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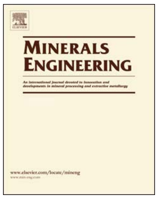

MINERALS ENGINEERING

# The leaching behavior of minerals from a pyrrhotite-rich pentlandite ore during heap leaching

Antti Arpalahti[a,*], Mari Lundström[b]

[a] Terrafame, Talvivaarantie 66, 88120 Tuhkakylä, Finland
[b] Aalto University, School of Chemical Engineering, P.O. Box 16100, 00076 Aalto, Finland

## ARTICLE INFO

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## ABSTRACT

Due to decreasing ore grades and increasingly complex ore bodies, the heap leaching of sulfide ores is of increasing interest. In this research, the heap leaching phenomena of a pyrrhotite-rich pentlandite ore was investigated for the first 150 days of operation in order to understand the phenomena taking place in the early phase of leaching in an industrial scale heap. The ore investigated originates from Terrafame (Finland) and contains approximately 20 wt% metal sulfides, the majority of which are pyrrhotite and pyrite. The nickel and zinc minerals of interest, pentlandite and sphalerite, are minor constituents of the ore. The oxidative leaching behavior of sulfidic minerals was shown to follow for the most part the order of nobility of sulfides. In the heap leaching investigated, pyrrhotite especially was shown to be far more reactive than pentlandite and sphalerite and thus the recovery of valuable metals can occur only after pyrrhotite dissolution. It was found that the nickel, zinc, and copper present in the irrigation solution can partially precipitate into the heap where more reductive metal sulfides, such as pyrrhotite and alabandite, are present, a metathesis phenomenon postulated elsewhere for copper and now confirmed in industrial scale operation. Pyrrhotite was also shown to create the majority of the reagent (acid and oxygen) demand and the majority of the reagent demand variation during the early days of heap leaching. In addition, the height of the heap was shown have an important role in determining the leaching time, due to physical, chemical, and practical limitations on acid feed. The acid demand for pyrrhotite leaching in low-oxygen consuming reactions was found to be higher (approx. 62 kg/tonne of ore) than the possibility to feed acid on a tall heap (23 kg/tonne of ore at maximum). This was shown to result in heavy precipitation of iron compounds, such as goethite. The results give more clarity for the initial stages of leaching at Terrafame and thereby enable clearer strategies to be formulated for solution circulation management according to heap age.

## 1. Introduction

Modern heap leaching came into operational practice in the mid-20th century. The first operations were for uranium in the 1950s followed by gold and copper in the 1960s (Ghorbani et al., 2016). The copper heap leaching operations started from oxide ores, and by the 1980 s the first sulfide copper heap leaching for ores such as chalcocite had appeared (Watling, 2006). Chalcopyrite bioheap leaching is still in a development stage with several teams around the world looking for the breakthrough (Watling, 2006; Mutch et al., 2010; Panda et al., 2012; Boxall et al., 2017).

In this study, the order of mineral leaching from pyrrhotite-rich pentlandite-containing black schist ore was investigated. The ore originated from Terrafame and contains several sulfide minerals: pyrite, pyrrhotite, alabandite, chalcopyrite, arsenopyrite, sphalerite, and the valuable nickel minerals pentlandite and violarite. Bioleaching of nickel, zinc, and copper from this ore has been extensively studied both in stirred tank reactors and columns since the 1990s and several studies have been published (Halinen, 2015; Riekkola-Vanhanen and Heimala, 1999; Riekkola-Vanhanen et al., 2001; Bhatti et al., 2009, 2012). Studies have also been published on the pilot testing from 2005 to 2007 and from the first months of full-scale heap operation (Riekkola-Vanhanen, 2013). However, there are no published results about the leaching chemistry occurring in the industrial scale heap. The current research focuses on the leaching phenomena of the minerals present in the ore during full-scale heap leaching operation. Specifically, the focus is on the leaching order of minerals and the leaching mechanisms driving the process. The purpose of this study is to better understand the initial period of leaching in the Terrafame operation and thereby enable clearer strategies to be formulated for solution circulation management according to heap age.

It has been suggested that pyrrhotite is less noble than the other

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* Corresponding author.
*E-mail addresses:* antti.arpalahti@terrafame.fi (A. Arpalahti), mari.lundstrom@aalto.fi (M. Lundström).

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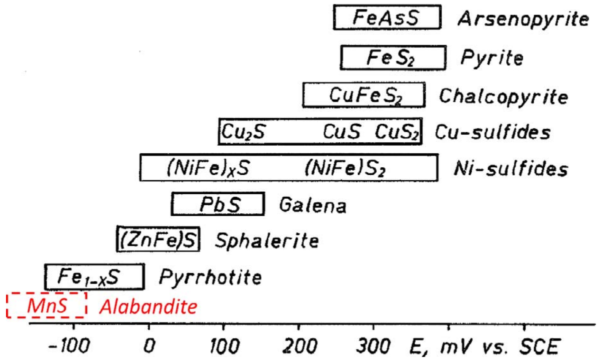

**Fig. 1.** Leaching potential of sulfide minerals present in the Terrafame ore (Riekkola-Vanhanen and Heimala, 1993) with alabandite added by the authors as an approximation based on observations in industrial scale operation (Arpalahti, 2016).

minerals present in the Terrafame ore, Fig. 1 (Riekkola-Vanhanen and Heimala, 1993). However, alabandite is known to be even less noble, having a leaching potential of as low as $< -100$ mV vs. SCE, modified in Fig. 1.

## 2. Materials and methods

The leaching behavior of the minerals present in pyrrhotite-rich pentlandite ore was investigated at an operating heap leaching plant (Terrafame, Finland) where the heap leaching is conducted in two stages. Freshly mined ore is stacked on the Primary Leaching pad, which is operated as a dynamic pad. This means here that the same liner area is used several times and a new heap is continuously stacked onto it while the old heap is continuously removed, or reclaimed, to another area. The retention time of the ore in Primary Leaching is approximately 1.5 years, after which the ore is reclaimed to the Secondary Leaching pad. There, the partially leached ore is stacked in multiple layers and secondary leaching is conducted with a retention time of approximately three years. Air is fed to both Primary and Secondary heaps.

Table 1 presents the average elemental analysis of the ore used to construct the test area described in Fig. 3 below. Using this data and knowledge of typical components in the ore, as presented earlier (Riekkola-Vanhanen and Heimala, 1993; Riekkola-Vanhanen, 2013), the amount of major sulfide components are estimated in Table 2 below.

The particle size distribution average of the construct is presented in Fig. 2. The p80 of the material was 7.15 mm on average.

Primary Leaching is divided into four sections, each from five to six million metric tons in size. These sections have individual ponds and thereby solution circulation. Unlike typical heap leaches (Ghorbani et al., 2016), the majority of the Pregnant Leach Solution (PLS) is recycled back to irrigation. This is conducted not for the heaps but with the next stage of the process in mind: the metal recovery plant. As both nickel and zinc are leached at the heaps and the aim is to recover them, sulfide precipitation was selected as the most effective and economic option. There are several reasons why solution recycling at the heaps is preferred for sulfide precipitation. First, as the solution is upgraded on concentration and irrigation kept optimal at the heaps and only a small bleed stream is taken from the heap to the metal recovery plant, the plant size can be kept minimal and hence the investment cost of the operation is lower. Second, sulfide precipitation operates efficiently to reach a suitable exit solution concentration. Hence, the higher the feed concentration, the higher the recovery through sulfide precipitation. Third, as both zinc and nickel are precipitated at the metals recovery plant and both are unwanted components in the other precipitates, a constant feed concentration to the metals recovery plant is desired in order to be able to operate it with the best quality possible.

**Table 1**
The major elements in the ore examined.

| Al, mg/kg | Ca, mg/kg | Cu, mg/kg | Fe, mg/kg | K, mg/kg | Mg, mg/kg |
|---|---|---|---|---|---|
| 48,840 | 14,590 | 1543 | 127,690 | 29,870 | 20,170 |
| Mn, mg/kg | Na, mg/kg | Ni, mg/kg | S, mg/kg | Si, mg/kg | Zn, mg/kg |
| 2988 | 4090 | 2594 | 122,100 | 172,440 | 4596 |

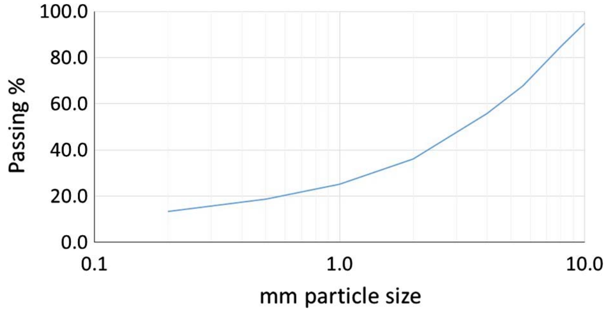

**Fig. 2.** Particle size distribution of the Terrafame raw material.

Primary and Secondary leaching have similar physical appearances: both are drip line irrigated from the top and aerated from the middle of the heap. Both are stacked with specific stacking equipment and laid out in wide strips. The height varies from 5.5 to 20 m, a typical case being 8.5 m.

The leaching behavior was investigated for the 150 first days of heap operation at a 132 m long heap section. Leaching yields of the metals of interest were determined by solution analysis, observing the concentration change across the heap sections. The irrigation solution was analyzed for temperature, pH, and dissolved metal (Ni, Mn, Fe, Zn) concentrations daily using a Thermo Scientific iCAP 6500 Radial View ICP-OES Spectrometer. The outlet solution drains every 66 m into an inspection well and temperature, pH, and metal concentrations were measured from this irrigation solution, albeit only twice per week. Two inspection well analyses, *Sample point 1* and *Sample point 2,* were used to observe the behavior of elements during the first 150 days of irrigation (leaching). The calculation of change across the heap takes an average of two weeks for an inspection well outlet minus the previous week's two-week average of the irrigation solution. This time shift is used in order to note the solution retention time in the heap. The heap continued normal industrial operation after the detailed 150-day observation period.

The analyzed heap had approx. 560,000 metric tons of ore and three irrigation cells of approx. 40 m in width and 330 m in length. The starting irrigation rate was 5 L/m$^2$h for each cell, with pH adjusted on average to 1.7, corresponding roughly to 2 m$^3$ of acid to 1000 m$^3$ of solution, or about 3.4 g/L free acid. The irrigation solution was collected via drainage to two wells and samples were taken from these wells, marked Sample point 1 and Sample point 2 in Fig. 2 above. 14 airlines were installed during the heap construction at a height of 4.5 m and 32 at a height of 1.5 m. The actual measured air flow rate averaged 210 L/s/pipe, resulting in 0.06 m$^3$/h/ton ore aeration on average. The air flow rate was measured sporadically throughout the analyzing period and did not vary much.

The analyzed heap is part of an approx. 5,500,000 metric ton heap system which shares the same circulating solution. The solutions from the heap outlet mix in a pond and are returned after pH adjustment to irrigation of all the heaps. This setup has the effect of the heap in question having metals in its irrigation as early as day 1. The irrigation solution analysis throughout the observation period can be found in Table 3.

The reagent demand of the ore calculations conducted in this research was based on the earlier published pilot head and residue grades