Rock Mass Characterization of Ajabanoko Iron Ore Deposit, Kogi State Nigeria

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Abstract
A reliable estimate of rock mass characteristic values is required for the design of both surface and underground mines. Rock samples of iron ore, granite and gneiss were collected from the Ajabanoko iron ore deposit and tested in the laboratory to determine engineering properties such as uniaxial compressive strength (UCS), tensile strength, unit weight, friction angle, cohesion, bulk density, and porosity. Other geotechnical parameters were determined using the rock mass characteristic equations, while the rock mass rating was carried out using Chart developed by Beniawski. The result obtained indicates that the uniaxial compressive strength (UCS) of the iron ore is 142.90 kN/m²; tensile strength is 6.23 kN/m²; porosity is 0.018; bulk density is 3.79 tons/m³. In addition the Young Modulus and the Bulk Modulus values are 17.78 GPa and 10.58 GPa respectively. The Rock Mass Rating (RMR) values obtained indicates that the rock mass can be classified as good quality rock. The rock mass characteristic values are relevant in slope design and are also used in pit design.

Keywords: rock mass; characteristic values; engineering properties; geotechnical parameters; rock mass rating

INTRODUCTION
Rock mass may be considered as non-homogenous construction materials built of fragments and blocks of various sizes (Palmstrom, 1996). In the exploitation of a mineral deposit, it is important to have a good understanding of the engineering properties of the rock. The adequate knowledge of the rock mass is vital during the design and the exploitation stages. Historically, the Mohr-Coulomb measures of friction angle (Φ) and cohesion (c) have been used to represent the strength of the rock mass (Karzulovic and Read, 2010). This values are usually obtained by carrying out strength test using shear box machine. Obtaining good triaxial measures of friction and cohesion for normal rock masses was not easy, hence the preferred means of overcoming these difficulties was to derive empirical values of friction and cohesion from rock mass classification schemes that were calibrated from experience (Karzulovic and Read, 2010). Knowledge of the strength characteristics of the rock mass is necessary to predict the reliability of the deposit during slope design. Reliable estimates of the strength and deformation characteristics of rock masses are required for almost any form of analysis for the design of surface excavation (Hoek and Karzulovic, 2000). Rock contains discontinuities of different types which affects the strength of the rock mass. For practical purposes a rock mass is intact delineated by discontinuities such as bedding planes, fractures, shear zones and faults, because of this it is consequently recognized that the strength of the rock mass is consequently lower than that of the intact rock (Esmaieli et al., 2009). Also to carry out an effective slope stability analysis of the deposit, knowledge of rock mass characteristic parameters such as uniaxial compressive strength, tensile strength is highly desirable. Hoek and Karzulovic (2000) suggested that Hoek-Brown failure criterion should only be applied to those rock masses in which there is sufficient number of closely spaced discontinuities, with similar surface characteristics, that isotropic behaviour involving failure on multiple discontinuities can be assumed.

The rock mass classification schemes that are in common use are RMR, Q System, GSI and RQD. Jade and Sitharam (2003) characterized the strength of rock mass under different confining pressure using statistical analysis. Also Franklin et al. (1988) carried out rock mass characterization using photo analysis. This study becomes relevant because of the need to have a good understanding of the rock mass characteristic values which is expected to be used in pit design. Lack of adequate rock mass data for effective mine design and planning could lead to defective pit design which might add to cost of mining the ore. Therefore the objective of this study is to characterize the Ajabanoko iron ore deposit with a view to obtaining rock mass data to be used for open pit design.

The study concentrated only on three rock types which were collected from the Central Ajabanoko iron ore deposit.
The study area for this project is Ajabanoko, located at Okene, Kogi State, Nigeria. Ajabanoko iron ore deposit is along longitude 6°15’50”N and 6°16’50”N and latitudes 7°37’25”E and 7°38’35”E and lies 4.5km Northwest of Itakpe hill.

The Ajabanoko deposit area falls within the Nigerian Precambrian basement complex, a suite of crystalline rocks exposed in over nearly half of the country extending west into Dahomeyan of Benin Republic and east into Cameroon (Amigun and Ako, 2009). The Ajabanoko area consists of a set of three closely related hills of basement rocks in which some large bands of iron ore occur. The ferruginous quartzite is the source of the iron ore mineralization in the area (Olade, 1978). These three hills which mark the Southern, Central and Northern ore zones are made up mainly of migmatite and biotite gneisses which trend in a northeast-southwest direction and dip mostly westwards. The dominant lithologic units of Ajabanoko deposit area are gneiss of migmatite, biotite and granite, ferruginous quartzites, granites and pegmatite (Amigun and Ako, 2009).

The nature of Ajabanoko iron ore deposit and the associated rocks indicate that they are residual concentrates derived from iron rich sediment, a volcanogenic sedimentary material (National Steel Development Authority (NSDA), 1976). This suggests that all the rocks in the area including the high grade metamorphic ones such as the gneisses and the low grade metamorphic ones such as the quartzites may have been derived from sedimentary materials which in turn were probably derived from an ancient volcanic source (National Steel Raw Material Exploration Agency, 1994). Four principal ore layers have been identified for the different ore zones (Nnagha, 1997). Four thick bands ranging from 1m to 5m in thickness and measuring 1.22km along strike have been identified in the deposit, and are classified as orebody I, orebody II, orebody III and orebody IV as shown in Table1 (National Steel Raw Material Exploration Agency, 1994). Petrologic studies of the ore have revealed four major types of ore composition similar to Itakpe Hill: (i) magnetite quartzites (ii) magnetite-hematite quartzites (iii) hematite-magnetite quartzite (iv) hematite-quartzite. The sum total of iron ore reserves in the entire deposit is 62.104 million tons in the C1 (indicated reserve) category and 25.952 million tons in the C2 (inferred reserve) category (National Steel Raw Material Exploration Agency, 1994).

**Rock Mass Characteristic Equations**

The rock mass characteristic values were estimated using Equations 1-7:

\[ E = \left(1 - \frac{D}{2} \right) \left[ \frac{\sigma_{ci}}{100} - 10 \right] \left( \frac{GSI - 10}{40} \right) \quad (1) \]

Equation 1 applies for \( \sigma_{ci} \leq 100 \) MPa, however the study made use of Equation 2 for \( \sigma_{ci} > 100 \)MPa

\[ E = \left(1 - \frac{D}{2} \right) \left[ \frac{\sigma_{ci}}{100} - 10 \right] \left( \frac{GSI - 10}{40} \right) \quad (2) \]

where \( D \) is the Hoek Brown’s parameter for the rock mass; \( m_b \) is the Hoek Brown’s parameter for the rock mass. \( \sigma_{ci} \) is intact compressive strength of the rock (MPa). \( GSI \) is Geologic Strength Index.

\[ m_b = m_i \exp \left( \frac{GSI - 100}{28 - 14D} \right) \quad (3) \]

where \( m_i \) is the Hoek Brown’s parameter for the rock mass; \( GSI \) is Geologic Strength Index.

\[ K = \frac{E}{3(1 - 2v)} \quad (4) \]

\[ G = \frac{E}{2(1 + v)} \quad (5) \]

\[ G \] is the Bulk Modulus (GPa)

**METHODOLOGY**

**Sample Preparation**

Lump iron ore rock samples were collected from Ajabanoko iron ore deposit, Okene Kogi State. The samples were cored in the laboratory using laboratory coring machine, TF-750 900 to form right-circular cylinder. Ten replicated core samples of the iron ore were produced and were cut to the required size using diamond saw. Ten core samples of other rock types such as biotite granite and banded gneiss of Ajabanoko iron ore deposit were produced. The ends of the core samples were finely ground to meet the testing standard suggested by ISRM (1989). Cutting and grinding to meet the height to diameter ratio of 2.50 were carried out. Tests such as shear strength, uniaxial compressive strength, tensile strength, bulk density and porosity were also carried out.

**RESULTS AND DISCUSSION**

**Rock Properties**

The average Fe content of the iron ore is 34.44% and the reserve estimate is 62.104 million tons as shown in Table 2. The density of rock varies and is related to the porosity of the rock. The density of rock is used to estimate the overburden of the deposit. The bulk density of the hematite-magnetite iron ore is 3.79 tons/m³ while that of the biotite granite is 2.89 tons/m³ and banded gneiss is 2.88 tons/m³ as shown in Table 3. The porosity of the rock explains how...
densely the material constituting the rock is packed and the value varies between 0 and 1. The iron ore has higher porosity value of 0.018 than granite which has a porosity value of 0.001 while the gneiss has a value of 0.0034 as indicated in Table 3. Density and porosity are important indicators to the strength of the rock material. Rocks with low density and high porosity are regarded as low strength rocks. When rock has high porosity, then the permeability will also be high. In iron ore deposit with porosity less than 2%, micro fissures are dominant. The porosity of rocks is affected by age, depth and in situ state of stress. The hematite-magnetite iron ore with high bulk density and low porosity is regarded as high strength rock.

The compressive strength of a rock is its capacity to withstand axially directed compressive forces and is also defined by the ultimate stress. The mean uniaxial compressive strength (UCS) of the iron ore is 142.90 MPa while that of the biotite granite and banded gneiss are 115.22 MPa and 73.63 MPa respectively as shown in Table 5. The failure pattern of all the samples tested on the triaxial machine is axial failure with the exception of one sample which shattered completely. This may be as a result of the quartzite vein in the sample. Also Schmidt Rebound Hammer was used on four iron ore samples; the equation developed by Aydin et al (2008) was used to estimate the UCS of the samples as indicated in Tables 4. The estimated UCS for the four iron ore samples varies from a lower limit of 109.15 MPa to an upper limit of 173.96 MPa with an average UCS value of 144.70 MPa. This value correlates with the UCS value of 142.90 MPa obtained from the laboratory as shown in Table 3.

The tensile strength of rock is defined by the ultimate strength in tension and is also regarded as the maximum stress the rock can withstand. The mean tensile strength recorded for the iron ore is 6.23 MPa which is low and also the mean tensile strength for the banded gneiss and biotite granite which are 5.28 MPa and 10.32 MPa respectively as shown in Table 3. The low tensile strength value is a common attribute of rock and this may be as a result of existence of micro cracks in the rock.

Tensile and shear strength are very important in rock mass characterization as rock fails mostly in tension and in shearing. The shear strength of rock is used to describe the strength of rock to resist deformation due to shear stress. Parameters such as friction angle and cohesion are measured from shear test. The friction angle for the iron ore, granite and gneiss obtained from the shear test carried out are 36.86°, 48.52° and 45.85° respectively. The iron ore core sample has the highest peak shear stress of 3090.91N/m² while 2857.14 kN/m² and 2642.86 kN/m² values are for banded gneiss and biotite granite respectively. The result obtained indicates that the higher the peak shear stress the lower is the friction angle.

An empirical relationship between UCS and porosity \( (n) \) of rock types such as iron ore, gneiss and granite rocks from Ajabanoko iron ore deposit has been developed as shown in Figure 1 and the result is as expressed in Equation 8.

\[
\text{UCS} = 61.39 + 4699n \\
R^2 = 0.974
\]

Also an empirical relationship between bulk density \( (\rho_b) \) and porosity \( (n) \) of rock types such as iron ore, gneiss and granite from Ajabanoko iron ore deposit has been developed as shown in Figure 2 and the result is as expressed in Equation 9.

\[
\rho_b = 2.516 + 64.08n \\
R^2 = 0.803
\]

**Rock Mass Characteristics Values for Ajabanoko Iron Ore Deposit**

Table 5 indicates a value of 12 for the Structural Condition Rating (SCR) for Ajabanoko iron ore deposit. The GSI value was further established using Hoek-Brown Rock Mass Classification Chart (Marinos and Hoek, 2000) with a GSI value of 55 as shown in Table 5. The RMR determined for the deposit is 60 as shown in Table 6. The RMR is a parameter which is used to measure the geotechnical quality of a rock mass and has a scale with a lower limit of zero and upper limit of 100. On the basis of the RMR, the rock mass is classified as good quality rock since the RMR falls between 61-80 (Karzulovic and Read, 2010). The Hoek-Brown failure criterion remains the most credible method of estimating the required strength parameter of a rock deposit. The unit weight of the samples of iron ore, biotite granite and banded gneiss are 35.84 kN/m³, 29.15 kN/m³ and 29.0 kN/m³ respectively. The rock mass Modulus varies from 3.83 GPa for granite and reaches an upper limit of 5.81 GPa for iron ore. The Bulk Modulus, \( K \), varies from 2.46 GPa for granite and reaches an upper limit of 3.72 GPa for iron ore as shown in Table 7. Consistently the Shear Modulus, \( G \), the GSI and the value varies between 0 and 1. The iron ore has higher porosity value of 0.018 than granite which has a porosity value of 0.001 while the gneiss has a value of 0.0034 as indicated in Table 3. Density and porosity are important indicators to the strength of the rock material. Rocks with low density and high porosity are regarded as low strength rocks. When rock has high porosity, then the permeability will also be high. In iron ore deposit with porosity less than 2%, micro fissures are dominant. The porosity of rocks is affected by age, depth and in situ state of stress. The hematite-magnetite iron ore with high bulk density and low porosity is regarded as high strength rock.

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\rho_b = 2.516 + 64.08n \\
R^2 = 0.803
\]

**CONCLUSIONS AND RECOMMENDATIONS**

Rock mass characteristic value for the deposit which includes Surface Condition Rating (SCR) is 12; Structure Rating (SR) is 65; unit weight is 35.84 kN/m³; Young Modulus is 5.81 GPa and Geologic Strength Index (GSI) is 60. Laboratory tests carried out shows that Uniaxial Compressive Strength (UCS) of iron ore is 142.90 MPa; that of granite is 115.22 MPa; and that of gneiss is 73.63 MPa. While the...
Tensile Strength for iron ore is 6.23 MPa; gneiss is 5.28 MPa; and granite is 10.32 MPa. The result further shows that as the UCS of the sample decreases, the friction angle increases. Shear test result shows that the higher the peak shears stress the lower the friction angle. Rock mass characteristic data obtained indicates a good relationship between porosity and UCS. It also shows a good relationship between density and porosity. This shows that the iron ore deposit is a competent rock and effort should be made to design bench geometry that takes into consideration the ore characteristics.

REFERENCES


Table 4: Correlation of UCS* with $R_L$ for the Iron Ore Samples

<table>
<thead>
<tr>
<th>S/No</th>
<th>Sample No</th>
<th>Rebound value, $R_L$</th>
<th>UCS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>i.</td>
<td>A</td>
<td>50.4</td>
<td>129.29</td>
</tr>
<tr>
<td>ii.</td>
<td>B</td>
<td>54.9</td>
<td>173.96</td>
</tr>
<tr>
<td>iii.</td>
<td>C</td>
<td>54.2</td>
<td>166.38</td>
</tr>
<tr>
<td>iv.</td>
<td>D</td>
<td>48</td>
<td>109.15</td>
</tr>
<tr>
<td></td>
<td>Average UCS value</td>
<td></td>
<td>144.70</td>
</tr>
</tbody>
</table>

*UCS = $1.6 \times 10^{-3} R_L^{3.47}$ (Aydin et al., 2008)

Table 5: Rock Mass Characteristic for Ajabanoko Iron Ore Deposit

<table>
<thead>
<tr>
<th>S/No</th>
<th>Rock mass characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>i.</td>
<td>Surface Condition Rating (SCR)</td>
<td>12</td>
</tr>
<tr>
<td>ii.</td>
<td>Volumetric Joint Count, J</td>
<td>55.98</td>
</tr>
<tr>
<td>iii.</td>
<td>Structure Rating (SR)</td>
<td>65</td>
</tr>
<tr>
<td>iv.</td>
<td>Geologic Strength Index (GSI)</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 6: Rock Mass Rating of Ajabanoko Iron Ore Deposit (Beniawski, 1979)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Rating</th>
<th>Qualitative Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCS</td>
<td>142.90 MPa</td>
<td>12</td>
<td>Very Strong</td>
</tr>
<tr>
<td>RQD</td>
<td>0</td>
<td>3</td>
<td>Very Poor</td>
</tr>
<tr>
<td>Joint Spacing</td>
<td>0.1-0.42m</td>
<td>10</td>
<td>Moderate</td>
</tr>
<tr>
<td>Condition of Joints</td>
<td>-</td>
<td>25</td>
<td>Slightly rough surfaces. Separation &lt; 1mm. Slightly weathered walls</td>
</tr>
<tr>
<td>Groundwater Condition</td>
<td>-</td>
<td>10</td>
<td>Damp</td>
</tr>
<tr>
<td>RMR</td>
<td>60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Geotechnical Properties of Ajabanoko Iron Ore Deposit

<table>
<thead>
<tr>
<th>Rock type</th>
<th>$Y$ (kN/m$^3$)</th>
<th>$\sigma_y$ (MPa)</th>
<th>m$_v$</th>
<th>GSI</th>
<th>$m_b$</th>
<th>C(KPa)</th>
<th>$\Phi$($^\circ$)</th>
<th>E(GPa)</th>
<th>v</th>
<th>K(GPa)</th>
<th>G(GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron ore</td>
<td>35.84</td>
<td>142.90</td>
<td>20</td>
<td>60</td>
<td>60</td>
<td>30.30</td>
<td>36.86</td>
<td>17.78</td>
<td>0.22</td>
<td>10.58</td>
<td>7.29</td>
</tr>
<tr>
<td>Granite Gneiss</td>
<td>29.15</td>
<td>115.22</td>
<td>10</td>
<td>60</td>
<td>60</td>
<td>4.62</td>
<td>48.52</td>
<td>17.78</td>
<td>0.22</td>
<td>10.58</td>
<td>7.29</td>
</tr>
<tr>
<td>Biotite Gneiss</td>
<td>29.0</td>
<td>73.63</td>
<td>5.61</td>
<td>60</td>
<td>60</td>
<td>5.61</td>
<td>45.85</td>
<td>15.26</td>
<td>0.22</td>
<td>9.08</td>
<td>6.25</td>
</tr>
</tbody>
</table>