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Ore Characterization and Quality Control Aspects of Gold Cyanidation: The CIL Plant as a Case Study in Sudan

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Abstract
Mineralogical and chemical studies are key to mineral processing because they present the problem of low-grade ores to the metallurgist or mineral processing engineer. Quality control operations are also significant in obtaining good products by flowing the sequences of processes. In this study, the ore was characterized, and quality control issues were discussed. Results showed that the gold grade is 9.7 g/ton, the minerals are mainly silicates, and the pH of the ore is high, which means that without pre-treatment, i.e., roasting, oxidation, etc., it can be cyanided directly. Therefore, the CIL plant could recover more than 90% gold. In quality control of the plant, from each unit at a different time, a representative sample and an accumulative sample were collected and then subjected to analysis like fineness and solid percentage, moisture, and conditions of cyanidation. The results showed steady operation conditions for each unit.

Keywords
Characterization; Quality control; Carbon in Leach (CIL); Cyanidation; Gold recovery.

Introduction

Gold is considered the first pure metal known to man and has been valued since ancient times. The reaction chemistry and electrical properties of gold metal (Au0) differ from those of other metals. It is unaffected by air and most chemical reagents such as acids and bases; even in nature (native metals), oxygen does not affect it (Massey et al., 2017). In nature, it occurs in its natural state or as telluride ore, and when it emerges as ore, it can be found with quartz and pyrite. Metallurgically, gold ore is classified into free-milling and refractory types; for free-milling gold ore, the gold recovery can be more than 90%, while in refractory gold ore, it is less than 50% (Vaughan, 2004; Lunt and Briggs, 2005). The decrease in gold recovery can be attributed to sulphide minerals and carbonaceous materials that act as consumers of dissolved reagents and oxygen or brig-robing of dissolved gold in solution (Chen et al., Larrabure and Rodríguez-Reyes, 2021). Therefore, this type of ore should undergo a pre-treatment stage before the gold extraction process. Pre-treatment includes high-pressure oxidation, roasting, oxidative reagents, and bio-oxidation.

In the mining industry, gold cyanide is widely used in gold recovery due to its high speed and affinity for dissolving gold in basic media, but it is considered one of the most toxic reagents for the environment (Vorster and Flatman, 2001; Adams, 2001). Therefore, extensive work has been done to discover alternative lixiviants for cyanide agents (Brent Hiskey and Atluri, 1988). Gravity separation methods were previously used to recover gold, and they are more environmentally friendly but provide low recovery when gold particles are found in a fine texture. Thus, centrifugal force is used to recover the fine gold because it makes the particle equal to or even higher than 50 times the gravity force (Alp et al., 2008).

The kinetics of gold cyanidation in eq. 1 depends on dissolved oxygen concentration (ppm), cyanide concentration, reaction time, pH, solid/liquid ratio, and temperature. In free milling gold cyanidation, a high recovery of ≥90% for gold is generally obtained at a cyanide concentration of 500–1000 ppm, dissolved oxygen of 8 ppm, a solid percentage of 45%, a pH of 11.5, a temperature of 30 °C, and a leaching time of 24 hr (Heath and Rumball, 1998; La Brooy et al., 1994).

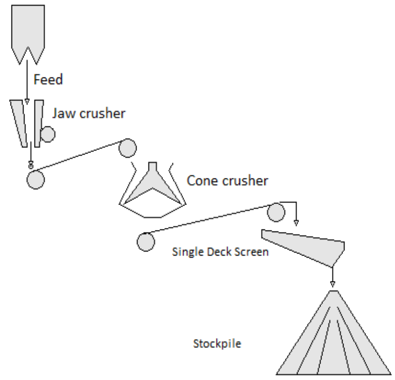
$$4Au + 8NaCN^{-} + 2H_2O + O_2 \rightarrow 4Au(CN)_2^{-} + 4NaOH^{-} \quad (1)$$

Mineralogical and chemical characterization aspects are some of the most important aspects considered key to treating or extracting minerals or metals in mineral processing (Hassan and Awdelkarim, 2019; Soares et al., 2020). This means that the behaviour of systems in mineral processing and their applications are essentially influenced by the physical properties (size, shape, surface area, specific gravity, bulk density, and pore structure) of the particles and the nature of the different solid-liquid interferences present. The characterization of physical and interface properties should be an integral part of new process development, plant and process design, and routine plant operation (Chander and Hogg, 1988). The recovery of valuable minerals or metals requires multiple stages of sequential processing operations. On the other hand, the mined ore must be subjected to crushing to a fine or desired size before being treated by beneficiation processes such as physical separation, chemical separation, and physio-chemical separation (Wills and Finch, 2015).

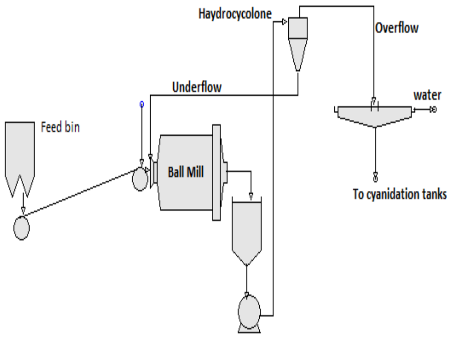
Mineralogical and chemical characterization investigations are primarily dependent on sampling; therefore, sampling is a critical factor in any material characterization process, so the reliability of characterization data is ultimately limited by the extent to which the sample used was truly representative of the population from which it was taken. The aims for sampling in the treatment plant are: to obtain information about entered ore for the processing plant to ensure valid metallurgical accountings, to examine the conditions of parameters at selected values during the process through the plant, and to make comparisons between the optimal requirements parameters for efficient processing and those present (Afewu and Lewis, 1998). The methods for taking a representative sample in the laboratory differ from those used in the factory (Fig. 1). Samples are collected from various locations, such as diamond drill and percussion machines, blast holes, relevant feed, and product streams. In the plant, the basic rule for correct sampling and sample preparation, whether wet or solid, is that all parts of the material to be sampled have the same homogeneity and can be conducted manually or automatically (Holmes, 2016).

Fig.1 Manual and automatic sampling in the plant.

The mineralogical study aims to define the texture and distribution of the mineral or metal of interest with other minerals in thin or polished samples. Thin or polished samples are prepared from bulk ore after collecting a representative sample (10–15 cm); generally, more than 10 samples are collected to characterize mineralization completely. The prepared samples are examined microscopically. In some cases, microscopes do not provide enough mineralization information, as X-ray diffraction can tell the mineralogist about the phases and structure of the chemical composition (Hawthorne, 2018; Motasim, 2020).



(1)



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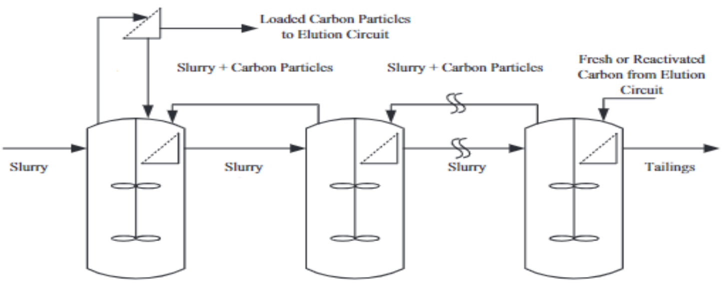

(3)

Fig.1 CIL plant.

In chemical analysis, the metal or metal oxide value is evaluated using classical chemical, atomic adsorption spectrophotometer (AAS), X-ray fluorescence (XRF), and inductively coupled plasma (ICP) analyses.

The carbon-in-leach (CIL) system in industrial gold mining is extensively used in gold cyanidation (Fig. 2). The CIL circuit consists of a series of gold-leach tanks from the ore and a counter-current flow of activated carbon to adsorb the gold from the solution in the same tanks. The CIL can concentrate the gold from 3.5–5.5 g/tonon in ore to 1.8–3000 g/tonon in carbon (Wadnerkar et al., 2015). The most important operation factors in the CIL plant, depending on the type of ore and gold contained, are leaching time, cyanide concentration, the pulp density of the thickener, and the fineness of the grinding product.

Quality control (QC) in mineral processing or the mineral industry aims to optimize the recovery and grade of the valuable mineral or metal by flowing the operation parameters in the plant, so it decreases the rate of mistakes and damages in plant equipment that is operated at high performance. In the CIL plant, quality control ensures that the crushing and screening work, the grinding rate, the thickener work, the gold extraction and adsorption work, and the allowed amount of free cyanide in the filter tailing are all at their best. In QC for each piece of equipment, a representative sample is taken every 2 hours or every hour for controlling and fowling, such as crusher samples, mill feed samples, mill product samples, overflow hydrocyclone samples, underflow, thickener underflow samples, cyanidation tank samples (slurry and carbon), tailing samples, and filter cake samples. Also, every month, a tailing dump sample is taken (Vorster and Flatman, 2001; Hodouin et al., 2001). Physical and metallurgical tests are performed on each sample, i.e., sieve analysis to determine the size distribution, calculation of the amount of gold in the feed and tailing, calculation of the amount of cyanide, calculation of the moisture in the feed and filter cake, electrowinning cell, etc.

Extensive exploration, prospecting, and processing work has been carried out in the study area (Sasmaz, 2020). This paper discussed the characterization of gold ore and quality control at the plant to increase plant productivity.

Materials and Methods

Raw material and characterization

Raw material

About 80–90kg of cumulative sample was taken from the belt conveyor of mill feed (crushing product) in gold plant block 30 in Red Sea State, Sudan. The sample was divided to take a representative sample for characterization via XRD, XRF, AAS, and fire assay.

Gold distribution

A representative sample of 5 kg was taken from the total sample and then subjected to a sieve analysis test at five fractions of sieves. The sample for each fraction was weighted and analyzed via fire assay.

Sample moisture

To calculate the moisture in the sample, about 1.5 kg was put in the oven for 2 hours, then eq. 2 (Wills and Finch, 2015). This test is required for mass balance calculation and water addition in milling circuits.

$$Moisture(\%) = \frac{M1 - M2}{M1} * 100 \qquad (2)$$

$M1$: weight of the sample before the drying

$M2$: weight of the sample after the drying

Specific gravity (SG)

In this test, a density bottle is used, and five samples of a representative soil sample fraction (-0.075mm) were examined to calculate the (SG), which (2 is used for the calculation (Rao, 2016).

$$SG = \frac{M2 - M1}{(M4 - M1) - (M3 - M2)} * Df \qquad (2)$$

Where:
Df: Density of fluid (water) (kg/m^3)
$M1$: weight of an empty bottle.
$M2$: wight of empty bottle + sample.
$M3$: wight of empty bottle + sample+ water.
$M4$: wight of empty bottle + water.

The pH determination

About 100g of the ground sample fraction (-0.075mm) was added and weighed into a beaker, and then the distilled water was added. The sample and water mixer were mixed using a glass rod magnetic stirrer for 30 minutes. The electrode of the pH meter was inserted into the pulp, and the pH value was determined (Thomas, 1996).

The quality control calculations

1. performance of crusher and screening:

An accumulative sample for every shift per day is taken from the product of the crushing, dried, divided to take about 6 kg, and then subjected to sieve analysis to calculate the size and gold distribution. The results are compared with the desired size of mill feed.

2. The moisture of mill feed

For every 2 hrs, about 3 kg of sample is taken from the belt of the mill, introduced to the oven at 100 ℃ for 2 hrs, and the moisture is calculated using **Chyba! Nenašiel sa žiaden zdroj odkazov.**. At the end of the shift, the average is calculated. The results are used to calculate actual feed and water consumption during grinding.

3. The performance of grinding (fineness):

For every hour, about one litter of samples from the product of the mill and hydrocyclone (overflow and underflow are taken. The samples are weighted to calculate the solid percentage (%) and then screened via size fraction (-0.075 mm) to calculate the fineness of the grinding (Rao, 2016).

4. A solid percentage of thickener products:

For every hour, about one litter from the thickener product is sampled and then weighted to calculate the solid percentage in the slurry, (3 (Wills and Finch, 2015). This test is necessary for the slurry flow rate in the tanks and the carbon distribution with pulp.

$$x(\%) = \frac{100S(D-1000)}{D(S-1000)} \tag{3}$$

D: Pulp density (kg/m^3).
S: Specific gravity of the ore (kg/m^3)

5. Solid percentage and carbon distribution in cyanidation tanks:

For every hour, about one litter is sampled from each tank and then weighted to calculate the solid percentage. This test indicates the performance of agitation. The same sample is screened through (0.05mm) to calculate the carbon in litter and then for a tank(m^3).

6. Filter cake moisture:

For every two hours, about 2 kg is taken from the product of the filter unit, placed into the oven at 100℃ for 2 hrs, and then the moisture is calculated using (2.

Metallurgical aspects:

The metallurgical calculation is conducted by taking accumulative samples from the flowing units:

- An accumulative sample (30kg) per shift from mill feed to know gold containing(g/tonon).
- An accumulative sample per shift from the product of the mill to know gold assay (g/tonon). An accumulative sample per shift from the product of thickener to determine the gold assay.
- An accumulative sample from each tank, about one litter every hour, to evaluate the cyanidation process and adsorption rate for each tank.
- An accumulative sample from the tailing tank, about one litter per hour, to determine the gold-containing.
- An accumulative sample from the filter cake of about 0.5 kg for each batch of filtration.
- A solution sample from each tank per hour to read the gold-containing solution(mg/mL).
- A solution sample from tank one and the final tank to read the consumption of cyanide (ppm/l) and Ph.

The extraction of plants can be calculated in general via (4 (Rao, 2016).

$$EX(\%) = \left(\left(\frac{S1-S2}{S1}\right) * M1 - \left(\frac{S3 * M2}{S1 * M1}\right)\right) * 100 \tag{4}$$

$M1$: Dry solid flow rate.
$M2$: Liqiud flow rate.
$S1$: Gold containing in mill feed (g/tononon).
$S2$: Gold containing in tailing (g/tononon).
$S3$: Gold containing in tailing solution (g/mL)

- The activity of carbon:

The approximately (4-5) vol.% activated carbon of the solution is weighed out and added to 1000 mL of gold cyanide solution (gold content is known) and then mixed for one hour. After that solution is filtered and gold-containing read via AAS, The capacity of carbon is calculated using (5 (Khosravi et al., 2017).

$$Capacity(\%) = \left(\frac{C_b - C_a}{C_a}\right) V * 100 \tag{5}$$

C_a: Gold content before adsorption.
C_b: Gold content after adsorption.
V: Volume of solution.

- Free cyanide calculation in filter cake and tailing dump:

About 80 g of filter cake sample is taken and placed into a beaker 150 ml, then 100 mL ammonia solution (2.5%) and mixed well. The pulp is filtered, and then 50 ml of filtrated solution is taken. About 10 ml of ammonia and potassium iodide as an indicator are added, then titrated with silver nitrate (0.01M). The free cyanide in a sample is calculated using (6.

$$Free\ cyanide\left(\frac{mg}{ton}\right) = \left(\frac{Cyanide\ in\ solution\left(\frac{mg}{mL}\right) * volume\ (L)}{weight\ of\ sample}\right) * 1000 \tag{6}$$

Results and discussions

Ore characterization

XRD result, as seen in Fig.2, shows that the minerals in the sample are Quartz (SiO_2), Calcite ($CaCO_3$), Dolomite ($CaMg\ (CO_3)_2$) and Kaolinite ($Al_2O_3.2SiO_2.2H_2O$). However, the XRF result **Chyba! Nenašiel sa žiaden zdroj odkazov.** contains mainly silicate, which is found in the XRD result. Furthermore, the gold *concentrates at a fine fraction size, as shown in Fig. 3.*

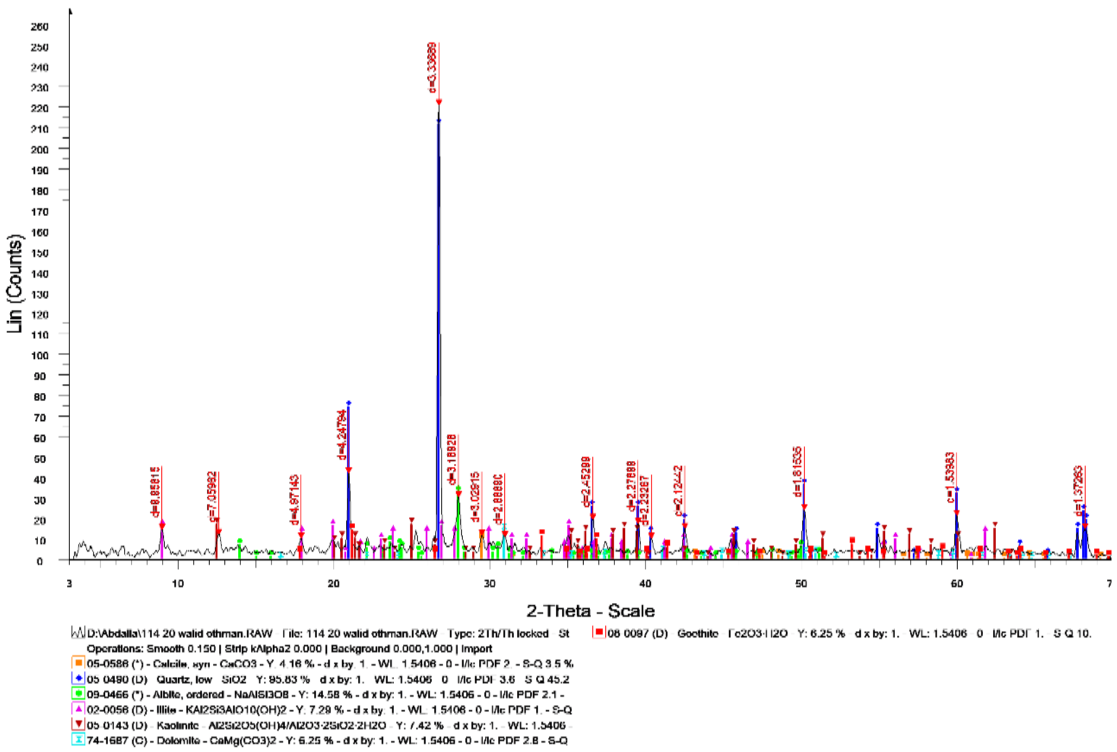

Fig.2.XRD analysis result.

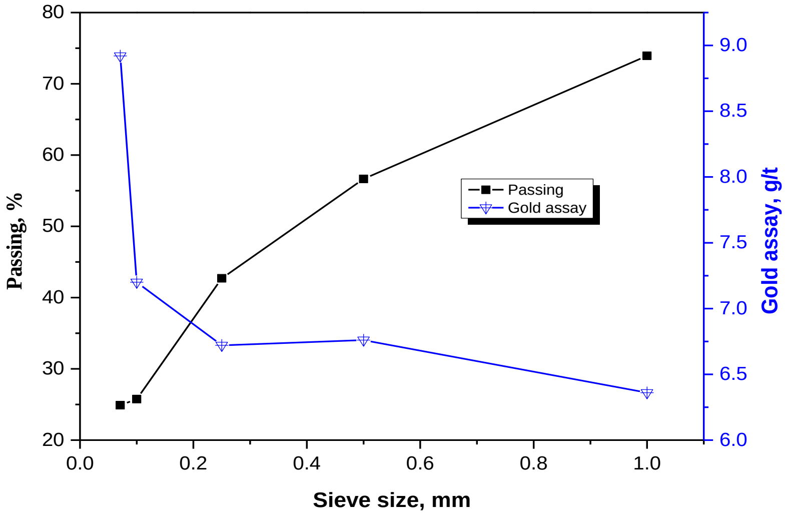

Fig. 3. Size and gold distribution.

Table 1. Result of XRF

Component	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	Cr_2O_3	MnO	$Fe_2O_3^{tot}$	CuO	ZnO	SrO
%	3.52	1.99	16.35	59.56	0.15	0.35	1.59	3.09	0.51	0.03	0.11	5.62	0.01	0.01	0.01

Physical characterization

Chyba! Nenašiel sa žiaden zdroj odkazov. shows the specific gravity of the ore. Due to the dominance of mineral silicates, the SG weight of the ore is approximately equal to the SG of quartz (2600 kg/m3). In addition, a moisture of 2.5% was determined.

Table 2. Density of ore (g/cm3)

Sample NO.	1	2	3	4	5	Average
S.G(g/cm^3)	2.82	2.48	2.64	2.78	2.69	**2.68**

The pH result can be seen in Table 3 shows that the alkalinity of the ore is high due to the appearance of Calcite ($CaCO_3$) and Dolomite ($CaMg(CO_3)_2$).

Table 3. pH examination result

Size mm	pH Test 1	pH Test 2	Average
+0.25	9.70	9.70	9.7
+0.5	9.55	9.35	9.45
+1	9.45	9.54	9.49

Quality control results

Chyba! Nenašiel sa žiaden zdroj odkazov. show the moisture of mill feed (feed rat 50 t/hr) for shift (12hr).

Table 4 Moisture of mill feed

Sample	1	2	3	4	Average
Moisture (%)	2	2.5	2.3	2	2.2

Table *1* presents the importance of calculation in the CIL plant and demonstrates that the high adsorption rate of gold is obtained in the middle tanks. The plant works at pH ≈10 via Ca $(OH)_2$ and dissolved oxygen at 8 ppm.

Table 1. CIL plant calculation

	Grinding Unit			
Unit	**Feed rate**	**Moisture (%)/solid%**	**Fineness (%) (-0.071) mm**	**Gold g/ton**
Mill feed	50	2.2	10	9.7
Mill product	48.9	68	25	9.6
Hydrocyclone feed	48.9	40	*	*
Hydrocyclone (o.f)	48.9	21	85	*
Hydrocyclone (u.f)	122.25	75	15	*
Thickener (u.f)	48.9	45	84	9.4
	Cyanidation tanks (180 m^3 /tank)			
Tank.NO	**carbon(g/mL)**	**gold ppm/mL**	**Solid (%)**	**Cyanide ppm**
1	0	7	45	600
2	18	6	44	500
3	16	5.5	44	390
5	15	3	44	250
6	19	2.2	43	180
7	22	1.02	43	109
8	18	0.9	43	80
9	15	0.3	42	50
10	12	0.08	42	42
11	0	0.025	41	25
	Filtration unit			
Average of moisture (%)		**Gold ppm/mL in solution**	**Gold/ton in cake**	**Cyanide g/ton**
22		**0.022**	**0.6**	25
	Mass and metallurgical calculation			
Water adding in mill		21.89		m^3/h
Water adding in cyclone feed		51.46		m^3/h
Amount of water cyclone (o.f)		183.96		m^3/h
Amount of water cyclone (u.f)		40.75		m^3/h
Water makeup in thickener		124.19		m^3/h
Amount of water thickener (u.f)		59.8		m^3/h
The filtrated water		45.97		m^3/h
Gold recovery		**93.75**		**%**

Conclusion

Characterization and quality control are considered key factors in ensuring a high recovery and performance for the CIL process. This study studied the investigations of ore mineralogy, physical properties, and chemical analysis in CIL plant operations. Moreover, the quality control procedure for each unit in the CIL operation was discussed. The XRD analysis revealed that the ore is dominated by silicate minerals, which means it can be subjected directly to cyanidation without pre-treatment. Dolomite mineral makes the consumption of lime low in obtaining the pH of cyanidation. The gold contents in the ore and tailing were 9.7 and 0.6 g/ton, respectively, which means the recyanidation can be used for the tailings to increase the recovery. The quality control investigation for each unit showed a steady process.

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