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Prediction of Uniaxial Compressive Strength (UCS) of Sakesar Limestone in Salt Range - Pakistan by Indirect Methods

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***ABSTRACT*—Intact rock specimens are routinely tested in the laboratory for uniaxial compressive strength (UCS) which is an important design parameter in rock engineering. However, laboratory measurement is always expensive and time consuming and is generally not available as part of the small projects. Alternatively, indirect tests are relied to estimate UCS of various rocks through developing simple correlations among the results of uniaxial compressive strength (UCS) and indirect tests on the same rock. In the present study, efforts were made to make such correlations for Sakesar Limestone of Central Salt Range. In the study cored rock specimens were tested for UCS tests, Point Load tests (PLT) and Schmidt Rebound Hammer Tests (SRHT). All the tests' results were analysed using statistical techniques to find their interrelationships. The developed relations indicated strong correlations between UCS and Point Load Index (PLI), and UCS and Schmidt Rebound number (Rn).From these relations, UCS is predictable from PLT and SRHT with a reasonable precision.**

KEY WORDS-Rock Mechanics, UCS, PLT, Schmidt Rebound Hammer, Sakesar Limestone, regression models

I. INTRODUCTION

Uniaxial Compressive Strength test measures the strength of intact rock in compression which is pivotal for the design of civil and mining engineering structures. However, it is expensive and time intensive in nature, particularly in case of small projects. A correlation between simple, straightforward and cheap tests (i.e. Point load Test and Schmidt Hammer Rebound Test) and Uniaxial Compressive Strength Test provides plausible alternative for estimation of UCS. The correlation factors vary widely depending upon the rock type, weathering grades, mineralogical formations and stratigraphic structures and number of test results being correlated. Therefore, for a reasonable and valid estimation of UCS from simple tests, calculation of the correlation factor on reasonable number of test results is inevitable to determine the UCS from the indirect tests. Hence, this study is proposed to develop correlations among the UCS tests, Point Load Tests (PLTs) and Schmidt Rebound Hammer Tests (SRHTs) for Sakesar limestone of the central Salt Range. It is believed that the correlation factors derived through these relationships would facilitate the Civil and Mining Engineering industry to large extent in addition to the contribution to the academics.

Very limited work has been conducted in the past in Pakistan with reference to the strength of the rocks, especially limestone which is commonly used as construction material like concrete and asphalt aggregate, and building show stones. Hence, the knowledge of its engineering properties will help to select the limestone of a specific in accordance with the specific project requirements. Since, the most commonly used UCST for determining UCS is very expensive and time consuming, indirect methods should be applied and correlated to actual test results. With the correlation factors in hand, UCS (being important design parameters) of the rocks can be estimated from PLT and SRHT to a reasonable accuracy.

The present study will contribute to the database of rock engineering properties which will facilitate the researchers and professionals to use local design parameters on important projects rather than adopting from the case histories around the world.

II. PREVIOUS STUDIES

Uniaxial Compressive Strength (UCS-σc) is an important parameter that defines the mechanical strength of intact rocks for designing the projects in and at rocks (Brady & Brown, 2005). Therefore, uniaxial compressive strength test is the widely conducted test (e.g. Hawkes & Mellor, 1970; Karakus et al., 2005; Rajabzadeh, 2011) that provides uniaxial compressive strength used to classify the rocks. The test procedure is standardised by the ISRM (1981) and ASTM (1986) that requires a well prepared cylindrical core specimen. According to ISRM (1981), there must be six tests from a single rock horizon for meaningful and conclusive results. However, this is not always possible to meet the ISRM requirement due to budget and time constraints.

Alternatively, many researchers (e.g. Akram&Bakar, 2007; Broch& Franklin, 1972; Dincer et al., 2004; Dincer et al., 2008; Gupta, 2009; Inoue &Ohomi, 1970; Kahraman, 2001; Kahraman et al., 2005; Kahraman &Gunaydin, 2007; Kilic, 2008; Kurtulus, 2010; Li, 2003; Potro, 2009; Sachpazis, 1990; Sheorey, 1984; Yilmaz, 2002) attempted to develop the relationships between results of UCS tests and other simple tests such as Point Load Test (PLT) and Schmidt Rebound Hammer Test (SRHT) for the estimation of UCS of the rocks.

PLT, firstly introduced by Deere and Miller (Deere & Miller, 1966), is a simple and time efficient test and is conducted on cored as well as field lump samples without the need of well-prepared specimens. The test provides Point Load Index (Is) which is directly proportional to the UCS of rocks. The value of Is is corrected for a 50mm core sample to determine Is(50) to avoid scaling effects as per ISRM (1985) and ASTM (2000). Because of the simplicity of the test, the approach has been used around the world and was commented to carry 20% error in the results (Pells, 1975). Various researches were undertaken to develop relationship of the Is(50) and the other mechanical properties (e.g. UCS, E,
v) of sedimentary rocks (e.g. Akram, 2007; Kahraman, 2001; Kilic, 2008), metamorphic rocks (e.g. Gupta, 2009; Kahraman, 2001; Kilic, 2008; Rajabzadeh, 2011) and igneous rocks (e.g. Gupta, 2009; Kahraman, 2001; Kilic, 2008; Potro, 2009; Rajabzadeh, 2011). In these studies, various empirical relations, a review is available in Table 1 (updated after (Fener et al., 2005)), were developed to estimate the uniaxial compressive strength of various rocks. Most of the relations are linear and value of correlation factor varies from 8 to 29 if zero intercept was used. Tsiambaos (G. Tsiambaos, Sabatakakis, N., 2004) and Grasso, Xuet al. Grasso (1992) found power relation between UCS and PL strength index. Palchik (2004) showed that the relation between UCS and PL strength is influenced by the porosity.

Schmidt Rebound Hammer Test (SRHT) is another indirect approach to find the UCS of the rocks. The test is non-destructive, simple and time efficient and can be conducted by applying the blow of the hammer on the rock and taking its rebound values. The main philosophy behind the test is that a rebound value (Rn) on particular rock is the measure of the density and hardness of the rock which in turn proportional to the compressive strength of the rock. Hence the rebound value (Rn) can be used to determine the UCS of rocks by using the empirical relations. The test was initially used to estimate the uniaxial compressive strength of the concrete structures (Kahraman &Gunaydin, 2007; Schmidt, 1951) and road works to verify the construction requirements. However, it has been widely used around the world for more than three decades in the discipline of rock engineering, geotechnical engineering and engineering geology following the early work by Deere and Miller (1966).The test procedure is standardised by both ASTM (2001) and ISRM (1987). Numerous researchers have focused this simple test in estimating UCS (e.g. Dincer et al., 2004; Gupta, 2009; Haramy, 1985; Inoue &Ohomi, 1970; Kilic, 2008) of various rocks, a review is available in Table 2 (updated after (Fener et al., 2005)). As shown in the table the relations are linear, power exponential and logarithmic suggested that no similarity between them. But, the relationships of UCS with Rn were found very encouraging and rigorous, and thus providing a base for their use in reasonably good estimation of the mechanical parameters. However, it is needful to check the Rn based estimation of UCS against the actual UCST results for a specific rock to calibrate the SRH and to find the difference in the estimated and actual results (Akram, 2007).

In view of the rigor of the PLT and SRHT for estimating UCS and modulus of the rocks, present research is proposed to apply on Sakesar limestone of the Salt Range. Previously, very few efforts (e.g. Akram, 2007) have been made to establish relationships between UCS and Is(50) and SRHT in Pakistan. Therefore, it is needful to extend these correlations to make best use of the optimum resources available for estimating the
rock engineering properties rigorou

Table 1 Correlations between UCS and Is$_{(50)}$ (Updated after (M. Fener, 2005))

Reference	**Equation**
Kahraman & Gunaydin (2009) for Sedimentary rocks	$q_u = 29.77\ I_s – 51.49$
for Metamorphic rocks	$q_u = 18.45\ I_s – 13.63$
for Igneous rocks	$q_u = 8.20\ I_s + 36.43$
Akram (2007) for Strong rocks	$q_u = 22.792\ I_{s50} + 13.295$
for Weak rocks	$q_u = 11.076\ I_{s50}$
Palchik (2004)	$q_u = k_1 e^{-k2n}$
Fener et al., (2005)	$q_u = 9.08\ I_{s50} + 39.32$
G. Tsiambaos & Sabatakakis (2004) Power relation	$q_u = 7.3(I_{s50})^{1.71}$
Linear relation	$q_u = 23\ I_{s50}$
Quane (2003) for Strong rocks	$q_u = 24.4\ I_{s50}$
for Weak rocks	$q_u = 3.86(I_{s50})^2 + 5.65\ I_{s50}$
Kahraman (2001) for 22 different rock type	$q_u = 8.41\ I_{s50} + 9.51$
for Coal measure rocks	$q_u = 23.62\ I_{s50} – 2.69$
Smith (1997)	$q_u = 14.3\ I_{s50}$
Chou (1996)	$q_u = 12.5\ I_{s50}$
Grasso et al. (1992) Power relation	$q_u = 25.67(I_{s50})^{0.57}$
Linear relation	$q_u = 9.30\ I_{s50} + 20.04$
Ghosh (1991)	$q_u = 16\ I_{s50}$
Tsidzi (1991)	$q_u = 14 + 82\ I_{s50}$
Cargill (1990)	$q_u = 23I_{s54} + 13$
Vallejo (1989)	$q_u = 8.6\text{-}16\ I_{s50}$
ISRM (1985)	$q_u = 20\text{-}25\ I_{s50}$
Gunsallus (1984)	$q_u = 16.5\ I_{s50} + 51.0$
Forster (1983)	$q_u = 14.5\ I_{s50}$
Singh(1981)	$q_u = 18.7\ I_{s50} – 13.2$
Read (1980) for sedimentary rocks	$q_u = 16\ I_{s50}$
for Basalt	$q_u = 20\ I_{s50}$
Hassani (1980)	$q_u = 29\ I_{s50}$
Bieniawski (1975)	$q_u = 23\ I_{s50}$
Broch & Franklin (1972)	$q_u = 24\ I_{s50}$
Deere & Miller(1966)	$q_u = 20.7\ I_{s50} + 29.6$
Fener et al., (2005)	$q_u = 15.3I_{s50} + 16.3$
q_u = UCS (MPa), I_s = point load index (MPa), k_1 and k_2 = empirical coefficients, n = porosity	

Table 2 Correlations between UCS and R$_n$ (updated after(M. Fener, 2005))

q = UCS (MPa), R = Schmidt hammer value, ρ = density	(g/cm^3) **Equation**
Kilic&Teymen(Kilic, 2008)	$q_u = 0.0137\ N^{2.2721}$
Fener(2005)	$q_u = 4.24e^{0.059Rn}$
Dincer et al.,(2004)	$q_u = 2.75N – 36.83$
Yasar (2004)	$q_u = 4 * 10^{-6} R_n{}^{4.2917}$
Yilmaz(2002)	$q_u = 2.27\ e^{0.054Rn}$
Katz(2000)	$q_u = 2.208\ e^{0.067Rn}$
Kahraman (2001)	$q_u = 6.97\ e^{0.014Rn\rho}$
Cargill(1990)for sandstones	$\ln q_u = 4.3 * 10^{-2}(Rn\rho) + 1.2$
for carbonates	$\ln q_u = 1.8 * 10^{-2}(Rn\rho) + 2.9$
Xu(1990)	$q_u = \exp\ (aR_n + b)$ a, b are constants
Sachpazis (1990)	$q_u = 0.2329R_n + 15.7244$
Ghose (1986)	$q_u = 0.88R_n – 12.11$
Haramy & Marco (1985)	$q_u = 0.994R_n – 0.383$
Sheorey et al. (1984)	$q_u = 0.4R_n – 3.6$
Singh (1983)	$q_u = 2R_n$
Kidybinski (1980)	$q_u = 0.4777e^{(0.045Rn + \rho)}$
Beverly (1979)	$q_u = 12.74e^{[0.0185(Rn\rho)]}$
Aufmuth (1973)	$q_u = 6.9 * 10^{[1.348\log(Rn\rho) – 1.325]}$
Deere and Miller (1966)	$q_u = 6.9 * 10^{[0.16 + 0.0087(Rn\rho)]}$

III. RESEARCH METHODOLOGY

A. Sampling

Rock core samples were obtained from more than 50 drilling sites located in central Salt Range (Figure 1). The samples with length to diameter ratio 2.5 to 3.0 were taken for uniaxial compression tests. Samples for PLT were taken right above or below of the UCS specimens to rule out any rock variation and to have both tests conducted in the same rock quality. All core specimens for both tests were ensured devoid of any defects that could cause inhomogeneity in specimen and induce scatter in the results. All samples including for PLT and UCST were carefully numbered with depths so as to have same number of sample for UCS and PLT at more or less same depth.

B. Sample preparation

Samples having greater length than diameter were consider suitable for PL diametral test (Figure 2a) and for PL axial test rock coresamples were cut in such a way that the length remain less than the diameter (Figure 2b). For UCST, the cores were cut from both ends to get the required length to diameter ratio (Figure 2c). Both ends made flat and parallel to meet the ISRM specifications.

C. Testing procedure

A total 82 samples were selected from prepared samples for testing. First, Schmidt rebound hammer test was performed diametrically and axially to get the value of Rn Using L-type hammer as it is a non-destructive test. Point load tester was used to execute PLT on diametrical (Figure 3a) and axial (Figure 3b) sample to acquire Is value, size correction was applied to get Is(50). Vertical load was applied on well prepared cylindrical samples till failure (Figure 3c) and UCS is calculated. It was also size-corrected equivalent to 50mm core diameter.

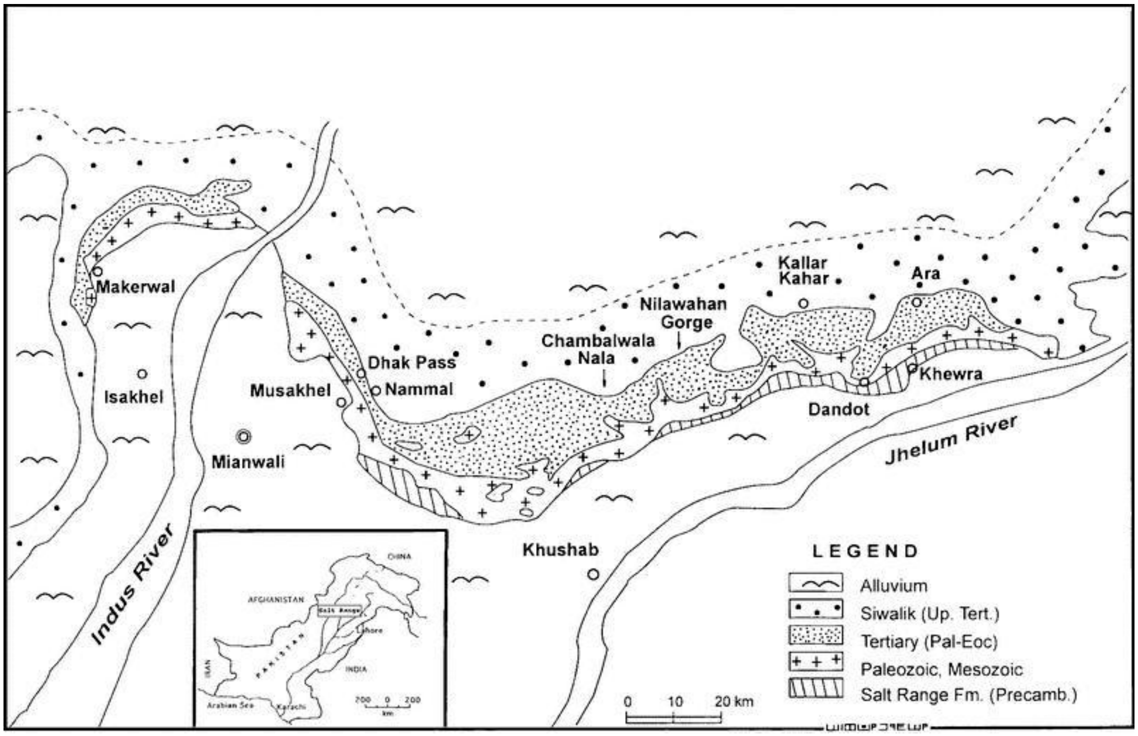

Figure 1 Geological Map of the Salt Range, Pakistan (after Pascoe, 1919)

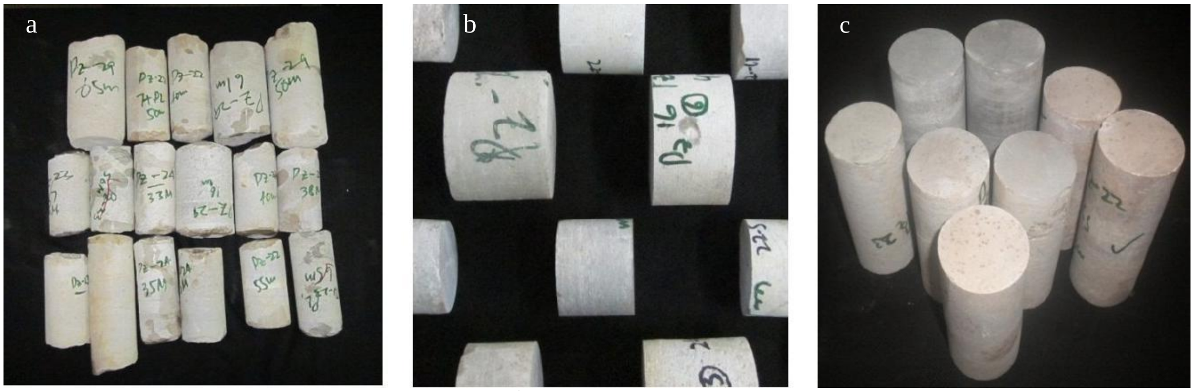

Figure 2 Prepared samples for (a) PLT diametral (b) PLT axial (c) UCST

Figure 3 Failed samples after (a) PLT diametral (b) PLT axial (c) UCST

IV. TEST RESULTS AND DISCUSSIONS

A. Statistical analysis

The variability of each test result was evaluated by using descriptive stat functions given in Table 3. The value of coefficient of variation in SRHT is well with-in acceptance limits while in PLT and UCST it shows that the data is relatively scattered. The coefficient of variation for UCS is 22.81 which is less than the Is(50). (Broch & Franklin, 1972) found that UCS test results are more scatter than PLT results while (Ghosh, 1991) found it opposite. In this research, Bieniawski's statement is supported as the PLT results are more scattered than the UCST results.

B. Regression analysis

The values of SRHT and PLT were correlated with corresponding UCST values using the method of regression analysis. In each correlation the equation of best fit line and coefficient of correlation were determined. Measured UCS has an exponential relation with both Rn axial and diametral as shown in Figure 4a &Figure 4b.

The equations of the lines are:

$$= 17.349 \quad 0.0 \quad 5 \quad (\tag{1}$$

$(R^2 = 0.637)$

$$= 21.2 \quad 9 \quad 0.0 \quad 58 \quad (\tag{2}$$

$(R^2 = 0.6376)$

Where $R_{n(a)}$ and $R_{n(d)}$are Schmidt rebound hammer values determined axially and diameterally respectively. The values of R^2 suggest that the above correlations are reasonably good.

Figure 5a shows a linear relation between UCS and Is(50) axial whileFigure 5b show a linear relation between UCS and I_s(50) diametral. Derived equations are:

$$= 9. \quad 32 \quad (50) \quad + 24.426 \tag{3}$$

$(R^2 = 0.377)$

$$= 1. \quad 7 \quad (50) \quad + 19.766 \tag{4}$$

$(R^2 = 0.6091)$

Equations (3) &(4) are linear equations for $Is_{(50)}$ axial and diametral respectively. R^2 value shows a moderate relation between UCS and $Is_{(50)}$ axial while the value of R^2 show a reasonable relation between UCS and $Is_{(50)}$ diametral.

C. Paired t-Test

Paired t-Test used to test the significance of the difference between paired means. The actual UCS values and predicted UCS values from SRHT and PLT were analysed using paired t-test. The test was performed using 95% confidence level. The value of t-statistic and p-valueare important. If p-value is greater than the 95% confidence level i.e. greater than 0.05 then there will be no difference between the actual and predicted values. Paired t-Test was executed for all the equations and it was found that p-value is greater than 0.05 for all four equations (Table 4); moreover the difference between the means is very small which suggested that there is no difference between the actual and predicted values.

D. Estimation capability of resulting equations

Predicted UCS values from SRHT and PLT were plotted against actual UCS to see the estimation capability of the resultant equations shown inFigure 6&Figure 7. The distance of points away from zero intercept line shows the error in estimation while the points on the line represent exact estimation. In Figure 6a,Figure 6b &Figure 7b data points are uniformly distributed along the diagonal line which indicates that these models are reasonably good while in Figure 7a some points deviate from the diagonal line which suggests that prediction of UCS from axial PLT is less reliable.

Table 3 descriptive statistical analysis

Descriptive stat	**SRHT (dia)**	**SRHT (axial)**	**PLT (dia)**	**PLT (axial)**	**UCS**
Mean	40.89	33.48	4.02	3.85	62.36
Standard Error	0.77	0.53	0.12	0.10	1.57
Median	41.67	33.33	4.09	3.99	61.89
Standard Deviation	7.01	4.82	1.05	0.89	14.23
Sample Variance	49.19	23.24	1.10	0.79	202.40
Coefficient of variation (%)	17.15	14.40	26.07	23.05	22.81
Skewness	0.15	0.19	-0.06	-0.20	0.64
Minimum	26.33	22.67	2.03	2.12	35.09
Maximum	59.33	46.33	6.01	5.50	106.08
Sum	3352.67	2745.33	329.92	315.72	5113.76
Confidence Level (95.0%)	1.54	1.06	0.23	0.19	3.13

Table 4 Paired t-Test of equations (1),(2)&(3) with equation (4)

t-Test: Paired Two Sample for Means

	equ 1	*equ 2*	*equ 3*	*equ 4*	*Actual UCS*
Mean	62.3630	62.3630	62.3630	62.3630	61.8889
Variance	202.4008	202.4008	202.4008	202.4008	131.1619
Observations	82.0000	82.0000	82.0000	82.0000	82.0000
Pearson Correlation	0.8121	0.7930	0.6146	0.7804	
df	81.0000	81.0000	81.0000	81.0000	
t Stat	0.5171	0.4799	-0.0003	0.0005	
P(T<=t) one-tail	0.3032	0.3163	0.4999	0.4998	
t Critical one-tail	1.6639	1.6639	1.6639	1.6639	
P(T<=t) two-tail	0.6065	0.6326	0.9998	0.9996	
t Critical two-tail	1.9897	1.9897	1.9897	1.9897	

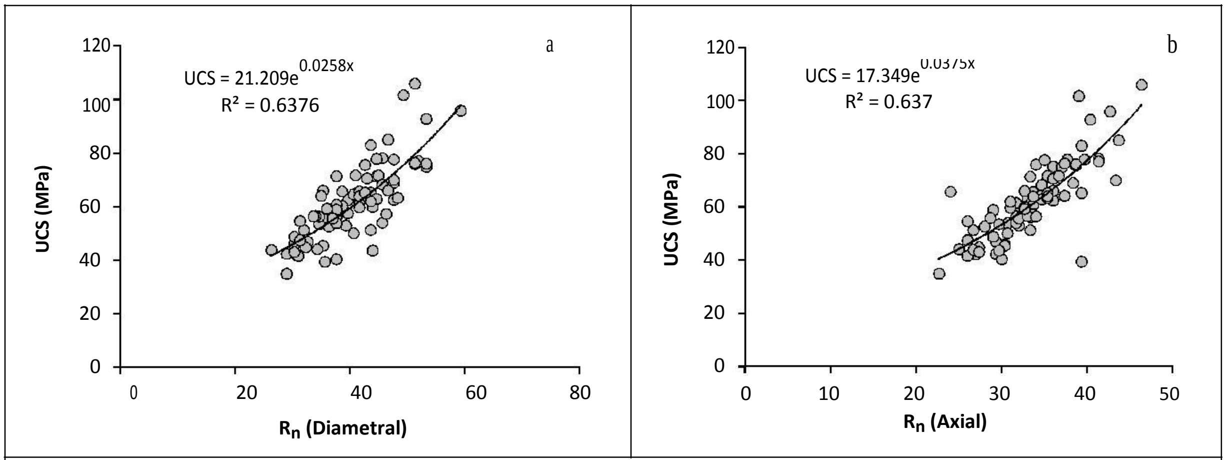

Figure 4 Correlation between UCS and R_n , (a) axial, (b) diametral

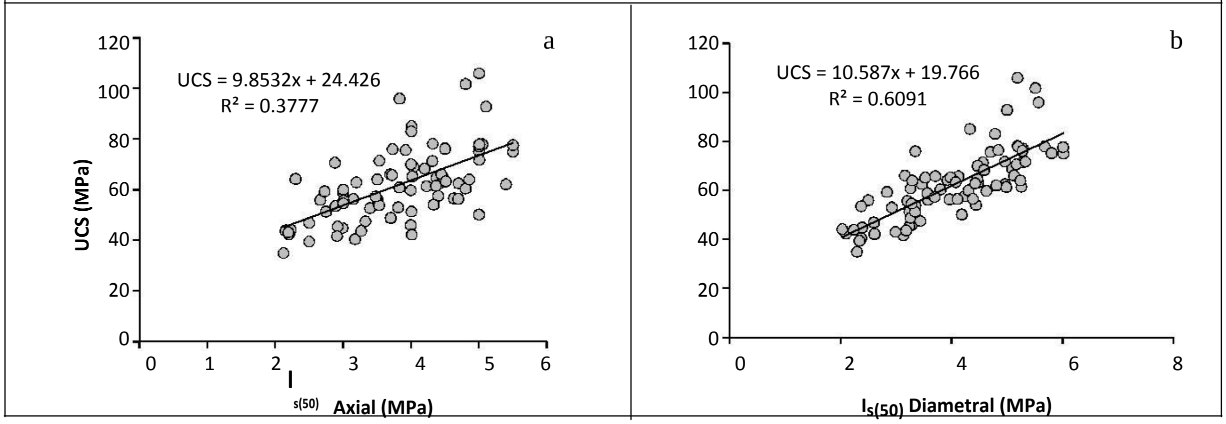

Figure 5 Correlation between UCS and Is(50) (a) axial (b) diametral

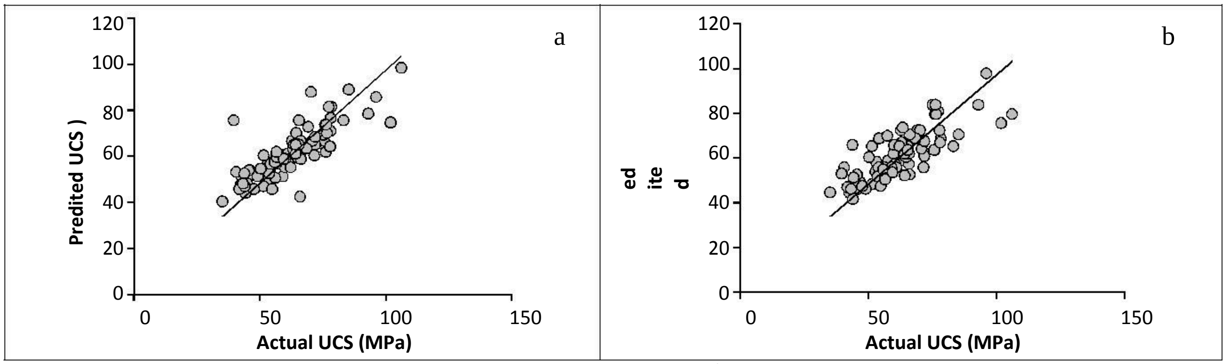

Figure 6 Estimated UCS versus actual UCS for equation (1) &(2)

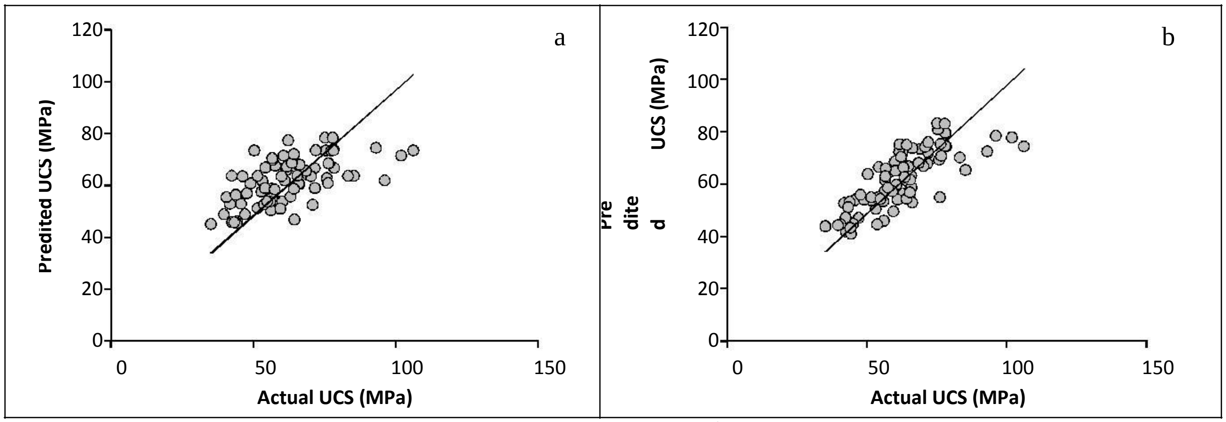

Figure 7 Estimated UCS versus actual UCS for equation (3) &(4)

V. CONCLUSION

The Schmidt rebound hammer test, point load test and uniaxial compression test were carried out on 82 core samples of Sakesar limestone taken from central Salt Range. Regression analysis was used to establish relations using the test results. The estimation capability of the derived equations was checked using paired t-test. The derived equations were found to have similar trend as of the previously developed relations. The variation is considered to be the result of rock variation with in rock specimens, presences of micro structures, rock fibre and texturetogether with the added effect of testing conditions. These equations were found good enough to predict UCS from SRHT &PLT, however care should be taken while using these relations as the developed correlations are area and rock dependant. Given the encouraging results from thesecorrelations, it has been planned to undertake further studies on rest of the rocks in Salt Range for the development of such relations to create a database. This will help the industry, students and researchers in estimate mechanical parameters of the Salt Range Rocks.

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