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# Extraction of metals from saprolitic laterite ore through pressure hydrochloric-acid selective leaching

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ABSTRACT

In this study, pressure hydrochloric-acid selective leaching was used to leach Ni and Co from saprolitic laterite ore on the basis of potential–pH diagrams constructed for Fe–Si–Cl–$H_2O$ and Ni–Si–Cl–$H_2O$ systems. The leaching of Ni, Co, Mg, Mn, and Fe was investigated under various conditions. The results showed that the optimal output was obtained under the following conditions: leaching temperature of 150 °C, HCl concentration of 350 g/L, liquid to solid ratio (l/s) of 1.0, and leaching time of 90 min. The saprolitic laterite and leached residue were characterized via X-ray diffraction analysis, infrared spectrometry, and mineral liberation analysis. The related acid leaching mechanism was analyzed based on the results, and the kinetics of the leaching process was discussed. The results of this study suggest that pressure hydrochloric-acid selective leaching is a viable method for efficiently leaching Ni from laterite ores.

## 1. Introduction

Nickel is a strategic metal that is primarily used to produce stainless steel and nonferrous alloys with high impact strength, high corrosion resistance, and other desirable electrical, thermal, and magnetic properties. Approximately 70% of the global land-based Ni is found in the form of laterite, which accounts for approximately 50% of the nickel produced worldwide (Fan and Gerson, 2013; Li et al., 2012). At present, because of decrease in the availability of sulfide ores, attention is increasingly being diverted to laterite ores (Norgate and Jahanshahi, 2010).

Laterite ores can be classified into two: limonite and saprolite (Pickles et al., 2014). Hydrometallurgical processes are preferred for recovering Ni and Co from limonite ores, whereas pyrometallurgical processes are used to produce ferronickel from saprolite ores. However, pyrometallurgical methods have several disadvantages, although 56.5% of the nickel produced in China in 2011 was obtained through such methods (Rao et al., 2013). The slag produced by pyrometallurgical processes accounts for approximately 80%–90% of the raw materials (Maragkos et al., 2009). However, the utilization rate of ferronickel slag is very low; thus, the large amount of slag generated during ferronickel production becomes a serious problem for ferronickel plants worldwide. Moreover, pyrometallurgical processes consume a large amount of energy because the operational temperature can be as high as ~1500 °C (Dalvi et al., 2004; Ren, 2006).

Given the drawbacks of pyrometallurgical processes mentioned above, hydrometallurgical processes have become increasingly attractive. Several leaching methods with different acids have been studied (Ma et al., 2013; McDonald and Whittington, 2008a,b). The most common lixiviant used in these methods is sulfuric acid. However, given the harsh leaching conditions (~250 °C, ~4 MPa) (Georgiou and Papangelakis, 1998; McDonald and Whittington, 2008b; Whittington and Muir, 2000), sulfuric-acid leaching may lose its appeal. The high inherent corrosiveness, high acid consumption, and low selectivity associated with chloride systems have impeded the use of hydrochloric acid in the extraction of Ni from laterite ores (McDonald and Whittington, 2008b). However, hydrochloric-acid leaching is still an attractive method because it allows for the extraction of large amounts of Ni and Co in a short period. As corrosion-resistant equipment has been successfully used to produce $ZrOCl_2$ (Guo and Dong, 2013; Xiong et al., 2002), the corrosive properties of hydrochloric acid might not be the main problem preventing the development of hydrometallurgical processes based on hydrochloric acid. Moreover, when hydrochloric acid is used as the lixiviant, it is relatively easy to recover the unused acid from the leaching solution (Olanipekun, 2000). The separation of metal chlorides through solvent extraction (SX) is simple, and concentrated chloride liquors produced through SX that contain nickel, iron, and magnesium can be spray roasted to produce pure nickel oxide, hematite, and magnesia, respectively (Kao and Juang, 2003; McDonald and

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Whittington, 2008a; Olanipekun, 2000; Zhu et al., 2014). Therefore, chloride-based commercial atmospheric leaching operations have been investigated and found to yield high Ni and Co extraction rates (Li et al., 2012; Olanipekun, 2000; Wang et al., 2012). However, the high concentration of Fe in the leaching solution hinders its after-treatment.

In this study, pressure hydrochloric-acid selective leaching was used to treat saprolitic laterite ore for extracting Ni and Co. A flowchart of the treatment process is shown in Fig. 1. Ni and Co were leached from laterite, while the majority of Fe remained in the residue in the form of FeOOH/$Fe_2O_3$. We studied various factors affecting the leaching of nickel, cobalt, manganese, iron, and magnesium, such as the reaction time, temperature, liquid to solid ratio (l/s) (vol./wt.), and hydrochloric-acid concentration. In addition, the mineralogical analysis of raw laterite and leached residue, which is an essential step for investigating the leaching mechanism, was performed to study the observed metal-dissolution behavior. The factors causing Ni loss were also analyzed. Moreover, the kinetics of the acid leaching process was studied to identify the rate-determining step.

## 2. Experimental

### 2.1. Materials

Raw laterite ore was acquired from Indonesia and vibration-milled, in which the percentage passing sieve number 200 was 90%. Chemical-content analysis indicated that this ore was a typical saprolitic laterite, containing 1.37 wt.% Ni, 11.7 wt.% Si, and 18.8 wt.% Fe (Table 1). All chemicals used were of analytical-reagent grade (Beijing Chemical Plant). The water used in the experiments and analyses was purified using a water super-purification machine (Milli-Q, Millipore).

### 2.2. Experimental apparatus and procedures

X-ray diffraction (XRD) analysis of the laterite was performed using an X-ray diffractometer (X'Pert Pro MPD, Panalytical Co.; 40 kV, 30 mA) with Cu Kα radiation. The infrared (IR) spectra of the laterite and acid leached residue were obtained using an IR spectrometer (Spectrum GX, Perkin-Elmer). The particle size of the residue was analyzed using a laser-diffraction particle-size analyzer (Mastersizer 2000, Malvern Instruments). The mineral analysis of the laterite ore and product samples was performed using a mineral liberation analyzer (MLA) with X-ray energy-dispersive spectroscopy (EDS) (MLA 250, FEI). The Raman spectra of the leaching solutions were acquired using a Raman spectrometer (LabRAM HR800, HORIBA Jobin Yvon). HSC Chemistry 5.0 software (Outokumpu Research, Finland) was used to construct the potential–pH (*E*–pH) diagrams.

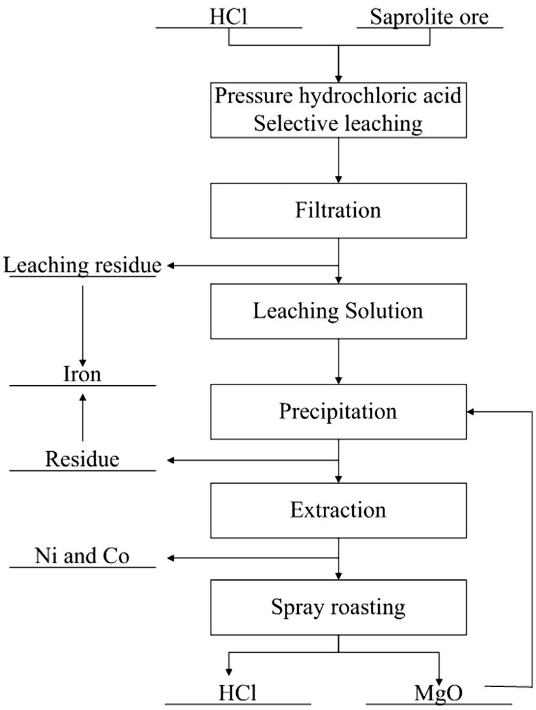

**Fig. 1.** Flowchart of pressure hydrochloric-acid selective leaching.

**Table 1**
Chemical composition of the saprolitic laterite.

| Component | Ni | Co | Fe | Cr | Al | Mg | Mn | Si |
|---|---|---|---|---|---|---|---|---|
| Content (wt.%) | 1.37 | 0.0583 | 18.8 | 0.939 | 1.87 | 10.8 | 0.245 | 11.7 |

The milled laterite ore was dried overnight in an oven at 105 °C before weighing. All experiments were conducted using the parameters listed in Table 2. The ore was added into a Teflon tank and mixed with a certain amount of HCl. Subsequently, the tank was placed in a steel autoclave, which was sealed and inserted into a temperature-controlled furnace. The autoclave was continuously rotated to ensure that the slurry was sufficiently suspended. After leaching, the slurry was filtered through a Buchner funnel and washed with deionized water. The filtrate and filter cake were separately collected and analyzed to determine the metal-leaching and mineral-dissolution behaviors.

### 2.3. Analysis procedures

To evaluate the leaching of metals, the filter-cake sample was dissolved and analyzed using inductively coupled plasma-optical emission spectrometry (ICP-OES, Optima 5300DV, Perkin-Elmer). The leaching of a metal was calculated using the following formula:

$$X\% = \left[1 - \frac{V \times M \times {}^{G_l}/_{G_i}}{m \times C_n}\right] \times 100 \qquad (1)$$

where $X\%$ is the leaching percentage of the metal; $M$ is the metal concentration in the HCl solution after the complete dissolution of the filter-cake sample (g/L); $G_l$ and $G_i$ are the total masses of the filter cake and filter cake sample, respectively (g); $m$ is the mass of the laterite ore used for the experiment (g); $C_n$ is the metal content in the laterite ore (%); and $V$ is the solution volume in the volumetric flask (L).

## 3. Results

### 3.1. Mineralogical study of saprolitic laterite ore

The ore was wet-sieved to achieve the appropriate size fraction. Large fractions were crushed, re-sieved, and combined with the smaller fractions, and a subsequent particle-size analysis indicated that the mean particle size of the laterite ore was 30.53 μm (Fig. 2). Furthermore, 90 vol.% of the laterite particles were less than 176.27 μm in size. The XRD pattern of the saprolitic laterite sample is shown in Fig. 3. In addition to saprolite and goethite, quartz was observed in this sample. In the IR spectra of the saprolitic laterite sample shown in Fig. 4, the

**Table 2**
List of process parameters studied during experiments.

| Studied parameters | Range | Fixed parameters |
|---|---|---|
| HCl concentration (g/L) | 150, 200, 250, 300, 350, 400 | l/s ratio = 1.0, 150 °C, 90 min |
| liquid to solid ratio, l/s (mL/g) | 0.8, 1.0, 1.2, 1.4, 1.6 | 350 g/L, 150 °C, 90 min |
| Leaching temperature (°C) | 120, 130, 140, 150,160 | l/s ratio = 1.0, 350 g/L, 90 min |
| Leaching time (min) | 15, 30, 45, 60, 90 | l/s ratio = 1.0, 350 g/L, 150 °C |