Gold dissolution and copper suppression during leaching of copper–gold gravity concentrates in caustic soda-low free cyanide solutions

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Abstract
In the cyanidation process, copper–gold deposits containing significant amounts of cyanide soluble copper can lead to high cyanide consumption with low gold extraction. The significant levels of weak acid dissociable (WAD) cyanide must then be destroyed prior to tailings disposal. This increases the cost to the gold mining companies to cover both the extra cyanide consumption in the leaching stage and the additional cost for cyanide recovery/destruction. Therefore, in this study, a selective cyanide leaching process of gold over copper from copper–gold concentrate (also see Oraby and Eksteen, 2014) containing 490 g/t Au and 0.97% Cu present as metallic copper, oxides and sulfides has been investigated. To decrease the cyanide consumption, cyanide is added into the leach solutions to maintain a ratio of cyanide to total reactive copper (CN/Cu) below 2. At low CN/Cu ratio, increasing the pH of solution can lead to the precipitation of solubilized copper as CuO/Cu(OH)2, releasing cyanide ions for further both gold and copper dissolution. A comparison of leaching gold in cyanide–caustic, cyanide–ammonia and conventional cyanidation processes has been made. Higher gold extraction and lower copper concentration in the final leach was achieved in the cyanide–caustic system than in either the cyanide–ammonia or conventional cyanidation processes. The effects of the caustic soda (pH) concentration or cyanide concentration on gold extraction and copper suppression have also been studied. The results show that at high pH (>12), the gold dissolution rate increases significantly in solutions containing caustic soda and cyanate at zero, or very low free cyanide concentration.

1. Introduction
The high cyanide consumption during the hydrometallurgical processing of high copper–gold ores or concentrates often makes the conventional cyanidation uneconomic. Cyanide consumption can be up to 2.3 kg of NaCN for every kilogram of Cu leached (Stewart and Kappes, 2012). The requirement in most cases is to remove WAD cyanide prior to final tailings disposal, usually by chemical oxidation which also adds to the cost of cyanidation. Alternatively other capital and operating cost intensive processes such as AVR and SART are added to recover the copper and cyanide (Muir et al., 1993; Nguyen et al., 1997). Currently many gold mines are facing the problem of treating gold ores containing significant amounts of reactive copper. Alternative process options include the recovery of copper and the recycle of cyanide to the leaching stage, using a variety of processes and technologies which were recently reviewed by Dai et al. (2012) such as AVR and SART, electrowinning and adsorption of copper cyanides on either activated carbon or ion exchange resins. However, these processes are rarely economic. La Brooy (1992) reported that 0.5% soluble copper was the critical level for direct cyanidation in oxide ores, while the critical level is 1% for sulfide ores.

For economic cyanidation applications, the preferred treatment of copper–gold resources is to selectively leach gold over copper rather than leaching both gold and copper followed by cyanide and copper recovery. One of these applications is the cyanide–ammonia process to leach gold over copper from oxidized ores which has been applied for over a century in the treatment of different gold–copper ores (Muir, 2011). The cyanide–ammonia system to leach gold over copper from oxidized ores which has been applied for over a century in the treatment of different gold–copper ores (Muir, 2011). The cyanide–ammonia system to leach gold over copper from oxidized ores has been studied using different gold–copper ores (Drok and Ritchie, 1997; Costello et al., 1992; Muir et al., 1995; La Brooy et al., 1991). However, the treatment of sulfide ores gave poor gold recovery and required higher reagent concentrations (Muir, 2011). It was also found that, due to the loss of volatile ammonia, a significant loss of gold and cyanide was observed due to the precipitation of gold as AuCN2CuCN (Muir et al., 1991; Dai et al., 2005). In addition, there are some environmen-
Some earlier studies focused on the concept of leaching copper–gold ores in cyanide deficient copper solutions. It was reported by Hedley and Kentro (1945) that gold could be dissolved by copper cyanide complexes. Copper–cyanide species (e.g. Cu(CN)\(_5^2\)) can enhance gold dissolution in the cyanidation process under the specific leaching conditions of zero or low free cyanide concentration by release of one or more of the associated cyanide ions (Muir et al., 1989; Van Deventer and Rees, 1999). However, the outcomes of other studies show that gold leaching occurred in air-saturated Cu(CN)\(_3^2\) solutions at a much slower rate than in free cyanide solutions (Breuer et al., 2005; Nugent, 1991).

At zero or low free cyanide concentration, low CN/Cu ratio and high pH, the precipitation of copper as Cu(OH)\(_2\) occurs as shown in Eq. (1) (Vukcevic, 1997). The released cyanide ions (Eq. (1)) can then be involved in further copper and gold dissolution as shown in Eqs. (2) and (3).

\[
\begin{align*}
4\text{Cu(CN)}_2^- + O_2 + 4OH^- + 2H_2O &\rightarrow 4\text{Cu(OH)}_2 \downarrow + 8\text{CN}^- \quad (1) \\
4\text{Cu} + 12\text{CN}^- + O_2 + 2H_2O &\rightarrow 4\text{Cu(CN)}_3^2^- + 4OH^- \quad (2) \\
4\text{Au} + 8\text{CN}^- + O_2 + 2H_2O &\rightarrow 4\text{Au(CN)}_2^- + 4OH^- \quad (3)
\end{align*}
\]

The precipitation of Cu(OH)\(_2\) at low cyanide/copper ratio and high pH was also observed by Dai and Breuer (2009). These authors also found that the pH at which the copper starts to precipitate decreases with increasing cyanide/copper ratio and increasing copper concentration. The increase in hydroxide ions enhances the precipitation of copper at low free cyanide concentration. Vukcevic (1997) concluded that the precipitation of copper as CuO, Cu\(_2\)O or Cu(OH)\(_2\) occurs as a parallel process to gold dissolution. Moreover, the presence of copper oxides enhances the copper precipitation. However, in the cyanide leaching of copper minerals, Cu(I) cyanide complexes can be formed which can then be involved in gold dissolution. In the cyanidation process small amounts of hydroxide ions from the reduction of oxygen can be released in the leach solution as shown in Eqs. (4) and (5).

\[
\begin{align*}
O_2 + 2H_2O + 4e^- &\rightarrow 4OH^- \quad (4) \\
O_2 + 2H_2O + 2e^- &\rightarrow H_2O_2 + 2OH^- \quad (5)
\end{align*}
\]

However, the additional contribution of these hydroxyl ions is insignificant given the low levels of dissolved oxygen available.

From the past research studies that deal with the treatment of gold–copper resources, it is known that the gold dissolution and copper suppression can be enhanced under one or both of the following leaching conditions:

- By leaching at low cyanide/reactive copper molar ratio, most of the cyanide will be involved in copper dissolution and mainly forms Cu(CN)\(_5^2\) and some Cu(CN)\(_3^2\) with no free cyanide left in the leach solution.
- By leaching at high pH (>12.5) using caustic soda, copper precipitates as CuO/CuO/Cu(OH)\(_2\) and releases cyanide ions. In the presence of copper sulfide minerals, leaching gold at high pH is performed by adding caustic soda instead of lime. Adding lime at pH > 11 can decrease the gold dissolution due to the formation of passivating films of gypsum on the gold surface (Kudryk and Kellogg, 1954).

Therefore, taking advantage of the cyanide ions released from copper precipitation at low cyanide/copper ratio and high pH using caustic soda as a pH modifier, the proposed work aims to optimize and enhance the leaching of gold from copper–gold resources containing high reactive copper contents. The research work also aims to reduce both cyanide consumption and copper concentration in the final leach solutions to avoid having to employ either the cyanide destruction or cyanide–copper recovery processes.

2. Experimental

All experiments were carried out using solutions prepared from analytical grade reagents and deionised water. The feed material for these experiments was a high copper–gold gravity concentrate (Falcon centrifugal concentrator product) diluted with silica powder (100% – 75 μm). The particle size of the concentrate used in the leaching experiments was 100% – 150 μm and 80% – 106 μm. The mineralogical composition of the diluted gravity concentrate was determined by the quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN) technique at CSIRO, Waterford, WA. The cyanide and sulfur speciation in the leach solution at various leach times was also carried out at CSIRO, Waterford, WA using High Performance Liquid Chromatography (HPLC). Leaching solution pH was initially adjusted using sodium hydroxide. Unless specified, the cyanide addition was 0.8 g/L NaN\(_3\) (16.3 mM CN\(^-\)). Leaching of gold–copper concentrate at 28.5% pulp density was conducted in a 2.5 L Winchester bottle using a bottle roller at a speed of 150 rpm, at room temperature. Bottles are left open to allow for atmospheric oxygen transfer, to ensure sufficient oxygen for leaching. At specified times, 25 mL samples of the leach slurry were filtered using a membrane filter (pore size 0.45 μm) and the solids returned to the leach. The clear solution was analyzed for gold and copper using Atomic Absorption Spectrophotometry (AAS). S, Si, Pb, Fe, As, Zn and Ni were analyzed by Inductively Coupled Plasma Optical Emission Spectrometry (ICP–OES). The gold content of the feed and residues was determined by fire assay at SGS Australia laboratory in Western Australia.

3. Results and discussion

3.1. Gold and copper dissolution

Preliminary experiments were conducted to evaluate the leaching of gold from a feed containing 490 g/t Au and 0.94% Cu as metallic copper, oxides and sulfides. The mineralogical composition of the feed was analyzed by QEMSCAN and the results are shown in Table 1. The total amount of the reactive copper in the treated concentrate can be estimated by reference to the solubility of different copper minerals in cyanide solution shown in Table 2. From the data shown in Tables 1 and 2, the percentage of the

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Wt, %</th>
<th>Mineral</th>
<th>Wt, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalocite/digenite</td>
<td>0.4</td>
<td>Arsenopyrite</td>
<td>0.00</td>
</tr>
<tr>
<td>Cu–metal</td>
<td>0.3</td>
<td>Quartz</td>
<td>87.1</td>
</tr>
<tr>
<td>Cuprite</td>
<td>0.2</td>
<td>Feldspar</td>
<td>1.3</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>0.2</td>
<td>Calcite</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Bornite</td>
<td>0.1</td>
<td>Dolomite</td>
<td>0.00</td>
</tr>
<tr>
<td>Covellite</td>
<td>&lt;0.1</td>
<td>Ankerite/dolomite</td>
<td>0.2</td>
</tr>
<tr>
<td>Exotic complex Cu–sulfides</td>
<td>&lt;0.1</td>
<td>Rutile/anatase/ilmenite</td>
<td>0.1</td>
</tr>
<tr>
<td>Cu boundaries</td>
<td>0.1</td>
<td>Hematite</td>
<td>0.2</td>
</tr>
<tr>
<td>Pyrite</td>
<td>7.1</td>
<td>Goethite</td>
<td>0.7</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>0.1</td>
<td>Others</td>
<td>1.8</td>
</tr>
</tbody>
</table>

| Minerals and Assays in bold are copper-containing minerals. |
reactive copper in the treated concentrate is 0.81% Cu. Table 3 also shows the elemental analysis of the gold–copper concentrate.

As a comparison, two preliminary experiments were conducted to leach gold from the copper–gold concentrate using solutions containing an initial 0.8 g/L NaCN and pulp density of 28.5% in the presence of 3 g/L NaOH (pH 12.6) and in its absence (pH 10.9, with lime as pH modifier). The gold extractions at these leaching conditions are shown in Fig. 1. It can be seen that the extraction of gold is significantly enhanced in the presence of copper-gold concentrate studied in this paper.

Table 3 also shows the elemental analysis of the gold–copper concentrate. After most of cyanide ions are consumed by copper leaching, and the free cyanide concentration is zero or very low and with the high pH, it is most likely that labile cyanide ions are released, mainly from the higher copper–cyanide complexes as shown in Eqs. 6–8.

\[
\text{Cu(CN)}_4^{3-} \rightarrow \text{Cu(CN)}_3^{-} + \text{CN}^- \quad (6)
\]

\[
\text{Cu(CN)}_3^{2-} \rightarrow \text{Cu(CN)}_2^- + \text{CN}^- \quad (7)
\]

\[
\text{Cu(CN)}_2^- \rightarrow \text{CuCN}^{-1} + \text{CN}^- \quad (8)
\]

The released cyanide ions can then be involved in further leaching of copper (Eq. (2)) and gold (Eq. (3)). In the presence of oxygen, Cu(CN)_2 complex can also be directly involved in the dissolution of gold as shown in Eq. (9) (Vukcevic, 1997).

\[
2\text{Au} + 2\text{Cu(CN)}_2^- + 2\text{H}_2\text{O} + \text{O}_2 \rightarrow 2\text{Au(CN)}_2^- + 2\text{Cu(OH)}_2 \quad (9)
\]

3.2. Cyanide speciation

Cyanide species were analyzed in the leach solutions containing an initial 1 g/L NaCN in the presence and absence of 3 g/L NaOH after 4, 24 and 48 h using HPLC. The cyanide speciation analysis includes total cyanide (CN\textsubscript{T}), free cyanide (CN\textsuperscript{−}), cyanate (CNO\textsuperscript{−}), thiocyanate (SCN\textsuperscript{−}) and weak acid dissociable cyanide (WAD). The results of cyanide speciation in the absence and presence of 3 g/L NaOH are shown in Figs. 3 and 4 respectively. It is clear that the WAD cyanide decreases significantly in the presence of sodium hydroxide (high pH). However thiocyanate and cyanate are higher in the presence of sodium hydroxide. This may be due to the reaction of cyanide with the oxide and sulfide copper minerals in the concentrate as shown in Eqs. (10) and (11).

\[
\text{Cu}_2\text{O} + 5\text{CN}^- + \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} \rightarrow 2\text{Cu(CN)}_2^- + \text{OCN}^- + 2\text{OH}^- \quad (11)
\]

Table 3

<table>
<thead>
<tr>
<th>Element</th>
<th>Au, ppm</th>
<th>Ag%</th>
<th>Cu%</th>
<th>As%</th>
<th>Fe%</th>
<th>Si%</th>
<th>Ni%</th>
<th>Al%</th>
<th>K%</th>
<th>Co%</th>
<th>Pb%</th>
<th>S%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration</td>
<td>490</td>
<td>0.01</td>
<td>0.97</td>
<td>0.19</td>
<td>2.90</td>
<td>46.74</td>
<td>0.02</td>
<td>0.50</td>
<td>0.17</td>
<td>0.09</td>
<td>0.03</td>
<td>2.85</td>
</tr>
</tbody>
</table>

Cyanide soluble minerals in bold in Table 2 also occur in significant proportions in the copper-gold concentrate studied in this paper.

A comparison, two preliminary experiments were conducted to leach gold from the copper–gold concentrate using solutions containing an initial 0.8 g/L NaCN and pulp density of 28.5% in the presence of 3 g/L NaOH (pH 12.6) and in its absence (pH 10.9, with lime as pH modifier). The gold extractions at these leaching conditions are shown in Fig. 1. It can be seen that the extraction of gold is significantly enhanced in the presence of NaOH (pH 12.6) and the gold extraction after 72 h reaches 93.6% but only 16.5% in the absence of NaOH (pH 10.9). The cyanide consumption was only 1.98 kg/tonne of such a copper–gold concentrate as it is well known that for each 1% of soluble copper in an ore consumption was only 1.98 kg/tonne of such a copper–gold concentrate as it is well known that for each 1% of soluble copper in an ore concentration decreases in the presence of NaOH from 374 mg/L after 1 h to 13.5 mg/L after 73 h. On the other hand, the amount of copper precipitated in the absence of NaOH was negligible. The high gold extraction, low cyanide consumption and low copper concentration in the final solution that were achieved using cyanide–hydroxide, is a promising approach to cyanidation of copper ores. In the presence of oxygen, Cu(OH)\textsuperscript{2+} and Cu(OH)\textsuperscript{3+} can be observed that the amount of dissolved copper in the presence of NaOH is significantly less than in its absence. As a result of the precipitation of copper oxides/hydroxides, the copper concentration decreases in the presence of NaOH from 374 mg/L after 1 h to 13.5 mg/L after 73 h. On the other hand, the amount of copper precipitated in the absence of NaOH was negligible. The high gold extraction, low cyanide consumption and low copper concentration in the final solution that were achieved using cyanide–hydroxide, is a promising approach to cyanidation of copper containing gold resources (Nguyen et al., 1997; Sceresini and Staunton, 1991; Tran et al., 1997).

Gold, copper and other elemental concentrations in the final leach solution are shown in Table 4. Total sulfur is much higher in the leach solution at higher pH (NaOH used) than that at a lower pH (no NaOH added).

The enhancement of both gold dissolution and copper precipitation in the presence of NaOH (High pH) under conditions of zero or very low free cyanide can be ascribed to the following mechanisms and reactions:

- At the initial time of leaching, cyanide rapidly dissolves most of the reactive copper (metallic, cuprite, and chalcocite) and forms different copper cyanide complex such as Cu(CN)\textsubscript{4}\textsuperscript{3−}, Cu(CN)\textsubscript{3}\textsuperscript{−}, and Cu(CN)\textsubscript{2}\textsuperscript{−}.

- After most of cyanide ions are consumed by copper leaching, and the free cyanide concentration is zero or very low and with the high pH, it is most likely that labile cyanide ions are released, mainly from the higher copper–cyanide complexes as shown in Eqs. 6–8.
3.3. Sulfur speciation

It is well known that most metal sulfides decompose in cyanide solutions to form different sulfur species including, sulfide, thiocyanate, sulfide, thiosulfate and polythionate ions (Marsden and House, 1992; Breuer et al., 2005). Sulfur species were analyzed in the leach solutions in the presence and absence of NaOH after 4, 24 and 48 h by HPLC using the same procedure described in Breuer et al. (2008). The reactions of cyanide with reduced sulfur species to produce sulfite, sulfate, thiosulfate and thiocyanate are briefly described by Luthy and Bruce (1979) as shown in Fig. 5.

The sulfur speciation includes sulfides, sulfite, thiosulfate and sulfate. The results of sulfur speciation in the absence and presence of 3 g/L NaOH are shown in Figs. 6 and 7 respectively. Not surprisingly, low levels of sulfide ions were present in the cyanide leach solutions in the absence and presence of sodium hydroxide as sulfide ions are rapidly oxidized to different sulfur species. This provides an advantage as the sulfide ions significantly hinder gold when leaching these minerals in free cyanide solutions (Breuer et al., 2005; Dai and Jeffrey, 2006). The sulfate results from the sulfite and thiosulfate oxidation. Sulfite is a known oxygen consumer, and rapidly reacts with dissolved oxygen to form sulfate (Hewitt et al., 2009). HPLC analysis has confirmed sulfate ions are the major product of the sulfide ion oxidation under both leaching conditions. In the presence of NaOH (high pH), the sulfate concentration increases linearly over time (Fig. 7). Thiosulfate and thiocyanate ions were also detected in higher concentrations in solutions containing NaOH. This confirms that the free cyanide ions released due to the copper precipitation can dissolve more of the reactive sulfide minerals and form sulfide ions which then are oxidized to different sulfur species. This cycle of copper precipitation followed by cyanide release and gold and sulfide minerals dissolution continues until most of the copper precipitates from the leach solution.

In the presence of soluble sulfide minerals, such as chalcocite, which generate sulfide ions in solution, the oxidation of sulfide ions to different sulfur species occurs on a conductive surface such as pyrite (Hewitt et al., 2009).

To evaluate the effect of pH modifiers, leaching experiments were conducted using industrial lime, calcium hydroxide (AR) and sodium hydroxide. The results presented in Fig. 8 show that gold dissolution is much faster and more complete in the presence of sodium hydroxide than with industrial lime or AR Ca(OH)₂. The presence of sulfate ions in high concentrations (as shown in Fig. 7) can lead to the precipitation of gypsum leading to passivation of the gold if lime is used.

3.4. Effect of pH (NaOH concentration)

The effect of sodium hydroxide addition and consequently the leaching pH value on the gold dissolution and copper precipitation in solutions containing 0.8 g/L NaCN are shown in Figs. 9 and 10. It

![Fig. 2. Copper dissolution from a copper–gold concentrate in 0.8 g/L NaCN solutions in the absence and presence of 3 g/L NaOH.](image)

Table 4
Gold and impurities concentrations in the final leach solutions containing 0.8 g/L NaCN in the presence and absence of 3 g/L NaOH.

<table>
<thead>
<tr>
<th></th>
<th>Au (mg/L)</th>
<th>Cu (mg/L)</th>
<th>Fe (mg/L)</th>
<th>Si (mg/L)</th>
<th>As (mg/L)</th>
<th>Pb (mg/L)</th>
<th>Ni (mg/L)</th>
<th>S (mg/L)</th>
<th>Zn (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 g/L</td>
<td>203.4</td>
<td>13.5</td>
<td>0.22</td>
<td>21.5</td>
<td>13.5</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>340</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>3 g/L</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>10.45</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>96.6</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>

![Fig. 3. Cyanide speciation of leaching solutions containing 1 g/L cyanide in the absence of NaOH (pH 10.9, by lime).](image)

![Fig. 4. Cyanide speciation of leaching solutions containing 1 g/L cyanide in the presence of 3 g/L NaOH (pH 12.6).](image)

![Fig. 5. Possible reaction of cyanide and oxygen with sulfide ions in aqueous solutions (Luthy and Bruce, 1979).](image)
can be seen from the data shown in Fig. 9 that gold dissolution increases significantly by the addition of sodium hydroxide even as low as 1 g/L OH⁻. Increasing the concentration of OH⁻ up to 5 g/L enhances both the gold dissolution (Fig. 9) and copper precipitation (Fig. 10). Gold extraction of 96.5% can be achieved in the presence of 0.8 g/L NaCN and 5 g/L NaOH by extending the leaching time to 72 h. The copper concentration in the final leach solutions after 72 h in the presence of 3 or 5 g/L NaOH was only about 6.5 mg/L.

3.5. Effect of cyanide concentration

The kinetics of gold dissolution in solutions containing 1 g/L NaOH in the presence of different initial cyanide concentrations...
was studied and the results are shown in Fig. 11. It can be seen that the gold dissolution increases with increasing initial cyanide concentration; however, increasing the initial cyanide concentration also increases the copper dissolution (Fig. 12). It was also found that increasing the initial cyanide concentration from 0.5 g/L to 1.6 g/L increases gold extraction from 61.5% to 78.4%, but the copper concentration in the final leach solution also increases from 99.5 mg/L to 475 mg/L. This observation suggests that any extra cyanide addition during the conventional cyanidation dissolves proportionally more copper than gold. It is well known that cyanide dissolves copper faster than gold in the treatment of copper resources containing reactive copper (Deschenes and Prudhomme, 1997; Jiang et al., 2001; Breuer et al., 2005).

3.6 Effect of high cyanide concentration

It has been shown in Figs. 11 and 12 that at high cyanide concentration (1.6 g/L) and low sodium hydroxide concentration (1 g/L), the dissolution of both gold and copper increase which leads to greater cyanide consumption. By increasing the concentrations of both cyanide and caustic (pH), some interesting results were observed, as shown in Figs. 13 and 14. Gold extraction was significantly enhanced and reached 97.9% after only 48 h leaching in solutions containing 1.6 g/L cyanide and 4 g/L NaOH. The increasing gold extraction in the presence of higher caustic concentrations (97.9% Au extraction at 4 g/L NaOH; 52.92% Au extraction at 1 g/L NaOH; and 13.75% Au extraction at 0 g/L NaOH) can be attributed to the high amounts of copper precipitated in the presence of high caustic (pH 12.85) as shown in Fig 14. The precipitation of copper releases more of the complexed cyanide for gold leaching as shown in Eqs. (1), (8) and (10).

3.7 Cyanide-ammonia and cyanide-caustic systems

In this section the gold dissolution from solutions containing cyanide-ammonia (0.8 g/L NaCN and 4 g/L ammonia), and solutions containing cyanide-caustic (0.8 g/L NaCN and 3 g/L NaOH) were studied. The results show (Fig. 15) that gold initially dissolves rapidly in the cyanide–ammonia and gold extraction reaches 75.6% after 24 h leaching. However by extending the leaching time up to 72 h, the gold extraction was not much improved (84.6%). However, gold extraction in solutions containing cyanide and caustic reached 93.6% after 72 h leaching. This difference in behavior can be attributed to the precipitation of copper and the subsequent release of free cyanide ions as shown in Fig. 16. After the first 24 h of leaching the copper concentration in the cyanide–ammonia solution is lower than in cyanide–caustic solution, with a higher gold concentration for the cyanide–ammonia solution (Fig. 15). The final copper concentrations after 72 h leaching in solutions containing cyanide–caustic and cyanide ammonia were 13.5 mg/L and 358.6 mg/L respectively.

Increasing the cyanide concentration to 1.2 g/L in the presence of 3 g/L NaOH, results in a gold extraction of 83.7% after 49.5 h leaching, as shown in Fig. 17. However, in a solution containing a similar cyanide concentration and 2 g/L ammonia, the gold extraction was only 72.6% at the same time. The final copper concentration in the cyanide–caustic solution was found to be much lower than copper concentration in cyanide ammonia system (Fig. 18). This may be attributed to the volatilization of ammonia during leaching as it was found that the pH of the leach solution decreases from pH 11.7 to pH 9.95 after 72 h. However, in the cyanide caustic system, the pH of the slurry was quite stable at 12.7 during the whole period of leaching. Fig. 17 shows also gold concentration...

Fig. 13. Gold extraction from a copper gold gravity concentrate in the presence of 1.6 g/L NaCN at different caustic concentrations (g/L).

Fig. 14. Copper dissolution from a copper-gold gravity concentrate in 1.6 g/L cyanide solutions at different NaOH concentrations (g/L).

Fig. 15. Gold extraction from a copper gold gravity concentrate in solutions containing cyanide–ammonia (0.8 g/L NaCN and 4 g/L ammonia), and solutions containing cyanide–caustic (0.8 g/L NaCN and 3 g/L NaOH).

Fig. 16. Copper in solution from leaching a copper–gold concentrate in solutions containing cyanide–ammonia (0.8 g/L NaCN and 4 g/L ammonia), and solutions containing cyanide–caustic (0.8 g/L NaCN and 3 g/L NaOH).
in solutions containing cyanide–ammonia–caustic is slightly higher than that in cyanide–caustic. In addition, solution copper concentration was about 13.9 mg/L after 49.5 h leaching in cyanide–ammonia–caustic which is much lower than in cyanide–ammonia (i.e. 234 mg/L).

Table 5 summarizes the gold extraction, copper concentration and cyanide consumption at different leaching conditions.

<table>
<thead>
<tr>
<th>System</th>
<th>Au (%)</th>
<th>Cu (mg/L)</th>
<th>CN consumed (kg/t)</th>
<th>Leaching time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 g/L NaCN + 3 g/L NaOH</td>
<td>93.6</td>
<td>13.5</td>
<td>1.98</td>
<td>73.0</td>
</tr>
<tr>
<td>1.6 g/L NaCN + 4 g/L NaOH</td>
<td>97.9</td>
<td>206</td>
<td>3.90</td>
<td>47.0</td>
</tr>
<tr>
<td>1.6 g/L NaCN + 6 g/L NaOH</td>
<td>21.5</td>
<td>825</td>
<td>4.10</td>
<td>47.0</td>
</tr>
<tr>
<td>0.8 g/L NaCN + 4 g/L NH₃</td>
<td>84.6</td>
<td>428</td>
<td>1.98</td>
<td>73.0</td>
</tr>
<tr>
<td>1.2 g/L NaCN + 2 g/L NH₃ + 3 g/L NaOH</td>
<td>87.9</td>
<td>635</td>
<td>2.98</td>
<td>49.5</td>
</tr>
</tbody>
</table>

4. Conclusions

Selective leaching of gold over copper from a copper–gold concentrate containing significant amounts of cyanide soluble copper has been achieved using cyanide solution and caustic soda as a pH modifier. The results showed that gold dissolution can be enhanced and cyanide consumption can be reduced if the leaching parameters are optimized. The important leaching conditions include cyanide concentration, CN/reactive copper ratio and pH of the leach solution. The study showed that gold extraction was significantly enhanced and cyanide consumption was also significantly reduced by leaching at low CN/Cu ratio and high pH (>12.6). Using caustic soda was found to be more effective than using lime as a pH modifier. At the optimum leaching conditions, the study showed that copper concentration and consequently WAD cyanide in the final leach solutions was very low. This result presents the twin advantages of a relatively low cyanide consumption and reduced cyanide destruction costs.

The results have also shown that leaching gold–copper concentrate in cyanide–caustic solutions in the presence of low or zero free cyanide can be accomplished with high gold extraction (97.6% Au), low cyanide consumption and low copper level in the final leach solutions. Consequently, it can be recommended that leaching gold from gold–copper concentrates or ores in cyanide–caustic solutions may address some of the problems of high cyanide consumption and high copper cyanide (WAD cyanide) in the final leach solutions.

This study also confirms that the phenomenon of the release of free cyanide ions due to the copper precipitation at low free cyanide and high pH. These cyanide ions are then involved in further dissolution of gold and reactive sulfide minerals. Sulfide ions produced are then re-oxidized to different sulfur species.

References


