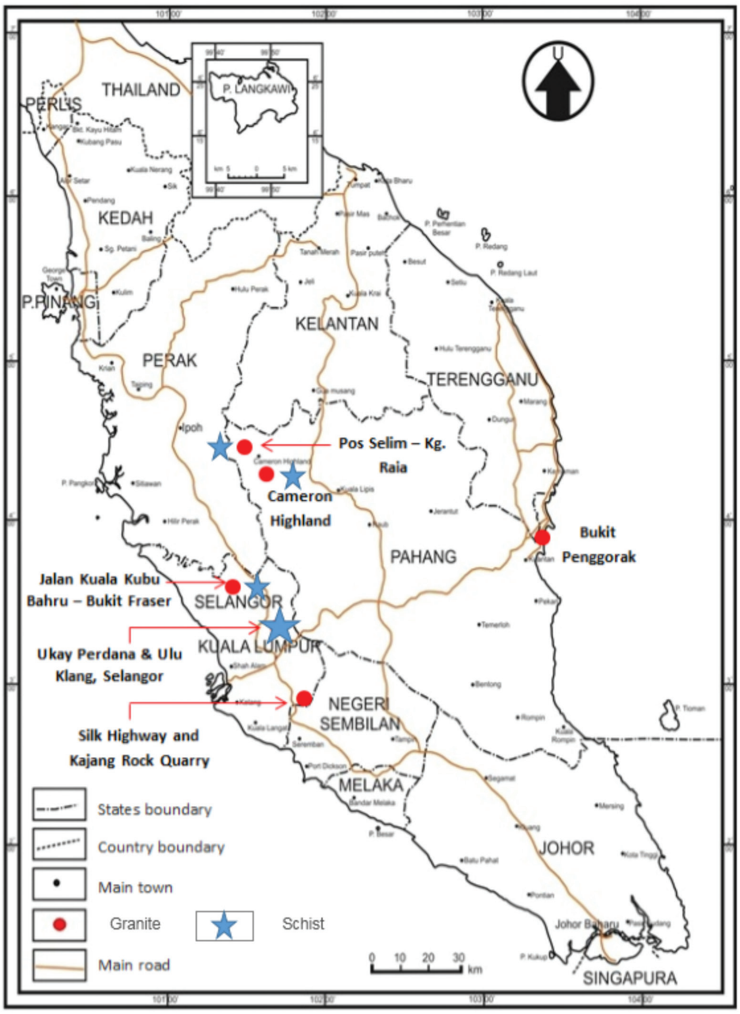

FIGURE 1. Location of study area

(1973), the study area at Kajang Rock Quarry is part of the Main Range granitoid bodies and is Triassic in age. The lithology along the Pos Selim - Kg. Raja Road comprises of metamorphic and igneous rocks (Oh 2008). Granites in this area are felsic from the Triassic age (Bignell & Snelling 1977).

24 schist samples were collected from seven localities (Figure 1). The age of the metamorphic rock along the road from Pos Selim to Kampung Raja in Cameron Highlands is Ordovician-Silurian in age. Its origin is by regional metamorphism resulting from igneous intrusion into clastic sediments that include shale and sandstone from the Permian age (Oh 2008). Strongly foliated, fine to medium-grained amphibole schist forms small isolated outcrops along the Kuala Kubu Bahru - Bukit Fraser Road in Selangor (Hutchison 2009). The age of the schist at Ukay Perdana Ulu Klang, Selangor is from the early Paleozoic era, from Cambrian to Ordovician (Gobbett 1964) and has been mapped as the Dinding Schist. The coordinate of the study areas are shown in Table 2.

METHODS

The samples were cored to right circular cylinders having a height to diameter ratio of 2:1 with a maximum lateral dimension up to 10 cm. The ends of the samples were trimmed and flattened to smooth surfaces and free of irregularities.

The ultrasonic testing was conducted based on ISRM (2007) using the apparatus PUNDIT Plus (Portable Ultrasonic Non Destructive Digital Indicating Tester) with a frequency of 50 kHz (Figure 2). Ultrasonic gel was applied on flat surface of the sample to act as a coupling medium and to enhance the transmission of ultrasonic waves. The samples were positioned on the sample holder between the transmitter and receiver. The transmitter and receiver were then pressed against the flat surfaces of the samples and pulse transmission was generated from the transmitter to the receiver.

The uniaxial compressive strength test was conducted based on ISRM (2007) using the apparatus DHR 2000 (Figure 3). The samples were placed with the flattened and smoothened ends between the top and bottom loading platens. Axial loading was applied continuously at a constant stress rate of 0.5-1.0 MPa/s. The samples failed within 5-10 min of loading.

The uniaxial compressive strength (UCS) of each rock material was calculated by dividing the maximum load (P) subjected on the sample by the original cross-sectional area (A).

Hence,

$$\text{UCS} = P / A. \tag{1}$$

Size correction factor was applied to samples that do not have the height to diameter ratio of 2:1. According to ASTM 1986, the size correction factor is given by:

$$\sigma_{corr} = \sigma_i / [0.88 + (0.24D/L)], \tag{2}$$

where σ_{corr} is the corrected uniaxial compressive strength value of an equivalent 2:1 (length/diameter) sample, σ_i is the measured uniaxial compressive strength value, D is the diameter of sample and L is the length of sample.

RESULTS AND DISCUSSION

A total of 70 and 24 ultrasonic and uniaxial compressive strength tests have been conducted on the granite and schist respectively. Figures 4 and 5 show the laboratory results of granite and schist plotted against the established empirical relationships between uniaxial compressive strength (UCS) and ultrasonic velocity travel time (t_p) established by Horsrud (2001), Lal (1999), McNally

TABLE 2. Coordinates of study area

Lithology	Study area	Longitude	Latitude
Granite	JKR Kuari Bukit Penggorak, Kuantan, Pahang	E103°24.316'	N03°59.006'
	Kajang Silk Highway (km 14.6), Selangor	E101°49.888'	N03°00.150'
	Kajang Rock Quarry, Semenyih, Ulu Langat, Selangor	E101°50.376'	N02°59.261'
Schist	Pos Selim Road - Kampung Raja, Cameron Highlands, Pahang/Perak		
	a) km 38-39	E101°17.162'	N04°34.063'
	b) km 29-30	E101°19.404'	N04°33.323'
	Pos Selim Road - Kampung Raja, Cameron Highlands, Pahang/Perak:		
	a) km 25-26	E101°19.572'	N04°34.436'
	b) km 23-24	E101°18.970'	N04°34.958'
	c) km 22-23	E101°19.164'	N04°35.098'
	d) km 21-22	E101°19.477'	N04°34.874'
	e) km 18-19	E101°20.734'	N04°34.919'
	Kuala Kubu Bahru Road-Bukit Fraser (km 15), Selangor	E101°42.865'	N03°34.062'
	Ukay Perdana, Ulu Klang, Selangor	E101°46.433'	N03°12.155'

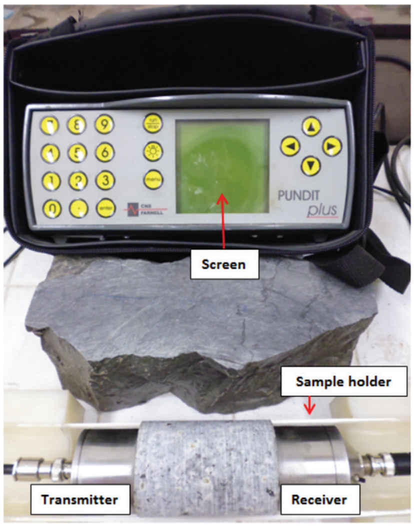

FIGURE 2. Apparatus PUNDIT Plus to conduct ultrasonic test

(1987) and Militzer (1973), respectively. The result showed that none of the correlations are able to estimate UCS accurately, due to reasons that the established relationships are for different lithologies and thus not suitable to be applied for samples collected in Malaysia.

Two new correlations that were proposed to estimate UCS from t_p were expressed as UCS = 217.2 $e^{-0.016(tp)}$ for granite and UCS = 1110.6 $e^{-0.037(tp)}$ for schist with the coefficient of determination (R^2) value for both granite and schist is 0.93 shows better estimation of UCS based on the strong correlations obtained.

The results of testing were analyzed at 95% confidence level by using SPSS statistical software Version 16. The minimum, maximum, mean and median values of UCS were 5, 109.88, 71.49 and 76.29 MPa, respectively, with a standard deviation of 28.16 MPa for granite. The minimum, maximum, mean and median values of t_p were 52.24, 242.28, 81 and 65.07 µs/ft, respectively, with a standard

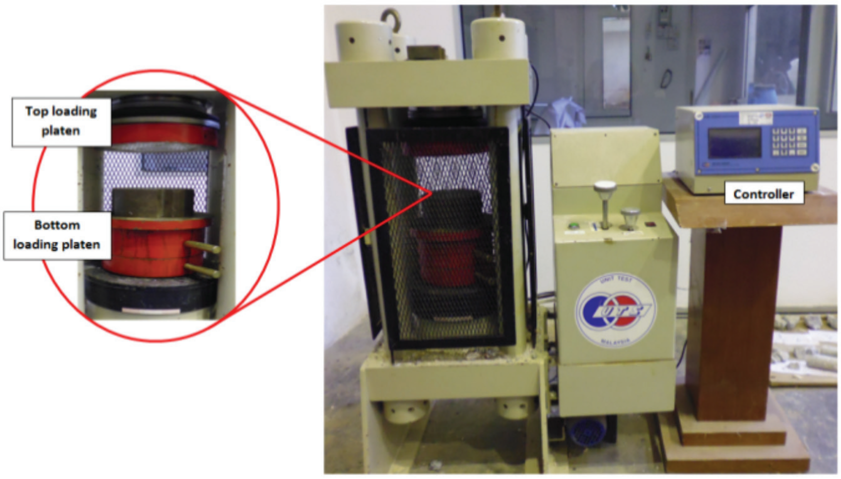

FIGURE 3. Apparatus DHR 2000 to conduct uniaxial compressive strength test

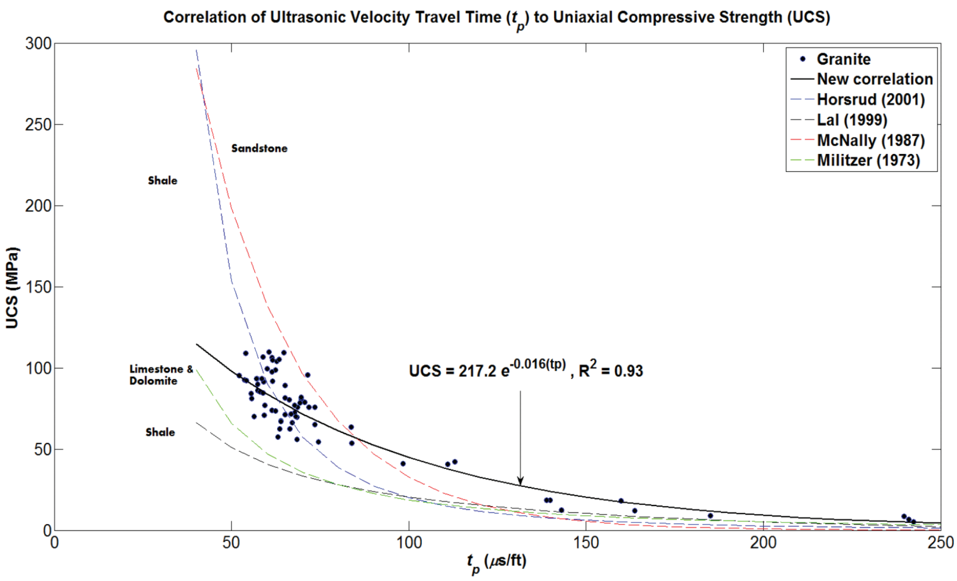

FIGURE 4. Comparison of laboratory test results of granite plotted together with the proposed correlation, empirical correlation by Horsrud (2001), Lal (1999), McNally (1987) and Militzer (1973)

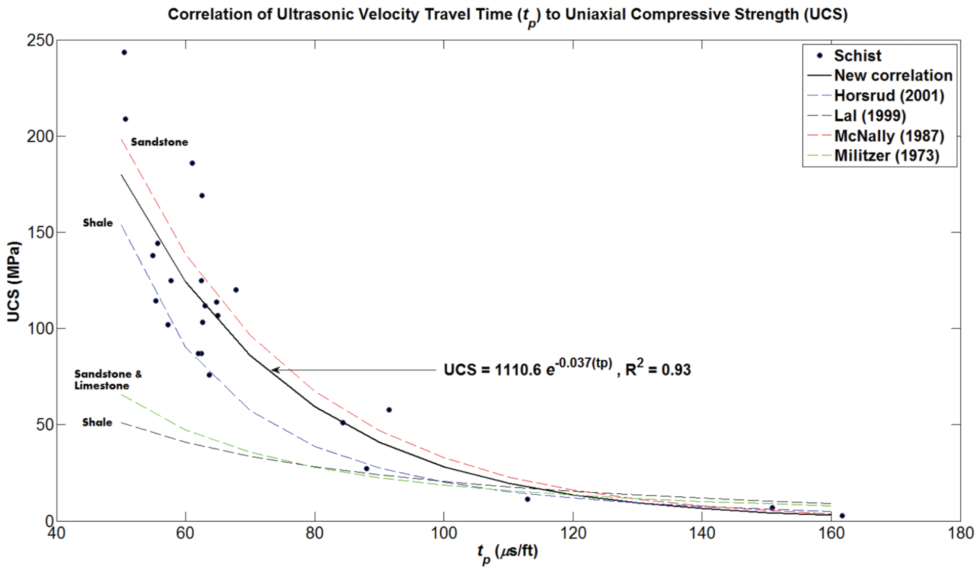

FIGURE 5. Comparison of laboratory test results of schist plotted together with the proposed correlation, empirical correlation by Horsrud (2001), Lal (1999), McNally (1987) and Militzer (1973)

deviation of 43.93 µs/ft for granite. Table 3 summarizes the statistical analysis results of granite.

The minimum, maximum, mean and median values of UCS were 2.5, 243.4, 104.9 and 109.4 MPa, respectively, with a standard deviation of 61.18 MPa for schist. The minimum, maximum, mean and median values of t_p were 50, 162, 74 and 63 µs/ft, respectively, with a standard deviation of 29.25 µs/ft for schist. Table 4 summarizes the statistical analysis results of schist.

Table 5 summarizes the calculated values of uniaxial compressive strengths of granite based on the proposed correlation, Horsrud (2001), Lal (1999), McNally (1987) and Militzer (1973). The values of uniaxial compressive strength ranges from 12.07 to 113.36 MPa, 3.60 to 295.54 MPa, 17.03 to 78.15 MPa, 1.84 to 284.31 MPa and 6.39 to 98.73 MPa, respectively.

The percentage of differences of uniaxial compressive strength predictions between the proposed and published correlations for granite was shown in Table 6. It can be seen that the percentage differences between the proposed correlation values and the published correlation values range from -160.72 to 89.78%.

Table 7 summarizes the calculated values of uniaxial compressive strengths of schist based on the proposed correlation, Horsrud (2001), Lal (1999), McNally (1987) and Militzer (1973). The values of uniaxial compressive strength ranges from 1.47 to 260.62 MPa, 3.6 to 295.54 MPa, 17.03 to 78.15 MPa, 1.84 to 284.31 MPa and 6.39 to 98.73 MPa, respectively.

Table 8 summarizes the percentage of differences of uniaxial compressive strength predictions between the proposed and published correlations for schist. It can be seen that the percentage differences between the proposed correlation values and the published correlation values range from -1060.9 to 70.01%.

The results clearly shows that the published correlations of Horsrud (2001), Lal (1999), McNally (1987) and Militzer (1973) are not suitable in prediction

TABLE 3. Summary of statistical analysis of granite analyzed at 95% confidence level by using SPSS statistical software Version 16

Parameter	No. of test	Min	Max	Mean	Median	Standard Deviation	Skewness
UCS	70	5 MPa	109.88 MPa	71.49 MPa	76.29 MPa	28.16 MPa	Positive
t_p	70	52.24 µs/ft	242.28 µs/ft	81 µs/ft	65.07 µs /ft	43.93 µs/ft	Negative

TABLE 4. Summary of statistical results of schist analyzed at 95% confidence level by using SPSS statistical software Version 16

Parameter	No. of test	Min	Max	Mean	Median	Standard Deviation	Skewness
UCS	24	2.5 MPa	243.4 MPa	104.9 MPa	109.4 MPa	61.18 MPa	Positive
t_p	24	50 µs/ft	162 µs/ft	74 µs/ft	63 µs/ft	29.25 µs/ft	Negative

TABLE 5. The calculated values of uniaxial compressive strengths of granite based on the proposed correlation, Horsrud (2001), Lal (1999), McNally (1987) and Militzer (1973)

t_p (μs/ft)	Proposed Correlation, MPa	Horsrud (2001), MPa	Lal (1999), MPa	McNally (1987), MPa	Militzer (1973), MPa
40	113.36	295.54	78.15	284.31	98.73
50	96.60	153.70	62.20	198.36	65.78
60	82.31	90.09	51.66	138.39	47.20
70	70.14	57.35	44.17	96.55	35.65
80	59.77	38.78	38.58	67.36	27.96
90	50.93	27.46	34.25	47.00	22.57
100	43.40	20.17	30.79	32.79	18.63
110	36.99	15.25	27.96	22.88	15.66
120	31.52	11.82	25.61	15.96	13.37
130	26.86	9.35	23.63	11.13	11.56
140	22.89	7.52	21.93	7.77	10.10
150	19.50	6.15	20.46	5.42	8.91
160	16.62	5.09	19.17	3.78	7.92
170	14.16	4.26	18.04	2.64	7.09
180	12.07	3.60	17.03	1.84	6.39
190	10.28	3.08	16.13	1.28	5.79
200	8.76	2.65	15.32	0.90	5.28
210	7.47	2.29	14.58	0.63	4.83
220	6.36	2.00	13.92	0.44	4.44
230	5.42	1.76	13.31	0.30	4.09
240	4.62	1.55	12.75	0.21	3.79
250	3.94	1.38	12.24	0.15	3.52

TABLE 6. Percentage of differences of uniaxial compressive strength predictions of granite between the proposed correlation with published correlations for sandstone (McNally 1987), limestone & dolomite (Militzer 1973) and shales (Horsrud 2001; Lal 1999)

t_p (μs/ft)	Horsrud (2001), %	Lal (1999), %	McNally (1987), %	Militzer (1973), %
40	-160.72	31.06	-150.81	12.90
50	-59.11	35.60	-105.35	31.91
60	-9.45	37.24	-68.12	42.66
70	18.24	37.02	-37.65	49.17
80	35.12	35.45	-12.70	53.22
90	46.08	32.76	7.73	55.69
100	53.53	29.07	24.46	57.08
110	58.76	24.40	38.15	57.65
120	62.49	18.73	49.36	57.58
130	65.19	12.02	58.54	56.97
140	67.12	4.19	66.06	55.88
150	68.48	-4.89	72.21	54.33
160	69.38	-15.35	77.25	52.35
170	69.92	-27.35	81.37	49.92
180	70.14	-41.10	84.75	47.04
190	70.09	-56.82	87.51	43.67
200	69.80	-74.79	89.78	39.79
210	69.28	-95.30	91.63	35.35
220	68.55	-118.72	93.15	30.29
230	67.60	-145.46	94.39	24.55
240	66.43	-176.00	95.41	18.06
250	65.05	-210.88	96.24	10.73

TABLE 7. The calculated values of uniaxial compressive strengths of schist based on the proposed correlation, Horsrud (2001), Lal (1999), McNally (1987) and Militzer (1973)

t_p (μs/ft)	Proposed correlation (MPa)	Horsrud (2001), (MPa)	Lal (1999), MPa	McNally (1987), MPa	Militzer (1973), MPa
40	260.62	295.54	78.15	284.31	98.73
50	180.02	153.70	62.20	198.36	65.78
60	124.35	90.09	51.66	138.39	47.20
70	85.89	57.35	44.17	96.55	35.65
80	59.33	38.78	38.58	67.36	27.96
90	40.98	27.46	34.25	47.00	22.57
100	28.31	20.17	30.79	32.79	18.63
110	19.55	15.25	27.96	22.88	15.66
120	13.51	11.82	25.61	15.96	13.37
130	9.33	9.35	23.63	11.13	11.56
140	6.44	7.52	21.93	7.77	10.10
150	4.45	6.15	20.46	5.42	8.91
160	3.07	5.09	19.17	3.78	7.92
170	2.12	4.26	18.04	2.64	7.09
180	1.47	3.60	17.03	1.84	6.39

TABLE 8. Percentage of differences of uniaxial compressive strength predictions of schist between the proposed correlation with published correlations for sandstone (McNally 1987), limestone & dolomite (Militzer 1973) and shales (Horsrud 2001; Lal 1999)

t_p (μs/ft)	Horsrud (2001), %	Lal (1999), %	McNally (1987), %	Militzer (1973), %
40	-13.40	70.01	-9.09	62.12
50	14.62	65.45	-10.19	63.46
60	27.55	58.45	-11.29	62.04
70	33.23	48.57	-12.41	58.49
80	34.64	34.97	-13.54	52.87
90	32.99	16.43	-14.68	44.93
100	28.75	-8.77	-15.84	34.19
110	21.98	-43.02	-17.00	19.89
120	12.47	-89.66	-18.18	1.01
130	-0.23	-153.29	-19.36	-23.88
140	-16.78	-240.31	-20.56	-56.72
150	-38.13	-359.62	-21.77	-100.11
160	-65.52	-523.55	-23.00	-157.60
170	-100.62	-749.32	-24.23	-233.98
180	-145.66	-1060.90	-25.48	-335.75

of UCS for both granite and schist since the percentage of differences is large.

Figure 6 shows the boxplot of t_p values for granite and schist. The results of t_p values for granite and schist are skewed left, which implies that more test results have higher value of t_p compared to the mean values. Figure 7 shows the boxplots of UCS values for granite and schist. The results of UCS for granite and schist are skewed right, which implies that more test results having lower value of UCS compared to the mean value.

CONCLUSION

Two new empirical correlations was established to estimate the value of UCS from ultrasonic velocity travel time (t_p) for granite and schist. The empirical correlation is UCS = 217.2 $e^{-0.016(tp)}$ for granite and UCS = 1110.6 $e^{-0.037(tp)}$ for schist. The coefficient of determination (R^2) value for both granite and schist is 0.93. Estimation of UCS values from these empirical correlations is a simple and fast method as t_p can be measured easily in the laboratory. Thus, this equation is expected to be useful as a practical approach in

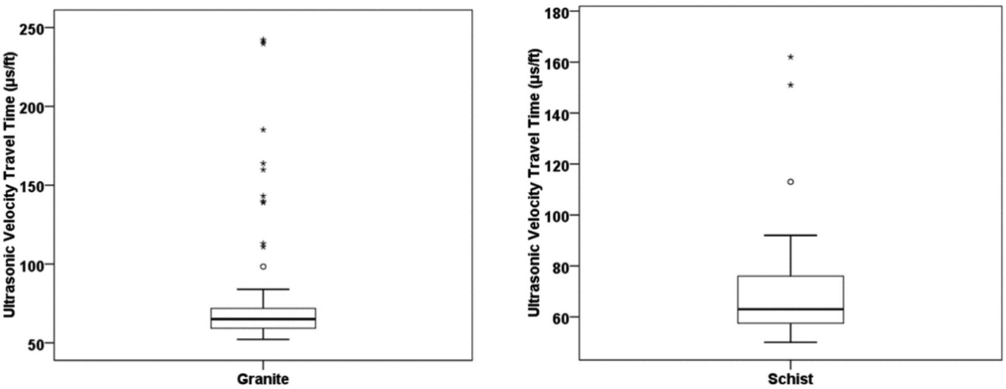

FIGURE 6. Boxplot of ultrasonic velocity travel time (t_p) results for granite and schist

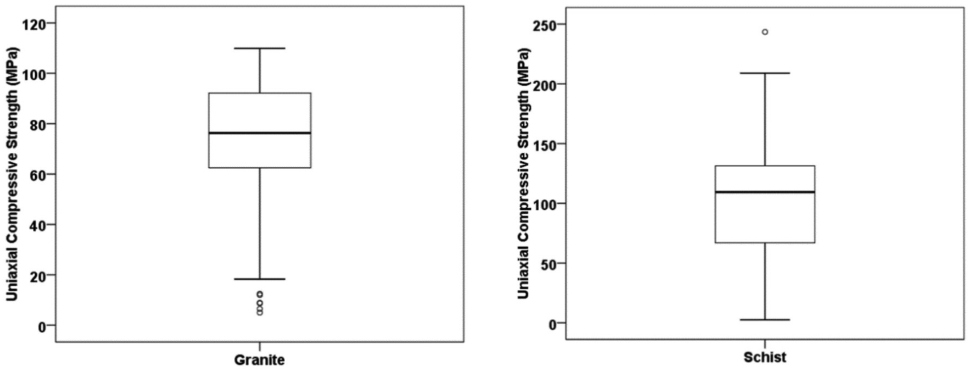

FIGURE 7. Boxplot of uniaxial compressive strength (UCS) results for granite and schist

geotechnical engineering for characterization of physical and mechanical properties of rock material and to predict the behavior of rock material under applied forces.

ACKNOWLEDGMENTS

This publication is based on work supported by the Government of Malaysia under grant Fundamental Research Grant Scheme FRGS/1/2014/STWN06/UKM/02/1 and e-Science Fund Grant Scheme 06-01-02-SF 1140. The authors would also like to acknowledge the support of the staff and facilities at Geology Program and Faculty of Science and Technology, Universiti Kebangsaan Malaysia.

REFERENCES

ASTM. 1986. Standard test method of unconfined compressive strength of intact rock core specimens. D 2938: 390-390.

Bignell, J.D. & Snelling, N.J. 1977. Geochronology of Malayan granites. *Overseas Geology and Mineral Resources* 47: 77.

Gobbett, D.J. & Hutchison, C.S. 1973. *Geology of The Malay Peninsular*. New York: John Wiley & Sons.

Gobbett, D.J. 1964. The lower palaeozoic rocks of Kuala Lumpur, Malaysia. *Fed. Museums Journal* 9: 67-70.

Horsrud, P. 2001. Estimating mechanical properties of shale from empirical correlations. *SPE Drilling and Completion* 16(2): 68-73.

Hutchison, C.S. 2009. *Geology of the Malay Peninsular*. New York: John Wiley & Sons.

ISRM. 2007. *The Complete ISRM Suggested Methods for Characterization, Testing and Monitoring: 1974-2006*. Ankara: ISRM Turkish National Group.

Lal, M. 1999. Shale stability: Drilling fluid interaction and shale strength. *SPE 54356. SPE Latin American and Carribean Petroleum Engineering Conference*. Caracas, Venezuela, Society of Petroleum Engineering.

McNally, G.H.N. 1987. Estimation of coal measures rock strength using sonic and neutron logs. *Geoexploration* 24: 381-395.

Militzer, M.a.S.P. 1973. Einige Beitrageder geophysics zur primadatenerfassung im Bergbau. *Neue Bergbautechnik, Lipzig* 3(1): 21-25.

Oh, H.T. 2008. Pemetaan geologi sepanjang km14-km27 Jalan raya Kg. Raja, Cameron Highland, Pahang-Pos Selim, Perak. Bachelors Degree Thesis, Geology Programme, National University of Malaysia, Bangi (Unpublished).

Scrivenor, J.B. 1931. *The Geology Malaya*. London: Macmillan.

Goh Thian Lai*, Ailie Sofyiana Serasa & Azimah Hussin
Geology Program, School of Environmental and Natural Resource Sciences
Faculty of Science and Technology
Universiti Kebangsaan Malaysia
43600 Bangi, Selangor Darul Ehsan
Malaysia

Abdul Ghani Rafek
Department of Geosciences, Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh, Perak Darul Ridzuan
Malaysia

Lee Khai Ern
Institute for Environment and Development (LESTARI)
Universiti Kebangsaan Malaysia
43600 Bangi, Selangor Darul Ehsan
Malaysia

*Corresponding author; email: gdsbgoh@gmail.com

Received: 5 May 2015
Accepted: 20 August 2015