International Journal of Novel Researches in Science, Technology & Engineering
Vol. 7 No. 1 June, 2024
ISSN 2141 825X
www.oasisinternationaljournal.org

Correlation of Strength Properties with Rotary Drill Penetration Rate in Soft and Hard Rock Using Linear Regression Analysis

by

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Abstract

Rock strength properties are important parameter for prediction of penetration rate on different rock types when drilling and boring tools are used in a quarry. The project research was conducted using the field data and rock samples collected from the four locations- (granite), Ilorin (MHQ); (limestone) Ibese (DCI); (limestone) Ewekoro (LEW) and (Calcite) Ikpeshi (FGI). For field analysis, the average bulk density and rebound hardness value of samples from the four location as determined in the laboratory in order to estimate Uniaxial Compressive Strength are 27.01kN/m^3, 58.6; 19.3kN/m^3, 41.4; 15.78 kN/m^3, 21.0; 25.98 kN/m^3, 43.2 respectively. The results of Uniaxial Compressive Strength as estimated from the correlation chart between average density and Schmidt hardness value shows that location (MHQ), has average strength value of 256MPa, while location (DCI) 62.04MPa; while location (LEW) 38.58MPa and location (FGI) 35.2MPa. The point load strength index for location (MHQ) has an average value of 10.67MPa, location (DCI) has 1.66MPa, location (LEW) has an average value of 4.47MPa and location (FGI) has 1.18MPa while the tensile strength as estimated from point load strength index for location (MHQ) is 16.01MPa, while location (DCI) is 2.484, location (LEW) is 6.70MPa and location (FGI) average value of 2.67MPa. The penetration rate as determined from field data show that location (MHQ) has an average penetration rate of 0.87 m/min, location (DCI) has an average penetration rate of 0.71 m/min, while location (LEW) has average penetration rate of 0.49 m/min and location (FGI) has average penetration rate of 0.97 m/min. The results obtained showed that penetration rate highly correlated for Schmidt rebound hardness value, bulk density, Uniaxial Compressive Strength, point load strength, and tensile strength.

Keywords: **Correlation, Strength, Properties, Drill, Penetration Rate, Soft & Hard Rock & Linear Regression**

Introduction

Prediction of the drilling penetration rate is one of the important parameters in mining operations. This parameter has a direct impact on the mine planning and cost of mining operations. Generally, effective parameters on the penetration rate is divided into two classes: rock mass properties and specifications of the machine, Yarali and Soyer (2013).The ability to predict the performance and efficiency of drilling machines is very important in mining operations. The rock drillability is one of the most important parameters for mine planning, development and economics of mine operations, (Altindag, 2004). Also knowledge of drillability of rocks in engineering projects has key role to determine drilling costs. Drillability is a term used in construction to describe the influence of a number of parameters on the drilling rate and the tool wear of the drilling too. In this evaluation, the drillability term was defined as a penetration rate (Köhler *et al*., 2011). The rough estimations of the rock drillability may cause a great risk in terms of mining operations, selection of mining machineries and equipment and final price of the product. Also the total drilling cost can be estimated by the drilling rate equations. These equations can be used to select the type of machine. Rock drillability depends on many parameters such as rock properties and specifications of drilling equipment, Thuro and Spaun (1996). Although drilling equipment parameters are controllable, rock characteristics and geological conditions are uncontrollable and cannot be changed.

The mechanical properties of rocks play important role in drilling operation such as prediction of fracture zone, well stability and other engineering techniques (Xu *et al*., 2016). Kahraman *et al*. (2003), stated that the specific energy (SE), the unconfined compressive strength (UCS), the Brazilian tensile strength, the point load strength and the Schmidt hammer rebound test values are the significant rock properties that influence the penetration rate in drilling operations. However, the UCS is the most dominant rock property for predicting penetration rate in rotary drills (Kahraman, 1999). According to Clark (1982), the UCS has a close correlation with penetration rate.

The penetration rate increases as rock compressive strength decreases. The behaviour of rock material under compression is important as the Uniaxial Compressive Strength of intact rock is a basic parameter for rock classification and rock mass strength criteria. Therefore, the strength characteristics of rocks are usually considered to be necessary for the design of rock structures, stability of rock excavations as well as influence rock fragmentation in quarry and working of mine rocks (Ojo and Olaleye, 2002).

Materials

The materials used on the field during the collection of samples includes GPS for taking the coordinates, hand shovel for picking the samples, sampling bag for collection of samples, masking tape and marker for labelling the samples and field notebook for recording the coordinates.

Methods

This research work is divided into two major aspects. Field work and laboratory work aspects. The field work involves the collection of samples used for the tests and the laboratory work encompasses all the tests carried out in the laboratory from thin section, bulk density using the ISRM standard. The tests were carried out on different samples from four locations.

Locations of Study Area

Four locations were chosen for sampling and Global Positioning System (GPS) device was used to obtain the coordinates of the study area (Table 1). The samples were labelled as A_1, A_2,

A_3, and A_4 and the coordinates were projected on the location map Figure 1 and Plate 1 – 4.

Table 1: Sample Description and Study Areas and their Coordinates

Sample Code	Sample Type	LGA	Coordinates of Location	
			Latitude	Longitude
MHQ	Granite	Ilorin South	8^0 34' 12.2" N	004^0 36' 52.2"E
DCI	Limestone	Yewa North, Ayetoro	06˚58′ 45.5″N	003˚ 04′ 23.7″E
LEW	Limestone	Ewekoro	06˚56′ 24″N	003˚ 13′ 09″E
FGI	Calcite	Akoko Edo, Igarra	07˚ 06′ 30″N	06˚18′ 23″E

Drilling experiments were carried out on twenty (20) different rock samples, five (5) from granite, five (5) from limestone, three (5) from limestone and five (5) from calcite at various locations within Nigeria granite (MHQ) MAN HARDI Nig. Ltd Quarry, Ilorin, Kwara State; limestone, (DCI) Dangote Cement, Ibese, Ogun State; Limestone (LEW) Lafarge, Ewekoro Works); Calcite (FGI) Freedom Group Mining and Mineral Processing Ikpeshi, Edo State).

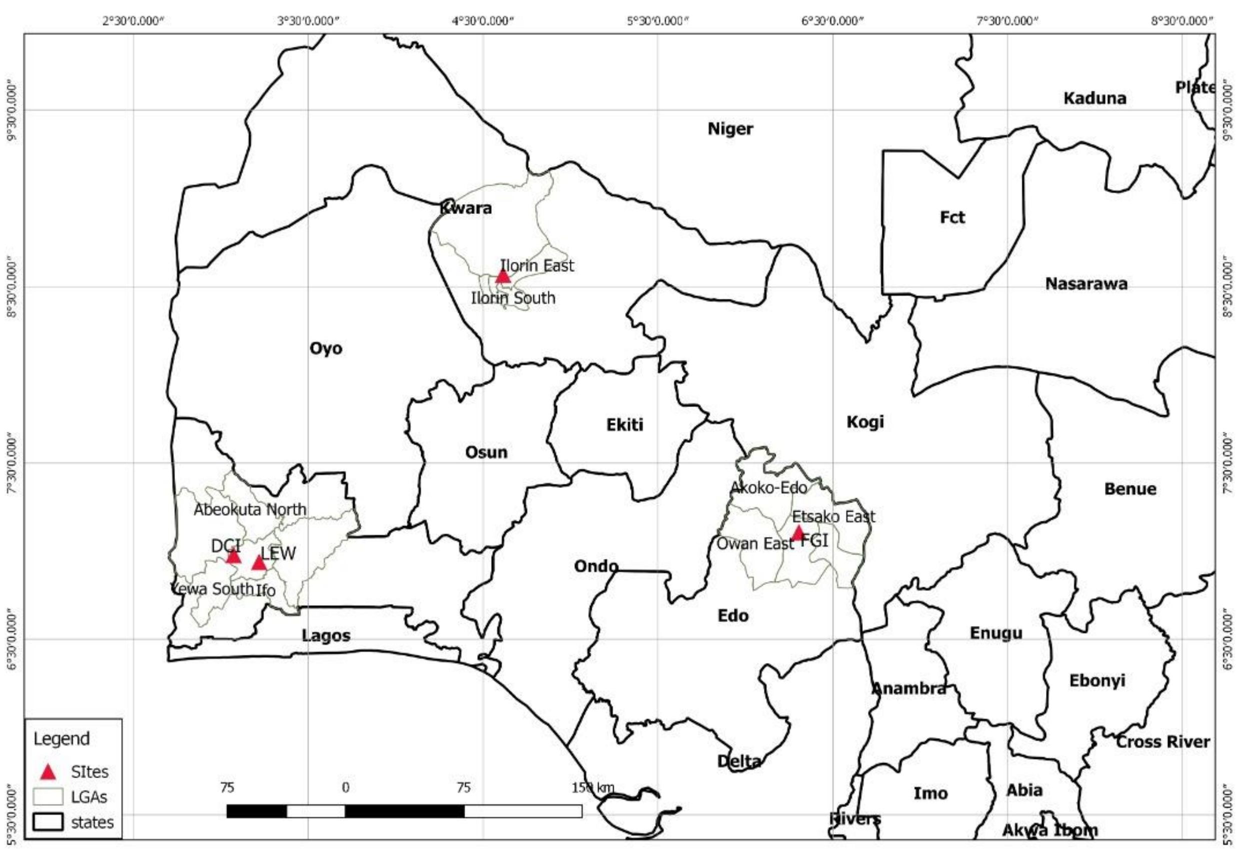

Figure 1: Map of Nigeria indicating the Study Area (DCI, LEW, FGI and MHQ)

Plate 1: Satellite imagery of DCI **Plate 2: Satellite imagery of FGI**

Plate 3: Satellite imagery of LEW **Plate 4: Satellite imagery of MHQ**

Sample Preparation

Twenty (20) rock samples were prepared for each group panel to the standard suggested by International Society of Rock Mechanics ISRM (1989) and American Society for Testing and Materials ASTM (2001) D5731.

Laboratory Work

The samples collected was used to determine the Schmidt Rebound Hardness, Bulk Density, Uniaxial Compressive Strength, Point Load Strength and Tensile Strength in accordance to the standards suggested by ISRM (1989) and rate of penetration rate of granite, limestone, calcite and dolomite.

Determination of Schmidt Rebound Hardness

Hardness is the resistance of a surface layer to be penetrated by another body of harder consistency (Jimeno *et al.*, 1995). The resistance of rock is a function of the hardness, composition of its mineral grains, porosity, degree of humidity etc. Nevertheless, the hardness of rock is the principal type of resistance that must be overcome during drilling. Once the bit is penetrated to the rock, the rest of the operation become easier. Hardness of rocks is determined by using Friedrich von Mohr's scale of hardness with the concept that any mineral can scratch anything that has a lower or equal number to it. The numbering is from 1 to 10 for standard scale for ten minerals. There is usually a certain correlation between hardness and compressive strength of rocks (Jimeno *et al*., 1995).

Determination of Bulk Density

Density is a measure of mass per unit of volume. It is sometimes defined by unit weight and specific gravity. Density is common physical properties. The three (3) samples were used to determine the bulk density of rock sample with distilled water of 250ml each. The Saturation and Buoyancy technique for irregular rock sample was adopted and the procedures follow the standard suggested by ISRM (1981). The saturated volume of the sample was calculated using Equation (1) and (2) respectively:

$$\text{Saturated volume of samples} = V_2 - V_1 \quad (1)$$

Where:

V_1 is the initial water level (ml); and

V_2 is the final water level in the cylinder after the immersion of the irregular rock sample (ml).

The bulk density of the rock samples was calculated using Equation 2:

$$\text{Bulk density of the rock samples} = \frac{M}{V_2 - V_1} \quad (2)$$

Where:

M is the mass of the sample (g);

V_1 is the initial water level (ml); and

V_2 is the final water level in the cylindrical beaker after the immersion of the irregular rock sample (ml).

Determination of Uniaxial Compressive Strength

The maximum force applied to a rock sample without breaking it. Units of stress are either reported in pond per square inch (psi in) or Newton's per square meter (N/m^2 in metric units). It is derived by dividing the force over the area upon which it acts. Stress is expressed in Equation 3. The Uniaxial Compressive Strength test is most widely used measure of the strength, deformation and fracture characteristics of the rock. The UCS values were estimated by using the chart named after Deere and Miller (1966) as presented in Figure 2.

$$\sigma = \frac{P}{A} \quad (3)$$

Where:

P is the engineering way of express force, N; and

A is the cross-sectional area, m^2

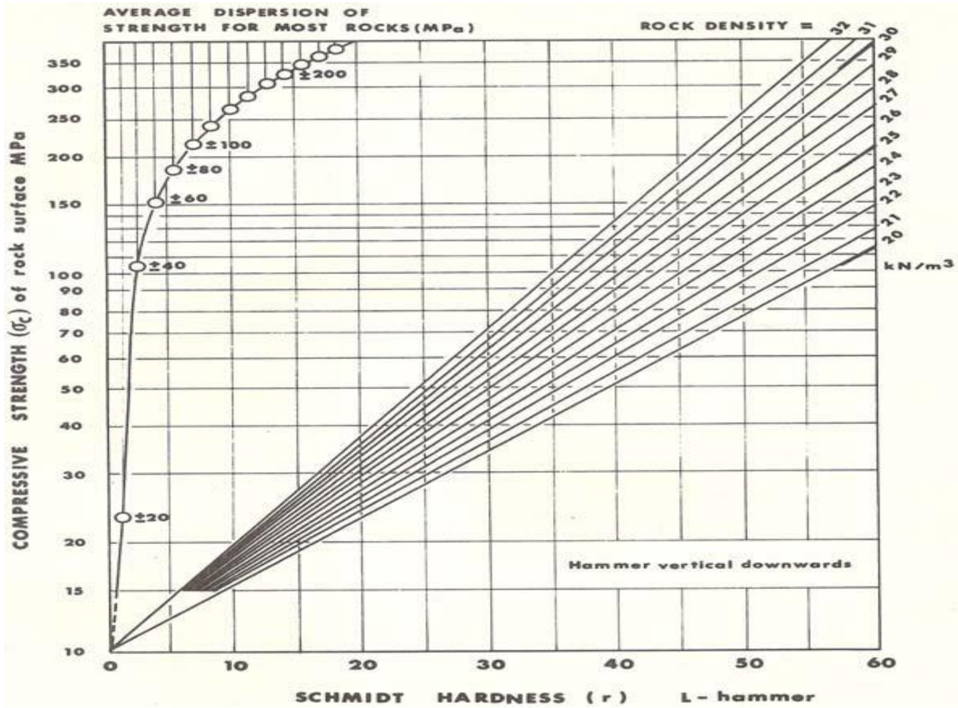

Figure 2: Correlation Chart for Schmidt (L) Hammer, Relating Rock Density, Compressive Strength and Rebound Number (Deere and

Determination of Point Load Index

The point load strength values were determined in accordance the procedures suggested by ISRM (1985) using Equations 4 – 7.

$$I_s = \frac{P}{D_e^2} \quad (4)$$

Where I_s is the point load strength index (MPa), P is the failure load (KN) and $D_e$is the equivalent diameter (mm).

$$D_e^2 = \frac{4A}{\pi} = \frac{4DW}{\pi} \quad (5)$$

Where D is the distance between load contact points (mm), W is the width of the sample (mm) and A is the minimum cross-sectional area of the loading points.

$$F = \left(\frac{D_e}{50}\right)^{0.45} \quad (6)$$

Where F is the correction factor.

$$I_{S(50)} = FI_s \quad (7)$$

Where $I_{(50)}$ is the corrected point load strength index.

Determination of Tensile Strength

The tensile strength of the rock samples was estimated based on the relationship suggested by Brook (1993) and ISRM (1989) which shows the general relationship between the point load strength (I_s) and the tensile strength (T_o) as expressed in Equation 8.

$$T_o = 1.5\, I_{s\,(50)} \quad (8)$$

Penetration Rate

A stop watch will be used to ascertain the actual time taken to drill blast holes. The time taken will be observed on a new button bit till it deteriorates and subsequently changed. The penetration rate is computed using Equation 9;

$$\text{Penetration Rate} = \frac{m}{t} \quad (9)$$

m is the drill depth, metre; and

t is the time taken to drill a blasthole, minute

Results and Discussions

Results of Bulk Density

The results of the bulk density are presented in Table 2;

Table 2: Bulk Density for Granite Samples (DCI, LEW, FGI and MHQ)

Sample	MHQ		DCI		LEW		FGI	
	g/cm^3	kN/m^3	g/cm^3	kN/m^3	g/cm^3	kN/m^3	g/cm^3	kN/m^3
A	2.73	26.77	1.89	18.52	i.72	16.86	2.69	26.37
B	2.79	27.35	1.94	19.02	1.48	14.51	2.59	25.39
C	2.76	27.04	2.04	20.00	1.71	16.77	2.60	25.49
D	2.73	26.76	2.01	19.71	1.64	16.08	2.71	26.57
E	2.77	27.15	1.97	19.31	1.50	14.70	2.66	26.08
Average	**2.76**	**27.01**	**1.97**	**19.31**	**1.27**	**15.78**	**2.65**	**25.98**
Range	**2.73 – 2.79**	**26.76 – 27.35**	**1.89 – 2.04**	**21.47 – 24.02**	**1.48 – 1.72**	**14.51 – 16.86**	**2.59 – 2.71**	**25.30-26.57**

Results of Schmidt Rebound Hardness

The readings of the Schmidt rebound value was presented in Table 3;

Table 3: Results of Average Rebound Value for the Locations (DCI, LEW, FGI and MHQ)

Sample	MHQ	DCI	LEW	FGI
A	60.0	43.4	22.10	45.1
B	59.6	43.9	21.40	44.5
C	59.4	40.6	20.60	43.2
D	57.2	39.8	20.40	42.5
E	56.8	39.1	20.42	40.9
Average	**58.6**	**41.4**	**21.0**	**43.2**
Range	**56.8 – 60.0**	**39.1 – 43.4**	**20.40 – 22.10**	**40.9 – 45.1**

Results of Strength Parameters

The results of Strength Parameter of MHQ are presented in Table 4;

Table 4: Results of Strength Parameter (MHQ)

S/N	Rebound Value	Bulk Density (kN/m^3)	UCS (MPa)	Point Load Index (MPa)	Tensile Strength (MPa)
1	60.0	26.77	240	10.00	15.00
2	59.6	27.35	275	11.46	17.19
3	59.4	27.04	270	11.25	16.88
4	57.2	26.76	230	9.58	14.37
5	56.8	27.15	265	11.04	16.56
Ave.	**58.6**	**27.01**	**256**	**10.67**	**16.01**
Range	**56.8 – 60.0**	**26.76 – 27.35**	**230 – 275**	**9.58– 11.46**	**14.37–16.88**

Table 5: Results of Strength Parameter (DCI)

The results of Strength Parameter of DCI are presented in Table 5;

S/N	Rebound Value	Bulk Density (kN/m^3)	UCS (MPa)	Point Load Index (MPa)	Tensile Strength (MPa)
1	43.4	18.52	63.8	2.185	3.278
2	43.9	19.02	63.6	2.061	3.092
3	40.6	20.00	61.8	1.664	2.496
4	39.8	19.71	60.6	1.254	1.881
5	39.1	19.31	60.4	1.114	1.671
Ave.	**41.4**	**19.31**	**62.04**	**1.656**	**2.484**
Range	**39.1 – 43.4**	**21.47 – 24.02**	**60.4 – 63.8**	**1.114–2.185**	**1.671-3.278**

Table 6: Results of Strength Parameter (LEW)

The results of Strength Parameter of LEW are presented in Table 6;

S/N	Rebound Value	Bulk Density (kN/m^3)	UCS (MPa)	Point Load Index (MPa)	Tensile Strength (MPa)
1	22.10	16.86	39.06	4.83	7.21
2	21.40	14.51	38.90	4.63	6.95
3	20.60	16.77	38.40	4.35	6.52
4	20.40	16.08	38.20	4.27	6.40
5	20.42	14.70	38.34	4.29	6.44
Ave.	**20.98**	**15.78**	**38.58**	**4.47**	**6.70**
Range	**20.40-22.10**	**14.51 – 16.86**	**38.30 – 39.06**	**4.27-4.83**	**6.40 – 7.21**

Table 7: Results of Strength Parameter (FGI)

The results of Strength Parameter of FGI are presented in Table 7;

S/N	Rebound Value	Bulk Density (kN/m^3)	UCS (MPa)	Point Load Index (MPa)	Tensile Strength (MPa)
1	45.1	26.37	36.6	3.369	5.054
2	44.5	25.39	36.4	1.639	2.459
3	43.2	25.49	34.9	1.455	2.183
4	42.5	26.57	34.2	1.241	1.862
5	40.9	26.08	34.0	1.192	1.788
Ave.	**43.2**	**25.98**	**35.2**	**1.779**	**2.669**
Range	**40.9 – 45.1**	**25.30-26.57**	**34.0 – 36.6**	**1.241 – 3.369**	**1.788-5.054**

Results of Penetration Rate of the Button Bit

The penetration rate results for five (5) consecutive drilling operations are presented in Tables 8 – 11;

Table 8: Result of Penetration Rate (MHQ)

The results of Penetration Rate of MHQ are presented in Table 8;

Hole Set Code	Total Depth (m)	Total Time Taken (min)	Penetration Rate (m/min)
DRM1	85.39	106.48	0.802
DRM2	85.58	95.22	0.899
DRM3	86.67	103.31	0.839
DRM4	85.23	98.23	0.868
DRM5	85.66	93.14	0.920
Average	**85.71**	**99.28**	**0.865**
Range	**85.23 – 86.67**	**93.14 – 106.48**	**0.80193 – 0.919690**

Table 9: Result of Penetration Rate (DCI)

The results of Penetration Rate of DCI are presented in Table 9;

Hole Set Code	Total Depth (m)	Total Time Taken (min)	Penetration Rate (m/min)
DRD1	12.67	20.44	0.62
DRD2	12.05	18.54	0.65
DRD3	12.63	18.30	0.69
DRD4	13.12	17.04	0.77
DRD5	12.55	15.31	0.82
Average	**12.60**	**17.93**	**0.71**
Range	**12.05-12.63**	**15.31-20.44**	**0.62-0.82**

Table 10: Result of Penetration Rate (LEW)

The results of Penetration Rate of LEW are presented in Table 10;

Hole Set Code	Total Depth (m)	Total Time Taken (min)	Penetration Rate (m/min)
DRL1	15.49	36.02	0.43
DRL2	15.47	38.33	0.42
DRL3	14.88	29.18	0.51
DRL4	15.34	27.89	0.55
DRL5	15.57	29.38	0.53
Average	**15.35**	**32.16**	**0.49**
Range	**14.88 – 15.57**	**29.18 – 38.33**	**0.42 – 0.55**

Table 11: Result of Penetration Rate (FGI)

The results of Penetration Rate of FGI are presented in Table 11;

Hole Set Code	Total Depth (m)	Total Time Taken (min)	Penetration Rate (m/min)
DRF1	11.57	15.25	0.76
DRF2	12.04	14.33	0.84
DRF3	11.11	11.57	0.96
DRF4	12.79	11.52	1.11
DRF5	11.35	9.79	1.16
Average	**11.77**	**12.49**	**0.97**
Range	**11.11 – 12.79**	**9.79 – 15.25**	**0.76 – 1.16**

Regression

Table 12: Summary of Correlation between Penetration Rate and their Empirical Equation

Correlation between Penetration Rate	Location	Rock Type	Equation No.	R^2	Empirical Equation
Schmidt Hammer (SH)	**MHQ**	**Granite**	**1**	**0.98**	$PR = -0.0352RH + 2.9188$
Bulk Density (BD)	**MHQ**	**Granite**	**2**	**0.75**	$PR = 0.3472\,BD - 8.5623$
UCS	**MHQ**	**Granite**	**3**	**0.96**	$PR = 0.0011\,UCS + 0.6172$
PLT	**MHQ**	**Granite**	**4**	**0.75**	$PR = 0.0536\,PL + 0.2619$
Tensile Strength (T_o)	**MHQ**	**Granite**	**5**	**0.75**	$PR = 0.0536T_o + 0.2619$
Schmidt Hammer (SH)	**DCI**	**Limestone**	**6**	**0.84**	$PR = -0.0354RH + 2.1739$
Bulk Density (BD)	**DCI**	**Limestone**	**7**	**0.99**	$PR = -0.1155\,BD + 0.9968$
UCS	**DCI**	**Limestone**	**8**	**0.92**	$PR = -0.0497\,UCS + 3.7904$
PLT	**DCI**	**Limestone**	**9**	**0.97**	$PR = -0.1733\,PL + 0.9968$
Tensile Strength (T_o)	**DCI**	**Limestone**	**10**	**0.97**	$PR = -0.1155\,T_o + 0.9968$

Schmidt Hammer (SH)	**LEW**	**Limestone**	**11**	**0.83**	$PR = -0.0725RH + 2.0097$
Bulk Density (BD)	**LEW**	**Limestone**	**12**	**1.00**	$PR = 0.0828\,BD - 0.7815$
UCS	**LEW**	**Limestone**	**13**	**0.95**	$PR = -0.1537\,UCS + 6.4192$
PLT	**LEW**	**Limestone**	**14**	**0.87**	$PR = -0.2247PL + 1.4933$
Tensile Strength (T_o)	**LEW**	**Limestone**	**15**	**0.89**	$PR = -0.1562\,T_o + 1.5352$
Schmidt Hammer (SH)	**FGI**	**Calcite**	**16**	**0.94**	$PR = -0.0995RH + 0.8882$
Bulk Density (BD)	**FGI**	**Calcite**	**17**	**1.00**	$PR = 0.339\,BD - 7.6807$
UCS	**FGI**	**Calcite**	**18**	**0.86**	$PR = -0.1066\,UCS + 1.2875$
PLT	**FGI**	**Calcite**	**19**	**1.00**	$PR = -0.1598\,PL + 1.2875$
Tensile Strength (T_o)	**FGI**	**Calcite**	**20**	**0.86**	$PR = -0.1066\,T_o + 1.2875$

Conclusion

This study examined the correlation of strength properties from four locations within Nigeria. (Granite), Ilorin: (Limestone) Ibese; (Limestone), Ewekoro; and (Calcite), Ikpeshi with rotary drill penetration rate using linear regression analysis. The correlation between the strength properties and penetration rate for location (MHQ) hard rock (granite) shows that there is a very strong relationship between penetration rate and Schmidt rebounds hardness value, bulk density, uniaxial compressive strength, point load strength and tensile strength while location (DCI) soft rock (limestone) shows that there is a strong relationship between penetration rate and Schmidt rebounds hardness value, bulk density, uniaxial compressive strength, point load strength and tensile strength. Other two locations (LEW) limestone and (FGI) calcite also show that there is a strong relationship between penetration rate and Schmidt rebound hardness value and uniaxial compressive strength and a moderately high relationship between penetration rate, point load strength and tensile strength. Therefore, if these strength properties for hard and soft rock are determined, the penetration rate could be predicted from the linear regression equation obtained for granite, limestone and calcite whenever rotary drills are used.

Recommendations

From the results of the research study the following are noted:

1. The research will aid quarry and mine operators to know the formation characteristics.
2. Select appropriate drilling tools for operations and also in planning and management.
3. Uniaxial Compressive Strength and tensile strength of rock are two important parameter for designing geotechnical structures such as tunnels, dams, rock slopes and selection of drilling bits.

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