Reprocessing historic tailings – three Chilean case studies

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ABSTRACT

The continuous depletion of mineral resources coupled with the ever-increasing global demand for metals have led to the exploitation of low-grade mineral deposits. Although the development of new technologies has enabled mining companies to process these low-grade ores, several challenges have arisen as a result. One of these challenges is the need to regrind an increased throughput to liberate the disseminated mineral, increasing energy consumption. Consequently, the environmental impact of processing low-grade ores is high, as more energy and water are required per ton of metal produced, and larger tailings dams are generated.

The exploitation of historic tailings can result in a sustainable and profitable strategy for mining operations. Many old tailings were produced by less efficient technologies than those available nowadays and have grades that are comparable or higher to the current typical head grades. Moreover, as the old tailings have already undergone a size reduction process, they require little additional regrind energy to reprocess them. In some cases, these tailings have been deposited in areas that are now required for mining expansions, or have been deposited under conditions that are no longer considered safe; hence the loading and hauling can be considered a sunk cost. The reprocessing of old tailings often comes with challenges, mainly associated with the chemical changes in the ore due to the presence of very fine weathered particles. Thus, the reprocessing strategy for each tailing dam can be considerably different.

In this work, three industrial cases from Chilean old tailings sites are presented where Aminpro was a participant in the execution of test work. Different problems and strategies are assessed, considering the effect of grinding, pH, reagents, and the use of different concentration methods, such as flotation and magnetic separation. Results are discussed in terms of metallurgical strategies and forecasted economic outcomes.

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INTRODUCTION

The continuous depletion of mineral resources, as well as the development of new technologies, has resulted in the exploitation of low-grade ores. For example, the head grades of Australian copper mines decreased from 15% copper content in 1880, to 5% in 1920, to less than 0.5% in the last decade (Rötzer & Schmidt, 2018). The exploitation of these low-grade deposits, however, require fine grinding to liberate the minerals, resulting in many challenges associated to increased power consumption and the processing of very fine particles (Ndlovu et al., 2013; Norori-McCormac et al., 2017; Subrahmanyam & Forssberg, 1990).

Processing efficiency has drastically improved in the last decades, with current tailings grades being considerably lower than last century; *e.g.* average copper content in tailings decreased from 0.8% in the 20th century to 0.1% nowadays (Falagán et al., 2017; Gordon, 2002; Mackay et al., 2018). Consequently, many historic tailings have higher or comparable grades to current ore deposits. The reprocessing of these historic tailings can have important economic and environmental benefits, as these materials have already been mined and ground, reducing the operating costs and the energy required to reprocess them. Furthermore, many of these tailings have either been deposited in areas that are now required for mining expansions, under conditions that are no longer considered safe (Falagán et al., 2017) or have negative environmental impacts due to weathering (Chen et al., 2014), hence requiring relocation. In these cases, the loading and haulage can be considered as sunk costs, improving the economical evaluation of such projects.

The reprocessing of these old tailings, however, entails considerable challenges, such as processing fine particles containing complex ores and gangues. The reprocessing methodologies, therefore, vary depending on the requirements of each dam (Edraki et al., 2014).

There are 744 tailing dams in Chile (Chilepolimetálico, 2019), of which, only 66 have over 5 million tons of material, and 28 have over 50 million tons. According to the geochemical information available for these large tailings (SERNAGEOMIN, 2020), at least 21 tailing dams would have an economical potential for the reprocessing of several metals, such as copper, molybdenum, silver, iron, cobalt, zinc and lead.

In this work, three industrial case studies of Chilean historic tailings are discussed. The first case corresponds to the reprocessing of secondary copper from an abandoned tailings dam. The second case study analyses the extraction of copper and molybdenum through the reprocessing of an old tailing dam that is being relocated due to safety concerns. The third case assesses the concentration of magnetite-hematite from two different tailing dams using magnetic separation, where the tailings do not belong to the processing company and are being assessed as part of a business model of tailings reprocessing

CASE STUDY 1: CONCEPTUAL ENGINEERING OF A REPROCESSING PROJECT

The tailings dam studied in this case is an inactive facility where tailings were deposited into a natural depression. This conceptual study focused on the reprocessing of the old waste to recover part of the copper-bearing minerals and molybdenite. To this end, a 2.5 tons sample was obtained from 17 different core samples representing the dam and sent to Aminpro for analysis. The samples were homogenized and treated as a global composite. The composite was physically and chemically characterized in triplicate. The characterization of the tailings showed, on average, a P100 of 500 μm, a P80 of 188 μm and a P50 of 45 μm, with a copper grade of 0.36%, mainly present as primary (15.5% chalcopyrite) and secondary (57% is chalcocite, 15.6% is covellite and 10.2% bornite) copper sulfides. The mineralogy showed that 83% of the tailings are silicates and 11.6% are phyllosilicates. Over 50% of the available copper minerals were occluded or highly disseminated, with an estimated particle size of liberation under 53 μm.

Metallurgical tests were performed to determine the optimal operating conditions for rougher and cleaner flotation. This enabled two process alternatives to be studied: a simple rougher-cleaner circuit with regrinding and a similar system but with pre-classification of the feed using hydrocyclones.

Exploratory rougher flotation tests were done on the global composite, using a Denver D-12 batch flotation cell. The base case considered conditioning the pulp at a standard condition with a pH of 8.5, 33% solids by weight and a P80 of 140 μm. The exploratory tests studied the effect of reagents type and dosage, testing 7 different collectors and 3 different frothers from different vendors at different dosages. An economical evaluation, considering the metallurgical results and reagent costs, was performed to define the optimal reagent suite (assuming metal prices of US$ 3/lb Cu and US$ 7.3/lb Mo). The optimal technical-economical results were obtained with the collector MX8522 (Solvay) at a dosage of 50 g/t, PAX at 5 g/t as the secondary collector, and FP511 (Nalco) and pine oil in a 20/20 g/t dose as the frother mix. Rougher flotation tests were performed with the defined reagent suite, varying pH, solids content and particle size, obtaining maximum batch recoveries of 87% Cu. These experimental results were used as inputs for the development of a predictive model of the grade-recovery of the rougher stage, based on logarithmic regressions, using the Aminfloat software (P. Amelunxen et al., 2014). The results, as shown in Figure 1, suggest that even higher recoveries can be achieved at lower particle sizes and that solid content has an important effect on performance.

Investigations were done to pre-classify the tailings using hydrocyclones, by sending the overflow (O/F) directly to the rougher flotation stage, while grinding the underflow (U/F), thereby reducing power consumption. A 2-inch hydrocyclone was used, varying the feed flow, solid content, pressure, and apex opening, to achieve a separation at 150 μm. The resultant U/F contained 56% of the available copper, while 44% was in the fine fraction overflow, with a P80 of 80 μm. The U/F was ground to a P80 of 130 μm.

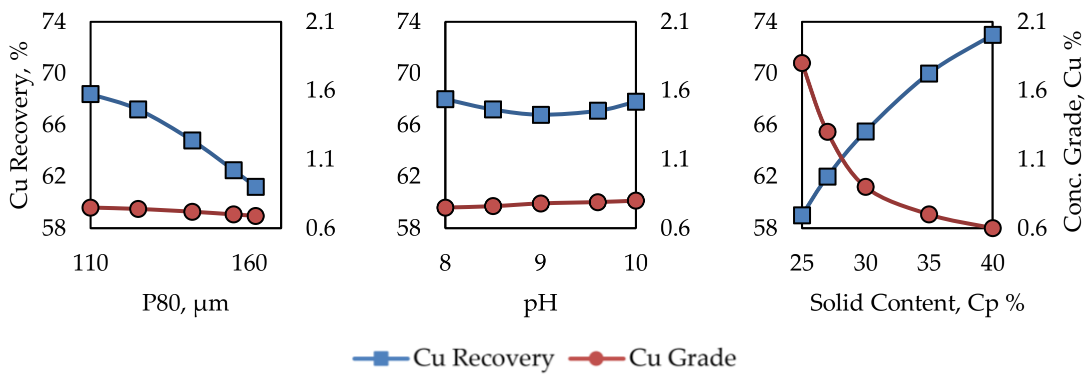

Figure 1: Effect of operating conditions on the performance of the rougher flotation of the historic tailings without pre-classification.

Optimized condition on both O/F and U/F streams gave a copper recovery of 54% and 83%, respectively. The combined recovery is 70%, which is notably similar to the projected recovery for the alternative without pre-classification, as shown in Figure 1.

The operating conditions for the cleaner stage were explored, using for feed the rougher concentrate produced by floating the U/F material in a Contact Cell™ (R. Amelunxen, 1993). With an optimized pH of 11.5, 15-20% solid content and a P80 of 40-45 µm, over 95% of the copper was recovered in cleaner tests performed in a bench-scale batch test. Cleaner tests in column flotation, however, resulted in a cleaner recovery of 65%, and the pyrite was not successfully depressed, resulting in 22% Cu grade concentrate. The overall recovery of the process was 52%.

An economical evaluation of the alternatives was simulated using Aminfloat, based on a standard concentrate sales contract, and considering the CAPEX, based on benchmarking tools (InfoMine, 2018), and OPEX according to the price of the consumables at the time. For a 30 Ktpd feed rate and a 10-year operation, the estimated profitability index of the project (NPV divided by investment) at this conceptual level is 1.46, excluding haulage costs. The technical economical evaluation is shown in Figure 2, indicating that the estimated optimal recovery of the plant is close to 55%, achieving an optimal revenue of 9.7 US$/ton that maximizes the total revenue of the project.

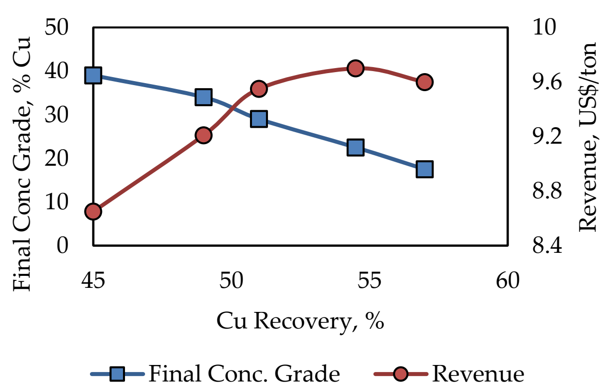

Figure 2: Grade-Recovery of the reprocessing plant with pre-classification and expected unitary revenue.

CASE STUDY 2: EXPLORATORY PROFILE OF THE REPROCESSING OF AN UNSTABLE TAILING FACILITY

The second case study corresponds to an inactive tailing's facility. This dam has experienced a series of failures throughout its history, generally associated with seismic activity, *e.g.* the 1928 collapse of the dam resulted in 55 fatalities (Machado, 1929). The company that owns these tailings has found in a recent survey some vulnerabilities on the seismic stability of the tailings, that make it necessary to move and redeposit these historic tailings in agreement with current safety standards and regulations. In this context, the company has decided to explore the option of reprocessing this material, to cover some of the costs involved in the hauling, transport and redeposition. To this end, core samples from different sectors of the tailings dam were obtained, producing 4 composites, which were sent to Aminpro for characterization and testing.

Based on previous experiences (see Case-Study 1), the tailings composites were screened on a 150# mesh (106 μm) individually, generating two size fractions for each composite. These fractions were characterized, and the results are shown in Table 1. The copper grade of the composites varied between 0.2% and 0.4% and are relatively similar between fine and coarse fractions. Table 1 also shows that most of the copper available in the coarse fractions was present as sulfides, while between 33% and 46% of the copper available was soluble in the case of the fine fractions.

Table 1: Chemical and physical characterization of the different composites

Composite	Fraction	Distr. (%)	CuT (%)	CuS (%)	CuS/CuT (%)	MoT (%)	P80 (μm)
1	Fine	49	0.384	0.155	40	0.02	61
	Coarse	51	0.41	0.036	9	0.016	241
2	Fine	62	0.272	0.109	40	0.015	60
	Coarse	38	0.379	0.037	10	0.013	230
3	Fine	86	0.207	0.069	33	0.014	28
	Coarse	14	0.245	0.051	21	0.012	280
4	Fine	62	0.246	0.112	46	0.015	61
	Coarse	38	0.223	0.047	21	0.014	211

Mineralogical assays performed on the original four samples before screening showed that the main copper-bearing minerals were covellite and chalcopyrite, which were partially liberated. XRD analysis of the composites (Figure 3) indicated they have a high content of clays, mainly illite and chaolite-chlorite. Whereas the clay content of most of the samples was in the low thirties, Composite #3 had considerably more (over 48%), resulting in a low P80 for the fine fraction, as seen in Table 1.

Exploratory flotation tests were performed varying pH, Eh and reagents, defining an optimal reagent suite for the rest of the tests. Flotation tests were performed at a solid content of 35%, using AP-3477C (45 g/t) as the primary collector, diesel (20 g/t) as the secondary collector, A76E (10 g/t) as the frother, NaSH to reach an Eh of -90 mV, and lime and/or sulfuric acid to adjust the pH. The best performance was obtained at pH 10 for both fine and coarse fractions, having Cu/Mo recoveries of up to 71%/63% for the fine fraction and 85%/63% for the coarse fraction, as shown in Figure 4.

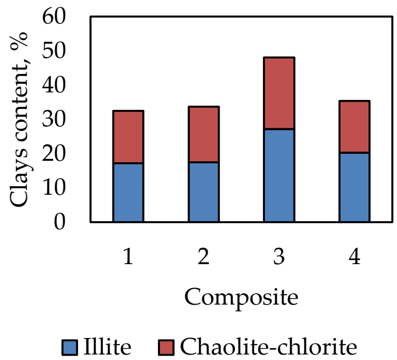

Figure 3: Content of clay in the composites without pre-classification

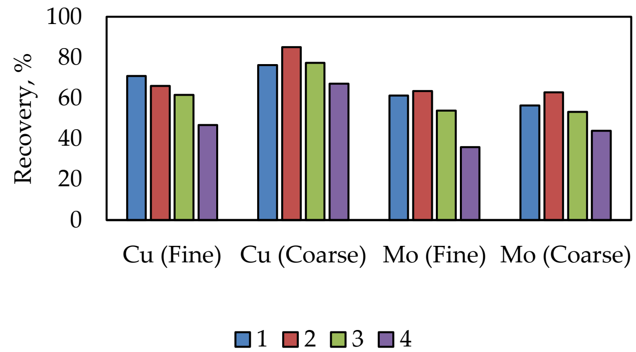

Figure 4: Rougher recoveries at optimal pH and reagents for fines and coarse fractions

Figure 4 shows that the performance of the rougher varies considerably between composites, with Composite 1 and 2 presenting the best performance. Further rougher tests were performed for the coarse fraction, varying the P80 between 70 μm and 110 μm, reaching an optimum at 90 μm, with a small improvement in the recovery up to 87% of Cu and 64% of Mo.

Different cleaner tests were performed for the different rougher concentrates generated for each size fraction. Tests considered the variation of pH and the addition of dispersant. Optimal results were obtained at a pH of 11.5 for all the tests, with recoveries over 90% Cu for the cleaning of coarse rougher samples. The cleaning of the fine rougher concentrate was enhanced using sodium silicate as dispersant, reaching recoveries between 70% and 87% Cu. The cleaner concentrates present an average copper grade of 2.78%, while the cleaner tailings present less than 0.17% Cu after 30 minutes of flotation. The best results were obtained with Composite 1: the coarse fraction reached a Cu recovery of 97%, with a concentrate grade of 4.02%, and the fine fraction reached a recovery of 86% with a grade of 1.19 %.

Considering the high content of clays, settling tests and rheological characterization were performed for the tailings generated from Composites 1 and 3. As expected, given the higher clay content, the highest shear stress was obtained for the tailings generated from the flotation of the fine fraction of the Composite 3 (166 Pa at 54.9% solid content).

This exploratory investigation is an ongoing project and further work is needed to develop conceptual engineering and assess the economic feasibility of this project. It has been recommended to examine the economies of processing the coarse fraction at a larger P80, aiming to reduce power consumption. It has also been recommended to study and optimize the different flows (fine and coarse) independently, as the mineralogy shows that the fine fraction presents an anomalous high content of clays. Cleaner stages would probably require to be separated for coarse and fine flows, to control the clays before merging the concentrates.

CASE STUDY 3: MAGNETITE REPROCESSING FROM TWO HISTORIC TAILINGS AS A BUSINESS MODEL

The third case study is a tailing reprocessing operation that renders services in the recovery of copper and molybdenum from tailing dams. Recently, the company has shown interest in expanding its assets by reprocessing two tailing dams that are rich in magnetite and economically attractive. Aminpro was awarded the contract to perform an exploratory study to characterize the 2 prospective tailing dams (T1 and T2) and investigate their magnetic concentration potential using two different techniques. Two 110 kg composite samples were provided, representing the T1 and T2 tailing dams.

Chemical characterization and physical information of T1 and T2 are shown in Table 2. They show that both samples have an interesting concentration of Cu and Fe, with low amounts of Mo, at quite different particle sizes. It was also found through ICP-MS that both samples had anomalously high phosphorous grades, around 0.45% P. The gas pycnometry showed that the specific gravities of the samples were relatively high, around 3.5, due to the presence of magnetite.

Table 2: Chemical and physical characterization of the samples

	Cu-T (%)	Fe-T (%)	Mo-T (%)	S (%)	P (%)	P80 (μm)	P50 (μm)	Specific gravity
T1	0.316	35.72	0.006	0.25	0.448	95	41	3.54
T2	0.273	27.54	0.005	0.35	0.431	142	52	3.38

Mineralogy showed that T1 and T2 are made up of magnetite-hematite by 49% and 36%, respectively; copper-bearing minerals in both samples are mainly oxides (such as chrysocolla and atacamite) with some occasional inclusions of chalcopyrite (as shown in Figure 5**¡Error! No se encuentra el origen de la referencia.**). Liberation analysis showed that over 85% of the magnetite-hematite is liberated (over 80% of the surface) in both samples.

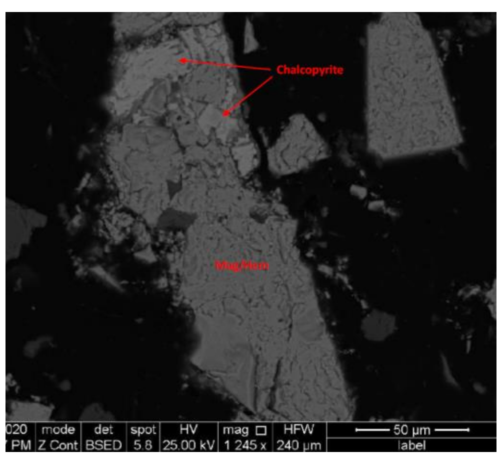

Figure 5: BSE image – T2 sample

Magnetic concentration tests were performed using a Davis tube, in duplicate. The Davis tube was equipped with a strong electromagnet capable of operating at a magnetic flux density of up to 4,000 gauss (G). Iron recoveries with the Davies tube averaged 81% for T1 and 74% for T2, generating a concentrate of 67% magnetite in both cases.

Further magnetic concentration tests were performed using an L8 drum, of 12" diameter by 6" long, with a variable magnetic flux density up to 1,200 G. Exploratory experiments were conducted in consideration of a layout of one rougher stage followed by 3 cleaner stages, as shown in Figure 6. The magnetic flux density and the solid content of the feed were varied while keeping constant the feed rate and the gap between the magnetic element and the drum constant for all the tests (8 lpm and 8 mm, respectively). Results in Figure 7 show that a final concentrate with an iron content of 60% could be produced after 3 cleaner stages, with recoveries of 86% for T1 and 81% for T2.

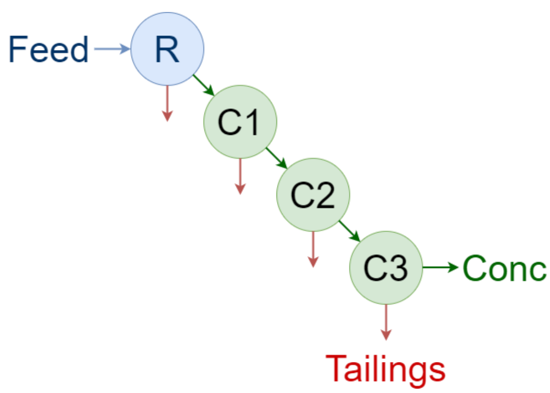

Figure 6: Magnetic concentration circuit, with 1 rougher and 3 cleaner stages.

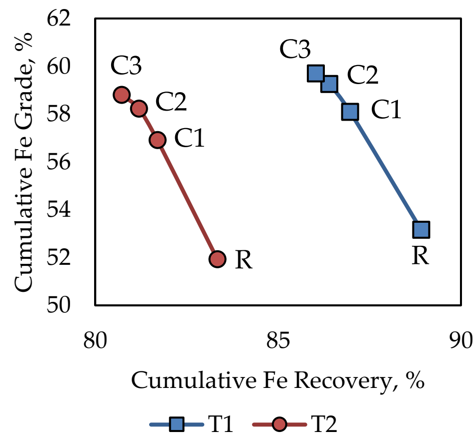

Figure 7: Cumulative performance of a circuit with 1 rougher and 3 cleaner stages.

Figure 7 suggests that the addition of more cleaning stages would not increase the cumulative grade. It was found that the main impurities in the final concentrates were copper (0.14%) and phosphorus (250-300 ppm), as shown in Table 3, which are too high for iron commercialization and could incur in penalties. The mineralogical analysis showed that the copper was mainly occluded within the magnetite-hematite. Consequently, it has been recommended to consider a grinding stage between the rougher and the first cleaner stage, to increase the Fe grade and liberate some of the impurities. Moreover, the chemical analysis per-stage showed that the rougher tailings have a P grade of 0.97% for T1 and 0.75% P for T2, which could be economically concentrated.

Table 3: Final concentrate grade and impurities

	Fe (%)	**Cu-T (%)**	**S (%)**	**P (ppm)**
T1	59.7	0.143	0.030	250
T2	58.8	0.147	0.094	315

The exploratory results obtained in this study are promising. The main recommendations are to conceptually estimate the economic feasibility of the process, explore optimization opportunities for the operating conditions and assess alternative plant designs to eliminate impurities and explore the opportunities and impacts of producing phosphorous as a by-product.

CONCLUSION

Three industrial case studies of Chilean tailings reprocessing have been discussed. The three projects present different challenges, opportunities, and motivations, showing that the reprocessing of historic tailings needs to be assessed case by case, as many variables are involved when evaluating these projects. Case study 1 was purely motivated by the economic opportunity, case study 2 motivation was the necessity of relocating the dam, presenting the opportunity of generating a profit or at least paying for the costs of hauling and transport; and case study 3 showed how the reprocessing of historic tailing can become a business model for a company, that assess different prospective dams as business opportunities.

It was observed that particle size, pH, reagents, and solid content are important variables that affect the overall performance. This observation opens new opportunities for reagent companies, as the flotation of historic tailings may need the development of specialized collectors and frothers, oriented to this kind of materials. Interestingly, both projects that studied copper recovery (case 1 and 2) from historic dams considered the pre-classification of the tailing by particle size, either by hydrocyclones or meshes, to reduce the power consumption associated to grinding. Particle size, degree of liberation and the presence of clays played a key role in the definition of the proposed circuits and flows, observing that different size fractions may require different treatments.

Finally, it was clearly shown in the case study 1 that the reprocessing of old tailings can be a profitable business alternative, with an estimated optimal revenue of 9.7 US$/ton and an estimated profitability index of 1.46, excluding haulage costs. The other two case studies are ongoing projects at an exploratory level, presenting promising results, with commercial grades and profitable recoveries. Particularly the third case study shows that the reprocessing of tailings can become a stand-alone business model, not associated with an existing mine or plant. This alternative opens the discussion for the study of optimal plant designs, geometallurgical models and extraction methods oriented exclusively to the reprocessing of tailings. It is expected to observe an increase in the number of tailing reprocessing projects in Chile and worldwide, as the head grades of new deposits decreases, new technologies allow for more efficient processes and more information is available about this alternative.

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