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Correlations of Uniaxial Compressive Strength and Modulus of Elasticity with Point Load Strength Index, Pulse Velocity and Dry Density of Limestone and Sandstone Rocks in Sulaimani Governorate, Kurdistan Region, Iraq.

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Abstract

The Uniaxial Compressive Strength (UCS) of rocks is important parameter in design of geotechnical engineering. If the rocks are affected by weathering agents, there will be difficult to obtain intact samples and to determine UCS in laboratory.Hence, the use of another engineering index of rocks as an alternative for determining UCShave been studied and investigated by researchers. The Pulse Velocity and Point Load tests are used as a quick, easy and non-expensive means of obtaining rock strength indexes. This paper presents an experimental study for correlating between Uiaxial Compressive Strength (UCS) and Point Load Index (PLI), Pulse Velocity (Vp), Dry Density andModulus of Elasticity (E) of limestones and sandstone rock samples. 80 specimens of limestones were obtained from Pila Spi and Lower Fars Formations and 46 specimens of sandstone were obtained from Tanjero Formation. Based on the results, for the first time in this region, a new good correlation is introduced to estimate the UCS and Efrom Pulse Velocity, Point Load Index and Dry Density.

I. Introduction

Sedimentary rocks are consolidated materials, resulted by cementation and compaction during diagenesis of sediments, consisting of clasts or detritus of preexisting rocks or of biogenic origin and are together with discontinuities, joints, fractures, faults, folds and foliation[1].

The uniaxial compressive strength (UCS) of rocks in designing structures is widely used by engineers. The method for determining this essential parameter in analysis of geotechnical problems needs a long time and many financial costs[2, 3].In addition, it is not always possible to obtain intact samples where the rocks are highly weathered [4, 5, 6].On the other hand, there are some indirect tests such as Point Load Index, rebound number of Schmidt hammer, indirect tensile strength, pulse velocity and others [7, 8].These tests are easier to carry out because they need less or no specimen preparation and the testing equipment is less advanced. Also, they can be used easily in the construction sites. The purpose of this study is to evaluate the correlations between the UCS test results and the corresponding test results of Pulse Velocity and Point Load Index. For this study, 126 specimens were collected from different locations and prepared as specimens of dimensions: 5cm x 5cm x 10cm

II. Previous Studies

Previous studies have shown that there is a relationship between UCS and other mechanical properties of rocks [2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16].D'Andrea*et al*, 1964 carried out uniaxial compression and point load tests on various rock types. They established the following linear regression model of correlation between UCS and Is(50); $q_u = 16.3 + 15.3\ Is_{(50)}$.Where $q_u$is the uniaxial compressive strength and Is is the point load strength index.Other researchers have investigated the correlation between UCS and Point Load Index for various types of rocks [18, 19, 20, 21, 22, 23].According to their studies, the strength conversion factor (k) value is within the range 20-25, when the UCS is calculated from the equation $UCS=k*Is_{(50)}$.
The focus of this study is to present the data analysis to correlate the UCS and E with Point Load Index (PLI), Pulse Velocity (Vp) and Dry Density for different sedimentary rocks.

III. Geological Setting

Block samples of the sandstone were brought from near the Germany Village (Figure 1). These blocks belong to the upper part of the Tanjero Formation and regarded as bedded sedimentary rocks, the thickness of beds range between 10-60 cm. The rocks are composed of alternation of very strong sandstone beds (thin and thick beds) with thin beds of the greenish marlstone, sometimes associated with conglomerate beds (Figure 2). In the local language, this sandstone called Bardy Dabashan and was used in construction. Many of the old houses of Sulaimani, as well as some of the government buildings and schools were built from this type of stone. The Tanjero Formation was defined by Dunnington in 1952. The type section of the formation in the Sirwan valley (SE of Sulaimani) consists of two divisions. The lower division consists of pelagic marl, and occasional beds of argillaceous limestone with siltstone beds in the upper part [24].The upper division comprises silty marl, sandstone, conglomerates, and sandy or silty organic detrital limestones. The constituents of sandstones are composed predominantly of particles of green igneous and metamorphic rocks. The formation was deposited as flysch in a rapidly subsiding foredeep basin. Planktonic fauna is abundant in the Tanjero Formation and indicates a Late Campaman-Maastrichtian age. The formation mainly occurs in the Balambo-Tanjero Zone.

The limestone rock samples used in this study consist of two types belonging to the Pila Spi and Lower Fars Formations. The samples of the first type (Pila Spi Formation) were collected from quarry of limestone rocks (Figures1, 2) used in decoration of buildings in Kurdistan Region (about 10 km to the west of Zarayen city in Sulaimani Governorate, near Blkan Village), and the samples of the second type (Lower Fars Formation) were obtained from one of the decoration companies in Sulaimani City.

The Pila Spi Formation was first described by Lees in 1930 from the Pila Spi area of the High Folded Zone [24].The original type section was submerged under the waters of the Derbendikhan Dam. The Pila Spi Formation is 100-200 m thick with well bedded bituminous, chalky, and crystalline limestones in the upper part with bands of white, chalky marl and with chert nodules towards the top. The lower part of the formation comprises well bedded hard, porous or vitreous, bituminous, white, poorly fossiliferous limestones. The limestones are sometimes oolitic with rare layers of gastropod debris. The Formation (Middle-Late Eocene age) was deposited in a shallow lagoon [24, 25].However, conglomerates occur at the base of the formation in the Derbendikhan area [26].

The Lower Fars Formation was defined from the Fars Province in Iran and introduced to Iraq by Busk and Mayo in 1918 [24].The type section has been located in the Al Fatha Gorge, 10 km north of Baiji town. The Formation is an evaporitic sequence with maximum thickness of 600 m and consists mainly of repeated cycles of mudrock, marl, limestone and gypsum, with lences of halite. In Iraq, the Formation is of Middle Miocene age [24].The Formation contains reserves of limestone and gypsum which is used for buildings decoration.

Figure-1: Location of Sandstone and Limestone Samples. (S:Sandstone, L: Limestone).

Figure- 2:A. Section of Sandstone beds (Tanjero Formation) near Germany Village-Sulaimani, the white arrows indicate sandstone beds and the black one indicates the greenish marlstone. B. Section of limestone beds (Pila Spi Formation) in Quarry near Blkan Village. C. Block of white limestone prepared to be transported to marble's Factory in Sulaimani City.

IV. Materials and Methods

In order to carry out this research, the samples were taken from three sites in the form of stone blocks. These blocks were sent to a sawmill marble for sample preparation in the form of prisms with size approximately 10x5x5 cm. The volume and the surface area of the specimens to be subjected to the compressive and point load testswere determined separately for each specimen. Total number of blocks was 63.From each block two specimens were prepared. Thespecimens are numbered from A1-1 to A20-1, A1-2 to A20-2, B1-1 to B23-1, B1-2 to B23-2 and C1-1 to C20-1, C1-2 to C20-2 for Limestone (Pila Spi Formation), sandstone (Tanjero Formation) and limestone (Lower Fars Formation) respectively. The two ends of each specimen were ground and polished by gridding machinein the geotechnical laboratory in the Engineering Faculty atUniversity of Sulaimani (Figure 3). Before testing, the specimens were placed in water for 72 hours to become saturated.

For this study, the following laboratory tests were carry out:

1. Water absorption;
2. Dry unit weight;
3. Saturated unit weight;
4. Porosity;
4. Point load strength tests;
5. Uniaxial compressive strength tests;
6. Pulse Velocity tests.

The determination of water absorption, dry unit weight, saturated unit weight and porosity was carried out depending on the volume, dry and saturated weights of specimens. The results of these properties are presented in Tables (1-6).

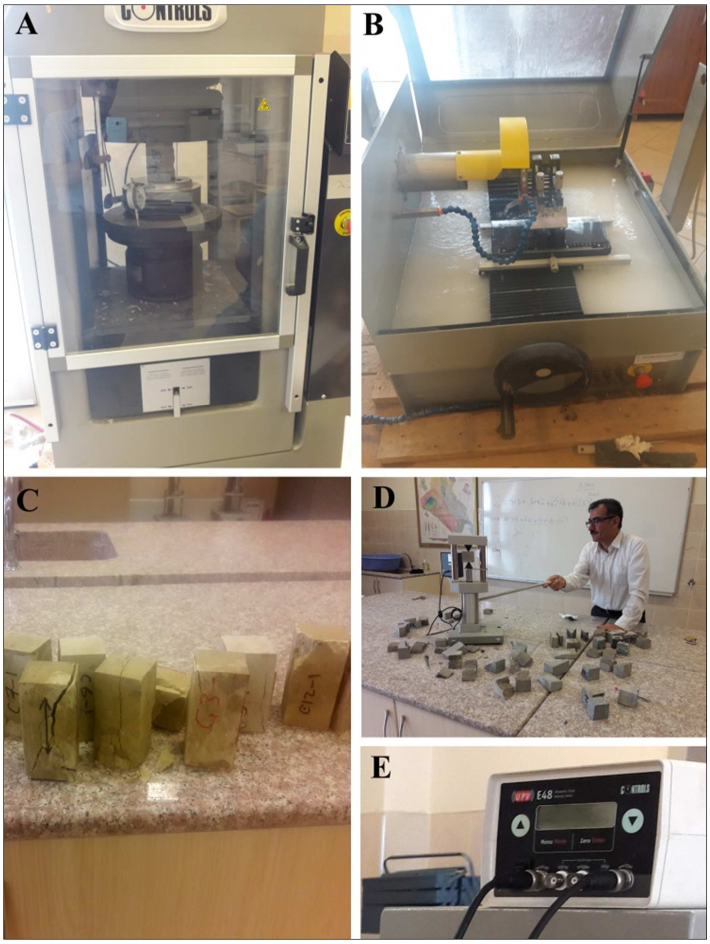

Figure-3: Apparatus used in this study. A- UniaxialCompressive machine. B. Grinding machine. C. Failed limestone speciments under compressive test. D. Point load machine. E. Ultrasonic Pulse Velocity apparatus.

A. Uniaxial Compressive strength and Pulse Velocity

The Ultrasonic Pulse Velocity (UPV) was first carried out on the specimens (A1-1 to A20-1, B1-1 to B23-1 and C1-1 to C20-1) to determine the ultrasonic velocity of longitudinal waves. The uniaxial compressive strength test was performed on the above mentioned specimens using compressive testing machine (Figure-3). During the test, the vertical load and deformation were recorded. The peak value in σ-ϵ_a curve was taken as the uniaxial compressive strength. The results obtained are shown in Tables 1, 2 and 3. In addition to UCS, the Modulus of Elasticity or Young's Modulus (E) has been obtained from the σ-ϵ_a curves (Figure-4, 5 and 6).

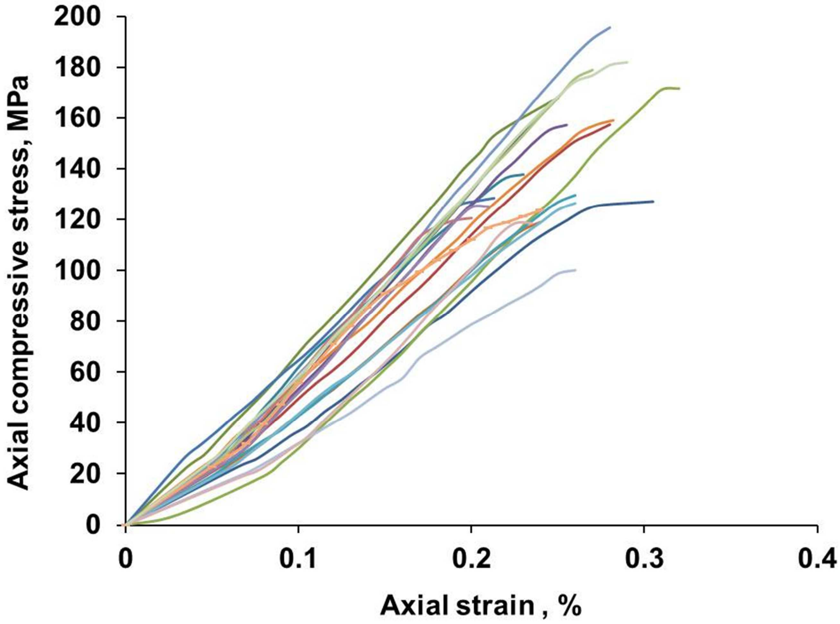

Figure-4: Stress-strain curves of limestone (Pila Spi Formation).

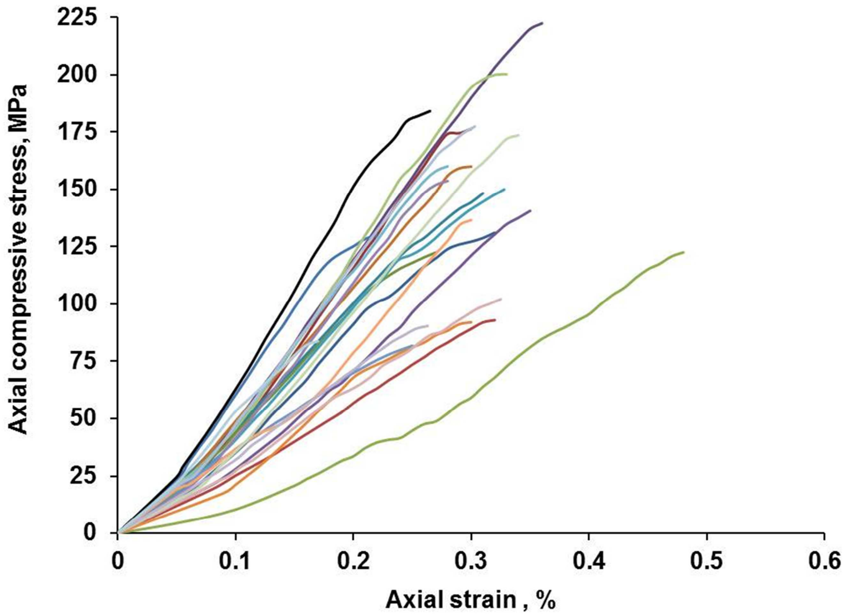

Figure-5: Stress-strain curves of Sandstone (Tanjero Formation)

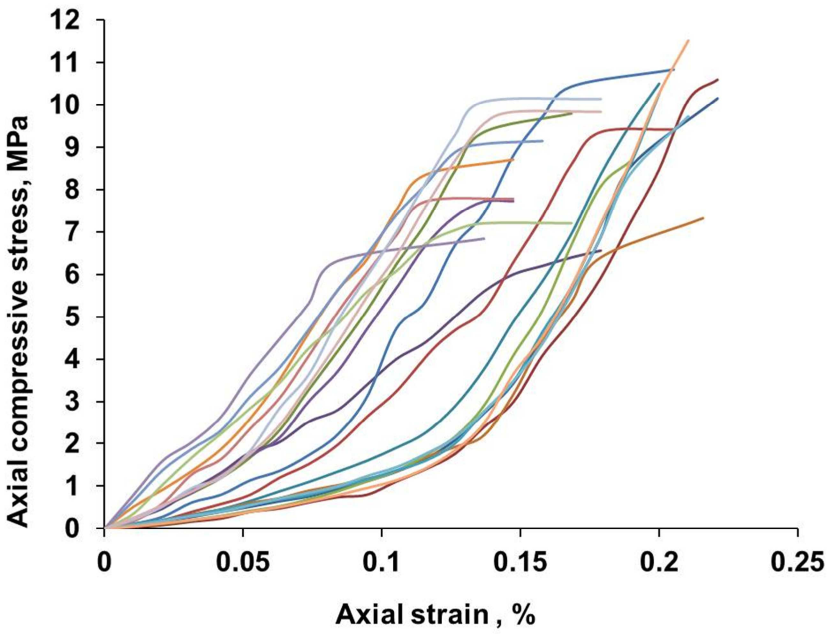

Figure-6: Stress-strain curves of Limestone (Lower Fars Formation).

B. *Point Load Strength*

The point load strength tests were performed according to the procedures suggested by [21] using equations:

$$\mathrm{Is} = \frac{P}{\mathrm{De}^2} \quad (1)$$

where Is is the point load strength index (MPa), P is the failure load in (kN) and De is the equivalent diameter (mm). For prismatic specimens the De is calculated as follows:

$$\mathrm{De}^2 = \frac{4A}{\pi} = \frac{4DW}{\pi} \quad (2)$$

where D is the distance between load contact points (mm), W is the width of the specimen (mm) and A is the cross-sectional area of a plane through the loading points.
Since the specimens tested in this study were not in standard size, the size correction procedure is necessary. Accordingly, the size correction was done following the procedure suggested in reference [21] as follows:

$$Is_{(50)}=f*Is \quad (3)$$

$$f=(De/50)^{0.45} \quad (4)$$

where f is the correction factor and $Is_{(50)}$ is the corrected point load strength index of a specimen of 50 mm diameter.

The dimensions of samples in this study for point load test are ideal compared to the dimensions suggested by [27].The Figure-7 shows the dimensions proposed by [27]. According to [18],the ratio of W/D should be between 0.3-1.0 and preferably close to 1.0 and the value of L should be at least 0.5 W. In present research the ratio of W/D is 1.0 and L=W. The results of the point load tests are given in Tables 4, 5 and 6 for samples A1-2 to A20-2, B1-2 to B23-2 and C1-2 to C20-2 respectively.

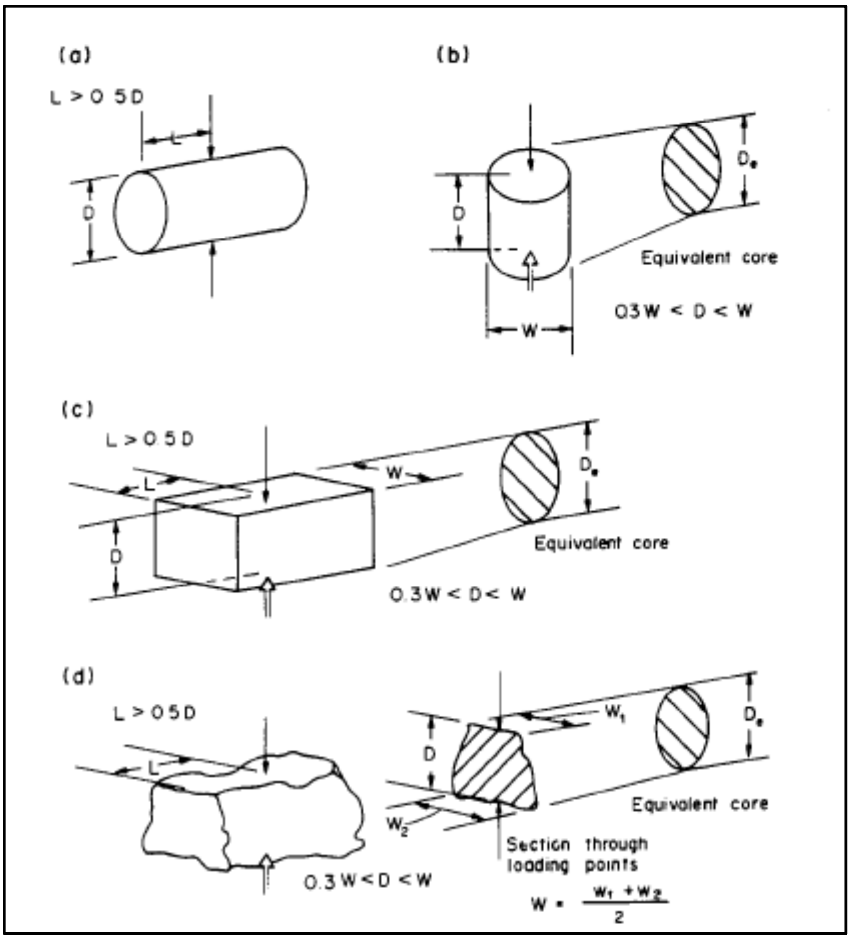

Figure-7: Rock samples dimensions for point load tests [27].

V. Results and Discussion

The results of physical properties of rocks used in this study, represented by water absorption, dry unit weight, saturated unit weight and porosity, are presented in Tables (1-6). The water absorption values range from 0.2-1.05, 1.48-3.02 and 2.47-11.28 for sandstone, limestone (Pila Spi Formation) and limestone (Lower fars Formation) respectively and exhibiting a great fluctuation. While the porosity values range from 0.51-4.67, 3.68-7.32 and 5.07-23.18 for sandstone, limestone (Pila Spi Formation) and limestone (Lower Fars Formation) respectively. These results prove that the lowest water absorption and porosity were found in sandstone, while the limestone of Lower Fars Formation has the highest water absorption and porosity due to the lower lithification and cementation during the diagenetic processes. It is widely known that unit weight changes with porosity of rock types, for this reason the lowest values of dry and saturated unit weight were found in limestone of Lower Fars Formation.

The values of uniaxial compressive strength range from 6.56 MPa (sample C4-1, Table 3) to 222.4 MPa (sample B4-1, Table 2). The values of point load strength $Is_{(50)}$ range from 0.38 MPa (sample C12-2, Table 6) to 10.05 MPa (sample B14-2, Table 5). The values of Young's modulusrange from 1.03 GPa (sample C5-1, Table 3) to 86.25 GPa (sample B14-1, Table 2). The values of pulse velocity range from 2.12 km/s (sample C16-1, Table 3) to 5.66 km/s (sample A20-1, Table 1), and the dry unit weight ranges from 1.88 g/cm^3 (sample C15-2, Table 6) to 2.59 g/cm^3 (sample B15-2, Table 5).

The correlations of uniaxial compressive strength (UCS) and modulus of elasticity (E) with point load index ($I_{s(50)}$), pulse velocity (Vp) of longitudinal waves and dry density (ρ_d) obtained for all rocks types under study are presented in Figure(8).

The correlation equations between UCS (in MPa) and point Load strength (in MPa), pulse velocity (in km/s) and dry density ($\frac{gr.}{cm^3}$), are shown in the Figure (8) are illustrated in the following:

The correlation equation between UCS and point load index with coefficient of determination(R^2) of 0.9267 can be predicted from equation (5)

$$\mathrm{UCS} = 17.57 * \mathrm{I_{s(50)}}^{1.155} \qquad (5)$$

The correlation equation between uniaxial compressive strength and pulse velocity (Vp) with R^2=0.9396 can be predicted from equation (6)

$$\mathrm{UCS} = 0.203 * \mathrm{Vp}^{4.2267} \qquad (6)$$

The correlation equation between UCS and dry densitywith R^2=0.9577 can be predicted from equation (7)

$$U\mathrm{CS} = 0.0006 * \rho_d{}^{13.608} \qquad (7)$$

The correlation equations between Young's modulus (in MPa) and point Load strength (in MPa), pulse velocity in km/s and dry density ($\frac{gr.}{cm^3}$), are shown in the Figure (8) are illustrated in the following:

The correlation equation between Young'smodulus and point load with R^2=0.7746 can be predicted from equation (8)

$$\mathrm{E} = 11.409 * \mathrm{I_{s(50)}}^{0.9322} \qquad (8)$$

The correlation equation between Young'smodulus (E) and pulse velocity (Vp) with R^2=0.8042can be found from equation (9)

$$\mathrm{E} = 0.295 * \mathrm{Vp}^{3.4522} \qquad (9)$$

The correlation equation between Young'smodulus (E) and dry density ($\frac{gr.}{cm^3}$)with R^2=0.7776can be predicted from equation (10)

$$\mathrm{E} = 0.0034 * \rho_d{}^{10.825} \qquad (10)$$

For comparing these equations with previous correlations obtained by other researchers as shown in Table (7) that presents the relationship between UCS and PLT. Most of these relationships are linearly correlated. However, as a result of this study, it was found the suitable relationship between measured indices and predicted mechanical properties (UCS and E) is a power curve. It is obvious that correlation equations predicted in this study have better agreement comparing with the previous studies. In present study, all equations are regression power with high value of R^2 that ranging between 0.7746-0.9577.

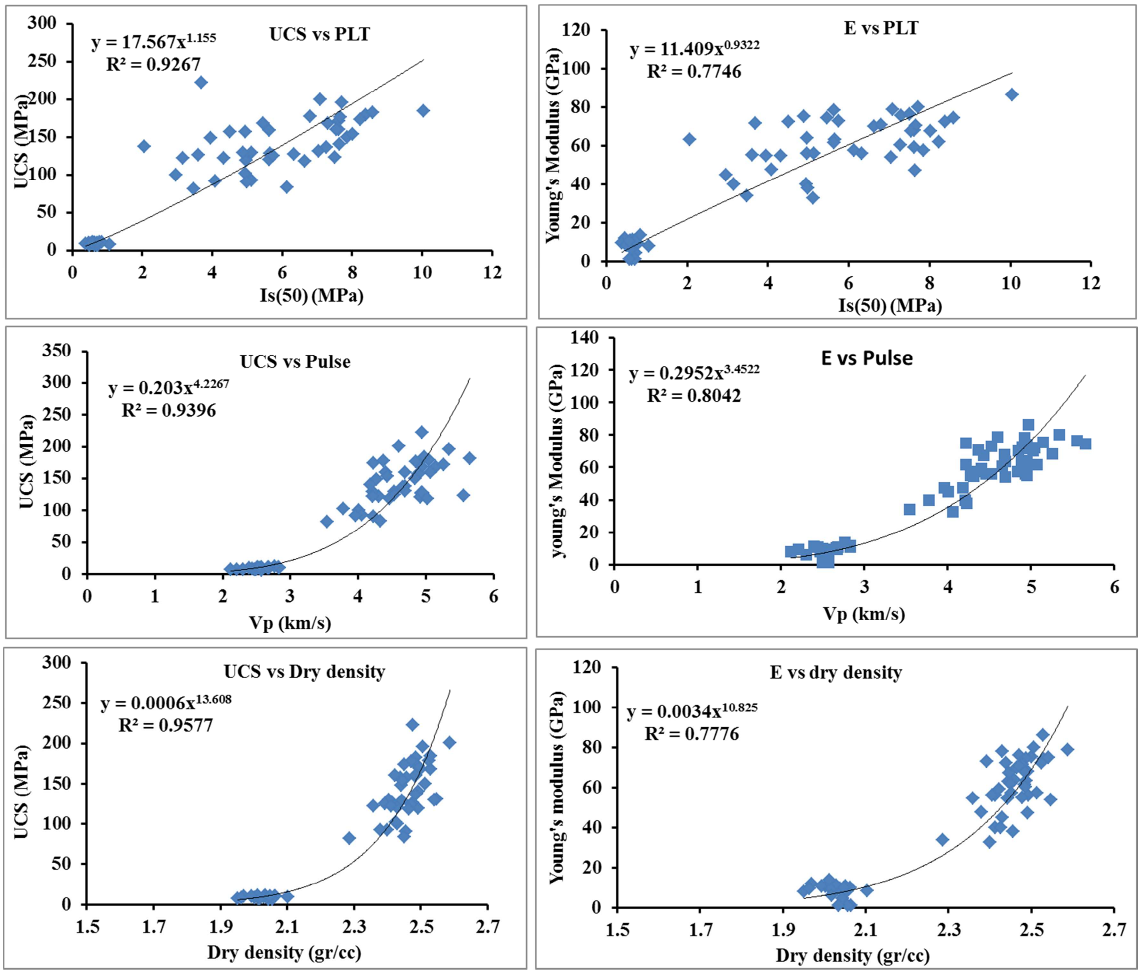

Figure-8: Correlations of Uniaxial Compressive Strength and Modulus of Elasticity with Point load Strength, Pulse Velocity and Dry Density.

As a result of this study, the UCS and E can be predicted using one of the following tests: the point load index, pulse velocity test and dry density of intact rock.Figures (9) and (10) show the measured UCS and E versus predicted UCS and E using equations (5 to 10) from simple regression analysis and equations (11 and 12) from multiple regression analysis. As can be seen, the predicted UCS and E models obtained from multiple regression analysis seems to be more reliable than those obtained from simple regression analysis. This is due to the fact that the mechanical properties of rock are a function of textural, physical, and mineralogical properties of rock [28].It should be noted that the correlation between measured and predicted mechanical properties (UCS and E) from dry density of intact rock is the most reliable than those predicted from either point load or P-wave velocity from simple regression analysis since the coefficient of determination (R^2) is higher than the others.

A multiple regression analysis was carried out on the results obtained in this study. The regression analysis gave the following correlations between the mechanical propertis (UCS and E) of the rocks and the indirect tests (point load indices, pules velocity and dry density tests):

$$UCS=-353.15+149.3*\rho_d +22.4*V_p +4.03*I_{s(50)} \qquad (11)$$

$$E=-96.5+32.3*\rho_d+15.1*V_p +1.55*I_{s(50)} \qquad (12)$$

Where UCS is the predicted uniaxial compression strength (MPa), E is the predicted Young's modulus (in MPa), ρ_d is the dry density in ($\frac{gr.}{cm^3}$) , V_p is P-wave velocity (km/s), and $I_{s(50)}$ is point load index (MPa).

The results of this study suggests that the mechanical properties (UCS and E) can be predicted by using one of the following indices: point load index, dry density, and P-wave velocity. However, using all of these indices using multiple regression can give more reliable results.

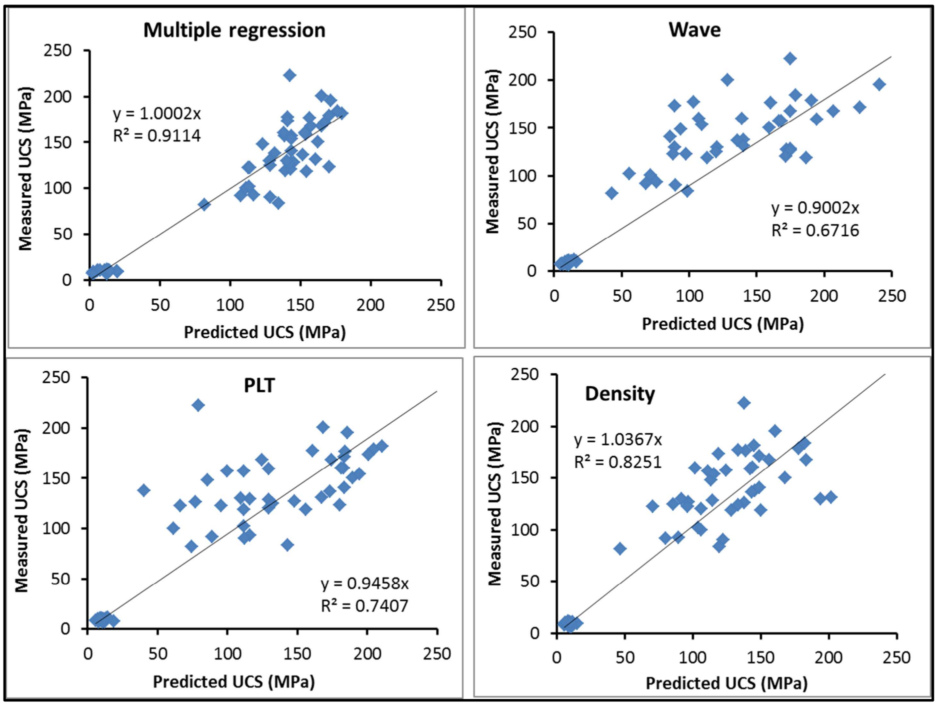

Figure-9: The relationship between the measured and predicted UCS values from the simple and multiple regression analysis.

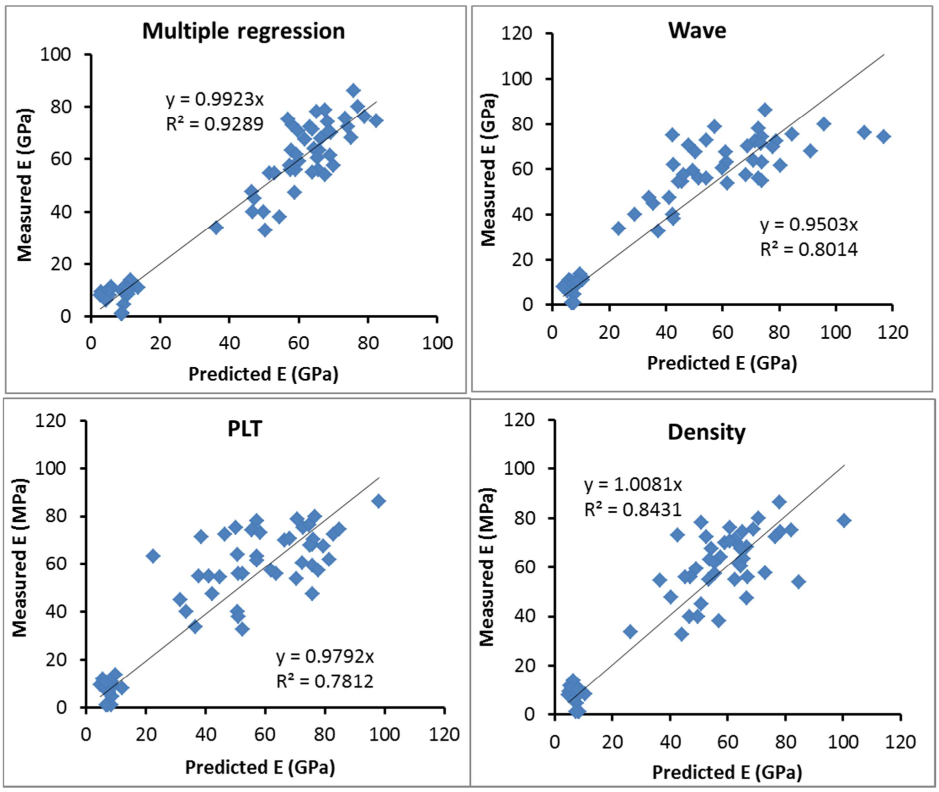

Figure-10: The relationship between the measured and predicted Young's Modulus values from the simple and multiple regression analysis.

Table-1: Limestone (Pila Spi Formation).

Sample No.	Volume of sample (cm^3)	Dry weight of sample (g)	Saturated weight of sample (g)	Water absorption (%)	Dry unit weight (g/cm^3)	Saturated unit weight (g/cm^3)	Porosity%	Ultrasonic Velocity of Longitudinal Wave. Vp(km/s)	Uniaxial Compressive Strength (MPa)	Modulus of Elasticity GPa
A1-1	268.14	647.18	665.14	2.78	2.41	2.48	6.70	4.93	127.08	56.000
A2-1	253.90	642.29	653.46	1.74	2.53	2.57	4.40	4.95	168.00	74.250
A3-1	267.59	669.07	680.83	1.76	2.50	2.54	4.39	5.15	168.00	75.450
A4-1	261.40	650.27	667.44	2.64	2.49	2.55	6.57	4.70	137.72	63.330
A5-1	263.96	657.94	675.93	2.73	2.49	2.56	6.82	4.47	118.92	56.000
A6-1	263.68	644.30	661.57	2.68	2.44	2.51	6.55	4.95	128.40	63.250
A7-1	270.17	664.28	680.21	2.40	2.46	2.52	5.90	4.89	157.32	64.070
A8-1	267.87	667.41	679.63	1.83	2.49	2.54	4.56	5.26	171.64	68.100
A9-1	274.68	669.90	684.06	2.11	2.44	2.49	5.16	4.90	157.16	72.500
A10-1	271.29	652.36	665.46	2.01	2.40	2.45	4.83	4.53	129.56	56.000
A11-1	271.56	674.36	685.96	1.72	2.48	2.53	4.27	5.07	159.00	61.560
A12-1	272.63	683.06	695.74	1.86	2.51	2.55	4.65	5.34	195.56	80.000
A13-1	272.11	661.26	674.61	2.02	2.43	2.48	4.91	4.93	120.48	78.250
A14-1	269.18	679.39	693.37	2.06	2.52	2.58	5.19	5.05	178.92	72.310
A15-1	267.88	640.81	653.31	1.95	2.39	2.44	4.67	4.53	125.00	73.000
A16-1	267.34	662.25	673.95	1.77	2.48	2.52	4.38	4.95	126.40	55.000
A17-1	264.77	654.29	666.97	1.94	2.47	2.52	4.79	5.56	123.64	76.290
A18-1	272.58	662.37	676.39	2.12	2.43	2.48	5.14	4.01	100.12	44.920
A19-1	267.88	660.20	671.63	1.73	2.46	2.51	4.27	5.02	118.52	70.000
A20-1	280.56	697.62	710.52	1.85	2.49	2.53	4.60	5.66	181.92	74.500

Table-2: Sandstone (Tanjero Formation).

Sample No.	Volume of sample (cm^3)	Dry weight of sample (g)	Saturated weight of sample (g)	Water absorption (%)	Dry unit weight (g/cm^3)	Saturated unit weight (g/cm^3)	Porosity %	Ultrasonic Velocity of Longitudinal Wave. Vp(km/s)	Uniaxial Compressive Strength (MPa)	Modulus of Elasticity GPa
B1-1	276.67	692.01	694.10	0.30	2.50	2.51	0.76	4.70	131.12	53.850
B2-1	282.85	706.07	707.90	0.26	2.50	2.50	0.65	4.85	176.40	70.310
B3-1	254.77	625.77	629.47	0.59	2.46	2.47	1.45	4.31	122.52	54.620
B4-1	259.93	642.80	644.76	0.30	2.47	2.48	0.75	4.95	222.40	71.500
B5-1	252.76	625.68	630.07	0.70	2.48	2.49	1.74	4.27	148.32	54.770
B6-1	264.14	647.51	651.18	0.57	2.45	2.47	1.39	4.41	160.00	59.290
B7-1	248.77	633.95	636.34	0.38	2.55	2.56	0.96	4.22	129.84	75.200
B8-1	252.93	620.11	626.02	0.95	2.45	2.48	2.34	4.06	92.96	32.780
B9-1	260.03	636.44	644.81	1.32	2.45	2.48	3.22	4.21	122.56	40.000
B10-1	244.88	610.74	613.00	0.37	2.49	2.50	0.92	4.18	140.64	47.330
B11-1	246.90	611.47	613.27	0.29	2.48	2.48	0.73	4.84	150.00	57.500
B12-1	257.27	621.49	626.49	0.80	2.42	2.44	1.94	3.96	92.04	47.550
B13-1	250.76	603.27	610.08	1.13	2.41	2.43	2.72	3.55	81.84	33.850
B14-1	249.82	633.21	634.73	0.24	2.53	2.54	0.61	4.97	184.12	86.250
B15-1	246.72	633.01	634.27	0.20	2.57	2.57	0.51	4.60	200.24	78.830
B16-1	254.23	639.02	641.00	0.31	2.51	2.52	0.78	4.43	153.72	67.500
B17-1	264.99	662.25	664.41	0.33	2.50	2.51	0.82	4.69	160.12	67.730
B18-1	255.94	635.72	637.90	0.34	2.48	2.49	0.85	4.66	136.64	60.500
B19-1	249.82	613.54	615.84	0.37	2.46	2.47	0.92	4.37	177.40	70.710
B20-1	242.53	573.62	577.70	0.71	2.37	2.38	1.68	3.78	102.16	40.000
B21-1	242.61	611.20	613.05	0.30	2.52	2.53	0.76	4.22	173.56	61.870
B22-1	252.14	614.03	622.09	1.31	2.44	2.47	3.20	4.23	90.40	38.050
B23-1	254.62	634.13	637.72	0.57	2.49	2.50	1.41	4.32	83.80	57.430

Table-3: Limestone (Lower Fars Formation).

Sample No.	Volume of sample (cm^3)	Dry weight of sample (g)	Saturated weight of sample (g)	Water absorption (%)	Dry unit weight (g/cm^3)	Saturated unit weight (g/cm^3)	Porosity %	Ultrasonic Velocity of Longitudinal Wave. Vp(km/s)	Uniaxial Compressive Strength (MPa)	Modulus of Elasticity GPa
C1-1	255.82	527.82	565.60	7.16	2.06	2.21	14.77	2.50	10.16	9.900
C2-1	240.00	488.00	522.20	7.01	2.03	2.18	14.25	2.67	10.60	9.180
C3-1	255.42	520.40	557.33	7.10	2.04	2.18	14.46	2.57	9.80	9.500
C4-1	239.93	490.39	524.50	6.96	2.04	2.19	14.22	2.57	6.56	4.500
C5-1	238.24	491.85	526.90	7.13	2.06	2.21	14.71	2.51	10.51	1.030
C6-1	241.07	495.64	528.90	6.71	2.06	2.19	13.80	2.49	7.32	1.040
C7-1	260.58	530.37	568.25	7.14	2.04	2.18	14.54	2.57	10.84	1.070
C8-1	268.79	545.47	585.85	7.40	2.03	2.18	15.02	2.40	9.42	11.090
C9-1	249.90	500.34	537.34	7.39	2.00	2.15	14.81	2.44	8.66	10.700
C10-1	242.77	473.64	511.49	7.99	1.95	2.11	15.59	2.47	7.73	8.050
C11-1	242.56	477.80	512.90	7.35	1.97	2.11	14.47	2.83	10.26	11.940
C12-1	253.86	498.45	535.25	7.38	1.96	2.11	14.50	2.50	8.71	9.460
C13-1	250.72	527.29	560.31	6.26	2.10	2.23	13.17	2.54	9.15	8.390
C14-1	258.55	521.06	559.30	7.34	2.02	2.16	14.79	2.21	7.78	9.200
C15-1	247.35	499.22	535.15	7.20	2.02	2.16	14.53	2.30	7.20	6.190
C16-1	240.08	493.44	549.08	11.28	2.06	2.29	23.18	2.12	6.84	8.120
C17-1	251.45	515.94	528.70	2.47	2.05	2.10	5.07	2.83	9.73	10.970
C18-1	244.80	492.51	526.95	6.99	2.01	2.15	14.07	2.76	11.52	13.710
C19-1	254.37	506.94	543.95	7.30	1.99	2.14	14.55	2.69	10.15	10.850
C20-1	236.38	484.16	520.50	7.51	2.05	2.20	15.37	2.67	9.84	10.150

Table-4:Limestone (Pila Spi Formation).

Sample No.	Volume of sample (cm^3)	Dry weight of sample (g)	Saturated weight of sample (g)	Water absorption (%)	Dry unit weight (g/cm^3)	Saturated unit weight (g/cm^3)	Porosity %	Point Load reading (kN)	Point Load strength Index I_s (MPa)	Point Load strength Index $I_{s(50)}$ (MPa)
A1-2	262.89	639.95	658.17	2.85	2.43	2.50	6.93	19.62	5.95	6.33
A2-2	258.82	654.87	666.19	1.73	2.53	2.57	4.37	16.85	5.14	5.46
A3-2	267.57	673.39	686.17	1.90	2.52	2.56	4.78	23.12	6.82	7.30
A4-2	263.18	656.64	673.14	2.51	2.50	2.56	6.27	6.44	1.92	2.06
A5-2	287.41	666.30	682.53	2.44	2.32	2.37	5.65	15.62	4.65	4.97
A6-2	264.99	643.12	662.53	3.02	2.43	2.50	7.32	17.77	5.28	5.65
A7-2	289.10	658.12	675.19	2.59	2.28	2.34	5.90	15.65	4.63	4.96
A8-2	269.44	671.58	684.95	1.99	2.49	2.54	4.96	24.19	7.12	7.63
A9-2	272.08	671.40	687.70	2.43	2.47	2.53	5.99	14.31	4.19	4.50
A10-2	267.64	659.50	672.22	1.93	2.46	2.51	4.75	16.12	4.80	5.13
A11-2	267.90	678.12	690.20	1.78	2.53	2.58	4.51	17.70	5.28	5.64
A12-2	268.43	679.12	693.07	2.05	2.53	2.58	5.20	24.20	7.22	7.71
A13-2	271.54	655.43	668.26	1.96	2.41	2.46	4.72	17.97	5.26	5.64
A14-2	269.45	673.30	686.77	2.00	2.50	2.55	5.00	26.42	7.84	8.38
A15-2	269.19	644.57	656.66	1.88	2.39	2.44	4.49	18.15	5.37	5.75
A16-2	268.90	664.64	677.06	1.87	2.47	2.52	4.62	11.42	3.37	3.61
A17-2	271.29	658.52	670.29	1.79	2.43	2.47	4.34	23.84	7.00	7.51
A18-2	272.85	669.06	682.83	2.06	2.45	2.50	5.05	9.49	2.76	2.97
A19-2	271.29	673.69	683.68	1.48	2.48	2.52	3.68	21.08	6.19	6.64
A20-2	274.50	684.67	696.53	1.73	2.49	2.54	4.32	27.30	8.02	8.59

Table-5:Sandstone (Tanjero Formation).

Sample No.	Volume of sample (cm^3)	Dry weight of sample (g)	Saturated weight of sample (g)	Water absorption (%)	Dry unit weight (g/cm^3)	Saturated unit weight (g/cm^3)	Porosity %	Point Load reading (kN)	Point Load strength Index I_s (MPa)	Point Load strength Index $I_{s(50)}$ (MPa)
B1-2	272.35	693.86	696.37	0.36	2.55	2.56	0.92	22.90	6.53	7.05
B2-2	288.68	715.47	719.00	0.49	2.48	2.49	1.22	26.00	7.00	7.65
B3-2	273.71	645.46	652.97	1.16	2.36	2.39	2.74	13.68	4.04	4.33
B4-2	264.09	654.26	657.39	0.48	2.48	2.49	1.19	11.71	3.45	3.69
B5-2	265.11	647.47	655.05	1.17	2.44	2.47	2.86	12.55	3.68	3.95
B6-2	275.81	668.21	674.82	0.99	2.42	2.45	2.40	24.40	7.08	7.61
B7-2	266.76	677.71	681.75	0.60	2.54	2.56	1.51	15.50	4.56	4.89
B8-2	269.48	646.57	653.63	1.09	2.40	2.43	2.62	16.12	4.79	5.12
B9-2	258.49	623.51	635.58	1.94	2.41	2.46	4.67	9.87	2.96	3.16
B10-2	262.37	653.74	655.58	0.28	2.49	2.50	0.70	23.67	7.17	7.64
B11-2	245.98	618.27	621.62	0.54	2.51	2.53	1.36	23.20	7.48	7.85
B12-2	265.64	632.20	640.85	1.37	2.38	2.41	3.26	13.00	3.80	4.08
B13-2	265.12	606.30	616.91	1.75	2.29	2.33	4.00	11.07	3.24	3.48
B14-2	247.94	626.97	629.96	0.48	2.53	2.54	1.21	29.80	9.57	10.05
B15-2	266.06	688.65	690.57	0.28	2.59	2.60	0.72	22.22	6.64	7.09
B16-2	267.18	653.43	657.30	0.59	2.45	2.46	1.45	25.68	7.47	8.02
B17-2	267.29	664.27	667.37	0.47	2.49	2.50	1.16	23.96	7.04	7.54
B18-2	254.97	633.53	636.97	0.54	2.48	2.50	1.35	22.43	6.84	7.27
B19-2	259.00	640.04	643.97	0.61	2.47	2.49	1.52	21.25	6.38	6.80
B20-2	256.99	623.46	629.97	1.04	2.43	2.45	2.53	15.39	4.65	4.96
B21-2	247.50	606.59	609.81	0.53	2.45	2.46	1.30	24.85	7.80	8.24
B22-2	266.53	654.57	661.43	1.05	2.46	2.48	2.57	15.74	4.66	4.99
B23-2	262.76	644.02	649.08	0.79	2.45	2.47	1.93	19.47	5.73	6.14

Table-6: Limestone (Lower Fars Formation).

Sample No.	Volume of sample (cm^3)	Dry weight of sample (g)	Saturated weight of sample (g)	Water absorption (%)	Dry unit weight (g/cm^3)	Saturated unit weight (g/cm^3)	Porosity %	Point Load reading (kN)	Point Load strength Index I_s (MPa)	Point Load strength Index $I_{s(50)}$ (MPa)
C1-2	265.00	536.43	571.65	6.57	2.02	2.16	13.29	1.98	0.62	0.66
C2-2	281.79	584.53	621.20	6.27	2.07	2.20	13.01	2.32	0.75	0.79
C3-2	267.50	546.07	582.44	6.66	2.04	2.18	13.60	1.87	0.59	0.62
C4-2	243.48	503.16	535.80	6.49	2.07	2.20	13.41	2.17	0.69	0.73
C5-2	247.00	508.89	543.40	6.78	2.06	2.20	13.97	1.94	0.59	0.62
C6-2	261.12	536.21	572.80	6.82	2.05	2.19	14.01	2.09	0.68	0.72
C7-2	277.61	567.36	603.90	6.44	2.04	2.18	13.16	1.76	0.54	0.57
C8-2	280.64	574.83	612.63	6.58	2.05	2.18	13.47	1.51	0.45	0.48
C9-2	230.07	455.24	487.54	7.10	1.98	2.12	14.04	1.60	0.57	0.58
C10-2	237.46	489.60	518.24	5.85	2.06	2.18	12.06	3.04	1.02	1.06
C11-2	234.74	468.21	503.30	7.49	1.99	2.14	14.95	1.27	0.45	0.46
C12-2	262.97	534.35	570.70	6.80	2.03	2.17	13.82	1.17	0.35	0.38
C13-2	269.57	529.47	566.70	7.03	1.96	2.10	13.81	1.65	0.50	0.53
C14-2	280.48	531.81	572.30	7.61	1.90	2.04	14.44	2.00	0.60	0.64
C15-2	284.37	534.74	575.90	7.70	1.88	2.03	14.47	1.98	0.60	0.64
C16-2	244.90	518.64	550.12	6.07	2.12	2.25	12.85	1.46	0.48	0.50
C17-2	256.03	516.50	553.40	7.14	2.02	2.16	14.41	1.95	0.62	0.66
C18-2	255.19	517.70	552.80	6.78	2.03	2.17	13.75	2.44	0.81	0.85
C19-2	258.98	511.72	548.00	7.09	1.98	2.12	14.01	2.06	0.68	0.71
C20-2	267.67	533.72	573.05	7.37	1.99	2.14	14.69	1.71	0.54	0.57

Table-7:Proposed correlation equations for UCS and PLI. (From [29]., Modified).

Author (s)	Suggested correlation equation
Broch and Franklin (1972)	UCS=23.7 PLI (Various rock types)
Bieniawski (1975)	UCS=23.9 PLI (Sandstones)
Hassani et al (1980)	UCS=29 PLI (Sedimentary rocks)
Read et al (1980)	UCS=20 PLI (Sedimentary rocks)
Das (1985)	UCS=18 PLI (Sandstone)
	UCS=14.7 PLI (Siltstone)
	UCS=12.6 PLI (Shale)
Hawkins and Olver (1986)	UCS=26.5 PLI (Limestone)
	UCS=24.8 PLI (Sandstone)
O'Rourke (1988)	UCS=30 PLI (Sedimentary)
Vallejo et al (1989)	UCS=17.4 PLI (Sandstone)
	UCS=12.6 PLI (Shale)
Grasso et al (1992)	UCS=25.67(PLI)0.57 (Power relation)
	UCS=9.30 PLI+20.04 (Linear relation)
Ulusay et al (1994)	UCS=19 PLI+12.7 (Sandstone)
Smith (1997)	UCS =24 PLI (Sandstone/limestone)
	UCS=12.6 PLI (Shale)
Rusnak and Mark (1999)	UCS=20.6 PLI (Sandstone)
	UCS=21.9 PLI (Limestone)
Tsiambaos and Sabatakakis (2004)	UCS = 7.3 PLI1.71 (Power relation)
	UCS = 23 PLI (Linear relation)
Fener et al. (2005)	UCS=9.08 PLI+39.32 (Various rock types)
Kahraman et al. (2005)	UCS=10.91 PLI+27.41(Various rock types)
Karaman and Kesimal (2012)	UCS=20.42 PLI-5.146 (Various rock types)

Conclusions

One hundred twenty six specimens of two types of limestone (soft and hard) and sandstone weretested and the results were analyzed for correlation of uniaxial compressive strength and modulus of elasticity with point load index, pulse velocity and dry density.Basing on the test results of point load strength index, P-wave velocity and dry density, some correlation equations were established, in order to calculate the uniaxial compressive strength and modulus of elasticity.Basing on the findings correlation equations, the following conclusions can be drawn:

1. The UCS and Young's Modulus (E) can be calculated using simple regression analysis,using equations (5 to 10);
2. The UCS and Young's Modulus (E) can be calculated using multiple regression analysis, using equations (11 and 12).
3. The predicted UCS and E models obtained from multiple regression analysis seems to be more reliable than that from simple regression analysis.

The correlation between measured and predicted mechanical properties (UCS and E) from dry density of intact rock is more reliable than those predicted from either point load or P-wave velocity from simple regression analysis since the coefficient of determination (R^2) is higher than the others.

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