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Research/Technical Note

Reducing Uncertainties in Gold Plant Design and Operations

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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 ºC 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.

$$W_i = \frac{44.5}{(P_1)^{0.23} \times (\text{Gbp})^{0.82} \times 10\left(\frac{1}{\sqrt{P_2}} - \frac{1}{\sqrt{F_2}}\right)} \quad (1)$$

where W_i is the work index, P_1 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.

Table 1. *Mineralogical assessment of rocks by modal percentage.*

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			Ore Minerals 4
Pyrrhotite		0.2	
Hematite		0.3	
Magnetite		Trace	
Total	100	100	100

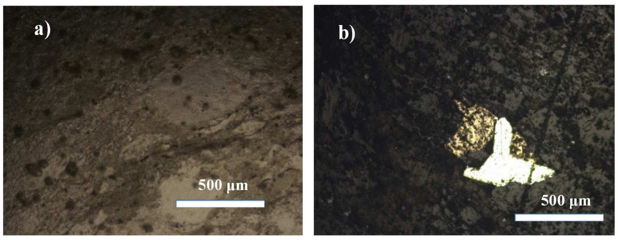

Figure 1. *Photomicrograph of Sandstone showing under reflected light and plane polarised light (a) recrystallised quartz into medium grains which are also sheared and marked by biotite corroded at the margin by further recrystallisation after crenulation cleavage (b) gold overprinted by chalcopyrite.*

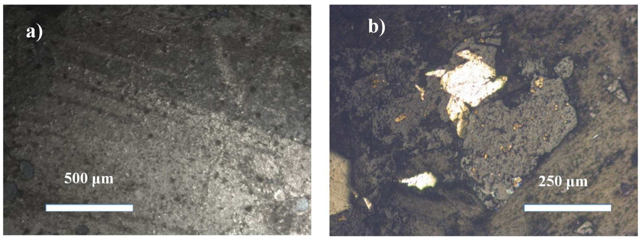

Figure 2. *Photo micrograph of granite showing (a) plagioclase corroded by quartz and overprinted by granular quartz (b) gold inclusion in gangue is overprinted by medium grained gold.*

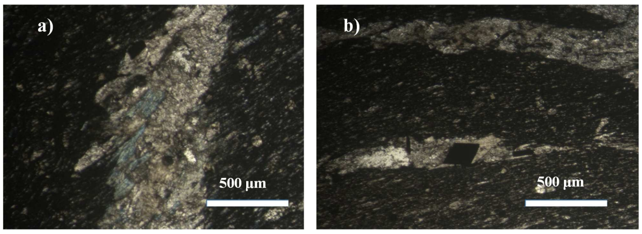

Figure 3. *Photo micrograph of Siltstone (a) a vein containing biotite which is aligned parallel to the main shear, overprinted by plagioclase and quartz (b) quartzo-feldspathic veins mark isoclinal fold which had been offset parallel to shear and overprinted by tabular euhedral and cubic opaque mineral.*

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

$$y=6E\text{-}0.5x^2+0.0071x+9.8816 \quad (2)$$

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.

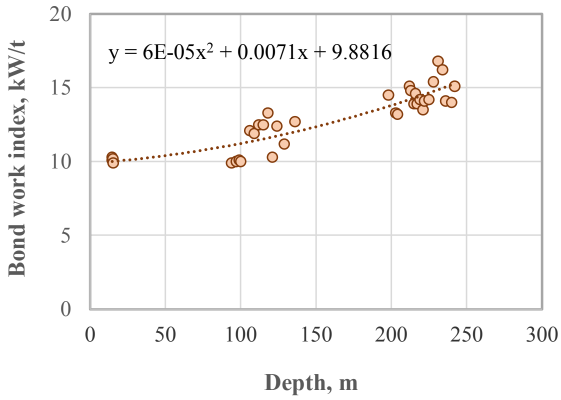

Figure 4. *Bond work indices as a function of depth.*

3.2.1. Mineralogical Study

Real ore samples were taken at a depth of 280 m and analysed to check the closeness of the model to reality. As indicated earlier, the ore is made up of three rock-types and these were tested individually, and the ratio of their blend determined. From the results in Table 3, sandstone had the lowest Bond work index of 13.4 kW/t, silts stone had 14.5 kW/t and granite, 16.3 kW/t.

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	-0.050
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

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

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, fresh and competent. It underwent weathering to produce sericite and chlorite. Though siltstone had more weathered material, it appears the combination of quartz and feldspar made it strong. Sandstone contained amphibole which though hard are not as hard as feldspar, and a little bit of sericite thus making it softer than the granite.

Based on the figures, granite had the highest work index and may be the major rock that controls hardness of the ore. The predicted value at 280 m was 16.3 kW/t and that is similar to the Bond work index of granite at the depth. With 80% granite in the ore at that depth, the Bond work index of the blend was 15.8 kW/t giving an error of 4%.

3.2.2. Implications on Plant Design and Operations

The conventional way of designing a plant is to determine the characteristics of a rock in terms of crushability, Bond work index, grindability, abrasive index and other properties that may affect the mill throughput. These properties are most of the time determined from drill core obtained during the exploration period. The drill core samples then become the main determinant for the selection of the treatment plant type suitable in treating the ore type. More often than not, situations are encountered where modification of the plant becomes necessary because the ore characteristics have changed and begin to impact negatively on the expected mill throughput as mining pits get deeper. At that stage, the energy requirements to achieve the required size reduction for the required throughput exceed that energy which was used in the initial plant design.

The first intervention most of the time is to supplement the initial energy input with additional size reduction equipment to achieve the required throughput. As may be expected, this intervention will require further injection of capital to achieve the required outcome. This then calls for a new thinking into the initial inputs that go into the determination of the plant selection 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 uttermost 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 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	5,008,928	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	213,006	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

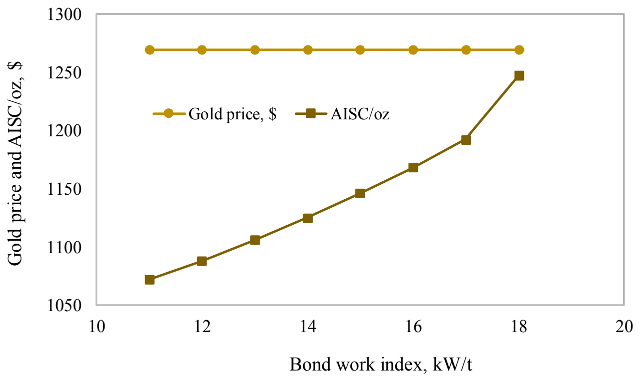

Figure 5. *Graph of change in Bond work index against gold price and cost.*

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.

Table 5. *Cost Centres for a Drilling Campaign.*

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 $BWI=6E\text{-}05x^2 + 0.0071x + 9.8816$.

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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