Strength Evaluation of Rocks in Amata–Lekwesi, Eastern Nigeria
Using Diamond Coring Bit Penetration Rate

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INTRODUCTION

Rotary drilling technology has continued to improve overtime both in the oil industry and for rock coring in determining the trends of mineral deposit and mine design. Since the evolution of rotary steer-able drilling technology in the late 1990s, there has been increased flexibility and greater reliability for drilling complicated well bore trajectories in some environments. The earliest directional drilling technology involved devices such as whip-stocks to deflect the drill bit, a method that offered limited control and that too frequently resulted in missed targets. The addition of steer-cable systems to rotary drilling has made exploration and production (E&P) companies routinely challenged well trajectories to intersect distant or multiple targets and to maximize oil and gas production. Musa et al (2003) also found out that steer-able drilling systems are able to compartmentalize reservoirs, deepwater reservoirs, environmentally constrained developments, distant platforms or drilling pads and even certain marginal fields in which economic success demands an accurate placement of a high quality borehole. Again, Logging-While-Drilling (LWD) can help refine trajectories to take advantage of the well placement capabilities of rotary steer-able systems (Tribe et al. 2003).

The strength of a rock material is a time-dependent property. If it is stressed above a certain level the material will creep, flow, and crack, until ultimate failure occurs. The United States Bureau of Mines (USBM) standardized procedure for rock test quotes loading rates between 689 to 2,758 kN /m² per sec, while American Society for Testing and Materials (ASTM) 6170-50 specifies a loading rate not more than 689 kN /m² per sec, or alternatively a rate of deformation (measured by the rate of lowering the compression –head of the testing machine) not greater than 1.3mm /min. Roberts, (1977) reported a uniaxial compressive strength of between 17.24–68.95 kN /m² in foliated rock specimen.

Protodiakonov (1962) proposed a method of assessing the uniaxial compressive strength of irregularly shaped rock fragments by measuring the individual volume and weight of each fragment specimen, and then crushing the specimen in a compressive press. He then quoted the mean breaking force (F) as being related to the specimen volume (V) in the form:

\[ \log F = 0.63 \log V \]

where \( f \) = 0.19\( f_c \)

\[ V = \text{specimen volume} \]

\[ f_c = \text{uniaxial compressive strength} \]

whereafter, a Protodiakonov number was evolved and used as an index of impact toughness in rock strength evaluation.
Hobbs, (1964) modified Protodiakonov’s technique by crushing irregularly shaped rock specimens between the jaws of a 10-ton hydraulic press. In this case the specimens are loaded parallel to their smallest dimension, and perpendicular to any lamination. The maximum height of each fragment in the direction of loading is measured before each test. After the fragment has been loaded to failure the area of contact of the ends of the fragment on the loading plates was also measured. This is done by placing a piece of carbon paper and a piece of graph paper between the specimen and each of the loading plates. After the test the area of the carbon imprint on each of the graph papers were measured, and the mean of two areas taken as the area of contact of the plates with the specimen. The results were analyzed statistically and plotted to determine the regression line of the compressive strength (f_c), relative to the average applied stress at fracture. And this was observed as:

\[ f_c = 0.917a - 3180 \text{ psi} \]  

(2)

The above equation follows when the compressive strength \( f_c \) is determined on cylinder of mudstone and siltstone measuring 1cm long by 1cm diameter. The time, trouble, and expense involved in making uniaxial compressive tests on rock materials by the proposed standard laboratory procedures, led many Geotechnical Scientists to seek other methods of approach in the assessment of rock strength. One of such methods is the in-situ drilling penetration rate.

Rock compressive strength from drilling tests have been evaluated by Tsoutrelis (1969) using the relationship between the penetration rate \( \mu \) of the rotary diamond drill, measured as penetration distance per revolution of the bit at the start of the drilling and the thrust \( F \) applied to the drill.

Rock hardness was measured by CERCHAR laboratory, France, using tungsten – carbide drill bit. Here the index of hardness is defined as the time taken to drill a hole 1cm deep, at a constant speed of rotation, and using a standard thrust \( F \) on the drill. Some rock strength classification has been done based on this and abrasivity test.

The concept of specific energy has also been applied by Teale (1965) to processes of rock excavation by drills and rotary boring and tunneling machines. Specific energy is here defined as the energy required for excavating a unit volume of the rock strength in relation to the effectiveness of any rock cutting process. The specific energy is determined by using a rotary drill on the rock material. In this operation, work is done by the thrust \( F \) and by the torque \( T \). In material Science, the strength of a material is its ability to withstand an applied stress without failure. The applied stress may be tensile, compressive or shear (Beer and Johnston, 2006).

The average strength of a rock mass surrounding a tunnel within a pillar or in the rock mass into which a slope has been excavated is dependent upon the degree of confinement provided by the mass (Hoek, 2005). Rock engineers widely use the Uniaxial Compressive Strength (UCS) of rocks in designing surface and underground structures (Akran and Baker, 2007). The uniaxial compressive strength of intact rock is the main parameter used in almost all engineering projects (Zorlu et al, 2008). The Uniaxial Compressive tests separate rock units into different strength categories in ASTM D5878 (ASTM, 2008) and these have been described by Gorski et al (2010).

This work intends therefore to evaluate in-situ rock strength and quality based on drill penetration rate \( \mu \) from the perspective of the energy concept, rock quality designation (RQD), and recovery of the cores and hence attempt making a strength classification of the rocks in the Amata – Lekwesi Area.

GEOLOGY OF THE STUDY AREA

Most researchers have classified the rock to have physical properties slightly resistance than most igneous rock but more resistance than most other sedimentary rocks (Pauzi et al, 2011). Feng et al (2009) has observed the process of initiation, propagation and coalescence on cracks under the influence of chemical corrosion. Soil deposits as well as their classifications and properties have been described (Guyer, 2010).

The general topography of the study area is characterized by gullied hill slopes underlain by unconsolidated sedimentary rock that dates back to the Upper Cretaceous. The general stratigraphic lithology in which the study area lies is presented in table 1.

MATERIALS AND METHODS

Slanzi Rotary diamond drilling rig (Plate I) instrumented to control and monitor various drilling parameters (thrust, rotary speed, torque, and penetration rate) was used with core barrels of 75mm and 101mm diameter respectively to sample basic intrusive rocks that intruded the Cretaceous Eze Aku and Asu River Group shales at Amata-Lekwesi, SouthEastern Nigeria (Fig.1). The core barrel is made up of hardened steel tubing, 150cm long and equipped with a cutting bit, which contains commercial diamonds at its cutting ends.

During sampling, the bit and core barrel rotate while a steady stream of water is pushed down through the hallow rods and barrel into the bit. The water serves as coolant and as a transporting agent in the process of bringing the cuttings up to the surface. Continuous sampling at 1.5 meters was carried out in each drill hole and the cores logged appropriately in core boxes for RQD indexing and other laboratory tests (Plate 2).
A total of 440 cores were recovered from 11 holes drilled over an area of 81,750m². A thrust of 2.5kg (24.5N) was maintained on the drill rig and the torque kept at 1460Nm for each drilling operation and the penetration rate (μ) measured in each hole.

Putting the speed of rotation of the drill bit at N–revolution per minute, the total work done in 1 minute is shown through a relationship between the thrust (F), penetration rate (μ) and the torque (T) (as shown in equation 3). Specific energy (Eₚ) is defined as the energy required for excavating a unit volume of rock. And putting the volume of rock cored in 1 minute as Vₛ from the specific energy concept, the work done by the thrust (F) and the torque (T) is related to the volume of rock cored and hence the penetration rate (μ).

\[
\text{Specific energy (Eₚ)} = \frac{\text{Work}}{\text{Volume}}
\]

\[
Eₚ = \frac{F}{Vₛ} + \frac{(2\pi N Vₛ)(NT/\mu)}{(2\pi N Vₛ)(NT/\mu)}
\]

The term \(F/Vₛ\) is the “thrust” component of the specific energy while \((2\pi N Vₛ)(NT/\mu)\) is the “rotary” component. T is the torque required to move a layer of rock of depth P in one revolution of drill, so putting P as the penetration per revolution of the rotary drilling,

\[
P = \frac{\mu}{N}
\]

So work done in N revolution = \(F\mu + 2\pi NT\) (4)

The ratio \(T/P\) may itself be used as a comparative index of specific energy in rock materials. Gaye has found that in a given cutting process the size of debris produced is a function of the specific energy and also a function of the ratio of compressive strength to specific energy (\(f_c/Eₚ\)). This ratio \(f_c/Eₚ\) is termed the rock number (Nr) which is approximately constant for a given cutting process irrespective of scale, provided that the tool is being operated under normal working conditions. By using the rock number (Nr) and observing the result of small-scale drill test, it is possible to give field engineers a sound qualitative estimate of the resistivity of various rocks to a particular mode of attack.

**RESULTS AND DISCUSSION**

A plot of Tsoutrelis drilling constant (Kₚ) against compressive strength (σc) of certain rocks (fig. 2) shows a decrease in drilling constant with increasing uniaxial compressive strength. This is consistent with the penetration result obtained at Amata-Lekwesi site which shows that more time is required to penetrate fresher and less fractured rocks with higher abrasivity (fig. 3a - j).

An index of rock quality was therefore drawn based on the percentage core recovery while drilling into the rock with diamond core drills and this was estimated using the relation:

\[
\frac{\text{Total core recovered} \times 10}{\text{Total length of hole}}
\]

The solid cores recovered (plate 2) were adjudged to have depended on the inherent strength of the rock mass, the nature and frequency of any discontinuities or plane of weaknesses within the material structure. A percentage recovery ranging from 60 to 100 was obtained (Table 3).

Further attempts were made at classifying the rocks based on the rock quality designation (RQD). All sections of the core less than 10cm long from any of the drill holes were discarded and the remainder expressed as a percentage of the total length of the drilled hole:

\[
\text{RQD} = \frac{\text{Recovered core} \times 100}{\text{Total length of drilled hole}}
\]

RQD indexing for the area are shown in table 2. The rock quality is estimated on the average to be 75%.

**CONCLUSION**

The uniaxial compressive strength is a basic rock property and its determination is often necessary before theoretical concepts of design can be applied, either in relation to the rock itself or to rock excavation processes. Any other strength measurement parameter that can relate with this is therefore adjudged a good index.

We have, on the basis of rotary drill penetration rate (μ), the RQD indexing and Total Percentage recovery classified the strength of rocks within the Amata–Lekwesi area. This approach afforded a faster approximation to understanding the strength of rock mass without using the conventional tests. By this classification process this work is believed to act as a guide to miners in the rock quarry industry on the strength and quality of the rocks they want to mine before venturing into the industry.

**REFERENCES**


Plate 1: Slanzi Diamond Rotary Rig used at the study site

Plate 2: Cored Samples for RQD Indexing and other Laboratory Tests

Figure 1: Map of the Study Location Showing AMATA-LEKWELE, Southeastern Nigeria.

Figure 2: A plot of Tsoutrelis drilling constant ($K_o$) against Compressive strength ($\sigma_c$) of certain rocks.

Figure 3a: Continuous Drilling Rate Log for boring # 2

Figure 3b: Continuous Drilling Log for boring # 1
Figure 3c: Continuous Drilling Rate Log for boring # 3

Figure 3d: Continuous Drilling Rate Logs for boring # 4

Figure 3e: Continuous Drilling Rate Log for boring # 5

Figure 3f: Continuous Drilling Rate Logs for boring # 6
Figure 3g Continuous Drilling Rate Log for boring #7

Figure 3h: Continuous Drilling Rate Logs for boring #8

Figure 3i: Continuous Drilling Rate Log for boring #9

Figure 3j Continuous Drilling Rate Logs for boring #10