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CORRELATION OF UNIAXIAL COMPRESSIVE STRENGTH WITH BRAZILIAN TENSILE STRENGTH AND INDEX PROPERTIES FOR SOFT SEDIMENTARY ROCKS

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ABSTRACT

Sedimentary Rocks composing the Thar Lignite basin Pakistan are of clastic origin. These rocks have comparatively low uniaxial compressive strength (UCS) values, and hence recognized as 'soft sedimentary rocks' in this study. UCS is a fundamental property of rocks, used by mine design engineers in designing the surface and underground excavations. The purpose of this study is to investigate the relationship between UCS with Brazilian tensile strength (BTS), and index properties of soft sedimentary rock formations at Thar Lignite basin. Various correlations between mechanical and physical properties of rocks have been developed previously. However, no significant correlation has been developed on UCS with BTS and index properties for soft sedimentary rocks. Numerous Rock samples from Two complete geotechnical drillholes at Block-IX Thar Coalfield were selected. Standard test procedures were implemented to determine the UCS, indirect Tensile and index properties such as point load strength, and shore Scleroscope hardness. The correlations between rock properties were established using simple and multiple regression techniques, and empirical equations were obtained. These equations can be used to predict the UCS and tensile strength of soft sedimentary rocks by performing simple index tests; which are quick, economical, and easier to be performed on the site.

Keywords: Soft Sedimentary Rocks; Thar Coalfield Pakistan; Uniaxial Compressive Strength; Index Properties; Shore Scleroscope Hardness.

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1. INTRODUCTION

As the rocks found near earth's surface are anisotropic in nature, their investigation is mainly required in the fields of mining, civil, petroleum and geo-environmental engineering in order to acquire their physical and mechanical properties [1, 2]. There are enormous discontinuities for instance fissures, joints, and weak surfaces that are present in rock mass because to their geological movement therefore significantly affect the mechanical behaviour of rock mass [3]. Geotechnical investigation plays a vital role in the execution of any rock engineering project by applying the rock mechanics principles for investigation of strata conditions and variation in rock types, assess their Strength, intrinsic and chemical behaviour, analyse the stability of slopes, identify the potential hazards and their associated risks related to Site conditions [4].

The mine design engineers asses the behaviour of the rockmass to set the design criteria for excavations and structures in mines [5]. The uniaxial compressive strength (UCS) and Tensile strength of rock material are the fundamental input design parameters [6, 7]. These strength properties are required for the design of underground mine structures, stability analysis of open-pit slopes, rock drilling and blasting in quarrying operations, and many civil engineering works [8, 9]. Testing of the rocks under uniaxial compression or tension is a simple mechanism yet expensive and time consuming. In order to perform a standard laboratory uniaxial test, rock core or cubical specimen are required which involve costly exploratory drilling and specialized cutting process. Additionally, the preparation of specimen as per standard shape and size is a problem. The specimen preparation becomes even more difficult if the rock is soft, weak or having joints. Therefore, the use of index testing methods, such as Point load index, and Shore Scleroscope hardness tests are often a suitable alternate for the estimation of UCS and tensile strength. These index testing procedures are performed by using portable equipment and require simple specimen preparation process which can be readily carried out on the site [10].

This study is performed on the rock samples acquired using borehole sampling from two geotechnical drillholes at Block-IX, Thar Coalfield Pakistan. Thar coalfield is located in south eastern region of the Sindh, Pakistan with the estimated coal reserves of 175 billion tons extended to the 9100 sq. km area [11]. The Lignite rank coal seams are deposited at depths between 130 meters and 250 meters [12]. Figure 1 presents the location of Thar coalfield and distribution of coalfield into 13 blocks, features the location of the studied area, i.e., Block-IX Thar Coalfield, Pakistan [13].

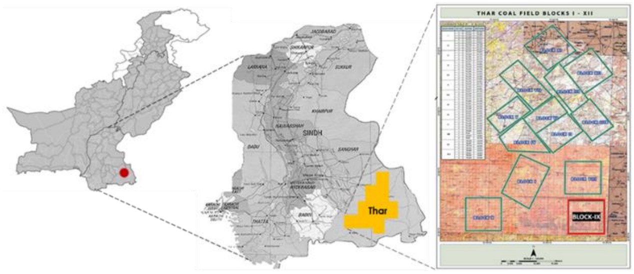


Figure 1. Location of Thar Coalfield and block-wise distribution of Coalfield.

In the Thar Coalfield, the granitic basement is unconformity overlain by sediments of Palaeocene to Eocene tertiary age Bara Formation. The coal seams are developed in this formation. These coal seams are bounded by top and bottom sand layer aquifers of the Subrecent and Bara formations respectively. The Sub-recent formation rest unconformity on the sediments of the Bara Formation. The stratigraphic column is topped by Recent formation Dune sands. Some portion of the Dune sand is recovered from the core drill run as intact core due to natural consolidation and silt/clay bonding, therefore considered as rock. The rock layers deposited above and in-between the coal sems are loosely consolidated and having a low compressive strength [11]. Due to the low compressive strength, the rocks overlying, and underlying coal formation are considered as “soft sedimentary formations” in this study.

2. PREVIOUS STUDIES

Intact rock sample when tested in the laboratory always contain some of the intrinsic properties of its parent rockmass hence the failure mode of that intact rock sample may be tensile failure, shear failure or combination. Every rock contains inherent micro-fractures and cracks and when they are subjected to load those tiny micro-fractures tend to extend; this phenomenon is known as Crack Propagation. If the load is not relieved, the crack propagation stage will enter into second phase, known as crack initiation in which a fracture plane has been physically developed within the rock and rock is said to have failed [14]. Thus, the determination of the rock properties is one of the most crucial aspects of rock engineering. Different types of tests are suggested as per standards such as for Uniaxial Compressive strength, Tensile strength and Point Load Index Strength which are useful in predicting the behaviour of rock and rock mass and a comparison can also be made with different rock types tested under same conditions. The Uniaxial compressive strength and Brazilian index tests are the common tests [15]. Various research studies have been done to determine the rockmass properties and predict the rock strength properties by using indirect methods [16-18]. The point load index was proposed as an indirect measure of the UCS and tensile strength of rocks by many researchers [19-21]. Chau and Wong, 1996 utilized results and proposed a simple analytical formula to calculate the uniaxial compressive strength based on the point load strength [22]. Another study was carried out to find the relationship between UCS and Point load strength for pyroclastic rocks with values less than 50 MPa. The study found significant relationship with strong exponential trends and the comparative analysis were made [23]. Yin et. al, 2017 carried out research on the reliability of the correlations between UCS and Point Load Strength Index of irregular lumps from Point load test. Distinct tests on cylinder cores was performed by applying diametric and axial loading conditions in order to obtain point load strength index [24]. The study found that the estimation of UCS from point load strength index acquired from point load test on irregular lumps is reliable. Elhakim, 2015 proposed correlations to estimate the UCS from point load tests for calcareous sandstone samples [25].

Kahraman, 2001 concluded the uniaxial compressive strength test as a primary method of evaluating the rock strength. The study found that the compressive strength of any rock can be easily estimated by the index testing because these utilize the portable Equipments. These index testing equipment are easy to handle, use and can test the specimen with a little or no preparation [26]. Kolapo investigated the relationship between point load strength index, UCS and Brazilian tensile strength of sandstone [27]. The results revealed significant correlations of point load strength index with UCS. The inconsistent results were also found for the correlation of UCS with indirect tensile strength because of the heterogeneity of the sandstone samples. Table 1 presents the studies carried out to correlate the uniaxial compressive strength and other rock strength properties.

Table 1. Equations correlating the UCS with other strength properties.

Author(s)	**UCS vs. PLI**	**UCS vs. BTS**	**UCS vs. SSI**
Arman (2021)	-	Gypsum UCS=4.23BTS+13.63	-
Teymen (2021)	-	-	$UCS=0.27SSI^{1.45}$
Teymen and Mengüç (2020)	$UCS=12.287Is^{1.2333}$	$UCS=7.7331BTS^{1.1967}$	$UCS=0.2759SSI^{1.4294}$
Hamdy (2020)	Weak Limestones UCS=11.33Is (white) UCS=13.7Is (Gray)	-	-
Sari (2018)	UCS=15.15Is	UCS=10.04BTS	-
Teymen (2018)	Tuff UCS=19.518Is-16.226	-	-
Minaeian and Ahangari (2017)	$UCS=16Is-2.87Is^2$	-	-
Shahri et al. (2016)	Marlstones UCS=20.413Is -8.916	-	-
Kahraman (2014)	for Igneous rocks $UCS=2.68e^{0.93Is}$ (Dry) $UCS=1.99e^{1.18Is}$ (Saturated) $UCS=2.27e^{1.04Is}$ (Dry and Saturated)	-	-
Nazir et al. (2013)	-	Limestone $UCS=9.25\ BTS^{0.947}$	-
Cobanoglu and Celik (2008)	Sandstone and Limestone UCS = 8.66 Is(50) + 10.85	-	-
Koncagül and Santi (1999)	-	-	Breathitt Shale UCS=895SSI+41977

Regression analyses have been established and used as valid methods for developing the relationships between mechanical and physical properties of rocks. It has been reported by many researchers that rock properties are influenced by rock type, degree of consolidation porosity, texture, water content, etc. However, no significant correlation has been developed on UCS regarding BTS and index properties for soft sedimentary rocks. This study aims to develop empirical relationships between:

a) Uniaxial Compressive Strength (UCS) and Brazilian Tensile Strength (BTS),

b) Uniaxial Compressive Strength (UCS) and Point load Strength index (PLS),

c) Uniaxial Compressive Strength (UCS) and Shore Scleroscope Hardness index (SSH),

d) Brazilian Tensile Strength (BTS) and Point load Strength index (PLS),

e) Brazilian Tensile Strength (BTS) and Shore Scleroscope Hardness index (SSH).

3. MATERIALS AND METHODS

This study involves 8 lithological units including Sand, soft sedimentary rocks and coal. The samples were selected to analyse various strength properties and develop the correlations between these properties to understand the overall strata behaviour. The experimental work involves various stages such as acquisition of geotechnical samples from Thar coalfield, selection of core samples, specimen (size and surface) preparation as per ISRM standards, marking and sealing of prepared specimen separately, for each type of test. Rock core samples were collected from two geotechnical drillholes, GT-01 and GT-02 from Block-IX, Thar Coalfield, Pakistan. Overall, 45 rock and coal samples were tested in this study following the standard testing procedures suggested by the International Society for Rock Mechanics (ISRM) [28]. The core sample diameters were ranging between 60 to 64 mm.

Figure 2-a shows the selected rock core samples which comprised of twenty samples (two of which were coal samples) from GT-01, and twenty-five samples (one of which was coal) from GT-02. Figure 2-b shows a Claystone sample prepared for UCS testing, before and after the failure under uniaxial compression.

Figure 2-a. Rock core samples selected for this study (drillholes GT-01 and GT-02).

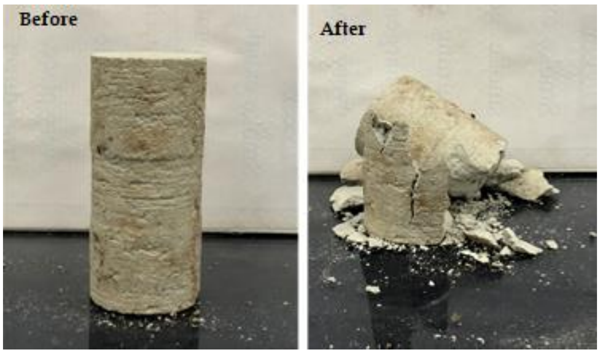


Figure 2-b. A Claystone Rock sample tested prepared and tested for UCS determination.

3.1 The Uniaxial (Unconfined) Compression Strength determination

The UCS tests were performed after the standard specimen preparation of the rock core samples (Fig: 2b) keeping the L/D ratio of 2.5. The diameters of the prepared specimen were measured by taking measurements at the right angles to the top, mid, and bottom of the specimen to an accuracy of 0.1 mm. The average diameter will be used for the determination of UCS using equation 1:

$$\sigma_c = \frac{P}{0.25\pi D^2}, \quad (1)$$

Where, "σ_c" is the Uniaxial compressive strength, "P" is the peak compressive load at which specimen failure initiated, and "D" is the average specimen diameter. The uniaxial compressive and Brazilian tensile strength tests were performed using Computer Control Electro-Hydraulic Servo Universal Testing Machine (Model: WAW-1000C) following the ISRM suggested methods for rock testing [28].

3.2 The Brazilian Tensile Strength (BTS) determination

The Brazilian test is most commonly performed in rock engineering to determine the indirect tensile strength of rocks. The core samples selected for this study were cut into disc shape having thickness to diameter ratio of 0.5. The diameter and thickness of the disc specimen were measured using calliper technique, and the tensile strength was calculated using equation 2:

$$\sigma_t = \frac{2P}{\pi DT} \quad (2)$$

Where, "σ_t" is the Tensile strength, "P" is the maximum compressive load applied on the disc vertically across its diameter and at which the specimen failed, "D" is the average diameter, and "T" is the average thickness of the prepared core sample. Figure 3 shows a prepared disc sample of coal before and after the failure under indirect tension.

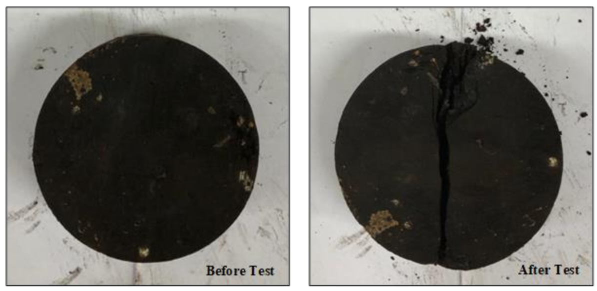


Figure 3. A Coal disc sample for tensile strength, before and after the failure under tension.

3.3 The Point-Load Strength (PLS) Index testing

The point-load strength procedure followed in this study is strictly compliant as suggested by ISRM [21]. The point-load strength index was determined using digital point-load equipment (Tecnotest, S-N:864010). The peak load at failure was recorded for each sample and the point-load strength index was calculated using equation 3.

$$I_s = \frac{P}{D^2} \quad (3)$$

Where, "I_s" is the un-corrected point-load strength index, "P" is the peak failure load at which specimen failed, and "D" is the average diameter of the specimen. Since the standard core diameter for point-load is 50 mm, and the core samples used in this study were greater than 50 mm diameter (i.e. 64 mm). Therefore, the corrected point-load strength was then obtained using Brook's size correction approach [29] as presented in equations 4 and 5.

$$I_{s(50)} = F \times I_s \tag{4}$$

$$F = \left(\frac{D_e}{50}\right)^{0.45} \tag{5}$$

Where, "$I_{s(50)}$" is the corrected point-load index, "F" is the core correction factor, and "D_e" is the equivalent core diameter (i.e. 64 mm for this study).

3.4 The Shore Scleroscope Hardness (SSH) Index determination

The Shore hardness testing was performed using Shore Scleroscope Tester (Type SH-D). The samples were tested with a minimum of 5 mm between indentations to prevent interference between rebound sites [30]. For each sample, 10 indentations were performed and hardness values were recorded. The average SSH value was determined as the mean value of the 10 observations for same rock sample.

One of the commonly applied techniques to acquire estimation equations for rock properties is through regression analysis. The regression analysis used in this study involves both regression techniques, i.e., simple and multiple analyses. MS Excel v. 365 and SPSS v. 26 were used for the regression and statistical analysis.

4. RESULTS, STATISTICAL ANALYSIS AND DISCUSSION

Extensive laboratory testing carried out for this study indicated that there is a significant variation in the strength and hardness values of the soft sedimentary formations. This lithological variation is due to different mineralogy, geological age of Formation, degree of consolidation, and weathering effect. The Subrecent Formation of Thar Coalfield is the thickest formation having different rock types, thus the results vary largely due to inconsistency of rock types. It can be observed that the Recent formation has lowest UCS value due to the presence of Dune sand which is a loosely consolidated stratum. Subrecent formation has higher UCS value due to the presence of fine grained consolidated rocks (i.e. Siltstones and Claystones).

This study revealed that all the rock samples are having low strength and hardness values. Table 2 presents the statistics of rock properties tested in this study. Overall UCS vary between 0.165 – 3.55 MPa with an average value of 1.335 MPa. The tensile strength was ranging between 0.172 – 0.487 MPa having an average value of 0.302 MPa. Point load strength was comparatively lesser ranging between 0.01 – 0.1 MPa at a mean value of 0.05 MPa. Shore hardness numbers range between 3 – 7.4 at an average hardness value of 4.84.

Table 2. Statistical results of the strength and harness properties of soft sedimentary rocks.

Rock Property	*N*	*Min*	*Max*	*Average*	*Standard Deviation*	*Variance*	*Standard Error*
UCS	45	0.165	3.55	1.335	0.804	0.646	0.120
BTS	45	0.172	0.487	0.302	0.082	0.007	0.012
PLS	45	0.01	0.1	0.050	0.0222	0.0005	0.003
SSH	45	3	7.4	4.835	1.118	1.251	0.167

To analyse the rock behaviour individually, total rock samples are categorized into eight lithological units as presented in Table 3. Four specimen of Dune sand of the Recent formation were tested and it was found to have most least values of strength parameters viz. UCS, BTS and PLS. However, the Dune Sand is slightly harder than the Subrecent formation Sandstone. The Subrecent formation includes three rock types, the strongest of these is found to be Siltstone with an average UCS of 1.688 MPa and BTS equal to 0.33 MPa. The coal bearing formation is Bara formation for which three type of rocks and coal samples were tested. Siltstone rock of the Bara formation shown high strength and hardness values (Table 3). The average UCS and BTS of the Coal samples were found to be 1.581 MPa and 0.334 MPa respectively with an average hardness of 4.9.

Table 3. Average values of rock properties for various rock types.

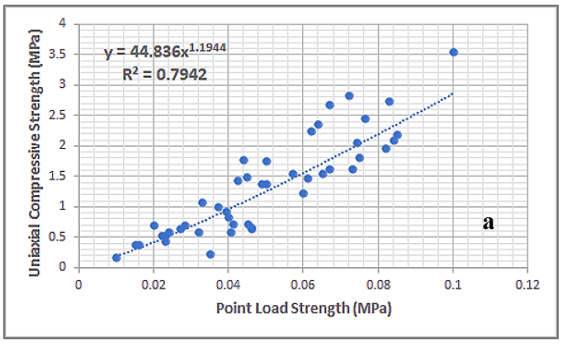
Rock Type	Formation	Number of Samples	UCS (MPa)	BTS (MPa)	PLS (MPa)	SSH (Num)
Dune Sand	Recent	4	0.512	0.221	0.026	3.32
Sandstone	Subrecent	2	0.616	0.244	0.039	3.25
Siltstone	Subrecent	8	1.688	0.333	0.063	5.19
Clayey Siltstone	Subrecent	7	0.571	0.220	0.028	4.34
Claystone	Bara	13	1.422	0.308	0.056	4.90
Siltstone	Bara	4	2.490	0.424	0.072	6.38
Clayey Siltstone	Bara	4	1.526	0.320	0.050	5.25
Coal	Bara	3	1.581	0.334	0.046	4.90

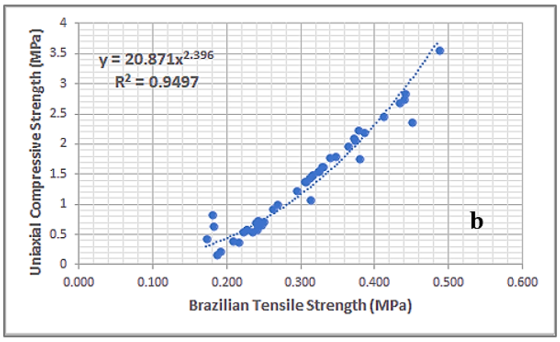
Initially, simple regression analyses were performed using different curve fitting approximations and five correlations were developed i.e., UCS-BTS, UCS-PLS, UCS-SSH, BTS-PLS, and BTS-SSH. The least-squares method was used to perform simple regression analysis. The equations for uniaxial compressive and Brazilian tensile strengths obtained from the regression analyses are summarized in Table 4 along with the descriptive statistics. Figures 4 (a-e) shows the plots for all five correlations. The confidence level of 95% (α=0.05) was used to obtain the empirical equations for uniaxial compressive strength and Brazilian tensile strength. It can be observed that all the simple regression models yield a very significant relationship as indicated by the Pearson correlation coefficient values. Amongst all five simple regression models, the strongest correlation was observed between UCS and BTS (R^2 = 0.9497), whereas the weakest correlation was found between BTS and PLS (R^2 = 0.7126). Student's t and f tests were performed to analyse the significant difference between each of the correlated data sets (Table 4). It was observed that the calculated t and f values are greater than the tabulated critical values. It was also seen that all the p-values which indicates the significance of corresponding t and f values were less than 0.05 value. The developed correlation equations were found to be reliable with t and f tests. Therefore, these equations can be used for analytical purposes reliably.

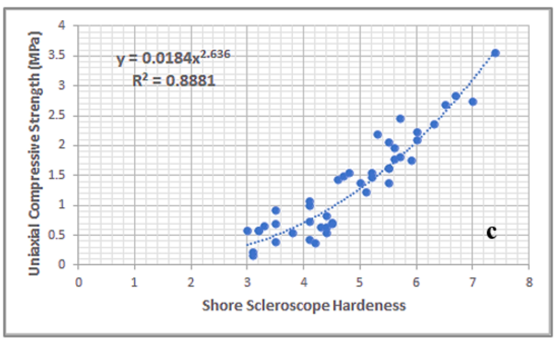
Table 4. Simple regression models for UCS and BTS.

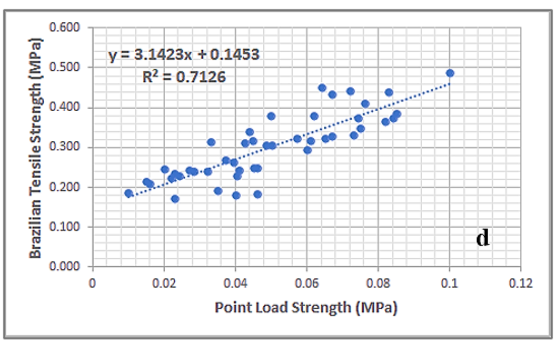
(at a = 0.05, df = N-1, and t-critical = 2.015, f-critical = 1.651).

Eq. #	*Equation*	*Curve*	*R^2*	*R*	*t value*	*f value*	*p value*
Eq. 1	$UCS = 20.871 \times (BTS)^{2.396}$	Power	0.9497	0.9745	28.493	750.82	0.00
Eq. 2	$UCS = 44.836 \times (PLS)^{1.1944}$	Power	0.7942	0.8912	12.882	160.52	0.00
Eq. 3	$UCS = 0.0184 \times (SSH)^{2.636}$	Power	0.8881	0.9424	18.474	267.73	0.00
Eq. 4	$BTS = 3.1423 \times (PLS) + 0.1453$	Linear	0.7126	0.8442	10.326	106.62	0.00
Eq. 5	$BTS = 0.1034e^{0.2143 \times (SSH)}$	Exponential	0.8215	0.9064	14.068	173.44	0.00









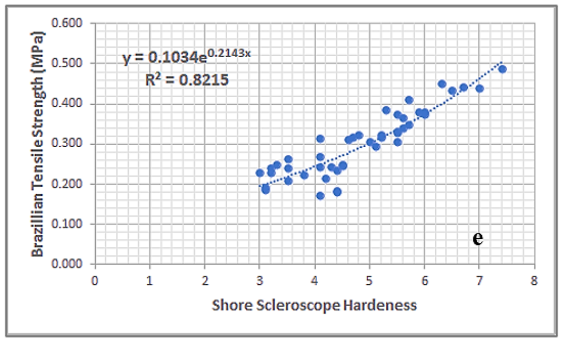


Figure 4 (a–e). Correlations between UCS, BTS and Index properties.

Finally, multiple regression analyses were performed to develop the equations using two and three independent variables for UCS and BTS being dependent variables respectively. The multiple regressions equations acquired for the estimation of UCS and BTS are presented in Table 5. *t* and *f* tests were performed which revealed that the multiple regression correlations are valid. Furthermore, stronger validation was shown by examining the variance inflation factor (VIF) for multicollinearity in multiple regression data sets. It is observed that VIF is less than 10 in all cases except one (Eq. 10). Out of eight multiple regression models, two models with the maximum number of independent variables were analysed by plotting the measured versus predicted values. The scatter plots thus obtained are presented in figure 5 (a-b). It was observed from the cross-correlation of measured and predicted values (fig. 5) that the predictability of these multiple equations is acceptable.

Table 5. Multiple regression models for estimation of rock properties.

Eq. #	Equation	R^2	t min	t critical	F value	Sig F change	VIF max	Durbin-Watson
6	UCS = 6.03BTS+6.82PLS+0.16SSH-1.6	0.971	3.529	2.019	428.512	0.000	5.90	2.435
7	UCS = 7.53BTS+8.78PLS-1.374	0.961	4.190	2.018	494.818	0.000	3.40	2.272
8	UCS = 7.01BTS+0.21SSH-1.77	0.961	4.186	2.018	494.462	0.000	4.84	2.213
9	UCS = 14.36PLS+0.43SSH-1.47	0.901	4.661	2.018	193.316	0.000	3.044	2.091
10	BTS = 0.114UCS-0.383-0.004SSH+0.188	0.947	0.564	2.019	231.232	0.000	10.66	2.281
11	BTS = 0.11UCS-0.382PLS+0.176	0.946	1.292	2.018	352.703	0.000	4.697	2.238
12	BTS = 0.104UCS-0.004SSH+0.181	0.945	0.552	2.018	340.484	0.000	6.912	2.278
13	BTS = 1.25PLS+0.045SSH+0.021	0.831	2.955	2.018	98.001	0.000	3.044	1.938

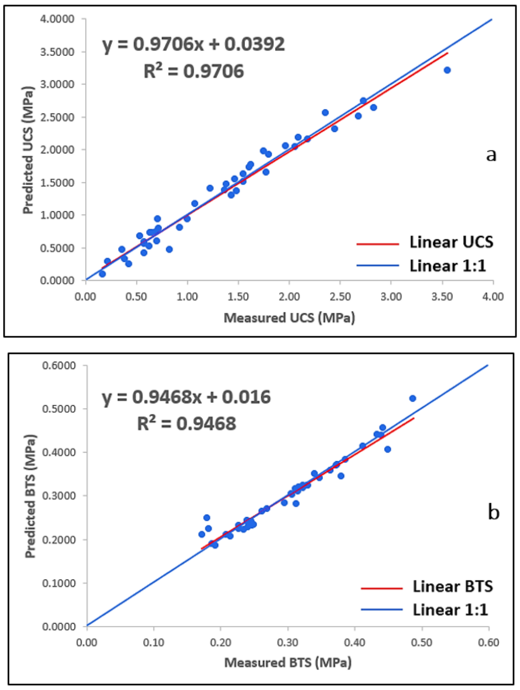


Figure 5 (a-b). Cross-correlation between measured and predicted values for multiple regression models.

All the simple and multiple regression models were analysed and found reliable for a confidence interval of 95%. However, the multiple regression models were found more reliable for the prediction of rock properties. All models are validated through detailed a reliability analysis; therefore, these equations can be used as empirical equations for the estimation of soft sedimentary rock properties.

CONCLUSIONS

The rock strata at Thar Coalfield Pakistan are of sedimentary origin. These rocks are comparatively soft sand have low UCS values. A detailed experimental work and statistical analyses have been carried out in this study for the estimation of rock properties of soft sedimentary rocks of Thar Coalfield. In addition to the commonly correlated rock properties such as UCS, BTS and PLS, this study aimed to focus on rock hardness property (Shore Scleroscope hardness) as well. Both, simple and multiple regression analyses were used to analyse the correlations between the rock properties.

From the simple regression analysis, the weakest relationship was found between the Brazilian tensile strength (BTS) and point load strength (PLS). From the simple regression studies the strongest correlation was seen between uniaxial compressive strength (UCS) and BTS.

The equations acquired from multiple regression models have higher coefficients of determination and analytical validation as compared to the simple regression equations. Simple equations are practically reliable when single independent variable (rock property) is used. However, if more than one rock properties are involved for the estimation purposes, multiple regression equations can be more accurate. Eight multiple regression equations were presented with high correlation coefficients which can be reliable to estimate the rock properties. It was concluded that the equations with three independent variables are more reliable as compared to rest of the multiple regression models.

DECLARATIONS

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Conflicts of interest/Competing interests:

The authors declare no any conflict of interest/ competing interests.

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Code availability: Not applicable.

Authors' contributions: **"Shafi Muhammad Pathan"** Conceptualized the study, developed the regression models using software tools mentioned in the manuscript. **"Zuhaib Ahmed Shaikh"** Performed the extensive laboratory testing (experimental work) for acquiring the rock properties used in this research work. **"Muhammad Burhan Memon"** assisted in writing the initial draft for the manuscript. **"Saleem Raza Chalgri"** reviewed and edited the final manuscript as per this journal template.

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