

LEACHING Zn FROM THE LOW-GRADE ZINC OXIDE ORE IN $\text{NH}_3\text{-H}_3\text{C}_6\text{H}_5\text{O}_7\text{-H}_2\text{O}$ MEDIA

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(Submitted: March 25, 2015 ; Revised: June 15, 2015 ; Accepted: July 21, 2015)

Abstract - In this research, the effect of different citric acid concentrations, ammonia concentration, temperature, leaching time, stirring speed and liquid-to-solid ratio on the zinc leaching from low-grade zinc oxide ore in a $\text{NH}_3\text{-H}_3\text{C}_6\text{H}_5\text{O}_7\text{-H}_2\text{O}$ system were studied. The results showed that the zinc leaching rate is only 4.7% when the citric acid concentration is 0 M, and the leaching efficiency of Zn increased with increasing citric acid concentration. Under the conditions: citric acid concentration of 1.0 M, ammonia concentration of 6 M, temperature of 25 °C, leaching time of 60 min, stirring speed of 300 rpm and the starting solid-to-liquid ratio of 1:5, 81.2% of Zn is leached. The mineralogical changes of the low-grade zinc oxide ores during the processes were characterized by X-ray fluorescence (XRF), X-ray powder diffraction (XRD), Scanning Electron Microscopy associated with Energy Dispersive Spectroscopy (SEM-EDS) and Fourier transform infrared spectroscopy (FT-IR). From the evidence we deduced that citric ions complexed with zinc ions, forming a Zn-citrate complex. As a result, the zinc leaching rate was improved without the risk of pollution or pretreatment. This makes it as a good choice for a more ecological treatment of hemimorphite.

Keywords: Low-grade zinc oxide ores; Hemimorphite; Ammonia leaching; Citric acid.

INTRODUCTION

Considering the huge reserves of low grade zinc oxide ores with high alkaline gangue (CaO and MgO) in the world (Li *et al.*, 2010), which is hard to handle by the traditional zinc smelting methods, recovering zinc from low grade oxide zinc ores has been a matter of discussion recently. The leach-solvent extraction-electro-winning process route is the most common method of extraction of zinc from low-grade zinc oxide ores (de Wet and Singleton, 2008). This is a material which can be processed by flotation (Irannajad *et al.*, 2009; Navidi Kashani and

Rashchi, 2008; Li *et al.*, 2013) and acid-leaching methods (Irannajad *et al.*, 2013; Xu *et al.*, 2010; Xu *et al.*, 2012; Li *et al.*, 2010; He *et al.*, 2010; He *et al.*, 2011). However, sulfuric acid leaching could not effectively recover zinc from a low grade oxide ore because of substantial iron dissolution (Yang *et al.*, 2013). Because of the complexities of mineralogical composition and structure, separation of zinc oxide minerals from their gangues by flotation is an extremely complex process (Majid *et al.*, 2014). Hence, with the high consumption of leaching acid, the treatment of low-grade oxidized zinc ores by hydrometallurgical methods is expensive and complex.

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The application of alkaline leaching techniques has become an increasingly important aspect in the recovery of base and precious metals from complex low grade zinc oxide ores (Santos *et al.*, 2010; Ding *et al.*, 2010; Yin *et al.*, 2010). However, alkaline leaching processing is often confronted with the problem of low-grade complex ores, especially zinc silicate. The low solubility of these ores does not usually allow for the recovery of the target metal, even by direct chemical leaching in many leaching reagents (Zhao *et al.*, 2009). Extracting zinc from hemimorphite by leaching in sodium hydroxide solution requires high temperature, pressure and alkalinity (Chen *et al.*, 2009). Currently, hydrometallurgy in ammonia has been considered as a prospective medium for the leaching of complex zinc ores of both oxide and sulfide types (Li *et al.*, 2014).

The use of organic acids for the extraction of metals has been studied by many researchers. It was reported that low molecular weight citric acid has been found to be effective in removing heavy metals by forming soluble complexes and chelates with metal ions (Chen *et al.*, 2003; Hongki *et al.*, 2013), and there is no concern about environmental problems after the treatment. Citric acid was found to be more active than H_2SO_4 . In hydrometallurgical treatments, the ability to recover metals or metal oxides depends on their chemical reactivities (Larba *et al.*, 2013). So citric acid seems more appropriate to use as a less costly and more environmentally friendly leachant.

Several papers have been published on the coordination of citric acid and transition metals, lead citrate (Kourgiantakis *et al.*, 2000), tungsten citrate (Zhang *et al.*, 2003), aluminum citrate (Matzapetakis *et al.*, 1999) and germanium citrate (Willey *et al.*, 2001). Based on previous work, a new hydrometallurgical process for low-grade zinc oxide ore is put

forward. In this work, the effect of the concentration of citric acid, ammonia concentration, temperature, leaching time, stirring speed and liquid-to-solid ratio on the leaching of zinc from low grade zinc oxide ore in the $NH_3-H_3C_6H_5O_7-H_2O$ system was studied. The aim of this work was to develop a new hydrometallurgical technology, which intends to provide a green and economic method to extract zinc from low-grade zinc oxide ores.

MATERIALS AND METHODS

Experimental Materials

The low-grade zinc oxide ores used were given by Lanping County of Yunnan Province, China. The main chemical composition of the low-grade zinc oxide ores obtained by chemical analysis is listed in Table 1. It can be observed that silica (SiO_2) and a high content of alkaline gangues ($CaO + MgO$) are the main components of the ore. The zinc content in this ore, around 6.01%, is considered to be low for a successful pyrometallurgical treatment for zinc recovery (Dutra *et al.*, 2006), which leads to the greater interest in the hydrometallurgical treatment. The XRD spectrum of the low-grade zinc oxide ore is shown in Figure 1. The XRD analysis shows that silica (SiO_2), calcium carbonate ($CaCO_3$), lead carbonate ($PbCO_3$), and hemimorphite ($Zn_4Si_2O_7(OH)_2 \cdot H_2O$) are the main chemical components. Table 2 for the mineral composition in zinc shows that the ore contains mainly 67.55% hemimorphite ($Zn_4Si_2O_7(OH)_2 \cdot H_2O$), 29.78% zinc carbonate ($ZnCO_3$), 1.53% zinc sulfide (ZnS), and 1.05% Franklinite ($ZnFe_2O_4$). Other zinc-containing phases, which, on the basis of the chemical analysis, could be present (Table 1) are probably below the detection limit.

Table 1: Chemical analysis of the main elements present in the zinc oxide ore.

Element	O	Si	Ca	Fe	Zn	Pb	Al	C	Mg	S
Weight (mass %)	46.73	13.03	9.19	8.11	6.01	6.41	4.43	4.30	0.52	0.45

Table 2: Main mineral composition of zinc in ore sample.

Phase composition	$(Zn_4Si_2O_7(OH)_2 \cdot H_2O)$	$ZnCO_3$	ZnS	$ZnFe_2O_4$
Zn Content (mass %)	4.06	1.79	0.092	0.063
Phase occupation ratio (%)	67.55	29.78	1.53	1.05

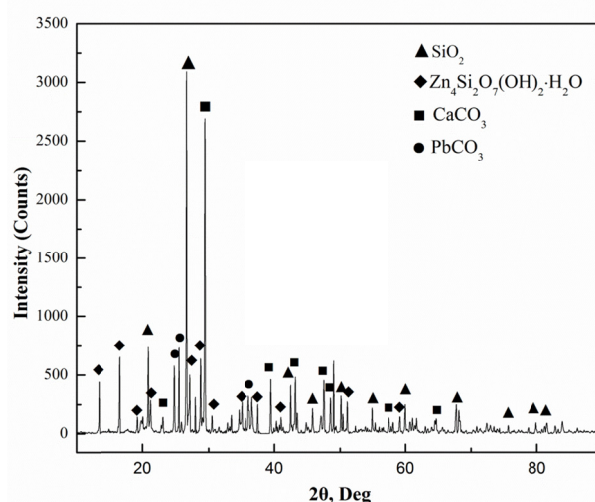


Figure 1: The XRD pattern of the low-grade zinc oxide ore.

Scanning Electron Microscopy associated with Energy Dispersive Spectroscopy (SEM / EDS) techniques were used for the morphological study of the low-grade zinc oxide ore, and the results are shown in Figure 2. Three typical phases were selected to analyze the element distribution in the low-grade zinc oxide ore. It is seen that Figure 2b (point 1 in

the black parts) shows that Zn, Si, O, Al, Fe, K and some other metal elements are mutually embedded in the ore sample. Figure 2c (point 2 in the white parts) reveals the regions enriched in lead-containing compounds. From Figure 2d (point 3 in the grey parts), it can be found that Si, O, Al, Fe, Pb coexist.

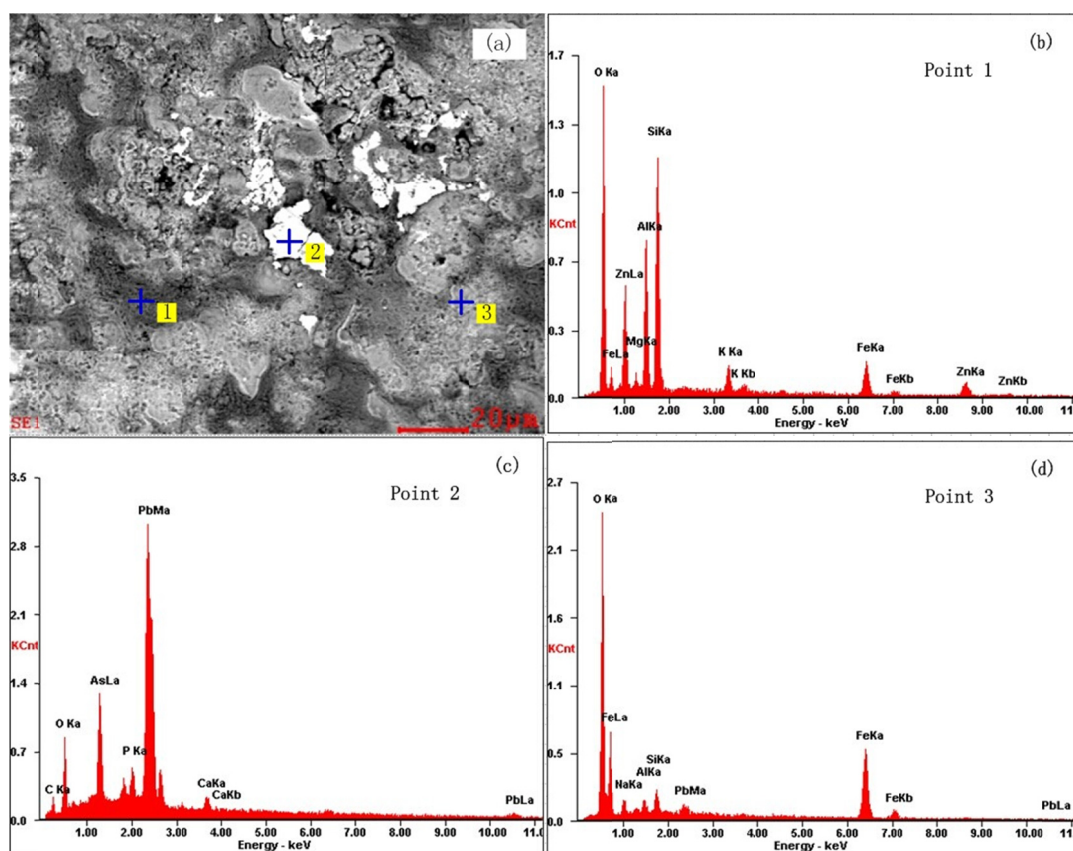


Figure 2: SEM image (a) and EDS patterns (b)-(d) in different area.

Experimental Method

The experiments used the -100 +200 mesh (74-149 μm) fraction as material.

Two-step leaching experiments were conducted in a 300 mL closed glass reactor equipped with a magnetic stirrer, and Figure 3 shows the flow diagram of the leaching process.

The general procedure for the leaching experiments was as follows: 20 g of samples was placed into the conical flask, 100 mL of the solution containing ammonia (6 M) with different concentrations of citric acid were placed in the reactor at 298.15 K, leaching time 1 h and magnetically stirred at 300 rpm. The leaching experiments were performed in triplicate. Zn content in the solution was determined. Zn in the filtrate was analyzed by EDTA titrimetric method. The leaching recovery of zinc (η_{Zn}) was calculated according to the following equation (Eq. (1)):

$$\eta_{\text{Zn}} = \frac{C_{\text{Zn}} \times V}{m \times C_{\text{Zn}}^0} \times 100\% \quad (1)$$

where η_{Zn} (%) is the leaching recovery of zinc, C_{Zn} (g/L) the zinc concentration of leaching solution, V (L) the leaching volume, C_{Zn}^0 (%) the zinc content of the low-grade zinc oxide ore, m (g) the mass of the low-grade zinc oxide ore.

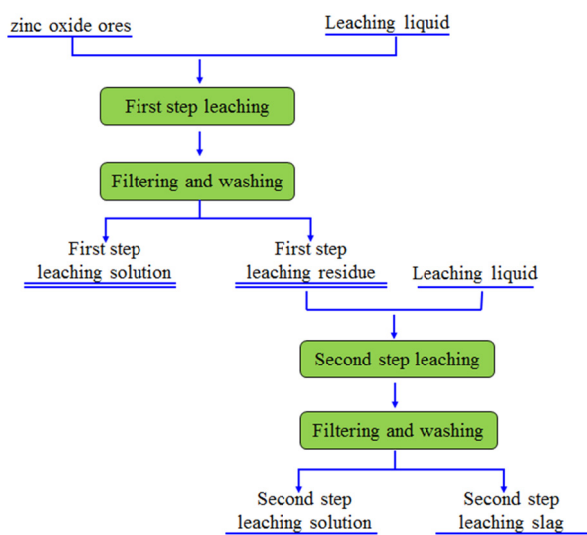
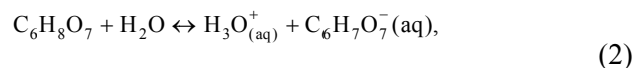


Figure 3: Flow diagram of the leaching process for low-grade zinc oxide ore leaching.

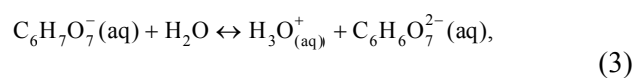
Thermodynamic Analysis for the Zinc - Citric Acid Medium

Citric acid contains three COO^- group and its structural formula is shown in Figure 4. The ionization

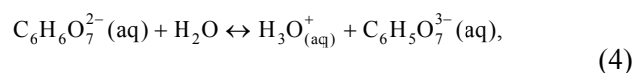
constants of citric acid are as follows: $\text{pK}_{\text{a}1}=3.13$; $\text{pK}_{\text{a}2}=4.76$; $\text{pK}_{\text{a}3}=6.40$, and show that the citric acid solution has a strong acidity. The main existing forms of ionized citric acid are related to the pH. Three carboxyls are contained in one $\text{C}_6\text{H}_8\text{O}_7$ molecule and, upon dissociation of 1 mol citric acid in 1 L distilled water, 3 M H^+ is theoretically produced (Li *et al.*, 2013). In fact, not all the H^+ is released to the solution. The dissociation reaction of citric acid can be expressed as follows (Demir *et al.*, 2006):



$$\text{K}_{\text{a}1} = 7.4 \times 10^{-4}, \quad \text{pK}_1 = 3.13$$



$$\text{K}_{\text{a}2} = 1.7 \times 10^{-5}, \quad \text{pK}_2 = 4.76$$



$$\text{K}_{\text{a}3} = 4.0 \times 10^{-7}, \quad \text{pK}_3 = 6.40$$

The fractions of each citrate species are shown as a function of pH at 298.15 K (Zárate-Gutiérrez and Lapidus, 2014), where it can be noted that $\text{H}_3(\text{Cit})$ predominates below $\text{pH} = 3$ and between 3 and 5 the $\text{H}_2(\text{Cit})^-$ species dominates; only above $\text{pH} = 5$ does $\text{H}(\text{Cit})^{2-}$ appear and, initiating at $\text{pH} = 7$, the Cit^{3-} ion. Because the pH of the reaction medium was more than 9, a basic reaction was carried out with respect to Eq. (4). Few studies focused on the structure of zinc citrate complexes with non-molecular structure. The compounds found are $\text{C}_{12}\text{H}_{14}\text{O}_{16}\text{Zn}_3$ (Che *et al.*, 2005) and $[\text{Zn}(\text{II})(\text{C}_6\text{H}_5\text{O}_7)_2 \cdot 4\text{NH}_4^+]$ (Swanson *et al.*, 1983).

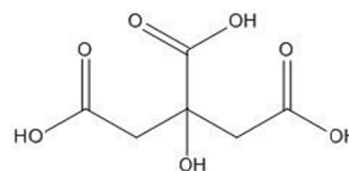


Figure 4: The structural formula of citric acid ($\text{C}_6\text{H}_8\text{O}_7$).

RESULTS AND DISCUSSION

Effect of Citric Acid Concentration

The study for the effect of citric acid concentration on the extraction of zinc was carried out by

varying concentrations in the 0-1.0 M citric acid range. The average leaching rates are shown in Figure 5, which shows that the leaching efficiencies of Zn increased with the increase of the citric acid concentration. At the low citric acid concentrations, namely 0 and 0.05 M, only 4.73% and 24.57% of zinc were extracted in the two-stage leaching, respectively. The zinc extraction was improved from 24.57% to 81.27% when the citric acid concentration increased from 0.05 to 1.0 M. Increasing the zinc extraction as the citric acid concentration increases is due to the citric acid concentration effect of increasing the $\text{C}_5\text{H}_7\text{O}_5\text{COO}^-$ activity, that results in further dissolution of zinc containing ore. 81.27% leaching efficiencies were obtained for Zn by two-stage leaching, under the following leaching condition: 6 M ammonia, 1.0 M in citric acid concentration, 60 min in leaching time, 298.15 K in temperature, and 300 rpm in stirring speed.

As seen in Figure 5, an increase in citric acid concentration increases the dissolution rate of zinc. During the process of leaching, citric acid is continuously consumed as it gets converted into product, resulting in a possible insufficient citric acid situation at low citric acid concentrations, limiting the maximum recovery. An increase in concentration is known to drive the reaction of zinc residue with citric acid, facilitating an increase in leaching.

The downstream processing of leach liquor can be the production of zinc by solvent extraction electro-winning or precipitation of Zn^{2+} after chemical separation of impurities.

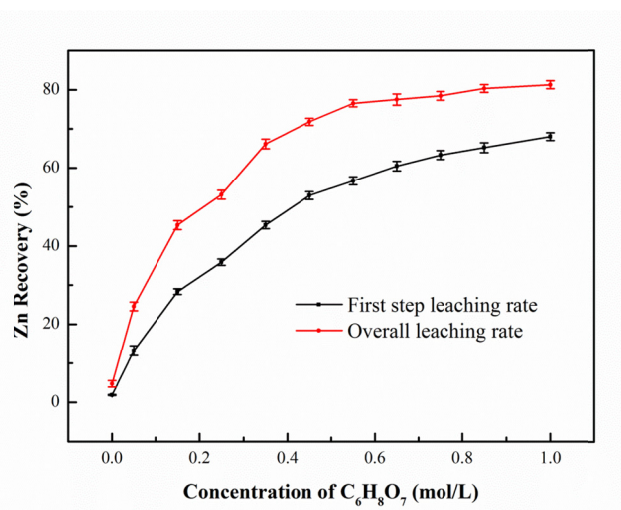


Figure 5: Effect of concentration of $\text{C}_6\text{H}_8\text{O}_7$ on zinc recovery from low-grade zinc oxide ores. Overall leaching rate represents the total leaching rate in the two steps; the first step leaching rate represents the leaching rate in the first step as shown in Figure 3.

Effect of Ammonia Concentration

Zinc oxide ore samples were leached for 60 min by two-step leaching to investigate the influence of the total ammonia concentration on the extraction of zinc. The leach conditions were as follows: citric acid concentration of 0.75 M; temperature set at 25 °C; stirring speed of 300 rpm; and liquid-to-solid ratio of 5:1. The results are shown in Figure 6.

As shown in Figure 6, with the increase of ammonia concentrations from 2.0 M to 8.0 M, the zinc leaching efficiency increased quickly from 23.06% to 80.21%. However, the solubility of zinc remained in a stable range of approximately 6 M.

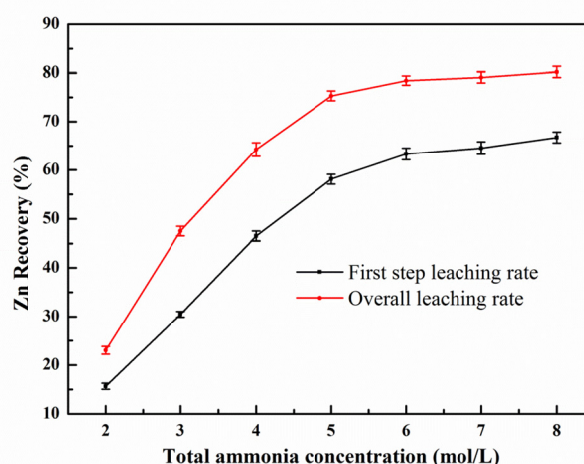


Figure 6: Effect of ammonia concentration on zinc recovery from low-grade zinc oxide ores.

Effect of Temperature

An investigation into the influence of temperature on zinc extraction was also performed. The conditions were the same as those detailed in the section of effect of ammonia concentration, except the ammonia concentration was adjusted to 6 M. The solubility of zinc in the $\text{NH}_3\text{-H}_3\text{C}_6\text{H}_5\text{O}_7\text{-H}_2\text{O}$ system under the same conditions was measured, and the results are shown in Figure 7.

The zinc leaching efficiency in the $\text{NH}_3\text{-H}_3\text{C}_6\text{H}_5\text{O}_7\text{-H}_2\text{O}$ system increased steadily with increased temperature. The zinc leaching efficiency remained in a constant range, which was close to saturation under the studied temperature. In this study, zinc extraction was found to exhibit a little impact with increased temperature.

Effect of Leaching Time

Figure 8 shows the effect of leaching time on

leaching efficiency of Zn for leaching time from 20 min to 90 min, maintaining citric acid concentration of 0.75 M; ammonia concentration of 6 mol/L; temperature set at 25 °C; stirring speed of 300 rpm; and liquid-to-solid ratio of 5:1. The leaching efficiency of Zn increased from 61.36% to 79.53% as the leaching time increased from 20 min to 90 min and the reaction was almost completed in 60 min. The results demonstrated that the duration of about 60 to 80 min duration is sufficient to achieve maximum efficiency.

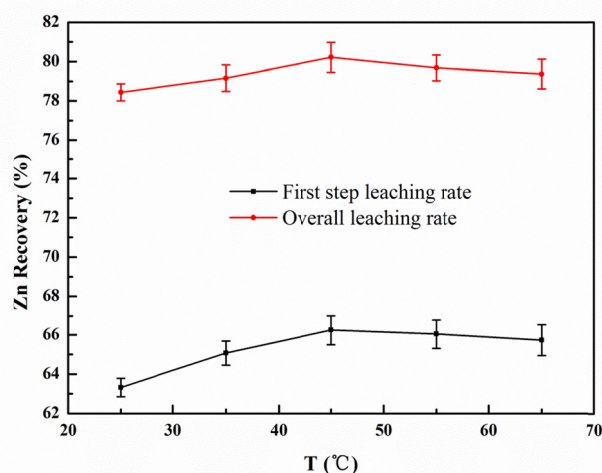


Figure 7: Effect of temperature on zinc recovery from low-grade zinc oxide ores.

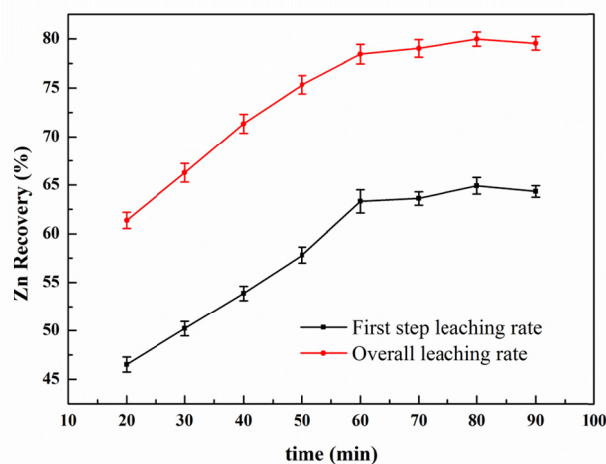


Figure 8: Effect of leaching time on zinc recovery from low-grade zinc oxide ores.

Effect of Stirring Speed

Under the technical parameters as follows: citric acid concentration of 0.75 M, ammonia concentration of 6 M, temperature of 25 °C and liquid-to-solid ratio of 5:1, the effects of stirring speed on zinc leaching efficiency were studied, and the results are

displayed in Figure 9. It can be observed that the leaching efficiency of Zn increased from 63.72% to 78.44% as the stirring speed increased from 200 rpm to 300 rpm, and that the stirring speed does not have a significant effect on the recovery of zinc after 300 rpm. This is because the ammonia leaching process of hemimorphite on the surface of the solid forms a thin diffusion layer at the solid-liquid interface. Increase the stirring speed reduces the diffusion layer thickness attached to the solid surface, thereby reducing the thickness of the diffusion layer, and increase the reaction rate and the dissolving process. But the stirring cannot destroy adhesion between solid and the diffusion layer, so the zinc leaching efficiency cannot be substantially increased when the speed exceeds 350 rpm.

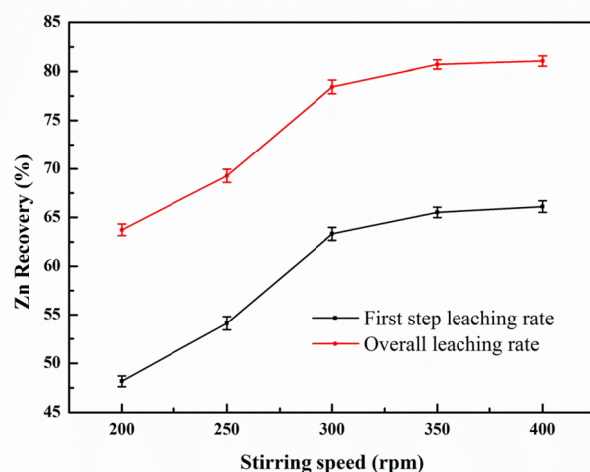


Figure 9: Effect of stirring speed on zinc recovery from low-grade zinc oxide ores.

Effect of Liquid-to-Solid Ratio

The leaching efficiencies of zinc were evaluated using various liquid-solid ratios. The leach conditions were as follows: citric acid concentration of 0.75 M; temperature of 25 °C; stirring speed of 300 rpm; and ammonia concentration as 6 mol/L and a leach time of 1h. The results are shown in Figure 10.

Figure 10 shows that the zinc leaching efficiency increases significantly from 65.75% to 80.85% with an increased liquid/solid ratio from 3 to 7. However, the zinc leaching efficiency remained in a stable range of approximately 5:1. This observation may point toward a possible cause of the difficult leaching characteristics of zinc oxide ore in the $\text{NH}_3\text{-H}_3\text{C}_6\text{H}_5\text{O}_7\text{-H}_2\text{O}$ system. At a low liquid-solid ratio (from 3:1 to 5:1), the zinc ion concentration in the solution increased rapidly. However, the zinc leaching efficiency is almost invariable in the range of 5:1 to 7:1. The possible

cause of this problem is that the extraction rate at low liquid-solid ratio might be controlled by the diffusion process and the diffusion resistance exists mainly in the concentration gradient, but is mainly by chemical reaction control in the latter stage.

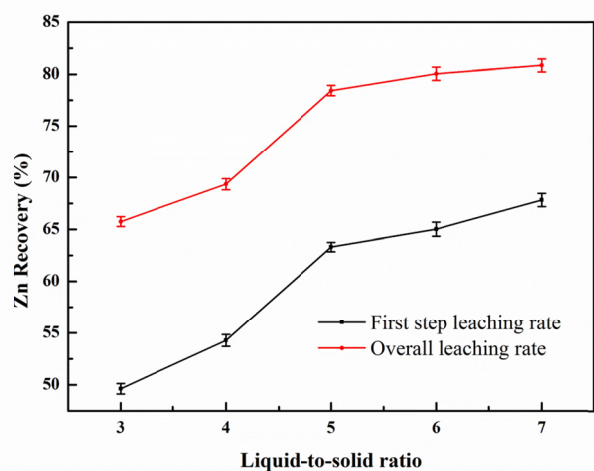


Figure 10: Effect of liquid-to-solid ratio on zinc recovery from low-grade zinc oxide ores.

FT-IR Analysis

In order to obtain more information on the crystal structure, we studied the vibrational spectra of the synthesized compound using FT-IR spectroscopic techniques. The experimental IR spectra recorded at room temperature are shown in Figure 11.

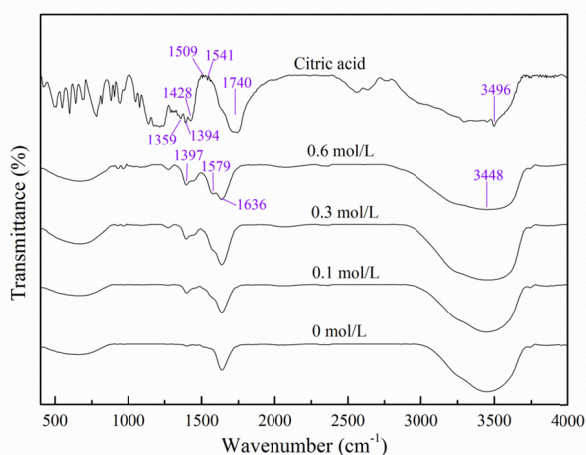


Figure 11: FT-IR of different citric acid concentrations.

The FT-Infrared spectra ($400\text{-}4000\text{ cm}^{-1}$) of solid citric acid and different citric acid leaching solutions were recorded in KBr and revealed the presence of vibrationally active carboxylate groups. Antisymmetric and symmetric vibrations for the carboxylate

groups of the coordinated citrate ligands were present in the spectra. In particular, antisymmetric stretching vibrations $\nu_{\text{as}}(\text{COO}^-)$ were present for the carboxylate carbonyls in the range $1562\text{-}1630\text{ cm}^{-1}$. The corresponding symmetric stretching vibrations $\nu_{\text{s}}(\text{COO}^-)$ for the same groups were present around $1350\text{-}1550\text{ cm}^{-1}$ (Kaliva *et al.*, 2006). The carboxyl vibration peaks ($\nu_{\text{C=O}}$: 1740 cm^{-1}) of citric acid, which shifted to lower frequencies (1579 cm^{-1} and 1397 cm^{-1}) compared with free citric acid. Asymmetric stretching vibrations and symmetric vibrations revealed the ionized COO^- groups from AC chelated with metal cations. The difference between the symmetric and antisymmetric stretches, $(\nu_{\text{as}}(\text{COO}^-) - \nu_{\text{s}}(\text{COO}^-))$, was greater than 200 cm^{-1} , indicating that the citrate carboxylate groups were either free or coordinated to zinc in a monodentate fashion (Tsaramyrsi *et al.*, 2001). Presence of a broad absorption band at 3496 cm^{-1} shows that the hydroxyl group of the citrate ligand is protonated. Because of the existing intermolecular H bond, the absorption band is shifted to lower frequency (Che *et al.*, 2005). In addition, the compound gives a strong absorption band at 3496 cm^{-1} , attributed to the vibration of the hydroxyl group of water. We found that the citrate ligand involved in coordination to zinc may further be ionized and thus undergo deprotonation at higher pH values (Zárate-Gutiérrez and Lapidus, 2014). In this respect, it could employ all of its carboxylates in coordination to zinc ion(s) possibly promoting a new assembly.

Steer and Griffiths (2013) noted that zinc extraction might be better explained by substituent group effects from Lewis acid/base theory. The substituent groups attached to the carboxylic acid functionality can play an important role. Although carboxylic acids are only partially dissociated 'weak acids', the carboxylate anion (RCOO^-) shown in Eq. (5) could potentially alter the extraction capability.



M – metal; R – organic substituent group.

Characterization of the Leaching Residue

Leaching Residue Characterization by XRD and XRF

The X-ray characterization of the leaching residue was performed after the process. The XRD patterns of the leached residue obtained with leaching by 1 M citric acid are shown in Figure 12. The XRD pattern of leach residue obtained was matched with

that of the raw ore. Obviously, in the presence of citric acid, the peak for hemimorphite ($\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$) diminished significantly. However, the peaks for PbCO_3 diminished marginally and the peaks for both SiO_2 and CaCO_3 were not diminished. As the overall recovery of Zn is directly related to hemimorphite leaching, the leaching residue can therefore be characterized as non-hazardous solid waste. This residue may be used as material for road construction or as stock feed for steel making plants, or just placed in landfill, if available, depending on the heavy metal contents, subject to an economic and technical feasibility study in each case.

Chemical compositions of the residues obtained at 6.0 M ammonia concentration, stirring speed of 300 rpm, solid-liquid ratio of 5:1 and leaching temperature of 25 °C after 0.05, 0.45 and 1.0 M citric acid leaching are shown in Table 3.

The results in Table 3 showed that, upon increasing citric acid concentration, Si and Fe enriched markedly while the Zn content decreased correspondingly. The main minerals in the leaching residue are quartz and small amounts of undissolved oxide minerals of iron, lead and calcium, associated with the dissolution of silica.

Morphology of the Leached Residue

To obtain more information about the distribution characteristics of the main metal elements, Scanning Electron Microscopy associated with Energy Dispersive Spectroscopy (SEM / EDS) techniques were used for the morphological study of the leaching residue leached by 1 M citric acid, and the results are shown in Figure 13.

The element distribution maps revealed a number of interesting aspects. The intensity of each image is indicative of the signal intensity of each ion. When ions overlap, this may or may not lead to areas in the last image in which only one colour can be seen. The bright particles (Figure 13a point 1), grey particles (Figure 13a point 2) and white particles (Figure 13a point 3) on the distribution maps, corresponding to the ions of O (Figure 13b), Si (Figure. 13c), Al (Figure 13d), Ca (Figure 13e), and Pb (Figure 13f), confirm the high content in the leaching residue of Ca, Pb and Al oxides and Si minerals. Figure 13g for the distribution map for Zn indicates that this is the metal with the low content, validating the results discussed above. The zinc did not get enriched in the leaching residue, and can be leached by citric acid.

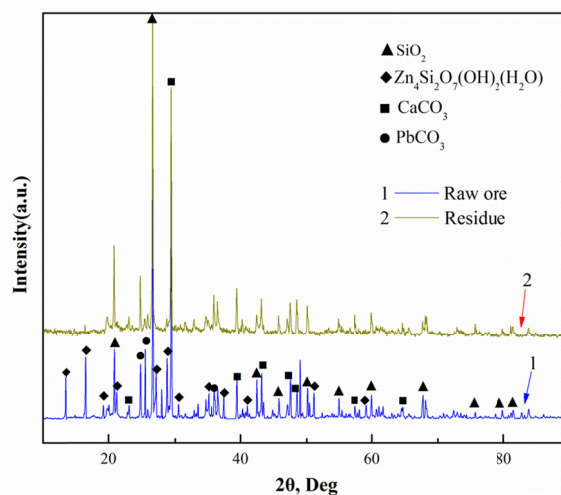


Figure 12: XRD patterns of the leaching residue and raw ore.

Table 3: Analysis of the leaching residue after leaching in different citric acid concentrations.

Concentration (M)	0.05	0.45	1.0
Zn (wt.%)	4.61	1.74	1.23
Si (wt.%)	13.62	14.69	15.02
Fe (wt.%)	8.40	8.98	9.31

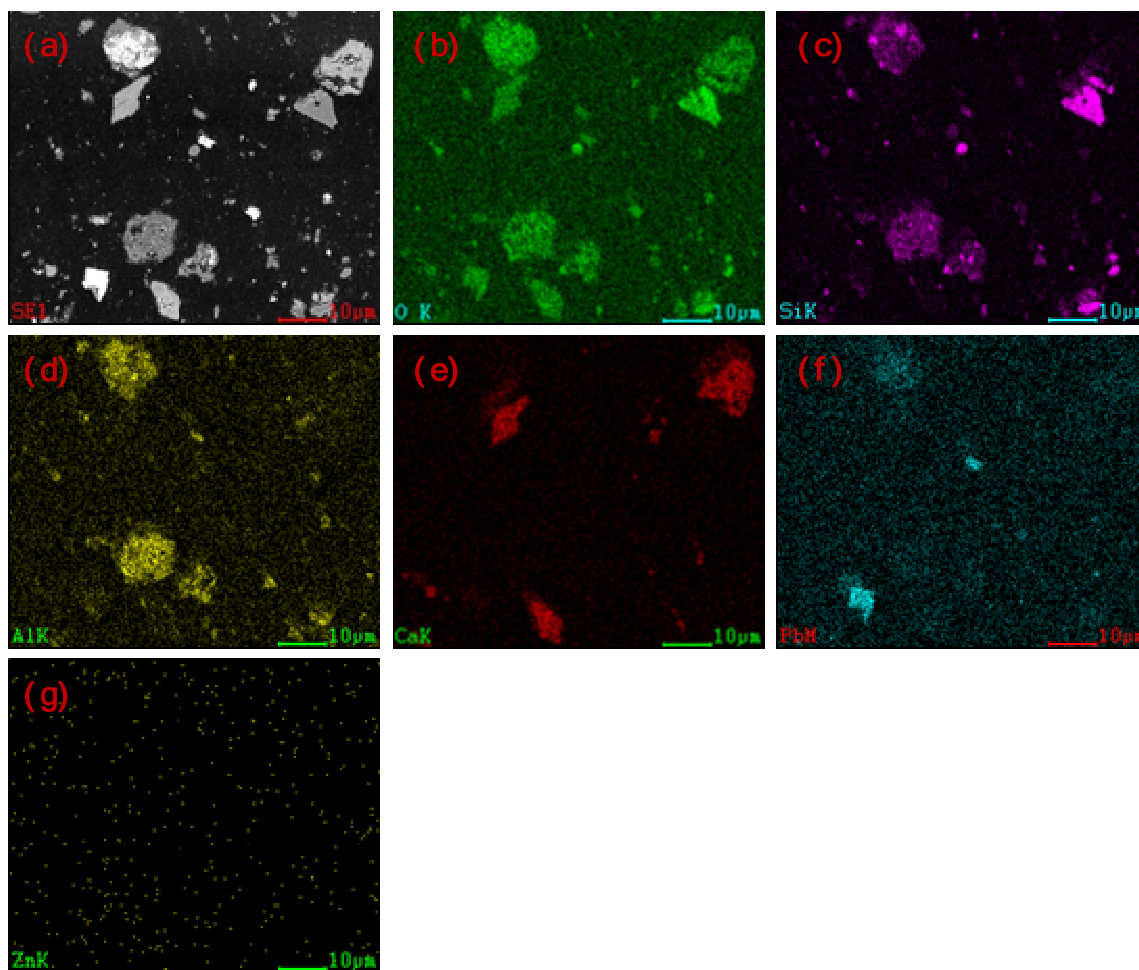


Figure 13: (a) SEM image of the leaching residue, EDS mapping of O (b), Si (c), Al (d), Ca (e), Pb (f), Zn (g).

CONCLUSIONS

The dissolution behavior of low grade zinc oxide ores in the $\text{NH}_3\text{-H}_3\text{C}_6\text{H}_5\text{O}_7\text{-H}_2\text{O}$ system was investigated.

(1) The concentration of citric acid was found to have an important role in low-grade zinc oxide ore dissolution, maximizing at 1 M, and a zinc leaching efficiency of about 81.2% was obtained, under the following leaching conditions: ammonia 6 M, temperature of 25 °C, leaching time of 60 min, stirring speed of 300 rpm and solid to liquid ratio of 1:5. The zinc leaching efficiency increased with the increase in citric acid concentration, liquid-solid mass ratio, leaching time, stirring speed and ammonia concentration.

(2) The FT-IR spectra reflect the changes in the structural group units and justify the leaching mechanism for zinc dissolution, and the complex demonstrated that the Zn (II) ion is coordinated. Three strong FT-IR bands at 1579 cm^{-1} and 1397 cm^{-1} were

found and they were assigned to a zinc–citrate complex in the aqueous solution.

(3) The results of XRD, IR, and SEM/EDS experiments indicate that hemimorphite is soluble, and the oxides of Si, Ca, Pb, Fe and Al are the main minerals in the leaching residue that are undissolved.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support from the National Program on Key Basic Research Project of China (973 Program, 2014CB643404), the National Natural Science Foundation of China (51404118), the Yunnan Province Young Academic Technology Leader Reserve Talents (2012HB008), the Yunnan Provincial Science and Technology Innovation Talents scheme Technological Leading Talent (2013HA002), and the 2014 PhD Newcomer Award in Yunnan Province (1319880207).

NOMENCLATURE

η_{Zn}	leaching rate of zinc, (%)
C_{Zn}	zinc concentration of leaching solution (g/L)
V	the leaching volume, (L)
C_{Zn}^0	the zinc content of the low-grade zinc oxide ore (%)
m	the mass of the low-grade zinc oxide ore (G)

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