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ORIGINAL PAPER

Prediction of Uniaxial Compressive Strength, Tensile Strength and Porosity of Sedimentary Rocks Using Sound Level Produced During Rotary Drilling

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Abstract The main purpose of the study is to develop a general prediction model and to investigate the relationships between sound level produced during drilling and physical properties such as uniaxial compressive strength, tensile strength and percentage porosity of sedimentary rocks. The results were evaluated using the multiple regression analysis taking into account the interaction effects of various predictor variables. Predictor variables selected for the multiple regression model are drill bit diameter, drill bit speed, penetration rate and equivalent sound level produced during rotary drilling (L_{eq}). The constructed models were checked using various prediction performance indices. Consequently, it is possible to say that the constructed models can be used for practical purposes.

Keywords UCS · Tensile strength · Porosity · Sound level · Sedimentary rock · Regression analysis

1 Introduction

Sedimentary rocks are derived either from pre-existing rocks through mechanical or chemical breakdown, or are composed of accumulations of organic debris. These rocks show a variety of engineering properties that may affect the quarrying operations, tunneling, mining and slope stability. Consequently, the expertise from geologists, civil, mining and petroleum engineers is required to design it effectively. Such designs often rely on laboratory tests on rock specimens prepared from samples gathered from the field. The usual tests performed include uniaxial compressive strength, Brazilian tensile strength, porosity and many tests. When dealing with laboratory tests, one will inevitably look for standard testing procedures. These testing procedures require high quality core specimens of proper geometry for the direct determination of these parameters. However, it is not always possible to obtain suitable specimens from highly fractured and/or weathered rocks especially in sedimentary rocks for this purpose. For this reason, most of the time, sedimentary rocks are not tested in detail and rock properties found from small groups of samples, which are usually the stronger and more easily prepared ones, are assumed to characterize a large rock mass. In a similar manner, testing of samples collected by incompetent sampling methods also gives unreliable results especially when any change in the moisture content might affect the rock properties. To overcome this difficulty, as an alternative, engineers use empirical and theoretical correlations among the various physico–mechanical properties of rocks to estimate the required engineering properties of rocks (Zhang 2005).

The process of drilling in general always produces sound as a by-product. The drilling process and its results are affected by various parameters of the rock material and the rock mass. Drilling has a direct and close relation with the rock mass, and thus would be affected by the geo–mechanical characteristics of the rock material, as well as the rock mass. Reviewing the studies, the most important rock mass parameters that affect the drilling are the UCS (point load index and Schmidt hammer) (Jimeno et al.

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1995; Ersoy and Waller 1995; Serradj 1996; Thuro 1997; Osanloo 1998; Rao and Misra 1998; Kahraman et al. 2000; Drake 2004; Singh et al. 1998), porosity (Thuro 1997; Osanloo 1998; Rao and Misra 1998) and tensile strength (Rao and Misra 1998; Kahraman et al. 2000). Lama and Vutukuri (1978) and Carmichael (1982) tabulated extensive lists of various mechanical properties of sedimentary rocks from different locations around the world. Kwasniewski (1989) listed UCS and porosity data of various sandstones. Jizba (1991) presented mechanical properties of sandstones and shales with a wide range of porosity recovered from different depths in a borehole in Texas, USA. Wong et al. (1997) presented a table of strength and other physical properties of several representative porous sandstones. Bradford et al. (1998) and Horsrud (2001) reported laboratory test results on the North Sea sandstone and shale, respectively. The acoustic identification of rocks during drilling process was studied by Zborovjan et al. (2003) and Miklusova et al. (2006). It was found that the processed acoustic signal obtained during rotary drilling using the Fourier transform could be used for control of the rock disintegration process. Many researchers have indirectly defined various rock properties using different approaches (Kahraman 2001; Grima and Babuska 1999; Singh and Singh 1993; Palchik 1999; Tugrul and Zarif 1999; Katz et al. 2000; Cargill and Shakoor 1990; Kahraman 1999). An attempt was made by Vardhan et al. (2009) to investigate the usefulness of sound level in determining rock or rock mass properties, such as compressive strength, using the jackhammer drill on laboratory scale, by fabricating a jackhammer drill setup, wherein, the thrust applied can be varied while drilling the vertical holes. It was suggested that there is a scope for further work in this area. Rajesh et al. (2010) also made an attempt to determine the rock properties through the filed investigation and the results were quite encouraging.

Based on the above discussion, it appears that the rock properties can be determined in the laboratory by various methods which are accurate enough. However, the authors have found very limited work in the literature regarding the estimation of rock properties based on sound levels produced during drilling.

The aim of this paper is to show the possibility of determining the relationship between the physical properties of sedimentary rock and sound level produced during rotary drilling using statistical methods.

2 Laboratory Investigations

The aim of this investigation was to find out the relationship of rock properties with sound level produced during drilling. To achieve this research goal, different sedimentary rocks were collected from the different locations of India taking care of representation of variety of strength. During the sample collection, each block was inspected for macroscopic defects so that it would provide test specimens free from fractures and joints.

2.1 Equipment/Instrumentations

2.1.1 Drilling Machine

In the laboratory, rock drilling operations were performed on BMV 45 T20, computer numerical controlled (CNC) vertical machining centre (Fig. 1). The experimental set-up was in a fibre and glass paned room of 5 m width, 6 m length and 9 m height. The important specifications of the CNC machine used were:

- Table size 450 mm × 900 mm
- Recommended optimum air pressure—6 bar
- Power supply—415V, 3 phase, 50Hz.

Carbide drill bits of shank length 40 mm and diameters of 6, 10, 16 and 20 mm were used for drilling operation. Machine was set to drill 30-mm drillhole length. Since the drilling method affects the sound produced, an attempt was made to standardize the testing procedure. Throughout the drilling process a relatively constant rotation speed (RPM), and a penetration rate (mm/min) were maintained in order to obtain the consistent data.

2.1.2 Sound Level Meter

The instrument used for sound measurement was a Spark 706 from Larson Davis, Inc., USA. The instrument was

Fig. 1 BMV 45 T20, CNC vertical machining center

equipped with a detachable 10.6 mm microphone and 7.6 cm cylindrical mast type preamplifier. The microphone and preamplifier assembly were connected by an integrated 1.0 m cable. A Larson Davis CAL 200 precision acoustic calibrator was used for calibrating the sound level meter. Before taking any measurement, the acoustical sensitivity of the sound level meter was checked using the calibrator.

2.1.3 *Uniaxial Compressive Strength*

Compressive strength is one of the most important mechanical properties of rock material used in excavation projects. AIM–317E–Mu micro-controlled compression testing machine was used for measurement of universal compressive strength. It has an intelligent pace rate controller, motorized pumping unit and loading unit with maximum loading capacity of 2,000 kN.

2.1.4 *Tensile Strength*

Rock material generally has a low tensile strength. The low tensile strength is due to the existence of micro cracks in the rock. The existence of micro cracks may also be the cause of rock failing suddenly in tension with a small strain. Tensile strength of rock was obtained from Brazilian test loading frame with 100 kN capacity, having a base and a cross head joined together with the two solid pillars with nuts. At the top, the pillars have long threads for height adjustment and on the base, a 100 kN hydraulic jack is centrally fixed between the pillars. This jack has an integral pumping unit and oil reservoir. A 100 kN capacity pressure gauge is fixed to the jack for indicating the load on the specimen and also an operating handle is provided with the jack.

2.2 Methodology

2.2.1 *Determination of Rock Compressive Strength*

To determine the UCS of the rock samples, 54-mm diameter NX-size core specimens, having a length-to-diameter ratio of 2.5:1 were prepared as per ISRM standards (Brown 1981). Each block was represented by at least three core specimens. The oven-dried and NX-size core specimens were tested using a microcontroller compression testing machine. The mean values of UCS of different rocks were considered for analysis.

2.2.2 *Determination of Rock Tensile Strength*

To determine the Brazilian tensile strength of the rock samples, 54 mm diameter NX-size core specimens, having a length less than 27 mm were prepared as per ISRM standards (Brown 1981). The cylindrical surfaces were made free from any irregularities across the thickness using the polishing machine. End faces were made flat to within 0.25 mm and parallel to within 0.25°. The specimen was wrapped around its periphery with one layer of the masking tape and loaded into the Brazil tensile test apparatus across its diameter. Load was applied continuously at a constant rate such that failure occurs within 15–30 s. Ten specimens of the same sample were tested and average results of Brazilian tensile strength of different rocks were recorded.

2.2.3 *Determination of Percentage Porosity of the Rock*

Porosity describes how densely the material is packed. To determine the porosity of the rock samples, the specimens were prepared and tested in accordance with ISRM standards (Brown 1981). Total porosity was measured by crushing the rock to fine powder and measuring the volume of powder by fluid displacement in a pycnometer. The total volume of pores was calculated as the difference between the volume of the specimen and that of the crushed particles. At least five samples of each rock type were used for measuring porosity. The average results of percentage porosity of different rocks were recorded.

2.2.4 *Determination of A-Weighted Equivalent Sound Level*

Test samples for rotary drilling, having a dimension of 20 × 20 × 20 cm were prepared by sawing off from block samples. During drilling, to overcome the vibration of rock block, it was firmly held by vise which was kept on the table of the machine. Sound level measurements were carried out for the rotation speeds of 150, 200, 250 and 300 RPM, and the penetration rates of 2, 3, 4 and 5 mm/min on each rock block.

For each combination of drill bit diameter, drill bit speed and penetration rate, a total of 64 sets of test conditions were arrived at drill bit diameter of 6, 10, 16 and 20 mm; drill bit speed of 150, 200, 250 and 300 RPM; penetration rate of 2, 3, 4 and 5 mm/min. A-weighted equivalent continuous sound level (L_{eq}) was recorded for all 64 different drill holes of 30 mm depth on each rock block. There were total 7 rock types. Out of these, 5 rock types were used for developing the model and two types were used to test the accuracy of the developed model, so in total 320 (i.e., 64 × 5) L_{eq} values were used for developing the regression model. For all measurements, the sound level meter was kept at a distance of 1.5 cm from the periphery of the drill bit (Fig. 2). For a particular condition and for the same rock block, the sound level was determined five times in relatively rapid succession. It was found that the recorded equivalent sound levels were almost consistent.

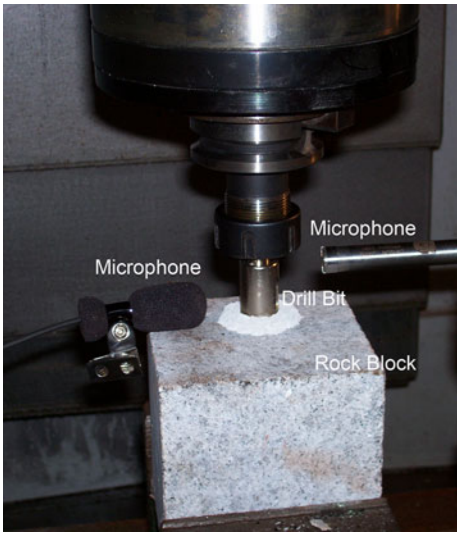

Fig. 2 Position of microphone from the drill setup

The arithmetic average of each set of five measurements was computed to yield an average A-weighted equivalent sound level for a particular condition.

For 15 min, the sound level was measured at 1.5 cm from the drill bit without drilling. The equivalent sound level of 65.2 dB was recorded without drilling, which was mainly due to the noise of the CNC machine.

It may be argued that sound produced from the CNC machine itself may affect the sound level measurement during the rock drilling. It is important to mention that if the sound level difference between the two sources is more than 10 dB, then the total sound level will remain the same as that of the higher source. Further, taking the measurement very close to the source will reduce the effect of sound produced from the other sources.

3 Results and Analysis

The results of the measurements of rock properties (UCS, tensile strength and percentage porosity) and range (maximum and minimum) of A-weighted equivalent sound level (L_{eq}) recorded during drilling of sedimentary rocks are given in Table 1. In order to establish the predictive models among the parameters obtained in this study, multiple regression analysis was performed using Minitab 15 software for windows.

3.1 Multiple Regression Analysis

The general purpose of multiple regression is to learn more about the relationship between several predictor variables and a dependent or criterion variable. The performance of the model depends on a large number of factors that act and interact in a complex manner. The mathematical modelling of sound level produced during drilling is influenced by many factors. Therefore, a detailed process representation anticipates a second order model. ANOVA was carried out to find which input parameter significantly affects the desired response. To facilitate the experiments and measurement, four important factors are considered in the present study. They are: drill bit diameter in mm (*A*), drill bit speed in RPM (*B*), penetration rate in mm/min (*C*) and equivalent sound level produced during drilling in dB (*D*). The responses considered are UCS, tensile strength and percentage porosity. The mathematical models for the rock properties with parameters under consideration can be represented by $Y = f(x_1, x_2, x_3, \ldots) + \varepsilon$ where Y is the response and x_1, x_2, x_3, are the process variables and ε is fitting error. A quadratic model of f can be written as $f = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ij} x_i^2 + \sum_{i<j}^{n} a_{ij} x_i x_j + \varepsilon$ where a_i represents the linear effect of x_i, a_{ij} represents the quadratic effect of x_i and a_{ij} in fourth term represents linear interaction between x_i and x_j. Then the regression models contain linear terms, squared terms and cross product terms.

In order to compare all the reasonable regression models, a backward elimination procedure was used as the screening procedure. Then the predictor variable having the

Table 1 Rock properties and range of A-weighted equivalent sound level values obtained during drilling of sedimentary rocks

Sl. no.	Rock sample	UCS (MPa)	Tensile strength (MPa)	Porosity (%)	A-weighted equivalent sound level L_{eq} (dB)	
					Min L_{eq}	Max L_{eq}
1	Sand stone	62.2	7.49	1.0815	105.8	110.2
2	Iron stone	83.2	10.27	0.2793	114.2	119.5
3	Lime stone	71.8	8.86	0.7392	109.9	114.9
4	Shell lime stone	17.2	2.21	4.5511	76.5	81.6
5	Marl	58.3	7.02	1.1987	104.3	108.9
6	Shale	15.2	1.95	5.5394	75.5	80.9
7	Chalk	21.3	2.73	3.2579	80.9	84.3

Table 2 Statistical results of the significant regression models

Model	Variables	Coefficient	Standard error	Standard error of estimate	*t* value	Tabulated *t* value	*F* ratio	Tabulated *F* ratio	Regression coefficient	Adjusted regression coefficient
Eq. 1	Constant	71.8640	2.93232	0.701557	24.508	±1.967428	21836.68	1.818728	0.8993	0.8993
	Drill bit diameter	0.2922	0.07612		3.839					
	Bit speed	0.0016	0.00455		2.345					
	Penetration rate	0.0171	0.22969		2.075					
	L_{eq}	−2.3069	0.06014		−38.358					
	(Drill bit diameter)^2	0.0080	0.00197		4.049					
	$(L_{eq})^2$	0.0217	0.00033		66.741					
	(Drill bit diameter × bit speed)	0.0005	0.00013		3.463					
	(Drill bit diameter × penetration rate)	0.0167	0.00653		2.551					
	(Drill bit diameter × L_{eq})	−0.0106	0.00048		−22.225					
	(Bit speed × L_{eq})	−0.0002	0.00004		−4.412					
	(Penetration rate × L_{eq})	−0.0072	0.00218		−3.279					
Eq. 2	Constant	14.7292	0.39297	0.0940194	37.481	±1.967428	34275.66	1.860438	0.8892	0.8891
	Drill bit diameter	0.0597	0.01020		5.851					
	Bit speed	0.0013	0.00061		2.143					
	Penetration rate	0.0487	0.03041		2.600					
	L_{eq}	−0.4146	0.00806		−51.437					
	(Drill bit diameter)^2	0.0012	0.00026		4.709					
	$(L_{eq})^2$	0.0034	0.00004		77.399					
	(Drill bit diameter × bit speed)	0.0001	0.00002		3.167					
	(Drill bit diameter × penetration rate)	0.0022	0.00088		2.462					
	(Drill bit diameter × L_{eq})	−0.0016	0.00006		−25.298					
	(Penetration rate × L_{eq})	−0.0014	0.00029		−4.615					
Eq. 3	Constant	25.7588	1.13225	0.288376	22.756	±1.967428	4168.94	2.399953	0.8815	0.8812
	Drill bit diameter	0.0777	0.01938		4.008					
	L_{eq}	−0.3721	0.02464		−15.103					
	$(L_{eq})^2$	0.0013	0.00013		9.907					
	(Drill bit diameter × L_{eq})	−0.0005	0.00020		−2.671					

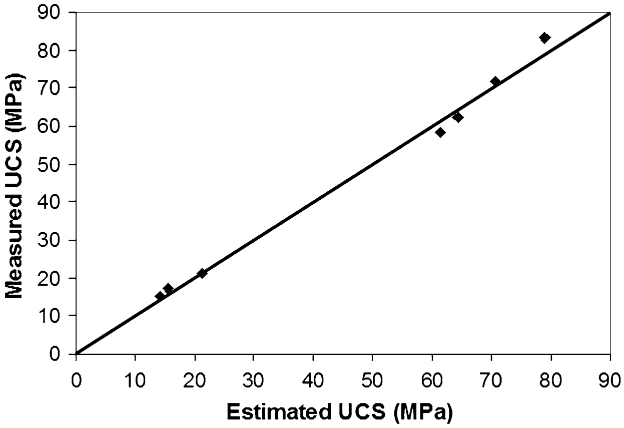

Fig. 3 Cross-correlation of UCS for Eq. 1

absolute smallest *t* statistic was selected. If the *t* statistic was not significant at the selected α level (95% confidence interval), the predictor variable under consideration was removed from the model and the regression analysis was performed using a regression model containing all the remaining predictor variables. If the *t* statistic was significant, the model was selected. The procedure was continued by removing one predictor variable at a time from the model. The screening was stopped when the predictor variable remaining in the model could not be removed from the system.

Multiple regression model to predict uniaxial compressive strength is:

$$\begin{aligned}\mathrm{UCS} = {} & 71.8640 + 0.2922 \times A + 0.0016 \times B + 0.0171 \\ & \times C - 2.3069 \times D + 0.0080 \times A^2 + 0.0217 \times D^2 \\ & + 0.0005 \times A \times B + 0.0167 \times A \times C - 0.0106 \times A \\ & \times D - 0.0002 \times B \times D - 0.0072 \times C \times D. \end{aligned} \tag{1}$$

Statistical result of the regression model (Eq. 1) is shown in Table 2. As seen, the selected model explains 89.93% of the total variation in the observed UCS tests. Figure 3 shows the cross correlation of predicted and experimentally determined values of UCS for Eq. 1.

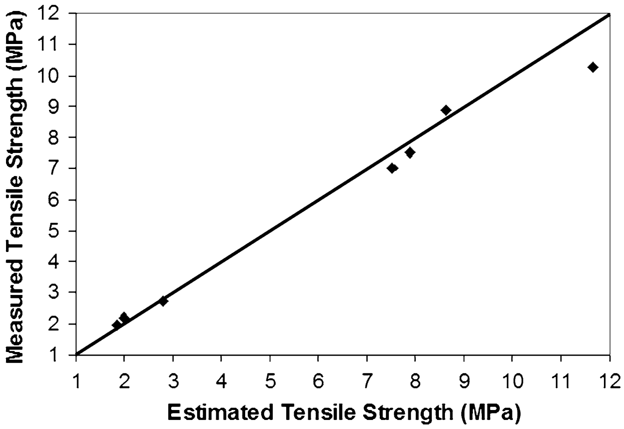

Fig. 4 Cross-correlation of TS for Eq. 2

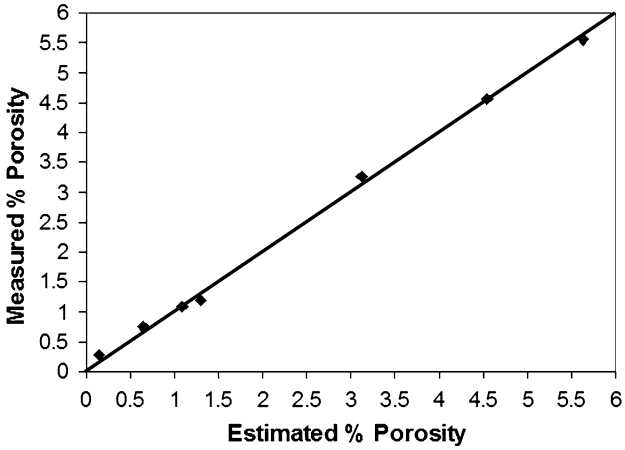

Fig. 5 Cross-correlation of percentage porosity for Eq. 3

Multiple regression model to predict tensile strength is:

$$\begin{aligned}\mathrm{TS} = {} & 14.7292 + 0.0597 \times A + 0.0013 \times B + 0.0487 \\ & \times C - 0.4146 \times D + 0.0012 \times A^2 \\ & + 0.0034 \times D^2 + 0.0001 \times A \times B + 0.0022 \\ & \times A \times C - 0.0016 \times A \times D - 0.0014 \times C \times D. \end{aligned} \tag{2}$$

Statistical result of the regression model (Eq. 2) is shown in Table 2. As seen, the selected model explains 88.91% of the total variation in the observed UCS tests. Figure 4 shows the cross correlation of predicted and experimentally determined values of tensile strength for Eq. 2.

Multiple regression model to predict percentage porosity is:

$$\begin{aligned}\%\ \mathrm{porosity} = {} & 25.7588 + 0.0777 \times A - 0.3721 \times D \\ & + 0.0013 \times D^2 - 0.0005 \times A \times D. \end{aligned} \tag{3}$$

Statistical result of the regression model (Eq. 3) is shown in Table 2. As seen, the selected model explains 88.12% of the total variation in the observed porosity tests. However, it is worth mentioning here that, the correlation obtained between percentage porosity and equivalent sound level might be just a consequence of the correlation between UCS and porosity, and not a direct physical relation. Figure 5 shows the cross correlation of predicted and experimentally determined values of percentage porosity for Eq. 3.

3.2 Validation of the Derived Model

The statistical results of the three models are given in Table 2. The correlation coefficients (R^2) of these equations are 0.8993, 0.8891 and 0.8812. These values are

Table 3 Performance indices of the developed regression models

Variable	Performance indices		
	RMSE	VAF (%)	MAPE
UCS	0.7129	89.9	2.5306
Tensile strength	0.1246	88.9	2.5248
Porosity (%)	0.2238	88.1	12.417

good, but they do not necessarily identify a valid model. The significance of R^2 values can be determined by the t test, assuming that both the variables are normally distributed and the observations are chosen randomly. The test compares a computed t value with a tabulated t value using the null hypothesis. For this test, a 95% level of confidence was chosen. If the computed t value is greater than the tabulated t value, then the null hypothesis is rejected, and there is a relationship between the dependent and predictor variables. If the computed t-value is less than the tabulated t value, then the null hypothesis is not rejected, and R^2 is not significant. As presented in Table 2, the computed t values are greater than the tabulated t values for all the equations, suggesting that the models are valid. This test follows an F-distribution with degrees of freedom $v_1 = 11$ and $v_2 = 319$ for Eq. (1), $v_1 = 10$ and $v_2 = 319$ for Eq. (2), $v_1 = 4$ and $v_2 = 319$ for Eq. (3), so that the critical region will consist of values exceeding 1.818728, 1.860438 and 2.399953 respectively. In this test, a 95% level of confidence was chosen. If the computed F-value is greater than the tabulated F-value, the null hypothesis will be rejected because there is a real relation between the dependent and predictor variables. Since the computed F-values were greater than the tabulated F-values for all the equations, the null hypothesis was rejected. Therefore, it was concluded that the models are valid.

To appreciate the estimation capability of the derived multiple regression equations, the scatter diagrams of the observed and estimated values were plotted (Figs. 3, 4, 5). Ideally, on a plot of observed versus estimated values the points should be scattered around the 1:1 diagonal straight line. A point lying on the line indicates an exact estimation. The points are scattered uniformly about the diagonal line in all the plots, suggesting that the models are reasonable.

3.3 Performance Prediction of the Derived Models

In fact, the coefficient of correlation between the measured and predicted values is a good indicator to check the prediction performance of the model. In this study, values account for (VAF) (Eq. 4) and root mean square error (RMSE) (Eq. 5) indices were calculated to control the performance of the prediction capacity of predictive model developed in the study (Alvarez and Babuska 1999; Finol et al. 2001; Gokceoglu 2002; Yilmaz and Yuksek 2008, 2009).

$$\mathrm{VAF} = \left[1 - \frac{\mathrm{var}(y - y')}{\mathrm{var}(y)}\right] \times 100 \tag{4}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y - y')^2} \tag{5}$$

where y and y' are the measured and predicted values, respectively. The calculated indices are given in Table 3. If the VAF is 100 and RMSE is 0, then the model will be excellent. Mean absolute percentage error (MAPE) which is a measure of accuracy in a fitted series value in statistics was also used to check the prediction performances of the models. MAPE usually expresses accuracy as a percentage (Eq. 6).

$$\mathrm{MAPE} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{A_i - P_i}{A_i}\right| \times 100 \tag{6}$$

where A_i is the actual value and P_i is the predicted value. The obtained values of RMSE, VAF and MAPE, given in Table 3 indicate prediction performances.

4 Conclusions

The UCS, TS and Porosity of sedimentary rocks were evaluated using the sound level produced during rotary drilling in the laboratory. Multiple regression analysis was performed, in order to establish the predictive models among the parameters obtained in the study.

The performance prediction values showed that the multiple regression models are good tools for minimizing the uncertainties and potential inconsistency of the correlations.

It appears that there is a possibility of estimating rock properties (UCS, TS and Porosity) using the proposed empirical relationships. The empirical relationship developed is not aimed at replacing the ISRM suggested testing methods, but rather as a quick and easy method to estimate the UCS, TS and porosity of sedimentary rock reported in this investigation. The population of the analyzed data is relatively limited in this study. Therefore, the practical outcome of the proposed equations would be very valuable, when the data are considered along with the interpretation based on the engineering experiences, with acceptable accuracy, at the preliminary stage of design.

In this investigation, frequency analysis of sound produced during drilling operation has not been reported. Frequency analysis of sound can be a useful technique to estimate the rock strength. Hence, it is suggested that future work can be carried out in this direction.

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