Correlation of Mechanical Properties of Some Rocks in South-Eastern Nigeria

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Abstract- The mechanical properties of five different rock types from south-eastern Nigeria were determined through uniaxial compressive strength (UCS) test, point load strength test, impact strength index test and natural density test. The results were correlated by using correlation coefficient and regression analyses. The equation of the best-fit line, and the correlation coefficient were determined for each regression. Among the four rock properties correlated in terms of drillability (penetration rate) of percussive or rotary drilling rig, the uniaxial compressive strength, the impact strength index and natural density are found to be the dominant properties affecting penetration rate of rotary drills.

Index Terms- uniaxial compressive strength, impact strength index, natural density, point load, correlation coefficient

I. INTRODUCTION

Rock aggregate is used in very different construction works such as building constructions and most public projects, including roads and highways, bridges, railroads etc. An enormous amount of aggregate is used in the world each year. The demand for crushed stone aggregate is increasing from day to day because of increasing expansion of highway and other construction works and decreasing natural aggregate resources in the world (Kahraman and Fener, 2007). The suitability of aggregate for use in a given type of construction is determined by evaluating the materials in terms of its physical and mechanical properties.

Most specifications for aggregates require the material to be strong (Al-Harthi, 2001; Ugur et al, 2010). Aggregates used must be tough and abrasion resistant to prevent crushing, degradation and disintegration when stockpiled, fed through an asphalt plant, and subjected to traffic loadings.

Deere and Miller (1966) published extensive research on the relation between shore hardness (SH) and uniaxial compressive strength (UCS) of 28 different rock types, using the C-2 type shore scleroscope. The SH values were also used to determine the UCS of rocks (Yasar and Erdogan, 2004; Shalabi et al., 2007; Tumac et al., 2007). Researchers have tried to develop empirical methods to estimate the uniaxial compressive strength of rocks by using tests such as Los Angeles abrasion, Point load index, Schmidt hammer, slake durability and shore hardness tests. These tests have less strict requirements for sample preparation than the uniaxial compressive strength (UCS) test and also cheap and easy to use. The correlation index tests are widely used to predict the UCS instead of measuring it.

This paper wants to correlate the various mechanical properties of the rocks around Lekwesi, in South-Eastern Nigeria. The mechanical properties to be considered are: Point load test, Impact strength test, density test and Uniaxial compressive strength test, considering their drillability.

The concept of specific energy was proposed by Teale (1965) as a quick means of assessing rock drillability. Teale defined specific energy as the energy required to remove a unit volume of rock. However, another definition of specific energy as the energy required to create a new surface area was given by Parthinker and Misra (1976). It was Rabia (1985, 1982) who concluded that specific energy in terms of either unit volume or new surface area is not a fundamental intrinsic property of rock, and that the breakage parameters or operational parameters control numerical value of specific energy. Wayment and Grantmare (1976), and Mahyera et al (1982) studying high energy hydraulic impactors concluded that, for a given rock type specific energy is proportional to the inverse root of the blow energy. Destruction of rocks, either by drilling, cutting breaking and sawing has some mechanical similarities. Specific energy is a common concept of rock destruction governing the efficiency of any rock excavation process. It was Hughes (1972) and Mellor (1972) who demonstrated that specific energy may be formulated thus:

$$SE = \sigma_c^2 / 2E \text{ ....equation (1)}$$

Where SE is the specific energy, E is the secant modulus from zero to load to failure and σ_c is the rock compressive strength.

Farmer and Garritty (1987) and Pool (1987) using the same concept as explained earlier showed that for a given power of road header, excavation rate in m^3/h may be predicted significantly using specific energy values as given in equation (1). Again, Krupa and Sekula and co-workers (1994, 1993) noticed that for a given power, advance rate of a full force tunnel boring machine is directly related to specific energy values as formulated in equation (1).

There are some models in percussive drilling or rotary cutting which assumed that thrust force is a product of rock compressive strength and tool projectile area, given good agreement between predicted and actual advance rate values (Roxbotough and Phillips, 1975; Bernola and Oyanguran, 1987). This fact emphasizes that rock compressive strength should be considered as one of the major properties in a model for estimating drilling rates (Akun and Karpuz (2005), Altindag (2004, 2006). However, in rotary drilling or in rock cutting using drag tools, tensile strength, compressive strength and shear strength are the dominant rock properties as explained by Evans and Pomeroy (1966) and Nishimatsu (1972).

Sinkala (1991) emphasized that reduction in a hole deviation is vital in order to minimize operational costs and stated that among the controllable factors with a major effect on hole trajectory deviation, are thrust, torque and operator. The main function of the thrust is to maintain bit-rock contact and to keep the drill string joints closed before the pulses arrive so that the energy losses are minimized. The torque is applied mainly to move bit inserts to new surfaces and simultaneously to tighten drill string joints before the arrival of stern waves (Sinkala, 1991). Sinkala then derived the following theoretical expression for minimum torque necessary to maintain constant bit rotation and found good agreement between actual and theoretical values.

$$\tau = \frac{FD}{3}\sqrt{\frac{R}{15f\theta}} \cdots \text{...................equation (2)}$$

where τ is the bit rotation torque, F is the thrust on the bit, R is the penetration rate, f is the piston impact frequency, D is the bit diameter, and θ is the button diameter.

The above consideration showed that automatic control of drilling parameters may be realized as rock condition changes. Sinkala's contribution enabled the sub-level intervals from LKAB-Kirum mine to be increased from 22 to 27m, thereby increasing the scale of mining and minimizing drilling cost.

II. RESEARCH ELABORATIONS

Basic intrusive rocks and shales of Cretacious age in parts of Eastern Nigeria were sampled using Slanzi rotary diamond drilling rig. Drilling performance was carried out on five different rock types within a mine area of 81,750m^2. Drill type, bit type and diameter, feed pressure, rotation pressure, blow pressure, air pressure, net drilling time, etc were recorded during the operation and hence the net penetration rate calculated for each rock type (table 1) and the samples were later subjected to the following tests:

Table 1: Drill Penetration Rates through Different Rock Types

Rock Type	Net Penetration Rate (m/min)
Lateritic Soil	0.75
Light Grayish Shale	0.44
Dark Grayish Shale	0.40
Carbonate Rock	0.12
Dolerite	0.03

Bit diameter, 76-89mm; rock drill power (14-17.5 kW); bpm (3000-3600); puldown pressure (60-80bar); blow pressure (100-120 bar); rotational pressure (60-70 bar).

2.1 Uniaxial Compressive Strength Test: Uniaxial Compressive Strength Test was performed on trimmed core samples having a diameter of 33mm and a length- to-diameter ratio of 2. The applied stress rate was in the range of 0.4 - 1.2MPa/s and the results are given in table 2

2.2 Point Load Test: This test was carried out on the cores having a diameter 33mm and a length of 66mm. The results were corrected to a specimen diameter of 50mm and the following results were obtained (Table 3).

2.3 Impact Strength Index Test: The device of Evans and Pomeroy (1966) was used in the impact strength index test. A 100g sample of rock in the size range 3,175 - 9.525 mm is placed in a cylinder of 42.86 mm diameter and a 1.8 kg weight is dropped 20 times from a height 30.48cm on to the rock sample. The impact Strength index was then measured (i.e. the amount of rock remaining in the initial size range after the test, table 4).

2.4 Density Test: Trimmed core samples were used in the determination of natural density. The specimen volume was calculated from an average of several calliper readings. The weight of the specimen was determined by a balance capable of weighing to an accuracy of 0.01 of the sample weight. The natural density values were obtained from the ratio of the specimen weight to the specimen volume. The average results of the tests are listed in table 5.

Table 2: Uniaxial Compressive Strength (UCS) Test

Rock Type	Mean Compressive Strength (MPa)	Standard Deviation	Coefficient of variation %
Lateritic Soil	18.74	12.56	67.02
Light Grayish Shale	74.55	11.79	15.81
Dark Grayish Shale	88.42	11.85	13.40
Carbonate Rock	109.13	8.34	7.64
Dolerite	180.50	11.73	5.23
Average			21.82

Table 3: Point Load Strength Test

Rock Type	Mean Point Load Strength (MPa)	Standard Deviation	Coefficient of variation %
Lateritic Soil	1.8	0.41	22.78
Light Grayish Shale	4.2	0.34	8.10
Dark Grayish Shale	4.6	0.32	6.96
Carbonate Rock	5.6	1.56	27.86

Dolerite	10.5	0.89	8.48
Average			14.84

Table 4: Results of Impact Strength Test

Rock Type	Mean Impact Strength	Standard Deviation	Coefficient of variation %
Light Grayish Shale	54.2	0.75	- 1.38
Dark Grayish Shale	61.5	0.27	- 0.44
Carbonate Rock	82.9	- 0.17	- 0.21
Dolerite	92.2	- 0.65	-.0.70
Average			- 0.68

Table 5: Natural Density Test

Rock Type	Density (g/cm^3)	Standard Deviation	Coefficient of variation %
Light Grayish Shale	2.21	0.12	5.43
Dark Grayish Shale	2.36	0.16	6.78
Carbonate Rock	2.73	0.13	4.76
Dolerite	2.98	0.21	7.05
Average			6.01

III. RESULTS AND FINDINGS

Two statistical analyses, coefficients of variation and regression analyses were used in this study.

3.1 Coefficients of variation

The coefficients of variation (CoV) were calculated to evaluate the variability of test results for each test and rock type as shown in tables 2 to 5. The CoV is obtained by dividing the standard deviation by the population mean and expressing it as percentage. The higher the CoV, the more variable are the results of a given test.

The uniaxial compressive strength (UCS) values range from 18.74 MPa for lateritic soil to 180.50 MPa for dolerite while the CoV range from 5.23% for dolerite to 67.02% for lateritic soil with overall average of 21.82% (table 2).

The point load strength index values range from 1.8MPa for lateritic soil to 10.5MPa for dolerite with the CoV ranging between 6.96% for light gray shale to 27.86% for shalley carbonate and an overall average of 14.84% (table 3).

The impact strength index range from 54.2 for the light grayish shale to 92.2 for dolerite with the CoV value ranging from 0.21% for shalley carbonate to 1.38% for light grayish shale with an overall average of 0.68 % (table 4)

The natural density values range from 2.21 g/cm^3 for light grayish shale to 2.98 g/cm^3 for dolerite while the CoV range from 4.76% for light Shelley carbonate to 7.05% for dolerite with overall average of 6.01% (table 5).

3.2 Regression Analysis

Penetration rates were correlated with the rock properties using the method of least-squares regression. The equation of the best-fit line, 95% confidence limits, and the correlation coefficient (r) were determined for each regression. As shown in the plots, there is an inverse relationship between penetration rate and the horizontal axis (Figures 1- 4).

The linear relationship between penetration rates and the UCS values shown in figure 1 verifies the theoretical consideration that thrust force and penetration rate are related to the product of rock compressive strength and tool projectile area. The equation of line is $y = -0.0045\sigma_c + 0.77$; $r = 9.4590 \times 10^{-01}$ or -0.95 with a standard error, Se = ± 0.50 where y is the penetration rate (m/min) and σ_c is the uniaxial compressive strength (MPa).

A linear relationship is seen between the point load index and the penetration rate (figure 2) and the equation of line is $y = -0.079P_l + 0.77$; $r = 8.932 \times 10^{-01}$ or -0.89 with a standard error, Se = ± 0.15 where y is the penetration rate and P_l is the point load index (MPa). Again, there is an inverse relationship between the penetration rate and point load index.

The plot of penetration rate as a function of the impact strength index is shown in figure 3. There also exist a linear relationship between penetration rate and the impact strength index as shown in the equation of line, $y = -0.011 I_s + 1.07$; $r = -9.955 \times 10^{-01}$ or -0.996 with a standard error, Se = ± 0.04, where y is the penetration rate and I_s is the impact strength index.

A linear relation between penetration rate and natural density is found in figure 4 with the equation of line as $y = -0.57\rho + 1.72$; r = -0.98; Se = ± 0.04 where y is the penetration rate and ρ is the natural density (g/cm^3).

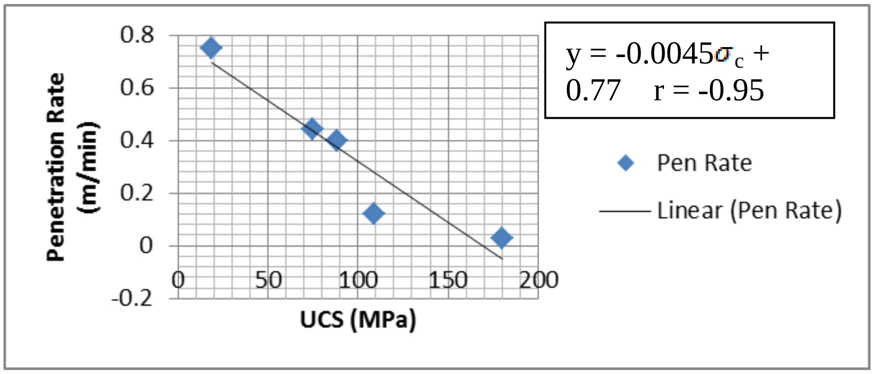

Fig 1: Penetration Rate versus Uniaxial Compressive Strength

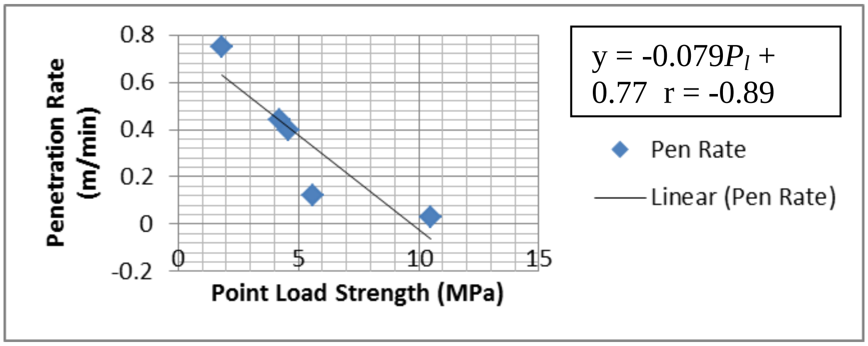

Fig 2: Penetration Rate versus Point Load Strength

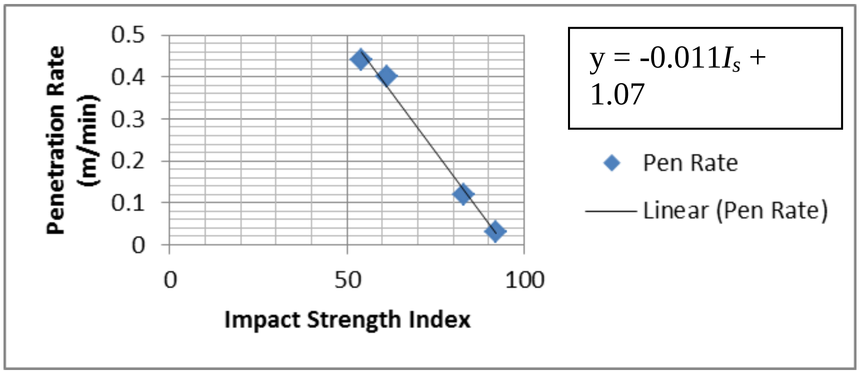

Fig 3: Penetration Rate versus Impact Strength Index

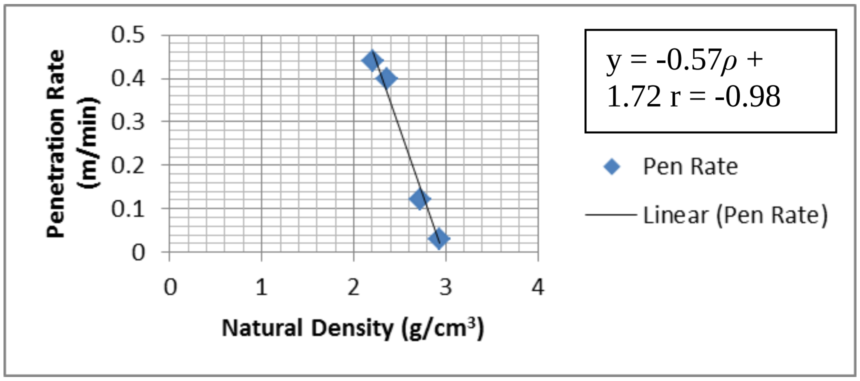

Fig 4: Penetration Rate versus Natural Density

IV. FINDINGS

The impact strength test yields the most consistent result of the four methods used. Only the coefficient of variation of the point load test is a little close to UCS while those of impact strength and natural density are far. Both UCS and point load have relatively high values of coefficient of variation, though the variability of their results is still within acceptable limits for most engineering purposes.

Theoretical considerations given in the paper shows that penetration rates of percussive drills are directly proportional to blow energy, blow frequency, energy transfer rate and inversely proportional to hole diameter and specific energy values. However, specific energy is not a fundamental intrinsic rock property and operational parameters like blow energy controls the numerical values of specific energy. It is concluded that for a given power of drilling, specific energy is a direct function of rock parameters and may be formulated as given in equation (1). There are some models in percussive or rotary drilling, assuming that thrust force for unit length of advance is a product of compressive strength and tool projectile area. These two realities explain the highly statistical relations between penetration rates and elastic modulus values.

From the rock properties adopted in this study, UCS exhibited the strongest correlation with penetration rate, followed by impact strength index and natural density while point load strength showed weak correlations.

V. CONCLUSIONS

The mechanical properties of four different rock types were determined and correlated by using correlation coefficient and regression analyses. The equation of the best-fit line, and the correlation coefficient were determined for each regression. Among the four rock properties correlated in terms of drillability (penetration rate) of percussive or rotary drilling rig, the uniaxial compressive strength, the impact strength index and natural density are found to be the dominant properties affecting penetration rate of rotary drills.

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