Research/Technical Note

Reducing Uncertainties in Gold Plant Design and Operations

Charles Amoah¹, * Grace Ofori-Sarpong², Richard Kwasi Amankwah²

¹Asanko Gold Ghana Limited, Obotan Operations, Manso Nkran, Ghana
²Department of Minerals Engineering, University of Mines and Technology, Tarkwa, Ghana

Email address:
charles.amoah@asanko.com (C. Amoah), gofori-sarpong@umat.edu.gh (G. Ofori-Sarpong), rkamankwah@umat.edu.gh (R. K. Amankwah)

*Corresponding author

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Abstract: The conventional way of designing a plant is to determine the characteristics of rocks in terms of crushability, grindability and other properties that affect the mill throughput. These properties are most of the time determined from drill cores obtained during the exploration period. Such initial exploration campaigns drill to levels shallower than the real pit that will be developed. Thus, as mining pits become deeper, the ore characteristics change and begin to impact negatively on the expected mill throughput. Such situations necessitate modification of the plant, and the first intervention usually is to supplement the initial energy input with additional size reduction equipment to achieve the required throughput. However, reconsidering the inputs used in determining the initial plant selection would help in reducing the setbacks during the operational period. To help reduce uncertainties and develop a predictive tool, this study considered a greenfield drilled up to 273 m, and the core samples obtained were tested to ascertain the variations in Bond work index to depths beyond 500 m. The study showed that within the section of the Asankragwa belt investigated, Bond work indices increased from 10.3 kW/t at the surface to 16.5 kW/t at a depth of 273 m. The Bond work index was established as a function of vertical depth in a pit (x) with the relation BWI=6E-05x² + 0.0071x + 9.8816. The predicted value at 280 m was 16.3 kW/t while that of the blend was 15.8 kW/t, giving an error of 4%. This novel relationship between the BWI and depth predicts the BWI beyond 500m with minimum mean square error. The use of the novel Bond work index and depth relationship will eliminate the uncertainty beyond the drilled depth and give a clear understanding of what the rock characteristics will be as pits become deeper. In addition, a savings of US$62,500 per diamond drill hole and US$25,000 per one reverse drilling after the 250 m depth can be made by the use of this model. This can result in massive savings considering the number of holes that would have to be drilled across the length of the pit.

Keywords: Bond Work Index (BWI), Asankragwa Belt, Plant Operations, Uncertainties, All in Sustaining Cost (AISC)

1. Introduction

According to Vallee [1, 2] investments in and the development of minerals resource projects depend on the quantity (tonnage) and quality (grades) of the resources in the deposit. However, due to variations in geological structures, different and complex genesis of ore bodies and other intangible mineral factors, the prediction of mineralisation is with great uncertainty. In the minerals industry, decision making is based primarily on data obtained from samples and sampling. This issue cuts across grass root exploration through to resource upgrade, resource or reserve estimation, production and mineral processing or extraction [3-6]. Challenges and errors in the prediction and evaluation of mineral resources, and hence geological forecasting occur due to uncertainties of the orebody, characteristics and geological processes, geological data and geological measurement inaccuracy. [7-13].

In the evaluation of mineral deposits, geological and grade uncertainties may be reduced by several techniques including probability theory, geostatistics, geological geometry, fuzzy sets/logic and neural networks [14-20]. Several codes and classifications are well established in grade and ore reserve estimation.
These well-developed models for reducing uncertainty in the geological environment may not have their direct equivalents in the processing plant. Thus, when the ore reaches the run-of-mine ore pad to be processed, each plant is expected to assess and develop a proactive plant operations strategy to accommodate the ore being processed. The development of some models to reduce uncertainties in the prediction of rock hardness and grindability characteristics, grade and the All-in sustaining cost in relation to metal price would contribute to knowledge and help the industry predict future trends.

One major area that requires investigation is the prediction of changes in grindability with depth. Initial drilling campaigns of mines target drill holes up to about 280 m. Thus, the initial design is done based on characteristics of ores within this depth. However, during operation, pits can go to depths of 400 m and beyond. In a situation where the rocks become harder, it gets to a point where the plant cannot deliver the expected tonnage. Unfortunately, drilling campaigns from the surface to depth up to 400 m are expensive and not generally embarked upon.

With an already installed motor, if pits become deeper, rocks become harder and Bond work indices increase, the design tonnage may not be achieved. Thus, to minimise uncertainties in a milling operation, it is important to accommodate the heterogeneity associated with grindability of the ore and develop a strategy to mitigate it. The development of such a relationship will eliminate some of the challenges that is encountered as the pit deepens.

This paper presents a study that was conducted in the Asankragwa belt of Ghana to develop a relationship between Bond index and the vertical depth in a pit. It is expected that great savings would be made from a model that can predict changes in Bond indices over the life of a pit.

2. Field and Laboratory Investigations

2.1. Field Investigations

Diamond-drill boreholes approximately 200 m apart with depth up to 273 m covering an area earmarked for four pits were selected for the investigation. The core from the boreholes were 63 mm in diameter and the samples comprised of both full cores, half cores and quarter cores taken from identifiable zones down the hole. Core sample length was generally between 20 and 30 cm and the depth and zone of the individual samples taken from the various boreholes were recorded. In all, about 100 kg of material was taken.

2.2. Laboratory Investigations

2.2.1. Drying

The samples collected from the field were dried for about 6 hours in a Gallenkamp oven at 110 °C and allowed to cool before recombining to form a composite sample for each of the areas being investigated.

2.2.2. Mineralogical Study

The samples received were analysed megascopically, and this revealed three rock types; granite, sandstone and siltstone. The selected samples were then investigated further by optical microscopy using thin and polish sections. Sections were prepared out of the samples and the rock forming minerals in thin sections were observed using a LEICA DMC EP Polarizing microscope. Polish sections were analysed for ore forming minerals using a Leitz POL binocular microscope.

2.2.3. Determination of Bond Work Indices

Representative samples of the three ore groupings were prepared to all passing 3.35 mm. The tests were performed according to the guidelines developed by F C Bond (Naper-Munn et al, 2006). After every grinding cycle, the mass of the minus 106 µm fraction was replaced with fresh feed to keep the mass of the mill feed constant. This cycle was repeated until the net mass of minus 106 µm material produced per mill revolution attained equilibrium with a circulating load of 250%. The Bond Work Index was calculated using Equation 1.

\[
W_i = \frac{44.5}{(P_0)^{0.23} \times (Gbp)^{0.82} \times 10^\left[\frac{1}{\sqrt{F_1}} - \frac{1}{\sqrt{F_2}}\right]}
\]

where \(W_i\) is the work index, \(P_0\) is the screen test size in microns, Gbp is the net grams undersize per revolution, \(P_2\) is the 80% product passing size in microns and \(F_2\) is the 80% feed passing size in microns.

3. Results and Discussions

3.1. Mineralogical Study

Megascopic analysis indicated that the ore within the section of the Asankragwa belt tested was made up of the major rock-types; sandstone, siltstone and granite. Table 1 presents the modal percentage of minerals in the samples. As presented, the most predominant mineral was quartz and is also the hardest. The other major mineral in granite was plagioclase while that in sandstone was amphibole. In the case of siltstone, chlorite was the next major mineral. The photomicrographs of sandstone, granite and siltstone are presented in Figures 1 to 3.

| Mineral   | Sandstone | Granite | Siltstone |
|-----------|-----------|---------|-----------|
| Quartz    | 56        | 60      | 50        |
| Amphibole | 20        | -       | -         |
| Plagioclase feldspar | 25 | 6       |
| Biotite   | 5         | 10      | -         |
| Chlorite  | -         | -       | 40        |
| Carbonate | 10        | -       | -         |
| Sericite  | 4         | 2       | -         |
| Gold      | 1         | -       | -         |
| Chalcopyrite | 3.5 | 1.5     |
| Arsenopyrite | 0.5 | 1       |
| Pyrite    | -         | -       | -         |
| Pyrrhotite| 0.2       | -       | -         |
| Hematite  | 0.3       | -       | -         |
| Magnetite | Trace     | -       | -         |
| Total     | 100       | 100     | 100       |

Table 1. Mineralogical assessment of rocks by modal percentage.
3.2. Grindability Assessment and Modelling

Quantitatively, grindability is the number of grams of a particular size that is generated for every revolution of a mill and qualitatively it is the ease with which rocks respond to grinding. The Bond Work Index (BWI) was used as a measure of grindability.

The samples picked from the surface to a depth of 273 m were tested for Bond work indices and the results are presented in Table 2. The data was modelled using polynomials of different orders and the one with the least error was selected. Polynomials of order 2, 3 and 4 gave mean square errors of 0.51, 2.476 and 1233.25 respectively. Thus, the order two was selected and the graph developed is presented in Figure 4, and the equation of the polynomial is shown in Equation 2

\[ y = 6E^{-0.5}x^2 + 0.0071x + 9.8816 \]  

When Equation 2 was used to predict the BWI up to 273 m, there was a significant alignment and correlation with the measured values as shown in the Table 2. This can therefore be confidently used to predict the BWI up to 500 m depth and beyond.

### Table 2. The real and predicted BWI with depth.

| Depth, m | BWI, kW/t | Predicted BWI | Error |
|----------|-----------|---------------|-------|
| 14.6     | 10.3      | 10.0          | 0.3   |
| 15.2     | 10.2      | 10.0          | 0.2   |
| 94       | 9.9       | 11.1          | -1.2  |
| 100      | 10        | 11.2          | -1.2  |
| 106      | 12.1      | 11.3          | 0.8   |
| 109      | 11.9      | 11.4          | 0.5   |
| 112      | 12.5      | 11.4          | 1.1   |
| 115      | 12.5      | 11.5          | 1.0   |
| 118      | 13.3      | 11.6          | 1.7   |
| 121      | 10.3      | 11.6          | -1.3  |
| 124      | 12.4      | 11.7          | 0.7   |
| 129      | 11.2      | 11.8          | -0.6  |
| 136      | 12.7      | 12.0          | 0.7   |
| 198      | 14.5      | 13.6          | 0.9   |
| 203      | 13.3      | 13.8          | -0.5  |
| 204      | 13.2      | 13.8          | -0.6  |
| 212      | 15.1      | 14.1          | 1.0   |
| 216      | 14.6      | 14.2          | 0.4   |
| 221      | 13.5      | 14.4          | -0.9  |
| 222      | 14.1      | 14.4          | -0.3  |
| 225      | 14.2      | 14.5          | -0.3  |
| 228      | 15.4      | 14.6          | 0.8   |
| 231      | 16.8      | 14.7          | 2.1   |
| 234      | 16.2      | 14.8          | 1.4   |
| 236      | 14.1      | 14.9          | -0.8  |
| 240      | 14        | 15.0          | -1.0  |
| 242      | 15.1      | 15.1          | 0.0   |
| 243      | 15.1      | 15.1          | 0.0   |
| 246      | 15.7      | 15.3          | 0.441 |
| 247      | 14        | 15.3          | -1.296|
| 248      | 16.2      | 15.3          | 0.867 |
| 249      | 14.9      | 15.4          | -0.470|
| 251      | 15        | 15.4          | -0.444|
| 260      | 15.7      | 15.8          | -0.084|
| 261      | 14.6      | 15.8          | -1.222|
| 273      | 16.5      | 16.3          | 0.208 |
Lynch [21] classified rocks based on their Bond work indices as soft (7 – 9), moderately hard (9 – 14), hard (14 – 20) and very hard (above 20 kW/t). Thus, sandstone is moderately hard while both siltstone and granite are hard rocks per the results here. Depending on the ratios in which these rocks appear in the ore at any given time, it has the potential to alter throughput and product particle size from the mill.

There is a relationship between the mineralogy and the Bond work index. Sandstone and granite had 60% quartz content, with granite also having 25% feldspar which was not present in the others. Feldspar is also of hydrothermal origin, pits get deeper. At that stage, the energy requirements to achieve because the ore characteristics have changed and begun to

determine from drill core obtained during the exploration period. The drill core samples then become the main

impacted by Bond work index. More especially, Sag-Ball Mill-Circuit (SABC) is very sensitive to variations in ore

impact negatively on the expected mill throughput as mining

situations are

changing the plant to avoid set-backs during the operational period.

In this research, a deposit on the Asankragwa belt was evaluated for mineralogy and grindability to aid selection of plant equipment for the Life-Of-Mine (LOM) of the deposit. The studies revealed that the mill throughput will be impacted as pit operations get deeper leading to revenue losses. The results show that BWI increases with depth, and thus, it will be of utmost benefit to develop a tool to determine the BWI as pits get deeper. More importantly, proactive steps should be taken to ensure that appropriate changes are made by way of budget and equipment footprint so that increased rock strength can be accommodated.

3.2.3. Impact of Change in Bond Work Index on Profitability

From the operational point, the mill throughput is always impacted by Bond work index. More especially, Sag-Ball Mill-Circuit (SABC) is very sensitive to variations in ore hardness and fragmentation.

In order to achieve the expected throughput, these factors need to be understood in the context of maintaining stable and consistent circuit performance.

SABC could therefore achieve a better performance and higher capacity through optimisation and improved controls if the ore variability with respect to hardness is overcome.

A study was carried on with deposit on the Asankragwa belt to evaluate the impact of the Bond work index on the mill feed rate. This was done by collating of particle size distribution sample population over time to give an idea of the size distribution with the various mill feed rate.

In this study, the degree of variation in hardness is typically between 10-20 Kwh/t and as such, it was clear that the plant capacity will be impacted by changes in hardness and fragmentation.

This impact of the Bond work index on the mill feed rate was used to run a sensitivity on the profitability of a typical mine on the Asankragwa belt using the 2018 production performance, i.e All-In Sustaining cost, gold produced and gold price at that time. This data is represented in Table 4 and Figure 5.

### Table 3. Bond work indices of rock-types.

| Sample Name | Net grams per revolution, g/rev | Bond Index, kWh/t |
|-------------|---------------------------------|------------------|
| Sandstone   | 1.302                           | 13.4             |
| Siltstone   | 1.176                           | 14.5             |
| Granodiorite| 1.012                           | 16.3             |

### Table 4. Change in bond work indices, cost of production and gold price.

| Bond index | Changes in Bond Work Indices | 11.2 | 12.0 | 12.8 | 13.6 | 14.4 | 15.2 | 16.0 | 16.8 | 17.6 |
|------------|------------------------------|------|------|------|------|------|------|------|------|------|
| Throughput |                              | 5,180,000 | 5,068,928 | 4,844,192 | 4,673,120 | 4,502,048 | 4,330,976 | 4,159,904 | 3,988,832 | 3,817,760 |
| Gold price |                              | 1,269.1 | 1,269.1 | 1,269.1 | 1,269.1 | 1,269.1 | 1,269.1 | 1,269.1 | 1,269.1 | 1,269.1 |
| All-in sustaining cost/oz |                       | 1,072 | 1,088 | 1,106 | 1,125 | 1,146 | 1,168 | 1,192 | 1,219 | 1,247 |
| Gold produced |                        | 227,772 | 220,250 | 231,006 | 205,484 | 197,962 | 190,439 | 182,917 | 175,395 | 167,872 |
| Mining |                              | 158,560 | 155,222 | 152,009 | 148,671 | 145,334 | 141,996 | 138,659 | 135,322 | 131,984 |
| Processing |                           | 57,802 | 56,785 | 55,806 | 54,789 | 53,772 | 52,755 | 51,738 | 50,721 | 49,704 |
| Overheads |                               | 27,720 | 27,720 | 27,720 | 27,720 | 27,720 | 27,720 | 27,720 | 27,720 | 27,720 |
| All-in sustaining cost (AISC) |                       | 244,082 | 239,727 | 235,534 | 231,180 | 226,825 | 222,471 | 218,116 | 213,762 | 209,408 |
The analysis based on the 2018 performance indicates that at a Bond work index of 18 Kwh/t, there is a break-even point of the AISC and the gold price. This implies that an intervention will be to influence the mill throughput to maintain production below the gold price.

The innovation in this analysis is that if the bond work index with depth is predicted using the novel relation coupled with the fragmentation model, a break-even point can be determined with the prevailing gold price and the forecasted AISC.

### 3.3. Financial Implications of the Model

From the tool that has been identified to correctly predict the BWI in relation to depth, it will be of importance to analyse the financial gains that could be derived.

To help understand the cost demands required to bring a target from initial exploration to an Indicated Resource, one major assumption is that the geological understanding is reasonable and acceptable and continuity of mineralization is good.

This scenario reflects a minimum cost to assess an area of 1000 m x 400 m to a depth of 200 m regardless of the amount of mineralization present. The minimum drilling required to take a project to an Indicated Resource category assuming ideal continuity and confidence in geologic modeling and mineralization is shown in the Table 5.

| Item                  | Unit cost, $ | RC cost, $ | DD cost, $ |
|-----------------------|--------------|------------|------------|
| RC/m                  | 65           | 65000      |            |
| DD/m                  | 200          | 200000     |            |
| Core cutting          | 0.5/m        | 500        |            |
| Fire assay/m          | 11           | 11770      | 11770      |
| Labour                | 27/day       | 1620       | 3240       |
| Pad construction      | 1000         | 10000      | 10000      |
| Compensation          | 1000/hole    | 10000      | 10000      |
| PPE 6                 | 150          | 950        | 950        |
| Logging               | 50/day       | 500        | 1000       |
|                       |              | 99840      | 237460     |
|                       |              | 99.84      | 237.46     |
| All up $/m cost       | 100/m        | 250/m      |            |

From Table 5 it is seen that the approximate cost in carrying out a diamond drill (DD) is US$250/m and that of a reverse drilling (RC) is US$100/m. Based on these estimates it is realized that the cost of carrying out a drilling operation for a hole up to a depth of 250 m will be US$62,500 and at a depth of 500 m the cost will be US$133,000. At the same distances an RC drilling will be US$25,000 and US$50,000 respectively. The additional drilling cost from 250 m to 500 m can be avoided with the use of the novel relationship between BWI and depth.

Great benefits could be derived by the use of the relationship between BWI and depth during the drilling campaign both in cost and technical information that is required in designing a plant so as to avoid any technical omission.

After drilling to 250 m depth the necessary laboratory test can be done on the samples to come out with the various design parameters. Most of the times these parameters up to the depth of 250 m are the ones which are used for designing. This eventually ends up with under-designing in most cases because not much information would have been obtained beyond the 250 m. From both technical and economic points of view, drilling will become a challenge up to 500 m from a single campaign.

It therefore becomes imperative to use this novelty that establishes the relationship between the BWI and depth. This allows the designer to incorporate and capture all the critical design parameters up to over 500 m in the choice of plant design. From the economic point of view, much savings will be made in drilling campaign by the use of this novelty to project and capture the information at no additional cost.

### 4. Conclusions

The study showed that the predominant rocks present in the section of the Asankragwa belt investigated were granite, siltstone and sandstone. The major mineral was quartz (~50%). Granite and siltstone had feldspar while sandstone contained amphibole. Bond work indices increased from 10.3 kW/t at the surface to 16.5 kW/t at a depth of 273 m. The Bond work index was established as a function of vertical depth in a pit (x) with the relation BWI=6E-05x^2 + 0.0071x + 9.8816.

The predicted value of 16.5 kW/t at 280 m was similar to the Bond work index of granite at that depth. With 80% granite in the feed, the Bond work index of the blend was 15.8 kW/t, giving an error of 4%. The use of the novel Bond work index and depth relationship will eliminate the uncertainty beyond the drilled depth and give a clear understanding of what the rock characteristics will be as pits become deeper.

In addition, a savings of US$62,500 per diamond drill hole and US$25,000 per one reverse drilling after the 250 m depth can be made by the use of the model. This can result in massive savings considering the number of holes that would have to be drilled across the length of the pit.

In addition, the novel relationship between the bond work index and depth will also provide an idea of the impact on mill feed rate. This will enable interventions to be made as to what level of mill feed rate will be required to achieve profitability.
5. Recommendations

The project has come out with a novel predictive tool on the determination of bond work index as mining is advanced deeper in the pit. This has been established based on a second order polynomial as established in Equation (2).

To increase the confidence in the use of this model, it is being recommended that more work should be done to come out with a more powerful tool for modelling the relationship between the depth and the bond work index.

Also, more work should be done to include a modifying factor that will be based on the changes in the mineral composition as mining is done and it gets deeper.

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