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# Diagnostic gold deportment studies and leaching behaviour of small-scale gold mining tailings from Eastern Region, Ghana

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## Abstract

Artisanal and small-scale gold mining (ASGM) sector employs about 80% of the mining workforce but only contributes about 20-30% of Ghana's gold production. The low gold production is linked to low recoveries associated with the activities because ofinadequate understanding of the chemical, mineralogical and metallurgical characteristics of the ores. This study examined the metallurgical characteristics of typical small-scale gold mining tailings to understand their grinding characteristics, gold deportment and cyanidation behaviour. The gold deportment results showed that 96.1% of the gold in the samples is free milling (can be leached directly with cyanide and recovered through carbon adsorption), whilst the remaining 3.9% of the gold in the samples is associated/locked up with other mineral phases (carbonates, sulphides, carbonaceous matter and quartz). The gold-by-size distribution also indicated that 73.1% of the gold is contained in coarser size fractions (+150 μm), 14.96% isfrom–150 μm to +75 μm size range, and 11.83% is contained in the finer size distribution (–75 μm). This suggests that incorporating a gravity recovery system during processing will be highly advantageous. The leaching kinetics results showed that gold recoveries achieved within 8, 16 and 24 h were 68, 73.8 and 76.4%, respectively. The corresponding total cyanide consumption rates after 8, 16 and 24 h of leaching were 550, 580 and 600 ppm, respectively. Generally, the gold recoveries and the cyanide consumption rates agree with industrial practices/results. Overall, the outcomes of the study support the view that some small-scale gold mining tailings are economically viable, and hence can be re-processed through efficient processes such as carbon-in-leach/carbon-in-pulp.

## Keywords

diagnostic leaching, artisanal and small-scale mining, cyanidation, tailings, gold, mercury

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# Diagnostic Gold Deportment Studies and Leaching Behaviour of Small-Scale Gold Mining Tailings from Eastern Region, Ghana

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## Abstract

**Artisanal and small-scale gold mining (ASGM) sector employs about 80% of the mining workforce but only contributes about 20−30% of Ghana's gold production. The low gold production is linked to low recoveries associated with the activities because of inadequate understanding of the chemical, mineralogical and metallurgical characteristics of the ores. This study examined the metallurgical characteristics of typical small-scale gold mining tailings to understand their grinding characteristics, gold deportment and cyanidation behaviour. The gold deportment results showed that 96.1% of the gold in the samples is free milling (can be leached directly with cyanide and recovered through carbon adsorption), whilst the remaining 3.9% of the gold in the samples is associated/locked up with other mineral phases (carbonates, sulphides, carbonaceous matter and quartz). The gold-by-size distribution also indicated that 73.1% of the gold is contained in coarser size fractions (+150 μm), 14.96% is from -150 μm to +75 μm size range, and 11.83% is contained in the finer size distribution (−75 μm). This suggests that incorporating a gravity recovery system during processing will be highly advantageous. The leaching kinetics results showed that gold recoveries achieved within 8, 16 and 24 h were 68, 73.8 and 76.4%, respectively. The corresponding total cyanide consumption rates after 8, 16 and 24 h of leaching were 550, 580 and 600 ppm, respectively. Generally, the gold recoveries and the cyanide consumption rates agree with industrial practices/results. Overall, the outcomes of the study support the view that some small-scale gold mining tailings are economically viable, and hence can be re-processed through efficient processes such as carbon-in-leach/carbon-in-pulp.**

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## 1. Introduction

The gold mining sector has been a major contributor to the socio-economic development of countries like South Africa, Ghana and Australia. These countries benefit from the sector through foreign direct investments (FDI), foreign exchange earnings and employment (for both skilled and unskilled) workforce [1−3]. In a typical gold mining-dependent country like Ghana, the mining activities legally occur in two forms; large-scale mining (LSM), characterised by heavy mechanisation/technology, and small-scale mining (SSM), characterised by low mechanisation and the use of rudimentary hand tools (e.g., pickaxes and shovels for digging gold-bearing materials) [4−6]. Whilst the LSM accounts for about 70% of the total gold output of Ghana, the SSM sector contributes approx. 30% of total gold production and (directly/indirectly) employs about 70% of the total workforce in the mining industry. The workforce employed by the SSM sector translates to approx. 1,000,000 people, hence making the sector worth considering in terms of its socio-economic development potential [6−13].

SSM is widely practised across the width and breadth of Ghana due to the favourable geological climate, especially for gold which has been mined since the pre-colonial times [14,15]. In the SSM sector, the gold deposits are classified as alluvial/eluvial, colluvial, and hard-rock/lode-vein, and this classification dictates the mining and

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processing methods. Typical traditional methods used in the exploitation of gold in Ghana are the "anomabo", "chisel and hammer", underground "ghetto", and the "dig and wash" methods [5]. Whilst the Anambo method is used to exploit gold-bearing gravel from riverbeds, the chisel and hammer are used for hard rock/quartz vein-type (lode) formations occurring mainly as outcrops [11]. Additionally, the underground "ghetto" method is used for hard rock from underground workings, whilst the "dig and wash" is used for alluvial gold deposits that occur on the banks of rivers, in old valleys, on terraces, or in the tailings dumps of old mine workings [16,17]. In recent times, the sector has evolved into the use of heavy-duty equipment such as excavators, Chinese-made diesel-powered rock crushers (locally called "changfa"), dredges, gravity concentrators and alluvial washing plant methods. A detailed description of the various methods employed in the SSM in Ghana is reported by Bansah [16,17].

Currently, the "Changfa" method is widely used by miners to extract gold from quartz vein-type ores/hard rock. The method originated from the brand name of a Chinese-made (changfa) diesel-powered rock crusher used for crushing excavated lode deposits. This extraction method typically involves excavating ore deposits manually with simple tools such as pickaxes, hammers, shovels or spades. The mined ores are then carried by women (as head load in most cases) or men using wheelbarrows to the changfa location for processing. The ores are then shovelled into the crusher for comminution (crushing/grinding). Notably, the crusher has a water pump connected to it, which "continuously pumps water, mostly from a sump onto a sluice board (usually lined with a blanket) connected to the crusher chute for washing. After a while, the changfa motor is shut down, and the blanket is removed and washed in a drum containing water to obtain the trapped gold for further processing" [5]. The concentrate obtained is further panned to get the final concentrate locally called "black" (the name is given to the final concentrate due to its black colour because of the presence of heavy minerals such as iron-oxide). The gold in the final concentrate is often recovered through the amalgamation process, followed by retorting/roasting to produce "sponge" gold which is further smelted into gold dore. Studies have shown that this process is characterised by low productivity as a result of its low gold recovery (approx. 30–50%) [18]. Hence tailings from these operations are known to have economic values. Notably, it can be estimated that about 1 million tonnes of tailings are generated annually by these miners in Ghana.

The low gold recoveries often recorded by the miners, especially those mining lode/vein type using the Chanfa and amalgamation process, can be attributed to an inadequate understanding of the chemical, mineralogical and metallurgical characteristics of the gold ores. Notably, the most efficient gold extraction processing route is directly related to the inherent mineralogical, chemical and metallurgical characteristics of the gold ore being processed [19–21]. Therefore, to process ores efficiently and profitably, in-depth knowledge of the nature (e.g., gold metal phases, grain size, liberation and the associated gangue minerals) of the ore is very relevant. However, the costs often involved in performing these analyses, the limited availability of these techniques/equipment (e.g., Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN), X-Ray Fluorescence (XRF) and Mineral Liberation Analyser (MLA)) and lack of adequate knowledge of the relevance of these analyses make it difficult for the miners to patronise them. Evidently, the miners process their ores based on "trial and error" without any indepth understanding of nature, hence the low recoveries often recorded.

As discussed earlier, the low gold recoveries associated with the SSM operations mean that much of the gold is still locked in the tailings. Evidently, some LSM companies in Ghana over the years have been buying these tailings from the SSM sites for further processing. Currently, several attempts are being made by investors, researchers and SSM companies to unlock the economic value of the SSM tailings in Ghana. This work sought to conduct gold deportment assessments and evaluate the behaviour of the tailings to chemical treatment using inexpensive and readily available techniques. Particularly, the minerals association, the liberation characteristics and the cyanide leaching behaviour of the tailing samples were examined.

## 2. Materials and methods

### *2.1. The study area*

This research was conducted at an SSM site in the Eastern region of Ghana. The gold deposit mined is within the Kibi gold belt, which is south and parallel to the "gold bank" Ashanti Gold belt (host to major gold-producing mines in Ghana) (Fig. 1). "The Kibi

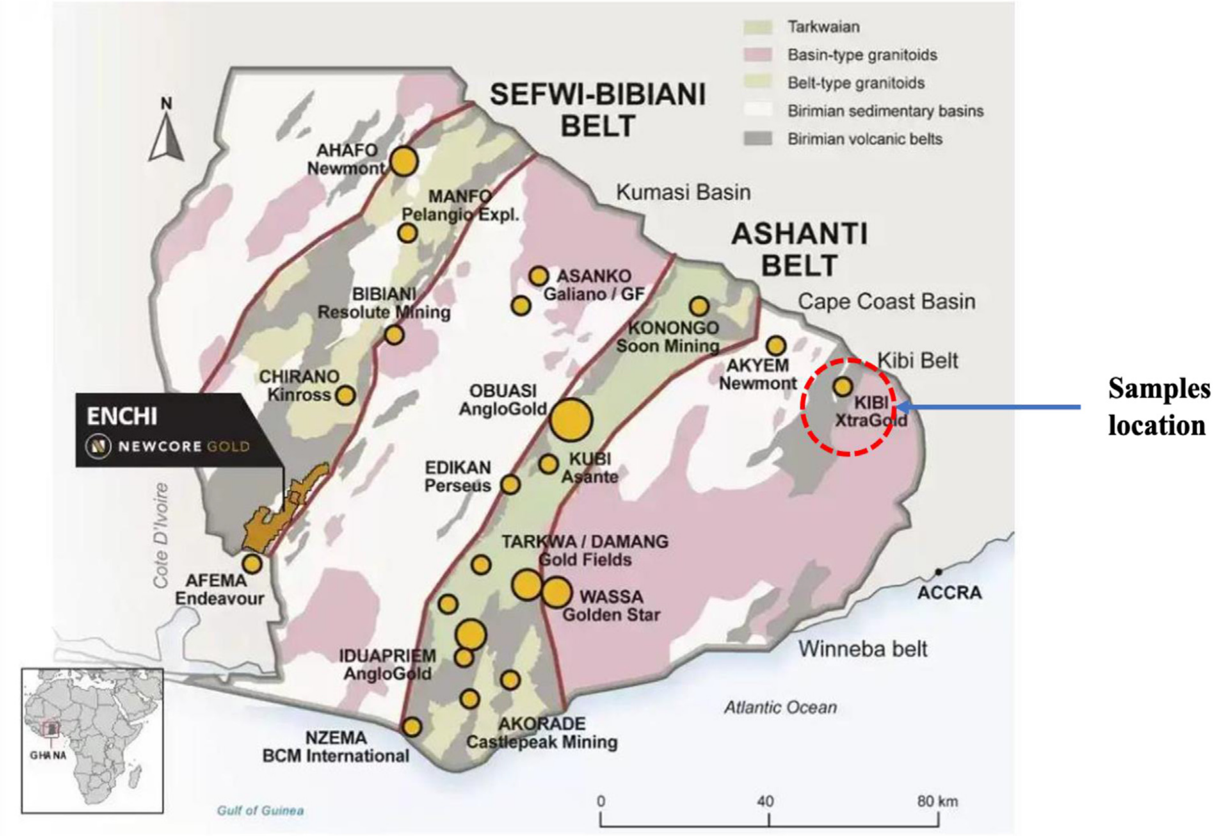

*Fig. 1. The geological map of southern Ghana with the various gold belt. The study area is within the Kibi belt, shown with a red circle (Map adopted from Newcore Gold).*

Gold Belt is the easternmost Birimian volcano-sedimentary belt in southern Ghana" [after 22 reporting 23]. "The NE-trending greenstone belt is approx. 60 km long; with its southern extremity truncated by a sizeable granitoid batholith, and its northern extremity appearingto be overlain by younger, flat-lying Voltaian sediments" [after 22 reporting 23]. "The Kibi Belt, a typical Birimian greenstone belt that shares several litho-tectonic and metallogenic similarities with the prospective Ashanti and Sefwi belts clearly hosts a significant resource of bedrock gold as evidenced by their extensive alluvial nature throughout the area" [after 22 reporting 23]. Notably, "substantial bedrock sources of gold are yet to be discovered in the area, and this may be simply due to the lack of systematic exploration as well as the presence of extensive alluvial cover along the lower slope of the Atewa Range and in nearby valleys" [after 22 reporting 23]. The deposit type targeted by these miners within the study area consists of orogenic mesothermal gold mineralisation of classic Ashanti-type of gold occurrence [22,23].

## *2.2. Materials*

The tailing samples (CAT 1–6) used were collected from a typical SSM site within the Eastern region of Ghana, where the "Chanfa" and amalgamation processing methods are employed. The average head Au grades of the samples (as collected) was analysed using fire assay method, and the results are highlighted in Table 1. A composite sample obtained from the mixture of CAT 1 and 2 was used for the gold-by-size distribution, diagnostic leaching, and cyanidation test works.

*Table 1. Average head gold (Au) grade from the tailing samples obtained from the same pile.*

| Sample ID | Average grade (g/t) |
|---|---|
| CAT 1 | 9.10 ± 2.51 |
| CAT 2 | 10.52 ± 3.20 |
| CAT 3 | 5.42 ± 2.42 |
| CAT 4 | 7.00 ± 1.53 |
| CAT 5 | 4.77 ± 1.13 |
| CAT 6 | 4.71 ± 1.70 |
| COMPOSITE | 9.86 ± 2.74 |

### *2.3. Gold-by-size grading analysis*

The SSM gold miners mostly do not investigate the nature of gold (e.g., the gold grain sizes), which determines the optimum level of grinding that ensures maximum liberation. Therefore, this test was carried out to determine the particles' size range that contained most of the gold grains. A split aliquot of approx. 500 g to approx. 1 kg of the composite sample was screened through sieve sizes 300, 150, 106 and 75 μm. The oversize of each screen and the undersize of the last screen were weighed, and fire-assayed for their gold content.

### *2.4. Diagnostic leaching procedure*

Generally, the adoption of a particular pretreatment/processing route in mineral processing is based primarily on the processing economics, which is heavily linked to overall gold recovery. The overall recovery is also dependent on factors such as the mode of occurrence and association of gold or the refractory nature of the ore. Therefore, once the nature of ore refractoriness is known, a processing strategy can then be developed to optimise the process variables to maximize gold recovery. Diagnostic leaching is one of the analytical tools developed to provide insight into the deportment of gold within the ore. This method involves the selective decomposition of the mineral phases and extracting the gold exposed from the mineral removed in the subsequent cyanide leaching step. A set of guidelines for the design of a diagnostic leaching experiment has been demonstrated by Lorenzen [24]. In this study, a five-stage sequential diagnostic leaching technique was employed to estimate the gold deportment in various minerals in a manner as described by Lorenzen [24]. 1 kg of the sample (with $P_{80}$ of 220 μm) was leached with cyanide for 24 h at 1.5 g/L cyanide strength and pH 10.5. Each residue was sequentially digested with HCl, $H_2SO_4$, and $HNO_3$, and each digestion step was followed by conditioning and 24 h cyanidation. The tailings obtained were roasted above 650°C to decompose carbonaceous matter and subjected to cyanidation. 50 g of the final cyanidation residue of the sample was fire assayed; the prill was digested and topped to 10 ml for AAS analysis to determine the gold in quartz. All leach solutions were extracted with DIBK and AAS finish.

### *2.5. Cyanidation and reagent consumption*

A laboratory cyanidation test was conducted to understand the leaching kinetics and overall recovery behaviour of the tailing samples. 1 kg of the composite sample milled to approximately 80% passing 106 μm was leached for 24 h. Thus, the sample was put into a 5 L leach bottle, and tap water was added to prepare a pulp of 54 wt.% solids. The pulp pH was adjusted to 11 with lime and initial free CN strength set to 1000 ppm. Leaching was conducted for 24 h with the bottle rolling to agitate and aerate the pulp. Periodic solution samples were picked for gold in solution, pH and Cyanide strength analyses within the time intervals of 2, 8, 16 and 24 h. It is worth mentioning that no further reagents (lime and CN) were added during the leaching period. At completion, the sample was filtered, and the pregnant solution was sampled and assayed for Au. Residue solids were washed and assayed for Au as well.

## 3. Results and discussion

### *3.1. Diagnostic gold deportment*

Table 2 shows the results for the distribution or deportment of gold in various mineral phases. The results indicate that 96.15% of the gold in the ore was recoverable by direct cyanidation, whilst 1.83% of the gold is locked in HCl digestable minerals such as carbonates, chlorite, and some oxides (e.g., magnetite). Moreover, gold locked in strong acids ($H_2SO_4$ and $HNO_3$) digestable minerals was 1.4%.

*Table 2. Summary of Au deportment analyses.*

| Au association/solubilization process | Au (g/t) | Au distribution (%) |
|---|---|---|
| Free milling Au (leached by direct cyanidation with carbon) | 9.48 | 96.15 |
| Au associated with carbonates | 0.18 | 1.83 |
| Au associated mild sulphide minerals | 0.07 | 0.71 |
| Au associated sulphide minerals | 0.07 | 0.71 |
| Au associated with carbonaceous matter | 0.00 | 0.00 |
| Undissolved Au (assumed to be associated with quartz and cannot dissolve) | 0.06 | 0.60 |
| **Total** | **9.86** | **100.00** |

The strong acid-digestable minerals include sulphide minerals (e.g., pyrite and arsenopyrite) [25,26]. The gold locked in the final residue was 0.60%, suggesting that these are very fine gold grains locked in remnant silicates such as quartz and felspar. Thus, only ultra-fine grinding may be able to liberate some of these fine gold grains [25,27]. Notably, the carbonaceous matter contained no gold. The results suggest that the tailings from the small-scale mining operations are free milling, meaning they can still be treated using the direct cyanidation method to recover about 96% of the gold with the right metallurgical processing routes and conditions.

### 3.2. Gold (Au)-by-size distribution

The Au-by-size distribution study helps to determine (i) the particle size distribution where the Au is found, (ii) processing route of the ores (either choosing direct cyanidation or combination with pre-gravity concentration), and/or (iii) extent of grinding efficiency that ensures maximum Au recovery [25,28–31].

Fig. 2 shows the plot of Au distribution and ore particle size for the tailing sample. The result indicates that Au occurs in all size fractions, with the majority of Au (50.8%) found in +300 μm size fractions. In addition, +150, +106, +75 and −75 μm size fractions contained 23.13, 9.2, 5.76 and 11.83% of the Au in the sample, respectively. Overall, the result shows that 73.21% of Au is associated with coarser (+150 μm) particle size fraction, whilst 14.96% of the Au was associated with −150 μm + 75 μm size range fraction, and 11.83% of Au was found in the finer (−75 μm) size fraction of the ore.

Moreover, the plot of Au grade and ore particle size distribution (Fig. 3) revealed that Au grade for +300, +150, +106, +75 and −75 μm particle size fractions were 11.64, 11.70, 11.16, 7.59 and 6.02 g/t, respectively. Thus, the coarser size fractions (+300 μm, +150 μm, +106 μm) host acumulative Au grade of 11.5 g/t, whilst the finer size fraction contain a cumulative Au grade of 6.81 g/t. This trend is similar to that shown in Fig. 2, where the coarser size fraction contained higher Au distribution. It is worth mentioning that the Au grade currently mined by the large-scale gold mining operations (LSM) in Ghana, especially those involved in surface mining, have average Au grades of less than 4 g/t. The relatively higher Au grade of the SSM tailings has, in recent times, attracted the attention of some LSMs and hence purchased these tailings to support their operations in terms of meeting production targets at a minimal cost.

### 3.3. Gold leaching behaviour and reagent consumption

Based on the deportment and liberation results obtained, gold extraction, leaching behaviour and cyanide consumption rate were studied for the

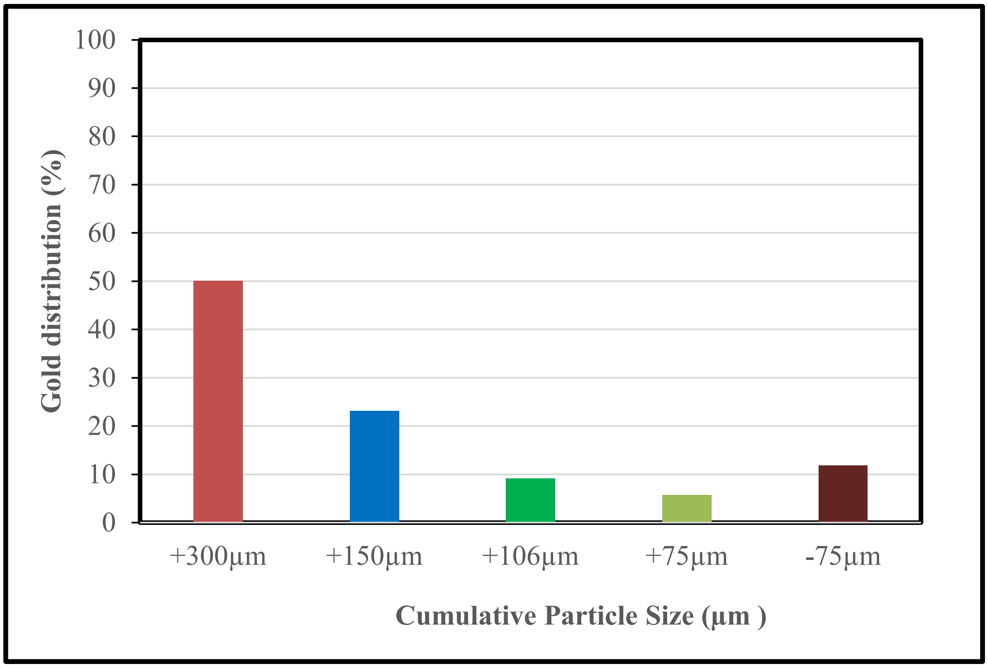

*Fig. 2. Au distribution (%) as a function of particle size distribution of the sample.*

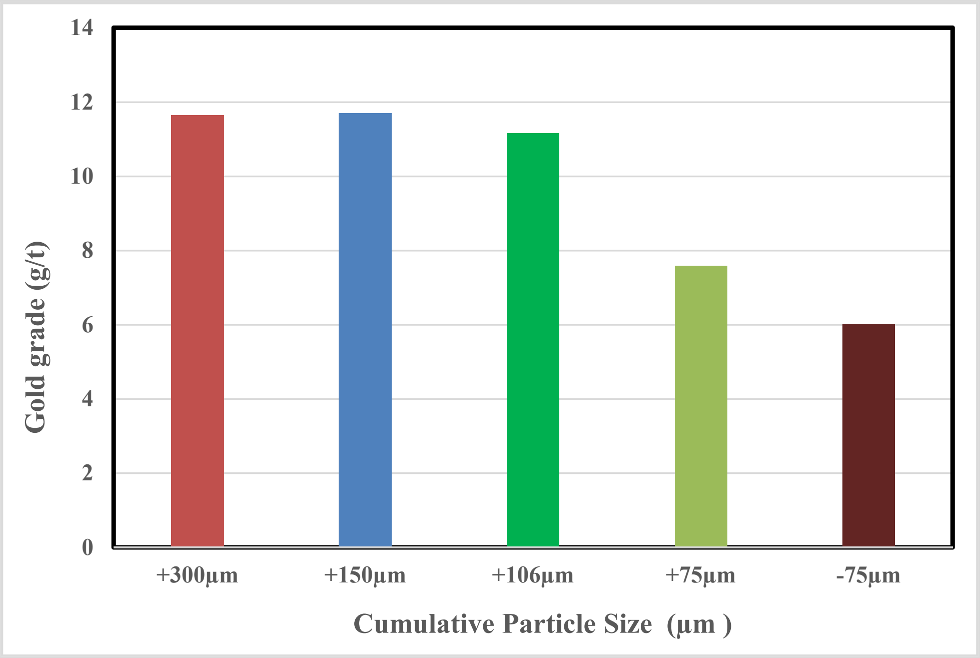

*Fig. 3. Au grade (g/t) as a function of cumulative particle size distribution (µm) of the sample.*

samples using direct cyanidation. The aim of this study is to establish the leaching kinetics and the time the optimum extraction/recovery could be achieved.

Fig. 4 and Table 3 show the results for gold leaching kinetics and extraction with corresponding cyanide consumption rates during 24 h cyanidation. The leaching test was conducted at a pH of 10.5 with an initial free cyanide concentration of 1000 ppm. Fig. 4 highlights that the cumulative Au extractions obtained after 2, 8, 16 and 24 h of cyanidation were 49.2, 68,0, 73.8 and 76.4%, respectively. The recovery results obtained after 24 h cyanidation is consistent with the nature of Au liberation and association in the samples as revealed by the gold deportment studies.

In terms of cyanide consumption, the results (Table 3) show that there was appreciable cyanide consumption of 510 ppm within the first 2 h of leaching, which increased to 600 ppm as overall consumption after 24 h leaching. Evidently, the cyanide consumption rate recorded during the 24 h

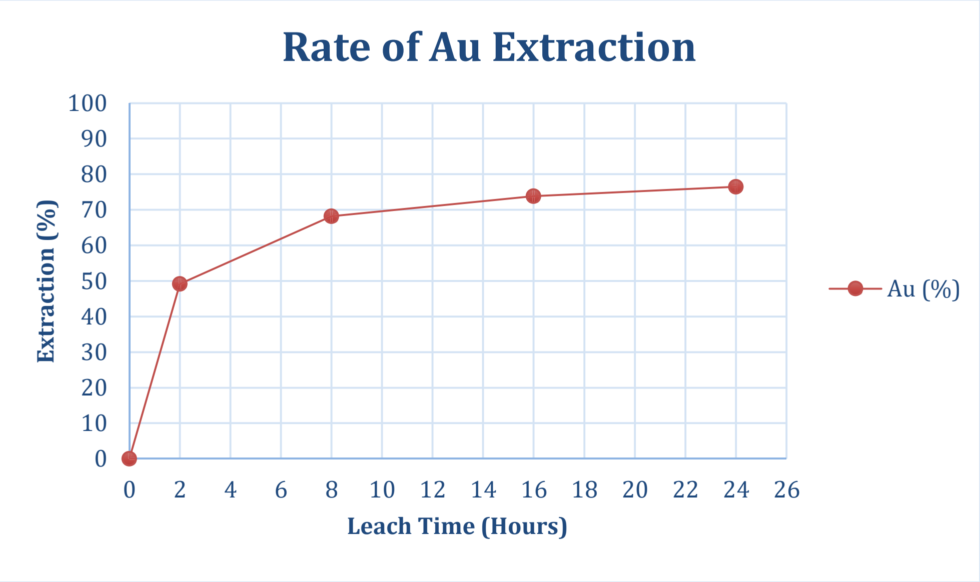

*Fig. 4. Cumulative Au extractions (%) as a function of time during 24 h bottle roll cyanidation.*

*Table 3. Leaching time, pH, residual cyanide concentration and Au recovery.*

| Leaching time (h) | pH | Free cyanide concentration in solution (ppm) | Cumulative recovery (%) |
|---|---|---|---|
| 0 | 11.00 | 1000 | 0.0 |
| 2 | 10.95 | 490 | 49.2 |
| 8 | 10.85 | 450 | 68.2 |
| 16 | 10.80 | 420 | 73.8 |
| 24 | 10.72 | 400 | 76.4 |

in this study is consistent with the industrial consumption rate that ranges between 200 and 1000 ppm [32,33].

Overall, the study has confirmed that the gold extraction methods used by the small-scale miners are still inefficient; hence much of the gold is left in their tailings. This means that ASGM tailings have economic value that could be unlocked through proper ore characterisation and modified extraction methods such as gravity concentration and cyanidation. For example, since most of the gold appeared to be within the coarser size fraction, one is encouraged to process the tailing first using gravity concentration and then re-grind the gravity tailings before subjecting it to further cyanidation processes such as CIL/CIP.

## 4. Conclusions

The outcomes of the gold deportment, size-by-size gold distribution and the leaching behaviour studies of the ASGM tailings are:

- The majority (96.1%) of the gold in the tailings is highly liberated, free milling and can easily be recovered through direct cyanidation.
- There is a potential presence of carbonaceous materials, sulphides and carbonate minerals containing some traces of gold (3.9%).
- The gold-by-size distribution showed that 73.1% of the gold is found in coarser size fractions (+150 μm), 14.96% found within −150 μm + 75 μm size range and 11.83% contained in the finer size distribution (−75 μm).
- Gold recoveries of 68.0, 73.8 and 76.4% were achieved after 8, 16 and 24 h of cyanide leaching and carbon adsorption, respectively.
- The cyanide consumption rates obtained after 8, 16 and 24 h of leaching were 550, 580 and 600 ppm, respectively.

## Ethical statement

The authors state that the research was conducted according to ethical standards.

## Funding body

This work received no external funding.

## Conflict of interest

None declared.

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