Estimation of Rock Strength Properties Using Selected Mechanical Parameters Obtained During the Rotary Drilling

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Abstract During the preliminary stage of rock engineering projects, the estimation of mechanical properties of rocks is most often required. The requirement of a large number of high-quality rock core samples is the major drawback when the mechanical rock properties are to be determined in a well-established rock mechanics laboratory. In this study, an attempt is made to estimate the uniaxial compressive strength and Brazilian tensile strength of sedimentary rocks using the selected mechanical drilling operating parameters obtained during the rotary drilling. The operating measured parameters such as the weight on bit or thrust and the vibration frequency induced at machine or drill head were acquired using the drill tool dynamometer and sound/vibration data acquisition system, respectively. The mathematical models were developed considering the drilling operational parameters (drill bit diameter, drill bit speed and penetration rate) and measured mechanical parameters (thrust and vibration frequency). The prediction potential of the developed models was assessed by the prediction performance indices. The outcome results revealed that the developed mathematical model using the approached method is significant and can be conveniently used for the estimation of mechanical properties of rocks during the rotary drilling.

Introduction

The rock characterization is the most important while carrying out engineering activities such as the civil constructions, excavation, quarrying operations, tunnelling, blast hole design. The fundamental mechanical properties of rocks such as uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) are often used as an important data while carrying out the rock engineering projects [1].The measurement of mechanical properties of rocks in the laboratory is trustworthy, but the major problem is that it requires high-quality, a large number of rock specimens with proper shape and size, highly finished with required accuracy [2]. The process of preparing the specimen for the laboratory test is expensive and time-consuming. Especially, in the case of sedimentary rocks, it is very difficult to obtain a sufficient amount of high-quality drilled cores from weak, highly fractured, weathered and thin layers of rock matrix [3]. Due to this reason, many times, the sedimentary rocks cannot be tested in detail and rock properties are determined at least from the available small group of better quality rock samples, and the whole rock mass is characterized based on the results obtained using that small group of samples. This sampling method may not produce reliable results especially when the rock properties are affected by the change of moisture content. Therefore, to eliminate this problem, the engineers and

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geologists have found an alternative way of measurement of rock properties indirectly by using the predictive empirical models [4].

Review of Pertinent Literature

Recently, many researchers attempted to estimate the rock properties during the rotary drilling and the results obtained have acceptable errors. During the rock drilling process, the drilling operational parameters and equivalent penetration rate, thrust, torque and sound level parameters have been used in many investigations to estimate the rock properties. Basarir and Karpuz [5] investigated the correlation of drilling operational parameters such as thrust, speed and penetration rate of the diamond drill bit with uniaxial compressive strength of rocks. The data were collected from different six exploration drilling activities. The obtained results revealed that the penetration rate is the most significant parameter with the coefficient of determination of 59.5%. Similarly, the thrust has also a strong effect on rock mass strength with the coefficient of determination of 24.8%. Kalantari et al. [6] developed a theoretical model to estimate the rock strength using the cohesion and internal friction angle of the rock. As a part of calculating these two parameters, the drilling parameters such as indentation rate, thrust on bit and torque developed were also used. It was observed that the recorded thrust force and torque were significantly changed when the different indentation rates and rotation speed were used in the machine during drilling. The results revealed that the proposed model developed using these data was able to correlate well with UCS. During the rock bolting operation in underground mine, Finfinger et al. [7] investigated the properties of overlaying rock bed. It was observed that as the drill bit moves to different layers having different strength, the significant variation of thrust and torque was found in the automated rock bolting monitoring system. A technique called "Seismic while drilling" was used in a couple of studies aimed at estimating the rock formations in oil and gas industries. The generation of noise due to interface of bit and rock was used as an acoustic source for surveying the area around a well and also for formation characterization while drilling [8–10]. During the drilling process carrying out around the oil well, the analysis of acoustic waves generated at the bottom hole assembly of drill unit could be used for estimation of surrounding formation properties of oil well [11]. Vardhan et al. [12] reported that sound level produced due to the interaction of bit and rock was increased as the thrust on a bit, air pressure and UCS of rock increases during the percussive drilling. The prediction of UCS, BTS and degree of porosity of the sedimentary rocks during the rotary drilling was investigated by Kumar et al. [13]. From the

experimental results, it was cleared that the sound level originated from the bit-rock interaction was increased as the UCS of rocks increases and the sound level was significantly reduced as the porosity of rocks increases. Yari and Bagherpour [14, 15] have attempted to an approximation of mechanical properties of some igneous and sedimentary rocks during the rotary drilling. For different rocks, the sound level signal was captured for a particular time using the sound data acquisition system (DAQ) system. Using the fast Fourier transformation (FFT), the frequency component was extracted from the time domain acoustic signals. Further, the five different dominant frequencies were selected from the signal and regressed against the UCS and BTS of rocks. The results revealed that the fourth dominant frequency was well correlated with both mechanical properties with a high coefficient of determination values. The identification of rocks based on the analysis of the acoustic signal parameter was studied by Zborovjan et al. [16]. It was reported that the frequency component of an acoustic signal could be a potential source for identification of rocks. Rostami et al. [17] attempted to identify the voids in rocks using the vibration signal captured during the drilling at drill head. It was reported that whenever the drill bit moves to a porous region of rocks, there would be a sudden decrease in the amplitude of vibration. The prediction of some physico-mechanical properties of sedimentary rocks during rotary drilling was carried out by Lakshminarayana et al. [18]. The prediction model was developed considering the drilling operational parameters and the dominant frequency of vibration produced at the spindle head of the machine. The assessment of the prediction capability of the model revealed that the used approach can estimate the physico-mechanical properties of rocks such as UCS, BTS and density with less error.

From the above discussion, it was confirmed that there will be a considerable change in operating measured parameters and acoustic or vibration parameters during the drilling process of different rocks. Therefore, the drilling operating parameters and acoustic or vibration parameters could be potential variables to develop the empirical prediction models of rock properties in both laboratory as well as in situ conditions. However, from the literature survey, it was found that the insufficient number of work is done using both operating and acoustic/vibration parameters together to predict the rock properties during the drilling process.

The main objective of this study is to assess the possibility of predicting the vital mechanical rock properties with insignificant errors during the rotary drilling process. In the current study, a laboratory setup was used to investigate the relationship of mechanical properties of sedimentary rocks with some important drilling parameters

acquired during rotary drilling process using the statistical approach.

Experimental Studies

The laboratory experimental setup as shown in Fig. 1 is comprised of a heavy-duty computerized numerical control (CNC) vertical machining center, a drill tool dynamometer, data acquisition system (DAQ) and rock samples. The rock drilling was carried out using a CNC vertical machining center. During drilling, a drill tool dynamometer was used for measurement of thrust acting and torque developed at bit-rock interface. The vibration frequency induced at the machine head during drilling was measured using a sound/vibration DAQ system. The rock drilling process was accomplished by using the 12- and 16-mm-diamond-core drill bits having the uniform shank length. The advantage of using the CNC machine for drilling process is that the number of required values for drilling operational parameters such as penetration rate, speed can be assigned in the numerical control programming itself. The experiment was conducted using the sedimentary rock samples such as shale, pink sandstone, red sandstone, banded sandstone and limestone. The collected rock samples were converted into specimens by cutting off them to a size 15 cm × 15 cm × 15 cm. The rigorous inspection was carried out for macroscopic defects such as fractures and joints during the collection of samples. Before testing the specimen for UCS and BTS, the specimen was completely dried using an electric oven. The purpose of drying the core sample in an electric oven is that if the different percentage of moisture content core samples are used for testing in the laboratory, there will be a considerable variation in rock strength properties and it may lead to poor correlation values. Therefore, as per the ISRM standards, it is strongly recommended to dry the core samples as well as cubic rock samples completely before their testing is to be carried out in laboratory. However, to relate the dry sample strength to natural moisture content sample of sedimentary rocks, Hawkins and McConnell [19] method can be used. Typically, UCS decreases with increasing moisture content, but the % decrease varies with the type of rock. The relationship between the UCS of dry sample and UCS of moisture content sample can be described by an exponential Eq. (1)

$$\sigma_{c(w)} = a e^{-bw} + c \tag{1}$$

where $\sigma_{c(w)}$ = UCS at different moisture content, w = water content (%) and a, b and c are the experimental constant values.

A drill tool dynamometer is a device used for measurement of thrust force acting and torque developed between bit and rock during the rock drilling process. In the current experiment, a digital type drill tool dynamometer was used. The dynamometer with the measuring range of thrust was 0 ± 5000 N with a sensitivity of 1 N, and similarly, the torque that could be measured was 0 ± 50 N-m with a sensitivity of 1 N-m. Basically, the dynamometer consists of a cylinder fitted with approximately 10 mm steel plates at both ends and plates are provided with the circular cuts for fasteners. The bottom plate is rigidly fixed to t-slots of machine table using the T-bolt and nut. Similarly, the machine vice is fixed directly to the top plate of dynamometer using the suitable bolt and
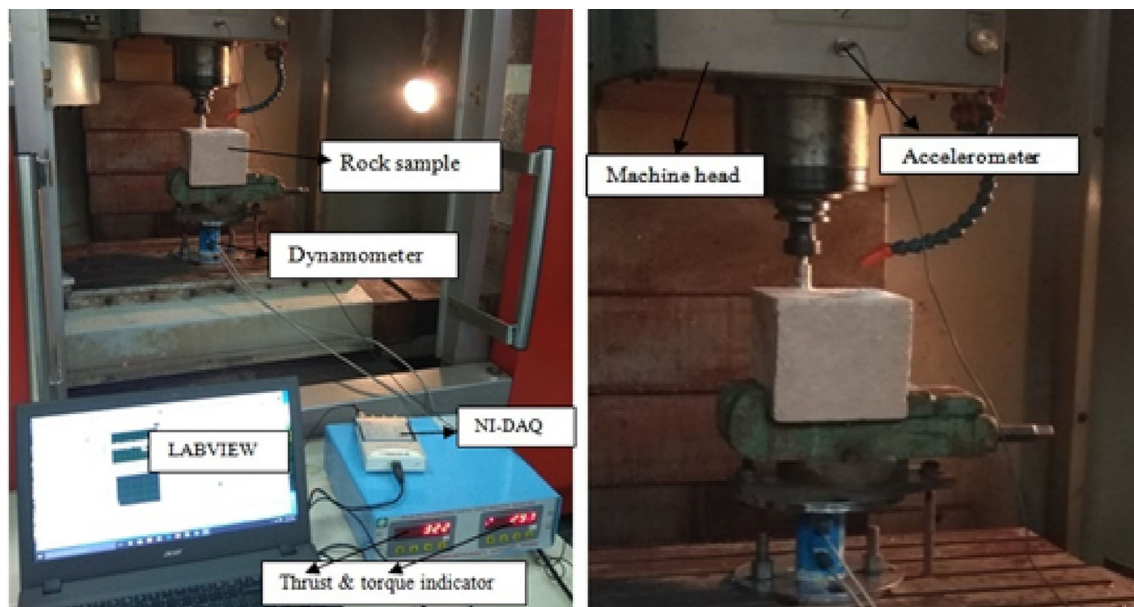

Fig. 1 Experimental setup

nuts. The analog signal generated in the dynamometer-hardware part is connected to the digital signal converter, and thus the value of thrust and torque is obtained through the digital displays.

The sound/vibration data acquisition system (DAQ) was used for capturing the vibration signal at the CNC machine head. The DAQ system comprised of NI-9234 model hardware (signal conditioning device), an integrated electronic piezoelectric (IEPE) accelerometer and compatible LabVIEW application software. A magnetic mount was used to install the IEPE accelerometers on the machine head. The line diagram of the experimental setup is shown in Fig. 2. Initially, the vibration sensor such as an IEPE accelerometer is installed on the machine head using the suitable magnetic mount. The analog signal coming out from the sensor is connected to DAQ hardware using a single-ended BNC connector. The function of the DAQ hardware is to convert the analog signal into a digital signal. In the next stage, the digital signal is processed with

the help of LabVIEW application software installed in a laptop and representing the vibration data in both time and frequency domain as shown in Figs. 3 and 4, respectively.

When a body is set to vibrate, in a designated frequency spectrum, the vibration energy would be more at a particular frequency and that frequency is called a dominant frequency. The example of dominant frequency (maximum frequency) at which the machine head ($Z = 327$ and 330 Hz) was vibrating for two different combinations of drilling operating parameters during the drilling of shale is shown in Fig. 4. The frequency domain data were derived from the vibration signal with the use of fast Fourier transformation (FFT) graphical program in LabVIEW application software. In a frequency spectrum, the corresponding reading of vibration frequency for the maximum amplitude of vibration is taken into account. For example, in Fig. 4a, the maximum vibration frequency is approximately close to the value of 327 Hz with the maximum amplitude of 0.28 g. Similarly, in Fig. 4b, the maximum

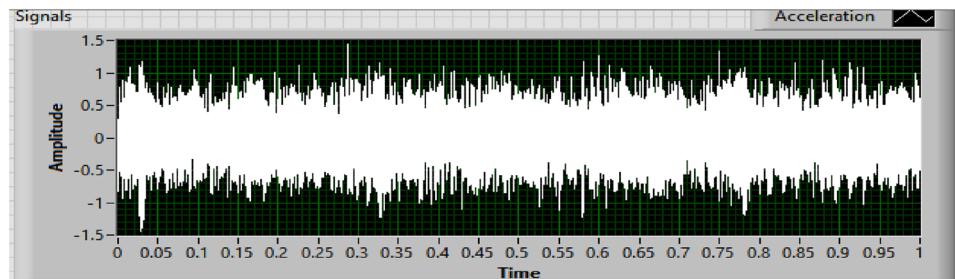**Fig. 2** Schematic diagram of the experimental setup
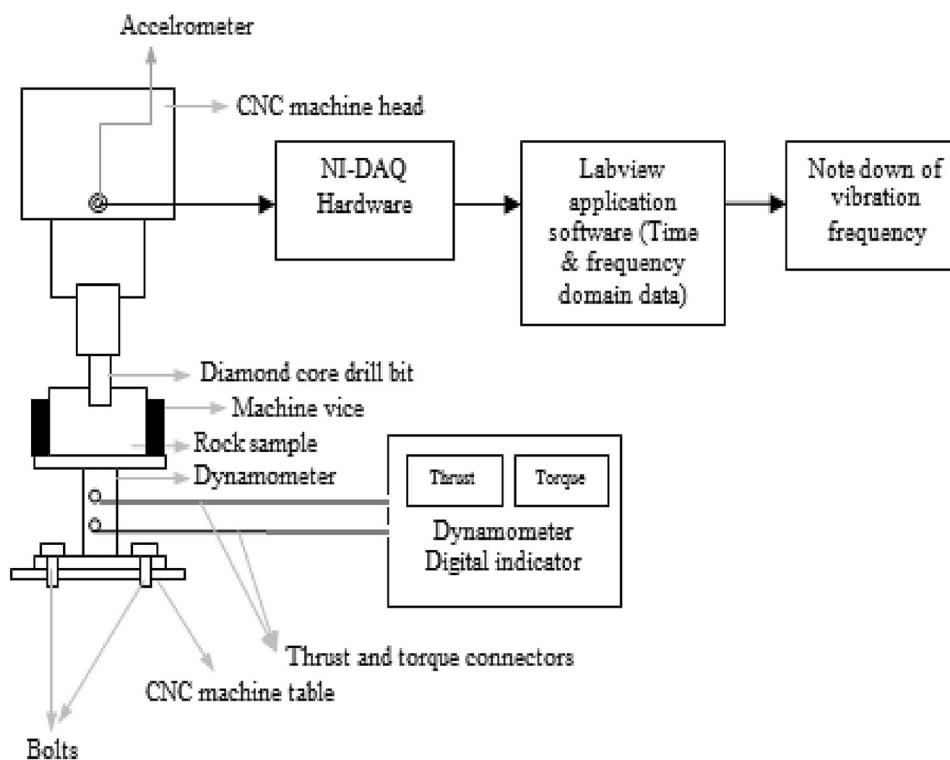
Specifications of DAQ hardware:
Channels—4 Numbers
Analog to digital converter resolution—24 bits
Sampling—1.562 to 51.3 K samples/s
Frequency—12.1072 MHz
Specification of vibration sensor (accelerometer):
Model: APC121B19 IEPE
Sensitivity: 9.81 Mv/g
Measuring range: ± 500g

Fig. 3 Time domain vibration signal

Fig. 4 Frequency domain vibration data
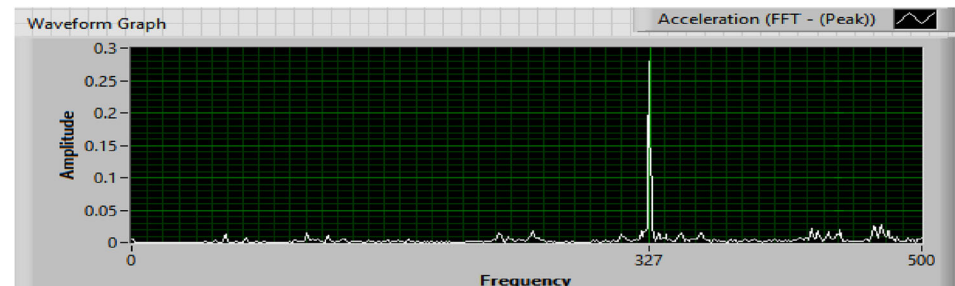
(a) Vibration frequency Z ~ 327 Hz
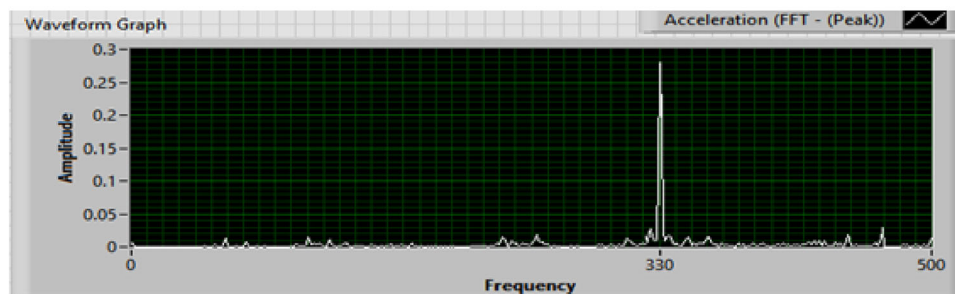
(b) Vibration frequency Z=330 Hz

vibration frequency of 330 Hz is taken for the corresponding maximum amplitude of vibration during the drilling of shale rock.

Methodology

The variation of thrust acting between bit-rock interface and the variation of vibration frequency induced at machine head during the use of various combinations of machine operating parameters for rock drilling process was recorded by the sophisticated measuring system. The rock specimen having the cube shape of size 15 cm × 15 cm × 15 cm was rigidly fixed in the CNC machine vice. The operational parameter such as penetration rate, bit speed and bit diameter was used for drilling each type of rock specimen. A total of 32 holes having a constant depth of 50 mm were drilled using the 32 (= 2 bit dia of size 12 and 16 mm × 4 bit speed of 400, 500, 600 and 700 r.p.m × 4 penetration rate of 2, 3, 4 and 5 mm/min) combinations of machine operational parameters. During the drilling for a particular machine operational parameter,

it was observed that the amount of thrust and torque acting and developed between the drill bit and rock was varied when the drill bit was continuously moving through a hole having the depth of 50 mm. During the drilling process under particular operating parameters, as the drill bit is moving to 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 mm depth, the corresponding reading of ten thrust values was taken down at identified depths using the thrust digital indicators of the dynamometer. The same procedure was continued for all the combinations of drilling operational parameters. Later, for development of mathematical models, the arithmetic average of ten thrust values selected from each drilling operating conditions was used. In parallel, the vibration signal of 1 s but having five iterations emanated from the machine head was also captured at the same identified depths for each drilling operating parameters and instantly its equivalent vibration frequency was noted down using the frequency domain data in LabVIEW application software. But the vibration frequency noted down for ten times during a particular operating condition was found almost consistent.

The direct measurement of uniaxial compressive strength and indirect tensile strength (Brazilian) was done in a rock mechanics laboratory. The UCS of different sedimentary rocks used for drilling purpose was measured using a hydraulic controlled compression testing machine having a uniform load rate capacity of 2000 KN/s. The procedure for the determination of UCS of standard-sized rock specimen was carried out using the guidelines suggested by the International Society for Rock Mechanics (ISRM). The tensile strength machine with 100 KN loading frame capacity was used to determine the Brazilian tensile strength. A standard size rock specimen was prepared and tested as per the ISRM standard procedure. At least three specimens were used for each testing of UCS and BTS of rocks. Later, the arithmetic mean of all three rock specimen was considered for statistical analysis purpose.

Data Analysis Approaches

During the drilling process, the variations of measured operating parameters are influenced by so many subcomponents in a complex manner. Therefore, the entire drilling process is clearly expressed by second-order multiple regression models. In this laboratory experimental investigation, 192 data (6 rock types × 32 machine operating conditions) of each measured parameters such as thrust and vibration frequency were obtained using the sophisticated measurement system during the rotary drilling process. Both measured parameters and machine operational parameters were used to develop the mathematical prediction models. Minitab 17 statistical application software was used to analyze the data and development of mathematical models. The quantitative studies of the influence of each parameter on responses (UCS and BTS) have gone through the analysis of variance (ANOVA) method. The considered drilling operational parameters are drill bit diameter (d) in mm, drill bit speed (s) in r.p.m and penetration rate (pr) in mm/min. Similarly, the measured parameters which are varying due to the drilling process are thrust (t) in Newton and vibration frequency (z) in Hertz. The variation of measured parameters during the drilling process (thrust and vibration frequency) is the function of machine operating parameters and strength properties of rocks. The mathematical model developed for constituting the interconnection between mechanical properties of rocks and considered variables can be written as $y = f(x_1, x_2, x_3, x_4, x_5) + \psi$, where y is the dependent variable such as UCS and BTS of rocks and x_1, x_2, x_3, x_4, x_5 are the drilling operational parameters and measured parameters, and ψ is fitting error. The general second-order regression model could be written as

$$f = a_o + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ij} x_i^2 + \sum_{i<j}^{n} a_{ij} x_i x_j + \psi \tag{2}$$

In Eq. (2), a_i characterizes the linear effect of x_i, a_{ij} in the second term represents the quadratic effect of x_i, and a_{ij} in the third term symbolizes the interaction effect of x_i and x_j. The backward elimination approach was used while developing multiple regression models. The significance of each variable was examined using the t test method. In this method, if the computed t value of considered variables was greater than the tabulated t values (which were selected for the corresponding degree of freedom at 95% confidence level), then only the variables were selected. Similarly, if the computed t value of any variable was less than the tabulated t value, that particular variable was not considered for further more analysis and regression simulation was continued using the reaming variables until the considered independent variables could not be removed from the model. At last, the matching formed regression model was preferred as a prediction model for a particular response.

Result and Discussions

The maximum and minimum values of measured operating parameters which are found in the data set of each rock sample are given in Table 1.

The best mathematical model is developed for prediction of uniaxial compressive strength and is given by the equation

$$\begin{aligned} UCS = {}& 188.3 - 29.79 \times pr - 1.535 \times s - 8.87 \\ & \times d + 0.4177 \times t + 1.167 \times z - 3.176 \\ & \times pr^2 + 0.000328 \times s^2 \\ & + 0.2341 \times pr \times s + 1.210 \times pr \times d - 0.02456 \\ & \times pr \times t - 0.2191 \times pr \times z \end{aligned} \tag{3}$$

Equation (3) expresses the best mathematical model established for prediction of UCS. From Table 2, it was seen that the developed model describes 96.34% of the entire variation in the observed UCS. The importance of regression coefficients is depicted in Table 3. The value of p for each term is statistically significant at $p < 0.05$ with 95% confidence level. Furthermore, the determined $\pm t$ values are also significantly greater than the tabulated t values (for 95% confidence level and 9 degrees of freedom, for $k = n - 1$, $t = 1.812$). From the ANOVA as shown in Table 4, it was observed that the variation of thrust is significantly influencing to define the UCS of rocks. The overall significance or validity of the model is checked using the F-test method. The computed F value shows a very high

Table 1 UCS and BTS values of rocks and a range of measured parameters values

Rock sample	UCS (MPa)	BTS (MPa)	Thrust (N)		Vibration frequency (Hz)	
			Min	Max	Min	Max
Shale	19.6	1.6	315	596	327	626
Pink sandstone	37.5	3.4	352	667	330	629
Red sandstone	65.0	4.2	401	761	337	642
Banded sandstone	72.4	7.5	421	799	340	656
Limestone-1	119	8.1	509	966	342	667
Limestone-2	142.6	10.2	541	1026	345	669

Table 2 Model summary for UCS

R^2	Adjusted R^2	Predicted R^2	Standard error
96.34	96.12	95.87	8.49

Table 3 Regression coefficients and their significance (UCS)

Predictors	Regression coefficients	T value	p value
Constant	188.3	5.53	0.000
pr	− 29.79	− 3.74	0.000
s	− 1.535	− 7.28	0.000
d	− 8.87	− 8.43	0.000
t	0.4177	15.43	0.000
z	1.167	5.20	0.000
pr^2	− 3.176	− 4.05	0.000
s^2	− 0.000328	3.09	0.002
pr × s	0.2341	3.98	0.000
pr × d	1.210	4.28	0.000
pr × t	− 0.02456	− 3.88	0.000
pr × z	− 0.2191	− 3.73	0.000

significance and hence confirms the adequacy of the models. Figure 5 implies the comparison of the UCS of rocks measured in the laboratory and the UCS predicted using the mathematical model. The predicted and measured values are found that they are very nearly accurate. Therefore, it was concluded that the developed models are highly efficient.

Similarly, the mathematical model is developed for prediction of Brazilian tensile strength and is given by the following equation

$$
\begin{aligned}
BTS =\ & 8.55 - 1.923 \times pr - 0.1972 \times s - 0.543 \times d \\
& + 0.02089 \times t + 0.2299 \times z + 0.000072 \times s^2 \\
& - 0.000115 \times z^2 + 0.001187 \times pr \times s + 0.0771 \\
& \times pr \times d - 0.001932 \times pr \times t
\end{aligned}
\tag{4}
$$

Eq. (5) is developed for the prediction of BTS with less error. The model summary as shown in Table 5 explained that 90.68% of the total variation in the observed BTS. The significance of regression coefficients of BTS is illustrated in Table 6. The computed absolute t values of each term presented in the model are sufficiently much higher than the tabulated t values (for 95% confidence level and 10 degrees of freedom, for $k = n - 1$, $t = 1.833$). Therefore, all the parameters are significantly influencing the BTS. The influence of each term over the BTS is explained in ANOVA as shown in Table 7. From the result of the adjusted sum of the square values (Adj SS) and F value, it was concluded that the variation of thrust is the most influencing factor for defining the response. Figure 6 indicates the comparison of the BTS of rocks measured in the laboratory and the BTS predicted using the prediction model.

Evaluation of Prediction Performance of the Developed Models

The efficiency of any developed system needs to be checked before implementing them to a real application. Therefore, the efficiency or effectiveness of the developed models is investigated using the three basic indices, i.e., variance account for (VAF), root-mean-square error (RMSE) and mean absolute percentage error (MAPE).

$$
VAF = \left[1 - \frac{var(m - p)}{var(m)} \right] \times 100
\tag{5}
$$

Table 4 ANOVA (UCS)

Source of variations	df	Adj SS	F value	p value
Regression	11	341,623	430.27	0.000
pr	1	1007	13.95	0.000
s	1	3829	53.05	0.000
d	1	5126	71.01	0.000
t	1	17,191	238.17	0.000
z	1	1953	27.06	0.000
pr^2	1	1181	16.36	0.000
s^2	1	690	9.56	0.002
pr × s	1	1142	15.82	0.000
pr × d	1	1323	18.32	0.000
pr × t	1	1086	15.05	0.000
pr × z	1	1005	13.92	0.000
Error	180	12,992	–	–
Total	191	354,615	–	–
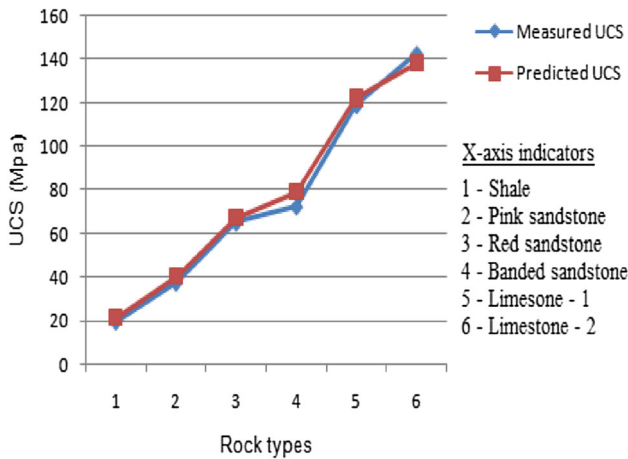
Fig. 5 Comparison of measured and predicted UCS

Table 5 Model summary for BTS

R^2	Adjusted R^2	Predicted R^2	Standard error
90.60	90.08	89.49	0.93

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(m-p)^2} \qquad (6)$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{(m-p)}{m}\right| \times 100 \qquad (7)$$

In Eqs. (5)–(7), the notations 'm' and 'p' are used for identifying the values of response measured in the laboratory and the response measured using the

Table 6 Regression coefficients and their significance (BTS)

Predictors	Regression coefficients	T value	p value
Constant	8.55	2.69	0.000
pr	− 1.923	− 3.37	0.001
s	− 0.1972	− 5.58	0.000
d	− 0.543	− 4.67	0.000
t	0.02089	7.43	0.000
z	0.2299	5.79	0.000
s^2	0.000072	2.79	0.006
z^2	− 0.000115	− 3.88	0.000
pr × s	0.001187	2.15	0.033
pr × d	0.0771	2.47	0.014
pr × t	− 0.001932	− 3.84	0.000

Table 7 ANOVA (BTS)

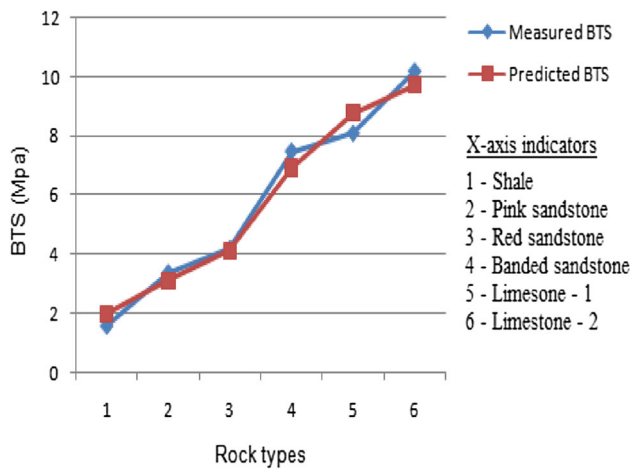| Source of variations	df	Adj SS	F value	p value
Regression	10	1539.93	174.38	0.000
pr	1	10.05	11.38	0.001
s	1	27.49	31.13	0.000
d	1	19.28	21.83	0.000
t	1	48.70	55.15	0.000
z	1	29.63	33.56	0.000
s^2	1	6.89	7.81	0.006
z^2	1	13.29	15.05	0.000
pr × s	1	4.07	4.61	0.033
pr × d	1	5.40	6.11	0.014
pr × t	1	13.01	14.74	0.000
Error	181	159.84	–	–
Total	191	1699.77	–	–

Fig. 6 Comparison of measured and predicted BTS

Table 8 Performance indices of the developed mathematical models

Response	Performance indices		
	VAF (%)	RMSE (response units)	MAPE (%)
UCS (Mpa)	96.30	8.49	11.38
BTS (Mpa)	90.68	0.91	15.30

predictive model, respectively. Similarly, the *N* symbolizes the total number of data used. If the computed VAF and RMSE values are 100 and 0, respectively, the model will exactly forecast the response with zero errors. The MAPE denotes the absolute percentage error or accuracy of the model. The calculated values of VAF, RMSE, and MAPE for the developed models are framed in Table 8.

Conclusions

In this study, the drilling operational parameters along with the parameters which were obtained during the drilling process such as thrust acting between the interaction of bit-rock and vibration frequency caused at drill head, while the process of rotary drilling was utilized to estimate the UCS and BTS of sedimentary rocks. The thrust and vibration frequency were measured for all the combinations of drilling operational parameters, and the same was used for developing the prediction models.

- During the rock drilling process, it was noted that the thrust acting between the interactions of bit-rock was considerably increased as the UCS and BTS of rocks increases.

- The change of vibration frequency induced at drill head was found moderately low as the UCS and BTS of rocks increased during the drilling process.
- At high spindle speeds, the thrust acting on the drill bit was significantly reduced.
- The assessment of the effectiveness of the developed mathematical model confirms that they are well capable of estimating the mechanical properties of sedimentary rocks with insignificant errors.
- Therefore, it was concluded that without core samples, the approached method can be conveniently used for preparatory assessment of UCS and BTS in the laboratory which is frequently used as a vital data for the design of many rock engineering projects.
- In addition, this method has more advantages over the regular laboratory method as the prime mechanical properties of rock can be estimated with a single experiment.

Suggestion for Future Work

In this study, the use of one more variable, i.e., torque in addition to existing variables to develop the UCS and BTS prediction models is not discussed. The addition of torque can be a useful variable to estimate the mechanical properties of rocks still with less error. In addition, the same approach can be extended to other rocks such as igneous and metamorphic rocks to test the reliability of experimental results.

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