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Circular Economy in the Metallurgical Mining Industry

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ABSTRACT

Mining tailings are slurry byproducts of mineral recovery. They generate serious environmental risks due to their toxicity when exposed to water and oxygen. Studies focus on eco-friendly alternatives for mitigating these environmental impacts. Processing these tailings enables a sustainable mineral production model through circular economy practices. This study evaluates using gold mining tailings to recover gold and produce bricks. Flotation tests obtained a concentrate with 86.66% gold recovery, containing sulfides (pyrite, arsenopyrite) and a tailing with silicates and oxides suitable for brick manufacturing and ornamental pieces. This approach promotes eco-friendly solutions and a greener approach to mining operations.

INTRODUCTION

The circular economy is an economic and systemic approach aimed at optimizing the use of resources, minimizing waste generation, and promoting sustainability. Unlike the traditional linear model of production and consumption, in which resources are extracted, used, and disposed eventually, the circular economy approach seeks to create a closed-loop system, where products, components, and materials are kept in use for as long as possible (Sanchez et al., 2021).

The primary objective of the circular economy is to maximize efficiency in the use of resources, reducing waste generation and the extraction of new resources. This includes the reuse, recycling, and valorization of materials and products at the end of their useful life. By doing so, these materials can become resources for other production processes (Lacy, 2020).

In mining, particularly in mineral processing and in some hydrometallurgical processes, tailings are generated in large amounts, since the main objective of these processes is to recover the valuable compounds found in small quantities through concentrates and metals. Mine tailings represent a substantial volume of waste generated by the mining industry, which leads to significant environmental and sustainability challenges. This is magnified due to the potential presence of toxic chemicals and heavy metals within the tailings, which, if not managed properly, can lead to soil, water, and ecosystem contamination. These tailings may contain valuable minerals that were not recovered during the initial extraction process (Zamora et al., 2019).

The application of circular economy in tailings management allows the recovery of these resources, which can have a positive economic impact and reduce associated environmental risks, such as soil and groundwater contamination. The circular economy, in this context, promotes more sustainable approaches to tailings management (Zamora et al., 2019). Tailings characterization techniques have been studied to identify valuable components and develop separation and recovery processes. In addition, the use of tailings as a raw material in the production of construction materials, such as bricks and ornamental products, or as fill material in the remediation of mining areas has been explored (Perales and Bascompta, 2021). This paper aims to analyze the challenges and issues associated with tailings management within the mining industry and provide recommendations and solutions for the effective implementation of circular economy strategies in this domain. In the specific case of this work, the objectives are as follows:

- Recover valuable resources from tailings of Poderosa's processing plant named Marañon,
- Minimize environmental impact,
- Generate products to market.

CHARACTERIZATION

The mineralogy and its composition were determined via X-ray diffraction (XRD) analysis conducted in the Cia. Minera Poderosa laboratory. The results are presented in Figure 1 and Table 1.

The mineral bonds in the Marañon tailings were analyzed through Scanning Electron Microscopy (SEM) at the FA INGENIEROS SAC laboratories. The results can be found in Table 2.

Using Energy-Dispersive Spectrometry (EDS) in the SEM, the presence of gold was identified within arsenopyrite. Based on previous experience, it is known that arsenopyrite exhibits refractory behavior to cyanidation.

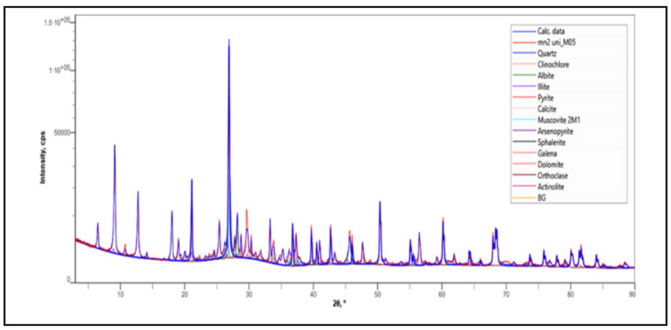

Figure 1. X-ray diffractogram, flotation tailings of Marañon processing plant. 40Kv/40 mA Cu-Ni

Table 1. Phases and composition of tailings from the Marañon processing plant

Mineral	Phases	Composition (%)
Quartz	SiO_2	52.07
Clinochlore	$(Mg,Fe)_5Al(Si_3Al)O_{10}(OH)_8$	11.79
Albite	$AlNaO_8Si_3$	9.42
Illite	$Al_2HKO_{12}Si_4$	9.20
Pyrite	FeS_2	5.69
Calcite	$CaCO_3$	3.63
Muscovite	$K(Al_2Fe_{12})(Si_3Al)O_{10}(OH)_2$	2.93
Arsenopyrite	AsFeS	2.14
Sphalerite	(Zn,Fe)S	1.72
Galena	PbS	0.24
Dolomite	$CaMg(CO_3)_2$	0.48
Ortoclase	$AlKO_8Si_3$	0.04
Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	0.64
Total		99.99

Table 2. SEM results of the Marañon tailings sample

Mineral	Description	Size (µm)
Gypsum	Fibrous form. Found intergrown with galena and pyrite.	<25
Arsenopyrite	Subhedral forms with rhombic habits. Found as free particles and intergrown with galena.	2-40
Galena	Irregular and subrounded forms. It is intergrown with arsenopyrite.	>20
Sphalerite	Irregular sizes. Found as free particles	>30
Pyrite	Irregular forms. It is intergrown with galena.	>20

Table 3. Marañón Tailings Assays

Sample	Au, g/t	Ag, g/t	Pb, %	Zn, %	As, %	Fe, %	S, %
Tailings	1.6	13.6	0.21	1.15	0.99	3.39	4.06

The results of the gold and silver assays, conducted at the Cia Minera Poderosa laboratory, are presented in Table 3.

The gold and silver values in particles were examined through particle size distribution assays. It was observed that 46.4% of the sample's mass was below 37 µm, and 90% of the gold and silver were found in particles smaller than 74 µm.

FLOTATION TESTS

Based on the Marañon tailings characterization, it was determined that regrinding this material was unnecessary. A series of preliminary flotation tests were conducted, where variations were made in the addition of collectors such as potassium amyl xanthate (PAX), sodium dithiophosphate (AR1404), and sodium isopropyl xanthate. These tests demonstrated the effectiveness of flotation for the recovery of gold and silver from the tailings, and a batch flotation testing scheme could be performed in open circuits using rougher, scavenger, and cleaner stages.

In the context of a closed-circuit mass balance, distribution coefficients were used, accounting for the recirculation of cleaner tailings and scavenger concentrate into the feed. The parameters and results are presented in Table 4 and Table 5.

Design of Experiments

An experimental design was performed with the tailings sample, to study the effect of the pH and the dosages of

Table 4. Parameters of the best flotation test

<74 µm, %	PAX, g/t	AR1404, g/t	Pine oil, g/t	pH
73.5	0.044	0.042	0.042	7.5

Table 5. Continuous mass balance of the best flotation test

Product	Assays, oz/st		Distribution, %		Ratio of Concentration
	Ag	Au	Ag	Au	
Conc Au-Ag	42.39	4.29	80.12	76.89	3.48
Tailings	4.24	0.52	19.88	23.11	
Calc. Feed	15.21	1.60	100.00	100.00	

PAX and AR1404 on gold recovery. A complete factorial design of 2^3 was selected, including three central point tests. The test from Tables 4 and 5 was taken as a central point. The main objective was to achieve around 90% gold recovery.

Examples of Real Cases

Using Cia Minera Lincuna and Cia Minera Huancapeti as a case study, the flotation method was adopted for the Pb-Zn circuit tailings (Yoplac, 2010). In this scenario, starting from Pb-Zn flotation tailings, with subsequent separation of pyrite and arsenopyrite. The best-case scenario achieved a 73.58% gold recovery using PAX, AR1404, and pH adjustment with sulfuric acid.

RESULTS AND DISCUSSIONS

Results Obtained from Flotation Tests

The test conditions and results are shown in Table 6.

Another important result is the mineralogical comparison between the initial sample and the final tailings, as presented in Table 7.

Table 6. Experimental design tests

N°	pH	PAX	AR1404	pH	Dosification (kg/t) PAX	Dosification (kg/t) AR1404	Au Recovery (%)
1	1	1	1	8.5	0.03	0.05	71.64
2	1	1	–1	8.5	0.03	0.03	76.51
3	1	–1	1	8.5	0.01	0.05	70.83
4	1	–1	–1	8.5	0.01	0.03	71.33
5	–1	1	1	6.5	0.03	0.05	86.66
6	–1	1	–1	6.5	0.03	0.03	82.38
7	–1	–1	1	6.5	0.01	0.05	70.85
8	–1	–1	–1	6.5	0.01	0.03	72.63
9	0	0	0	7.5	0.02	0.04	76.89
10	0	0	0	7.5	0.02	0.04	81.60
11	0	0	0	7.5	0.02	0.04	80.99

Table 7. Mineralogical comparison of tailings

Mineral	Phases	Initial Sample	Final Tailings
Quartz	SiO_2	52.07	61.65
Clinochlore	$(Mg,Fe)_5Al(Si_3Al)O_{10}(OH)_8$	11.79	15.70
Albite	$AlNaO_8Si_3$	9.42	—
Illite	$Al_2HKO_{12}Si_4$	9.20	—
Pyrite	FeS_2	5.69	0.27
Calcite	$CaCO_3$	3.63	3.73
Muscovite	$K(Al_2Fe_{12})(Si_3Al)O_{10}(OH)_2$	2.93	17.93
Arsenopyrite	AsFeS	2.14	—
Sphalerite	(Zn,Fe)S	1.72	—
Galena	PbS	0.24	—
Dolomite	$CaMg(CO_3)_2$	0.48	0.71
Ortoclase	$AlKO_8Si_3$	0.04	—
Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	0.64	—

Analysis and Discussion of Results

Minitab software was used for conducting a statistical analysis of the results, with the recovery of gold considered as the dependent variable. The most significant variable was the dosage of PAX, followed by pH in the second position, and lastly, the dosage of R1404.

In Figure 2, regarding the effect of the independent variables over gold recovery, it can be observed that the dosage of PAX has a significantly positive effect on gold recovery, followed by pH, while in the case of R1404, its effect is almost negligible.

Based on this analysis, an empirical model was formulated, which is shown in Equation 1.

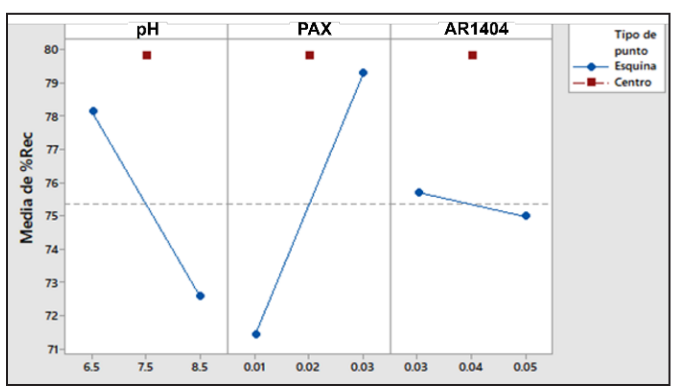

Figure 2. Effect of independent variables on gold recovery (Adapted from Minitab Software)

$$Rec\ Au\ (\%) = 25.2 + 6.05 * pH + 2145 * PAX + 660 * AR1404 - 245 * pH * PAX - 98 * pH * AR1404 + 2113 * PAX * AR1404 + 4.7(\text{central point}) \quad (1)$$

whose correlation coefficient (R^2) is 0.9148, indicating that all the collected data is valid. Finally, optimizing Equation 1, the optimal values to use would be a dosage of PAX: 0.03, AR1404: 0.05 kg/t, and a pH of 6.5 to achieve a Gold Recovery of 86.66%

Analysis of the Environmental Impact and Subsequent Use of Tailings

Analyzing the assays of the initial sample and the final tailings obtained from the flotation tests carried out, the following can be observed. The initial sample, concerning its sulfide mineralogical composition, consists of 9.79% sulfides, with 5.69% being pyrite, 2.14% arsenopyrite, and 0.24% galena. In terms of alkaline mineralogical composition, it contains 4.11% alkaline minerals, with 3.63% being calcite and 0.48% dolomite. On the other hand, the final tailings sample regarding the sulfide mineralogical composition, has 0.27% of sulfides where the total is pyrite. Regarding the alkaline mineralogical composition, it has 4.44% in alkaline minerals, where 3.73% is calcite and 0.71% is dolomite.

In order to know whether the sample will generate acid mine drainage (AMD), it is crucial to determine the net neutralization potential (NNP) of the sample. NNP is calculated based on the content of sulfide minerals, which quantifies the acid potential (AP), contrasted with the net content of acid-consuming or alkaline minerals (NP). NNP is defined by the following Equation 2.

$$NNP = NP - AP \quad (2)$$

where

AP= %S*31.25 kg $CaCO_3$/1,000 kg

NP= kg $CaCO_3$/1,000 kg

Table 8. Tailings net neutralization potential (NNP)

Sample	Assays, %		Potential (t $CaCO_3$/1000kg)			Ratio
	$CaCO_3$	S^{-2}	AP	NP	NNP	NP/AP
Initial sample	3.89	4.03	125.9	38.9	–87.04	0.3
Final tailings	4.12	0.14	4.4	41.2	36.83	9.4

Considering the following criteria:

- If NNP > +20 kg CaCO3/1000 kg of material, no acid drainage will occur, or if NP/AP > 3.
- If NNP < 0 and NP/AP < 1, in this case, acid drainage will occur.

According to these criteria and using the data from the assays of the initial and the final tailings samples, the results are presented in Table 8.

According to these results, the conclusion is that the initial sample of tailings from the Marañon processing plant will indeed produce acid mine drainage, generating a risk of arsenic discharge in the liquid effluents of these tailings. Regarding the final tailings from the flotation tests after the flotation of all sulfides, it will not produce acid mine drainage and, consequently, will not release arsenic into the solution due to having an NNP greater than 20.

Another advantage of this method is the potential to reduce the volume of disposed tailings by manufacturing bricks for the construction industry near the Poderosa mine. Additionally, ornamental products can be manufactured using only cement and sodium silicate at ambient temperatures. In Figures 3 and 4, both bricks and ornamental products can be seen.

CONCLUSIONS AND RECOMMENDATIONS

Characterization of Marañon tailings revealed that gold was found in high concentrations in arsenopyrite. Once the particle size distribution indicated that 90% of gold and silver were located in particles below 74 µm. This indicated

Figure 3. Manufactured bricks using final tailings from flotation tests

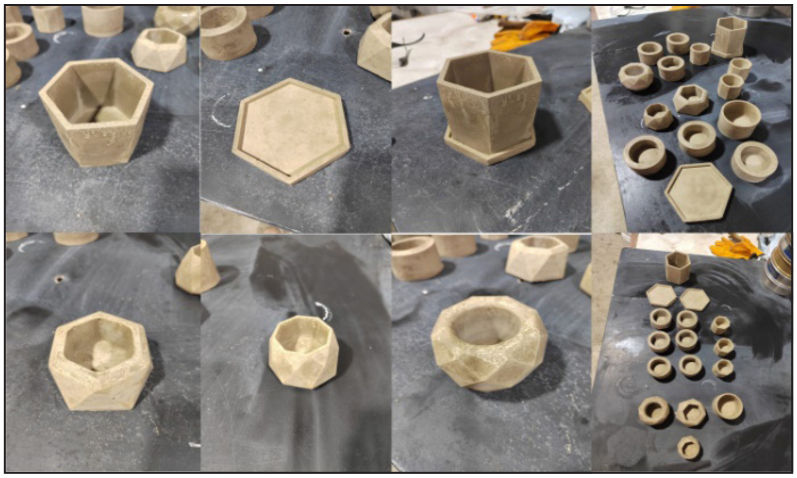

Figure 4. Manufactured ornamental pieces using final tailings from flotation tests

that arsenopyrite was found in this fine size and could harm the environment due to its potential toxicity as a contaminant for soil and water.

Flotation has proven to be a very good method to recover valuable elements from these tailings and to eliminate the toxic elements from them.

The application of the circular economy to tailings management in mining has demonstrated significant environmental benefits. This includes reducing waste generation and the minimization of negative impacts on ecosystems. Additionally, it has also shown significant economic benefits. This is due to the recovery of valuable materials such as gold and silver, as well as the potential to reuse treated tailings in other production processes, such as the manufacturing of bricks and ornaments with clean tailings, without causing negative environmental impacts.

It is recommended to carry out in-depth work on the separation of quartz from chlorite: In the case of quartz to obtain a pure product for the glass industry. Chlorite has several applications and uses in different fields: It is used in metallurgical processes as a leaching agent and as a source of magnesium for the production of alloys and metal products. In construction, chlorite is used as a filler material in cement and concrete products, providing additional strength and durability. It is used in the manufacture of ceramics and porcelain, as it acts as a melting agent and helps improve the physical properties of ceramic materials. In the cosmetics and personal care industry, chlorite is used in makeup products, such as eye shadows and powders, due to its ability to provide color and texture.

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24-019

Comparative Mineralogy of the 5-Element Arsenide Vein Systems of the Black Hawk District, Grant County, New Mexico

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ABSTRACT

Five-element style deposits are unusual hydrothermal systems that are typically characterized by a nickel-cobalt-arsenic-silver-bismuth metal assemblage. This mineralization is often represented by abundant native silver, arsenic, or bismuth, and followed by nickel, cobalt, and iron arsenides (skutterudite, safflorite, nickeline, rammelsbergite, and lollingite). The Black Hawk district in Grant County, New Mexico is one of the few examples of this mineralization style in the United States. Despite the differences in formation temperature, depth of emplacement, and host rocks between five-element style deposits worldwide, there are commonalities in mineralogy, ore texture, and composition. A detailed exploration of the native metal and arsenide phases will be performed to compare ore forming fluids between systems and the effects on styles of mineralization and paragenesis, as well as to aid in broader classification of the deposit style. Mineralogy and mineral relationships of the Black Hawk District and other five-element deposits worldwide will be characterized by reflected light petrography, scanning electron microscopy, X-ray diffraction, and electron microprobe analysis. Mineralogical phase diagrams will be generated to better understand the driving processes and evolution of the systems through native metal and arsenide precipitation.

PURPOSE OF STUDY

The purpose of this study is to analyze the five-element vein deposits of New Mexico's Black Hawk District in Grant County by performing detailed mineralogical and chemical analyses. This unusual type of deposit, being enriched in nickel, cobalt, silver, and uranium, makes it a target to explore for critical minerals. A more detailed understanding of the mineralogy and compositions of the deposit, as compared to other five-element deposits around the world, will better inform sourcing and production of critical minerals. Critical minerals of interest from this deposit style include cobalt, nickel, arsenic, and bismuth.

Five-element deposit types are uncommon around the world and are unusual in the elements present as well as the minerals that form (Markl et al., 2016). Typical five-element deposits contain a silver- nickel-cobalt-arsenic-bismuth assemblage, sometimes alongside copper, uranium, lead, zinc, mercury, and antimony. These often occur as native silver, bismuth, and arsenic, with minor sulfides, as well as arsenides of cobalt and nickel. The arsenides are of particular interest, because previous studies described several different mineral species, some of which have since been discredited, namely smaltite and chloanthite, which were erroneously determined to be arsenic deficient members of the skutterudite group (OEN et al., 1984). These arsenides have been reported from other deposits to show chemical zoning of nickel, cobalt, and iron, giving greater insight into ore fluid evolution.

PREVIOUS STUDIES

Despite the historical and modern importance of this deposit style, the processes of formation have been poorly understood. The study by Markl et. al. (2016) attempts to explain the main formation mechanism of five-element style deposits. By examining many classical European five-element deposits, and compiling information on other