Evaluation of Empirical Equations to Estimate the Mechanical Properties of Sedimentary Rocks Using Ultrasonic Pulse Velocity (UPV)

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Abstract: The Uniaxial Compressive Strength (UCS) and Young's modulus (E) of sedimentary rocks are the most significant geotechnical parameters for rock classifications and the stability analysis of the foundation of building and underground structures. The UCS and E can be predicted using a non-destructive method such as the Ultrasonic Pulse Velocity (UPV) test. Many empirical equations have been proposed by the researchers to predict the mechanical properties of rock materials using UPV; however, the evaluation of these equations has not been studied yet according to authors' knowledge. This study aims to find out the most reliable empirical equation to predict the UCS and E using UPV test for sedimentary rocks. The reliability of empirical equation was studied using statistical analysis of data from this study and data of literature. The most reliable empirical equations to predict the UCS and E from UPV for sedimentary rocks have been selected based on R^2 and RMSE.

Keywords: Sedimentation, Ultrasonic Pulse Velocity, Empirical Equations, Sedimentary Rocks

1. Introduction

Sedimentary rocks are formed by sedimentation and stabilization of this substance on the surface of the earth and inside water bodies. Sedimentation is the collective name of processes that cause the stability of mineral or organic particles in their place. The sedimentary lithosphere of the continents of the earth's crust is about 73% of the Earth's current surface (Wilkinson et al., 2008). The Ultrasonic pulse velocity (UPV) is the most conventional non-destructive test for determining the elastic parameters of rock. It is carried out as the basic test in some of the geotechnical engineering projects. The procedure for calculating the UPV test has been standardized by both the American Society for Testing and Materials (ASTM, 1984) and the International Society for Rock Mechanics (ISRM 1981). The ultrasonic method offers the possibility of obtaining these parameters without changing the internal structure of the sample and at relatively low costs. P-wave velocity measurements can be achieved through three different methods in the laboratory: the direct method, semi-direct method, and indirect method (Kahraman, 2002). Ultrasonic pulse velocity tests were carried out using the direct method. ISRM (1981) defines three methods of measurement: the high and low-frequency ultrasonic pulse techniques and the resonant method. Indirect methods employing simple index parameters such as the Schmidt hammer, porosity, P-wave velocity (Oyler et al., 2010).

Some researchers, including Birch (1960, 1961) and Deere and Miller (1966) have studied the relationships between rock properties and pulse velocity. They have conducted that the sound velocity is closely related to the rock properties. The literature review reveals the need of reliability study to determine the best empirical equations to predict UCS and E from UPV test. The aim of this paper to study the reliability of the empirical Equations to Estimate Uniaxial Compression Strength (UCS) and Young's Modulus (E) of Sedimentary Rock using Ultrasonic pulse velocity (UPV) based on collected data from literature. In addition, the most reliable empirical equations to predict the UCS and E using UPV for some sedimentary rocks are recommended.

2. Literature Review

In this study, thirty-eight empirical equations about UCS and V_p also thirteen empirical equations about E and V_p for limestone rocks have been collected from previous studies as summarized in Tables 1 and 2 respectively. Additionally, twenty-four empirical equations about UCS and V_p and ten empirical equations about E and V_p for sandstone rocks from previous studies have been collected as summarized in Tables 3 and 4 respectively.

Table 1: Summary of empirical equations of UCS for limestone

References	Equations	Eq. No.
Militzer and Stoll (1973)	$UCS = 2.45*(V_p)^{1.82}$	1
Golubev and Robinovich (1976)	$Log(UCS) = 0.358*(V_p) + 0.283$	2
G.Oktan (1988)	$UCS = 36*V_p – 31.18$	3
Kahraman (2001)	$UCS = 9.95*(V_p)^{1.21}$	4
Yasar and Erdogan (2004)	$UCS = 31.546*V_p – 63.7066$	5
Çobanoğlu and Çelik (2008)	$UCS = 56.71*V_p – 192.93$	6
Diamantis et al. (2009)	$UCS = 110*V_p – 515.56$	7
	$UCS = 0.0026*exp^{(1.9Vp)}$	8
Moradian and Behnia (2009)	$UCS = 165.05* exp^{(-4.45107/Vp)}$	9
Kurtulus et al. (2012)	$UCS = 53.3*V_p – 132.629$	10
	$UCS = 20.7*V_p – 24.729$	11
Yagiz (2011)	$UCS = 0.258*(V_p)^{3.543}$	12
	$UCS = 49.4*V_p - 167$	13
Hakan and Kanik (2012)	$UCS = 0.0049 (1000*V_p/14) + 12$	14
	$UCS = 0.0032 (1000*V_p/12) – 427$	15
	$UCS = 0.001 (1000*V_p/25) +30$	16
	$UCS = 0.001 (1000*V_p/21) +26$	17
	$UCS= 0.0009 (1000*V_p/60) + 38$	18
Babacan et al. (2012)	$UCS = 12*V_p – 5.95$	19
Yurdakul and Akdas (2013)	$UCS = 37* V_p – 101.733$	20
Nefeslioglu (2013)	$UCS = 2.258013*V_p + 0.060749$	21
	$UCS = 3.313262*V_p – 0.814776$	22
	$UCS = 4.751294*V_p – 2.354974$	23
	$UCS = 4.585574*V_p – 2.230556$	24
	$UCS = 1.779459*(V_p)^{1.409563}$	25
	$UCS = 1.902589*(V_p)^{1.031474}$	26
	$UCS = 1.642474*(V_p)^{1.277730}$	27
Reyer and Philipp (2014)	$UCS = 2.26*(V_p)^{2.351}$	28
	$UCS = 8.535*exp^{(0.5*Vp)}$	29
	$UCS = 29*V_p – 19.09$	30
	$UCS = 23.763*exp^{(0.3*Vp)}$	31
Najibi et al. (2015)	$UCS = 3.67*(V_p)^{2.14}$	32

Vasanelli et al. (2016)	$UCS = 18.5*V_p - 37$	33
	$UCS = 15.9*V_p - 27$	34
Briševac et al. (2017)	$UCS = 1.5991*exp^{(0.7112*Vp)}$	35
	$UCS = 7.1465*exp^{(0.3551*Vp)}$	36
Ghafoori et al.(2018)	$UCS = 3.73*(V_p)^{2.1}$	37
Alshkane et al. (2018)	$UCS = 23.52*V_p + 19.51$	38

Table 2: Summary of empirical equations of E for limestone

References	Equations	Eq. No.
Yasar and Erdogan (2004)	$E = 10.672*V_p - 18.7065$	39
Moradian and Behnia (2009)	$E = 2.06*(V_p)^{2.78}$	40
Yagiz (2011)	$E = 20.1*V_p - 53$	41
Nefeslioglu (2013)	$E = 0.146710*(V_p)^{1.418268}$	42
	$E = 0.228951*V_p - 0.075984$	43
	$E = 0.391869*V_p - 0.179741$	44
	$E = 0.018725*exp^{(1.638227*Vp)}$	45
	$E = 0.441939*V_p - 0.269430$	46
	$E = 0.018831*exp^{(1.832345*Vp)}$	47
Najibi et al. (2015)	$E = 0.169*(V_p)^{3.324}$	48
Stan-Kłeczek (2016)	$E = 74*Ln(1000*V_p) - 572$	49
Ghafoori et al.(2018)	$E = 0.07*(V_p)^{3.623}$	50
Alshkane et al. (2018)	$E = 22.5332 *exp^{(0.5094*Vp)}$	51

Table 3: Summary of empirical equations of UCS for sandstone

References	Equations	Eq. No.
Freyburg (1972)	$UCS = 35*V_p - 31.5$	52
G.Oktan (1988)	$UCS = 36*V_p - 31.18$	53
Kahraman (2001)	$UCS = 9.95*(V_p)^{1.21}$	54
Chary et al. (2006)	$UCS = 156.4*V_p - 692.41$	55
	$UCS = 14.4*V_p - 24.856$	56
Moradian and Behnia (2009)	$UCS = 165.05* exp^{(-4.45107/Vp)}$	57
Khandelwal and Singh (2009)	$UCS = 133.3* V_p - 227.19$	58
Mishra and Basu (2013)	$UCS = 50*V_p - 126.4$	59
Nefeslioglu (2013)	$UCS = 2.258013*V_p + 0.060749$	60
	$UCS = 3.313262*V_p - 0.814776$	61
	$UCS = 4.751294*V_p - 2.354974$	62
	$UCS = 4.585574*V_p - 2.230556$	63
	$UCS = 1.779459*(V_p)^{1.409563}$	64
	$UCS = 1.902589*(V_p)^{1.031474}$	65
	$UCS = 1.642474*(V_p)^{1.277730}$	66
Reyer and Philipp (2014)	$UCS = 21.774*(V_p)^{0.98}$	67
	$UCS = 4*(V_p)^2 - 9*(V_p) + 11.5$	68
	$UCS = 29*V_p - 19.09$	69
	$UCS = 23.763*exp^{(0.3*Vp)}$	70
Butel et al. (2014)	$UCS = 1.11* exp^{(0.9*Vp)}$	71

Armaghani et al. (2016)	UCS = 17.783*$(V_p)^{1.099}$	72
Aşcı et al.(2017)	UCS = 14.6*V_p – 26.22	73
Wang et al. (2017)	UCS = 10.9*V_p + 5.42	74
Alshkane et al. (2018)	UCS = 23.52*V_p + 19.51	75

Table 4: Summary of empirical equations of E for sandstone

References	Equations	Eq. No.
Moradian and Behnia (2009)	E = 2.06*$(V_p)^{2.78}$	76
Khandelwal and Singh (2009)	E = 4.9718* V_p – 0.7151	77
Nefeslioglu (2013)	E = 0.146710*$(V_p)^{1.418268}$	78
	E = 0.228951*V_p – 0.075984	79
	E = 0.391869*V_p – 0.179741	80
	E = 0.018725*$\exp^{(1.638227*Vp)}$	81
	E = 0.441939*V_p – 0.269430	82
	E = 0.018831*$\exp^{(1.832345*Vp)}$	83
Najibi et al. (2015)	E = 0.169*$(V_p)^{3.324}$	84
Alshkane et al. (2018)	E = 22.5332 *$\exp^{(0.5094*Vp)}$	85

3. Materials and Methods

3.1 Limestone

Forty block samples of limestone were collected to perform UCS, E and UPV tests from two different formations includes Pila Spi Formation in the Sulaimani city and Lower Fars Formation in the Mosul city from north of Iraq. The test results of this study have been used to check the reliability of literature empirical equations about limestone rocks.

3.2 Sandstone

From Tanjero Formation in the Sulaimani city, twenty-three sandstone block samples were collected to conduct UCS, E and UPV tests. Additionally, fifty-six UCS with V_p data of sandstone from Kurtuluş et al. (2016) and twenty-three E with V_p data of sandstone from Reyer and Philipp (2014) have been collected. Afterwards, the literature data were added to the test result data of current study to check the reliability of literature empirical equations that developed for the sandstone rocks.

3.3 Ultrasonic Pulse Velocity (UPV) Test

To perform UPV test, the block samples with size approximately 100x50x50 mm were prepared. The two ends of each specimen were ground and polished by gridding machine for conducting UPV.

3.4 Uniaxial Compressive Strength (UCS) and Modulus of Elasticity (E) Tests

The uniaxial compressive strength for the prepared samples was performed by using same samples that used for UPV test. Compressive testing machine was used for conducting UCS test. During the UCS test, axial load with axial deformation were recorded to create the stress- strain curve and finding the E.

4. Statistical Analysis

Both the coefficients of determination (R^2) and the Root Mean Square Error (RMSE) for the regression model predictions have been used to determine the accuracy of the model predictions as defined in the following Eqs. (86 and 87):

$$R^2 = \left(\frac{\sum_i (X_i - X^-) * (Y_i - Y^-)}{\sqrt{\sum_i (X_i - X^-)^2} \sqrt{\sum_i (Y_i - Y^-)^2}} \right) \quad (86)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - X_i)2}{N}} \quad (87)$$

Where:
R^2 = coefficient of determination
RMSE = root mean square error
Y_i = actual test value.
X_i = calculated value from the model.
$\bar{y}$ = mean of actual test values.
$\bar{x}$ = mean of calculated values and
N = is the number of data points.

5. Results and Discussions

5.1 Limestone

Based on the test results, ultrasonic pulse velocity (V_p) was used for predicting of the uniaxial compressive strength (UCS) and Young's modulus (E). Also, thirty-eight empirical equations of UCS and thirteen empirical equations of E have been collected from different studies as mentioned before (Tables 1 and 2). The statistical analyses of the test results have been conducted, as summarized in Table 5. Afterwards, the test results of V_p have been used as the input parameter to the empirical equations for predicting the UCS and E. The results of the R^2 and RMSE have been conducted as presented in Tables 6 and 7 for UCS and E equations respectively.

From Tables 6 and 7 it can be concluded that the mechanical properties of limestone rocks can be obtained using V_p. Additionally, nine empirical equations of UCS include Eqs. (2, 3, 5, 10, 28, 29, 30, 32 and 37) and six empirical equations of E include Eqs. (39, 41, 45, 48, 49 and 50) are more reliable compared with other empirical equations based on RMSE. However, Eq. (10) for predicting UCS and Eq. (49) for predicting E that was created by Kurtulus et al. (2011) and Stan-Kłeczek (2016) respectively, are the best equations since their RMSE values were the minimum. In addition, the correlation between measured and predicted values for UCS and E from V_p have been developed for the most mentioned reliable empirical equations of UCS and E as shown in Figures 1 and 2 respectively.

Table 5: Summary of statistical analysis for limestone

Parameters	UCS(MPa)	E(GPa)	V_p (km/sec)
No. of data	40	40	40
Maximum	195.6	80	5.656
Minimum	6.6	1.03	2.12
Mean (average)	76.9	3.75	3.738
Standard deviation	71.1	30.46	1.256
C.O.V	92.45	81.24	33.59

Table 6: Summary of RMSE and R^2 for the UCS equations of limestone

Equations	RMSE (MPa)	R^2	Eq. No.
$UCS = 2.45*(V_p)^{1.82}$	72.286	0.9452	1
$Log(UCS) = 0.358*(V_p) + 0.283$	28.274	0.8738	2
$UCS = 36*V_p – 31.18$	38.979	0.2384	3
$UCS = 9.95*(V_p)^{1.21}$	57.990	0.9482	4
$UCS = 31.546*V_p – 63.7066$	40.335	0.9481	5
$UCS = 56.71*V_p – 192.93$	60.080	0.9481	6
$UCS = 110*V_p – 515.56$	194.331	0.9481	7
$UCS = 0.0026*exp^{(1.9Vp)}$	77.241	0.5926	8
$UCS = 165.05* exp^{(-4.45107/Vp)}$	59.046	0.9453	9
$UCS = 53.3*V_p – 132.629$	19.175	0.9481	10
$UCS = 20.7*V_p – 24.729$	51.648	0.9481	11
$UCS = 0.258*(V_p)^{3.543}$	50.787	0.9115	12
$UCS = 49.4*V_p - 167$	61.801	0.9481	13
$UCS = 0.0049 (1000*V_p/14) + 12$	94.413	0.9481	14
$UCS = 0.0032 (1000*V_p/12) – 427$	507.739	0.9481	15
$UCS = 0.001 (1000*V_p/25) +30$	84.307	0.9481	16
$UCS = 0.001 (1000*V_p/21) +26$	86.565	0.9481	17
$UCS= 0.0009 (1000*V_p/60) + 38$	80.219	0.9481	18
$UCS = 12*V_p – 5.95$	67.529	0.9481	19
$UCS = 37* V_p – 101.733$	48.883	0.9481	20
$UCS = 2.258013*V_p + 0.060749$	96.087	0.9481	21
$UCS = 3.313262*V_p – 0.814776$	93.019	0.9481	22
$UCS = 4.751294*V_p – 2.354974$	89.108	0.9481	23
$UCS = 4.585574*V_p – 2.230556$	89.594	0.9481	24
$UCS = 1.779459*(V_p)^{1.409563}$	92.023	0.9477	25
$UCS = 1.902589*(V_p)^{1.031474}$	97.033	0.9481	26
$UCS = 1.642474*(V_p)^{1.277730}$	95.062	0.9481	27
$UCS = 2.26*(V_p)^{2.351}$	37.172	0.9387	28
$UCS = 8.535*exp^{(0.5*Vp)}$	36.396	0.9222	29
$UCS = 29*V_p – 19.09$	38.204	0.9481	30
$UCS = 23.763*exp^{(0.3*Vp)}$	43.196	0.9393	31

$UCS = 3.67*(V_p)^{2.14}$	29.634	0.9417	32
$UCS = 18.5*V_p – 37$	65.745	0.9481	33
$UCS = 15.9*V_p – 27$	67.826	0.9481	34
$UCS = 1.5991*exp^{(0.7112*Vp)}$	64.702	0.8936	35
$UCS = 7.1465*exp^{(0.3551*Vp)}$	74.857	0.9355	36
$UCS = 3.73*(V_p)^{2.1}$	32.382	0.9422	37
$UCS = 23.52*V_p + 19.51$	52.186	0.9481	38

Table 7: Summary of RMSE and R^2 for the E equations of limestone

Equations	RMSE (GPa)	R^2	Eq. No.
$E = 10.672*V_p – 18.7065$	23.808	0.9584	39
$E = 2.06*(V_p)^{2.78}$	82.404	0.9364	40
$E = 20.1*V_p – 53$	17.160	0.9584	41
$E = 0.146710*(V_p)^{1.418268}$	47.029	0.9569	42
$E = 0.228951*V_p – 0.075984$	47.288	0.9584	43
$E = 0.391869*V_p – 0.179741$	46.772	0.9584	44
$E = 0.018725*exp^{(1.638227*Vp)}$	28.958	0.6647	45
$E = 0.441939*V_p – 0.269430$	46.658	0.9584	46
$E = 0.018831*exp^{(1.832345*Vp)}$	132.737	0.6091	47
$E = 0.169*(V_p)^{3.324}$	23.392	0.9219	48
$E = 74*Ln(1000*V_p) –572$	9.189	0.9525	49
$E = 0.07*(V_p)^{3.623}$	31.395	0.9125	50
$E = 22.5332 *exp^{(0.5094*Vp)}$	165.909	0.9261	51

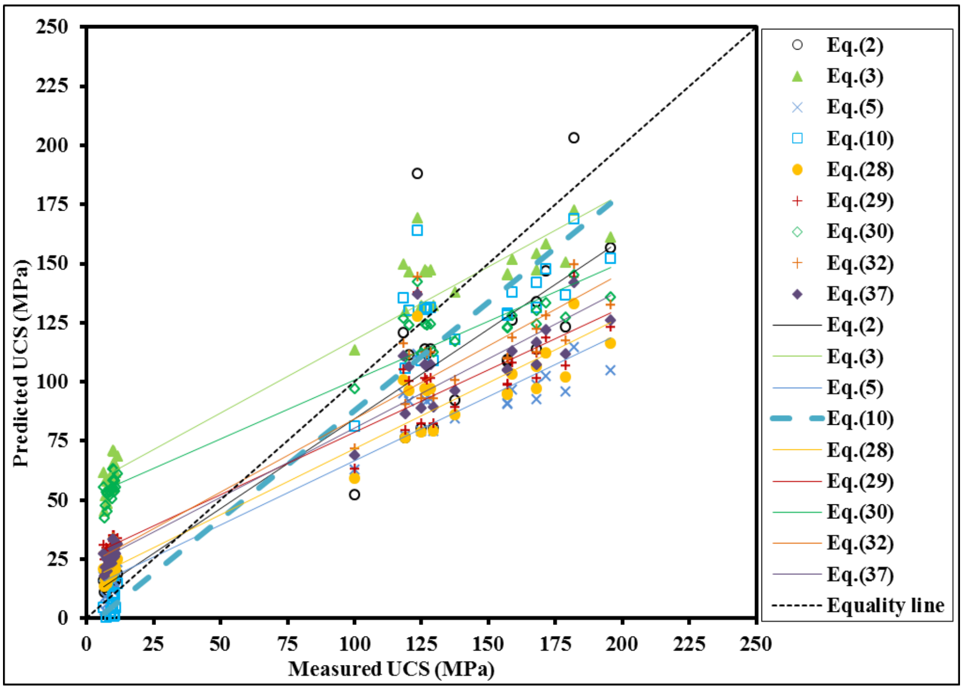

Figure 1: Correlation between measured and predicted UCS for limestone

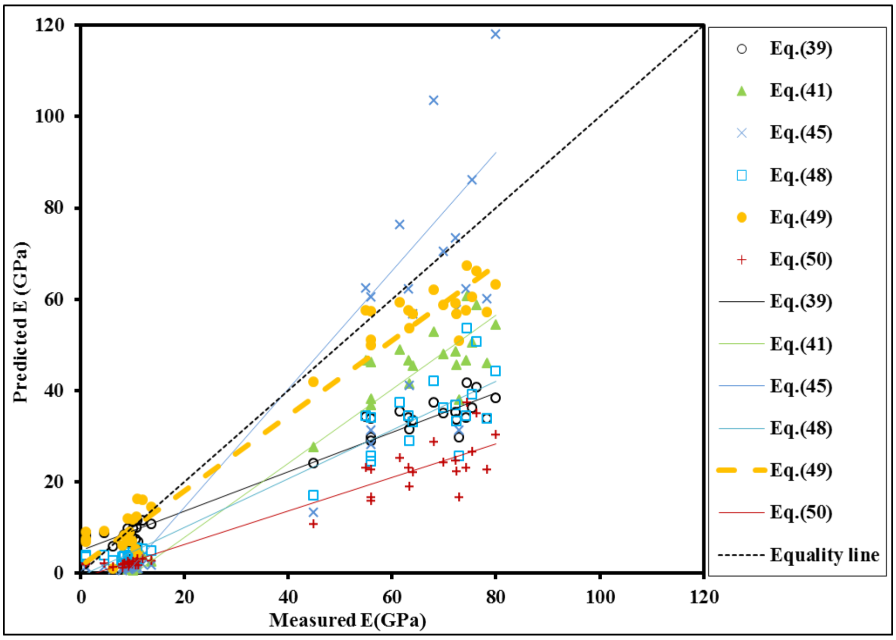

Figure 2: Correlation between measured and predicted E for limestone

5.2 Sandstone

Twenty-three measured data of this study and fifty-six data of previous studies have been used for prediction of the UCS. Moreover, twenty-three measured data of this study and twenty-three data of previous studies have been used to predict E using V_p. twenty-four empirical equations of UCS and ten empirical equations of E have been collected from different studies as mentioned before (Tables 3 and 4). The statistical analysis for this study data and data of previous studies have been achieved as summarized in Table 8. The measured V_p data have been used as the input parameter for the empirical equations to predict the UCS and E. Additionally, the result of the R^2 and RMSE were conducted for UCS and E equations as presented in Tables 9 and 10 respectively.

From Tables 9 and 10 it can be decided that eight empirical equations of UCS include Eqs. (52, 53, 59, 67, 69, 70, 72 and 75) and three empirical equations of E include Eqs. (77, 81 and 84) are more reliable compared with other empirical equations based on RMSE. However, Eq. (69) for predicting UCS that was created by Reyer and Philipp (2014) and Eq. (81) for predicting E of sandstone rocks that was created by Nefeslioglu (2013) are the best equations since their RMSE values were the minimum. In addition, the correlation between measured and predicted values for UCS and E from V_p have been developed for the most mentioned reliable empirical equations of UCS and E as shown in Figures 3 and 4 respectively.

Table 8: Summary of statistical analysis for sandstone

Parameters	UCS(MPa)	V_p (km/sec)[a]	E(GPa)	V_p (km/sec)[b]
No. of data	79	79	46	46
Maximum	222.4	6.01	86.25	4.981
Minimum	9.65	1.89	6.8	2.074
Mean (average)	88.58	4.002	40.56	3.869
Standard deviation	52.21	1.001	21.52	0.892
C.O.V	58.93	25.01	53.05	23.25

a V_p used for predicting UCS
b V_p used for predicting E

Table 9: Summary of RMSE and R^2 for the UCS equations of sandstone

Equations	RMSE (MPa)	R^2	Eq. No.
$UCS = 35*V_p – 31.5$	30.020	0.6343	52
$UCS = 36*V_p – 31.18$	31.503	0.6343	53
$UCS = 9.95*(V_p)^{1.21}$	52.949	0.63	54
$UCS = 156.4*V_p – 692.41$	112.439	0.6343	55
$UCS = 14.4*V_p – 24.856$	68.602	0.6343	56
$UCS = 165.05* \exp^{(-4.45107/Vp)}$	53.494	0.6444	57
$UCS = 133.3* V_p – 227.19$	218.680	0.6343	58
$UCS = 50*V_p – 126.4$	32.447	0.6343	59
$UCS = 2.258013*V_p + 0.060749$	91.941	0.6343	60
$UCS = 3.313262*V_p – 0.814776$	88.875	0.6343	61
$UCS = 4.751294*V_p – 2.354974$	84.984	0.6343	62
$UCS = 4.585574*V_p – 2.230556$	85.472	0.6343	63
$UCS = 1.779459*(V_p)^{1.409563}$	88.190	0.6251	64
$UCS = 1.902589*(V_p)^{1.031474}$	92.920	0.6337	65
$UCS = 1.642474*(V_p)^{1.277730}$	91.090	0.6284	66
$UCS = 21.774*(V_p)^{0.98}$	33.412	0.6347	67
$UCS = 4*(V_p)^2 – 9*(V_p) + 11.5$	58.557	0.5887	68
$UCS = 29*V_p – 19.09$	28.791	0.6343	69
$UCS = 23.763*\exp^{(0.3*Vp)}$	34.087	0.5972	70
$UCS = 1.11* \exp^{(0.9*Vp)}$	49.820	0.446	71
$UCS = 17.783*(V_p)^{1.099}$	34.136	0.6324	72
$UCS = 14.6*V_p – 26.22$	68.940	0.6343	73
$UCS = 10.9*V_p + 5.42$	58.219	0.6343	74
$UCS = 23.52*V_p + 19.51$	30.632	0.6343	75

Table 10: Summary of RMSE and R^2 for the E equations of sandstone

Equations	RMSE (GPa)	R^2	Eq. No.
$E = 2.06*(V_p)^{2.78}$	67.924	0.6392	76
$E = 4.9718* V_p – 0.7151$	28.515	0.6638	77
$E = 0.146710*(V_p)^{1.418268}$	44.799	0.6627	78
$E = 0.228951*V_p – 0.075984$	45.019	0.6638	79
$E = 0.391869*V_p – 0.179741$	44.505	0.6638	80
$E = 0.018725*exp^{(1.638227*Vp)}$	25.655	0.4601	81
$E = 0.441939*V_p – 0.269430$	44.398	0.6638	82
$E = 0.018831*exp^{(1.832345*Vp)}$	43.542	0.4301	83
$E = 0.169*(V_p)^{3.324}$	27.112	0.6236	84
$E = 22.5332 *exp^{(0.5094*Vp)}$	144.129	0.6335	85

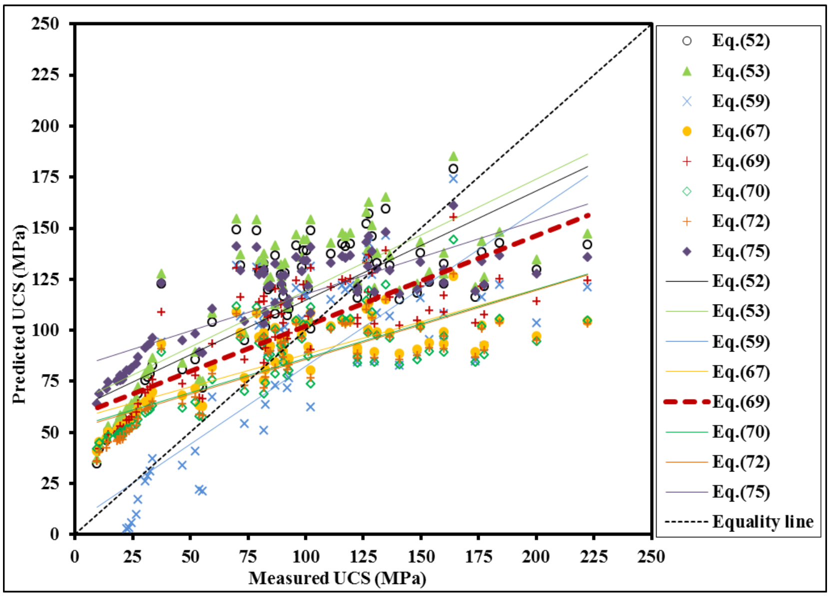

Figure 3: Correlation between measured and predicted UCS for sandstone

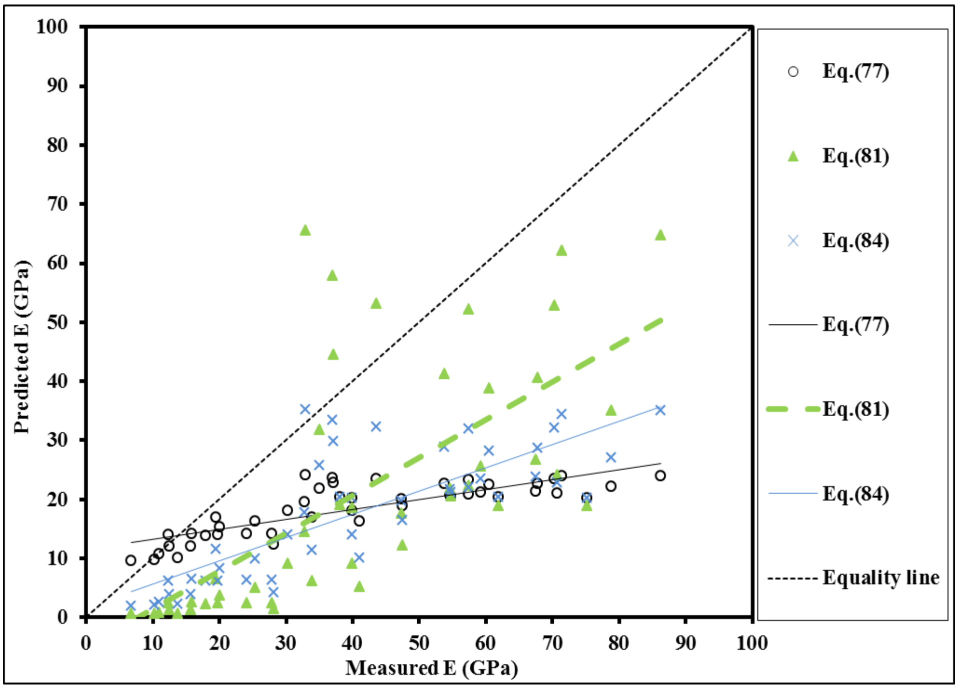

Figure 4: Correlation between measured and predicted E for sandstone

6. Conclusion

In this study, the reliability of empirical equations that were developed by researchers to predict UCS and E using UPV test was studied. The equations were checked based on the measurements in the current study and data collected from the literature. In this study the following conclusions can be drawn:

1. The equation that was proposed by Kurtulus et al. (2011) with $R^2 = 0.9481$ and RMSE = 19.175 MPa has a good performance to predict UCS from UPV for limestone rocks.
2. The equation that was proposed by Stan-Kłeczek (2016) with $R^2 = 0.9525$ and RMSE = 9.189 MPa has a good performance to predict Es from UPV for Limestone rocks.
3. The equation that was proposed by Nefeslioglu (2013) with $R^2 = 0.6251$ and RMSE = 22 MPa has a good performance to predict UCS from UPV for sandstone rocks.
4. The equation that was proposed by Nefeslioglu (2013) with R2 = 0.4601 and RMSE = 25.655 GPa has a good performance to predict UCS from UPV for sandstone rocks.

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