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The New Empirical Formulae for predicting the Unconfined Compressive Strength of limestone from Kohat Basin, Pakistan

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Abstract

Limestone is regarded as one of the most important construction materials for mega-engineering projects. The evaluation of strength and durability characteristics of limestone is a pre-requisite for its use in any engineering project. The rock's compressive strength is obtained using the Unconfined Compressive Strength (UCS) test and Point Load Index (PLI). However, in large projects, performing UCS test is time-consuming, needs effort and is costly, while PLI can be misleading in the case of anisotropic rocks. In such cases, the implementation of the non-destructive tests is useful that are cost-effective and reduce time. Schmidt Hammer Test (SHT), is an indirect method to estimate the UCS and PLI. The test is easy and quickly applicable in the laboratory as well as in the field. Strength tests, such as UCS, PLT, and SHT were performed on rock samples of two Eocene formations i.e, Shekhan Formation (SF) and Kohat Formation (KF) of Kohat Basin. A strong linear relationship obtained between the SHT and UCS for the limestone of SF and KF having a correlation coef. of 0.827 and 0.840, respectively. Furthermore, strong linear relationship is also obtained between the SHT and PLI having a correlation coef. of 0.727 and 0.758, respectively. This study presents new correlations with high accuracy for the prediction of UCS and PLI from indirect SHT.

Keywords: Schmidt hammer test, Compressive strength, Point load, Regression models, Empirical relationships, Kohat Basin.

1. Introduction

The mechanical characterization of rocks is important in designing various structures in rock formations. The compressive strength tests, such as Unconfined compressive strength (UCS) and Point Load Index (PLI) are widely used in determining the mechanical behaviour of rocks. The obtained results can help in designing and construction of major engineering projects such as underground excavations, foundations, dams, slope stability as well as in classifying the rocks for other geotechnical purposes. These tests are performed according to the specifications provided by the American Society for Testing and Materials (ASTM) and the International Society for Rock Mechanics (ISRM). The testing involves transportation of the rock bulk samples to the laboratory and sample preparation, i.e. cutting them in cubical shape or cylindrical cores. However, this process is hectic, expensive and time-consuming. Furthermore, sample selection and preparation from weathered and fractured rock masses is a challenge. Under such conditions, it is important to adopt other simple, cost-effective and indirect techniques for performing the required tasks without compromising the reliability and accuracy (Wang and Aladejare, 2015, 2016; Aladejare, 2016). The indirect methods that involve Schmidt Hammer Test (SHT) and Ultrasonic Pulse Velocity (UPV) are very useful with little or no sample preparation and can be performed in the field (Ju et. Al., 2017). However, due to the non-availability of UPV data, the scope of this research is limited to SHT only.

Schmidt hammer is comprised of a spring-loaded mass, an electronic or sliding pointer and a plunger. N-values are recorded when hammer is pressed against the rock surface. SHT (that gives the N-values) was designed as a mean of non-destructive testing to determine compressive strength of concretes in finished structures. This test was applied for many years due to the promising results it has showed (Schmidt, 1951; Hucka, 1965). Besides the use of SHT in concrete studies, this test was also suggested to predict the compressive strength of the discontinuity wall surface. In practice, N-type SH is used for concretes with impact energy of 2.207 Nm. Whereas the L-type SH is used for rocks with impact energy of 0.735 Nm. With the advancement in rock mechanics, it was established that SHT can be applied for determining several other rock properties, like, rock discontinuities (Shang et al, 2017), strength of rock discontinuities (ISRM, 1981), Young's modulus (Torabi et al., 2018), mine roof control (Kidybinski, 1980) and the UCS (Wang and Wan, 2019; Aliyua et al., 2019). Moreover, different authors proposed several empirical equations for predicting the UCS and PLI from SHT for calcareous (limestone) rocks (Torabi et al., 2010; Arslan et al., 2015; Selçuk and Yabalak, 2015; Momeni et al., 2015; Selçuk and Nar, 2016; Jamshidi et al., 2016; Azimian, 2017; Hebib et al. 2017; Karakul, 2017; Ghasemi et al. 2018; Demirdağ et al., 2018; Kong and Shang, 2018; Petrakis and Komnitsas, 2018).

For N-value, a sufficient number of impacts/readings are the priority factor for ensuring the reliability of the hardness measurements (Kovler et al., 2018). The procedure for estimating the N-values varies widely as suggested by different researchers as well as the ASTM and ISRM. The ASTM does not specify any hammer type and recommends applying at least 10 impacts for rocks with the UCS ranging from 1 to 100 MPa. On the other hand, the ISRM recommends that the rocks having UCS ranging between 20 to 150 MPa, the L-type hammer should be employed by averaging the upper 50% of at least 10 impacts. According to Aydin (2009) and Viles et al., (2011), a total number of 30 N-values should be recorded perpendicular to the tested surface to reduce the risk of frictional sliding of the plunger tip, with single impacts separated by at least a plunger width. Winkler in (2009) suggested that a large number of impacts increases statistical significance, lowers the probability of outliers and the influence of lithological heterogeneities or micro-weathering.

Torabi et al., (2010), concluded that several empirical equations introduced for the determination of the uniaxial compressive strength of rocks, based on the N-value showed relatively low correlation coef. Due to the fact that a single equation was adopted for all rock types. The equation will yield a much higher correlation coef. If one specific relationship between N-value and UCS is introduced for one rock type, under particular geological circumstances. They focused their research on the particular geologic conditions, under which they developed the correlation between UCS and N-values with the correlation coef. of 0.86. In their research, it was presumed that the geologic conditions acting on the formation imposed some common characteristics on the rock types in the formation.

Several researchers worked on different rock types and developed correlations between UCS and N-values, while limited research is performed on the correlation of PLI with N-values (see Table 1). Minaeian and Ahangari in 2013, developed a linear relationship of UCS with N-values and UPV of limestone with a correlation coeff. of 0.94 and 0.94 respectively. They concluded that proposed equations can be used to predict rock strength from SHT and UPV and are applicable for carbonate formations of analogous geologic character. Karaman and Kesimal (2014), tested 47 samples of different rocks for UCS and N-values and derived a linear, logarithmic and exponential regression analysis with a correlation coeff. of 0.84, 0.91 and 0.95 respectively. Azimian observed linear relationship between UCS and N-values with R2 value of 0.919 for all tested limestone rocks. Kong and Shang (2018), concluded that there was a strong correlation between UCS and index test results when homogeneous bricks were used, which indicates that UCS of a rock can be estimated accurately when lithological heterogeneity is removed.

Akram et al., (2015) measured UCS, N-values and PLI of Sakesar Limestone of Central Salt Range, Pakistan and developed a correlation of SHT with UCS and PLI having R2 0.637 and 0.377, respectively. They observed that the regression equations were found to have a similar trend as of the previously developed relations. The variation is considered to be the result of rock variation within rock specimens, presences of microstructures, rock fiber and texture together with the added effect of testing conditions. These equations were found good enough to predict the UCS from N-values & PLI. Arslan et al., (2015), tested 24 samples of Limestone belonging to Sakesar limestone and Nammal Formation to measure the UCS, N-values and PLI and then developed a correlation of N-values with UCS and PLI with a correlation coeff. of 0.777 and 0.906 respectively. However, care should be taken while using these relations as the developed correlations are area and rock dependent.

This paper establishes a correlation between the compressive strength measured by UCS, PLI, and N-values. Tests were performed on rock samples of two Eocene formations i.e, Shekhan Formation (SF) and Kohat Formation (KF) of Kohat Basin and new empirical equations are established.

2. Geology of the study area

The study area lies in the northern part of Kohat Basin. Figure 1 shows the geology of the study area and surroundings, with the sampling sites. The stratigraphic framework of the study area can be grouped into Paleocene, Eocene and Rawalpindi Group. Paleocene age rocks (Lockhart Limestone and Patala Formation) are conformably overlain by the Eocene rocks (Kohat Formation, Mami Khel Clay, Shekhan Formation, and Panoba Shale). These are in turn unconformably overlain by the fluvial molasse sediments of the Rawalpindi group of Miocene (Meissner et al. 1974; Shah, 1977).

The Shekhan Formation dominantly consists of massive-thin bedded, yellowish-grey nodular limestone. The thickness of the formation in the selected site is 52 m. The formation is best exposed in the east of the Kohat city in Shekhan Nala section (Shah, 2009). The Kohat Formation represents the top of the Eocene sequence within the Kohat Basin. The thickness of the formation in the selected site is 61 m. The formation is composed of thin-thick bedded foraminiferal limestone and yellow-green shale at the base (Meissner et al., 1974). Lockhart limestone of Paleocene age is composed of finely crystalline grey limestone and Patala Formation consists of splintery shale interbedded with argillaceous limestone (Shah, 1977). The Panoba Shale of Eocene sequence is composed of greenish-grey shale (Hanif et al., 2013). The Mami Khel Clay consists of silty and calcareous clays (Meissner et al., 1974). The Murree Formation of Miocene is comprises of reddish-purple sandstone and shale. The base of Murree Formation is marked by an unconformity with the underlying Kohat Formation. Kamlial Formation dominantly consists of greenish-grey sandstone and red shale (Fatmi, 1973).

Table 1. Equations correlating the SHT with UCS and PLI.

Reference	Equation	R^2	Rock type
Torabi et al 2010	UCS = 0.0465N-value - 0.1756PLI +27.68	0.862	Siltstone, sandstone, shale, argyle
Minaeian and Ahangari (2013)	UCS = 0.678N-value UCS =0.056UPV	0.935 0.942	Stuff, limestone, marl
Karaman and Kesimal (2014)	UCS = 0.1383N-value $^{1.743}$ UCS = 0.097N-value$^{1.8776}$ UCS = 4.2423N-value – 81.92	0.91 0.95 0.84	Sedimentary rocks, igneous rocks
Akram et al. (2015)	$UCS = 17.349e\ 0.0375R$ $UCS = 9.8532Is\ 50\ a + 24.426$	0.637 0.377	Sedimentary carbonate rocks
Arslan et al. (2015)	UCS = 23.80 e$^{0.032\text{N-value}}$ PLI = 2.113 N-value + 13.67	0.777 0.906	Limestone
Armaghani et al. (2016)	UCS=4.928N-value –128.45	0.491	Granite, metamorphic, sedimentary rocks
Azimian (2017)	UCS = 2.664N-value – 35.22	0.919	Limestone
Kong and Shang (2018)	UCS= 0.30N-value$^{1.43}$	0.97	Magnesian limestone, Woodkirk sandstone

3. Material and methods

A total number of eighty bulk and grab samples (40 from each formation) of two Eocene geologic formations i.e., Shekhan Formation (SF) and Kohat Formation (KF) were collected from the Kohat Basin, Khyber Pakhtunkhwa, Pakistan (Table 2). For sampling and to cover all the lithological variations within these formations, two sites were selected where SF and KF were noticeably exposed. The SF is yellowish-grey, nodular and thin-massive bedded in the selected site. The KF is predominantly composed of hard and thin-bedded light grey limestone with intercalations of shale. The limestone samples were collected after every 20 meters interval from both the formations, covering all the variations such as fossils, weathered and fresh exposures, grain sizes, and mesoscopic textures and structures. The cores samples were prepared according to the specifications provided by the ASTM for Preparing Rock Core as Cylindrical Test (D-4543-19). For each sample, core with length to diameter ratio (L/D) of 2.0-2.5 having a diameter of not less than 50 mm was used. The samples represented intact rocks with some macro and micro-cracks. The SHT was performed according to the ASTM Standard Test Method for Determination of Rock Hardness by Rebound Hammer Method (D5873-14). The L-type hammer was used and ten impact readings were recorded from each sample. The hammer was held vertically downwards and at right angles to the horizontal core faces to avoid the need of a correction factor to obtain a UCS value. The average of these readings was taken as N-values.

For the evaluation of UCS, ASTM standard test method for Compressive Strength and Elastic Moduli of Intact Rock Core sample (D7012-14) was adopted. This test was performed on eighty core samples (40 for each formation) (Table 1). These cores were drilled from the bulk samples, collected on the basis of lithological variations. Cores were obtained by core cutting machine and then lapped using polishing and lapping machine. The UCS values were calculated using equation 1

$$\sigma_{UCS} = \frac{F}{A} \text{ ---------- (eq. 1)}$$

Where,

σ_{UCS} = Uniaxial compressive strength (MPa)
F = Maximum failure load (N)
A = section area of the sample (mm).

The PLI was obtained according to the specifications, provided by ASTM Standard Test Method for Determination of the Point Load Strength Index of Rock (D5731-16). The test was performed on eighty irregularly shaped samples (40 for each formation) grabbed from the study areas. The sample size ranged from 1-4 inches (in length) and 1-2 inches (in width). The PLI was calculated using equation 2.

$$I_S = \frac{P}{{D_e}^2} \text{ ---------- (eq. 2)}$$

Where

I S = Uncorrected point load strength index
P = Failure load (N)
$D_e^2 = 4A/\pi$ for lump tests, mm^2

In irregular lump test, a size correction was applied to obtain a unique PLI value using equation 3.

$$F = \left(\frac{D_e}{50}\right)^{0.45} \text{ ---------- (eq. 3)}$$

Size-corrected point load strength index was calculated using equation 4.

$$I_{s(50)} = F\ X\ I_s \text{ ---------- (eq. 4)}$$

4. Results and discussions

Table 2 shows the results of UCS, PLI and N-values. The maximum UCS values of SF and KF are 121 and 96 MPa, while the minimum values are 80 and 60 MPa, respectively. The maximum PLI values of SF and KF are 115 and 105 MPa, while the minimum values are 85 and 39 MPa, respectively. The higher strength values of SF are due to the low fossil content, and lesser amount of microfractures and stylolites in the studied samples. In contrast, KF showed abundant microfossils, mesoscopic fractures and stylolites that resulted in low strength values. Table 3 shows the statistical analysis performed on the data.

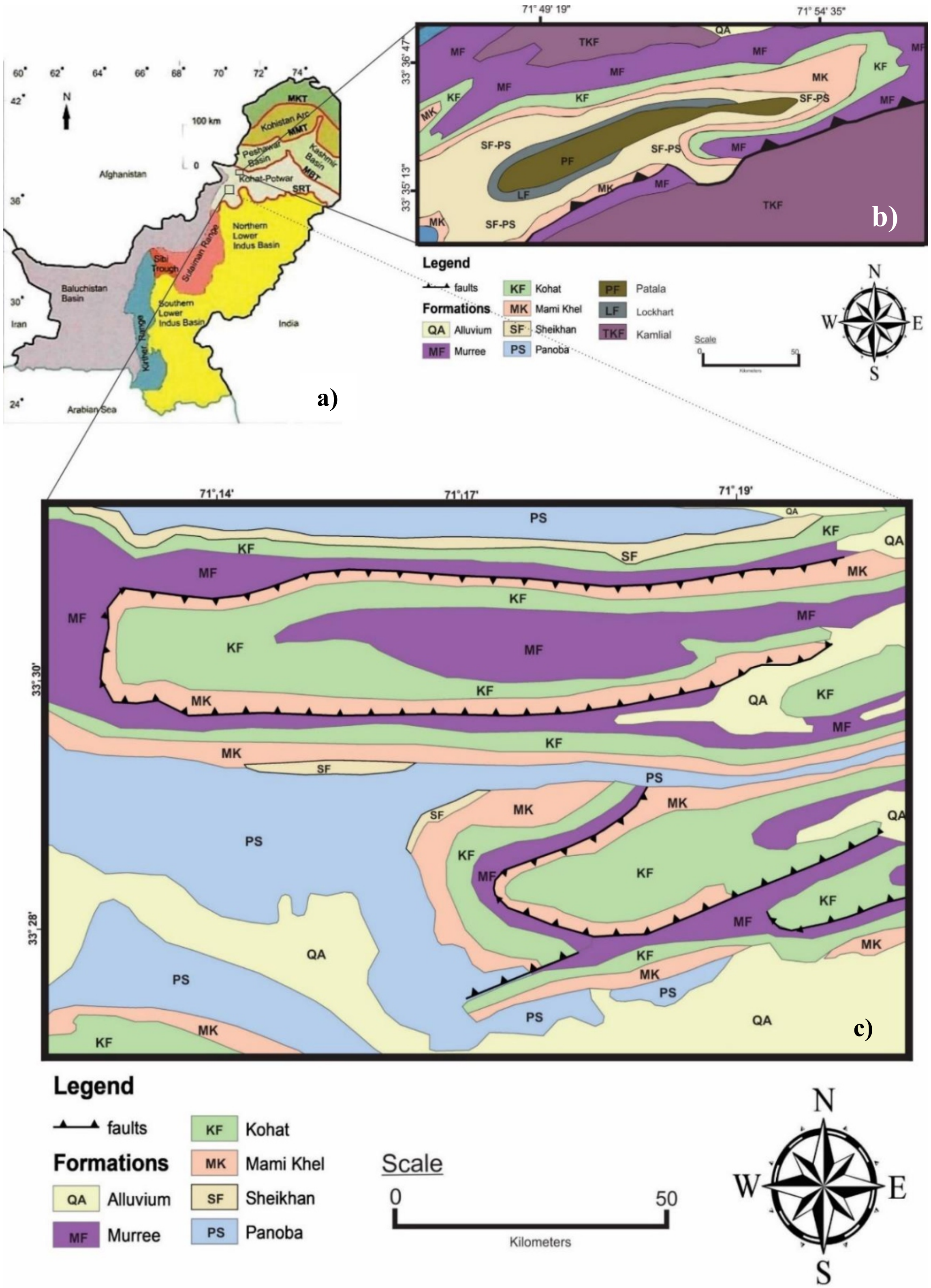


Fig. 1. Showing the maps of study areas within the Kohat Basin. a. Geological map of Pakistan (After Hanif et al., 2014). b. Panoba anticlinorium (site 1 for sampling). c. Shekhan Nala Section (site 2 for sampling). Fig 1 (b and c) are modified after Ahmed, S., 2003.

Shekhan Formation

$$UCS = 1.300N\text{-value} + 46.20$$

$(R^2 = 0.83)$ ---------- (eq. 5)

Kohat Formation

$$UCS = 1.705N\text{-value} + 21.79$$

$(R^2 = 0.84)$ ---------- (eq. 6)

A strong linear relationship is observed between PLI and N-values of the studied limestone. A strong correlation coef. of 0.73 & 0.76 is present between these properties for Shekhan and Kohat Formation, respectively (Figure 2; c & d). The best-fit trend line has the following equation (eq. 7 & 8) for the relationship between PLI and N-value.

Shekhan Formation

$$PLI = 0.851N\text{-value} + 64.01$$

$(R^2 = 0.727)$ ---------- (eq. 7)

Kohat Formation

$$PLI = 2.975N\text{-value} - 24.81$$

$(R^2 = 0.758)$ ---------- (eq. 8)

The derived empirical equations are used to predict the values of UCS and PLI in Figure 3. The predicted values of UCS and PLI from the corresponding equations are plotted against the measured values, on 1:1 line (doted). The solid line (the line of best fit) represents the data on a scattered plot. The values of UCS and PLI of both the formations lie close to the 1:1 line suggesting a fairly good prediction (R2 > 0.7).

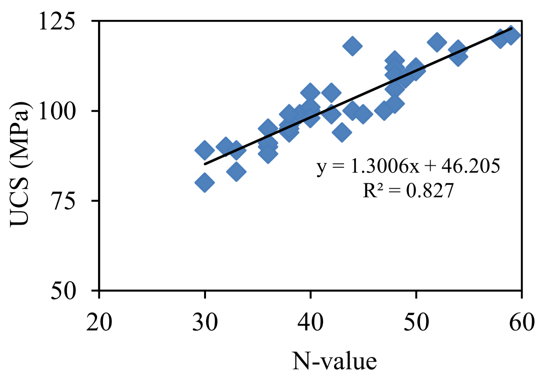
Various researchers such as Minaeian and Ahangari (2013), Karaman and Kesimal (2014), Armaghani et al., (2016), Azimian (2017), Kong and Shang (2018) showed that their derived regression equations are not applicable to other lithologies as they are developed for different rock types. It is clearly evident from this research that different equations were observed for both SF and KF, such as shown in equation 5 to 8. Hence, for every rock/formation, there will be a need to measure the UCS, PLI and N-value to establish a unique relationship between these parameters. These equations show that despite being the same rock type, both SF and KF possess different, UCS, PLI and N-values. The resulting equations can be used to calculate the UCS and PLI in this region by performing simple SHT. The obtained relationship can be used as a quick reference to suggest a preliminary value for UCS and PLI for these limestones only. It is suggested that such procedure be followed for each rock type in a specific geological situation and develop a unique relationship between the UCS, PLI and N-value. For this research, the specific geological situation is a sedimentary basin i-e Kohat Basin.

Table 2. Overall results of tests performed for each sample.

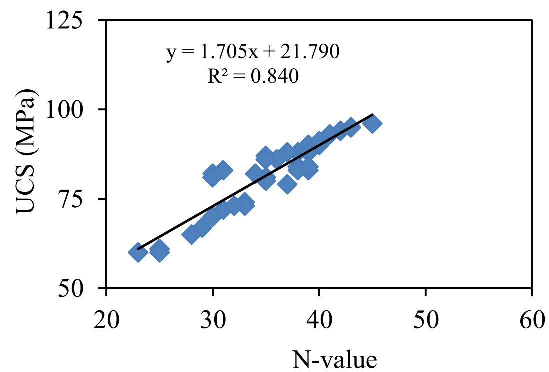
Sample No.	Shekhan Formation			Kohat Formation		
	N-value	UCS (MPa)	PLI (MPa)	N-value	UCS (MPa)	PLI (MPa)
1	48	114	110	30	70	70
2	40	105	102	38	84	80
3	39	99	98	31	72	72
4	38	94	98	40	90	95
5	36	90	93	39	83	69
6	40	101	100	25	61	41
7	47	100	109	33	74	69
8	38	96	98	33	73	70
9	32	90	91	40	91	89
10	38	95	95	25	60	39
11	33	83	94	39	89	93
12	40	100	101	23	60	40
13	42	105	103	29	67	44
14	48	112	111	30	82	70
15	36	95	98	28	65	44
16	30	89	88	38	88	80
17	40	101	101	38	83	80
18	48	110	109	35	81	75
19	40	101	108	43	95	93
20	38	99	99	35	80	80
21	58	120	110	45	96	105
22	54	115	106	42	94	104
23	44	118	107	40	91	100
24	43	94	93	37	88	89
25	49	109	103	39	90	101
26	50	112	104	35	87	89
27	44	100	99	30	81	82
28	42	99	97	32	73	79
29	36	91	90	41	93	102
30	36	88	89	39	90	100
31	59	121	115	39	88	89
32	52	119	110	31	83	80
33	48	106	103	30	81	80
34	54	117	110	37	79	80
35	30	80	85	39	84	82
36	40	98	95	43	95	105
37	50	111	104	36	86	88
38	33	89	90	35	86	88
39	45	99	98	34	82	83
40	48	102	100	40	91	101

Table 3. Statistical analysis of data obtained from various tests.

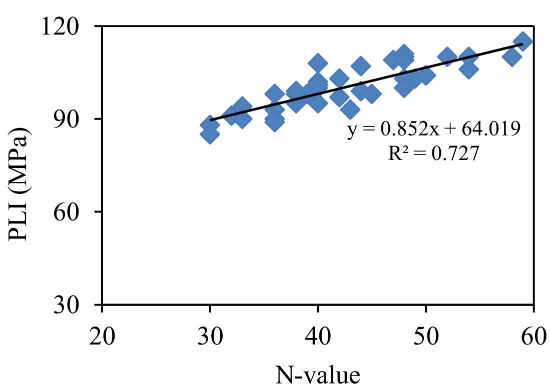
Tests performed		Max.	Min.	Mean.	Standard Deviation
SF	UCS	121	80	101.67	10.51
	PLI	115	85	100.35	7.34
KF	UCS	96	60	82.15	9.95
	PLI	105	39	80.5	18.28



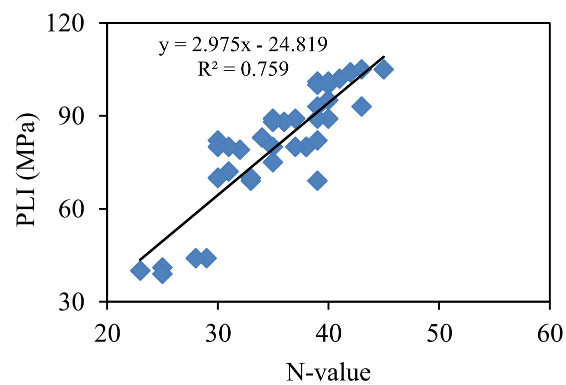
a) Shekhan Formation



b) Kohat Formation



c) Shekhan Formation



d) Kohat Formation

Fig. 2. Plots showing correlations between (a) UCS and N-value of Shekhan. Formation (b) UCS and N-value of Kohat Formation (c) PLI and N-value of Shekhan Formation (d) PLI and N-value of Kohat Formation

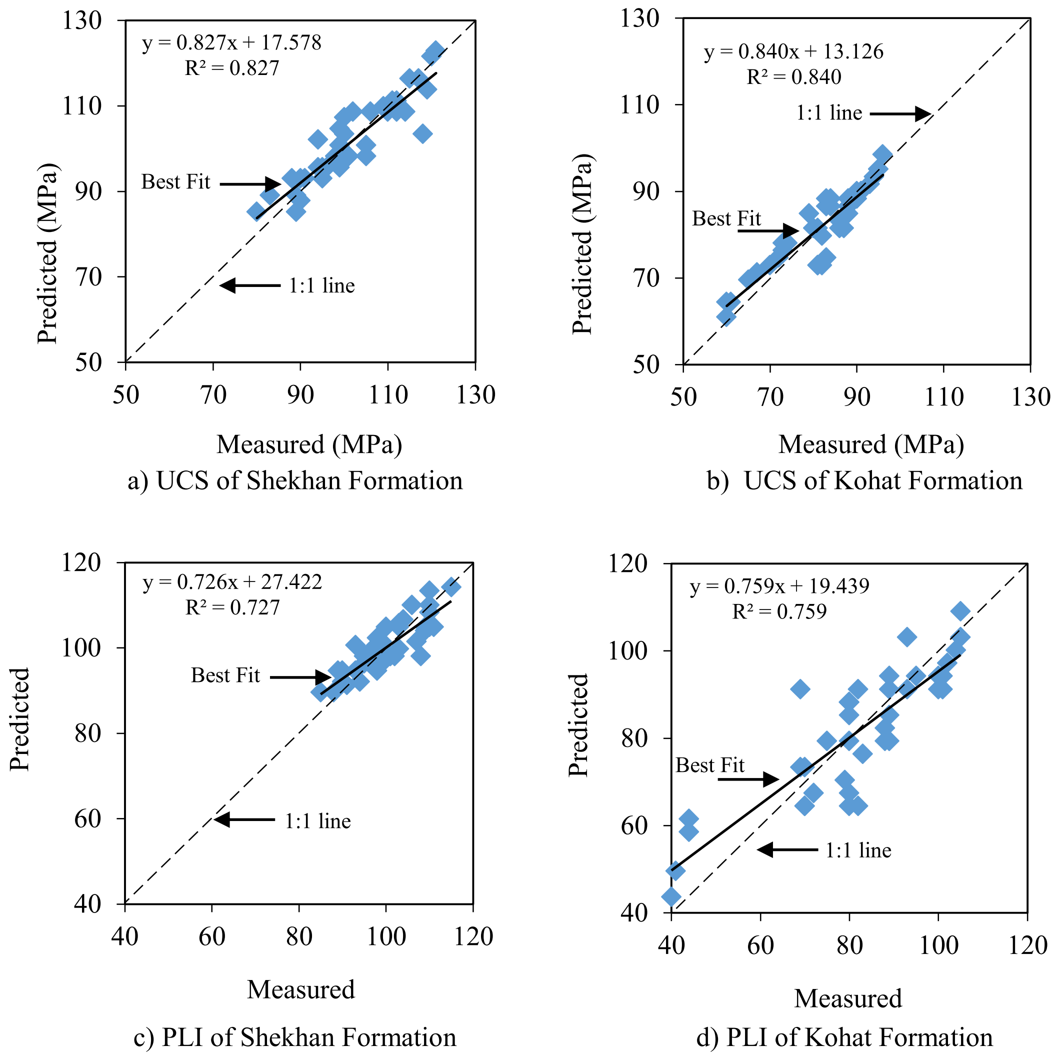


Fig. 3. Plots showing Predicted vs Measured values (a) UCS of Shekhan Formation (b) UCS of Kohat Formation (c) PLI of Shekhan Formation (d) PLI of Kohat Formation.

5. Conclusions and recommendations

This work establishes a correlation between the compressive strength measured by UCS, PLI, and N- values. Tests were performed on rock samples of two Eocene formations i.e, Shekhan Formation (SF) and Kohat Formation (KF) of Kohat Basin and new empirical equations were established. The study indicates that the UCS and PLI of limestone rocks can be estimated from their N-values by using simple empirical relations. A strong linear relationship is obtained between the UCS and N-values for the limestone of SF and KF having correlation coef. of 0.83 and 0.84, respectively. Furthermore, a strong linear relationship is also obtained between the PLI and N-values for the limestone of SF and KF having a correlation coef. of 0.73 and 0.76, respectively. From the results, unique equations were developed for the both formations which shows that a single equation is not applicable for the similar rock type of the same area, as investigated limestones (Kohat Basin) resulted in different equations. Nevertheless, further research in this area is required to determine the effects of deformation (folding and faulting) on the geomechanical properties of rocks. The qualitative values such as porosity, grain shape, size and its origin should also be taken into account for getting a better correlation between compressive strength and N-values.

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Authors' Contribution

Abdul Rahim Asif proposed the main concept, conducted experimental work, did statistical analysis and wrote the draft. Syed Samran Ali Shah, did provision of relevant literature. Jahanzeb khan, did technical review before submission and proof read of the manuscript.

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