Evaluating the Relationship between Strength Properties and their Ratios in some Selected Granitic Outcrops

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Abstract. This paper evaluates the variations in the characteristics properties of some granitic rocks and their relationships with uniaxial compressive strength (UCS). Twenty rock samples were selected from different locations in order to determine their rebound hardness number (RN), porosity (n), specific gravity (GS), modulus of elasticity (E), rock mass rating (RMR) and blastability index (BI). The UCS and other rock properties were coordinated such that each of the properties or their ratios is compared individually with UCS. Regression statistics was used to predict UCS from the variables and the results when compared with measured UCS shows that 94 percent of the predicted UCS was explained by the measured UCS. The relationship between UCS and other parameters show that UCS increases linearly with RMR and RN with R2 values of 0.92 and 0.84 respectively while it reduces in value with n at R2 value of 0.78 but a weak relationship was observed with GS and BI with R2 value of 0.42 and 0.33 respectively. Ratios of E/UCS, RMR/BI and UCS/GS were also evaluated and their relationships shows that the correlation coefficient of RMR/BI and E/UCS, UCS/GS and E/UCS and, RMR/BI and UCS/GS are 0.86, 0.92 and 0.74 respectively. The blastability index which relate the strength of rocks with fragmentation ability using explosive have no linear relationship with other strength parameters.

Key words: Uniaxial compressive strength, rock mass rating, blastability index, granitic rocks, rebound hardness, sensitivity analysis

Introduction

Rocks are not homogeneous and isotropic and even on small scale the homogeneity varies (Boii and Braun, 1991: 45-48). Structure of rocks has a significant impact on their geo-mechanical and dynamic properties. The study of rock masses is important to the economic evaluation of mining activities as it is directly related to strength properties of rock. Rock mass comprises several different rock types and it is affected by different degrees of fracturing in varying stress conditions. Sirveiya and Thote (Sirveiya and Thote, 2012: 2-3) reported in their study that the strength of rock mass decreases with the increase in frequency of joints, bedding planes, fractures, pores and fissures and the deformability of rocks depend on their orientation. Therefore, rock mass properties are governed by rock joint and rock material parameters, as well as boundary conditions. Rock strength largely depends on the nature of its mineral composition. The basic intact rock properties for rock characterization are the UCS, the elastic modulus (E) and the poisson's ratio (v) and are called strength parameters in this paper. Other strength properties are derived from the combinations of two or three of the strength parameters. These other strength properties measure the elastic stability of the strength properties of the intact rock.

Rock fragmentation is being resisted by the rock strength and the evaluation of this resistance was done by Lilly (1986: 89-92) and was developed into Blastability Index (BI).

Some of properties that influence strength of rock materials are porosity, density and internal friction. Uniaxial compressive and tensile tests are aimed for classification and characterization of intact rock's strength while rebound hardness test is intended for in-situ rock. Worthwhile to know is that the relationship between rebound hardness index and the UCS can produce a factor for plane of weakness. An attempt for comprehensive evaluation of rock mass by Bieniaswki (Bieniawski, 1973: 335-344) resulted into the popular Rock Mass Rating (RMR) system evaluate rock mass.

According to Hentz et al. (2004), density of rock is closely correlated with its strength. Low-density rocks are deformed and broken quite easily, requiring relatively low energy factors, while denser rocks need a higher quantity of energy to achieve satisfactory fragmentation (Jimeno et al., 1995: 160-180) as well as good displacement and swelling. Increasing density increases the impedance of the rock mass

Porosity tends to reduce the efficiency of blasting operations. The lengths of strain wave-induced cracks in a highly porous rock are calculated to be only about 25% of those in non-porous rock of identical mineralogy (Choudhary et al., 2016: 89-101).

Study Areas

Samples were collected for laboratory and field analysis from locations in Ondo, Ogun, Oyo, Edo States and Federal Capital Territory of Nigeria. Ondo State lies between 4˚ 00' 00'' to 6˚ 00' 00'' E and 5˚ 27' 00'' to 8˚ 09' 00'' N. It covers an area of over 18, 239.49 square kilometers, bounded by Kwara, Kogi, and Ekiti States in the north, Edo and Delta States in the east, Ogun, Oyo and Osun States in the west and it is bounded in the south by the Atlantic Ocean. Ogun State is located geographically between 60˚ 59' 44" to 60˚ 62' 15" N and 30˚ 03' 26" to 30˚ 05' 45" E. Edo State is on 5° 26' 24'' to 7° 20' 24'' N and 5° 24' 0'' to 6° 27' 0'' E. The State has a land mass of 19,794 km square. Edo State is low lying except towards the north axis where the Northern and Esan plateaus range from 183 meters of the Kukuruku Hills and 672 meters of the Somorika Hills. Also, Oyo State is bounded in the south by Ogun State, in the north by Kwara State, in the west, it is partly bounded by Ogun State, while in the East by Osun State. It is located between 7˚ 00' 00'' to 8˚ 00' 00'' N and 3˚ 00' 00'' to 5˚ 00' 00'' E, while the Federal Capital Territory is situated in the central part of Nigeria, between 8° 25' 00'' to 9° 25' 00'' N and 6° 47' 00'' and 7° 40' 00'' E. It is bounded in the north by Kaduna State, in the west by Niger State, in the east by Nasarawa State and Kogi State in the south-west (Fig. 1).

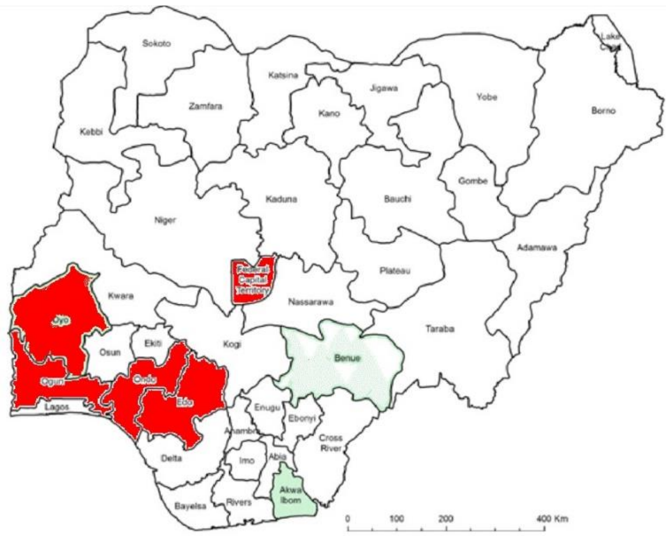

Fig. 1. Location of the Study Areas dotted with Red on Nigeria Map

Table 1. Study Locations

Locations	*Company's Name*	*Code*
Iju, Ondo State	Sizhe Global Ltd	OD1
Ore, Ondo State	Raycon Quarry	OD2
Ifon, Ondo State	Japaul Quarry	OD3
Ore, Ondo State	Levante Quarry	OD4
Oba-Ile, Ondo State	Stoneworks Ltd	OD5
Akure. Ondo State	FCC Quarry	OD6
Abeokuta, Ogun State	Labstar Quarry	OG1
Abeokuta, Ogun State	A & B Quarry	OG2
Abeokuta, Ogun State	Multiverse Quarry	OG3
Abeokuta, Ogun State	Triumphant Quarry	OG4
Ogun State	CGCC Quarry	OG5
Ibadan, Oyo State	Prestige Quarry	OY1
Onigambari Oyo State	Kunlun Quarry	OY2
Ibadan, Oyo State	Takol Quarry	OY3
Ibadan, Oyo State	Eminent Quarry	OY4
Iyuku, Edo State	Julius Dinga Ltd	ED3
Kubwa, FCT	Zeberceed Nig. Ltd	AB1
Dutse, FCT	CGC Quarry	AB2
Lugbe, FCT	Inorganic Quarry	AB3
Mpape, FCT	Arab Contractors	AB4

Material and Methods

Twenty rock samples were tested for the determination of the parameters used in this work from each of the aforementioned locations in Nigeria. Mean of each of the data set was used to represent the data value of the selected locations.

Rebound Hardness Number Measurement

Intact strength of the rocks in the selected locations were determined using L-Type Schmidt hammer. The measured test values for the samples were ordered in descending order. The lower 50% of the values were discarded and the average upper 50%s values obtained as the Schmidt Rebound hardness. The procedures followed the standard suggested by ISRM (Ulusay and Hudson, 2007: 221-229).

Determination of Uniaxial Compressive Strength

The uniaxial compressive strength (UCS) of the rock samples were determined using 1100kN compression machine in accordance with ISRM (Brown, 1989: 24-29). The rocks samples were positioned on the machine platen. The machine was jacked manually, with the release valve closed, sealing off the exhaust system and letting the pump to build up pressure for the activation of the ram. Applied load was monitored on the gauge and the load at which the sample failed load was recorded. The uniaxial compressive strength was determined using equation (1).

$$C_0 = \frac{P}{A} = \frac{P}{WD} \qquad (1)$$

where Co is uniaxial compressive strength (MPa), P is applied peak load (kN), W is width of the sample (m) and D is the height of sample (m).

Determination of Porosity

Representative rock samples of irregular geometry with mass of about 50 g were prepared for porosity determination in accordance with the standard and procedure suggested by ISRM (Brown, 1989: 75-105).

Estimation of Specific Gravity

Samples collected from the study areas were prepared in the laboratory and their specific gravities were determined in accordance with the standard and procedures suggested by International Society of Rock Mass (Ulusay and Hudson, 2007: 221-229).

Rock Mass Rating

Response of rock to compressional forces is important because uniaxial compressive strength of rock is a major parameter for rock classification and rock mass strength conditions (Okewale and Olaleye, 2013: 25-30). Thus, Classification of rock mass in the selected locations were done using rock mass rating (RMR) method in accordance with Bieniawski (1986: 89-92). Five parameters, that is, strength of rock, rock quality designation (RQD), spacing of joints, condition of joints and groundwater conditions, were used to estimate RMR as shown in Equation 2.

$$RMR = \sum(i + ii + iii + iv + v) \tag{2}$$

where i, ii, iii, iv and v represents the rating of individual parameters in accordance with Bieniawski (1986: 89-92).

Measurement of Discontinuities Spacing

A scanline of 200 m was taken across an already cut face of the deposit for the geological mapping. The discontinuity spacings were measured along the scanline. A measuring tape calibrated in mm divisions and compass clinometer used along the scanline on the exposure such that the surface trace of the discontinuity set was approximately perpendicular to the tape. The Frequency i.e. the numbers of discontinuities per unit distance; and the number of joint sets within the mapped area were also measured in accordance with ISRM standard and adapted from Harrison and Hudson (2001) using Equation 3.

$$D_f = \frac{N}{L} \tag{3}$$

where L is the length of the sampling line is meters and N is number of discontinuities intersected by the scanline. The average spacing of the joint sets was calculated according to Palmström (2005: 362-377) as shown in Equation 4.

$$S_a = \frac{(S_1 + S_2 + S_3 + S_4 + \cdots \ldots\ldots + S_n)}{n} \tag{4}$$

where S_1, S_2, S_3, S_n are average spacing for each of the joint sets and *n* is the number of joint sets.

Determination of Rock Quality Designation Index (RQD)

The RQD of the rock studied was calculated empirically from the quantitative estimates obtained from the visible traces of discontinuities of the exposed rock surface. Palmström (1982: 221-228) suggested that, when no core is available but discontinuity traces are visible in surface exposures, the RQD may be estimated from the number of discontinuities per unit volume (J_v). The relationship used by Palmström to estimate RQD from clay- free rock masses from the volumetric joint count was adopted in the study and the mathematical relations is shown in Equation 5.

$$RQD = 115 - 3.3J_v \tag{5}$$

The volumetric joint count (J_v) is a measure of the total number of joints (discontinuities) intersecting a volume of rock mass. It is defined by number of joints per cubic meter or in a unit volume of rock mass (Palmström, 1996: 69-108). It is measured from joint set spacings within a volume of rock mass as shown in Equations 6 and 7.

$$J_v = \sum_{i=1}^{j} \left(\frac{1}{S_i}\right) \tag{6}$$

$$J_v = \sum_{i=1}^{j} \left(\frac{1}{S_i}\right) + \left(\frac{N_r}{5}\right) \tag{7}$$

where S_i represent the average joint spacing in meters for the *i*th joint set and j is the total number of joint sets except the random joint set, Nr is the random joints, where random or irregular jointing occurred and it is considered by assuming a random spacing (Sr) usually set to 5 m (Palmström, 1996: 69-108).

Orientation of Discontinuities

The dip which is the maximum declination of the mean plane of the discontinuities were measured with compass clinometer and were recorded in degrees as a two-digit number within the range of 0˚ to 90˚. The dip direction which is also known as the azimuth of the dip were also measured with compass clinometer in degrees, counted clockwise from the true north and expressed as a three-digits.

Determination of Blastability Index

Blastability index developed by Lilly (1986: 89-92) was used to determine the rock mass quality of the selected locations by combining the dynamic strengths of rocks, their spacing and orientation of joints planes and cracks as well as lithology and thickness of bedding. Rating for joint plane orientation (JPO) was arrived at with consideration of the collective effect of the joints measured at the selected locations. This rating was used throughout the estimation of the BI. BI is given by Equation 8 while Table 2 gives the description and ratings of index values.

$$BI = 0.5(RMD + JPS + JPO + SGI + HD) \tag{8}$$

where RMD is rock mass description, JPS is the joint plane spacing, JPO is the joint plane orientation, SGI is the specific gravity influence and HD is the hardness value on Mohs scale.

Data Analysis

The variations in independent parameters obtained were analysed with their corresponding dependent parameters using regression statistics. The R^2 values obtained were used to describe the percentage variations in the regression line of fit. Also, the Significance factor of regression equations and P values of parameters where used to determine statistical significance of regression equations and parameters respectively.

Table 2. Description of Blasting Index

Geomechanically Parameters	Rating
Rock Mass Description (RMD)	
Powdery/friable	10
Blocky	20
Totally Massive	50

Joint Plane Spacing (JPS) Close (< 0.1 m) Intermediate (0.1 to 1 m) Wide	 10 20 50
Joint Plane Orientation (JPO) Horizontal Dip out of face Strike out of face Dip into face	 10 20 30 40
Specific Gravity Influence (SGI)	$= 25 \times Density - 50$ (tons/m^3)
Hardness, Mohs Scale (HD)	$= \frac{UCS + 23.7}{47.6}$
Source: Lilly (1986: 89-92).	

Results and Discussion

Table 4 shows the strength properties of granitic rocks from 19 different locations with the UCS values ranges from 74.30 to 210.10 MPa with an average value of 111.70 MPa and standard deviation of 36.40, while E varies from 44.26 to 69.90 GPa with average value of 51.32 GPa and standard deviation of 6.87. The GS ranges from 2.48 to 2.83 with average value of 2.67 and standard deviation of 0.089, while the porosity ranges from 0.72 to 2.62 percent with mean value of 1.71 and standard deviation of 0.57. The BI values have the minimum of 48.43 and maximum of 74.68 with mean value of 58.37 and standard deviation of 6.98, while that of RMR varies from 50 to 115 with mean value of 73.68 and standard deviation of 18.31. The RN ranges from 35.8 to 58.45 with average value of 47.41 and standard deviation of 5.48.

The rock properties considered in this paper were coordinated such that each of them was compared individually with another strength properties of the rocks to see if there exists a relationship. Also, the ratios of E to UCS, RMR to BI and UCS to GS were compared with each of the other parameters for evaluation of their degree of association and to see value of their regression statistics.

Table 4. Results of Strength and other Rock Properties

LOCATION	RMR	BI	n (%)	E (GPa)	R_N	Gs	UCS (MPa)	$\frac{UCS}{G_S}$	$\frac{RMR}{BI}$	$\frac{E}{UCS}$
OD1	79	54.5383	1.58	51.16	50.52	2.65	110.85	41.8302	1.44852	0.46152
OD2	67	51.6891	1.80	49.38	43.65	2.63	101.40	35.8304	1.29621	0.48698
OD3	62	53.455	1.96	47.42	47.30	2.58	91.02	35.2791	1.15985	0.52098
OD4	85	60.8731	1.21	52.69	49.98	2.75	118.92	43.2436	1.39635	0.44307
OD5	65	49.0016	1.82	48.25	44.60	2.52	95.45	36.4313	1.32649	0.50550
OD6	59	63.227	2.12	47.03	43.36	2.52	88.95	33.1903	0.93315	0.52872
OG1	65	63.227	1.73	50.06	49.45	2.55	105.01	41.1804	1.02804	0.47672
OG2	53	74.6833	2.53	45.06	35.80	2.44	78.52	30.2000	0.70966	0.57387
OG3	50	68.5737	2.62	44.26	39.90	2.34	74.30	27.1168	0.72914	0.59569
OG4	59	60.2794	2.46	45.75	41.80	2.52	82.20	31.3740	0.97878	0.55657
OG5	60	53.8624	2.06	47.38	46.60	2.45	90.80	34.5247	1.11395	0.52181
OY1	85	54.0777	1.34	52.55	52.01	2.67	118.20	44.2697	1.57181	0.44459

OY2	70	59.8655	0.80	67.66	54.76	2.98	198.25	71.5704	1.83745	0.34129
OY3	72	61.9564	0.72	69.90	58.45	2.83	210.10	74.2403	1.85614	0.33270
OY4	66	67.8309	1.79	49.53	43.25	2.44	102.20	38.7121	0.97301	0.48464
ED3	90	52.0201	1.02	55.76	49.56	2.78	135.22	54.5242	1.7301	0.41237
AB1	89	54.688	1.16	53.85	51.60	2.71	125.10	47.2075	1.62741	0.43046
AB2	67	59.7876	1.79	48.90	50.30	2.59	98.88	36.8955	1.12063	0.49454
AB3	59	60.1944	2.24	47.23	46.20	2.50	90.01	33.0919	0.98016	0.52472
AB4	80	48.4252	1.54	51.38	51.10	2.63	111.98	43.7422	1.65203	0.45883

Uniaxial Compressive Strength and other Rock Properties

The influence of other properties of rock on UCS was evaluated and a comparative relationship was done using statistical analysis. The UCS is the intact rock strength that was measured in the laboratory and it was used to estimate E, while the RN measured the in-situ rock mass strength and this include the discontinuity properties of the rock mass. Discontinuities reduce intact rock strength by creating zones of weakness. Consequently, analysis of the extent to which rock mass properties influence UCS of rocks in the selected locations were done using regression models. The results from the measured rock mass properties were used for rock mass classification, to determine the average condition of the rock in-situ in terms of strength. The plot of the relationships is represented by broken lines and the best line of fit for regression statistic is defined by R2 value and it is shown on the plots.

The relationship between the UCS and porosity (n) of rocks in the selected locations are presented in Fig. 2. The degree of association between these parameters measured using correlation coefficient R2 of 0.78 is negative. This is a strong inverse relationship. That is, UCS reduces with increasing value of porosity and vice versa. The relationship is similar with what was reported by Rajabzadeh et al. (2011: 113-122).

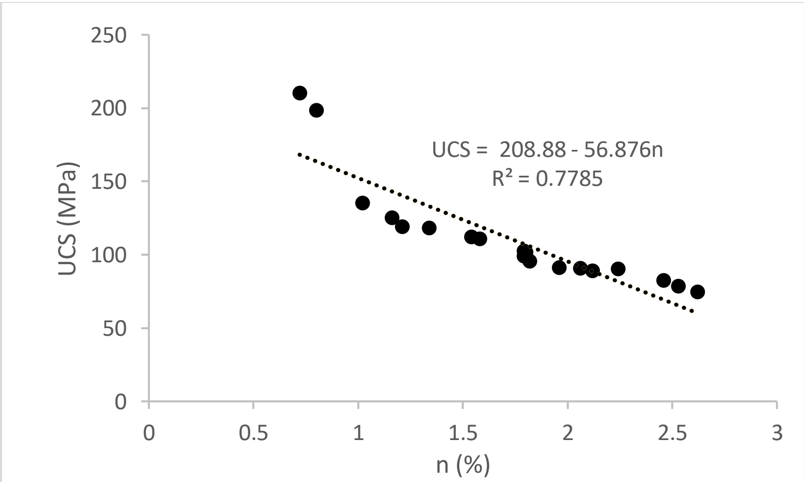

Fig. 2. UCS vs n

Fig. 3 shows the relationship between UCS and the RMR. It can be deduced that a very strong positive linear relationship exists between these parameters with R^2 of 0.92. This means that the UCS. depends strongly on the RMR. That is, as the values for RMR increases so UCS increases. In the actual sense, if rock structures are homogenous and have no discontinuity, laboratory samples will be a true representative of the rock in-situ and the coefficient of correlation could be 1. The correlation for these granitic rocks may be from the fact that the considered rocks are not weathered and the influence of their discontinuity properties are not well and similarly water penetration rate into granitic rocks is low.

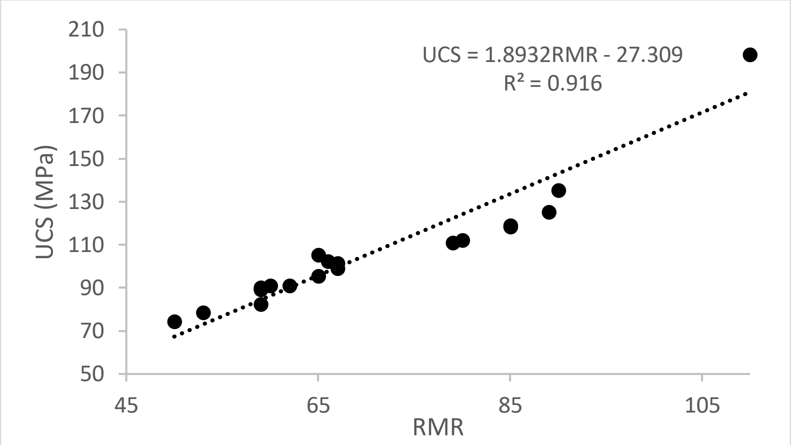

Fig. 3. RMR vs UCS

A linear function plot between UCS and R_N is shown in Fig. 4 The R^2 of this relationship is 0.84, The UCS can be predicted from the R_N using the mathematical relationship on the Fig. 4. The R_N is the value for the strength of in-situ rock mass and these results differ from that of the laboratory because several planes of weakness might had been considered. This is the reason for variations in the UCS values from the laboratory and that of R_N gotten from the field.

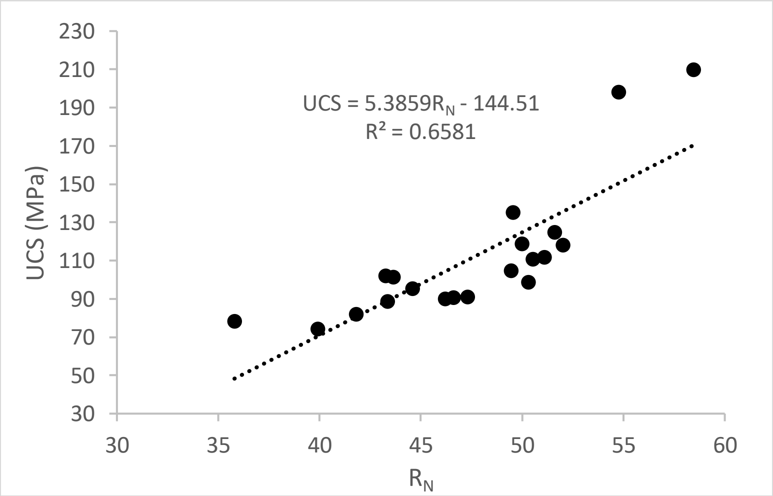

Fig. 4. UCS vs R_N

The specific gravity (G_S) for the selected granitic rocks varies from 2.34 to 2.98. Despite the little variations, it can be seen that UCS of rocks increases with G_S and a strong relationship with R^2 value of 0.77 was observed as shown in Fig. 5. This result is in line with some literatures (Yasar and Erdogan, 2004: 871-878).

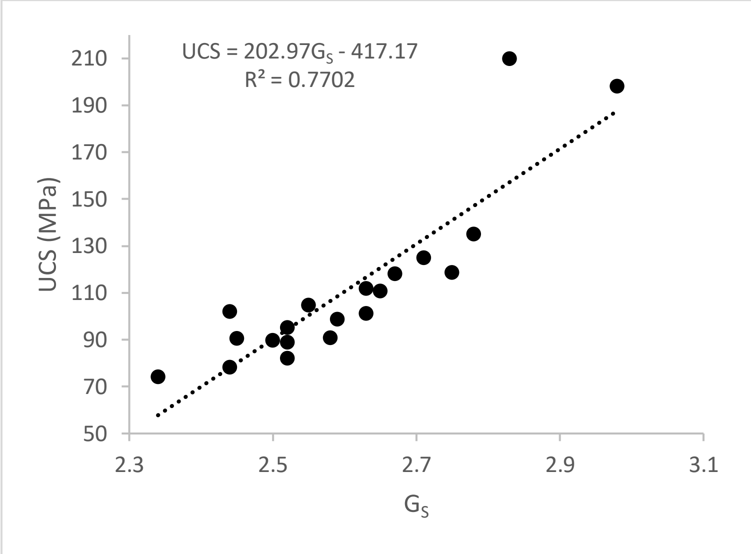

Fig. 5. UCS vs G_S

Figs 6 and 7 explained the relationship between RMR, R_N and n. A strong linear relationship was observed between RMR and R_N with R^2 value of 0.75 (Fig.6). The relationship shows that RMR increases with R_N and vice versa. Also, Fig. 7 shows the relationship between RMR and n. It can be seen from the figure that as n increases RMR reduces. A very strong degree of association exists between these parameters with R^2 of 0.91.

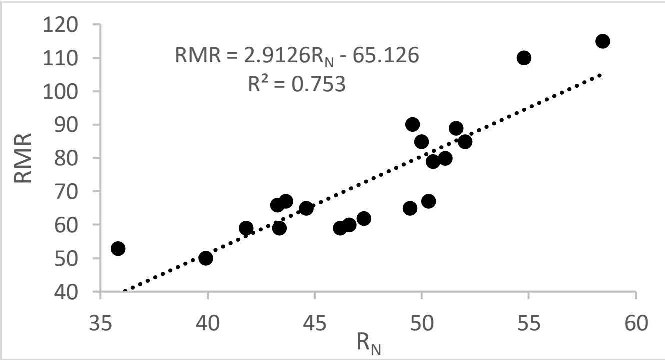

Fig. 6. RMR vs R_N

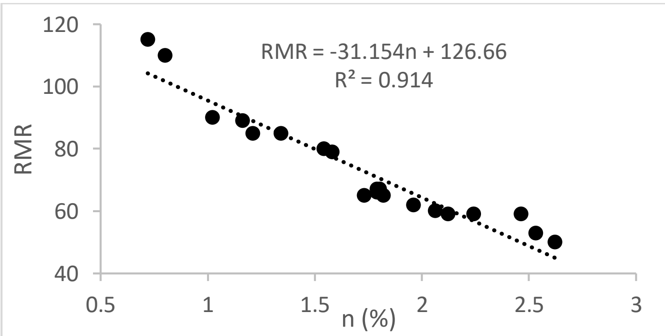

Fig. 7. RMR vs n

Relating Blastability with Rock Properties

Blastability can simply be regard as the resistance of rocks to blasting. This is expected to be related to lateral and longitudinal strain of rocks as well as their damped quality. In this paper, Lilly's blastability index principle (Lilly, 1986: 89-92) was evaluated and possibility of relationship with other rock properties were examined and the results are shown on Figs. 8-12. From the charts it can be seen that these relationships are very weak. This may be due to the fact that blasting index considered some rock parameters that were not captured in this paper. Nevertheless, measurement of resistance to blasting is also a function of inherent strength of rock masses as well as their elastic properties.

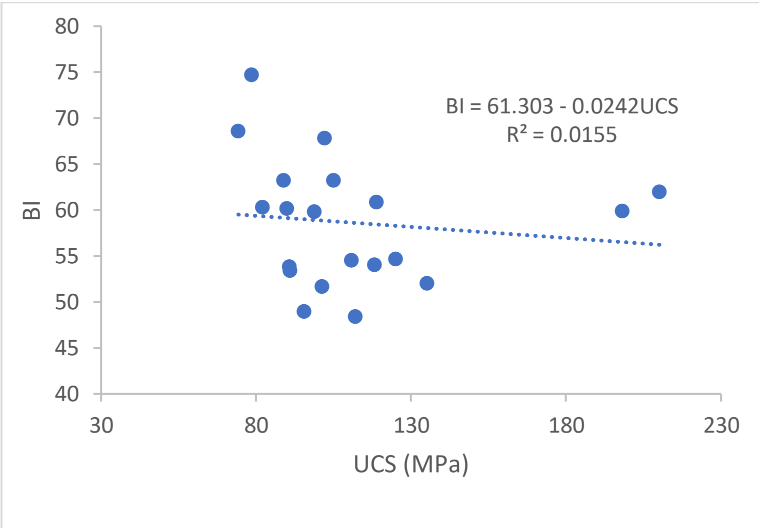

Fig. 8. BI vs UCS

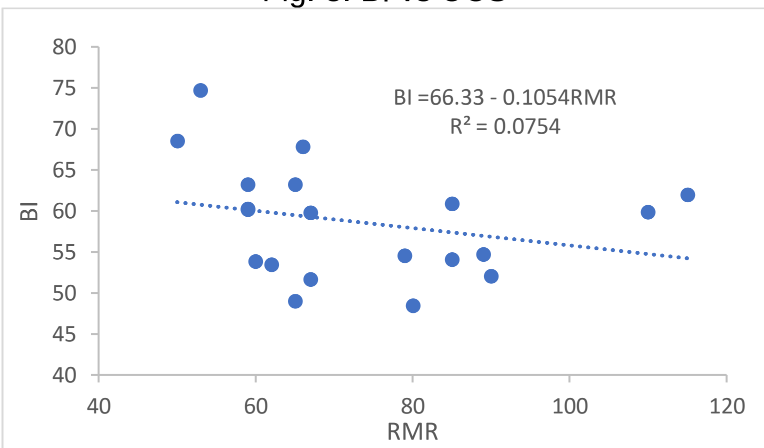

Fig. 9. BI vs RMR

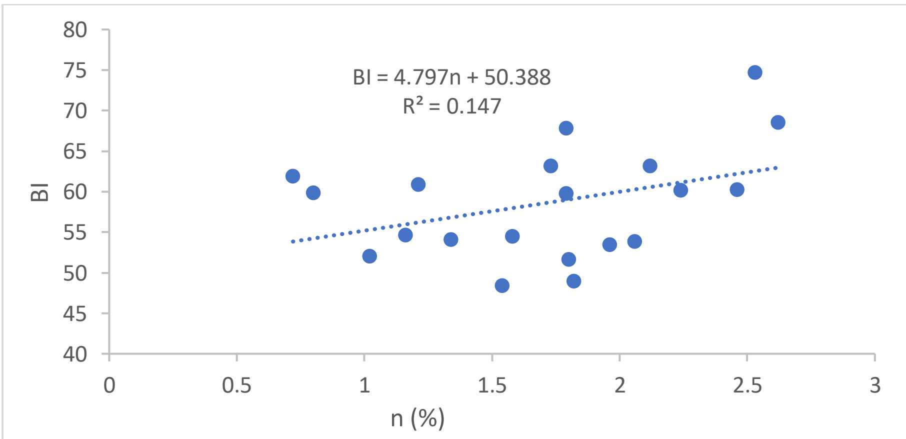

Fig. 10. BI vs n

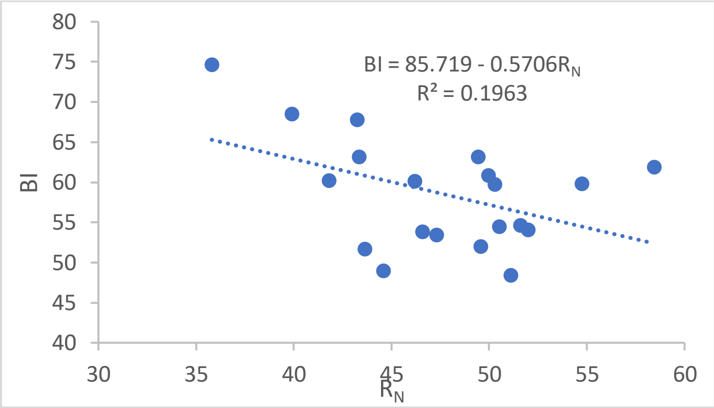

Fig. 11. BI vs R_N

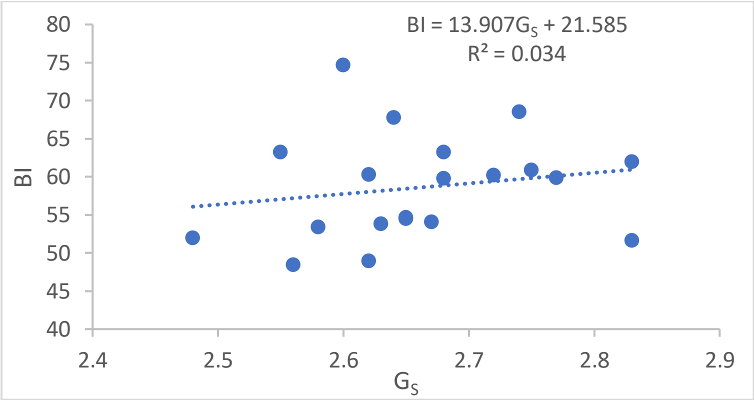

Fig. 12. BI vs G_S

Prediction of UCS using Multivariate Regression

Regression statistic was used to predict UCS from other rock properties considered in this paper excluding E. This is due to the fact that E was derived from UCS and their relationship may influence the outcome. The prediction model is presented in Equation 2 and shows a significance factor of 2.0E-08. This means that the predictive model is statistically significant as the significance factor is less than 0.05. The P-values which is a measure of the statistical significance of predictive variables in a regression statistic shows the reliability and importance of the predictive variables. The most determinant variable for prediction of UCS is the RMR which have a P-value of 0.008 which is below acceptable value of ≤ 0.05 (McLeod, 2019). The degree of variation explained by the UCS predictive model (Equation 9) is 0.94 which represent a very strong correlation.

$$UCS = 2.13\text{RMR} + 0.53\text{R}_N + 0.65\text{BI} + 24.45\text{G}_s + 11.43\text{n} - 192.24 \qquad (9)$$

where UCS is uniaxial compressive strength (MPa), R_N is Rebound hardness number, G_s is specific gravity and n is porosity (%). The variations in the predicted and measured UCS are presented in Fig. 13.

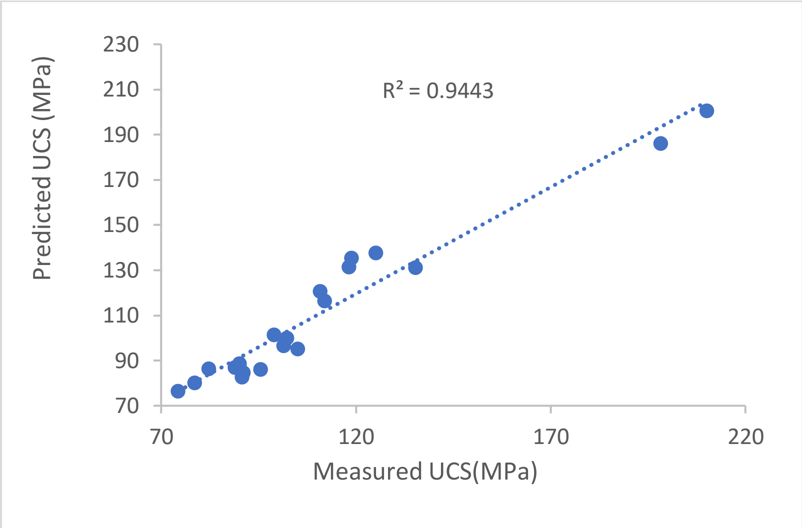

Fig. 13. Predicted vs Measured UCS

Evaluating the Relationship of Rock Properties Ratio

This paper exploits the possibility of understanding the relationships of ratio of rock properties. For this purpose, the ratios of rock mass rating to blastability index, modulus of elasticity to uniaxial compressive strength and uniaxial compressive strength to specific gravity were considered for evaluation and their respective degrees of association with other properties and among themselves were considered. This will help in estimation of a property is two other ones are given.

Ratio of Rock Mass Rating to Blastability Index

The rebound hardness index and uniaxial compressive strength are related to the ratio of rock mass rating to blastability index by positive linear functions with correlation coefficient of 0.79 and 0.69 respectively (Figs. 14 and 15), while it is negative linear function with porosity with correlation coefficient of 0.87 as shown in Fig. 16. The increase in the ratio of rock mass rating to blastability index due to subsequent increase in rebound hardness index and uniaxial compressive strength indicate that the strength of representative rock samples and in-situ rock masses measured respectively dictate the rating and the ability of rock mass to resist fragmentation and that porosity reduces strength of rock linearly. This is key to the design and evaluation of production rate in aggregates production as it dictates the type and volume of explosives to be used.

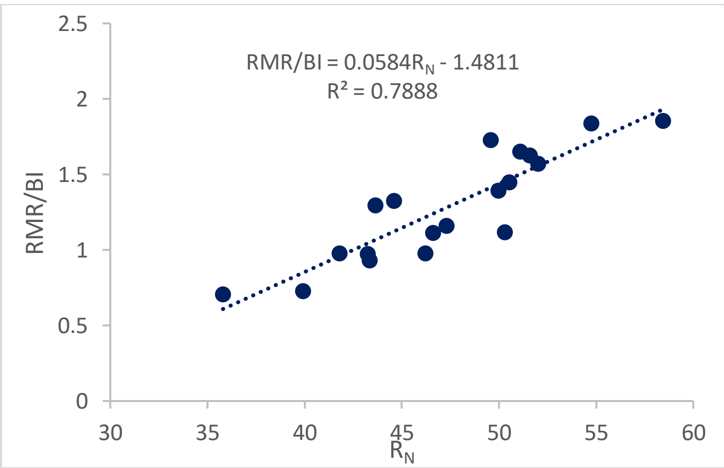

Fig. 14. RMR/BI vs R_N

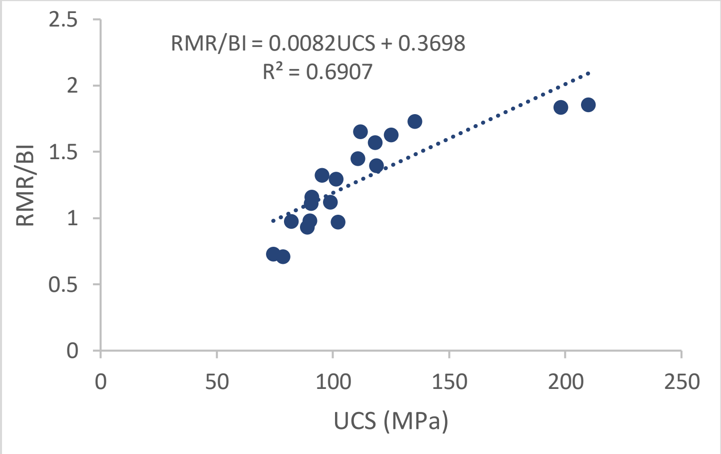

Fig. 15. RMR/BI vs UCS

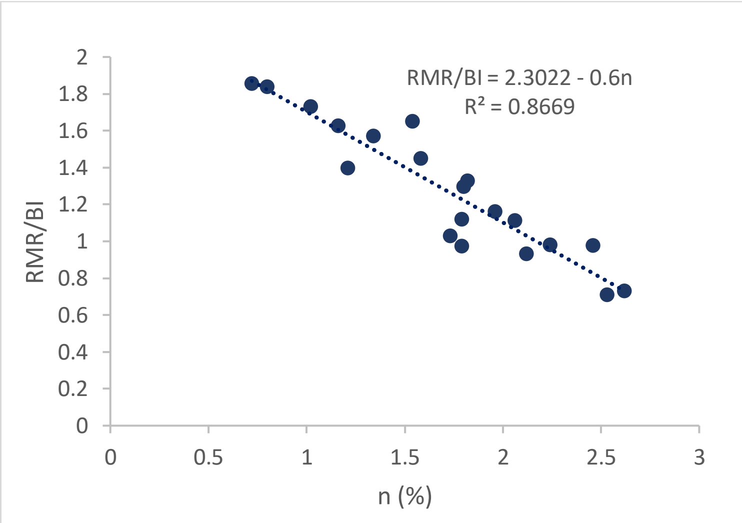

Fig. 16. RMR/BI vs n

Ratio of Uniaxial Compressive Strength to Specific Gravity

The ratio of uniaxial compressive strength to specific gravity was compared with porosity, rock mass rating and rebound hardness index and their results are presented in Figs. 17, 18, and 19 respectively. Positive linear relationship was observed between the ratios and rock mass rating as well as rebound hardness index but negative linear relationship with porosity. Very strong relationships were observed between porosity as well as rock mass rating and the ratio (UCS/G_S) with correlation coefficient of 0.82 and 0.94 respectively (Figs. 17 and 18), while a strong relationship was observed in the case of rebound hardness index with correlation coefficient of 0.68 (Fig. 19).

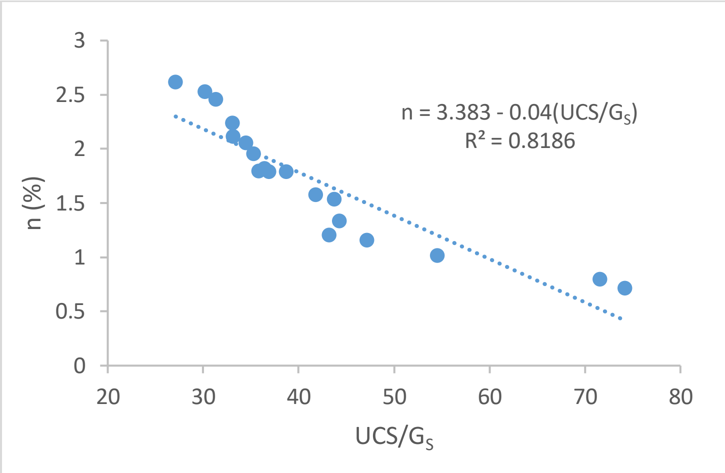

Fig. 17. n vs UCS/G_S

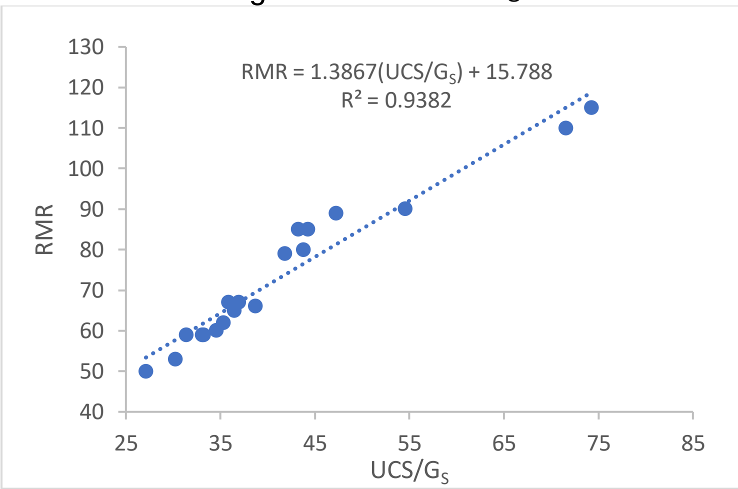

Fig. 18. RMR vs UCS/G_S

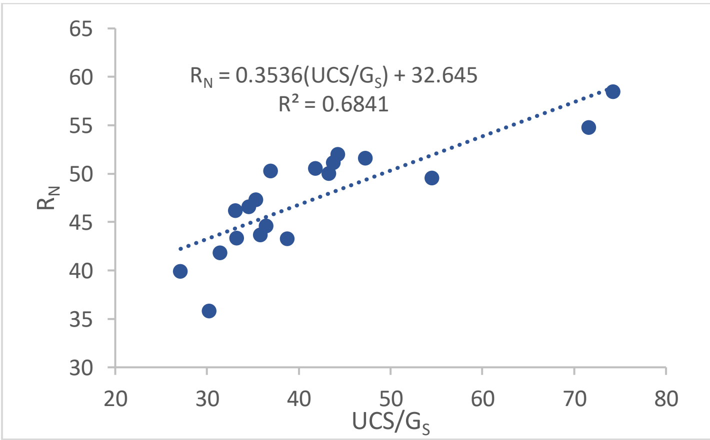

Fig. 19. R_N vs UCS/G_S

Ratio of Modulus of Elasticity to Uniaxial Compressive Strength

The slope of the relationships between ratio of modulus of elasticity to uniaxial compressive strength and four rock parameters namely blastability index, porosity, rebound hardness index and rock mass rating were done for comparison. Fig. 20 shows a very strong positive linear function for relationship between the ratio (E/UCS) and porosity with correlation coefficient of 0.96. The implication of this is that the porosity increases linearly with the ratio. Nonetheless, the slope of relationship between the ratio and rebound hardness index as well as rock mass rating shows negative linear function that have very strong relationship with correlation coefficient of 0.80 and 0.95 respectively (Figs. 21 and 22).

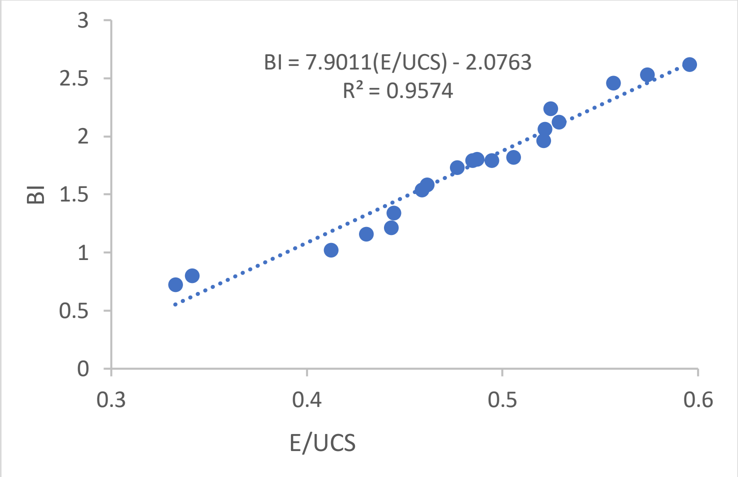

Fig. 24. E/UCS vs n

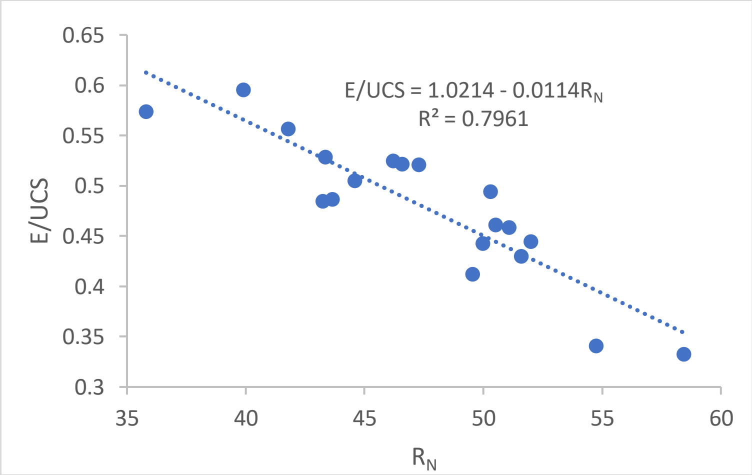

Fig. 25. E/UCS vs R_N

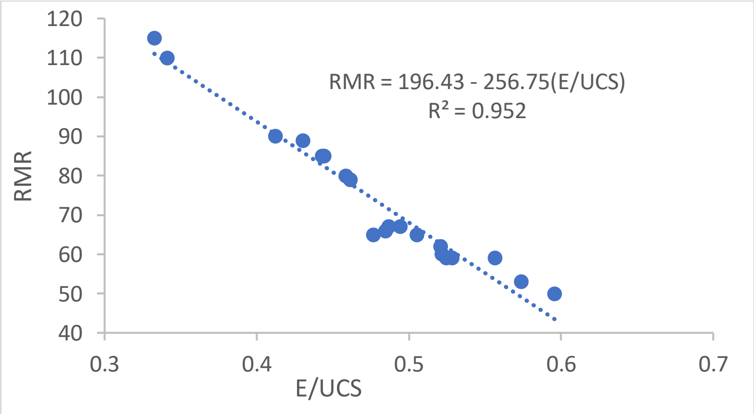

Fig. 22. RMR vs E/UCS

Relationship between the Ratios

Three ratios were considered in this paper and for emphasis sake they are rock mass rating to blastability index, modulus of elasticity to uniaxial compressive strength and uniaxial compressive strength to specific gravity. The relationships between these ratios were examined. The slope of the relationship between RMR/BI and UCS/G_S is presented in Fig. 23 and the result shows a strong positive linear function with correlation coefficient of 0.73. That is, RMR/BI increases as UCS/G_S increases. Nonetheless, the slope of the relationship between RMR/BI and E/UCS shows a negative linear relationship that is very strong with correlation coefficient of 0.86 (Fig. 24). Likewise, the relationship between E/UCS and UCS/G_S is a very strong linear function with correlation coefficient of 0.92 as shown in Fig. 25.

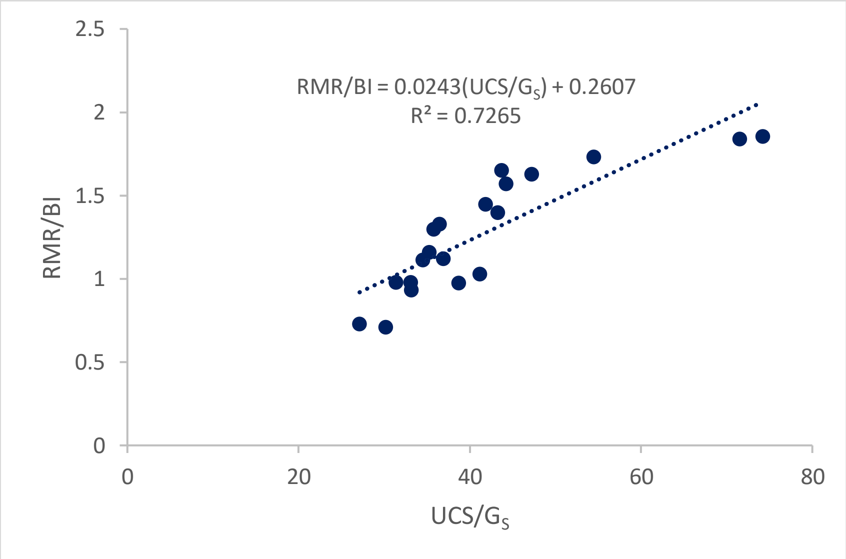

Fig. 23. RMR/BI vs UCS/G_S

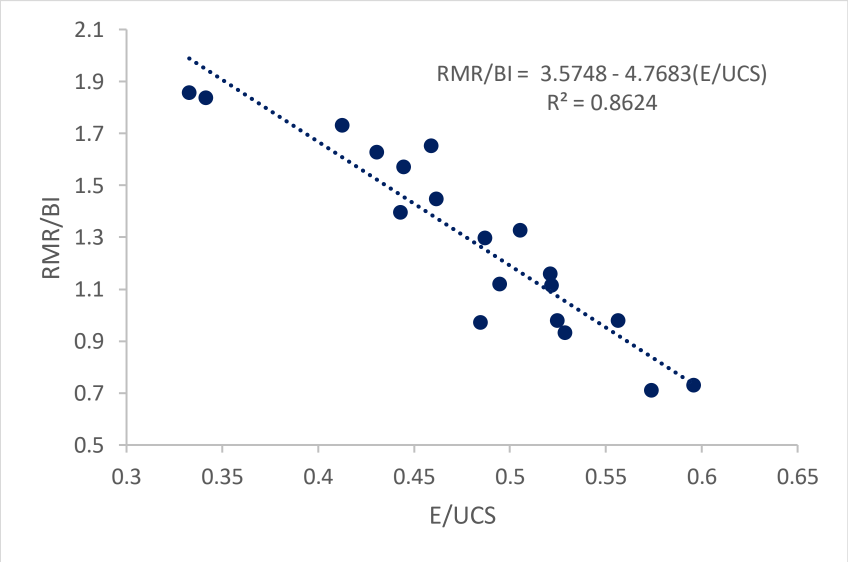

Fig. 24. RMR/BI vs E/UCS

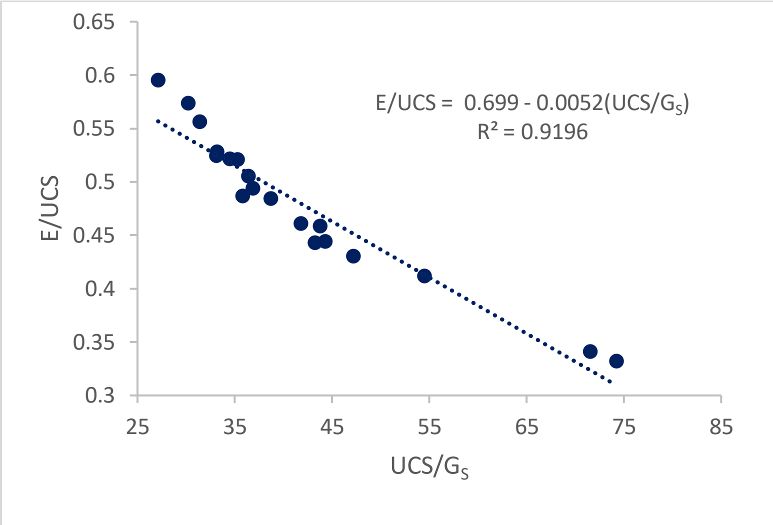

Fig. 25. E/UCS vs UCS/G_S

Sensitivity Analysis

Sensitivity analysis was conducted to determine the effects of contributing parameters on UCS. That is, the degree of sensitivity of the model resulting from variation of an input variable. This shows the importance of each of the input variable (hardness rebound number, specific gravity, blastability index, rock mass rating and porosity) in the prediction of the output variable (Uniaxial compressive strength). As it is shown of Fig. 26, porosity has the highest influence in UCS prediction with value rated 0.87, followed by RMR (0.47), while blastability index is the least influential parameter in UCS prediction.

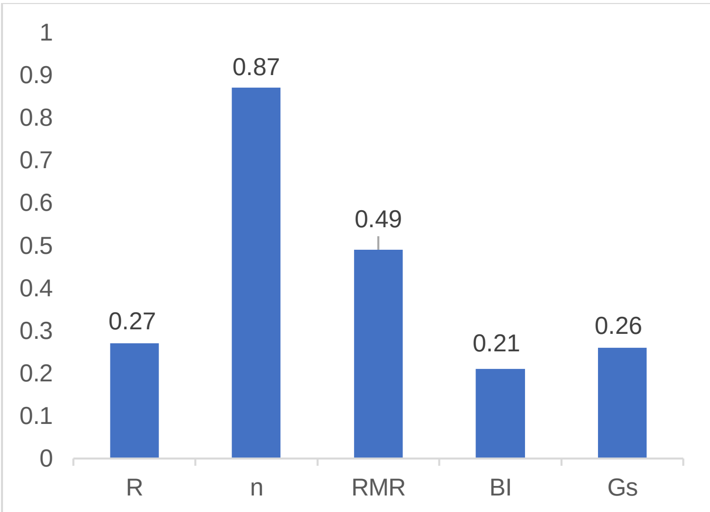

Fig. 25. Strength of input Parameters in UCS Prediction

Conclusion

The relationships between UCS, E, n, R_N, G_S and BI been evaluated in this paper are meant to predict one of the parameters when one or two of them are available. Also, the relationships between their ratios are meant to evaluate how the combination of any strength parameters affect other parameters. The main conclusions for the relationships between rock parameters and their ratios can be stated as follows:

1. The blastability index which relate the strength of rocks with fragmentation have very weak linear relationships with other strength parameters.

2. Rebound hardness index, rock mass rating and uniaxial compressive strength shows in their relationships that the higher their values, the greater the strength of either in-situ rocks or representative samples tested in the laboratory. Their relationships with one another is positive.

3. Porosity is a major parameter that reduces the strength of rocks as it shows negative relationships with all parameters for estimation of rock strength.

4. The model developed for uniaxial compressive strength can be used for prediction of UCS for granitic rocks as 94 percent of the measured UCS were accounted for in the predicted UCS.

References

Bieniawski, Z. (1973). Engineering classification of jointed rock masses: Transaction of the South African Institution of Civil Engineers, 15(12), 335-344. Available at: http://worldcat.org/issn/00097845

Boii, C.B., Braun, K. (1991). Tectonic fabric and blasting in dolomite rocks. 7th International Congress on Rock Mechanics, Aachen. Available at: https://hrcak.srce.hr/file/20657

Brown, E.T. (1989). ISRM. Rock Characterization Testing and Monitoring. International Society for Rock Mechanics Commission. Oxford: Pergamon Press.

Choudhary, B.S., Sonu, K., Kishore, K., Anwar, S. (2016). Effect of rock mass properties on blast-induced rock fragmentation Int. J. Mining and Mineral Engineering, 7(2), 89-101. https://doi.org/10.1504/IJMME.2016.076489

Harrison, J. P., Hudson, J. A. (2001). Engineering Rock Mechanics Part 2: Illustrative Worked Examples. London: Elsevier.

Hentz, F., Daudeville, L., Donze, F. (2004). Identification and validation of a discrete element model for concrete. Journal of Engineering Mechanics, 30(6). https://doi.org/10.1061/(ASCE)0733-9399(2004)130:6(709)

Jimeno, C.L., Jinemo, E.L., Carcedo, F.J.A. (1995). Drilling and Blasting of Rocks: Rotterdum: Brookfield Publication. Available at: http://worldcat.org/isbn/9054101997

Lilly, P. A. (1986). An empirical method of assessing rock mass blastability. Proceedings of large open pit planning conference. Parkville, Victoria: AusIMM, pp. 89-92.

McLeod, S.A. (2019). What a p-value Tells You About Statistical significance. Simply Psychology. Available at: https://www.simplypsychology.org/p-value.html

Okewale, I. A., Olaleye, B.M. (2013). Characterization of Some Selected Limestone Deposits in Ogun State, Nigeria for Prediction of Penetration Rate of Drilling. IOSR J. Eng. 3(7), 25-30. https://doi.org/10.9790/3021-03712530

Palmström, A. (1982). The Volumetric Joint Count- A Useful and Simple Measure of the Degree of Rock Jointing. Proceedings of the 4th International Congress International Association Engineering Geology (Delphi), 5, 221-228.

Palmstrom, A. (1996). RMi- A system for Characterizing Rock Mass Strength for Use in Rock Engineering. J. of Rock Mech. and Tunneling Tech., 1(2), 69-108. https://doi.org/10.1016/0886-7798(96)00028-4

Palmström, A. (2005). Measurements of and Correlations between Block Size and Rock Quality Designation (RQD). Tunnels and Underground Space Technology, 20, 362-377. https://doi.org/10.1016/j.tust.2005.01.005

Rajabzadeh, M., Moosavinasab, Z., Rakhshandehroo, G. (2011). Effects of Rock Classes and Porosity on the Relation between Uniaxial Compressive Strength and Some

Rock Properties for Carbonate Rocks. Rock Mechanics and Rock Engineering, 45, 113-122. https://doi.org/10.1007/s00603-011-0169-y

Sirveiya, A.K., Thote, N.R. (2012). Assessing the effect of rock mass properties on rock fragmentation. In: Measurement and Analysis of Blast Fragmentation. Boca Raton: CRC Press.

Ulusay, R., Hudson, J.A. (2007). ISRM. The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974-2006. Ankara: International Society of Rock Mechanics.

Yasar, E., Erdogan, Y. (2004). Correlating sound velocity with the density, compressive strength and Young's modulus of carbonate rocks. Int. J. of Rock Mech. & Min. Sci. 41, 871-878. https://doi.org/10.1016/j.ijrmms.2004.01.012