Acid Bake–Leach Process for Recovering Copper and Cobalt from Oxide and Sulphide Concentrates

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A sulphuric acid bake–leach method for the treatment of copper–cobalt oxide and sulphide concentrates was investigated. Detailed chemical and mineralogy analysis of the sample was studied using atomic absorption spectrometry, X-ray diffraction, X-ray fluorescence and scanning electron microscopy. Mineralogical analysis showed that the sample contained both oxide- and sulphide-bearing minerals. Nearly 86% copper was in the oxide form, while more than 50% cobalt was in the sulphide form. A detailed scanning electron microscopy analysis revealed that most of the mineral oxide particles were embedded in the gangue mineral matrix, i.e., SiO_2 phase, while sulphide particles were well liberated. Under optimal conditions, the highest recoveries achieved were 96% for copper and 90% for cobalt. The effect of acid concentration, baking temperature and baking time were studied. The best acid concentration was found to be 50% H_2SO_4. The optimum baking temperature was in the range of 200–250 °C, beyond which recoveries decreased. Leaching time of 30 min was recommended because the recoveries of copper and cobalt were 93% and 83%, respectively, whereas extraction of iron was only 4%.

INTRODUCTION

Cobalt is classed as a material for use in energy devices and systems, namely in high-temperature superalloys, magnets and energy storage devices; e.g., lithium-cobalt oxide batteries (Schmidt *et al*., 2016). Copper is widely known as a good conductor of electricity in both pure and alloyed form with aluminium. Worldwide, the demand for these two metallic components is increasing with the rising demand for built environment and digital devices.

Zambia and the Democratic Republic of Congo (DRC) produce more than half of the world's cobalt (Shedd, 2015) and hold about one tenth of the global copper reserves (Crundwell *et al*., 2011). The deposits near the surface contain oxide ores, while sulphide ores are found deeper in the deposit (Crundwell *et al*., 2011; Prasad, 1989). Table I gives the common copper and cobalt minerals found in the Central African Copperbelt region of DRC and Zambia. Gangue minerals include dolomite ($CaMg(CO_3)_2$) and quartz (SiO_2). The metal content varies from one mine to another, with copper occurring in larger quantities (4–6% Cu) than cobalt (0.4% Co) (Prasad, 1989).

The method of recovering copper and cobalt from oxide ores/concentrates involves leaching, solvent extraction (SX) and electrowinning (EW). A reductant, such as sodium metabisulphite (SMBS; $Na_2S_2O_5$), is added during leaching to convert insoluble cobalt (Co^{3+}) to soluble cobalt (Co^{2+}) according to Equation [1] (Meshram *et al*., 2015; Miller, 2009). One of the disadvantages of using reductants is that reductants are expensive and hence increase the operating costs.

Table I: Common copper/cobalt minerals found in Central African Copperbelt region (Crundwell et al., 2011; Prasad, 1989).

	Mineral	Formula
Oxides	Malachite	$Cu_2CO_3(OH)_2$
	Pseudomalachite	$Cu_5(PO_4)_2(OH)_4$
	Cornetite	$Cu_2(PO_4)(OH)_3$
	Cuprite	Cu_2O
	Azurite	$Cu_3(CO_3)_2(OH)_2$
	Chrysocolla	$CuOSiO_2.2H_2O$
	Heterogenite	CoOOH
Sulphides	Chalcocite	Cu_2S
	Digenite	$Cu_{1.8}S$
	Carrollite	Co_2CuS_4
	Bornite	Cu_5FeS_4
	Chalcopyrite	$CuFeS_2$

$$2Co_2O_3 + Na_2S_2O_5 + 3H_2SO_4 \rightarrow 4CoSO_4 + Na_2SO_4 + 3H_2O. \quad [1]$$

Sulphide-bearing copper and cobalt minerals cannot be leached at room temperature because they are insoluble in acid under normal conditions. Therefore, sulphide concentrates are first roasted to convert the acid-insoluble sulphide minerals into soluble oxides and sulphates. The roast calcine is then leached in sulphuric acid to dissolve copper and cobalt. Recovery of metal from the solution involves SX, precipitation and EW. Reactions taking place during roasting are represented by Equations [2] and [3] (Sithole *et al*., 2017):

$$2MS(s) + 3O_2(g) \rightarrow 2MO(s) + 2SO_2(g) \text{ (dead roast);} \quad [2]$$
$$MS(s) + 2O_2(g) \rightarrow MSO_4(g) \text{ (sulphating roast),} \quad [3]$$

where M represents a metal, *i.e*., copper, cobalt or iron.

Even though sulphation roasting has been applied to copper–cobalt sulphide and oxide concentrates, the process has the following limitations:

- more energy may be required for a material having low sulphur content because the reactions may be endothermic;
- there is emission of sulphur dioxide (SO_2) gas, which is harmful to the environment, as shown by Equation [2];
- the copper and cobalt oxide minerals may form complex acid-insoluble compounds, such as ferrites, and thus result in low metal recovery (Shishin *et al*., 2015; Yaming *et al.,* 2015).

Owing to the limitations of the available methods for processing complex sulphide–oxide ores/concentrates, there is need to study the extraction of copper and cobalt from mixed sulphide–oxide minerals. One of the methods that has attracted a lot of interest is the acid bake–leach process. Many studies have been carried out to investigate the potential of this method for recovering valuable metals from different materials, such as converter slag, spent catalysts (e.g., Co–Mo/Al_2O_3), lithium-ion batteries and enargite (Cu_3AsS_4) concentrates (Arslan and Arslan, 2002; Behnajadya and Moghaddam, 2017; Gülay, 2006; Kim *et al*., 2009; Meshram *et al*., 2015; 2016; Parhi *et al*., 2015; Safarzadeh *et al*., 2012; Safarzadeh and Miller, 2013; 2014; Turan and Safarzadeh, 2012). Sulphuric acid bake–leach process involves baking of a material with H_2SO_4 at a low temperature (< 350 °C) to convert the mineral sulphides to sulphates. The baked products, which are water or dilute-acid soluble, are then leached out to solubilise copper and cobalt.

Sulphuric acid baking follows a similar reaction mechanism to that of conventional sulphating roasting. Sulphur trioxide (SO_3) gas plays an important role in acid baking process. During acid

baking, SO_3 (g) can be generated from either decomposition of sulphuric acid, Equation [4], or reaction of SO_2 with O_2, Equation [5]:

$$H_2SO_4 \rightarrow SO_3 + H_2O; \quad [4]$$
$$2SO_2 + O_2 \rightarrow 2SO_3. \quad [5]$$

Equation [4] is very endothermic at low temperatures (i.e., $\Delta H_{473.15}$ = 129.4 kJ), therefore, it may not contribute so much to acid baking at low temperature (i.e., 200 °C) (Safarzadeh *et al*., 2014); however, due to exothermic reactions of the overall acid baking process, the local temperature may be high enough to catalyse Reaction [4]. In contrast, Equation [5] is very exothermic at low temperatures, with $\Delta H_{273.15}$ = −197.7 kJ and $\Delta H_{473.15}$ = −198.3 kJ. The SO_3 gas generated from Reactions [4] and [5] reacts with the metal oxides resulting in formation of sulphates. Equations [6] and [7] show the general reactions for acid baking of oxides and sulphides, respectively:

$$MO + H_2SO_4 \rightarrow MSO_4 + H_2O; \quad [6]$$
$$MS + O_2 + H_2SO_4 \rightarrow MSO_4 + SO_2 + H_2O. \quad [7]$$

Table II gives equations representing reactions likely to occur during acid baking of some copper and cobalt minerals with their corresponding change in enthalpy (ΔH) and Gibbs free energy (ΔG) at 200 °C calculated using *HSC Chemistry 6.0* software. As shown in Equations [8] to [17], the enthalpy changes for all reactions, except Equations [11] and [15], are very negative, meaning that the reactions are highly exothermic. Therefore, it can be concluded that less energy is required for the process. Table II also shows that acid baking of sulphides is possible, even in the absence of oxygen, as presented by Equations [11] and [15]; however, due to the positive values of ΔH, additional heat is needed to bake the sulphides when oxygen is not present. The resulting products of sulphuric acid-baking process are sulphates, which can easily be leached in water or dilute acid.

Table II: ΔH and ΔG for acid-baking reactions for copper–cobalt sulphide–oxide concentrates.

Reaction	No	$\Delta H_{473.15}$ (kJ)	$\Delta G_{473.15}$ (kJ)
$CuO + H_2SO_4 \rightarrow CuSO_4 + H_2O$	[8]	–88.8	–79.7
$Cu_2CO_3(OH)_2 + 2H_2SO_4 \rightarrow 2CuSO_4 + 3H_2O + CO_2$	[9]	–109.9	–179.6
$CoO + H_2SO_4 \rightarrow CoSO_4 + H_2O$	[10]	–124.1	–110.9
$Cu_2S + 6H_2SO_4 \rightarrow 2CuSO_4 + 6H_2O + 5SO_2$	[11]	201.1	−160.2
$Cu_2S + H_2SO_4 + 2.5O_2 \rightarrow 2CuSO_4 + H_2O$	[12]	–941.5	–695.9
$Cu_2S + 2H_2SO_4 + 2O_2 \rightarrow 2CuSO_4 + 2H_2O + SO_2$	[13]	–713.0	–588.7
$Cu_2S + 2H_2SO_4 + O_2 \rightarrow 2CuSO_4 + 2H_2O + S$	[14]	–410.9	–287.8
$CoS + 4H_2SO_4 \rightarrow CoSO_4 + 4H_2O + 4SO_2$	[15]	124.8	−195.8
$CoS + H_2SO_4 + 1.5O_2 \rightarrow CoSO_4 + H_2O + SO_2$	[16]	–560.7	–517.2
$2CoS + 2H_2SO_4 + O_2 \rightarrow 2CoSO_4 + 2H_2O + 2S$	[17]	–517.3	–432.5

Arslan and Arslan (2002) studied acid baking of slag material with 2.64% Cu, 0.095% Co, 0.67% Zn and 47.2% Fe. Metal extractions of 88% Cu, 87% Co, 93% Zn and 83% Fe were achieved after baking the slag for 2 h at 150 °C and leaching at 70 °C. In another study, metal recoveries of 74% Co and 79% Cu were achieved after baking a slag (chemical composition: 0.98% Cu, 0.49% Co and 51.47% Fe) for 1 h at 200 °C and leaching it in hot water (Gülay, 2006). Kim *et al*. (2009) reported metal extractions of more than 90% Co, Mo and 93% Al after baking a spent Co–Mo/Al_2O_3 catalyst at 300 °C for 2 h and leaching at 95 °C for 1 h. Similar findings were reported by Parhi *et al*. (2015) from their investigation of acid-bake–leach process for selective dissolution of copper from a spent catalyst.

Advantages of the acid bake–leach method include:

- low operating temperature (< 350 °C);
- both oxide and sulphide minerals are sulphated;
- the reactions are highly exothermic and hence less energy is required.

Even though acid baking has been applied in recovering copper and cobalt from slag and low-grade copper and cobalt materials, there are no studies that have been carried out on acid baking–leaching of copper–cobalt oxide and sulphide concentrates; therefore, this research investigated acid baking followed by water leaching of copper–cobalt oxide and sulphide concentrates.

MATERIALS AND METHODS

A copper–cobalt concentrate was obtained from Chambishi Metals Plc on the Copperbelt province in Zambia. Chambishi Metals obtains this concentrate from DRC. The chemical analysis is shown in Table III, from which it can be observed that the sample is rich in copper and cobalt. The chemical analysis in Table III shows that the sample has high silica content. Atomic absorption spectrophotometry (AAS) analysis was carried out and the results are shown in Table IV, from which it can be observed that nearly 86% of the copper was soluble in acid, whereas only 40% of the cobalt is soluble in acid. Based on the AAS analysis in Table IV, it would not be economical to directly leach cobalt from this material as more than half of cobalt was insoluble in acid.

Table III: X-ray fluorescence analysis of the as-received copper–cobalt concentrate.

Element	O	Cu	Co	Al	Si	Mg	Ca	Fe	P	S	K	Ti
Mass (%)	69.84	12.45	5.52	1.06	14.43	6.58	2.91	2.28	0.06	0.54	0.99	0.44

Table IV: Atomic absorption spectrophotometry analysis of the as-received copper–cobalt concentrate.

TCu (%)	ASCu (%)	TCo (%)	ASCo (%)
12.30	10.60	6.39	2.76

The particle size of the sample was 80% passing 75 μm. Sulphuric acid used in this study was analytical grade (98% by mass). The tests were done in duplicate and the average was used to plot the graphs. All the samples were analysed by AAS and X-ray fluorescence (XRF) techniques.

Acid Baking Experiments

A 20 g solid sample was mixed with a predetermined sulphuric acid concentration and baked in the furnace preheated to the required temperature. All baking tests were carried out at a concentrate–acid ratio of 1 to 1 (mass/volume). After baking, the sample was cooled to room temperature and weighed to determine the mass change. The samples were baked at different temperatures so as to understand the effect of temperature on metal dissolution. The baked sample was then ground in a ceramic mortar and pestle.

Leaching Experiments

Ground baked sample was leached in water in a Pyrex beaker at solid–liquid ratio of 1 to 2.5. All leaching experiments were carried out at room temperature. The sample was continuously stirred during leaching with a mechanical agitator at the speed of 400 revolutions per minute. The pH of the solution was always less than 1.0. After leaching, the slurry was filtered and the solution was taken for AAS analysis. The residue was thoroughly washed, dried and analysed for metal content using AAS and XRF techniques.

Scanning Electron Microscopy

For the scanning electron microscopy (SEM) analysis, a representative portion of the sample was mounted in epoxy resin with 33% epoxy harder. The mounted sample was ground down on different silicon carbide papers. The ground sample was polished down to 1 μm. The polished sample was analysed by SEM equipped with an energy-dispersive X-ray spectrometer (EDX), which allows phase quantification and elemental mapping. Several areas of the sample were analysed at different magnification to understand the phase distribution.

RESULTS AND DISCUSSION

Mineralogy Analysis

Figure 1 shows the x-ray diffraction (XRD) pattern for the copper–cobalt sulphide–oxide concentrate sample. Copper was mainly in oxide form, with malachite ($Cu_2CO_3(OH)_2$) appearing as the major phase. The oxidized deposits of the Central African Copperbelt region also contain copper in form of phosphates, i.e., pseudomalachite ($Cu_5(PO_4)_2(OH)_4$) and cornetite ($Cu_3(PO_4)(OH)_3$) (Prasad, 1989). The XRD pattern confirms the presence of $Cu_5(PO_4)_2(OH)_4$ in the mineral sample. For cobalt, carrollite ($CuCo_2S_4$) was the main sulphide phase in the mineral concentrate. Figure 1 also shows some mineral complexes and gangue minerals, such as SiO_2 and $CaMg(CO_3)_2$, which were present in the sample. It is clear from Figure 1 that more SiO_2 than $CaMg(CO_3)_2$ appeared in the sample. This agrees well with results obtained from chemical composition analysis presented in Table III.

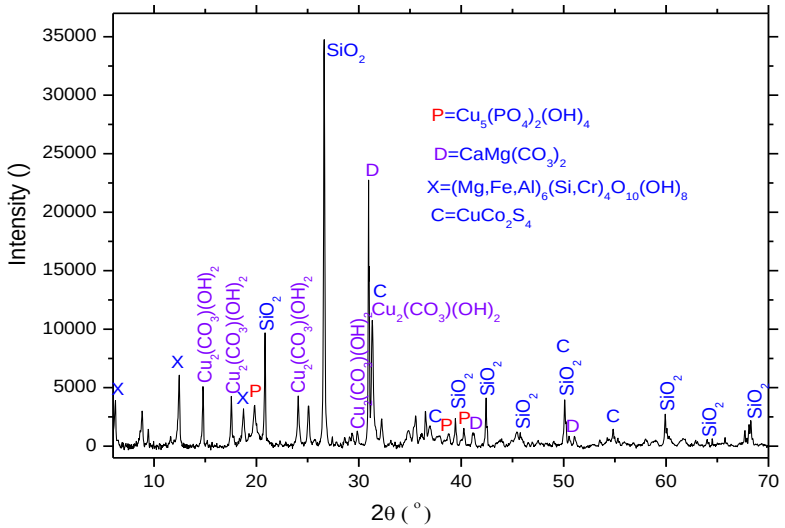

Figure 1: X-ray diffraction pattern of the as-received copper-cobalt concentrate.

SEM was carried out to analyse phases present in small quantities (< 1 mass%). Several areas of the sample were analysed by EDX to quantify minor phases. Elemental mappings for the as-received copper–cobalt mineral concentrate are presented in Figure 2. Figure 2(a) shows Cu–P–O phases. These phosphates of copper were also confirmed in the XRD analysis (see Figure 1). Other phases that can be seen in Figure 2(a) are Cu–O, Cu–Si–O and Cu–P–O–Si. It is evident from the elemental mappings that most of the copper was contained in the oxide form, which agrees with chemical composition analysis presented in Table IV. Cobalt mineral phases detected by SEM–EDX were of the Co–O, Co–S and Co–Fe–S type. The cobalt oxide mineral in the concentrate might have been heterogenite (CoOOH) because this is the most common oxide form of cobalt in the Central African Copperbelt region (Crundwell *et al.*, 2011; Prasad, 1989). Figure 2(b) also shows particles of Cu–Co–S and Fe–S, which were analysed as carrollite and pyrite (FeS_2) by SEM–EDX analysis. Carrollite was also confirmed in the XRD analysis (see Figure 1). Most of the iron was contained in the pyrite mineral as well as compounds of copper and cobalt (i.e., Cu–Fe–S and Co–Fe–S), as shown in Figure 2(a) and (b). It is also clear from Figure 2 that sulphide particles were well liberated compared with oxide particles. Most of the oxide particles were embedded in gangue minerals, i.e., silica and compounds of calcium and magnesium. Based on this analysis, direct leaching is not suitable because of high acid consumption by the gangue, low metal recoveries and long leaching times.

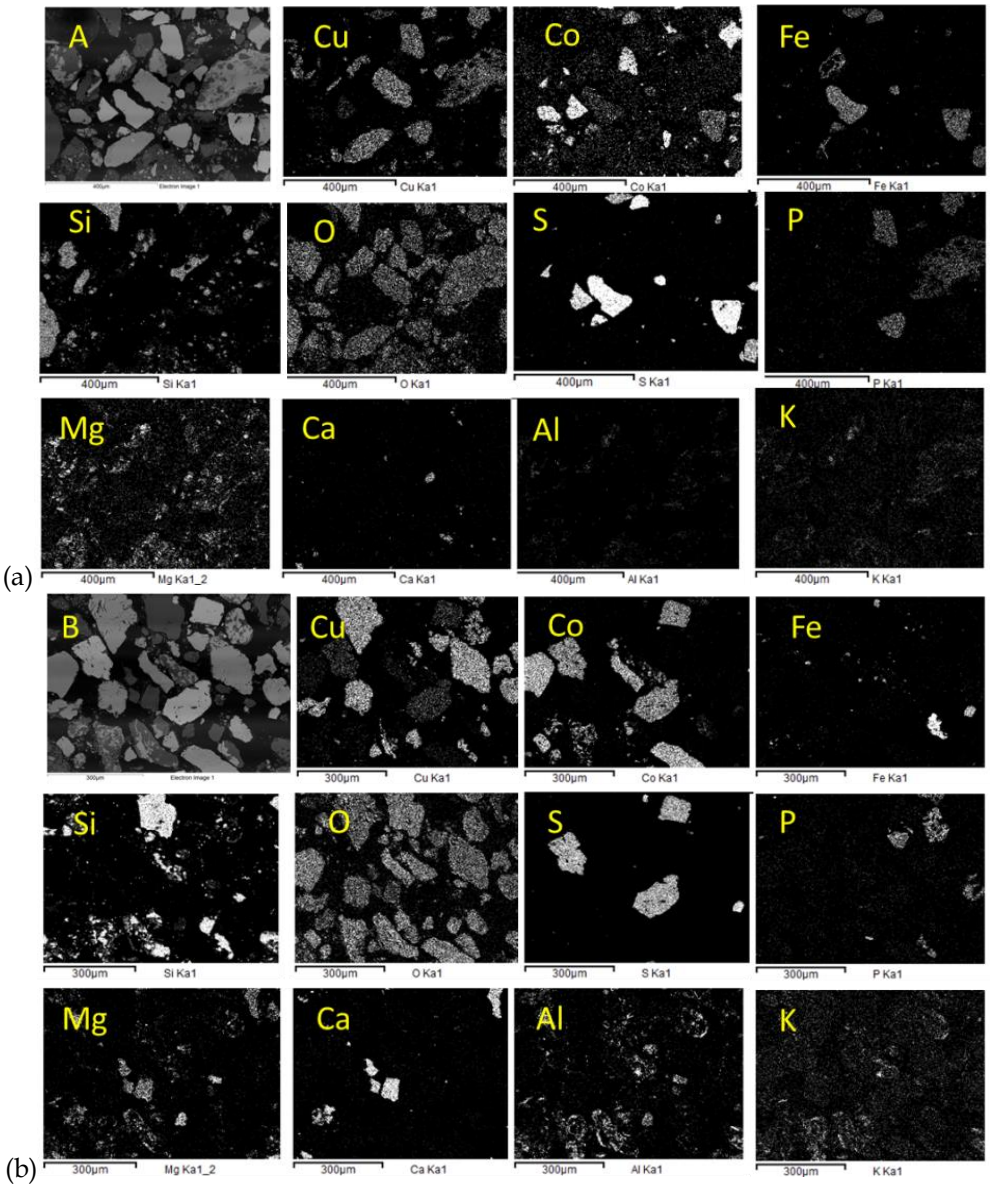

Figure 2: Elemental mapping for the as-received copper–cobalt concentrate (SEM-EDX).

Results on Leaching Tests for the Baked Samples

Effect of acid concentration on metal extraction

To study the effect of acid concentration on baking, the sample was baked at acid concentrations of 15%, 25%, 50% and 75% H_2SO_4. The baking time and temperature were maintained for 1 h and 200 °C, respectively. Each sample was then leached for 1 h at room temperature. The results showing the effect of acid concentration are presented in Figure 3, from which the following important observations were made:

1. more copper was leached out than cobalt or iron, at low acid concentration (less than 50% H_2SO_4);
2. cobalt recovery increased as acid concentration was increased up to 50% H_2SO_4.

From Observation 1, more copper was leached out than cobalt and iron. This is because most of the copper in the sample was in oxide form, which is readily leached in mild acid, while cobalt was mainly sulphide and required more acid to convert it to sulphate (see Table IV).

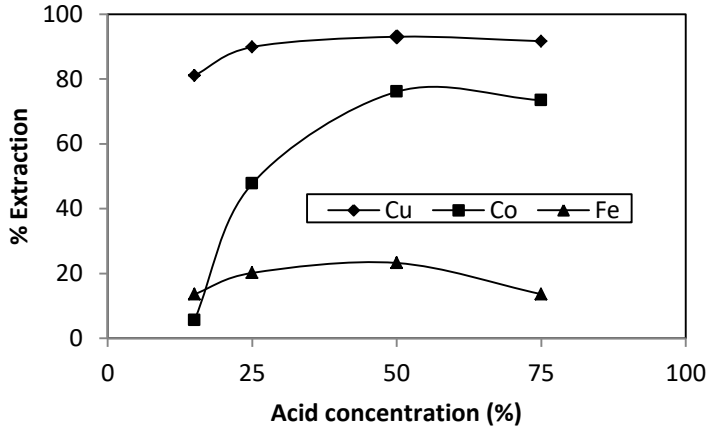

Figure 3: Effect of acid concentration on metal dissolution. (Baking conditions: temp. 200 °C, time 1 h and concentrate:acid ratio 1:1. Leaching conditions: temp. 25 °C and time 1 h.)

The maximum dissolution was observed at 50% H_2SO_4 for all metals (i.e., 93.1% Cu, 76.1% Co and 23.3% Fe). Further increase in acid concentration resulted in a slight decrease in metal extraction. The slight decreases in copper, cobalt and iron extractions may have been due to increased dissolution of other metals in the sample. i.e., calcium, magnesium, as shown in Table V.

Table V: Extent of dissolution of calcium, magnesium and aluminium at different acid concentrations.

Leach liquor	Extent of leaching (%)		
	Ca	Mg	Al
15% H_2SO_4	48.1	75.1	17.4
25% H_2SO_4	57.7	79.9	31.1
50% H_2SO_4	70.4	83.7	42.5
75% H_2SO_4	80.8	90.1	53.8

Effect of baking time on metal extraction

The effect of baking time on metal dissolution is shown in Figure 4. The results indicate that 30 min baking time was sufficient to transform the phases of the mineral concentrate, which could then dissolve 91.4% Cu, 74.1% Co and 21.7% Fe. Metal extraction increased steadily with baking time and reached a maximum at 90 min (i.e., 94.0% Cu, 83.6% Co and 24.8% Fe). Further increase in baking time resulted in decreased cobalt and iron extraction. Similar findings were reported by Gülay (2006), who reported a drop in cobalt and iron dissolutions after 1 h of baking a slag in acid at 200 °C. Many authors have not discussed the reason for this decrease in metal dissolution, however, Safarzadeh *et al*. (2012) explained that such a decrease may be due to formation of insoluble compounds. Insoluble compounds could have formed as the result of decomposition of metal sulphates as the local temperature might be high due to exothermic reactions, as shown in Table II. For example, iron sulphate might have decomposed to insoluble hematite as shown in [Equation 18]:

$$2FeSO_4 = Fe_2O_3 + SO_2 + SO_3. \quad [18]$$

Effect of baking temperature on metal extraction

The influence of baking temperature on metal extraction was studied by varying temperature of the furnace between 100 °C and 350 °C. Results of the effect of baking temperature on metal dissolution are presented in Figure 5. Temperature is particularly important in extraction of metals from sulphide minerals because sulphides are very stable under normal conditions. During sulphide processing, an increase in temperature increases the rate of diffusion resulting in increased oxidation rate of sulphides to soluble sulphates (Yaming *et al*., 2015).

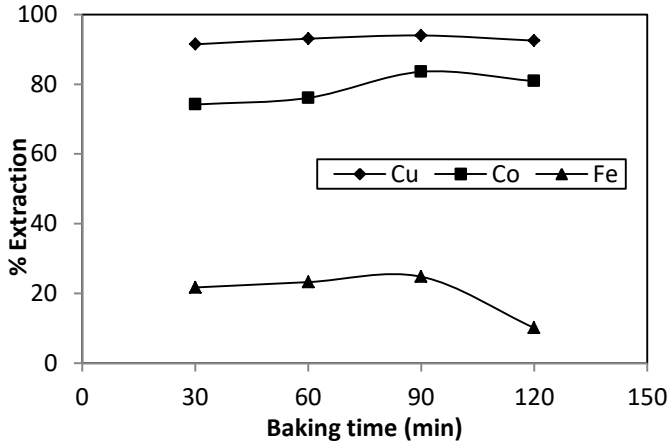

Figure 4: Effect of baking time on metal dissolution. (Baking conditions: temp. 200 °C, acid concentration 50% H_2SO_4 and concencentrate:acid ratio 1:1. Leaching conditions: temp. 25 °C and time 1 h.)

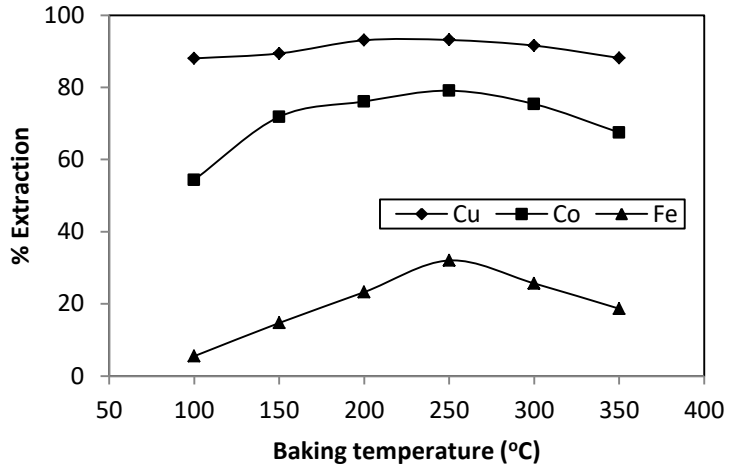

Figure 5. Effect of baking temperature on metal dissolution. (Baking conditions: time 1 h, acid concentration 50% H_2SO_4 and concencentrate:acid ratio 1:1. Leaching conditions: temp. 25 °C and time 1 h.)

As can be observed from Figure 5, cobalt and iron extractions were low at 100 °C, whereas copper extraction was high. From mineralogy analysis, cobalt and iron were mainly in sulphide form; therefore, 100 °C may not have been high enough to transform the sulphides to soluble sulphates. In contrast, copper extraction was high, even at low baking temperature (100 °C). This is because copper in the sample was mainly in oxide form, which easily dissolves in acid at room temperature. Baking temperature of 100 °C simply accelerated the reaction of the oxides with acid, thereby increasing metal dissolution. Increase in baking temperature resulted in increased metal dissolution for both copper and cobalt, as shown in Figure 5. Maximum extraction was observed in the temperature range of 200–250 °C. Increasing baking temperature beyond 250 °C resulted in decreased extraction for copper and cobalt. Arslan and Arslan (2002) explained the reason for this decrease when they stated that there is considerable water formation with either $H_2SO_{4(l)}$ or $H_2SO_{4(g)}$ at temperatures above 200 °C. As the water forms during the reactions, it decreases the concentration of H_2SO_4, which results in low vapour pressure of H_2SO_4 at the same temperatures. Therefore, reactions with liquid H_2SO_4 are more likely to occur up to 200 °C. Additionally, the rate of evaporation of sulphuric acid increases above 300 °C (boiling point of H_2SO_4: 337 °C). Therefore, the decrease in metal extraction beyond 300 °C might have been due to increased rate of evaporation of sulphuric acid, which led to slow or incomplete sulphation of minerals in the concentrate (Meshram *et al*., 2016; Parhi *et a*l., 2015).

Effect of leaching time on metal extraction

After investigating the effects of acid concentration, baking time and baking temperature on metal dissolution, the optimum conditions of 50% H_2SO_4, 90 min baking time and 200 °C baking temperature were selected for further study of influence of leaching time on metal extraction. The effect of leaching time is shown in Figure 6. Dissolution for all metals increased with leaching time. It is also clear from Figure 6 that 30 min leaching time was sufficient to dissolve more than 92% Cu and 83% Co with less than 4% Fe extraction. From the above observation, it can be concluded that 30 min is the best leaching time because there was more copper and cobalt dissolution and less iron going into solution.

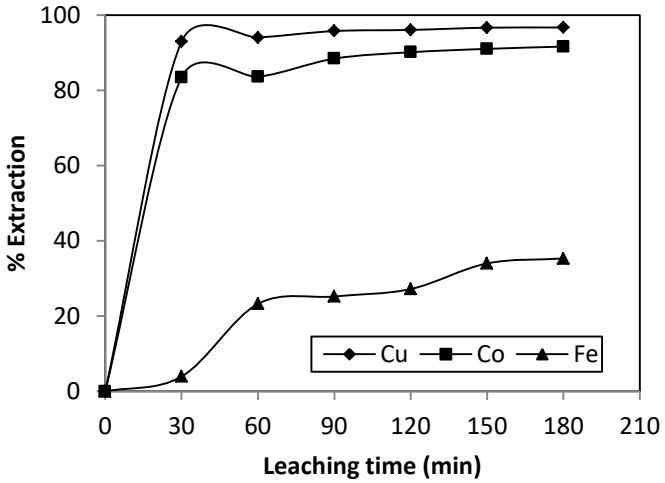

Figure 6: Effect of leaching time on metal extraction. (Baking conditions: temp. 200 °C, time 90 min, acid concentration 50% H_2SO_4 and concentrate:acid ratio 1:1. Leaching conditions: temp. 25 °C.)

It is important to note that, unlike direct leaching, which requires more time to achieve good metal recoveries, acid bake–leach method achieves higher metal recoveries within a shorter period of time. This observation is in agreement with previous studies on acid bake–leach process of other types of material. For example, in their study of metal recovery from spent lithium-ion batteries, Meshram *et al*. (2016) reported recoveries of 78.6% Li and 80.4% Co after leaching the baked sample for 1 h at 75 °C. Therefore, the high dissolution rate is due to fast leaching of the baked products (sulphates). Increase in leaching time beyond 30 min showed a marginal increase in copper and cobalt recovery. This might have been due to slow leaching of incomplete (partially) sulphated baking products after the soluble copper and cobalt were leached out. High extraction efficiencies of more than 96.0% Cu and 90.1% Co were achieved after 2 h of leaching while iron extraction was below 27.2%.

A proposed flowsheet for acid baking followed by water leaching of complex sulphide–oxide minerals is presented in Figure 7.

CONCLUSIONS

This study has shown that it is possible to extract copper and cobalt from sulphide and oxide concentrates. Analysis of the sample showed that both oxide and sulphide minerals were present in the sample; nearly 86% copper was in oxide form while less than 40% cobalt was oxide. Acid baking followed by water leaching proved to be a good method for extracting copper and cobalt from sulphide and oxide concentrates due to its high extraction efficiencies; for example, 96% Cu and 90% Co recoveries were achieved after baking the concentrate for 90 min at 200 °C and leaching in water for 2 h. Leaching time of 30 min proved to be the best because extraction efficiencies for copper and cobalt were high (92% and 83%, respectively), while iron extraction was low (less than 4%). Additionally, acid baking followed by water leaching has the advantage of its lower operating

temperature (< 350 °C) compared with the roast–leach–electrowin process (> 600 °C). Owing to its ability to extract metals from oxide and sulphide minerals, acid bake–leach process can be used for treatment of mixed oxide–sulphide ores/concentrates.

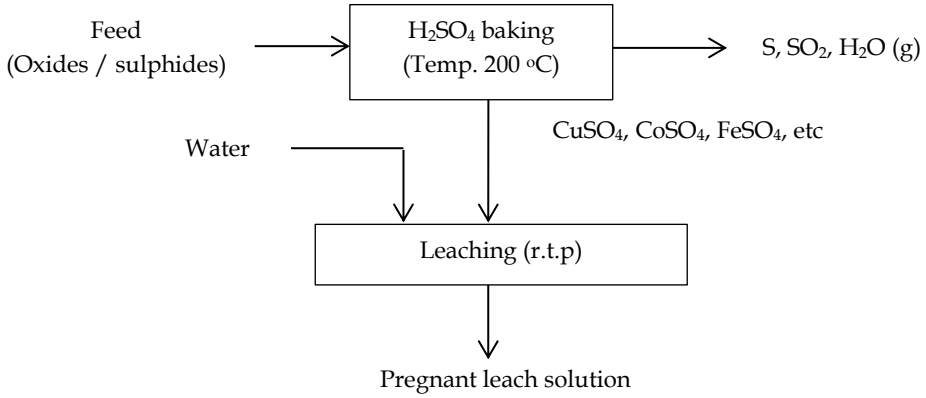

Figure 7: Proposed flowsheet for acid bake–leach process for sulphide and oxide minerals.

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