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Mill leaching: a viable substitute for mercury amalgamation in the artisanal gold mining sector?

Marcello M. Veiga*, Denise Nunes, Bern Klein, Janis A. Shandro*, P. Colon Velasquez, Rodolfo N. Sousa

University of British Columbia, Norman B. Keevil Institute of Mining Engineering, 6350 Stores Road, V6T 1Z4, Vancouver, BC, Canada

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A B S T R A C T

Artisanal small-scale gold miners (ASM) occasionally employ whole ore amalgamation by adding mercury into ball mills to recover gold. In this process, 25–30% of the mercury added is lost to the environment. It is also inefficient less than 30% of gold is recovered. Amalgamation, followed by cyanidation, has been observed at many artisanal mining sites. This combination poses additional environmental and health consequences. Tests with ore samples from Talawaan, North Sulawesi, Indonesia indicate the possibility of replacing mercury by cyanidation in the ball mill, reaching gold extraction of 93% in 6 h of leaching. The gold in the Indonesian ore sample is fine and less than 8% of gold recovery was obtained with gravity concentration of the ore ground 80% below 0.25 mm, which is a reasonably fine grain size for artisanal gold operations. Replacing mercury addition with cyanidation in ball mills was implemented in one artisanal gold mining operation in Portovelo, Ecuador, achieving 95% of gold extraction in 8 h of mill leaching. This technique demonstrated a drastic improvement in gold recovery. It was found to be a simple, inexpensive technique well accepted by local miners. The results from laboratory and field tests are promising; however a thorough investigation into the socio-economic and environmental aspects of this presented alternative must be conducted prior to introduction.

1. Introduction

Due to its efficiency, gold amalgamation is a common practice in the artisanal and small-scale mining (ASM) sector. At the same time, however, it generates significant mercury (Hg) emissions, resulting in a host of health-related and environmental problems. ASM practices release approximately 1000 tonnes of Hg annually to the environment. There are 10–15 million artisanal miners [1] in more than 70 countries [2] working directly with gold, and due to lack of knowledge and alternatives, thousands of miners and community members have been poisoned by Hg [3]. It is estimated that 30% of Hg used by ASM is lost to the atmosphere when miners roast amalgams in open air. Approximately 70% of Hg is lost when the whole ore is amalgamated; either through the utilization of copper-amalgamation plates or through the addition of Hg directly into ball mills [1].

When Hg is used inside ball mills to amalgamate the whole ore, as observed in Indonesia, Ecuador and Colombia, the amount of Hg lost is at least 10 times the amount of gold produced. It has also been observed in various field trips to these countries that the amalgamation of the whole ore in ball mills is a very ineffective process and gold recoveries are usually not higher than 30%. When only a small portion of concentrate from sluice boxes or centrifuges is amalgamated, the Hg_{lost}:$Au_{produced}$ ratio is around 1 and can be even lower if retorts are used to recycle the evaporated Hg during the roasting process [4]. The amount of gold recovered by amalgamation of concentrates is not always higher than when the whole ore is amalgamated since recovery is governed by gold grain liberation, i.e. by the efficiency of the grinding process. However, Hg loss is substantially higher when amalgamation is conducted in ball mills. Tailings from whole ore amalgamation usually contain 50–200 mg of Hg/kg of ore and are often discharged into water streams. Discharged Hg can then be oxidized and complexed; these are the preliminary steps in the transformation of metallic Hg into a more toxic form, methylmercury [5]. In addition to developing environmental awareness programs, it is crucial to work towards the elimination of practices such as the amalgamation of the whole ore and evaporation of Hg from amalgams in open air.

The replacement of mercury amalgamation with any other process seems to be a site-specific issue. Replacement is dependant on investment capacity, level of education and motivation of miners. Support of local authorities to promote and sustain technological alternatives is critical. To date, no panacea or methodology

* Corresponding authors. Tel.: +604 822 4332; fax: +604 822 5599.
E-mail addresses: veiga@mining.ubc.ca (M.M. Veiga), janisjokinen@hotmail.com (J.A. Shandro).

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that can be widely promoted exists. Each case must be studied carefully and a thorough evaluation of the socio-economic context must be conducted before suggesting any alternative process. With this in mind, the objective of this study was to evaluate the technical feasibility and environmental advantages of introducing an alternative process, such as cyanidation in ball mills (herein referred as "mill-leaching") replacing completely the use of Hg.

The first part of this study was conducted in the laboratory using ore samples from Talawaan, North Sulawesi, Indonesia. Unfortunately, field implementation in Indonesia was not feasible, as the Indonesian Government introduced legislation restricting the use of cyanide in artisanal gold mining operations (however, miners continue to gain access to and use cyanide in their operations, as they have for over a decade). The administrative procedure for the use of cyanide in North Sulawesi for research purposes would be far too complex and slow. As an alternative, field tests were conducted in Portovelo–Zaruma, Ecuador. As Ecuadorian artisanal miners perform whole ore amalgamation in ball mills, the results of this investigation are easily applicable to other sites with similar characteristics, such as Talawaan, Indonesia or Northeast Antioquia, Colombia. This study was part of the Global Mercury Project, a project sponsored by the Global Environmental Facility (GEF), United Nations Development Programme (UNDP) and implemented by the United Nations Industrial Development Organization (UNIDO).

2. Gold processing techniques and ASM

Since the invention of gold cyanidation in the late 1800s, this process has replaced amalgamation for industrial operations as it is more efficient at extracting fine gold. In addition, most cyanide compounds decompose in the environment into less or non-toxic forms (nitrogen and carbon dioxide). Conversely, Hg remains in the environment in its metallic form or eventually forms more toxic and persistent soluble compounds.

In ASM operations, the capital and operating costs required to process gold ores either by amalgamation or cyanidation are usually higher than the manual ore extraction costs, except when the processing is conducted in a very rudimentary way, such as manual panning, as observed in some parts of Africa [6,7] and Asia [8]. Just a few artisanal miners can afford to have their own processing plants. This has created a number of "custom" or "toll" milling centers which are Processing Centers in which miners pay to crush, grind, concentrate and extract the gold from their ores. This practice has been observed by the authors in field trips to countries such as Brazil, Chile, Colombia, Indonesia, Ecuador, Tanzania, Venezuela and Zimbabwe. In Zimbabwe for example, there were as many as 243 Processing Centers operating as of September 2007 [9]. The proliferation of this procedure was quickly noticed since, worldwide, the Processing Center's owners adopted the cheapest and less efficient process to recover gold for their clients: amalgamation. Gold processing is typically offered to miners for free or a token fee, if miners agree to leave tailings at the Centers. These Centers rarely recover more than 30% of the gold brought by the miners. The residual gold left in the Centers is then extracted by cyanidation from the mercury contaminated tailings. A key issue in this scenario, is that cyanide dissolves not only gold but also any remaining Hg left behind from the amalgamation process, forming mercury cyanide, which is either more bioavailable or easier to be methylated than metallic Hg when discharged into the water streams. The environmental impacts of mercury cyanide released by ASM can be followed by high levels of Hg in fish in regions where amalgamation and cyanidation have been used simultaneously [10–12].

There are several alternatives to replace Hg amalgamation with other reagents such as thiosulphate, thiourea, bromine, chlorine, etc., although most are not suitable or affordable to artisanal miners [13–17]. Importantly, technology is only one of the three barriers discussed by Hilson [18] to implement cleaner mining practices. The legislative and economic barriers can be very complicated in the artisanal gold mining sector as most governments are not prepared to understand the benefits and idiosyncrasies of this poverty driven activity. Any change on labor procedures used by the artisanal miners will not be possible if governments do not engage mining communities in dialogue in a transparent way, considering their needs and expectations. In contrast, the field-intervention approach is rewarding as results of technological changes are visible and measurable. Unfortunately, the implemented measures are rarely sustainable if a permanent technical assistance is not established [19]. Hilson [20] discussed several cases of interventions in ASM sites to reduce Hg emissions and observed the lack of sustainability of these endeavors, in many cases due to lack of institutional support. Education at all levels seems to be the most sustainable procedure to introduce cleaner procedures into ASM sites [21].

Cyanide is definitely the most promising reagent to replace mercury. Almost the totality of mining companies uses sodium or potassium cyanide to leach gold. The process works very well and exposed grains of gold finer than 0.2 mm can be leached in 24 h in low concentrations of cyanide (50–1000 mg/L of cyanide), in alkaline solutions (pH10-11), under aeration: $4Au + 8CN^- + O_2 + 2H_2O = 4Au(CN)_2^- + 4OH^-$. Once gold is in solution, it can be precipitated with zinc ($2Au(CN)_2^- + Zn = Zn(CN)_4^{2-} + 2Au$) or adsorbed on activated carbon (usually 5–10 kg Au/tonnes of carbon). The advantage of the carbon process is no filtration is needed since carbon is mixed with the ore pulp (around 30% solids), screened, washed and the gold is desorbed with a caustic solution with or without cyanide and ethanol. The zinc precipitation process (known as Merrill–Crowe Process) is simpler but, the solution must be clear (e.g. settled or filtrated) and, for efficient precipitation, air must be removed. The zinc process has been used by many artisanal miners in Ecuador and Colombia and is useful when the gold grade of the gravity concentrate being leached is high, otherwise this could saturate the activated carbon resulting in gold loss to the solution.

Any technical solution to be successfully implemented in ASM regions must be simple, fast, inexpensive, and more efficient than amalgamation. Worthwhile attempts to introduce efficient and affordable processes to replace amalgamation have not resulted in any significant breakthrough. This is the case of the iGoli process developed by MINTEK in South Africa [22,23], a process to dissolve gold from gravity concentrates with hypochlorite in acidic medium followed by precipitation with sodium metabisulphate. Despite the efforts of the South African Institute in demonstrating the high gold recovery levels of this process over amalgamation, there is a long educational process to convince miners that this alternative process is better than any traditional one. All other methods using gravity concentration to completely replace amalgamation have not succeeded for all cases, since this depends on the mineralogical characteristics of the ore. The most recent developments, the iCon–Falcon centrifuge (iCon–Falcon Concentrators, http://www.iconcentrator.com) and the magnetic sluice box promoted by Cleangold® [24] are great advances on recovering more gold by gravity concentration, but the recovery efficiency depends on the characteristics of the gold ore such as shape of the gold grains, type of deposit, gold grain size, liberation, and type of associated minerals. The iCon is a low weight (100 kg) centrifuge manufactured by Falcon Concentrators that can process up to 2 tonnes of ore/h. This centrifuge was designed for artisanal miners and operates with variable speed (up to 150 G). Most parts of the machine