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## INFLUENCE OF PRE-AERATION ON CYANIDE LEACHING OF A NON-REFRACTORY SULPHIDE GOLD AND SILVER ORE

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**Abstract:** The leaching behaviour of a sulphide gold-silver ore was investigated in terms of a relationship between gold and silver extractions and cyanide consumption. Ninety five Au % and 88.0% Ag extractions were obtained under the determined conditions of 24 h leaching duration, -74  $\mu\text{m}$  particle size, 40% solids ratio, 4  $\text{g}/\text{dm}^3$  NaCN concentration, and 450 rpm stirring speed with NaCN consumption of 3.35  $\text{g}/\text{dm}^3$ . Since the NaCN consumption was higher than in industrial applications,  $\text{Pb}(\text{NO}_3)_2$  and  $\text{H}_2\text{O}_2$  additions and aeration using an air pump were tested during leaching in order to decrease the consumption. While  $\text{Pb}(\text{NO}_3)_2$  addition with aeration caused a decrease in the metal extractions, the individual or combined additions of  $\text{H}_2\text{O}_2$  and aeration could not provide a reduction in the cyanide consumption. Therefore, the effect of the pre-aeration followed by cyanidation was tested. Eventually, applying 4 h of pre-aeration before a shorter leaching duration of 12 h provided 92.0% Au and 90.5% Ag extractions with a reduced NaCN consumption of 2.44  $\text{g}/\text{dm}^3$ .

**Keywords:** nonrefractory sulphide gold–silver, cyanidation, lead nitrate, hydrogen peroxide, aeration

### Introduction

Cyanidation has been in use for recovering gold for almost a century due to its advantages such as simplicity and feasibility (Yang et al., 2010a,b,c). The improvement in leaching kinetics, leaching agent costs, and environmental issues are the major challenges (Liu and Yen, 1995).

The leaching behaviour of gold in the presence of sulphide minerals depends strongly on both the amount of dissolved sulphur and the oxygen concentration in solution (Dai and Jeffrey, 2006). Since the dissolution of sulphide minerals consumes oxygen, a reduction in the gold-leaching rate occurred associated with low dissolved oxygen in the pulp. The equations related to cyanide consumption and passivation of gold with sulphide is as follows (Deschenes, 2005):

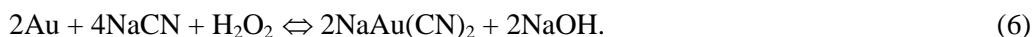
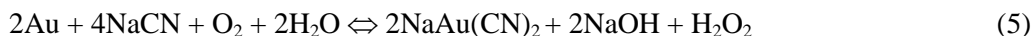


(x = 1, 2, 3..).

The effect of a higher oxygen level in the pulp containing sulphide minerals and their dissolved ions was investigated by Yen and Aghamiran (2002). They suggested that gold-bearing sulphide minerals could be divided into three groups based on their effect on gold leaching. The first group has a negative effect (stibnite, chalcocite, and pyrrhotite). The second group neither seriously reduces nor greatly enhances gold-leaching (pyrite, chalcopyrite, arsenopyrite, and sphalerite) while the third group that improves gold leaching (galena).

According to Weichselbaum et al. (1989), with the addition of trace amounts of sodium sulphide to the cyanide solution, gold leaching is prevented because of the formation of a passive layer of Au<sub>2</sub>S on the gold surface. Similar results were obtained by Lorenzen and Van Deventer (1992) on gold leaching with reactive sulphide minerals like pyrrhotite. In another study, Jeffrey and Breuer (2000) investigated the effect of sulphur species using gold containing 5% silver instead of high purity gold. They suggested that dissolved sulphide reduces the rate of gold leaching by forming a monolayer of sulphur species.

The concentration of cyanide used varies depending on the mineralogical structure of the ore. Generally, the cyanide concentration practiced industrially is in the range of 0.15 to 0.5 g/dm<sup>3</sup>. However, the feed material may contain significant amounts of cyanide consumers and/or high silver content (*i.e.*, >20 g/Mg). In such cases, higher cyanide concentrations, in the range of 2 to 10 g/dm<sup>3</sup> NaCN, are needed. For those ores, gold recoveries may be reached above 90% indicating that the ore is non-refractory (Marsden and House, 2006). Although acceptable extractions can be obtained with those types of nonrefractory ores, cyanide consumption remains high, and it needs to be reduced. Therefore, many studies have been carried out on the basis of cyanide-oxygen interaction, which is described for alkaline cyanide solutions in the Bodlander equations:



In order to speed up the gold and silver dissolution, higher oxygen and cyanide concentrations should be provided but high cyanide concentrations also increase cyanide consumption (Ellis and Senanayake, 2004). The use of oxygen or auxiliary

oxidizing reagents such as sodium peroxide, potassium permanganate, bromine, and chlorine are essential for the dissolution of gold under normal conditions. However, these auxiliary oxidants are not used anymore due to their cost and complications involved in their handling (Yannopoulos, 1991; Guzman et al., 1999; Cruells et al., 2000; Nugenta et al., 1991; Xie and Dreisinger, 2009).

The effect of hydrogen peroxide on gold leaching is a controversy subject. According to Zurilla et al. (1978) and Kirk et al. (1978), the dissolution rate of gold in oxygen-free solutions containing hydrogen peroxide is very slow, and the oxide layer formation on gold surface prevents gold leaching to take place. Other studies showed that the amount of hydrogen peroxide can be significant parameter on gold leaching. The gold leaching rate increased using a concentration of  $0.015 \text{ mol/dm}^3 \text{ H}_2\text{O}_2$  in a solution of  $0.01 \text{ mol/dm}^3 \text{ NaCN}$  at pH 10. On the other hand, the same studies demonstrated that smaller quantities of hydrogen peroxide (*i.e.*,  $< 0.0025 \text{ mol/dm}^3$ ) prevented the gold dissolution rates at higher pH such as  $>11$  (Guzman et al., 1999). Although hydrogen peroxide seems to be the most suitable alternative to atmospheric oxygen, its industrial use is questioned since it has a potential to oxidize cyanide resulting in high cyanide and peroxide consumptions and passivates the gold surface (Knorre et al., 1993; Ball et al., 1989; Habashi, 1967).

On the other hand, gold surfaces can be passivated by sulphide minerals bearing Cu, Fe, and Zn. In the literature, advantages of oxygen and  $\text{Pb}(\text{NO}_3)_2$  for the kinetics of gold dissolution and/or cyanide consumption during the leaching of ores containing sulphide minerals was reported (Weichselbaum et al., 1989; Dufresne et al., 1994; Deschenes and Wallingford, 1995). Deschenes et al. (2002) indicated that lead nitrate addition increases gold leaching kinetics by reducing the detrimental effect of metallic sulphides, and decreases cyanide consumption. Morrison (1994) explained the role of lead nitrate as a catalyst at the surface of the gold preventing passivation. It also inhibits the dissolution of metallic sulphides providing a decline in cyanide consumption. On the contrary, it was found that lead nitrate is detrimental to the cyanidation when not added properly. It can prevent the dissolution of gold and increase cyanide consumption (Deschenes and Prud'homme 1997; Dufresne et al., 1994; Deschenes and Fulton, 1998). It has also been reported that the effect of lead nitrate was especially noticeable at low cyanide concentrations while there was no advantage at high cyanide concentrations (Weichselbaum et al., 1989).

The present research work aims at evaluating the leaching behaviour of non-refractory sulphide gold-silver ore. First, the characterization of the ore sample was initially accomplished by mineralogical analysis. Then, fundamental industrial cyanidation parameters such as leaching duration, cyanide concentration, particle size, and solids ratio were tested. After the optimising the experimental conditions, other parameters such as  $\text{Pb}(\text{NO}_3)_2$  addition, use of oxidizing reagents, and aeration were tested in order to increase gold and silver recoveries and decrease cyanide consumption.

## Experimental

### Material and methods

#### Materials

The gold ore sample used in the present study was obtained from Canakkale Region of Turkey. The sample was crushed below 2 mm using jaw, cone, and roll crushers in turn. A representative sample was taken from the crushed ore for the chemical and mineralogical analyses. The chemical analysis of the gold ore sample is given in Table 1. According to the result of the chemical analysis, the sample assays 18.85 mg/dm<sup>3</sup> Au and 120 mg/dm<sup>3</sup> Ag.

Table 1. Chemical analysis of the gold ore sample

Element	Content (mg/dm <sup>3</sup> )	Element	Content (%)
Au	18.85	Al	1.04
Ag	120	Ca	0.05
As	137.5	Fe	3.51
Bi	511	K	0.03
Zn	79	Mg	0.02
Co	41.8	Na	0.01
Cu	182	S	0.8
Se	51	Si	41

Mineralogical analyses were performed on polished section samples employing QEMSCAN (Quantitative Evaluation of Minerals by Scanning Electron Microscopy). The gold ore sample is dominated by pyrite and quartz, and the remainder is kaolinite. Other minerals are negligible, and including trace amounts of tetrahedrite, tennantite, sulphides, and sulpho-salts. The sample contains particles of well liberated pyrite, moderately inter-grown tetrahedrite, and minor sulphides/sulpho-salts. Sulphides are liberated from non-sulphide phases. Quartz and kaolinite are highly liberated but retain mutual intergrowths. Gold exists in clusters of native gold grains inter-grown with silver sulpho-salts. A significant amount of gold is contained in liberated particles of electrum. The remaining gold occurs as small and encapsulated grains of native gold, electrum, and calaverite. Silver primarily occurs as large chlorargyrite grains and some relic argentite. The association of Au and Ag minerals with pyrite is dominant. Pyrite contains most of the accounted iron, and the remaining iron is mainly locked in Fe-Ti oxides and steel contamination. Almost all the sulphur (99%) comes from pyrite and the remaining sulphur is locked in minor sulphides and some sulphates. Au-Ag occurrences in the sample were observed as native gold (95-100% Au and 0-5% Ag), argentian native gold (80-95% Au and 5-15% Ag), electrum (20-

80% Au and 20-80% Ag), calaverite (AuTe<sub>2</sub>, ~37% Au), chlorargyrite (AgCl), argentite (Ag<sub>2</sub>S), and jalpaite-proustite (Ag<sub>3</sub>CuS<sub>2</sub>-Ag<sub>3</sub>AsS<sub>3</sub>). SEM images of the samples are shown in Figs. 1a-d.

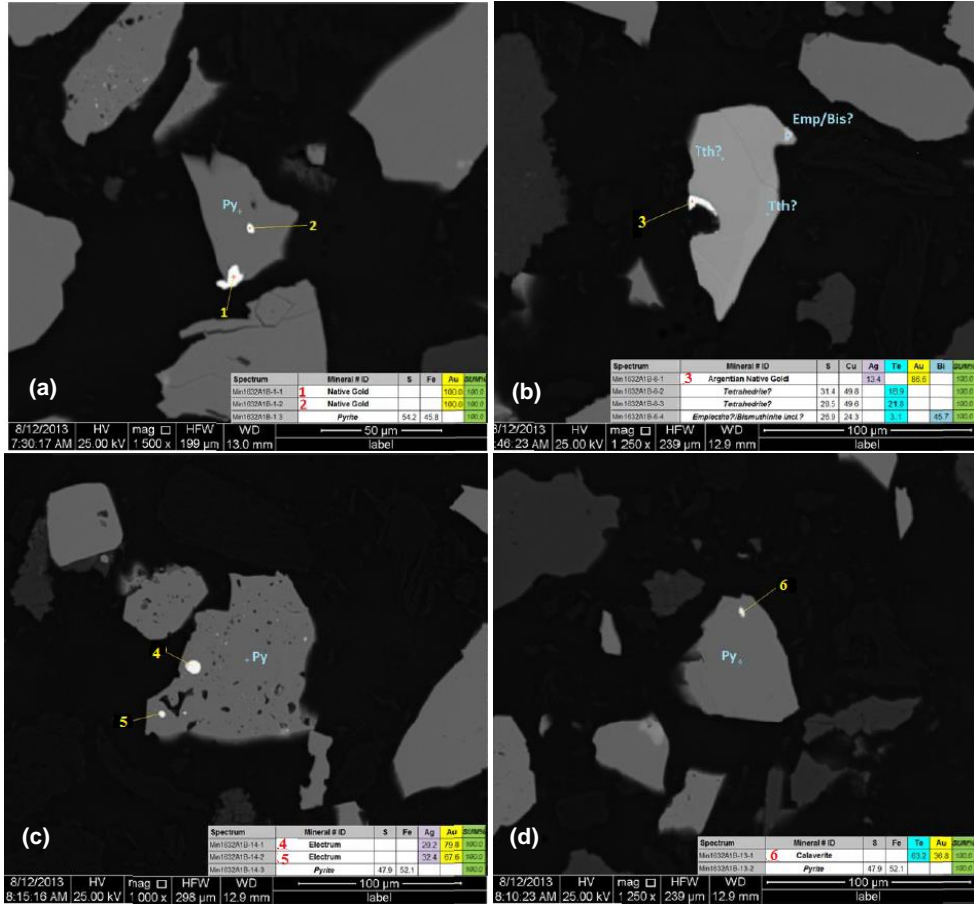


Fig. 1. SEM images of the ore sample (a) 1-native gold, 2-native gold (b) 3-argentine native gold (c) 4-electrum, 5-electrum (d) 6-calaverite

## Methods

The representative sample was ground below 100 μm using a ring mill for the agitation leaching tests, which are conducted in a beaker employing a mechanical mixer (IKA RW20) with teflon coated impeller speed at 450 rpm. Analytical grade NaCN (Merck) was used for the cyanidation process, where lime was used as a pH regulator to keep pH (WTW 3401 pH meter) between 10.5 and 11. After the leaching was complete, the solid-liquid separation was performed with a vacuum filter. In order to determine free cyanide concentration in the pregnant solution, the titration process was performed using standard silver nitrate (0.02 mol/dm<sup>3</sup>) solution and rhodamine as

indicator. The dried leach cake was assayed for Au and Ag employing fire assay method.

In the cyanidation tests, parameters such as leaching duration, cyanide concentration, particle size, and solids ratio were tested. After the conditions were optimized, the effect of  $\text{Pb}(\text{NO}_3)_2$  was investigated in the presence of hydrogen peroxide and aeration. Furthermore, pre-aeration tests were carried out as there is sulphide minerals present.

## Results and discussion

### Effect of leaching time

To investigate the effect of leaching time, the experiments were carried out at different leaching durations (12, 24, 48, and 96 h). All experiments were accomplished with  $1 \text{ g/dm}^3$  NaCN concentration at 10% solids ratio, at room temperature, and  $-100 \mu\text{m}$  particle size. The results presented in Fig. 2 show that the optimum leaching time is 24 h where the extractions of gold and silver are 95.89% and 90.35%, respectively. As seen in Fig. 2, leaching time of 24 h was found to be a critical value since Ag recovery decreased beyond this leaching time. Despite long leaching durations are preferred for silver extraction; probably because of relatively low NaCN concentration it did not increase in this case.

The highest silver recoveries were obtained at leaching times of 12 and 24 h. However, the increasing the leaching time beyond 24 h had a negative effect on Ag extraction. The reason for that situation was thought to be the precipitation of silver sulphide compounds. The silver sulphide layer formed particularly on the surface of electrum could not be oxidized due to the deficiency of dissolved oxygen in pulp. Marsden and House (2006) reported that a silver sulphide layer of 1 to 2  $\mu\text{m}$  thickness forms on the surface of electrum in the presence of sulphide ions. The consisted layer prevents the reaction of electrum with sodium cyanide, and decreases dissolution kinetics of silver.

### Effect of NaCN concentration

NaCN concentrations of 0.5, 1.0, and  $2.0 \text{ g/dm}^3$  were tested to examine the effect of cyanide concentration on the dissolution of Au and Ag. As it can be seen from Fig. 3, 95.9% Au and 90.35% Ag recoveries were achieved at  $1 \text{ g/dm}^3$  NaCN concentration. When  $2 \text{ g/dm}^3$  NaCN was used, a minor increase in the recoveries was obtained for both metals. Since the increase in the recoveries was not significant, it was decided to conduct test at  $1 \text{ g/dm}^3$  NaCN concentration in further studies.

### Effect of particle size

The effect of particle size on the dissolution of Au and Ag was investigated with different particle sizes below 150, 100, 74, 53, and 38  $\mu\text{m}$ . According to the results given in Fig. 4, the metal recoveries increased as the particle size decreased. It is known that the dissolution rate of Au and Ag generally increases as the particles size decreases due to an increase in gold liberation and/or surface area of gold particles as

the result of flattening or physical breakage during grinding except ores containing cyanides (Marsden and House, 2006). As seen from Fig. 4 leaching of the -74  $\mu\text{m}$  particle size fraction yielded recoveries above 90%, and an increase in the recovery of the finer particle is marginal.

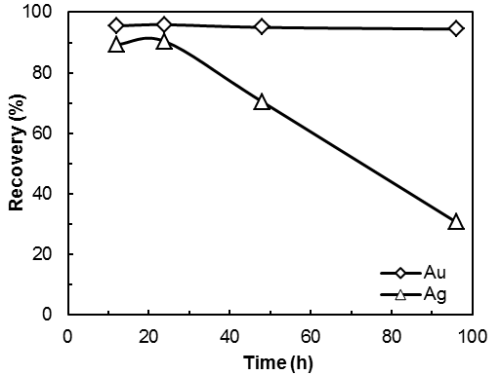


Fig. 2. Effect of leaching time on gold and silver recoveries (1 g/dm<sup>3</sup> NaCN concentration, 10% solids ratio, -100  $\mu\text{m}$  particle size, and 450 rpm stirring speed at room temperature)

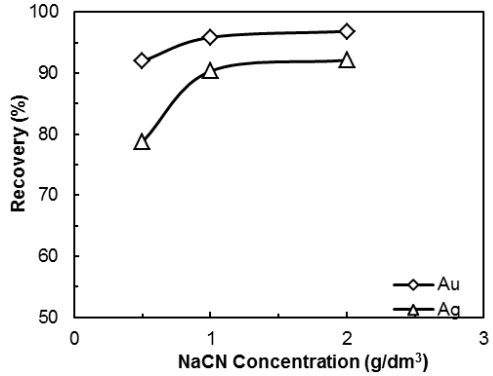


Fig. 3. Effect of NaCN concentration on gold and silver recoveries (10% solids ratio, 24 h cyanidation time, -100  $\mu\text{m}$  particle size, and 450 rpm agitation speed at room temperature)

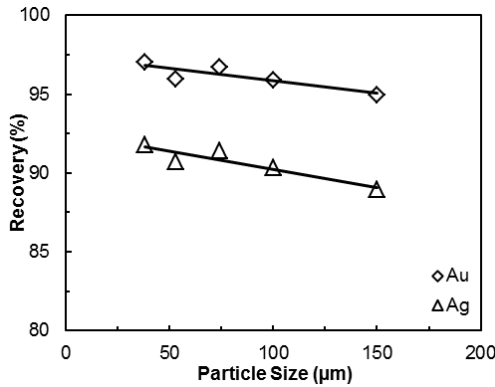


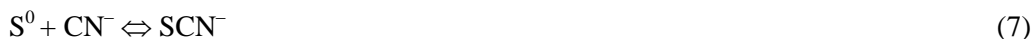
Fig. 4. Effect of particle size on gold and silver recoveries (10% solids ratio, 1 g/dm<sup>3</sup> NaCN concentration, 24 h cyanidation time, and 450 rpm stirring speed at room temperature)

**Effect of solids ratio**

The effect of different solids ratios such as 10, 20, 30, 40, 50% (w/w) on the cyanidation were tested at varying NaCN concentrations under the optimum conditions determined from the previous experiments. According to the results demonstrated in Fig. 5, the highest Au and Ag recoveries were achieved as 98.26% and 95.22%, respectively, at 10% solids ratio and 4 g/dm<sup>3</sup> NaCN concentration.

Even though the highest recoveries were obtained at 10% solids ratio, the leaching is usually performed at higher solids ratios, that is between 35% and 50%, in industrial applications. Therefore, 40% solids ratio with the same NaCN concentration was chosen for the following tests. The optimum leaching parameters at 40% solids ratio were 24 h cyanidation time,  $-74 \mu\text{m}$  particle size,  $4 \text{ g/dm}^3$  NaCN concentration, and 450 rpm stirring speed under atmospheric conditions. Under these conditions, the NaCN consumption was  $3.35 \text{ g/dm}^3$ .

A concentration of  $4 \text{ g/dm}^3$  NaCN seems to be too high compared to the concentration used in industrial applications, which is around  $0.5 \text{ g/dm}^3$ . However, Marsden and House (2006) reported that cyanide concentrations from 2 to  $10 \text{ g/dm}^3$  in the presence of silver contents may be above  $20 \text{ g/Mg}$ . Since the ore sample used in this study contains  $120 \text{ mg/dm}^3$  Ag, the use of  $4 \text{ g/dm}^3$  NaCN concentration would be suitable. On the other hand, the reason for relatively high NaCN consumption may be attributed to the presence of sulphur species, which reacts with cyanide to form thiocyanate, sulphate, sulphide, and polysulphide ions or leads to sulphur coatings on the gold surface. Thiocyanate increases NaCN consumption as seen in the following reactions (Marsden and House, 2006):



The adverse effect of sulphur species on cyanide consumption may be prevented by using  $\text{Pb}(\text{NO}_3)_2$ , oxidizing reagents, and aeration individually or in combination.

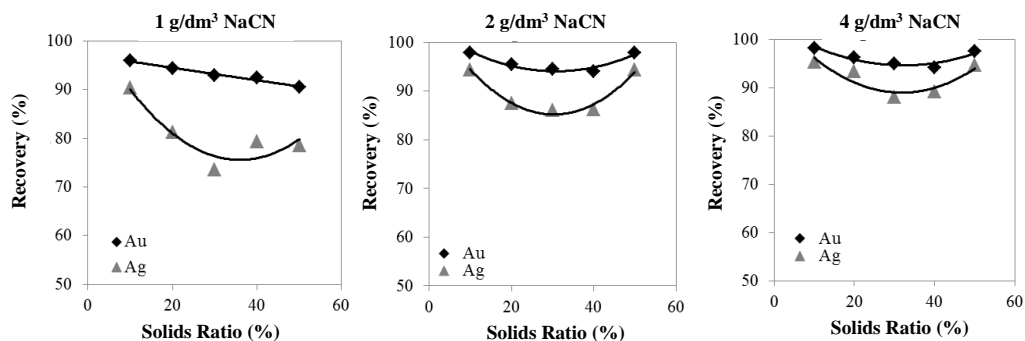


Fig. 5. Effect of solids ratio in the presence of 1-2-4  $\text{g/dm}^3$  NaCN (24 h cyanidation time,  $-74 \mu\text{m}$  particle size, and 450 rpm stirring speed at room temperature) on recovery

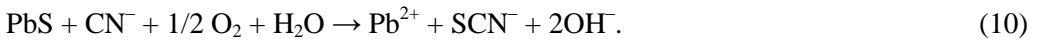
### Effect of lead nitrate

The effect of lead nitrate was investigated in order to improve gold extraction and minimize the cyanide consumption. Different amounts of lead nitrate (100, 200, and



400 g/Mg) were used at a 6 dm<sup>3</sup>/min aeration rate. The leaching conditions were 4 g/dm<sup>3</sup> NaCN concentration, 40% solids ratio, pH 10.5-11.0, and 24 h stirring duration. As it is seen from Table 2, the addition of lead nitrate did not provide any beneficial effect on gold-silver recovery nor cyanide consumption, whereas the lead nitrate addition caused a significant decrease in gold and particularly silver recoveries.

The lead forms an insoluble hydroxide and possibly some lead sulphate depending on pH and sulphate concentration in solution. It is known that in the presence of sulphide minerals, lead nitrate precipitates sulphides. Therefore, formation of a sulphide film on the gold surface is prevented (Breuer et al., 2008, Deschenes et al., 2000; Hedley and Tabachnick , 1968). In the presence of cyanide, thiocyanate is formed due to the oxidation of lead sulphide (Breuer et al., 2008):



In the presence of excess amounts of sulphide species in the leaching solution, sulphide ions react with oxygen much faster to form polysulphides. At that point, oxidation of sulphide ions is accelerated with the existence of lead sulphide in the absence of cyanide in leach medium. As seen from the following reactions, lead sulphide acts as a catalyst in the oxidation reactions (Breuer et al., 2008):

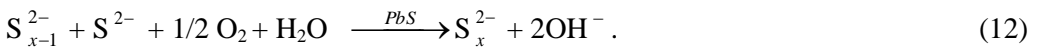


Table 2. Effect of lead nitrate on gold-silver recovery and NaCN consumption (40% solids ratio, 4 g/dm<sup>3</sup> NaCN concentration, 24 h leaching time, -74 µm particle size, and 450 rpm stirring speed at room temperature)

Amount of lead nitrate (g/Mg)	Gold recovery (%)	Silver recovery (%)	NaCN consumption (g/dm <sup>3</sup> )
0	95.03	87.99	3.35
100	62.69	79.30	3.88
200	52.97	44.46	3.88
400	65.93	25.59	3.83

It has been reported by many researchers that the addition of lead nitrate improves the rate of gold dissolution and NaCN consumption due to the presence of excess amounts of sulphur species in their leach slurries. Considering the high NaCN consumption values obtained, it is seen that the dissolved lead(II) ions precipitated sulphur ions to form lead sulphide. However, in the presence of air and cyanide, lead sulphide oxidized leading to thiocyanate formation, and thus leaving little amount of dissolved sulphur species in the leach solutions. Therefore, the use of lead nitrate did not provide any improvement in the results.

### Effect of oxygen

Liu and Yen (1995) reported that the effect of sulphide minerals on the dissolution of gold and silver depended on the sulphide mineral and oxygen contents in solution. Yen and Aghamiran (1998) suggested that oxygenation of the pulp had a positive effect on gold leaching in the presence of pyrrhotite, pyrite, sphalerite, and chalcopyrite. Therefore, the relationship between NaCN consumption, gold-silver recoveries and oxygen addition to the pulp was investigated.

The introduction of oxygen as hydrogen peroxide ( $H_2O_2$ ), at different dosages during leaching was investigated under optimum conditions obtained previously. The results are demonstrated in Table 3. According to the repeated experiment results, it is seen that the test results slightly improved at  $0.005 \text{ mol/dm}^3$   $H_2O_2$  concentration where Au-Ag recoveries were 95.15% and 92.44%, respectively, with  $3.90 \text{ g/dm}^3$  NaCN consumption. When  $H_2O_2$  concentration increased to  $0.020 \text{ mol/dm}^3$ , Au and Ag extractions were obtained as 96.64% and 90.35%, respectively, with  $3.64 \text{ g/dm}^3$  NaCN consumption. The reason for relatively higher cyanide consumption can be attributed to the oxidation of NaCN by  $H_2O_2$ . It seems that  $H_2O_2$  acted as an oxidizing agent rather than an oxygen source.

The leaching tests performed at  $4 \text{ g/dm}^3$  NaCN concentration resulted in high NaCN consumptions. Also, the effect of  $H_2O_2$  addition on lower ( $1 \text{ g/dm}^3$ ) NaCN concentration was investigated. However, the tests showed that metal extraction values remained below 70%.

Table 3. Effect of  $H_2O_2$  addition on gold-silver recovery and NaCN consumption (40% solids ratio,  $4 \text{ g/dm}^3$  NaCN concentration, 24 h leaching time,  $-74 \mu\text{m}$  particle size, and 450 rpm stirring speed at room temperature)

Amount of $H_2O_2$ ( $\text{mol/dm}^3$ )	Gold Recovery (%)	Silver Recovery (%)	NaCN Consumption ( $\text{g/dm}^3$ )
0	95.03	87.99	3.35
0.005	95.15	92.44	3.90
0.010	95.29	91.27	3.80
0.015	96.05	90.93	3.75
0.020	96.64	90.35	3.64

According to Habashi (1967) cyanide concentration and dissolved oxygen directly influence the rate of gold dissolution. The dissolution rate depends on the cyanide concentration at low cyanide concentrations, and it is related to the oxygen concentration at high cyanide concentration:

$$v = 0.5_{CN^-} \delta^{-1} [CN^-] \quad (13)$$

$$v = 2AD_{O_2} \delta^{-1} [O_2] \quad (14)$$

where  $A$  is gold surface,  $D$  is diffusion coefficient, and  $\delta$  is thickness of the boundary layer (Deschenes and Wallingford, 1995).

Oxygen can be introduced into solution by bubbling air into the slurry. It was done at a rate of a 6 dm<sup>3</sup>/min capacity. According to the results given in Table 4, Au and Ag recoveries reached up to 96% and 92%, respectively, in the case of bubbling air only. When the results are compared, the addition of 0.005 mol/dm<sup>3</sup> H<sub>2</sub>O<sub>2</sub> and bubbling air provided similar recoveries. However, a simultaneous usage of air and peroxide caused a detrimental effect on Ag recovery. The reason for that was thought to be the presence of excess oxygen in the medium, which prevented Ag dissolution as in the case of increased amounts of H<sub>2</sub>O<sub>2</sub>. It is known that the dissolved oxygen is appears when hydrogen peroxide decomposes into oxygen and water in solution as follows:



It has been suggested that high dissolved oxygen concentrations may cause passivation of the gold-silver surface due to an oxide layer formation (Cathro et al., 1961).

Table 4. Effect of oxidant types on gold and silver recoveries and NaCN consumption (40% solids ratio, 4 g/dm<sup>3</sup> NaCN concentration, 24 h leaching time, -74 μm particle size, and 450 rpm stirring speed at room temperature)

Oxidant Type	Gold Recovery (%)	Silver Recovery (%)	NaCN Consumption (g/dm <sup>3</sup> )
–	95.03	87.99	3.35
0.005M H <sub>2</sub> O <sub>2</sub>	95.15	92.44	3.90
Air + 0.005M H <sub>2</sub> O <sub>2</sub>	96.07	70.25	3.95
Air	96.36	91.80	3.98

On the other hand, NaCN consumptions had a parallel trend to Au recoveries. The main objective of studying the effect of oxygen enriched medium was to reduce NaCN consumption. However, the results obtained showed that introducing oxygen into the solution during leaching process caused an increase in NaCN consumption and improvement of Au and Ag extractions. Therefore, the effect of pre-aeration was studied to increase further the Au and Ag dissolution.

**Effect of pre-aeration**

The pre-aeration was carried out by bubbling air into the slurry for 4 h at 40% solids ratio. In the course of pre-aeration, NaCN was not added. However, the pH value was kept constant around 10.5-11.0. After finishing the pre-aeration operation, 4 g/dm<sup>3</sup> NaCN was added, and leaching was accomplished for 12, 18, and 24 h periods. The results are presented in Table 5. According to the test results, 12 h of leaching time was found to be sufficient, which provided 92% Au and 90.5% Ag recoveries. Furthermore, NaCN consumption decreased to 2.44 g/dm<sup>3</sup> (Fig. 6). Therefore, the

effect of pre-aeration time as 2 and 8 h followed by a 12 h leaching process was investigated. In the case of 2 and 8 h pre-aeration times, Au and Ag extractions were obtained at 4 h pre-aeration time considerably reduced, with smaller NaCN consumption equal to  $2.04 \text{ g/dm}^3$  and  $1.51 \text{ g/dm}^3$ , respectively.

Table 5. Effect of pre-aeration on gold and silver recoveries and NaCN consumption (40% solids ratio,  $4 \text{ g/dm}^3$  NaCN concentration, 4 h pre-aeration time,  $-74 \mu\text{m}$  particle size, and 450 rpm stirring speed at room temperature)

Leaching Duration (h)	Gold Recovery (%)	Silver Recovery (%)	NaCN Consumption ( $\text{g/dm}^3$ )
12	92.04	90.52	2.44
18	85.28	89.78	3.41
24	71.39	91.52	3.45

It can be suggested that pre-aeration made the leaching environment rich in oxygen and oxidized sulphide species, allowing the gold and silver particles to be exposed. During pre-aeration, NaCN was not introduced into the leaching to prevent NaCN to oxidise. As long as pre-aeration time increased, the oxygen concentration in the leach medium also increased as expected. However, longer pre-aeration times than 4 h had a negative effect on gold dissolution while silver dissolution was not affected. The reason for that the result was thought to be oxide layer formation which caused passivation of the gold surface and inhibited gold leach solution.

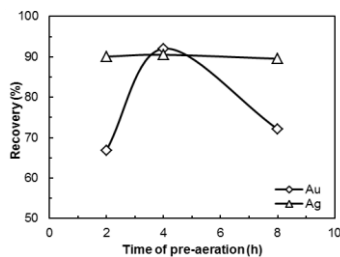


Fig. 6. Effect of time of pre-aeration (40% solids ratio,  $4 \text{ g/dm}^3$  NaCN concentration, 12 h cyanidation time after pre-aeration time of 2, 4, and 8 h,  $-74 \mu\text{m}$  particle size, and 450 rpm stirring speed at room temperature)

## Conclusions

This investigation has characterized non-refractory sulphide gold-silver ore and presented its leaching behaviour under oxidizing conditions. During leaching of the sulphide ores, sulphur species react with sodium cyanide and prevent the formation of a film layer on gold and silver surfaces. Since it was reported in the literature that lead nitrate prevents the formation of a sulphide film on gold and silver surfaces and decreases NaCN consumption, different dosages of lead nitrate were used in this

study. Nevertheless, the dissolved lead(II) ions precipitated sulphur ions and formed lead sulphide, while in the presence of air and cyanide, lead sulphide oxidized simultaneously leading to thiocyanate formation.

Although slight improvements were observed in the gold and silver extractions with H<sub>2</sub>O<sub>2</sub> addition, air injection, and the combination of air/peroxide, NaCN consumption did not reduce because of the oxidation of cyanide by the severe oxidizing conditions. Therefore, an alternative way of aeration prior to cyanidation was performed, which provided the oxidation of sulphide ions rather than cyanide. Accordingly, cyanidation following pre-aeration of the leach slurry for 4 h resulted in above 90% Au and Ag recoveries. NaCN consumption was reduced to 2.44 g/dm<sup>3</sup> from 3.35 g/dm<sup>3</sup>, and the leaching time was reduced from 24 h to 12 h.

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