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Estimating rock properties using sound signal dominant frequencies during diamond core drilling operations

Ch.Vijaya Kumar [a,*], Harsha Vardhan [a], Ch.S.N. Murthy [a], N.C. Karmakar [b]

[a] Department of Mining Engineering, National Institute of Technology Karnataka, Surathkal, India
[b] Indian Institute of Technology (BHU), Varanasi, India

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ABSTRACT

In many engineering applications such as mining, geotechnical and petroleum industries, drilling operation is widely used. The drilling operation produces sound by-product, which could be helpful for preliminary estimation of the rock properties. Nevertheless, determination of rock properties is very difficult by the conventional methods in terms of high accuracy, and thus it is expensive and time-consuming. In this context, a new technique was developed based on the estimation of rock properties using dominant frequencies from sound pressure level generated during diamond core drilling operations. First, sound pressure level was recorded and sound signals of these sound frequencies were analyzed using fast Fourier transform (FFT). Rock drilling experiments were performed on five different types of rock samples using computer numerical control (CNC) drilling machine BMV 45 T20. Using simple linear regression analysis, mathematical equations were developed for various rock properties, i.e. uniaxial compressive strength, Brazilian tensile strength, density, and dominant frequencies of sound pressure level. The developed models can be utilized at early stage of design to predict rock properties.

1. Introduction

Drilling is one of the significant extraction methods in a wide range of engineering applications, which is basically accompanied by noise production. Noise/sound signals have been widely used in other areas of engineering applications. However, its application to mining, geotechnical and petroleum fields is very limited when determining the physico-mechanical properties of rocks prior to the onset of a project. The direct or conventional rock testing method generally is expensive and time-consuming with respect to the required high accuracy.

According to Vardhan et al. (2009), for effective blast hole design and other construction projects, rock properties are critically important. The rock properties are not readily available for mining and construction sites. As a result, it is needed to send rock blocks to a laboratory or tested in situ, which is a time-consuming process. As the drilling process is one of the important steps for the projects, with noise generated as an outcome. For this, it is likely that these noise/sound signals could be used for the purpose of rock characterization, also be useful for determining the physico-mechanical properties of rocks during drilling.

Obert (1941) and Obert and Duall (1942) utilized acoustic frequencies to estimate rockburst potential in metal mines. It was found that different stress states in rocks produce various acoustic noises. Then they used sub-audible noises to predict the rockburst in underground metal mines. Hardy et al. (1972) discussed acoustic emission (AE) applications to rock mechanics problems. Rafavich et al. (1984) conducted laboratory investigation on petrographic characteristics of carbonate rock and acoustic properties with a vast range of rock lithology. The rock composition indicated that porosity is the most influence factor for P- and S-wave velocities. The results based on rock property used for evaluation of lithology and porosity show the changes in the seismic section from Williston Basin (USA and Canada). McNally (1990) investigated the relationship between the uniaxial compressive strength (UCS) and the sonic log for Basin Bowen in Australia.

Zborovjan (2001, 2002) and Zborovjan et al. (2003) identified rock types based on hidden Markov model for rock drilling operations. The Markov model recognized the particular sound signals of every rock type being drilled. It was concluded that the information contained in a rock when drilled can be well captured

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* Corresponding author.
E-mail address: vijayakumarch.nitk@gmail.com (Ch.Vijaya Kumar).

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Table 1
Different rock samples collected in India.

Location	Rock type
Veldurthy Village, Kurnool District, Andhra Pradesh, India	Ochre
Khammam Village, Kothagudem District, Telangana, India	Bituminous coal
Padubidri Village, Udupi District, Karnataka, India	Laterite
Bethamcherla Village, Kurnool District, Andhra Pradesh, India	Pink limestone
Bethamcherla Village, Kurnool District, Andhra Pradesh, India	Iron stone
Kurnool Village, Kurnool District, Andhra Pradesh, India	Marble
Chodavaram Village, Visakhaptnam District, Andhra Pradesh, India	Moon white granite
Gauripatnam Village, West Godavari District, Andhra Pradesh, India	Basalt

in the frequency ranges from 5000 Hz to 8000 Hz. Miklusova et al. (2006) and Krepelka et al. (2007) investigated the rock strength characteristics and feasibility of utilization of optimum control parameters such as thrust and speed during drilling operations. It was found that the sound signal changes depending on the drilling regime. They concluded that the sound signal can be used for control of rock disintegration process. Gradl et al. (2008) carried out drill bit diagnosis using noise of a drill bit during drilling operations based on acoustic data. It was reported that the bit characteristics and bit diagnosis (broken teeth and bit balling) could be performed using the noise of a bit in real time based on acoustic data.

Fig. 1. CNC drilling machine BMV 45 T20.

Later, Vardhan and Murthy (2007) and Vardhan et al. (2009) introduced a novel concept of quantification of rock properties by utilizing sound pressure level generated during drilling. Various types of rock samples were used to investigate rock properties using fabricated jackhammer drill machine. It suggested that this technique could be used for quantification of rock properties. Kumar et al. (2011a, b, c, 2013a, b) investigated the quantification of various rocks (sedimentary, metamorphic, and igneous) properties using sound pressure level produced in rock drilling operations. A set of mathematical equations was developed for predicting various rock properties with an acceptable degree of accuracy. Kivade et al. (2015) employed multilayer perception (MLP) and radial basis function (RBF) as two neural network methods for predicting geomechanical properties of rocks using sound pressure level produced in percussive drilling. Delibalta et al. (2015) quantified physico-mechanical properties of rocks using noise level. It was concluded that the sound pressure level increases with the increase in rock density and decreases with the increase in porosity. Shreedharan et al. (2014) identified the rock types based on acoustic fingerprinting.

As can be seen, most of the previous scholars utilized equivalent sound pressure level to predict physico-mechanical properties of rocks. Very few investigations were done on rock identification using frequency analysis. Earlier investigators have suggested more detailed works in this direction (Kumar et al., 2011b). Nevertheless, the sound signal processing from rock drilling operations has rarely been studied over the past years. Hence, the objective of this study is to predict the physico-mechanical properties of rocks using dominant frequencies from rock drilling operations (by varying speed of rotation, penetration rate, and drill bit diameter) using frequency analysis.

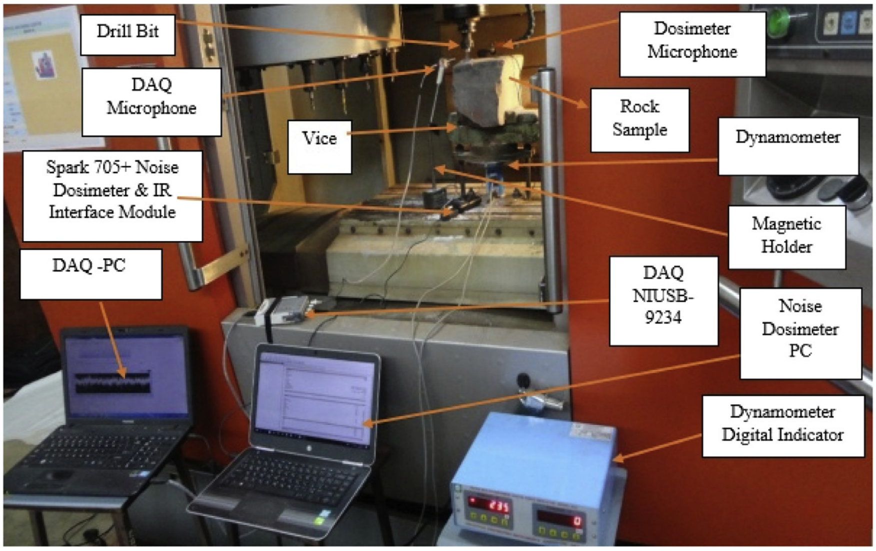


Fig. 2. Experimental set-up of CNC drilling machine BMV 45 T20.

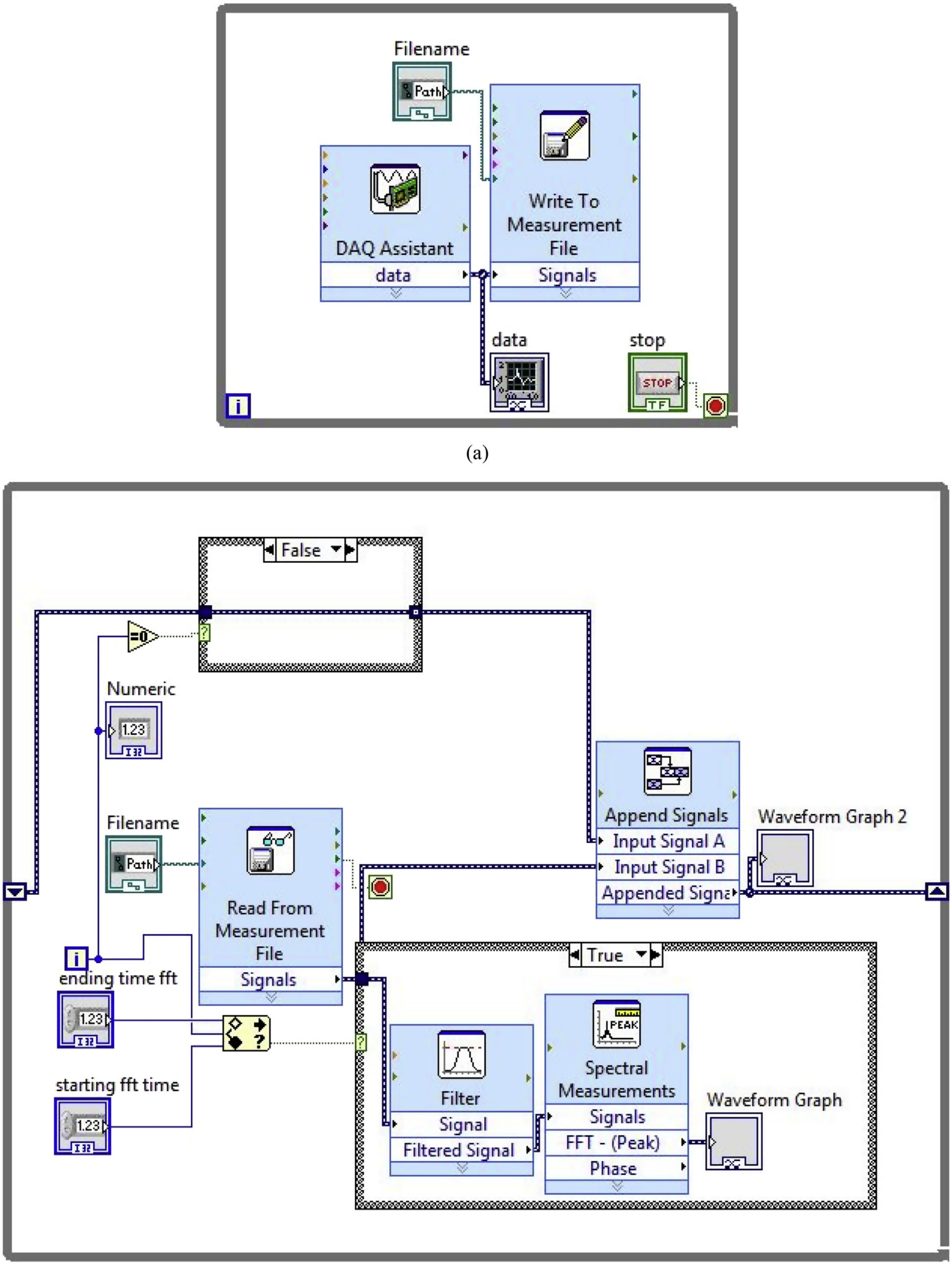
2. Rock samples

The tests were carried out on cubic rock samples of 20 cm in side length. A total of eight different rock samples were used in these tests, which were collected from different locations of Andhra Pradesh, Telangana and Karnataka of India. Table 1 lists the locations and rock types collected. The rock samples were inspected for any macroscopic defects, fractures, and joints before conducting the test.

3. Test equipment

3.1. CNC drilling machine

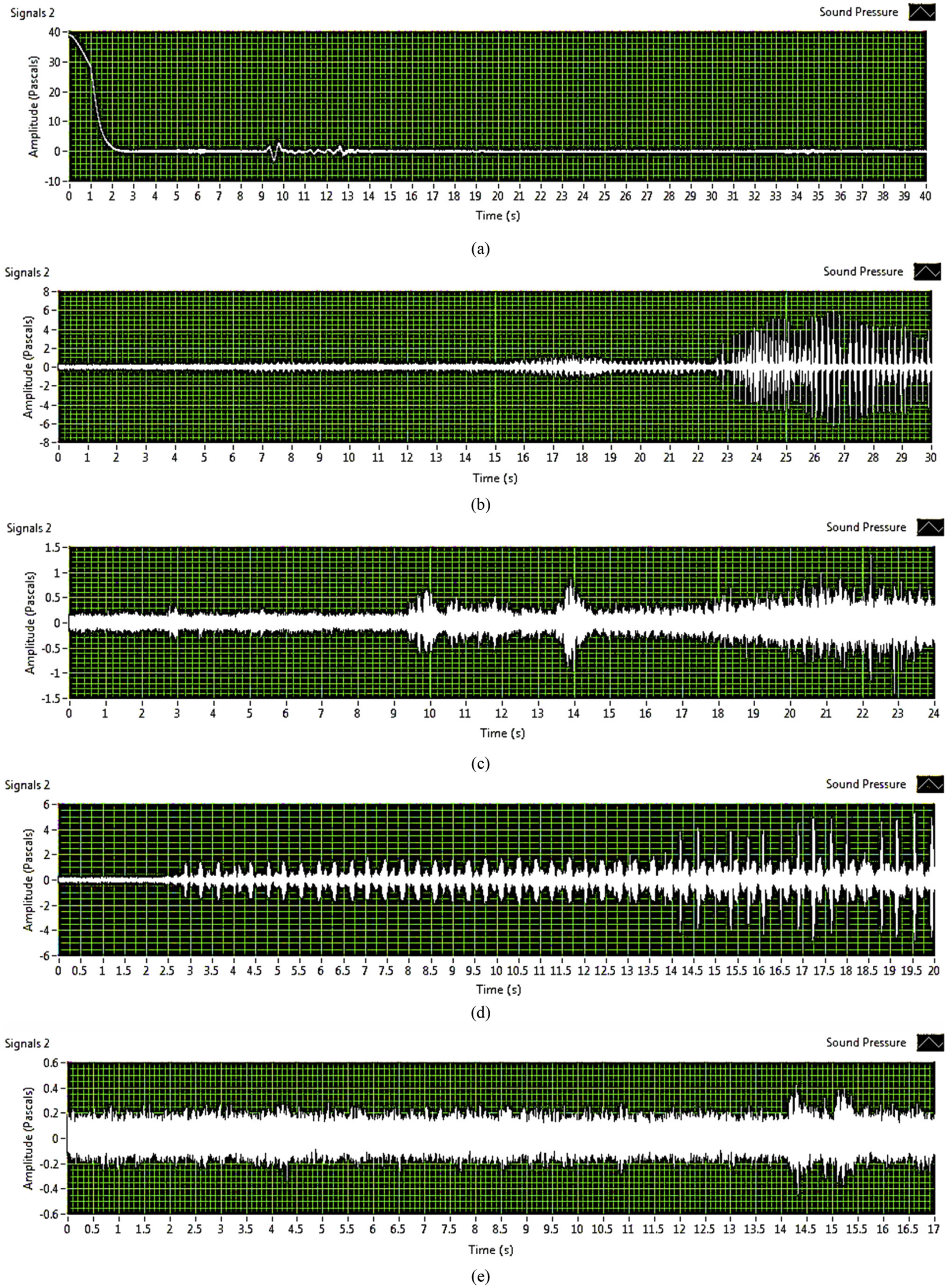
All the rock drilling tests were conducted using automated CNC drilling machine BMV 45 T20, as shown in Fig. 1. The experimental room was covered completely with glass and fiber panel with dimensions of 6 m in length, 5 m in width, and 9 m in height. The CNC



(a)

(b)

Fig. 3. Labview block diagram code utilized for (a) acquiring the sound signal data from microphone and (b) sound signal analysis.



(a)

(b)

(c)

(d)

(e)

Fig. 4. Time-domain plots for various rock types: (a) ochre, (b) bituminous coal, (c) laterite, (d) pink limestone, and (e) iron stone.

Table 2
Rock properties for generation and validation of prediction model.

Purpose	Rock type	UCS (MPa)	BTS (MPa)	Density (g/cm^3)
Model generation	Ochre	14.77	1.02	2.38
	Bituminous coal	16.37	1.09	1.75
	Laterite	39.99	1.87	2.93
	Pink limestone	51.49	2.32	2.49
	Iron stone	120.25	7.54	3.6
Model validation	Marble	24.05	2.58	2.59
	Moon white granite	28.83	2.98	2.64
	Basalt	54.13	5.58	2.85

Table 3
Five dominant frequencies for selected rock samples (unit: Hz).

Rock type	F_1	F_2	F_3	F_4	F_5
Ochre	5579	6900	6941	7994	8000
Bituminous coal	6002	7732	8507	8512	8522
Laterite	5880	5998	6025	6999	7168
Pink limestone	5510	5991	6800	7910	7970
Iron stone	4000	4100	5641	6494	7650

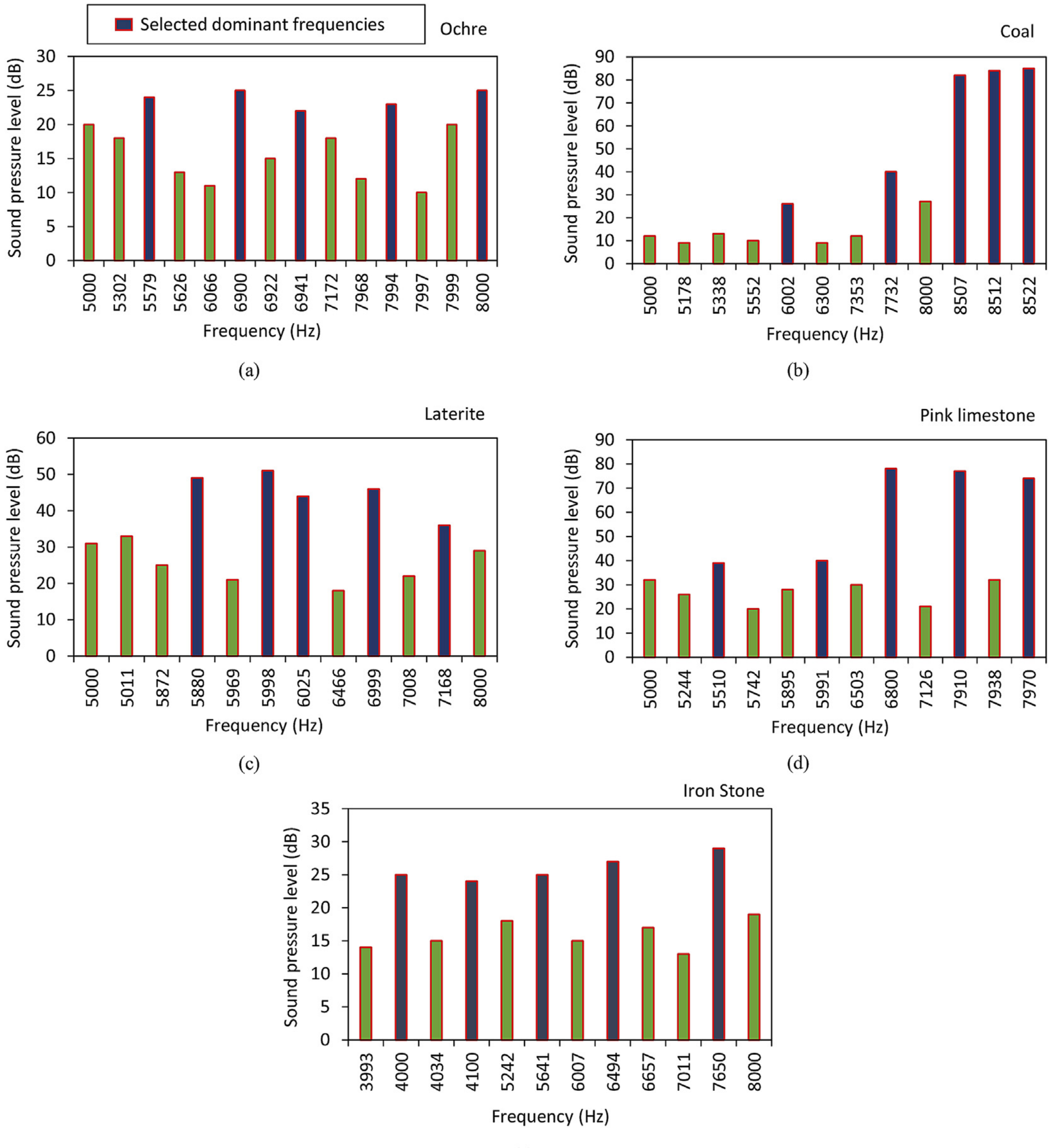
Table 4
Summary of dependent variables used in prediction model.

Dependent variable	R^2	Adjusted R^2	Standard error
UCS	0.914	0.885	14.59412
BTS	0.935	0.913	0.80226
Density	0.96	0.946	0.159

machine has a 450 mm × 900 mm table, 6 bar optimum air pressure (1 bar = 100 kPa) and was connected to power supply of 415 V, 3 phase and 50 Hz.

3.2. Data acquisition system

Data acquisition is a process of measuring sound pressure level recorded with computer program. The data acquisition system consists of computer, microphone (G.R.A.S. 40PH), data acquisition card hardware (NI USB-9234 from National Instruments (NI)) along



(a) (b) (c) (d) (e)

Fig. 5. Five dominant frequencies for selected rock types: (a) ochre, (b) bituminous coal, (c) laterite, (d) pink limestone, and (e) iron stone.

Table 5
Analysis of variance (ANOVA) for dependent variables.

Dependent variable	Model	Degree of freedom	Sum of squares	Mean square	*F*-value	Significant *P*-value
UCS	Regression	1	6760.48	6760.48	31.741	0.011
	Residual	3	638.965	212.988		
	Total	4	7399.445			
BTS	Regression	1	27.719	27.719	43.068	0.007
	Residual	3	1.931	0.644		
	Total	4	29.65			
Density	Regression	1	1.812	1.812	71.657	0.003
	Residual	3	0.076	0.025		
	Total	4	1.887			

Table 6
Coefficients of the presented linear model for predicting UCS, BTS and density.

Dependent variable	Frequency	Unstandardized coefficients		Standardized coefficient beta	*t*-value	Significant value
		B	Standard error			
UCS	F_2	235.349	33.788		6.965	0.006
		−0.03	0.005	−0.956	−5.634	0.011
BTS	F_1	20.392	2.709		7.526	0.005
		−0.003	0	−0.967	−6.563	0.007
Density	F_4	8.88	0.742		11.972	0.001
		−0.001	0	−0.98	−8.465	0.003

Table 7
Predicted and measured UCS values and model errors.

Rock sample	Measured UCS (MPa)	Predicted UCS (MPa)	Error (%)
Marble	24.05	24.059	3.7422
Moon white granite	28.83	28.859	0.1005
Basalt	54.13	54.149	0.0351

Table 8
Predicted and measured BTS values and model errors.

Rock sample	Measured BTS (MPa)	Predicted BTS (MPa)	Error (%)
Marble	2.58	2.581	0.0387
Moon white granite	2.98	2.982	0.0671
Basalt	5.58	5.581	0.0179

Table 9
Predicted and measured density values and model errors.

Rock sample	Measured density (g/cm^3)	Predicted density (g/cm^3)	Error (%)
Marble	2.59	2.591	0.0386
Moon white granite	2.64	2.641	0.0378
Basalt	2.85	2.851	0.035

with Labview software. It is a more effective measuring instrument compared with traditional systems (Forouhamajd et al., 2015). The Labview is a commercially available software for data analysis of any measurement system. For recording a sound signal, the G.R.A.S. 40PH microphone and NI USB-9234 data acquisition card were used for measuring sound pressure level in the diamond core drilling operations. The microphone was highly sensitive to recording accurate sound signals generated during rock drilling operations. The microphone was connected to the NI USB-9234 data acquisition card channel with USB cable, which was connected to the personal computer (PC) with Windows operating system (64-bit). The entire system was capable of recording sound signals at various frequency bands from diamond core drilling operation with a sampling rate of 51.2 kHz.

3.3. *Uniaxial compression test equipment*

The compression testing machine AIM-317E-Mu was used for measurement of UCS of cylindrical rock samples as per International Society for Rock Mechanics (ISRM) suggested methods (Brown, 1981). The maximum loading capacity of this testing machine was 2000 kN.

3.4. *Brazilian tension test equipment*

The tensile strengths of the rock samples were determined indirectly by Brazilian tensile strength (BTS) testing machine as per the ISRM suggested methods (Mellor and Hawkes, 1971; Brown, 1981) due to non-availability of direct determination of tensile strength in our laboratory.

4. Methodology

4.1. *Determination of uniaxial compressive strength*

The UCS of rock sample was determined as per the ISRM suggested methods (Brown, 1981). For this, NX-size oven-dried cylindrical core samples of regular geometry with diameter of 54 mm and ratio of length to diameter equal to 2.5 were prepared in the laboratory. The load was continuously applied until the samples failed, and the total applied load on sample was recorded. Five tests were carried out on each type of rock samples, and the mean value of the UCSs of different rocks was considered for analysis.

4.2. *Determination of Brazilian tensile strength*

Core samples of 54 mm in diameter (NX-size) having thickness approximately equal to sample radius were prepared as per the ISRM suggested methods (Mellor and Hawkes, 1971; Brown, 1981). The cylindrical surfaces were polished to avoid any irregularities around the thickness of the sample in the laboratory, and the end faces were made flat within ±0.25 mm and parallel to within ±0.25°. The sample was loaded into BTS testing machine across its diameter. The load was applied continuously until the sample failed and the maximum load at failure was recorded. Ten tests were carried out on each type of rock samples as per the ISRM recommendation and the mean value of BTSs of different rocks was arrived.

4.3. Determination of rock density(ρ)

The density of rock generally varies due to its porosity. The density of every core sample was determined after removal of moisture from it (Ulusay and Hudson, 2007). The dry density of rock sample can be obtained by

$$\rho = M/V \tag{1}$$

where ρ is the dry density of the rock, M is the mass of the sample, and V is the volume of the sample.

4.4. Sound measurement

The experimental set-up for carrying out drilling comprises CNC machine on rock blocks and sound pressure level measurement, as shown in Fig. 2. The rock blocks were held firmly at a particular position during drilling using a vice and with the help of two long nuts and bolts. The sound pressure level was measured for a few experimental combinations by varying diamond core drill bit diameter (6 mm, 10 mm, 16 mm, 18 mm and 20 mm), speed (150 rpm, 200 rpm, 250 rpm, 300 rpm and 350 rpm, where rpm represents the revolution per minute), and penetration rate (2 mm/min, 3 mm/min, 4 mm/min, 5 mm/min and 6 mm/min) using DAQ microphone with the help of Labview software. Under each drilling condition (drill bit diameter, speed and penetration rate), the drilling has been carried out for separate drilling times. For all sound pressure level measurements, the microphone was kept at a distance of 1.5 cm away from the outer edge of the drill bit diameter, as shown in Fig. 2. Also, Fig. 2 shows a dynamometer, a dynamometer digital indicator, a noise dosimeter with the microphone, and a dosimeter PC used for determination of specific energy. However, description of specific energy is beyond the scope of this paper. The sound signals during drilling were captured by the microphone connected to the computer using DAQ NI USB-9234 (data acquisition module from NI) 24-bit ADC (analog to digital converter), which was allowed to capture 51,200 samples within one second. The resolution of the response was maintained at 1 Hz by reading all the samples. This module was connected to the system and the data were obtained using serial communication. Fast Fourier transform (FFT) was adopted to obtain the resonant frequencies with their amplitudes of sound pressure level. The graphical programming language software (NI Labview) was used for signal analysis to capture the accurate signals generated from the rock drilling operations.

The FFT is a method known as fast computational algorithm for discrete Fourier transform (DFT). Using this algorithm, the time-domain signals can be transformed to frequency spectrum. It converts a signal into individual spectral components and thereby provides frequency information about the signals. The FFT representation of signals from time domain to frequency domain is given by

$$X(f) = F[x(t)] = \int_{-\infty}^{+\infty} x(t)\mathrm{e}^{-j2\pi ft}\mathrm{d}t \tag{2}$$

where $X(f)$ is the FFT, $x(t)$ is the time-domain signal, $j2$ is the imaginary number, π is the constant, and ft is the frequency to be analyzed.

The DFT maps divide time sequences into discrete frequency representations, which can be written as

$$X_k = \sum_{i=0}^{n-1}\left(x_i \mathrm{e}^{\frac{-j2\pi ik}{n}}\right)(k = 0,\ 1,\ 2,\ \ldots,\ n-1) \tag{3}$$

where x is the input sequence, X is the DFT, k is the constant, and n is the number of samples in both the discrete time and the discrete frequency domains.

Acquired data from the microphone (Fig. 3a) were put into a fast Fourier analyzer to convert the time-domain signals to frequency-domain signals. Append signals toolkit (Fig. 3b) was also used to understand the time-domain response of the whole signal, and the FFT was done based on peak amplitude observed from the time-domain plots. The FFT spectra were obtained after filtering the raw data obtained from the experimental measurement. A Butterworth band pass filter (Fig. 3b) was used to ensure that the FFT is free from noisy signals with the help of Labview software. Hence, the sound measurement is considered to be accurate and noisy signals are avoided. The Labview block diagram code for sound signal measurement is shown in Fig. 3.

In selected rock blocks, the acoustic recording begins after the drill bit penetrates into the rock block as a conflict brink (the distance between the outermost point of a drill bit and the level that the entire surface of the rock will be involved with drill bit) distance. The sound signals during drilling were measured up to 40 s, 30 s, 24 s, 20 s and 17 s corresponding to ochre, bituminous coal, laterite, pink limestone, and iron stone, respectively. Sample lengths of durations 40 s, 30 s, 24 s, 20 s and 17 s were captured and used for frequency analysis. The time-domain plots are shown in Fig. 4. It was emphasized that, as per selection of the speeds in this investigation, the required time for one complete rotation of the drill bit is 0.4 s, 0.3 s, 0.24 s, 0.2 s and 0.17 s corresponding to drilling speeds of 150 rpm, 200 rpm, 250 rpm, 300 rpm and 350 rpm, respectively. But these sample lengths at times 0.4 s, 0.3 s, 0.24 s, 0.2 s and 0.17 s are not sufficient for analyzing the rock strength peak amplitude from the time-domain plots. Hence, we consider drilling times of 40 s, 30 s, 24 s, 20 s and 17 s, instead of 0.4 s, 0.3 s, 0.24 s, 0.2 s and 0.17 s, corresponding to ochre, bituminous coal, laterite, pink limestone, and iron stone, respectively.

5. Results and analysis

5.1. Rock properties

The rock properties were determined as per the ISRM suggested methods, as listed in Table 2.

5.2. Time-domain frequency analysis

The drilling sound signals were analyzed using FFT after capturing the sound signals from rock drilling operations. The time-domain plots are shown in Fig. 4. The 40 s, 30 s, 24 s, 20 s, and 17 s time-domain data were selected for the analysis. These times represent that the entire surface of the drill bit has been involved with entire surface of the rock sample. The peak amplitude of FFT was selected for the analysis at the 40th, 26th, 22th, 19th, and 14th second FFT from time-domain plots, corresponding to ochre, bituminous coal, laterite, pink limestone, and iron stone, respectively, as this peak amplitude at each time node contains the maximum energy carried in the noise spectrum. All spectrogram algorithms were plotted using Hanning function. The spectrogram algorithms of five rock samples (dominant frequencies) modeled are shown in

Fig. 5. The sampling rate for recording drilling sound signals was 51.2 kHz.

Five dominant frequencies were extracted from the FFT of each selected rock, where the highest sound pressure level (dB) was determined. These frequencies, called as dominant frequencies corresponding to each rock type, are given in Table 3. At each drilling condition, the drilling has been carried out for separate drilling times. For example, a drilling condition of (6, 150, 2) (drill bit diameter = 6 mm, speed = 150 rpm, and penetration rate = 2 mm/min) was used for ochre to drill for 40 s to obtain frequencies F_1–F_5, as listed in Table 3. Similarly, the cases of bituminous coal, laterite, pink limestone, and iron stone used corresponding drilling conditions of (10, 200, 3) to drill for 30 s, (16, 250, 4) to drill for 24 s, (18, 300, 5) to drill for 20 s, and (20, 350, 6) to drill for 17 s to obtain frequencies F_1–F_5. The standard deviation and uncertainty were within limits for prediction of UCS, BTS and density using the dominant frequency of sound signals. The results given in Table 3 are in line with Zborovjan (2001, 2002) and Zborovjan et al. (2003), wherein it was proposed that the relevant sound signal of rocks ranges between 5000 Hz and 8000 Hz.

5.3. Modeling of rock properties

After extraction of the rock dominant frequencies, simple linear regression analysis was performed on the relationship between rock physico-mechanical properties and dominant frequencies using SPSS statistics software. In the prediction model, rock properties were selected as dependent variables and frequency as independent variable. All the selected frequencies F_1–F_5 corresponding to rock properties like UCS, BTS and density were checked. For modeling of UCS, frequency F_2 was significant compared with other dominant frequencies. Similar trend was

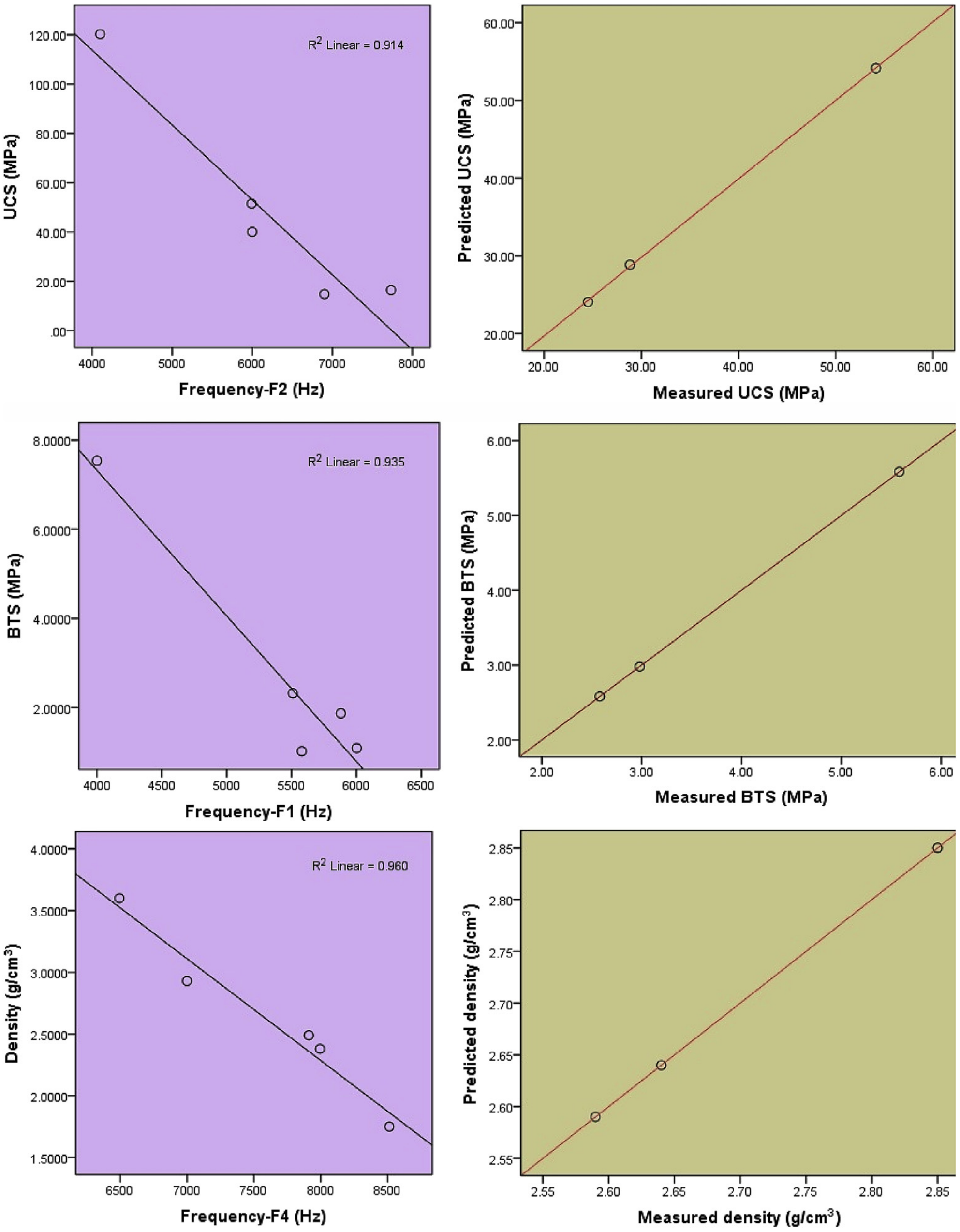


Fig. 6. Simple linear regression model and distribution of validation points for UCS, BTS and density.

observed for the case with BTS and density. A set of satisfactory mathematical equations (Eqs. (4)–(6)) was derived for quantification of rock properties, i.e. UCS, BTS and density, wherein the coefficients of determination (R^2) are 0.914, 0.935 and 0.96, respectively (Table 4), and F- and P-values represent the analysis of variance (ANOVA) (Table 5). P-value should be less than 0.05 to be considered as statistically significant parameter. The coefficients of the prediction models are given in Table 6.

$$UCS = 235.349 - 0.03F_2\left(R^2 = 0.914\right) \tag{4}$$

$$BTS = 20.392 - 0.003F_1\left(R^2 = 0.935\right) \tag{5}$$

$$\rho = 8.877 - 0.001F_4\left(R^2 = 0.96\right) \tag{6}$$

After development of the prediction model, three rock types (marble, moon white granite, and basalt) were used for validation. Tables 7–9 give the predicted values, corresponding to the measured values, and the model errors. It can be seen that the developed models predicted all physico-mechanical properties with error less than 4%. The comparison of the simple linear regression model with corresponding validation model is shown in Fig. 6.

6. Conclusions

Estimation of the physico-mechanical properties of rocks in the shortest possible time is one of the important issues in mining, geotechnical and petroleum fields. The direct rock testing methods are expensive and time-consuming upon required accuracy. An attempt was made to quantify the rock properties using sound pressure level at dominant frequencies during the diamond core drilling operation. In this context, the acoustic frequencies were analyzed using FFT during drilling operations to predict the physico-mechanical properties of rocks, i.e. UCS, BTS and density in the shortest possible time. After analyzing sound signals, results show that there is a satisfactory mathematical relationship between physico-mechanical properties of rocks, i.e. UCS, BTS and density, and sound pressure level at the second, first and fourth dominant frequencies from rock drilling operations. The developed equations for quantification of rock properties can be used in field with an acceptable degree of accuracy. In the present work, prediction of the rock properties using frequency analysis technique was used in the diamond core drilling operation. It is suggested that the future investigation could be carried out in this direction using wavelet techniques for quantification of rock properties.

Conflicts of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Ch. Vijaya Kumar is pursuing his PhD degree in Department of Mining Engineering, National Institute of Technology Karnataka (NITK), India. He obtained his B.Tech (Mechanical Engineering) and M.Tech (CAD/CAM) from Jawaharlal Nehru Technological University, Hyderabad. His area of interest covers drilling, vibration and acoustics, design, manufacturing process, and robotics. Currently, he is working in the area of rock drilling, rock cutting, rock mechanics, and estimation of rock properties using sound signals.

Dr. Harsha Vardhan is Associate Professor in Department of Mining Engineering of NITK Surathkal. He holds B.Tech in Mining Engineering from NITK Surathkal and PhD from Indian Institute of Technology (IIT) Dhanbad. He is a recipient of “Career Award for Young Teachers” from AICTE; “Young Scientist Award” from Ministry of Science and Technology, India and “Engineering Gold Medal & DN Thakur Award” from MGMI, India. He also received Award for Best Research Publication in Engineering Sciences from Government of Karnataka in 2012. He is an active researcher and is a member of several committees constituted by various governments and professional bodies.

Prof. Ch.S.N. Murthy obtained his M.Tech and PhD in Mining Engineering from IIT Dhanbad and IIT Kharagpur, respectively. He is currently working as a Professor in Department of Mining Engineering, NITK Surathkal, India. His research is focused on rock drilling, mine planning and rock mechanics. He received MEAI SRG – Information Technology Award in 2015–2016. He is an active researcher and completed several R&D projects sponsored from various government and private agencies.

Prof. N.C. Karmakar obtained B.Tech (Hons) with First Class and First Rank in Mining Engineering in 1981 from IIT Kharagpur, M.Tech (by Research) from IIT Dhanbad and PhD from IIT Kharagpur. At present, Prof. Karmakar is working in Department of Mining Engineering at Indian Institute of Technology (BHU), Varanasi. He is the recipient of several awards and honors like Dr. Rajendra Prasad Memorial Gold Medal of Institution of Engineers (India), Bala Tandan Award of MGMI, Best Paper Award of Bio-Environmentally Degradable Polymer Society, and Alumnus Award from IIT Kharagpur, among others.