PREDICTION OF UNIAXIAL COMPRESSIVE STRENGTH OF KIRANA HILLS DOLERITE BY ULTRASONIC PULSE WAVE VELOCITY

M.U. Khan, M. Z. Abu Bakar*, M. Akram, Y. Majeed, N. Aadil* and M. B. Hayat

Mining Engineering Department, University of Engineering and Technology, Lahore, Pakistan
*Geological Engineering Department, University of Engineering and Technology, Lahore, Pakistan
Corresponding Author: yasirbinmajeed@uet.edu.pk

ABSTRACT: This study was aimed at to explore the existence of any possible correlation between sonic wave velocity (V_P) and uniaxial compressive strength (UCS) of dolerites of Kirana hills, situated in the province of Punjab, Pakistan. The experimental results were statistically analyzed using the method of least square regression to explore the existence of any correlation between V_P and UCS. Three correlation equations having reasonably good R^2 values were established and validated by an independent set of samples of the same rock. The majority of the computed values of UCS from the developed correlation equations were found to lie within acceptable statistical confidence limits.

Key words: Uniaxial compressive strength, sonic wave velocity, correlation, correlation coefficient, confidence interval.

(Received 13-04-2013 Accepted 02-09-2015).

INTRODUCTION

A comprehensive laboratory database of engineering and mechanical properties of rocks is essential for the characterization of any site and other mining, geological and geotechnical engineering applications. Uniaxial compressive strength (UCS) is required more often than any other design parameter by mining/rock engineers (Bieniawski, 1974; Cargill and Shakoor, 1990). Because of the discontinuous and variable nature of rock masses, it is sometimes difficult for rock engineers to directly obtain the specific design parameters of their interest. So, as an alternative they use empirical or theoretical correlations to estimate the required engineering properties of rocks (Szlavin, 1974; Zhang, 2005). Although the testing procedure to determine UCS has been standardized by both (ISRM, 1981 and ASTM, 2010) but the suggested methods are time consuming and expensive requiring more sophisticated test setup. Thus, estimation of strength properties of rocks by non-destructive/indirect testing is gaining popularity. Non-destructive/indirect testing is simpler in nature, provides quicker results, involves low cost, and requires less sophisticated testing equipment. Sonic velocity test is one among the numerous non-destructive and indirect test which is commonly employed to estimate the UCS of rocks. In addition to UCS estimation, sonic velocity test is also used to determine other mechanical and physical properties of rocks like different elastic moduli, tensile strength, point load index, porosity, density etc. (Grasso *et al.,* 1992; Kurtulus *et al.,* 2011).

A large number of researchers (Chary *et al.,* 2006; Entwisle *et al.,* 2005; Horsrud, 2001; Kahraman, 2001; Sharma and Singh, 2007; Tugrul and Zarif, 1999; Vasconcelos *et al.,* 2007; Wannakao *et al.,* 2009; Yasar and Erdogan, 2004 and Yagiz, 2010) have proposed index to strength conversion factors. These factors have been found to be rock dependent (Fener *et al.,* 2005; Akram and Abu Bakar, 2007). A limited number of studies correlating UCS with the results of indirect strength indices have been reported for the rocks of Pakistan. The current study is aimed at correlating UCS with the sonic wave velocity (V_P) of selected rock samples of dolerite from Kirana hills. No such work has been reported so far for Kirana hills rocks. Dolerites are encountered at several locations in Kirana hills, where extensive underground development work is in progress. Moreover, these dolerites are being significantly utilized as cladding material, road base, riprap and concrete aggregates in the country. Results of the current research would be beneficial for the designers, planners and contractors operating in the study area.

Geology and Location of the Research Area: Kirana hills are probably the oldest rocks in the Punjab plains that are leftover of wide spread igneous activity within the Malani basin (Kochhar, 1999; Bhushan, 1999). The Kirana rocks are the sub areal projection of Sargodha ridge (Menke and Jacob, 1976; Farah *et al.,* 1979). The rocks of Kirana have been divided into two main groups (Chaudary *et al.,* 1999) as illustrated in Figure 1. The area concerned to this study lies under “Hachi Volcanics” Group. “Hachi Volcanics” are further sub divided into two formations. The collected rock samples lie in “Volcanic Formation” which consists of dolerites, andesite, dacites, dacitic tuff, rhyolites and rhyolitic tuff. The rocks were exposed in the surrounding areas of Chiniot, Sargodha, Rabwa, Shahkot and Sangla Hill.

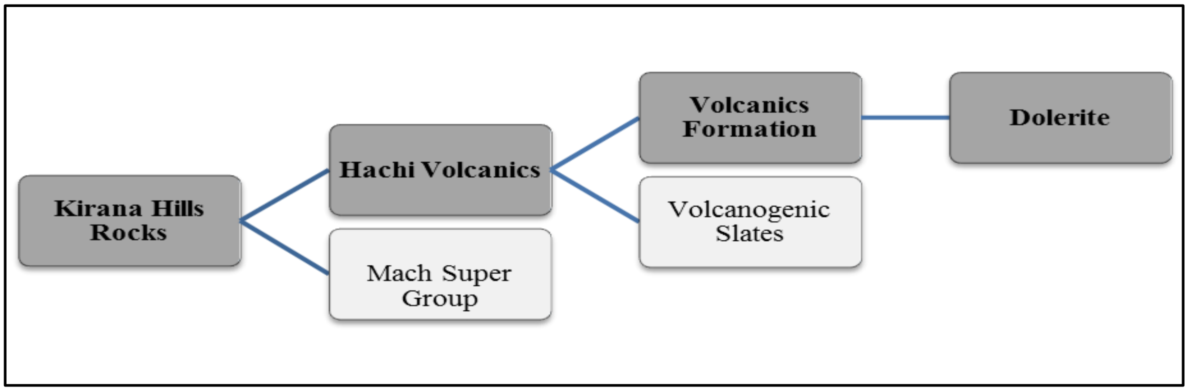

Figure 1. Flowchart of Geology of Kirans Hills (Chaudary *et al.*, 1999)

MATERIALS AND METHODS

Sample Collection: Blocks of dolerite were collected from various locations of Kirana hills (Figure-2). The size of the collected block was large enough to have multiple cores from a single block. The collected blocks were examined carefully for any visible defect/flaw. Blocks which had any visible discontinuity and signs of weathering were discarded. Table 1 summarizes some physical and mechanical properties of the selected rock type.

Figure 2. Sample Collection Area

Table 1. Showing Physical and Mechanical Properties of Kirana Hills Dolerite

Rock Property	SI Units	English Units
Uniaxial Compressive Strength	220 MPa	32000 psi
Brazilian Tensile Strength	11 MPa	1600 psi
Poisson's Ratio	0.30	0.30
Young's Modulus	65 GPa	9430 psi
Density	2845 kg/m^3	178 lb/ft^3

Core Cutting and Sample Preparation: A total of 150 rock cores were drilled from the selected rock blocks. Cores dimensions were maintained as suggested by ASTM (2008) standards. UCS was determined by using standard cylindrical cores. Sonic velocity tests were performed on the same core samples for determining V_P.

Sonic Velocity Testing: V_P was determined as per ASTM (1995) standards by using Portable Ultrasonic, Non-destructive Digital Indicating Tester (PUNDIT). To determine V_P rock cores were placed in between the receiver and the transmitter transducers and the travel time of sonic wave through the specimen was noted. To improve the contact between the transducers and the samples a thin layer of grease was applied at the end faces of each specimen. Schematic arrangement of sonic velocity testing is shown in Figure 3. V_P was calculated by using the following formula:

V_P = Distance travelled by sonic wave/ Travel time of wave(1)

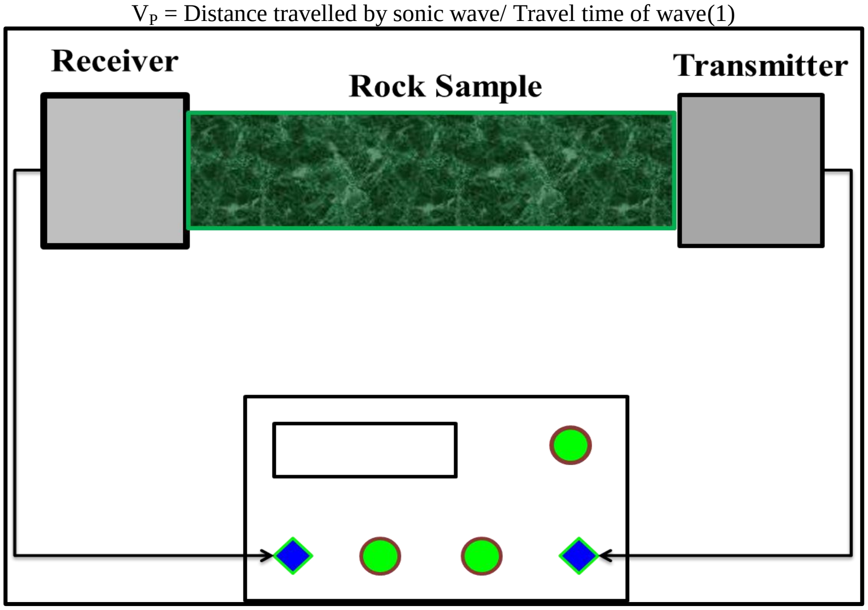

Figure 3: Schematic of Sonic Velocity Testing Setup

Compressive Strength Testing: The UCS tests of the rock samples were conducted according to ASTM (2010). 200 Tons capacity, Shimadzu Universal Testing Machine (UTM) was used for the determination of UCS. The prepared cylindrical cores were loaded in the UTM axially. Axial load was applied at a constant rate. The loading rate was controlled in such a way that the breakage occurred in 5-10 minutes. UCS was calculated by noting the failure load, cross sectional area of the specimen by using the following relation:

UCS = (Failure load) / (Initial cross sectional area of specimen) (2)

Statistical Analysis: Data was analyzed using technique adopted from Lyman and Longnecker (2010) to find correlations between the UCS and Vp and their validation.

RESULTS AND DISCUSSION

Test results of present study were plotted by keeping V_P as a regressor and UCS as a response variable and then analyzed statistically by using coefficient of correlation (R^2). Reasonably good R^2 values were obtained for all predicted correlation equations (Figure 4 and Table 2).

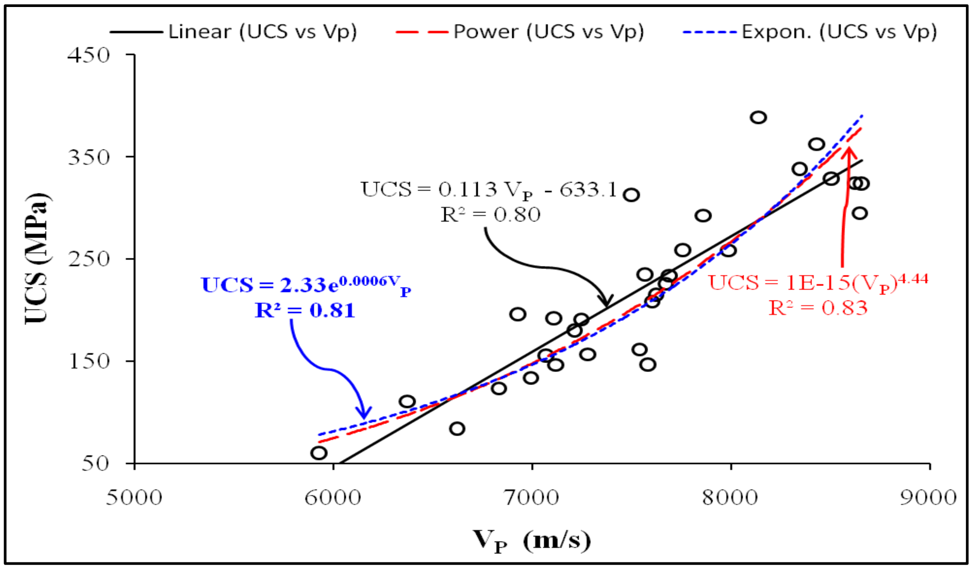

Figure 4. Scatter Plot of V_P against UCS with Different Fitted Functions

Table: 2. Developed Equations with their R^2 Values.

Correlation Equations		R^2 Value	Function
$UCS = 0.113\ V_P - 633.1$	(3)	0.80	Linear
$UCS = 1E\text{-}15\ (V_P)^{4.44}$	(4)	0.83	Power
$UCS = 2.33e^{0.0006\ (V_P)}$	(5)	0.81	Exponential
Note: In all above equations i.e. V_P was in (m/sec) and resulting UCS was in (MPa).			

Three different correlation equations based on R^2 values were established by using three different mathematical functions i.e. linear, power and exponential. Figure 4 show the scatter plot of V_P against UCS with different fitted functions. Table-2 show the developed equations along with their respective R^2 values. A number of previous studies have reported linear, power and exponential relationships for the prediction of UCS from sonic velocity (V_P) for both sedimentary and igneous rock types. Brief literature review is given in Table 3.

The significance of the developed correlations 3, 4 and 5 was confirmed by employing a few statistical analysis techniques. Table 4 summarized the mean, standard deviation, coefficient of variation, range of UCS and V_P at 95% CI. Coefficient of variation (COV) was used to evaluate the variability of test results. COV expressed as a percentage was calculated by dividing the standard deviation with the mean and multiplying by 100. To validate the prediction performance of the developed correlations the UCS values were computed from equations 3, 4 and 5 derived in this study for igneous dolerites and the earlier relationships were established by Entwise *et al.* (2005), Tugrul and Zarif (1999) and Vasconcelos *et al.* (2007) specifically for igneous rocks. For the purpose of validation sonic wave velocity tests were performed on a separate set of seven dolerite core samples. The obtained values of V_P were then used to determine UCS of these samples which are presented in Table 5. It was observed that the UCS values computed from the correlation equations 3, 4 and 5 were found to lie within the 95% confidence interval of the original measured UCS values, which validated the estimation capabilities of the derived equations. It was further noted that the UCS values worked out by using the power and exponential functions proposed by Entwisle *et al.* (2005) showed over estimation and also lie out side the 95% confidence interval range. On the other hand the UCS values estimated by using linear functions developed by Vasconcelos *et al.* (2007) and Tugral and Zarif (1999) mostly lie within the 95% CI which closely match with the linear function i.e. equation 3, developed in the present study.

Figure` 5 show the plots of measured and predicted UCS of rock samples by equations 3, 4 and 5 respectively. A 45° line i.e. 1:1 line indicated the line where predicted and actual UCS values were equal. Points plotted above the 1:1 line indicated an over estimation situation. Figure 5 also indicated that the UCS values computed from the linear and exponential functions lie above the 1:1 line in majority of the cases; whereas all the UCS values calculated from power function lie below the 1:1 line. For underground excavations design, values computed from the developed linear and exponential functions overestimated the UCS, which involved safety and economic risks. Whereas for use of power function under estimates for UCS, care must be exercised while using either of these derived functions for estimation of the UCS values.

Table. 3. Review of Literature.

Sr. No	Researchers	Correlation Equations	R^2	Rock Type	Units
1	Chary *et al.* (2006)	$\sigma_c = 0.156\,(V_P) - 692.4$ $\sigma_c = 0.014\,(V_P) - 24.86$	0.80 0.51	Sedimentary	σ_c (MPa) and V_P(m/s)
2	Entwisle *et al.* (2005)	$\sigma_c = 0.783\, e^{0.882\,(V_P)}$ $\sigma_c = 0.0292\,(V_P)^{4.79}$	0.53 0.53	Igneous	σ_c (MPa) and V_P(Km/s)
3	Horsrud (2001)	$\sigma_c = 0.77\,(V_P)^{2.93}$	0.99	Sedimentary	σ_c (MPa) and V_P(m/s)
4	Kahraman (2001)	$\sigma_c = 9.95\,(V_P)^{1.21}$	0.83	Sedimentary	σ_c (MPa) and V_P(Km/s)
5	Sharma and Singh (2007)	$\sigma_c = 0.064\,(V_P) – 118$	0.90	Sedimentary	σ_c (MPa) and V_P(Km/s)
6	Tugrul and Zarif (1999)	$\sigma_c = 35.5\,(V_P)\ _-\ 55$	0.80	Igneous	σ_c (MPa) and V_P(Km/s)
7	Vasconcelos *et al.* (2007)	$\sigma_c = 0.041(V_P)_{(dry)} - 36.31$	0.72	Igneous	σ_c (MPa) and V_P(m/s)
8	Wannakao *et al.* (2009)	$\sigma_c = 1.86\, e^{0.0004(V_P)}$ (Shallow) $\sigma_c = 0.95\, e^{0.0011(V_P)}$ (Intermediate) $\sigma_c = 1.86\, e^{0.0013(V_P)}$ (Deep)		Sedimentary	σ_c (MPa) and V_P(m/s)
9	Yasar and Erdogan (2004)	$V_P = 0.032\,(\sigma_c) + 2.02$	0.80	Sedimentary	σ_c (MPa) and V_P(Km/s)
10	Yagiz (2010)	$\sigma_c = 0.258\,(V_P)^{3.543}$ $\sigma_c = 49.4\,(V_P) – 167$	0.92 0.89	Sedimentary	σ_c (MPa) and V_P(Km/s)

Note: "σ_c" is Compressive Strength; "V_P" is Sonic Wave Velocity.

Table 4. Showing 95% Confidence Interval Data of UCS Range and Other Statistical and V_P

Statistical Parameters	UCS (MPa)
Mean	221.03
Standard Deviation (S.D)	85.36
Coefficient of Variation (COV) %	37.71
95% CI	190.49 to 251.57

Table 5. Showing Measured UCS values based on this study, and comparison of predicted UCS values based on current study and work by previous studies for igneous rocks using V_P of validation samples.

Sample #	Vp (m/s)	Measured UCS (MPa)	Predicted UCS (MPa): Linear Function: This Study (Equation 3)	Linear Function: *Vasconcelos et al.* (2007)	Linear Function: Tugral and Zarif (1999)	Power Function: This Study (Equation 4)	Power Function: *Entwisle et al.* (2005)	Exponential Function: This Study (Equation 5)	Exponential Function: *Entwisle et al.* (2005)
S31	7850.70	245	254.03	285.57	223.69	196.51	564.93	258.86	796.08
S32	7458.60	191	209.72	269.49	209.78	156.53	441.99	204.59	563.33
S33	7490.50	185	213.33	270.80	210.91	159.52	451.12	208.55	579.40
S34	7550.80	193	220.14	273.27	213.05	165.31	468.78	216.23	611.05
S35	7831.20	248	251.83	284.77	223.01	194.35	558.24	255.85	782.50
S36	8061.70	254	277.87	294.22	231.19	221.07	641.46	293.79	958.91
S37	7546.40	191	219.64	273.09	212.89	164.88	467.47	215.66	608.69

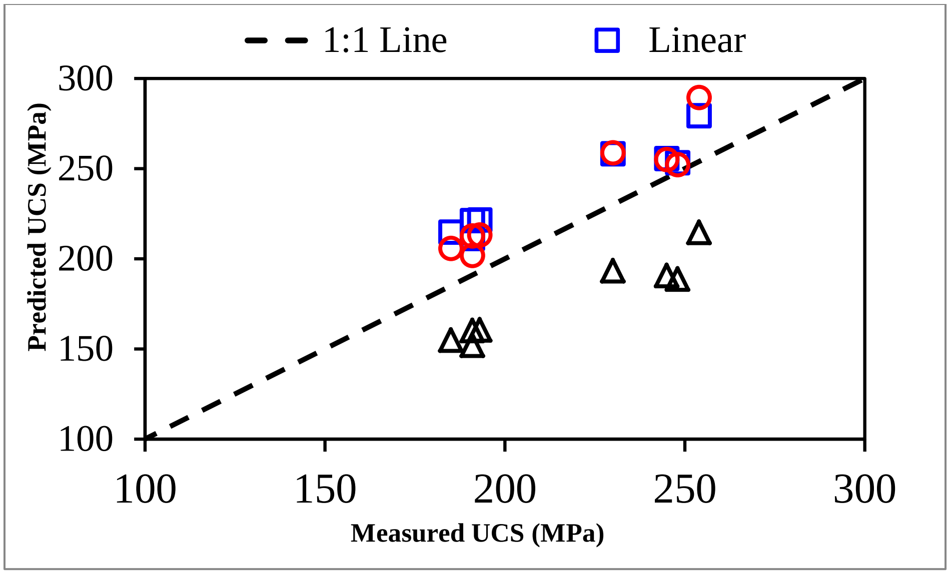

Figure 5. Measured and predicted UCS

Conclusions: In this study V_p and UCS of Dolerites from Kirana hills were determined in the laboratory. When test results were interpreted statistically, significant linear, power and exponential prediction functions were found. The majority of UCS values calculated from the derived equations were found to lie within 95% CI which shows the statistical validation of established relationships. This can be inferred that power function out of the three developed correlation equations can be used with confidence for the safer estimation of UCS of Dolerites from Kirana hills area.

REFERENCES

Akram, M. and M.Z. Abu Bakar (2007). Correlation between uniaxial compressive strength and point load index for salt-range rocks. Pakistan Journal of Engineering and Applied Sciences (1): 1-8

ASTM D-4543 (2008). Standard practices for preparing rock core as cylindrical tests specimens and verifying conformance to dimensional and shape tolerances. American Society for Testing Materials

ASTM D-7012 (2010). Standard test method for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures. American Society for Testing Materials

ASTM D-2845 (1995). Standard test method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock; American Society for Testing Materials

Bhushan, S. K. (1999). Neo proterozoic magmatism in Rajasthan. Proceedings Seminar on Geology of Rajashtan, MLS University, Udaipur, 101-110

Bieniawski, Z. T. (1974). Estimating the strength of rock materials. Journal of the South African Institute of Mining and Metallurgy, 313-320

Cargill, J. S. and A. Shakoor (1990). Evaluation of empirical methods for measuring the UCS of rock. International Journal of Rock Mechanics and Mining Sciences, 27: 495-503

Chary, K. B., L.P. Sarma, K. J. P. Lakshmi, N. A. Vijaya kumar, V. N. Lakshmi and M.V.M.S. Rao (2006). Evaluation of engineering properties of rock using ultrasonic pulse velocity and uniaxial compressive strength. Proceedings National Seminar on Non-Destructive Evaluation, Hyderabad National Geophysical Research Institute, Hyderabad, 500 007

Chaudary, M.N., S.A. Ahmad and A. Mateen (1999). Some postulates on the tectono-magmatism, tectono-stratigraphy and economic potential of kirana malani-basin, Indo Pakistan. Journal of Hydrocarbon, Res. Islamabad, Pakistan, 11: 52-68

Entwisle, D. C., P. R. N. Hobbs, L. D. Jones, D. Gunn and M. G. Raines (2005). The relationship between effective porosity, uniaxial compressive strength and sonic velocity of intact borrowdale volcanic group core samples from sallafield. Geotechnical and Geological Engineering, 23: 793-809

Farah, M. A., M. A. Ahmad and M. N. Butt (1979). Gravity field of the burried shield in the punjab plain Pakistan. Bull. Soc. Am., 88: 1147-1155

Fener, M., S. Kahraman, A. Bilgil and O. Gunayadin (2005). A comparative evaluation of indirect methods to estimate the compressive strength of rocks. Rock Mechanics and Rock Engineering, 38(4): 329-343

Grasso, P., S. Xu and A. Mahtab (1992). Problems and promises of index testing of rocks. Proceedings of the 33rd U.S. Symposium on Rock Mechanics, Balkema, Rotterdam, PP. 879–888.

Horsrud, P. (2001). Estimating mechanical properties of shale from empirical correlations. SPE, SINTEF Petroleum Research, SPE Drilling and Completion

ISRM (1981). Rock characterization, testing and monitoring, ISRM Suggested Methods. Ed. Brown E.T. Pergamon Press, Oxford

Kochhar, N. (1999). A comparative study of malani representative of tusham hills (Haryana India) and kirana hills (Pakistan). Proceedings of the 3rd South Asia Geological Congress, Lahore, Pakistan

Kahraman, S. (2001). Evaluation of simple methods for assessing the uniaxial compressive strength of rock. International Journal of Rock Mechanics and Mining Sciences, 38: 981-994

Kurtulus, C., A. Bozkurt and H. Endes (2011). Physical and Mechanical Properties of Serpentinized Ultrabasic Rocks in NW Turkey. Pure and Applied Geophysics, Vol. 10.

Lyman, R. and M. Longnecker (2010). An introduction to statistical methods and data analysis. Sixth Edition, Brooks/Cole Cengage Learning, Canada

Menke, W.H. and K.H.C. Jacob (1976). Seismic pattern in Pakistan and north India associated with continental collision; Bull. Seismal. Soc. Amer. Elcerrito, Colorado, 66: 1695-1712

Sharma, P.K. and T. N. A. Singh (2007). Correlation between p-wave velocity, impact index, slake durability and uniaxial compressive strength. Bull. Eng. Geol. Environ., 67: 17-22

Szlavin, J. (1974). Relationships between some physical properties of rock determined by laboratory tests. International Journal of Rock Mechanics & Mining Sciences, 11: 57-66

Tugrul, A. and I. H. Zarif (1999). Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from turkey. Engineering Geology, 51: 303-317

Vasconcelos, G., B. L. Paulo, C.S.A. Alves and J. Pamplona (2007). Prediction of the mechanical properties of granites by ultrasonic pulse velocity and schmidt hammer hardness. 10th North American Masonry Conference. St., Louis, Missouri, U.S.A.

Wannakao, L., S. Sriputorn, and J. Trirat (2009). Correlations between mechanical and ultrasonic wave properties of claystone from mae-moh coal mine. Rock Mechanics, Fuenkajorn & Phien-wej (eds), ISBN 978 974 533 624 7 351

Yagiz, S. (2011). P-wave velocity test for assessment of geotechnical properties of some rock materials; Indian Academy of Sciences. Bull. Mater. Sci., 34(4): 947–953

Yasar, E. and Y. Erdogan (2004). Correlating sound velocity with the density, compressive strength and young’s modulus of carbonate rocks. International Journal of Rock Mechanics and Mining Sciences, 41: 871–875

Zhang, L. (2005). Engineering properties of rocks. Elsevier Publ. Amsterdam, 4: 1-290.