Uni-Axial Compression Strength – Point Load Index Correlations for Sedimentary Rock Units

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ABSTRACT
Correlations between point load index and uni-axial compression strength were known to be dependent on rock type and rock strength. In this work, results of more than 898 tests on rock core samples from over 28 different sites across Libya were used in correlating uni-axial compressive strength with diametrical point load index. Data were collected from six different types of sedimentary rock units. A linear regression analysis based on least square values was performed on collected data. Results yielded an overall correlation factor of 12.3 for all tested rock types at a reasonable correlation coefficient. Correlation factors were also determined for each individual rock type which showed that weaker rocks tend to have lower correlation factors than stronger ones. Results are believed to help in obtaining better estimation of uni-axial compression strength from point load indices for these local rock formations.

RÉSUMÉ
Il est admis que les corrélations entre l'indice de poinçonnement $I_{S(50)}$ et la résistance uni axiale en compression sont liés au type et à la résistance de la roche. Pour cette étude, plus de 898 résultats de tests sur des carottages de roches prélevés à travers 28 différents sites de Libye ont été nécessaires afin de rapprocher la résistance uni axiale en compression et l'indice de poinçonnement diamétral. Les informations récoltés sont issus de six différents types de roches sédimentaires. L'analyse de ces informations ont été traités par régression linéaire basée sur la méthode des moindres carrés. Les résultats ont révélés un facteur global de corrélation de 12.3 sur tous les types de roches testés. La réalisation de facteur de corrélation individuel sur chaque type de roche a montré que les roches les plus tendres présentaient un coefficient de corrélation plus faibles que les roches les plus dures. Les résultats présentés dans cette étude permettront d'obtenir une meilleure estimation de la résistance uni axiale a la compression à partir des indices de poinçonnement pour ces types de formations rocheuses.

1 INTRODUCTION

The uni-axial compression strength of intact rock units is one of the most important characteristics used in rock mass classification and evaluation of mechanical behavior of rocks under various loading conditions. It is usually obtained from direct loading of rock core samples in the uni-axial compression mode as described in ASTM D 2938 testing procedure. This requires core samples of length/diameter (L/D) ratio of between 2 and 3. In some cases due to the thin bedding nature of rock masses, only samples of L/D ratio of less than 2 (short of being adequate for this test) can be obtained, even with using small coring diameters. In such cases, point load tests are used to roughly evaluate the compressive strength of intact rock pieces. Despite the fact that point load test was standardized in a number of professional bodies (as in ISRM, and ASTM), the use of test results is still, in most cases, bound to proper correlations with uni-axial compression test on the same rock formation.

Due to the difference in failure mode from that of the uni-axial compression test, results of point load test are considered only a qualitative indicator of strength of rocks rather than used in evaluating strength value. Despite this argument, however, point load index, in many cases, remains the only source of information of strength of intact parts of rock masses which has to be used in a way or another in translating such data into more engineering physical values.

In this paper, results of 385 pair of tests were used in correlating uni-axial compression strengths from point load indices for 5 different types of sedimentary rock units. Tested samples were extracted from formations distributed over the entire Libyan territories during site investigation works. The prime author was involved in all site investigation works from which these data sets were collected.

2 PREVIOUS CORRELATIONS

Brock and Franklin (1972) and Bieniawski (1975) had found that the uni-axial compression strength (UCS) can be estimated from the point load index using a correlation factor of 24 (UCS = 24 $I_{s(50)}$). This formula was intensively used and believed to represent a universal approximation of the compression strength of intact rock units from low cost, easily and quickly performed loading test. Carter et. al. (1977) have shown that slightly lower correlation factor (between 21 and 22) was obtained for Coal measure rock types. Later studies had shown that the correlation factor between UCS and PLI varied within a broad range between as low as 8 to as high as 30. Rusnak and Mark (2000), presented a good summary of published comparisons between point load and uni-axial compression strength tests on sedimentary rocks.

These high variations in correlation factors are mainly due to differences in tested rock types, locations (geological history), and compressive strength of rock units. As an example of these variations, the one reported by Smith (1997) in which the correlation factor varied between a value of 8 for rocks with UCS of less than 1000 psi (6.9 MPa) to a value of 24 for rock samples with UCS of more than 6000 psi (41.5 MPa). Similar studies (Akram, and Abu Bakar, 2007) showed high differences in correlation factors for the same rock type due to differences in geological history. Most attempted trials to correlate UCS from PLI were associated with large scatter and relatively low correlation coefficients.

3 UNI-AXIAL COMPRESSION AND POINT LOAD TESTS FOR INTACT ROCK SAMPLES

The uni-axial compression test is considered, by many geotechnical engineers, as a reference for measuring compression strength of intact rock samples. In many cases where sample geometry restricts the use of uni-axial test, compression strength is estimated through the point load test. The advantage of the point load test is that it is quicker and cheaper to run than the uni-axial test, besides its handling of short core samples. In point load test (either axial or diametrical), as the sample is loaded, highly concentrated stresses are initiated directly beneath the conical steel platens, due to the small contact area, causing failures on multi-planes. As loading continues, failure planes progressively propagate deep into the inside of the sample causing it to fail in a split (tension) mode. This, however, is different from the mechanism of failure associated with the uni-axial compression test where shear failure is usually occurs along a diagonal failure plane in homogeneous rock units. Sample orientation, loading mode and failure mechanism associated with point load test are, in most cases, different from those encountered in-situ. Due to the above indicated reasons, this test may lead to erroneous results especially in dealing with anisotropic rock mass conditions. Apart from that, results of point load test need to be correlated with results of uni-axial compression test on the same rock formations. Such correlations on the same rock unit are not always available especially in rock masses of narrowly spaced horizontal joints.

3.1 Uni-Axial Compression Test

The uni-axial compression test of rock samples were performed in accordance with ASTM D 2938 standard procedure. All tested samples had length/diameter (L/D) ratio of between 2 and 3. Shorter samples tend to overestimate the strength due to machine base interference whereas longer samples tend to underestimate the compression strength due to the weakening associated with the buckling effect.

In the uni-axial test, if sample faces are not cut even and parallel, stress within the high parts of the sample will result in under-estimation of compressive strength. This was believed to be a significant source of errors if not carefully handled. For this reason, special attention was paid to the cutting and trimming of core samples prior to testing in the uni-axial compression mode.

3.2 Point Load Test

Point load test was performed in accordance with the recommended procedure given in ASTM D 5731 standard. Throughout this work, diametrical point load test type was used in which loading is applied along the sample diameter (perpendicular to the longitudinal sample axis). All tested samples measured L/D ratio of at least 1. In this test, rock sample is loaded through a conical steel platens until failure. The point load index (I_s) is calculated using the following formula: $I_s = P/D^2$, (where P is the failure load, and D is the sample diameter). Resulted point load index is then normalized to sample diameter of 50 mm by applying a correction factor (F) to account for variations in sample diameter. The correction factor (F) is calculated using the following formula: $F = (D/50)^{0.45}$, (where D is the diameter of tested rock core sample in mm).

Both of uni-axial and point load tests were performed on rock core samples at their natural (as found) moisture contents. This was due to fact that all used data were collected from results of site investigation works aimed at investigating the "as-observed" in-situ condition of these sites. It is understood, however, that variation in rock moisture can have an effect on measured strength, especially on fine grained calcareous rock types (Calcarenites). Most of the collected data were for samples retrieved from depths below the active zone of seasonal moisture variations where moisture variations were very minimal.

4 TYPES AND PROPERTIES OF TESTED SEDIMENTARY SOURCE ROCKS

Six types of sedimentary rocks, retrieved mainly from exploration works, were involved in this work. Calcarenites, limestones, marls and marly limestones, sandstones, gypsum rocks, and claystones represent the source of core samples data base.

The calcarenite, which represent the source of about 45 % of data, is a Quaternary deposit belongs to the Pleistocene era formed along the coastal strip in a marine environment. It is mainly composed of white fine to medium grained calcareous material, and as a marine deposit, most of this rock type contains fossil fragments. The calcarenite is generally considered weak rock unit as the uni-axial compression strength is mostly within the weak to moderately weak range (as per BS 5930 rock strength rating) with a mean value of about 9.5 MPa. Formations composed of limestones are spread over large areas of Libyan geological map. Properties of encountered limestone units are generally variable from solid strong to porous, vuggy and moderately weak units. Mean uni-axial compression strength of tested limestone units measured about 38.5 MPa. Solution cavities are common features in some limestone units which added another source for the heterogeneity of such rocks. Wide range of Limestones were involved from pure limestones to dolomitic limestones, marly limestones and Caliches. Marly limestones are classified with marls in one category due to their similar properties and behavior. Properties of marls and marly limestones were generally dependant on relative existence of clay and calcareous material in this rock. Some of these rock units contained fossil fragments and vugs. Marls were generally weak whereas strength of marly limestone units increased as marl content decreases but generally within the weak to moderately strong range (mean value of about 17.1 MPa). Small number of data was obtained from weak units of sandstones (with a mean UCS of about 3.9 MPa) and gypsum rock (with a mean UCS of 5.8 MPa). Dry and semi-arid nature of the area helped in preserving large gypsum deposits near Sirt area. The claystone cores involved in this work resulted from exploration job in the south western town of Ghat near the border with Algeria and Niger. This claystone unit was remarkably strong along its vertical axis in the uni-axial loading condition (mostly within the moderately strong to strong range) recording a mean UCS value of about 38.0 MPa, but showed a high degree of lamination (varved). This resulted in extremely low diametrical point load indices for the claystone units.

5 UCS AND PLI DATA BASE – DESCRIPTIVE STATISTICS

Selection methodology of data was based on the following criteria:

(i) Every pair of tests, which represent a single correlative point, includes one uni-axial compression test and at least one point load test. In cases where more than one PLI test is performed against the corresponding UCS test, the average value of PLI tests was used.

(ii) Every single pair of data was taken from a single borehole.

(iii) Each pair of tests involves rock core samples mostly from the same core run. In very limited cases, the corresponding core sample was taken from an adjacent run but within the same formation with no major depth gap (not more than 4.5 m apart).

Six rock types were involved in this analysis from which 401 pairs of data were extracted. Distribution of tests over rock types and represented geological units are given in Table 1.

Median, median standard deviation, coefficient of variation, and skewness of UCS and PLI values were calculated for each rock type and, then, for all data except the claystone set. Summary of statistical characteristics of the utilized data are given in Table 2.

As presented in Table 2, coefficient of variation and skewness value are indicators for data statistical quality for both UCS and PLI data. For UCS, scatter was highly pronounced for the calcarenite data followed by the Marly limestone & Marl, whereas the Gypsum rock measured the least. In PLI data set, the largest scatter was associated with those from the sandstone rocks followed by the Marly limestone and Marl, then the Calcarenite, whereas, the Gypsum rock and the Limestone measured the least scatter in PLI data

Table 1. UC and PL tests versus rock types and represented geological units.

	Number of Represented Geological Units	Number of UC Tests	Number of Corresponding PL Tests.
Calcarenite	13	179	221
Limestone	10	106	137
Marly Limestone	10	68	75
Gypsum	2	19	21
Sandstone	1	13	18
Claystone	1	16	25

Table 2. Summary of statistical characteristics of used UCS and PLI data.

	Calcarenite	Limestone	Gypsum	Sandstone
Median UCS (MPa)	6.10	32.22	5.84	2.15
Median SD of UCS	10.49	25.85	1.62	3.49
Coeff. of Variation of UCS Data (%)	110.11	67.05	27.91	89.72
Skewness of UCS Data	3.02	1.07	0.04	1.63
Median Is(50) (MPa)	0.61	2.72	0.68	0.25
Median SD of Is(50)	0.73	1.62	0.29	0.30
Coeff. of Variation of Is(50) Data (%)	81.73	54.78	40.09	93.65
Skewness of PLI Data	1.61	0.50	0.47	2.05

Table 2. Summary of statistical characteristics of used UCS and PLI data (continued).

	Marl & Marly Limestone	Claystone	All (except Claystone)
Median UCS (MPa)	9.75	34.25	8.70
Median SD of UCS	17.28	13.06	21.22
Coeff. of Variation of UCS Data (%)	100.89	34.38	114.80
Skewness of UCS Data	2.15	0.59	2.05
Median Is(50) (MPa)	0.96	0.10	1.00
Median SD of Is(50)	1.11	0.35	1.43
Coeff. of Variation of Is(50) Data (%)	85.53	182.06	94.61
Skewness of PLI Data	2.23	3.88	1.58

6 REGRESSION ANALYSIS

UCS readings and their corresponding values of PLI were subjected to regression analysis using version 17 of SPSS. In this program, the method of least square regression analysis was employed.

Regression analysis, at first, included all collected UCS-PLI pairs of data except that of the claystone. This involved 385 pairs of UCS-PLI readings from 5 different rock types. Then, regression analysis was made for each rock type.

7 RESULTS AND DISCUSSIONS

7.1 Regression Analysis between UCS and PLI for All Tested Rock Types

Plots of uni-axial compression strengths versus the corresponding values of point load indices for data from all tested rock types (excluding the claystone) are shown in Figure 1. Figure 1 also shows the regression line obtained from the zero-intercept formula.

The zero-intercept linear regression is represented by formula [1].

$$UCS = 12.30\ PLI \qquad [1]$$

This regression analysis was associated with a correlation factor (r) of 0.908 which is considered reasonable when dealing with rocks. The coefficient of determination resulted in this regression was 0.824. This means that the fitted regression formula explains 82.4 % of the total variation in the data about the average of UCS (PLI explains 82.4 % of the variability in UCS). The

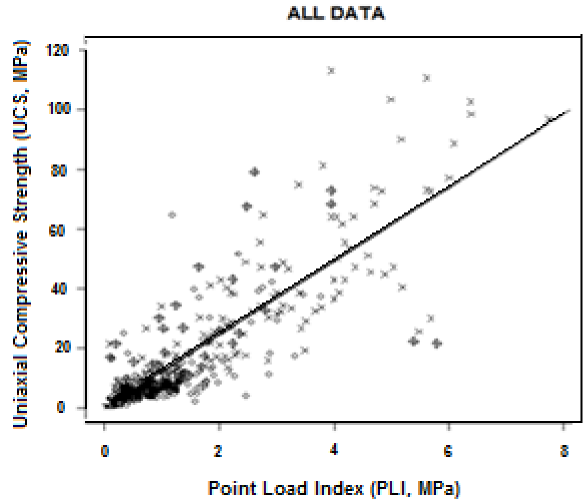

Figure 1. Regression between uniaxial compressive strength and point load index for all rock types [Calcarenite (◊), Limestone (x), Marly Limestonr or Marl (❖), Gypsm rock (■), Sandstone (Δ)]

remaining 17.6 %, which formula [1] cannot explain, is believed to be attributed to the variations in rock density within the single pair of data besides other factors as those associated with heterogeneity and isotropy of rock material. Density of rock cores is an indicator of the state of sample porosity and presence of vugs. Much better and realistic correlations can be achieved by adding sample density effect to the analysis. Another source of scatter was attributed to the variations in moisture contents of tested rock samples. Effect of moisture variations on resulted correlations is believed to be more pronounced for fine grained calcareous rock types.

7.2 Regression Analysis between UCS and PLI for Each Tested Rock Type

Uni-axial compression strengths and the corresponding values of point load indices are plotted for each rock type. Plotted data and resulted regression lines for Calcarenite, Limestone, Marly limestone & Marl, Sandstone, and Gypsum Rock are shown in Figures 2, 3, 4, 5, and 6 respectively. Zero intercept regression for these rock types resulted in correlation factors of 12.94 for the Limestone, 11.78 for the Marl and Marly Limestone, 9.79 for the Calcarenite, 9.68 for the Sandstone, and 7.38 for the Gypsum rock. Once again these regressions were associated with acceptable values of correlation coefficients. Summary of coefficients of correlations and coefficients of determinations associated with zero intercept linear regression analysis for each rock type and collective data are given in Table 3.

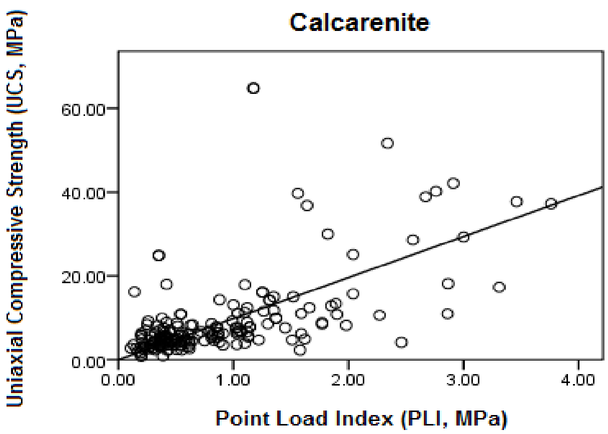

Figure 2. Regression between uniaxial compressive strength and point load index for Calcarenite

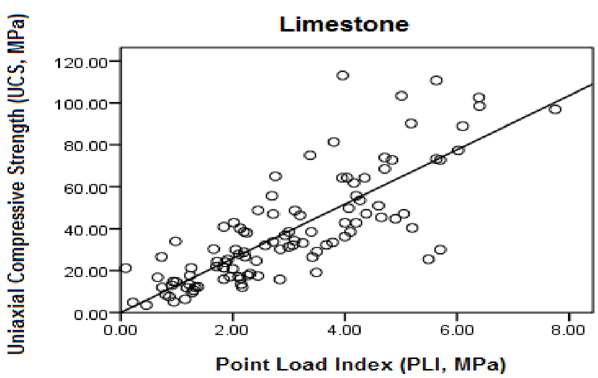

Figure 3. Regression between uniaxial compressive strength and point load index for Limestone

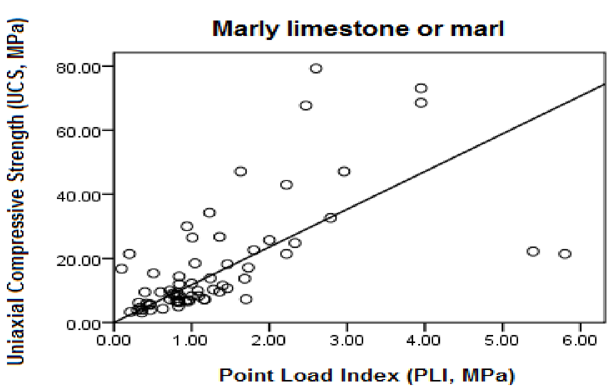

Figure 4. Regression between uniaxial compressive strength and point load index for Marly Limestone & Marl

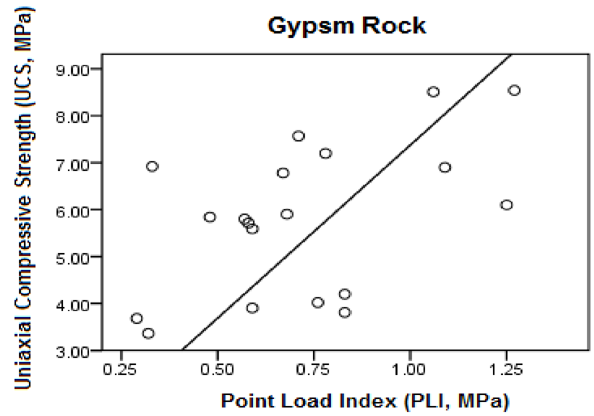

Figure 5. Regression between uniaxial compressive strength and point load index for Gypsum rock

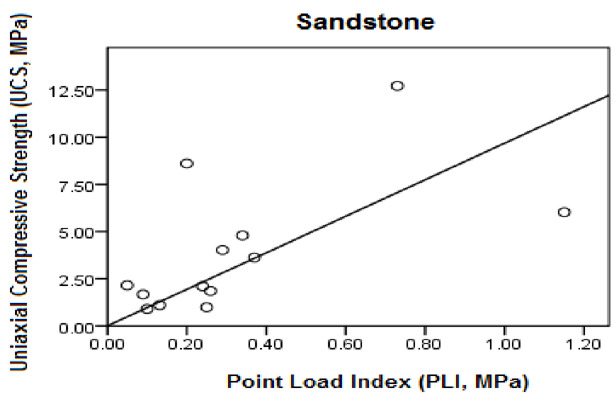

Figure 6. Regression between uniaxial compressive strength and point load index for Sandstone

Table 3. Summary of r and r^2 values associated with zero-intercept regression analysis of rock units and correlation factors.

Rock type	Number of involved data points	Correlation Factor	r	r^2
Calcarenite	179	9.79	0.801	0.641
Limestone	106	12.94	0.942	0.888
Marly Limestone & Marls	68	11.78	0.826	0.682
Gypsum Rock	19	7.38	0.947	0.897
Sandstone	13	9.68	0.82	0.672
All Data	385	12.30	0.908	0.824

r = Coefficient of Correlation
r^2 = Coefficient of Determination

7.3 Claystone Behaviour in Uni-axial Compression and Diametrical Point Load Tests

Observed results of uni-axial compression tests on the claystone showed remarkably high strength values as summarized in Table 2. It recorded a median value of about 34 MPa (moderately strong as per BS 5930) at relatively low scatter (coefficient of variation of about 34.4 %).

Results of diametrical point load tests on this rock type showed very drastically low indices (median point load index of 0.10 MPa) with high scatter as the coefficient of variation measured 182 %. This was due to the laminated nature of the encountered claystone rock type. Lamination causes the tested samples to split along the weakest plane of lamination. The estimated PLI in this manner is irrelevant to the compression strength along the longitudinal axis of the sample. In such cases, diametrical point load test becomes inappropriate and should not be used in estimating compression strength of such deposits when actual loading is perpendicular to lamination planes.

8 CONCLUSIONS

Data of rock strength consists of 385 pairs of uni-axial compression strengths and corresponding point load indices were used in evaluating correlation factors for sedimentary rock units from 28 different sites in Libya. A linear regression analysis based on least square method was employed. Results of regression analysis of data for all rock types yielded an overall correlation factor between UCS and PLI of 12.3 at a reasonable correlation coefficient. Correlation factors of 12.94, 11.78, 9.79, 9.68, and 7.38 were obtained for Limestone, Marly Limestone & Marl, Calcarenite, Sandstone, and Gypsum Rocks respectively. This clearly supports the suggested trend of decrease in the correlation factor for rocks as uni-axial compression strength decreases. Results of these correlations are believed to help in having better estimation of rock strength from results of point load tests on the tested rock types.

Diametrical point load test was shown to be inadequate for laminated claystone type where failure is likely to occur in a splitting tension mode on weak laminated planes.

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