Characterization of amalgamation tailings from ASGM in Sekotong area, West Nusa Tenggara, Indonesia, and its potential added value

A Wahyudi*, W Surono, I Rodliyah and H E Mamby
Research and Development for Mineral and Coal Technology (TEKMIRA), Ministry of Energy and Mineral Resources (ESDM), Bandung, Indonesia

*Corresponding author’s e-mail: a.wahyudi80@esdm.go.id

Abstract. Artisanal and small-scale gold mining (ASGM) in Indonesia still uses mercury in amalgamation process to extract gold form the ores. The process easily produces gold but at the same time produces very dangerous mercury waste. In this study, a comprehensive series of tests were carried out on amalgamation tailings from the ASGM in Sekotong area, West Nusa Tenggara. The tailings contain mercury up to 150 ppm, above the safe threshold, and gold up to 20 ppm which is intended to be recovered. Furthermore, mineral liberation analysis (MLA) and gravity recoverable gold (GRG) test were performed to determine the feasibility of recovering gold from the tailings. The liberation degree of the gold started from particle size of 37 μm causes challenging to recover it. However, the GRG test confirmed that the gold was still feasible to be recovered by gravity concentration.

1. Introduction
Based on the data from the United Nations Environment Programme, the source of environmental mercury contamination is dominated by the artisanal and small-scale gold mining (ASGM) [1,2]. The UN report states that Indonesia is the third largest emitter of mercury in the world, after China and India. It is also reported that there has been a significant increase in mercury use and pollution in Indonesia’s ASGM sector over the past two decades [3,4,5].

Mercury usage as a means to amalgamate gold, or amalgamation, is the most common method of gold recovery used by ASGM. Despite its toxicity, miners prefer to use this technique for a variety of reason. Mercury is considered to be easy to be used and readily available agent. Meanwhile amalgamation is considered as simple, effective and cheap methods for gold extraction [6,7].

Poor conduct and inappropriate waste disposal management in ASGM is a serious hazard for the environment and human health. Mercury-containing tailing which is left in the open environment will be washed; eroded and volatilized and its leads to cause contamination to soil, food source and local water [8,9]. The occurrence of microbial methylation activities that transformed inorganic mercury into organic mercury such as methylmercury, phenyl mercury, and ethyl mercury, is the most toxic form of mercury and can be accumulated in living organism including human body through food chain [2]. Mercury poisoning can result in death, mental retardation, dysarthria, blindness, neurological deficits, loss of hearing, developmental defects, and abnormal muscle tone [7,10]. Another major source of mercury emissions is contributed by burning amalgam activities to vaporize mercury. The inhalation of mercury vapor can produce harmful effects on the nervous, digestive, and immune systems and the lungs and kidneys and may be fatal [11,12].
The application of cyanidation methods represented a major advance for the gold mining industry because it allowed for higher recoveries than the prevailing mercury amalgamation methods [12]. Cyanidation is being promoted as an alternative to amalgamation by groups seeking to reduce the mercury consumption of ASGM. At Sekotong District of West Lombok, miners applied the amalgamation process followed by cyanidation process to recover as much gold as possible from the gold ore. Besides ore, the residual sludge from the amalgamation process is reprocessed through cyanidation, which is called tong. Based on Krisnayanti [6] observation, ASGM activities occur alongside farming and agriculture areas. Tailings of the amalgamation and cyanidation processes are generally discharged directly into rice paddies which have been informally re-designated as tailings ponds. Improper design of these tailing ponds allows tailing that still contains soluble complexed mercury and various other heavy metals flows freely to the environment. Elevated concentration of soluble mercury increased potential to contaminate the environment, bio-methylate enters the food chain. Results of a survey at ASGM location at Sekotong indicated that the amalgamation and cyanidation tailings still contained in average of 428.91 ppm mercury and 310.33 ppm Hg, respectively [13].

Mercury-free and more environmental-friendly processing technologies are urgently needed to protect the environment and human health. The purpose of this article is to characterize amalgamation tailing from Sekotong District, West Nusa Tenggara and evaluate the potency of gold recovery by gravity concentration methods.

2. Methods

Amalgamation tailings were obtained from four locations in Sekotong area, West Nusa Tenggara, Indonesia, and labelled as AT-1, AT-2, AT-3, and AT-4. The tailings were collected by grab sampling from the tailing ponds using a shovel. The samples were then analyzed in the laboratory for their mercury and gold. The mercury content was analyzed using cold vapor atomic absorption spectroscopy (CVAAS), while the gold content used fire assay and atomic absorption spectroscopy (AAS), and the heavy metals content employed inductively coupled plasma mass spectrometry (ICP-MS). Sieving analysis was conducted to observe particle size distribution and gold distribution within each size fraction using a screen in several sizes from 850 μm to 25 μm. Mineral liberation analysis (MLA) was conducted to observe the liberation degree of the precious metals from their associated minerals for each size fraction using an optical microscope. The types of metals and minerals detected by optical microscope were determined by comparing them with a data base of mineral’s morphology. Gravity recoverable gold (GRG) analysis was conducted using Knelson concentrator to determine the quantity of gold within the samples that can be recovered [14].

3. Results and discussion

3.1. Amalgamation tailings characterization

3.1.1. Contents of Hg, Au, and other heavy metals. Table 1 shows the content of mercury, gold and other heavy metals available in four amalgamation tailing samples. The data shows that there is a correlation between the mercury and the gold contents. Naturally, the higher the mercury content within the tailings the higher the gold one. It is indicated that the Hg within the tailings is physically bound to the gold. As a result, such the tailings are potential to be recovered for its gold.

Of the four samples, there is a significant distinction between the Hg and the Au contents. The AT-1 contains low Hg and Au contents, namely 19.55 and 0.66 ppm. However, such the Hg content is above the permitted threshold, namely 2 ppm [15]. It needs to be recovered in terms of reducing the content. AT-2, AT-3, and AT-4 samples retain the high Hg content, so are their gold content, especially in AT-2 and AT-4 samples. Referring to the heavy metal content within amalgamation tailing sample, almost all samples retain low content of Ag and high content of Cu.
Table 1. The contents of Hg, Au and heavy metals within amalgamation tailings

| Elements | AT-1 | AT-2 | AT-3 | AT-4 |
|----------|------|------|------|------|
| Hg (ppm) | 22.20 | 61.67 | 64.96 | 153.07 |
| Au (ppm) | 1.85  | 13.97 | 9.03  | 20.38  |
| Ag (ppm) | <0.01 | <0.01 | <0.01 | <0.01  |
| Cu (ppm) | 147   | 499   | 88.59 | 1913   |
| Cd (ppm) | 2.80  | 4.72  | 3.15  | 4.59   |
| Zn (ppm) | 53.17 | 59.33 | 27.39 | 36.39  |
| Pb (ppm) | 313   | 43.24 | 50.23 | 48.10  |
| Ni (ppm) | 18.38 | 24.45 | 12.08 | 16.43  |
| Cr (ppm) | 73.71 | 45.96 | 33.31 | 43.57  |
| S (%)    | 1.94  | 2.48  | 0.56  | 3.18   |

3.1.2. Sieve analysis. Particle size distribution for four amalgamation tailings are shown in Figure 1. The four samples have similar particle size distribution, namely passing 850 μm sieve (100%), and similar P80 point. P80 means 80% of the particles pass the particular sieve size. This parameter is usually used for determining the average of the particle size of the sample. Thus, all of the samples are classified as fine particles by having P80 between 65 and 100 μm. Table 2 shows the gold distribution for each size fraction.

![Figure 1](image1.png)

**Figure 1.** Particle size distribution of the amalgamation tailings

Table 2 shows that the gold is distributed in all fractions. By the trend, the finer particle size tends to a higher gold content. All of the samples have the highest gold distribution at particle size less than 25 microns. It means the process to extract gold from the samples might be more difficult and complex due to its fine particles.

3.1.3. Mineral liberation analysis (MLA). Figure 2 shows the liberation degree of electrum (gold) in AT-4, the sample which has the highest content of Au, by showing its mineragraphy pictures at several fractions. However, mercury cannot be detected using optical microscope due to its characteristic which has transparent appearance and liquid form at room temperature.
| Sieve (µm) | Mass (g) | Au (ppm) | Mass (%) | Au unit (mg) | Au distribution (%) |
|------------|----------|----------|----------|--------------|-------------------|
| 850        | 0.0      | 1.38     | 5.0      | 0.03         | 3.8               |
| 425        | 1.1      |          |          |              |                   |
| 300        | 1.2      |          |          |              |                   |
| 212        | 1.8      |          |          |              |                   |
| 150        | 4        |          |          |              |                   |
| 106        | 16.2     |          |          |              |                   |
| 53         | 115.6    | 0.51     | 23.9     | 0.06         | 6.6               |
| 38         | 65       | 0.93     | 13.4     | 0.06         | 6.8               |
| 25         | 45       | 0.16     | 9.3      | 0.01         | 0.8               |
| <25        | 233.7    | 3.14     | 48.3     | 0.73         | 82.1              |
| Total      | 483.6    | 1.85     | 100.0    | 0.89         | 100.0             |

(a) Code: AT-1

| Sieve (µm) | Mass (g) | Au (ppm) | Mass (%) | Au unit (mg) | Au distribution (%) |
|------------|----------|----------|----------|--------------|-------------------|
| 850        | 0.0      | 7.51     | 3.8      | 0.14         | 2.1               |
| 425        | 0.0      |          |          |              |                   |
| 300        | 0.3      |          |          |              |                   |
| 212        | 1.6      |          |          |              |                   |
| 150        | 5.4      |          |          |              |                   |
| 106        | 11.8     |          |          |              |                   |
| 53         | 102.5    | 5.2      | 20.6     | 0.53         | 7.7               |
| 38         | 72.9     | 9.32     | 14.7     | 0.68         | 9.8               |
| 25         | 63.5     | 16.42    | 12.8     | 1.04         | 15.0              |
| <25        | 238.4    | 19.03    | 48.0     | 4.54         | 65.4              |
| Total      | 496.4    | 13.97    | 100.0    | 6.94         | 100.0             |

(b) Code: AT-2

| Sieve (µm) | Mass (g) | Au (ppm) | Mass (%) | Au unit (mg) | Au distribution (%) |
|------------|----------|----------|----------|--------------|-------------------|
| 850        | 2.3      | 13.25    | 11.5     | 0.22         | 4.3               |
| 425        | 4.5      |          |          |              |                   |
| 300        | 4.4      | 3.69     | 7.2      | 0.15         | 2.9               |
| 212        | 8.5      |          |          |              |                   |
| 150        | 20.4     |          |          |              |                   |
| 106        | 39.0     | 5.54     | 7.0      | 0.22         | 4.3               |
| 53         | 163.8    | 5.38     | 29.5     | 0.88         | 17.6              |
| 38         | 75.6     | 5.32     | 13.6     | 0.40         | 8.0               |
| 25         | 52.3     | 6.4      | 9.4      | 0.33         | 6.7               |
| <25        | 185.2    | 16.4     | 33.3     | 3.04         | 60.5              |
| Total      | 556.0    | 9.03     | 100.0    | 5.02         | 100.0             |

(c) Code: AT-3

| Sieve (µm) | Mass (g) | Au (ppm) | Mass (%) | Au unit (mg) | Au distribution (%) |
|------------|----------|----------|----------|--------------|-------------------|
| 850        | 0.6      | 10.61    | 11.2     | 0.75         | 9.7               |
| 425        | 3.0      |          |          |              |                   |
| 300        | 2.3      | 25.79    | 3.7      | 0.47         | 4.7               |
| 212        | 2.5      |          |          |              |                   |
| 150        | 9.9      |          |          |              |                   |
| 106        | 56.9     | 13.25    | 11.5     | 0.75         | 7.5               |
| 53         | 207.9    | 12.81    | 42.1     | 2.66         | 26.5              |
| 38         | 61.2     | 12.13    | 12.4     | 0.74         | 7.4               |
| 25         | 39.8     | 28.38    | 8.1      | 1.13         | 11.2              |
| <25        | 109.4    | 39.28    | 22.2     | 4.30         | 42.7              |
| Total      | 493.5    | 20.38    | 100.0    | 10.06        | 100.0             |

(d) Code: AT-4

Table 2. Gold distribution of amalgamation tailings
Figure 2. Mineragraphy of AT-4 at several fractions (El = electrum, Py = pyrite, Hem = hematite, Cc = chalcocite, NL = non-metal)

Figure 2 shows that the liberation degree of gold (electrum) is started from a particle size of 37 µm. Above the size, the gold is still interlocked with other minerals, such as pyrite. The finer the particles the higher the liberation degree. The highest liberation degree of gold held at a particle size of less than 25 µm. It means that technique to recover gold will be more challenging. Common gravity concentrations, such as shaking table and jig, cannot concentrate fine particles [16]. It needs gravity concentration with centrifugal force to concentrate the fine particles, such as using Knelson concentrator.

3.2. Potential added value

The potential added value of the amalgamation tailing was determined using gravity recoverable gold (GRG) test. Based on the GRG test, the samples will be categorized into two types, namely feasible and infeasible to be recovered. The former means that the sample is economically feasible to be treated by gravity concentration while the latter is not feasible. Gravity concentration is considered economical if the gold recovery from the concentrate is bigger than 25% [16]. The GRG results of the amalgamation tailing samples are summarized in Table 3. Due to the particle size of the samples has already less than 850 µm (fine particles), the GRG test was conducted using as-received grain sizes of the samples.
### Table 3. Summary of the GRG test results

| Stream     | Mass (g) | Mass (%) | Au (ppm) | Au dist. (%) | Hg (ppm) | Hg dist. (%) |
|------------|----------|----------|----------|--------------|----------|--------------|
| Con 1      | 75.7     | 0.3      | 4.32     | 0.4          | 300.98   | 9.3          |
| Con 2      | 76.7     | 0.3      | 10.73    | 1.0          | 20.3     | 90.7         |
| Tail 2     | 22018    | 99.3     | 3.75     | 98.6         | 20.3     | 90.7         |
| Feed calc. | 22170    | 100.0    | 3.77     | 100.0        | 20.3     | 100.0        |
| Feed HG    | 1.85     |          |          |              | 22.20    |              |

| Stream     | Mass (g) | Mass (%) | Au (ppm) | Au dist. (%) | Hg (ppm) | Hg dist. (%) |
|------------|----------|----------|----------|--------------|----------|--------------|
| Con 1      | 82.3     | 0.4      | 1286.74  | 29.4         | 1301.76  | 15.7         |
| Con 2      | 78.8     | 0.4      | 273.17   | 6.0          | 52.35    | 84.3         |
| Tail 2     | 21447    | 99.3     | 10.86    | 64.6         | 62.17    | 95.0         |
| Feed calc. | 21608    | 100.0    | 16.68    | 100.0        | 100.0    |              |
| Feed HG    | 13.97    |          |          |              | 61.67    |              |

| Stream     | Mass (g) | Mass (%) | Au (ppm) | Au dist. (%) | Hg (ppm) | Hg dist. (%) |
|------------|----------|----------|----------|--------------|----------|--------------|
| Con 1      | 83.2     | 0.4      | 179.09   | 7.5          | 423.35   | 5.0          |
| Con 2      | 81.4     | 0.4      | 64.22    | 2.6          | 62.17    | 95.0         |
| Tail 2     | 21135    | 99.2     | 8.45     | 89.9         | 100.0    |              |
| Feed calc. | 21300    | 100.0    | 9.33     | 100.0        | 100.0    |              |
| Feed HG    | 9.03     |          |          |              | 64.96    |              |

| Stream     | Mass (g) | Mass (%) | Au (ppm) | Au dist. (%) | Hg (ppm) | Hg dist. (%) |
|------------|----------|----------|----------|--------------|----------|--------------|
| Con 1      | 77.8     | 0.4      | 1257.01  | 24.7         | 458.65   | 2.2          |
| Con 2      | 80.1     | 0.4      | 436.39   | 8.8          | 150.82   | 97.8         |
| Tail 2     | 21396    | 99.3     | 12.27    | 66.4         | 100.0    |              |
| Feed calc. | 21554    | 100.0    | 18.34    | 100.0        | 100.0    |              |
| Feed HG    | 20.38    |          |          |              | 153.07   |              |

AT-2 and AT-4 show the total distribution of gold within the concentrate (con. 1 and con. 2) around 35.4% and 33.5% respectively. It means both samples are feasible to be concentrated by gravity concentration method. Yet the gold within the tailings is still high enough, namely around 65%. The gravity concentration seems not effective to recover the gold within the tailings due to the particle size of gold is too fine and results in the gold loss. To recover such gold particles, it is suggested to use chemicals, such as the cyanidation process.

The distribution of gold in AT-1 and AT-2 is only 1.4% and 10.1% respectively. This makes that the tailings of both samples are infeasible to be recovered by gravity concentration. Leaching seems the best method for processing both AT-1 and AT-2 tailings. Summary of gold distribution of the samples resulted from GRG test is presented in Figure 3.
Figure 3. Gold distribution in concentrates and tailings of the samples resulted from GRG test

In the field, the sample sometimes comes from not only one location but also from another site. The study also comprises a simulation if all samples are mixed to be a composite sample to evaluate whether gravity concentration method is feasible or not to process such the sample. Table 4 illustrates recovery calculation for the composite sample.

| Sample | Stream | Mass (g) | Au (ppm) | Au in feed (µg) | Au in conc. (µg) |
|--------|--------|----------|----------|----------------|-----------------|
| AT-1   | Feed   | 22170    | 1.85     | 41015.30       | --              |
|        | Con 1  | 75.7     | 4.32     | --             | 327.21          |
|        | Con 2  | 76.73    | 10.73    | --             | 823.64          |
| AT-2   | Feed   | 21608    | 13.97    | 301865.16      | --              |
|        | Con 1  | 82.3     | 1286.74  | --             | 105898.86       |
|        | Con 2  | 78.8     | 273.17   | --             | 21526.08        |
| AT-3   | Feed   | 21300    | 9.03     | 192334.76      | --              |
|        | Con 1  | 83.16    | 179.09   | --             | 14893.08        |
|        | Con 2  | 81.37    | 64.22    | --             | 5225.38         |
| AT-4   | Feed   | 21554    | 20.38    | 439268.28      | --              |
|        | Con 1  | 77.82    | 1257.01  | --             | 97820.61        |
|        | Con 2  | 80.07    | 436.39   | --             | 34941.96        |
| Total  |        |          |          | 974483.49      | 281456.82       |
Based on such condition, the recovery of the composite sample is:

\[
\text{\% Recovery } Au = \frac{\text{Au unit con}}{\text{Au unit feed}} \times 100\% = \frac{281456.82}{9748349} \times 100\% = 29\%
\]

(1)

Using a ratio composition among four samples, namely 1:1:1:1 the recovery percentage is 29%. It means that the composite of the amalgamation tailings is still feasible to be concentrated its gold content by gravity concentration [16]. However, the concentration of mercury is still high both in concentrate and tailing (Table 3) and is not able to be recovered well using gravity concentration. Therefore, the recovery of mercury should be carried out first, such as by roasting method, prior to reprocessing the tailing to recover the gold [17].

4. Conclusions

Amalgamation tailings from ASGM in Sekotong, West Nusa Tenggara, still contain high mercury above the safe threshold. The tailings also still contain gold which is intended to be recovered. The reprocessing of the tailings should be conducted properly and safely. The mercury content should be recovered first before continuing the process to recover the gold. The characterization of gold in the tailing is distributed in very fine particles. The liberation degree of the gold started from particle size of 37 \( \mu m \) causes challenging to recover it. The GRG test confirmed that the composite tailings is still feasible to be recovered by gravity concentration.

References

[1] UNEP 2000 Global Mercury Assessment 2013: Sources, Emissions, Releases and Environmental Transport (Geneva, Switzerland)

[2] Gasong B T, Abrian S and Sigit Setyabudi F M C 2017 Methylmercury Biosorption Activity by Methylmercury-resistant Lactic Acid Bacteria Isolated From West Sekotong, Indonesia HAYATI J. Biosci. 24 182–6

[3] BaliFokus 2015 International Mercury Treaty Enabling Activities Program (IMEAP) 1–13

[4] Spiegel S J and Veiga M M 2006 Global Impacts of Mercury Supply and Demand in Small-Scale Gold Mining

[5] Spiegel S J, Agrawal S, Mikha D, Vitamerry K, Le Billon P, Veiga M, Konolius K and Paul B 2018 Phasing Out Mercury? Ecological Economics and Indonesia’s Small-Scale Gold Mining Sector Ecol. Econ. 144 1–11

[6] Krisnayanti B D, Anderson C W N, Utomo W H, Feng X, Handayanto E, Muradinsa N, Ikram H and Khususiah 2012 Assessment of environmental mercury discharge at a four-year-old artisanal gold mining area on Lombok Island, Indonesia J. Environ. Monit. 14 2598–607

[7] Drake K, Kiefer A M and Veiga M M 2016 Cyanidation of Mercury-Contaminated Tailings: Potential Health Effects and Environmental Justice Curr. Environ. Heal. reports 3 443–9

[8] Moreno F N, Anderson C W N, Stewart R B and Robinson B H 2004 Phytoremediation of Mercury-Contaminated Mine Tailings by Induced Plant-Mercury Accumulation Environ. Pract. 6 165–75

[9] Hindersah R, Risamasu R, Kalay A M, Dewi T and Makatita I 2018 Mercury contamination in soil, tailing and plants on agricultural fields near closed gold mine in Buru Island, Maluku J. Degrad. Min. Lands Manag. 5 1027–34

[10] Rice K M, Walker E M, Wu M, Gillette C and Blough E R 2014 Environmental mercury and its toxic effects J. Prev. Med. Public Heal. 47 74–83

[11] WHO 2006 Exposure to Mercury: A major public health concern Prev. Dis. Through Heal. Environ. 4

[12] Gibb H and O’Leary K G 2014 Mercury exposure and health impacts among individuals in the artisanal and small-scale gold mining community: A comprehensive review Environ. Health Perspect. 122 667–72
[13] Krisnayanti B D 2018 ASGM status in West Nusa Tenggara Province, Indonesia J. Degrad. Min. Lands Manag. 5 1077–84
[14] Laplante A R and Clarke J 2006 A Simple Gravity-Recoverable Gold Test Proceedings of the 38th Annual Meeting of the Canadian Mineral Processors (Ottawa, ON, Canada: Canadian Institute of Mining, Metallurgy and Petroleum) pp 23–37
[15] Alloway B J 1995 Heavy Metals in Soils (London, UK: Blackie Academic and Professional, Chapman and Hall)
[16] Veiga M M and Gunson A J 2020 Gravity concentration in artisanal gold mining Minerals 10 1–50
[17] Jønsson J B, Appel P W U and Chibunda R T 2009 A matter of approach: the retort’s potential to reduce mercury consumption within small-scale gold mining settlements in Tanzania J. Clean. Prod. 17 77–86

Acknowledgment
The authors thank to BPPT, KLHK, and UNDP in the GOLD-ISMIA Project for its involvement in the research.