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Effect of Curing Time and Ferric Chloride on a Copper Concentrate with a High Arsenic Content

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Abstract: As a result of changes in copper mineralogy, various treatment options for copper sulfides have been explored, including pretreatment processes aimed at enhancing material permeability and improving the dissolution of valuable minerals. Despite its significance, this topic has only recently gained attention. In this research, a copper concentrate with a high arsenic content was studied, with enargite (Cu_3AsS_4) as the main mineral phase. The objective was to evaluate the effect of pretreatment on copper extraction efficiency prior to leaching. Three key variables were investigated: curing time (0, 5, 10, and 15 days), H_2SO_4 dosage (0, 70, 140, and 210 kg/t), and $FeCl_3$ concentration (0, 0.5, 1, and 1.5 M). The sample was characterized both before and after pretreatment, revealing the formation of new species such as $CuSO_4{\cdot}5H_2O$ and $Cu_2Cl(OH)_3$ under optimal conditions of 15 days curing time, 70 kg/t of H_2SO_4, and 1 M $FeCl_3$. Copper extraction solely through curing reached 20.79%. The analysis suggests that curing time is the most influential factor in the process, accounting for 46% of the overall contribution. In comparison, sulfuric acid and ferric chloride contribute less, with 20% and 10% contributions, respectively.

Keywords: enargite; copper sulfides; curing; pretreatment; leaching; digenite; ferric chloride

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1. Introduction

According to the Chilean Copper Commission (Cochilco) [1], projections for the period 2022–2034 indicate a significant decline in hydrometallurgical copper production. In 2022, the hydrometallurgical production was 1.38 Mt, and it will decrease to 0.713 Mt by the year 2034, representing a 48.4% reduction in total production. The main factor in this decline is the depletion of copper oxide reserves due to the transition from oxide to sulfide copper reserves. It is worth noting that 70% of the sulfide copper mineral reserves are attributed to chalcopyrite ($CuFeS_2$). Therefore, the hydrometallurgical treatment of copper concentrates and/or sulfide minerals could represent an increase in copper production using existing hydrometallurgical plants.

A problem arises when chalcopyrite is treated via hydrometallurgical processes because it presents slow dissolution kinetics, a consequence of a passivating layer that hinders contact between the mineral and the leaching solution [2]. Further complicating this issue is the presence of enargite (Cu_3AsS_4), a mineral often found in association with chalcopyrite and other sulfur-containing minerals related to copper and arsenic [3].

Enargite and chalcopyrite are classified as refractory minerals under conventional leaching conditions. Moreover, the presence of arsenic in enargite presents a challenge, particularly in copper concentrate treatment. Any copper concentrate with an arsenic content exceeding 0.5% is categorized as a complex concentrate. This leads to penalties for impurities in the commercial value of the copper concentrate [4].

In recent years, several studies have focused on the effect of pretreatment in the leaching of primary copper sulfides, mainly chalcopyrite. However, there is a notable scarcity of research specifically addressing the effect of pretreatment on enargite. Rivera-Vasquez and Dixon [5] used pyrite as a catalyst in a ferric sulfate acidic media, achieving the highest copper extraction at 80 °C, with a pyrite to enargite ratio (Py:En) of 4 in 24 h.

Jahromi et al. [6] conducted a comprehensive investigation into leaching in a chloride media with and without the use of activated carbon (AC) and with a novel carbon-based catalyst called Lanxess Lewatit® AF 5. The results showed a copper extraction of 65%, 92%, and 96% after 96 h. The optimal leaching conditions were achieved at cupric and ferric concentrations of 5 g/L, a concentrate to catalyst ratio of 1:2, and a temperature of 90 °C. This study provides valuable insights into enhancing leaching efficiency through the use of innovative catalysts and conditions. Other studies that evaluated the dissolution kinetics of enargite include Herreros et al. [7], Viñals et al. [8], Riveros and Dutrizac [9], and Hernández et al. [10].

As mentioned earlier, there is currently no available information on this topic for enargite pretreatment studies. Nevertheless, for the purpose of drawing comparisons, we highlight some relevant studies involving chalcopyrite. Chalcopyrite shares similar characteristics with enargite and serves as a valuable mineral for providing insights and references on the subject. Examples of pretreatment application to chalcopyrite include the following: Cerda et al. [11] used a sample with chalcopyrite (1.21% wt) and bornite (0.54% wt) as the main copper minerals under different types of leaching (flask, reactor, and mini-column). The variables studied for pretreatment were chloride concentration (20, 50, and 90 kg/t), curing time (7, 20, and 40 days), and temperature (20 and 50 °C). A maximum of 93% copper extraction was obtained when treated with 90 kg/t Cl-, 40 days of curing, and 50 °C flask leaching.

Hernández et al. [12] studied the effect of agglomeration and pre-leaching curing on a sample composed mainly of chalcopyrite, using mini-columns in acid–chloride–nitrate media. The variables studied were the addition of sodium nitrate ($NaNO_3$) (11.7 and 23.3 kg/t), sodium chloride (NaCl) (2.1 and 19.8 kg/t), curing time (20 and 30 days), and curing temperature (25 and 45 °C). A 58.6% copper extraction was obtained under the conditions of 23.3 kg/t of $NaNO_3$, 19.8 kg/t of NaCl, and 30 days of curing at 45 °C without leaching. Subsequently, after the pretreatment stage, leaching in mini-columns was conducted for the samples, varying parameters such as temperature (25 and 45 °C) and chloride concentration (20 and 40 g/L). The optimal copper extraction for the mini-column leaching test was 63.9% at 25 °C, with a chloride concentration of 20 g/L.

Quezada et al. [13] worked with a sample consisting mostly of chalcopyrite, aiming to evaluate the effect of pretreatment before leaching using different concentrations of sodium chloride (NaCl), potassium nitrate (KNO_3), sulfuric acid (H_2SO_4), and varying curing times (0 to 15 days). Their optimal extraction was 23% with a NaCl concentration of 25 kg/t, a H_2SO_4 concentration of 15 kg/t, and a curing time of 15 days. According to their ANOVA analysis, parameter A (curing time) had the most significant contribution to variation in the Cu extraction (56.36%), parameter B (H_2SO_4) had an extremely low contribution (1.78%), and parameter C (NaCl) had a moderate contribution (23.09%). Most of these contributions are statistically significant, according to the p-values obtained (significant A and C at a 99% confidence level). It is worth mentioning that, in the study, the concentration of KNO_3 did not prove to be a significant parameter in copper extraction. However, a point of comparison in this study, as well as in studies by Cerda et al. [11] and Hernández et al. [12], is observed in the improvement of the copper extraction percentage with increasing chloride concentration (Cl), which proves to be a relevant factor in the search for optimal parameters.

The objective of the current study is to evaluate the impact of curing pretreatment on copper extraction from a concentrate with high arsenic content. The main variables of these curing tests are curing time (days), sulfuric acid (H_2SO_4), and ferric chloride ($FeCl_3$). The results were subjected to an analysis of variance (ANOVA) to identify the optimal combination of parameters. Interactions between variables were not considered for the analysis. Predictive models support this assumption, but additional tests may be conducted later for confirmation. In addition to the curing test and ANOVA analysis, a comprehensive characterization was performed before and after the sample underwent the pretreatment. Techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and atomic absorption spectrometry (AAS) were used for this purpose. These methods helped identify the existing mineral phases and those formed during the pretreatment process, providing valuable insights into the structural changes associated with the agglomeration and curing pretreatment.

2. Materials and Methods

2.1. Materials and Procedure

The procedure used for the mineral analysis is based on the previous works of Quezada et al. [2,13]. The sample, a copper concentrate with a P80 of 57.9 µm, was obtained from an operational mining plant in Antofagasta, Chile. A chemical composition analysis was performed using a Varian Atomic Absorption Spectrometer, Model Spectra AA 55B. Mineralogical data were obtained by an X-ray diffraction (XRD) analysis using a diffractometer (Bruker, model D8 Advance, Karlsruhe, Germany), using a scanning range of 5–70° 2 θ and a step size of 0.020° 2 θ with a step time of 1 s. The interpretation of the X-ray data to determine crystalline phases was performed using the software X'Pert HighScore Plus Version 3.0 (PANalytical, Almelo, Netherland). A Qemscan analysis was performed using a Model Zeiss EVO 50 (Zeiss, Oberkochen, Germany) with Bruker AXS XFlash 4010 detectors (Brusker, Billerica, MA, USA) and Software iDiscover 5.3.2.501 (FEI Company, Brisbane, Australia). Morphological characterization was obtained using a scanning electron microscope (SEM, Hitachi SU5000, Tokyo, Japan).

2.2. Experimental Design

In this study, the effects of 3 variables were analyzed regarding copper extraction. These variables were curing time, sulfuric acid concentration (H_2SO_4), and ferric chloride concentration ($FeCl_3$). The ranges of variable values and the number of trials were designed according to an experimental matrix performed with the Taguchi method using the Minitab software (17.1.0, LLC, State College, PA, USA). The Taguchi method involves a set of mathematical procedures aimed at finding improvements in a process through the execution and collection of data, and there are various studies that utilize this optimization method for evaluating the impact of variables involved in the process [14–16]. It is based on the systematic application of the Design of Experiments (DOE) [17]. The designed matrix was an L_{16} (4^3) with 3 variables and 4 levels (see Tables 1 and 2).

Table 1. Experimental design with L_{16} (4^3) orthogonal array for Taguchi method.

Sample	Matrix L_{16} (4^3)		
	A	B	C
	Curing Time (days)	H_2SO_4(kg/t)	$FeCl_3$ (M)
1	1	3	2
2	4	4	4
3	1	2	4
4	2	2	2
5	3	4	2
6	4	3	1
7	3	3	3
8	1	1	1
9	3	2	1
10	4	2	3
11	2	4	1
12	2	3	4
13	2	1	3
14	1	4	3
15	4	1	2
16	3	1	4

Table 2. Variables and levels of the experimental matrix.

	Parameters	Levels			
		1	2	3	4
A	Curing time (days)	0	5	10	15
B	H_2SO_4 (kg/t)	0	70	140	210
C	$FeCl_3$ (M)	0	0.5	1	1.5

The aim of this study is to maximize the performance values of the established variables. To achieve this objective, Equation (1) was employed. In this equation, 'SN' denotes the characteristic performance to be optimized, 'n' represents the number of trials conducted for a particular combination, and 'Y_i' signifies the performance value at the i-th trial [14]. It is worth nothing that all experiments were conducted twice under identical operating conditions.

$$SN = -10Log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right] \quad (1)$$

However, there is the possibility that the optimal values for the trial may not be included in the orthogonal design. In such cases, optimal values can be determined using a balancing feature of the orthogonal matrix. Equation (2) represents the additive model that can be utilized for this purpose. In this equation, 'μ' represents the overall average of the performance value, 'X_i' is the fixed effect of the combination of parameter levels used in the i-th experiment, and 'e_i' is the random error of the i-th experiment [14].

$$Y_i = \mu + X_i + e_i \quad (2)$$

2.3. Curing Experiments

The experiments were conducted with 5 g of the sample to determine the optimal combination of curing time, sulfuric acid concentration (H_2SO_4), and ferric chloride concentration ($FeCl_3$). A solid–liquid ratio of 1/100 g/mL (5 g/0.5 mL) was used to evaluate the samples. The samples were homogenized to form the agglomerate and subsequently covered to prevent evaporation. The samples were kept at room temperature (25 °C) for curing with established times of 0, 5, 10, and 15 days (Figure 1). After the corresponding time period, the samples were washed with a solution consisting of distilled water with 0.5 g/L of sulfuric acid using a digital RW20 mechanical stirrer at 450 rpm for 5 min at room temperature. Finally, this solution was filtered using a vacuum pump, model 1636 Thomas, and the copper concentration in the filtrate was determined by a Varian Atomic Absorption Spectrometer, Model Spectra AA 55B.

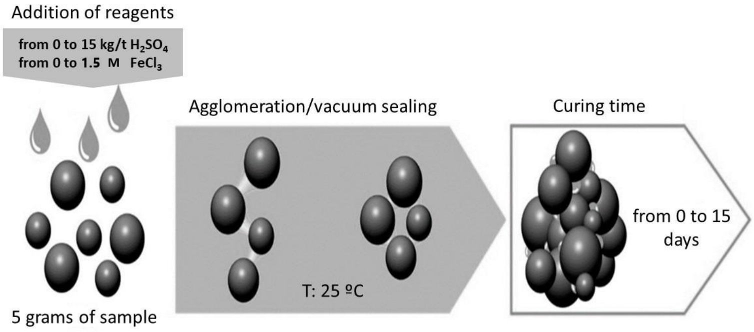

Figure 1. Agglomeration and curing procedure.

3. Results and Discussion

3.1. Characteristics of Initial Ore Samples

The elements of interest found in the sample obtained from AAS were 36.26% Cu, 13.36% Fe, and 6.44% As. According to the Qemscan analysis presented in Table 3, the main mineral species found were the tetrahedrite/tennantite/enargite group with 35.9%, followed by pyrite with 22.4%, and the chalcocite/digenite group with 16.6%. Other species to consider with lower presence were bornite with 6.01%, chalcopyrite with 4.66%, and covellite with 3.98%.

Table 3. Qemscan analysis of the sample before pretreatment.

Mineral	% Mass	Mineral	% Mass
Chalcocite–digenite	16.6	Alunite	0.32
Covellite	3.98	Quartz	2.11
Chalcopyrite	4.66	Kaolinite group	1.09
Bornite	6.01	White Micas (Muscovite)	1.17
Tetrahedrite/tennantite/enargite	35.9	Smectite group (Montmorillonite/Nontronite)	0.05
Other copper minerals	2.15	Pyrophyllite/Andalusite	0.22
Pyrite	22.4	Others	1.11
Sphalerite	2.27		
Copper oxides/hydroxides	0.02	Total	100

Regarding the XRD analysis presented in Figure 2, it is observed that the main minerals found are enargite, pyrite, and chalcopyrite. Concerning the SEM analysis shown in Figure 3, a similar atomic proportion of copper and sulfur (Cu~60%—S~37%) is found compared to the empirical formula of pure chalcocite (Cu~67%—S~33%), providing indications of the presence of this mineral. Furthermore, the chemical data of Figure 3 are present in Table 4.

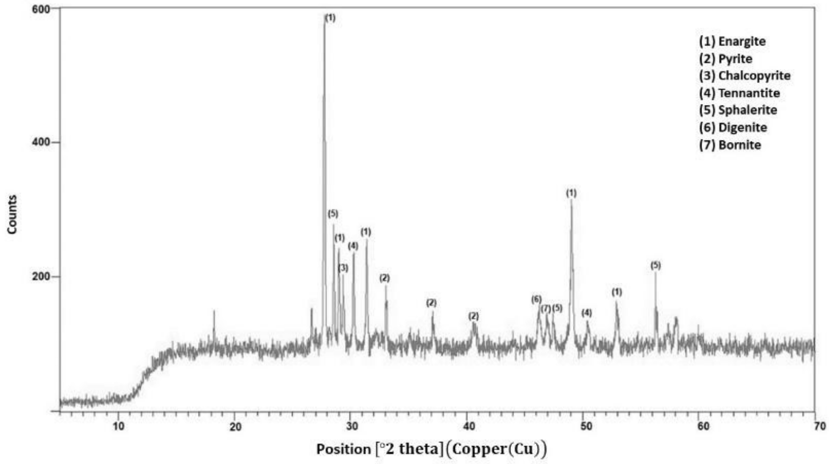

Figure 2. XRD of the concentrate before pretreatment.

Table 4. SEM-EDS analysis of the sample before pretreatment (Figure 3).

	(1) Pyrite	(2) Enargite	(3) Quartz	(4) Chalcopyrite	(5) Digenite
O	---	---	70.1	---	---
Si	---	---	29.6	---	---
S	65.9	49.2	---	49.5	37.0
Cl	---	---	---	---	---
Fe	33.8	0.40	0.10	25.1	3.10

Table 4. *Cont.*

	(1) Pyrite	(2) Enargite	(3) Quartz	(4) Chalcopyrite	(5) Digenite
Cu	0.30	37.4	0.20	25.4	59.9
Zn	---	---	---	---	---
As	---	13.0	---	---	---
Sb	---	0.10	---	---	---
Total	100	100	100	100	100

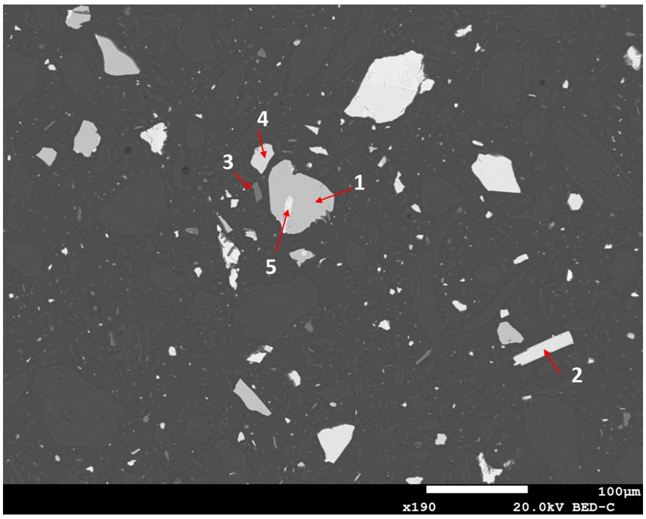

Figure 3. Sample analyzed by SEM before pretreatment: (1) is pyrite, (2) is enargite, (3) is quartz, (4) is chalcopyrite, and (5) is digenite.

3.2. Pretreatment and ANOVA Analysis

The results presented in Table 5 correspond to the copper extraction generated by each of the three variable combinations used in the experiments. The combination that achieved the highest copper extraction was sample No. 10 with 20.8%, whose variables consisted of a curing time of 15 days, 70 kg/t of sulfuric acid (H_2SO_4), and 1 M ferric chloride ($FeCl_3$).

Table 5. Percentages of copper extraction from the experiments.

No.	Curing Time (Days)	H_2SO_4 (kg/t)	$FeCl_3$ (M)	Copper Extraction (%)	No.	Curing Time (Days)	H_2SO_4 (kg/t)	$FeCl_3$ (M)	Copper Extraction (%)
1	0.00	140	0.50	4.66	9	10.0	70.0	0.00	10.5
2	15.0	210	1.50	9.57	10	15.0	70.0	1.00	20.8
3	0.00	70.0	1.50	6.45	11	5.00	210	0.00	5.05
4	5.00	70.0	0.50	8.22	12	5.00	140	1.50	10.0
5	10.0	210	0.50	6.48	13	5.00	0.00	1.00	8.58
6	15.0	140	0.00	15.4	14	0.00	210	1.00	4.66
7	10.0	140	1.00	6.59	15	15.0	0.00	0.50	6.04
8	0.00	0.00	0.00	3.36	16	10.0	0.00	1.50	12.1

An increase in copper extraction was demonstrated with the increase in curing time of the samples, regardless of the experimental variables [5,11,13]. This effect is observed in Figure 4a, which illustrates the behavior of the curing time variable over time. The point of maximum efficiency of the variable may even be at longer times than those evaluated in these experiments. Regarding the impact of the H_2SO_4 and $FeCl_3$ concentrations, depicted in Figure 4b and 4c, respectively, it is feasible to ascertain optimal concentrations for achieving maximum copper extraction. These findings align with previous research [5,9,18] that demonstrates enhanced copper or arsenic extraction through the addition of these reagents.

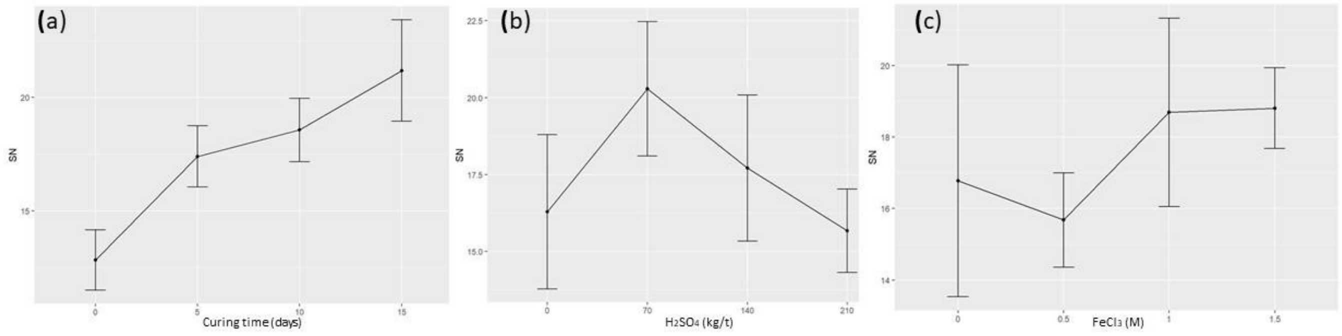

Figure 4. Effect of (**a**) curing time (days), (**b**) concentration of H_2SO_4, and (**c**) concentration of $FeCl_3$ on the optimization criterion SN for the percentage of Cu extraction.

In Table 6, it is determined that parameter A (curing time) has the highest contribution (45.76%) among the three parameters to the percentage of extracted Cu. Parameter B (acid concentration) has a moderate contribution (20.31%), and parameter C (ferric chloride concentration) has a lower contribution (10.08%). All these contributions are statistically significant according to the *p*-values obtained; A, B, and C are significant variables at a 95% confidence level.

Table 6. Influence of parameters on the % of copper extraction (*df* = degrees of freedom, *SSE* = sum of squares error, *MSE* = mean square errors).

	Parameters	*df*	*SSE*	*MSE*	*F* Value	Contribution	*p*-Value
A	Curing time (days)	3	265.349	88.45	14.07	45.76%	0.00002447
B	Acid concentration (kg/t)	3	117.779	39.26	6.245	20.31%	0.00313200
C	Ferric chloride concentration (M)	3	58.446	19.482	3.099	10.08%	0.04764300
	Error	22	138.303				
	Total	31	579.877				

3.3. Characteristics of Cured Ore Samples

Based on the data obtained in Table 7, it can be seen that the variation in the percentage of copper before and after pretreatment was 7.4% lower, with a 20% decrease in weight, confirming the effect of pretreatment on copper extraction from the concentrate. In analyzing the variation in arsenic before and after pretreatment, we found that it was 1.51% higher. This confirms that the enargite present in the sample was not affected by the pretreatment, and the extracted copper did not originate from it.

Table 7. Percentages of copper and arsenic in the concentrate before pretreatment (*BP*) and after pretreatment (*AP*).

Analyzed Element	*BP* (%)	*AP* (%)
Copper (Cu)	36.260	28.860
Arsenic (As)	6.4400	7.9548

Figure 5 illustrates the images derived from the SEM equipped with X-ray microanalytical mapping of cured particles. This analysis reveals that enargite is not susceptible to attack in a chloride media, as evidenced by the smooth surfaces and defined contours observed. However, the presence of Cu-Cl-O compounds is observed in the areas adjacent to these particles, suggesting a leaching of other copper mineral species present.

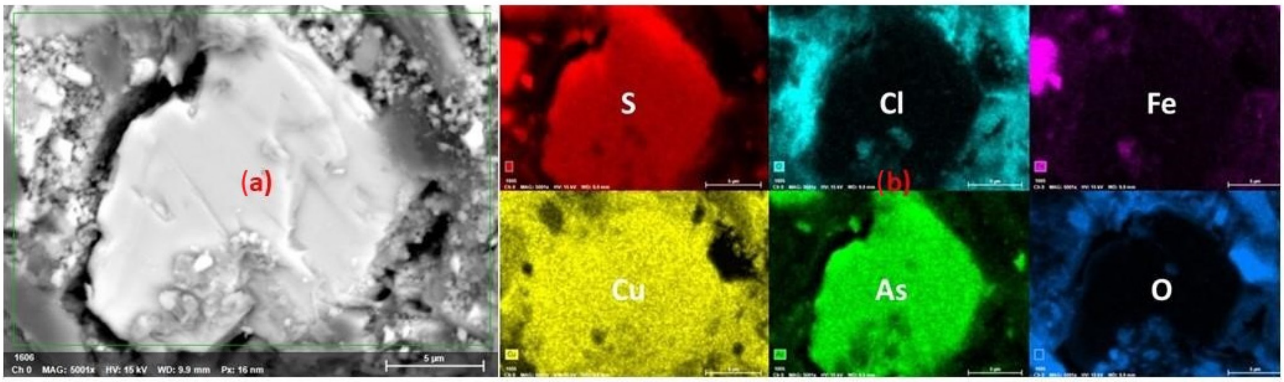

Figure 5. **(a)** SEM microanalytical mapping of pretreated sample using a curing time of 15 days, 70 kg/t of sulfuric acid (H_2SO_4), and 1 M ferric chloride ($FeCl_3$). (**b**) Presence of elements in (**a**).

The image allows for the analysis of enargite particles that have undergone chemical attack, resulting in a product composed of Cu-Cl oxides. Additionally, particles likely composed of chalcopyrite can be observed due to their Cu-Fe-S composition, showing more pronounced attack, distinguishable by small fragments of the original particle and a higher proportion of Cu-Cl oxide products. Iron is not part of the solid reaction products in the image.

The results of the XRD analysis confirm and complement the SEM analysis regarding the generation of reaction products formed by Cu-Cl oxides, as shown in Figure 6. Species such as $Cu_2Cl(OH)_3$ and ($Cu(SO_4)$ *$5H_2O$) are detected, which were not part of the original sample. The peaks corresponding to enargite are clearly marked, indicating limited reaction with the curing media. The above is consistent with the proposal of [7], associated with the refractory nature of the enargite mineral.

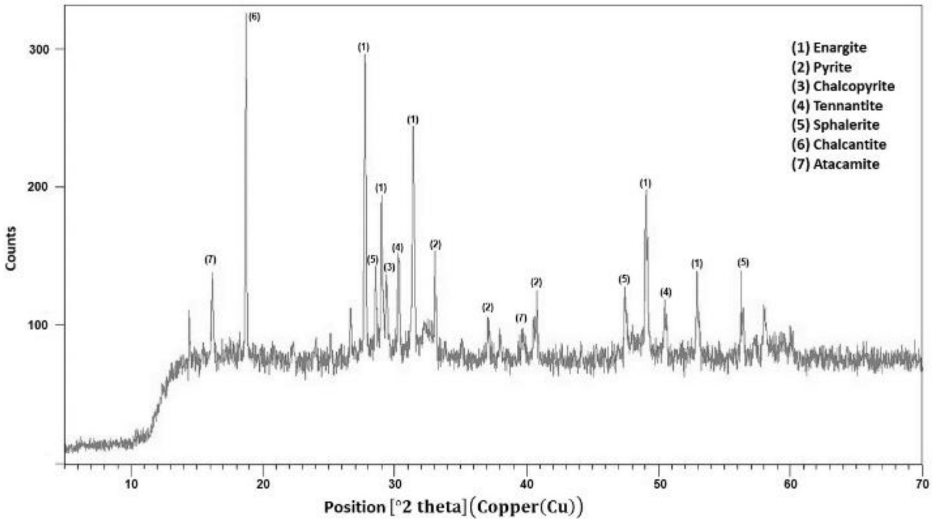

Figure 6. X-ray diffractogram of pretreated sample using a curing time of 15 days, 70 kg/t of sulfuric acid (H_2SO_4), and 1 M ferric chloride ($FeCl_3$).

Figure 7 shows the diffractogram of the original sample and the sample after curing pretreatment. The superimposition of the curves makes it easier to see the crystalline species, which may appear as the product of a chemical reaction. In this case, it is possible to observe the peaks representative of oxidized species such as chalcanthite and atacamite.

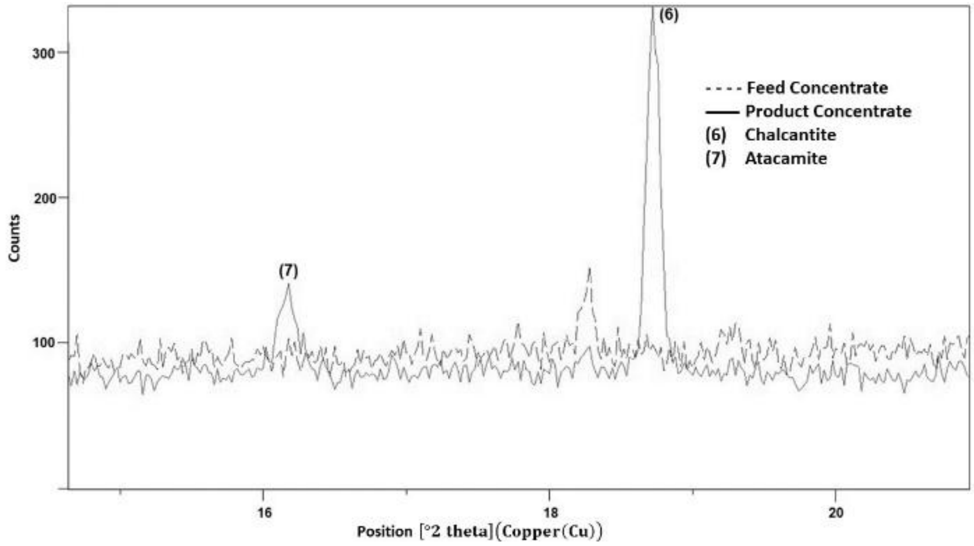

Figure 7. Phases generated by the pretreatment.

Subsequently, analyzing Figure 8, it is observed that the bornite and digenite disappeared with the pretreatment. The digenite has its most important characteristic angle at 46.294°, and the bornite has its most important characteristic angle at 46.945°. Interpreting this information together with the unchanged peaks of the enargite, it can be inferred that after the copper oxide was extracted, the next most soluble mineral would be digenite [19], and therefore, the extracted copper would come from this mineral. This inference is supported by the significant presence of this mineral in the concentrate, being the second copper-containing mineral present after enargite.

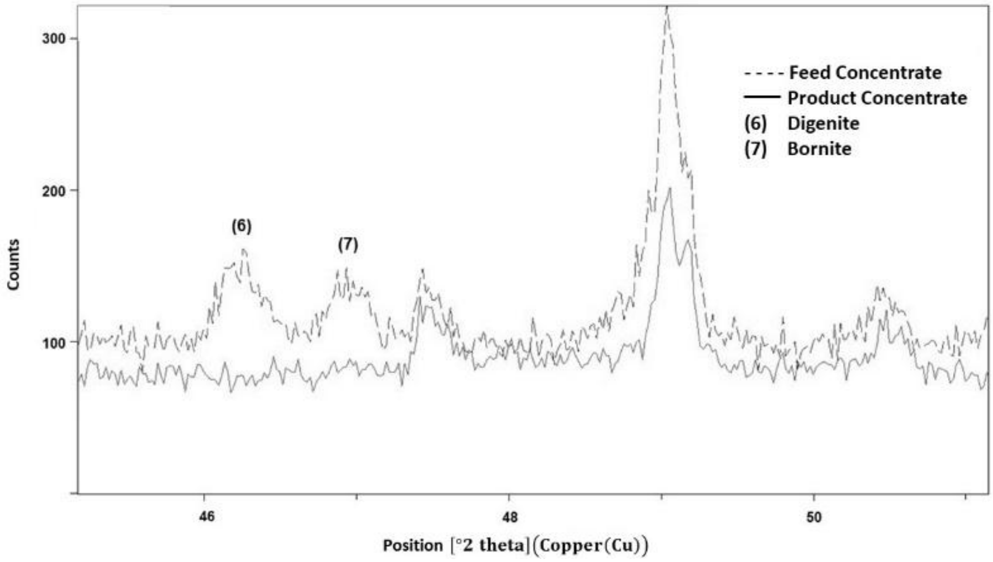

Figure 8. Phases dissolved by the pretreatment.

Moving on to the consideration of the reactions that occurred, first, we observe the information obtained from Figure 7, and in line with a study conducted by Lee et al. [20], the transition from a sulfide to copper sulfate has been confirmed. Therefore, we would consider Reaction 1 as the initial stage, with the conversion of chalcocite–digenite to copper sulfate ($CuSO_4$), identified by software as chalcanthite. Additionally, this process generates a portion of worn digenite that would transform into covellite (CuS).

$$0.1875Cu_{1.8}S + 0.1500H_2SO_4 + 0.1500O_2 \rightarrow 0.1500CuS + 0.1875CuSO_4 + 0.1500H_2O \quad \text{(R1)}$$

Meanwhile, in Senanayake's study [21], he investigated the benefits of adding chloride in the leaching of copper sulfides with sulfuric acid, obtaining copper hydroxychloride as a product of covellite. Furthermore, [22] proposes that on the surface of a copper ore (chalcocite) multiple reactions can occur, mainly following as a reference the dissolution mechanism proposed by [23]. Examining Figure 7 and the XRD analysis, a copper hydroxychloride called atacamite ($Cu_2Cl(OH)_3$) is identified. This would be the result of the addition of ferric chloride ($FeCl_3$) to the sample; however, we must consider the addition of iron that was not originally present. The assumption is that the interaction of worn digenite (covellite) from Reaction 1 with ferric chloride would only generate iron (Fe^{2+}) and sulfur (S) in their elemental forms. Along with sulfuric acid (H_2SO_4) and its sulfate ion ($SO_4{}^{-2}$) produced upon dissolution, we could consider the combination of these two ions to form iron sulfate ($FeSO_4$). To substantiate this theory, the data obtained by XRD of the sample after pretreatment were analyzed by the phase interpretation software, specifically looking for compounds formed by iron (Fe), sulfur (S), and oxygen (O).

In Figure 9, the comparison of characteristic angles is shown, corresponding to the most relevant for the identification of sphalerite (28.517°) and the second most important for the compound $Fe(SO_4)$ (OH) * $2H_2O$ (28.554°), identified by software as parabutlerite. Thus, the formation of iron sulphate under the conditions used could be possible, and its identification is complicated by the initial presence of sphalerite. The presence of this new species is argued by mentioning that it was a nonexistent species in the concentrate before pretreatment, considering that it was amorphous. Therefore, the XRD analysis more easily identified sphalerite, giving it priority in the angle overlap due to its greater crystallinity. It is concluded that the second stage would correspond to Reaction 2.

$$\begin{aligned} 0.8125Cu_{1.8}S + \quad & 0.9100H_2O + 0.1300FeCl_3 + 0.5850O_2 \\ & \rightarrow 0.3900Cu_2Cl(OH)_3 + 0.1300(Fe(SO_4)(OH) * 2H_2O) + 0.6825CuS \end{aligned} \tag{R2}$$

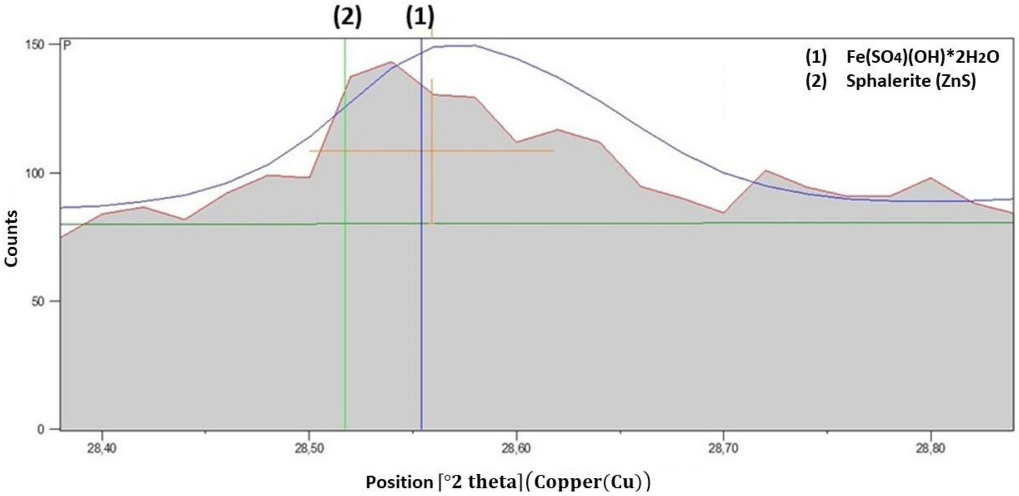

Figure 9. Comparison of the characteristic angles of parabutlerite and sphalerite.

Finally, combining Reaction 1 and Reaction 2 and supported by the applied characterization techniques, the final reaction is obtained, corresponding to Reaction 3.

$$\begin{aligned} 1.0000Cu_{1.8}S + \quad & 0.1500H_2SO_4 + 0.1300FeCl_3 + 0.7600H_2O + 0.7350O_2 \\ & \rightarrow 0.1875CuSO_4 + 0.3900Cu_2Cl(OH)_3 + 0.1300(Fe(SO_4)(OH) * 2H_2O) \\ & + 0.8325CuS \end{aligned} \tag{R3}$$

4. Conclusions

According to the analysis of variance (ANOVA), the most effective combination for optimizing copper extraction from an enargite-rich concentrate involves a curing time of 15 days, the addition of 70 kg/t of sulfuric acid (H_2SO_4), and a 1 M concentration of ferric chloride ($FeCl_3$). However, these parameters do not show a significant impact on enargite and chalcopyrite dissolution.

The analysis suggests that curing time is the most influential factor in the process, accounting for 46% of the overall contribution. In comparison, sulfuric acid and ferric chloride contribute less, with 20% and 10% contributions, respectively. Therefore, it is recommended to extend the curing time and increase the acid concentration to improve the process efficiency.

The curing treatment in chloride media proves to more effective for bornite and chalcocite, while enargite and chalcopyrite remain unaffected.

The mineralogical analyses suggest that the treatment could transform copper sulfide into copper sulfate, specifically through the conversion of chalcocite–digenite into copper sulfate. Additionally, there is some transformation of digenite into covellite.

We consider it important to carry out leaching tests to continue the research. Thus, with leaching tests, the effect of pretreatment can be measured in a complete extraction cycle. In addition, leaching residues could provide answers on the passivation of sulfide minerals and comparisons between samples with and without pretreatment.

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