EVALUATION OF THE PERFORMANCE OF ATLAS COPCO SDR4 ROTARY DRILL IN SAGAMU LIMESTONE FORMATION, NIGERIA

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ABSTRACT

This paper deals with the estimation of performance of rotary drill (Atlas Copco SDR4) in a limestone formation. Rock samples were collected from four different faces exploited at Sagamu Limestone Quarry. These samples were tested in the laboratory for uniaxial compressive, point load strength index and tensile strength. The chemical composition of the samples was determined using X-Ray Fluorescence spectrometer. Also, penetration rate and drill bit consumption were determined by measuring blast-hole with time taken and the length of worn bit button as drilling progresses for each of the blast-holes respectively. The results obtained revealed that Mogaji end has highest values of 105.97 MPa, 3.65 MPa, 5.30 MPa for uniaxial compressive, point load and tensile strength respectively. Results also revealed that Mogaji end is the most abrasive of the Sagamu limestone formation having the highest values of Equivalent Quartz Content (EQC) and Rock Abrasivity Index (RAI) of 35.079% and 37.17% respectively. Analysis of the drilling cost of the different faces showed that Mogaji end was the most costly to drill with drilling cost of N 2,951.54/m and the least drilling cost was recorded at the Sagamu end with the drilling cost of N1, 822.12/m. The lowest penetration rate and highest bit consumption were recorded at Mogaji end. Thus, the Atlas Copco SDR 4 rotary drill best performance was achieved at Sagamu end where the rock has lowest values of strength parameters and Rock Abrasivity Index while the rotary drill performance was poorest at Mogaji end where the rock has highest values of strength parameters and Rock Abrasivity Index were recorded.

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1.0 INTRODUCTION

Drilling operation precede blasting in rock excavation. Drilling like the other exploitation stages has a direct and close relationship with rock mass, this could also be affected by the characteristics of the rock material, the rock mass as well as types of drilling equipment and tools employed (Jimeno et al., 1995). Therefore, recognition of the drilling environment and in-situ rock mass properties would be a great help in selecting the type of drilling system, estimating the performance of the drilling system, the number of drilling rigs and mine production rate (Hudson and Dussealt, 1989).

Rotary drills have been extensively used in open pit mines, quarries and construction sites all over the world. Major advances in the 20th century is said to have permitted holes as deep as 10 km to be drilled in extremely difficult rocks (Tamrock, 2002). In rotary drilling, the disintegration of rock occurs as a result of a concurrent action of the bit load (that is pressure and torque). Under the effect of the
pressure, the bit penetrates the rock while the torque shears the rock. Rotary drilling practices are characterized by a definite combination of axial bit thrust, speed of its rotation and air consumption for removing the cuttings from the drilled holes (Brently et al., 1964). The rock mass properties and engineering properties (uniaxial compressive strength, point load strength index, discontinuity) may significantly affect the performance of rotary drill (Blyth and Freitas, 1998). Adebayo et al. (2010) were of the view that understanding the drillability and strength characteristics will give quarry/mine operators the likely response of rock to drilling and excavation.

On the rotary drilling, rotational speed, thrust, torque, efficiency of operator and flushing are the operational variables, known as the controllable parameters that affects the performance of the rotary drill. Rock properties and geological conditions are the uncontrollable parameters. Although, many attempts have been made to correlate the drillability with the rock properties, the rock characteristics affecting rotary drilling have not been completely defined (Bilgin and Kahraman, 2003). Singh et al. (2006) revealed that compressive strength may not directly related to the drilling rate of a drill bit. Onan and Mufuoglu (1993) stated that drilling strength, hardness and triaxial strength of rock exhibited reliable correlations with drilling efficiency.

They developed a penetration rate model for application to tri-cone rotary bits in soft rock formations. Kapruz et al. (1990) concluded that a rough correlation exists between penetration rate and size range of cuttings. Yummelin (1998) showed that compressive strength is not directly related to the drilling rate of a drill bit. The model is a function of the drill power and the physical properties of the rocks. Rate of penetration of a drill bit refers to the drillability of a drill bit into the rock measured in metre per minute (Bell, 1992). It is the measure of the ease with which a machine forces its way into a rock per time (Hudson and Dusseault, 1989). Fast and economical penetration rate depends on the mineralogical structure of the rock, drilling machine, geo-mechanic characteristics of the rock, competence of the driller and the choice of drilling tools appropriate for the rock (Bilgin et al., 1993). It must however be noted here that penetration rate increases with rotation speed in a proportion that is slightly lower than the unity, up to a limit imposed by the rate of cuttings removal (Jimeno et al., 1995). The objectives of this paper therefore are to determine some selected properties of the limestone, bit wear, penetration rate of the rotary drill on limestone and estimate the performance of the rotary drill.

2.0 MATERIALS AND METHODS
2.1 Materials

The following materials were used: cored rock samples obtained from the field, cuboids shaped rock samples, tri-cone drill bit, Atlas Copco SDR4 rotary drill and X-ray fluorescence spectrometer.

2.2 Description of the Study Area

The coordinates of points in Sagamu are (6°38′49″ N; 3°33′43″ E); (6°40′51″3′44″44″E) and (6°, 46′53″N 3° 36′55″ E) (6° 50′ 54″ N 3° 38′ 46″ E). Sagamu and Ewekoro deposits fall within the Ewekoro depression. The sedimentary rock in the southwestern Nigeria are part of those deposited within the Dahomey embayment which extends from the Volta to Ghana through the republic of Benin to the okitipupa ridge (Adegoke et al., 1976). The Sagamu formation is a massive bioclastic Paleocene carbonate rock exposed in Sagamu and Ewekoro areas in the Dahomey Basin. Dahomey basin also known as the Dahomey Embarkment is a very extensive sedimentary basin in the continental margins of the Gulf of Guinea that extends from southeastern Ghana on the west, through southern Togo and Southern Benin Republic to southwestern Nigeria.

2.3 Determination of Uniaxial Compressive Strength

The uniaxial compressive strength was carried out in accordance with the ISRM (1985) methods. This procedure was repeated for all the cored samples and the compressive strength was determined using Equation 1

\[ C_o = \frac{P}{A} \]  

(1)

Where P is the maximum load at failure gotten from
the test, A is the cross-sectional area of the specimen (mm²) and Co is the uniaxial compressive strength (Mpa).

### 2.4 Determination of Point Load Strength Index

The point load strength index was carried out using ISRM (1985) and ASTM (2006) suggested standard procedures. These procedures were

\[
I_S = \frac{P}{D_e}
\]  
(2)

repeated for all the cored samples and the point load strength value was determined using Equation 2. Where, P is the load at failure in (kN) and De is the equivalent core diameter in (m).

### 2.5 Determination of Tensile Strength

The tensile strength of the samples were estimated using the formula that was suggested by ISRM (1985) and Brook (1985). The general relationship between the uniaxial compressive strength (Cₜ), the point load strength index (Iₜ) and the tensile strength (Tₜ) as expressed in the Equation 3.

\[
Cₜ = 20Tₜ = 30Iₜ
\]  
(3)

### 2.6 Determination of Density.

The specimen was properly dried in the oven at 105°C for 24 hour. The mass was determined by weighing the sample after drying. A measuring cylinder was properly washed and was filled with distilled water to the level of 600 ml. The dried sample was gently dropped inside the water. The new volume of water was determined through reading from the calibrated cylinder and was taken as the volume of the mass of the specimen. The density of the sample can be determined using Equation 4.

\[
\text{Density} = \frac{\text{mass}}{\text{volume}}
\]  
(4)

### 2.7 Determination of Chemical Composition of Limestone

The rock samples were pelletized and were placed in the X-ray fluorescence spectrometer to allow the beams of the X-ray light to fall on each sample. The percentages of the minerals and element present in the sample were measured. However, the samples prepared for the X-ray fluorescence analysis were prepared in accordance with ASTM (2003) C-114. The same procedure was repeated for all the remaining pelletized samples.

### 2.8 Determination of Equivalent Quartz Content

The equivalent quartz content (EQC) of the rock samples was obtained by multiplying the percentage of minerals present in rock by the mineral's Rosiwal abrasiveness value as expressed in the Equation 5 (Thuro 1996).

\[
\text{EQC} = \sum A_i R_i \% \quad (5)
\]

Where: n is number of minerals, A is mineral amount (%), and R is Rosiwal abrasiveness (%).

### 2.9 Determination of Rock Abrasivity Index

The multiplication of the equivalent quartz content and its corresponding uniaxial compressive strength of the rock samples gives the rock abrasivity index of the samples (Plinninger et al., 2002), this is expressed in Equation 6.

\[
\text{RAI} = \text{EQC} \times C_o
\]  
(6)

Where, EQC is Equivalent Quartz Content (%), Co is Uniaxial compressive strength (MPa)

### 2.10 Determination of Rate of Penetration.

The determination of the penetration rate was determined by dividing the time taken (to drill a hole) divided by the cumulative of the depth drilled.

### 2.11 Determination of Drilling Costs

The total drilling cost was calculated using Equations 7 - 16 proposed by (Jimeno et al., 1995).
\( C_x = \text{purchase price} - \text{residual value} \\
\text{hours of life} \)

Where, \( C_A \) is depreciation cost and Purchase price is approximately \#85,875,256
Residual value = 12% of purchase price = 10,305,030.72
Cost of Interest rate, insuranc
\( N \) is the no of years of service life = 12

\( C_i = \frac{N+1}{2N} \times \text{purchase price} \times \% \text{ (interest + insurance + tax)} \div 2700 \)  

(8)

The no of working hours in a shift is averagely 2hrs 30mins, then the no of working hours per year is 2hrs 30mins × 3(shifts) × 30(days) × 12(months) = 2700 hrs/year.
Maintenence cost (\( C_m \)) was determined using Equation 9.cce and taxes was determined using Equation 8.

\( C_m = 6 \times 10^3 \times \text{Purchase Price} \)  

(9)

The Labour cost (\( LC_o \)) is computed using data obtained in the Quarry for an operator and helper. The operator collects N60,000 and the helper collects N35,000
\( LC_o = \text{Driller Salary/month + Helper Salary/month} = \) 

\[ LC_o = \frac{\text{Driller Salary/month} + \text{Helper Salary/month}}{\text{days of month}} \]  

(10)

\[ LC_o = \frac{\text{labour cost/day}}{\text{hours of work/day}} \]  

(11)

The cost of energy (\( C_e \)) was estimated from the data obtained from Sagamu Quarry.

The machine consumes 32 litre/hour. A litre of diesel cost N150.

\( C_e = 32 \times 150 = N4,800/\text{hr} \)  

(12)

The time taken to drill each hole was different even in the same faces was different, the cost of fuel was calculated individually.

The Cost of oil and grease(\( C_l \)) was calculated using

\[ \text{Equation 13.} \]

\[ C_t = 20\% \text{ of } C_e \]  

(13)

Cost of bits, pipe and stabilizer (\( C_b \))
Cost of Bit, Cost of Stabilizer = 240,000 and cost of Drill pipe

\[ \text{Cost of bit/m}(C_{ib}) = \frac{\text{Cost of Bit}}{\text{total length drill}} \]  

(14)

Cost of drill stabilizer/ m =

\[ \frac{\text{Cost of drill stabilizer}}{\text{Total length Drill}} \]  

(15)

\( C_b = \text{Cost of bit} + \text{Cost of Drill pipe} + \text{Cost of Stabilizer} \)  

(16)

\[ C_t = \frac{CA+CI+CM+CO+CE+CL}{VM} \times C_b \]  

(17)

2.12 Determination of Bit Wear Rate

The bits that the measurement were taken from were the ones used by the quarry section of the Sagamu plant. The measurements were taken with the use of a vernier caliper. The wear rate was determined using Equation 18.

\[ \text{The tooth wear rate is } = \frac{\text{tooth wear}}{\text{total depth drilled}} \]  

(18)

3.0 RESULTS AND DISCUSSION

3.1 Analysis of Composition of Limestone for Different Faces

Table 1 presents the chemical composition of limestone faces operated in Sagamu Quarry. The Silica content varied from 8.93% for Mogaji end to 6.565% for Lagos end. This result revealed that Mogaji end has the highest calcium carbonate (CaCO\(_3\)) while Main face has the least calcium carbonate (CaCO\(_3\)). Sagamu end, Mogaji end and Main face contain same percentage of Na\(_2\)O while Lagos end contain 0.0055% of Na\(_2\)O.
Table 1: Chemical Composition for Sagamu Quarry Limestone Faces

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sagamu End (%)</th>
<th>Mogaji End (%)</th>
<th>Lagos End (%)</th>
<th>Main Face (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOI</td>
<td>38.39</td>
<td>38.67</td>
<td>39.865</td>
<td>39.45</td>
</tr>
<tr>
<td>SiO₂</td>
<td>7.2</td>
<td>8.93</td>
<td>6.565</td>
<td>7.66</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.86</td>
<td>1.13</td>
<td>1.305</td>
<td>0.88</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.17</td>
<td>1.29</td>
<td>1.245</td>
<td>1.16</td>
</tr>
<tr>
<td>CaO</td>
<td>43.31</td>
<td>59.89</td>
<td>48.61</td>
<td>48.54</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>88.99</td>
<td>91.96</td>
<td>86.8</td>
<td>86.67</td>
</tr>
<tr>
<td>MgO</td>
<td>1.303</td>
<td>0.76</td>
<td>1.49</td>
<td>1.0</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.06</td>
<td>0.18</td>
<td>0.125</td>
<td>0.23</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.01</td>
<td>0.12</td>
<td>0.0055</td>
<td>0.01</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.38</td>
<td>0.78</td>
<td>0.62</td>
<td>0.3</td>
</tr>
<tr>
<td>H₂O</td>
<td>9.98</td>
<td>6.99</td>
<td>12.315</td>
<td>12.11</td>
</tr>
<tr>
<td>L.S.F</td>
<td>158.01</td>
<td>209.00</td>
<td>233.175</td>
<td>218.76</td>
</tr>
<tr>
<td>SR</td>
<td>4.93</td>
<td>2.96</td>
<td>2.58</td>
<td>3.77</td>
</tr>
<tr>
<td>AR</td>
<td>0.75</td>
<td>0.77</td>
<td>1.045</td>
<td>0.825</td>
</tr>
</tbody>
</table>

3.2 Physico-Mechanical Properties and Resistance Potential Indices to Drilling Tool

Table 2 presents the summary of physico-mechanical properties and wear potential index of Sagamu limestone formation. The tensile, uniaxial compressive strength and point load strength index of the rock varied from 4.12 – 5.30 MPa, 82.42 – 105.97 MPa and 2.88 – 3.65 MPa respectively. This result revealed that Mogaji end exhibited the highest strength parameter and it is classified as high strength rock it is expected this formation will offer highest resistance to bit penetration rock when compared to other faces operated by the Quarry. The density varied from 2210 kg/m³ for Lagos end to 3210 kg/m³ for Sagamu end. The Equivalent Quartz Content (EQC) and Rock Abrasivity Index (RAI) varied from 26.82% - 35.08% and 22.21 - 37.17 respectively. Mogaji end has the highest EQC and RAI this means that the penetration will be lower when working on this formation and higher wear rate of drilling tool will be experienced when working on this formation. This indicates that Mogaji end is the most abrasive of the faces and Sagamu end has the least Abrasivity Index (RAI). It could be inferred that Mogaji end limestone formation contains resistance minerals with high silica content which eventually cause low penetration rate and high wear rate.

Table 2: Summary of Selected Properties of Sagamu Limestone Formation

<table>
<thead>
<tr>
<th>Samples</th>
<th>To (MPa)</th>
<th>Co (MPa)</th>
<th>Is (MPa)</th>
<th>EQC (%)</th>
<th>RAI</th>
<th>Density (kg/m³)</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagamu End</td>
<td>4.12</td>
<td>82.42</td>
<td>2.84</td>
<td>26.82</td>
<td>22.21</td>
<td>3210</td>
<td>Medium Strength</td>
</tr>
<tr>
<td>Mogaji End</td>
<td>5.30</td>
<td>105.97</td>
<td>3.65</td>
<td>35.08</td>
<td>37.17</td>
<td>3100</td>
<td>High Strength</td>
</tr>
<tr>
<td>Lagos End</td>
<td>4.81</td>
<td>96.23</td>
<td>3.32</td>
<td>31.67</td>
<td>30.48</td>
<td>2210</td>
<td>Medium Strength</td>
</tr>
<tr>
<td>Main Face</td>
<td>4.14</td>
<td>82.81</td>
<td>2.91</td>
<td>28.68</td>
<td>23.64</td>
<td>2690</td>
<td>Medium Strength</td>
</tr>
</tbody>
</table>
3.3 Analysis of the Bit Wear Rate

The highest wear rate observed was in Bit D with 0.0020444 mm/m and the lowest tooth wear rate was observed in the Bit C with 0.0011667mm/m. Bits B and A had 0.0012669 mm/m and 0.0014609 mm/m respectively. Table 3 shows that bit D again had the highest bearing wear rate with 0.0014756 mm/m, bit A had the lowest 0.0008477mm/m. Bit B and A have wear rate of 0.0009124 mm/m and 0.0008477 mm/m respectively. Figure 1 presents depth drilled by the four bits used on the all the faces, it was observed that bit A, bit B and bit C drilled the lowest depth on Mogaji end limestone formation. This can be attributed to the fact that Mogaji end formation has the highest bit wear potential as a result of its high abrasiveness and at same time will offer more resistance to bit advance into the rock.

<table>
<thead>
<tr>
<th>BITS</th>
<th>Tooth wear (mm)</th>
<th>Bearing wear (mm)</th>
<th>Total depth (m)</th>
<th>Tooth wear rate (mm/m)</th>
<th>Bearing wear rate (mm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit A</td>
<td>3.55</td>
<td>2.06</td>
<td>2430</td>
<td>0.0014609</td>
<td>0.0008477</td>
</tr>
<tr>
<td>Bit B</td>
<td>3.18</td>
<td>2.29</td>
<td>2510</td>
<td>0.0012669</td>
<td>0.0009124</td>
</tr>
<tr>
<td>Bit C</td>
<td>3.22</td>
<td>2.55</td>
<td>2760</td>
<td>0.0011667</td>
<td>0.0009239</td>
</tr>
<tr>
<td>Bit D</td>
<td>4.60</td>
<td>3.32</td>
<td>2250</td>
<td>0.0020444</td>
<td>0.0014756</td>
</tr>
</tbody>
</table>

Figure 1: Depth drilled by the Bits in the Formations

3.4 Analysis of the rate of penetration and Drilling Cost

Table 4 presents drilling rate components and cost of drilling in the quarry faces. It was observed that the highest penetration rate was obtained from Sagamu end of 1.049 m/min and lowest rate of penetration was observed in Mogaji End with 0.663m/min. The drilling cost varied from N 127, 548.87 for Sagamu end to N 206, 608.81 for Mogaji end. The performance characteristics of rotary drill in the faces operated in Sagamu varied from poor in Mogaji end to very high performance in Sagamu end. The poor performance of the drilling on Mogaji end limestone formation may be due to very high strength rock parameters and very abrasive nature of the formation. This had led to low penetration, high fuel consumption and high wear rate. It had greatly increased the cost of drilling on Mogaji end formation.
<table>
<thead>
<tr>
<th>Name of Face</th>
<th>Depth (m)</th>
<th>Time taken (min)</th>
<th>ROP (m/min)</th>
<th>Average ROP (m/min)</th>
<th>Total Drilling cost</th>
<th>Average drilling cost (N)</th>
<th>Performance Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagamu End</td>
<td>70</td>
<td>66.55</td>
<td>10.49</td>
<td>1.059</td>
<td>127,548.87</td>
<td>12,754.87</td>
<td>Very High</td>
</tr>
<tr>
<td>Mogaji End</td>
<td>70</td>
<td>105.65</td>
<td>6.625</td>
<td>0.659</td>
<td>206,608.81</td>
<td>20,660.86</td>
<td>Poor</td>
</tr>
<tr>
<td>Lagos End</td>
<td>70</td>
<td>84.95</td>
<td>8.246</td>
<td>0.835</td>
<td>148,376.26</td>
<td>14,837.63</td>
<td>Medium</td>
</tr>
<tr>
<td>Main Face</td>
<td>70</td>
<td>75.2</td>
<td>9.312</td>
<td>0.9252</td>
<td>144,204.47</td>
<td>14,420.45</td>
<td>High</td>
</tr>
</tbody>
</table>

4.0 CONCLUSION

This paper has evaluated physic-mechanical properties limestone for estimation of performance of the rotary drill. The strength parameters of the rock suggest that Mogaji sample offered the highest resistance to penetration with compressive strength value of 105.97 MPa while Sagamu end with 82.42 MPa offered the least resistance to penetration when drilling since the face has the lowest compressive strength. According to a classification by Deere and Miller (1966), Mogaji end is a very high strength rock while Lagos, Main and Sagamu rocks are high strength rocks. Mogaji end offered the highest wear to the bit among the four faces since the four bits were all of insert tricone bit. The insert tricone bit D had the highest tooth wear rate and bearing wear rate and it had the lowest drill life of 2250m. The reason for the high wear of bit at Mogaji end could be attributed to high values Equivalent Quartz Content and the Rock Abrasivity Index. Therefore, the insert tricone bit performed poorly at Mogaji end of the quarry. Furthermore, among the four formations, Mogaji recorded the least penetration rate, therefore highest fuel consumption was experienced during drilling as well as highest wear rate. This have consequently summed up to record the highest cost of drilling out of the four formations. Finally, Atlas Copco SDR4 Wagon drill performance is very high at Sagamu end, high at Main Face, fair at Lagos End and poor performance at Mogaji end.

5.0 RECOMMENDATION

It is therefore recommended that bit that has insert button with higher hardness value should be used for drilling Mogaji end and optimum machine parameter should be determined for better performance.

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REFERENCES


Tamrock, (2002): Surface Drilling and Blasting Published in Finland by Tamrock, pp. 445-455.
