



## Adsorption behaviour of copper and gold Glycinates in alkaline media onto activated carbon. Part 2: Kinetics



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### ABSTRACT

The kinetics for the competitive adsorption of gold and copper onto activated carbon from synthetic alkaline glycine solutions was studied. The adsorption rate for both gold and copper at the initial stage was modelled using the Fleming  $k_n$  adsorption kinetic model. The coefficient of variation ( $R^2$ ) of the model were close to unity for both gold and copper adsorption data. The effects of pH, free glycine, ionic strength, initial gold and copper concentrations and carbon concentration were assessed on the adsorption kinetics of these two metals. The results showed that > 98% of gold was adsorbed onto activated carbon in 6 h or less under all studied conditions. According to the adsorption tests results, carbon concentration is the only parameter that significantly affected the initial gold adsorption rate. For all other studied parameters, the initial adsorption rate is quite robust, with a few variations in process conditions only affecting it slightly. Activated carbon was found to be very selective for gold glycinate complexes over copper glycinates, with over 99.0% gold adsorbed in 24 h and < 15% copper adsorbed in the same duration under optimum conditions from a solution containing 2 ppm gold and 40 ppm copper.

### 1. Introduction

The two main technologies used for the concentration and purification of alkaline cyanide leach liquors are the carbon-in-pulp (CIP) and carbon-in-leach (CIL) processes. These processes have been described in detail by several authors (Dahya and King, 1983; Laxen, 1984; Nicol, 1984; Stange, 1999). Both these technologies use activated carbon, a highly porous carbonaceous adsorbent with a large internal surface area and consequently high adsorption capacity. The CIP process, the most commonly used process, accounts for 80% of the world's total gold production. Commercially it is suited for processes requiring removal of small amounts of gold (2 ppm) (McDougall et al., 1980). One of the main advantages of the recently developed alkaline glycine system for gold ore leaching is the ability of the gold glycinate complex to effectively adsorb onto activated carbon (Tauetsile et al., 2018; Oraby and Eksteen, 2015). This renders the existing well established CIP and CIL processes useful for the new alkaline glycine system. The impetus for developing the glycine alkaline leach system, as is the case with other studied cyanide alternative lixiviants, is the increasing practical difficulties and environmental concerns arising from usage of cyanide for gold extraction from copper gold ores. The adsorption isotherms for gold-copper glycinate systems have been recently studied

(Tauetsile et al., 2018), but an investigation of the adsorption kinetics of these systems has not been presented to date.

The reaction rate of an adsorption process is one of the most critical evaluation element used during process operation design of an adsorption circuit. This parameter can be enumerated from kinetic experiments analysis. Activated carbon is known to have a complex structure including a surface with heterogeneous properties and pores with a wide variety of size ranges. The rate of reaction is dependent on both the chemical properties of the carbon surface and the pore distribution of the carbon structure. The surface of the carbon is made up of different functional groups formed from heteroatoms such as nitrogen, oxygen, hydrogen and sulphur (Shafeeyan et al., 2010). Oxygen containing groups like carboxylic acid groups and hydroxyl groups make up most of the outer surface also known as the basal plane of the activated carbon (Boehm, 1994; Mattson and Mark, 1971; Puri, 1970). Adsorptive behaviour of activated carbons is to a great extent influenced by the nature of the complexes present on the surface (Otake and Jenkins, 1993). The porous and large internal surface area of the carbon is ascribable to the presence of pores whose size and shape differs substantially. The pores are classified into one of the following three groups depending on the size of their diameter; macropores (> 50 nm), mesopores (2–50 nm) and micropores (< 2 nm) (Daud and Ali, 2004).

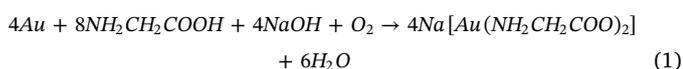
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Coconut shell based activated carbon, the most preferred carbon for CIP and CIL circuits, has the majority of its internal structure characterised by fine pores of radius < 1 nm thereby exhibiting a high internal surface area and by default high adsorption capacity (Hashimoto et al., 1979).

The overall rate of gold adsorption onto activated carbon is believed to be controlled by three major mechanisms: 1) film diffusion: mass transport of gold (I) complex from the bulk of the solution through the hydrodynamic boundary layer encircling the carbon particle. This is a very rapid process; 2) pore diffusion: mass transport of the dissolved gold complex from the solution filling the pores onto the active sites of the carbon; and 3) surface diffusion; migration of the already adsorbed gold complex along the internal walls from the macropores into the micropores (Demopoulos and Cheng, 2004; Jones et al., 1989; Le Roux et al., 1991; Nicol, 1984).

Adsorption by carbon is the proposed method for gold recovery from glycine leach liquors. In the presence of a soluble oxidant like hydrogen peroxide, at moderate to slightly elevated temperatures (23–60 °C), gold can be leached by glycine at neutral to alkaline pHs to form a gold glycinate complex. Using caustic as a pH modifier, the stoichiometry of gold dissolution in alkaline glycine solution is as shown in Eq. (1) (Eksteen and Oraby, 2015):



In addition to containing gold glycinate complexes, leach liquors of pure glycine system are envisaged to contain high concentrations of glycine copper complexes as  $Cu^{2+}$  ions play a strong catalytic role during the leaching process (Eksteen and Oraby, 2015). Moreover, copper is often present as a nuisance element or a metal of economic value and can be therefore also leached (Eksteen et al., 2017a; Eksteen et al., 2017b; Tanda et al., 2017; Oraby and Eksteen, 2014). A sound knowledge of the mechanisms governing the adsorption of these metal complexes on carbon is of outmost importance as it will allow optimum usage of the carbon during solution purification. However a study is still needed to improve knowledge on the adsorption of the gold glycinate complex. The objective of this paper is to investigate the competitive adsorption kinetics of gold and copper in a pure alkaline glycine system under different experimental conditions. Factors whose influence was studied on the adsorption kinetics of these two metals include pH, free glycine concentration, initial gold and copper concentrations and ionic strength of the solution. A kinetic model was also used to fit the experimental data and the corresponding constants evaluated.

## 2. Materials and methods

### 2.1. Sorbent characteristics

Fresh activated carbon, PICAGOLD® G210AS produced by Jacobi Carbons derived from coconut shell was used in the study. Prior to use, the carbon was mechanically sized to  $-2.36 + 2.00$  mm and stored in a sealed container at ambient temperature. The carbon was used as it is with no further treatment. The surface area of the granular carbon as determined by the  $N_2$ BET method was  $894.1286 \pm 46.6926$  m<sup>2</sup>/g.

### 2.2. Adsorbates

Gold glycinate solutions were prepared by leaching a 24ct (99.99%) gold sheet (10 cm × 2.5 cm × 0.03 cm) supplied by A&E Metals in an alkaline glycine solution. The leaching solution was prepared by adding 15 mL hydrogen peroxide (30% w/v, Rowe Scientific) and 15 g/L glycine (> 99%, Sigma-Aldrich) to 500 mL of millipore water. The solution was then buffered to pH 11 using NaOH (ThermoFisher Scientific). In a beaker, the solution containing the gold sheet was then heated to

60 °C and stirred at 400 rpm using teflon coated magnetic stirrer bars. The temperature was maintained at 60 °C throughout the leach process. The beaker was covered to prevent evaporation. Copper was added to the gold glycinate solution as  $CuSO_4 \cdot 5H_2O$  (Asia Pacific Specialty Chemicals). All used reagents were of analytical grade.

### 2.3. Adsorption experiments

Loading tests were performed with the sized fresh carbon to provide a carbon concentration of 2 g/L (0.4 g carbon in 200 ml of solution). The solution contained an initial gold and copper concentration of 2 mg l<sup>-1</sup> and 40 mg l<sup>-1</sup>, respectively unless otherwise stated. The traditional bottle-on-rolls method was used for the experiments. The experimental runs were carried in sealed 2.5 L Winchester bottles (OD 44 cm and L 30 cm) at room temperature (approx. 23 °C). The mixture was bottle rolled for 24 h at 105 rpm with 5 mL samples taken at times, 0, 0.5, 1, 2, 4, 6, and 24 h. At the time of sampling, all samples were taken using the 10 ml Terumo syringe and filtered using a 0.22 μm FilterBio® CA syringe filter to remove any present carbon fines and prevent further adsorption. The copper and gold concentrations in solution were determined by an Agilent 55B AAS model atomic adsorption spectrometer.

## 3. Results and discussion

### 3.1. Adsorption kinetic model

The adsorption results for both copper and gold were modelled using the Fleming M, (1984) k,n method. The Fleming k,n method is the first carbon adsorption model published for gold adsorption. It is defined as:

$$\Delta Auc = k \times Aus \times t^n \quad (2)$$

where  $k$  and  $n$  are model parameters.  $k$  is the kinetic or rate constant ( $h^{-1}$ ),  $n$  is a model parameter representing the adsorption strength,  $t$  is the adsorption time (h),  $Aus$  is gold (or metal) in solution (ppm) at time  $t$ ,  $\Delta Auc$  is gold metal (ppm) adsorbed on carbon from  $t = 0$  up to a certain time  $t$  (ppm). The linearized form of the equation is:

$$\ln\left(\frac{\Delta Auc}{Aus}\right) = \ln k + n \ln t \quad (3)$$

In the following sections, the adsorption kinetics of gold and copper were conducted in an alkaline glycine solution containing 2 ppm Au and 40 ppm Cu at pH 11. The effects of glycine concentration, pH, initial gold and copper concentration, carbon concentrations and ionic strength are evaluated below.

### 3.2. Effect of free glycine concentration

Adsorption kinetic tests for the competitive loading of Au and Cu from a alkaline glycine solutions at glycine concentrations of 1, 5, 10 and 15 g/L were performed. The results are presented in Fig. 1. According to Fig. 1(a), overall Au adsorption recoveries are insensitive to free glycine concentration, with over 99% recovered in the first six hours at various glycine concentrations. For copper, as can be seen from Fig. 1(b), the higher glycine concentration suppresses copper adsorption. However, the dependence of copper adsorption on free glycine concentration is significant between glycine concentrations of 1 and 5 g/L. Beyond 5 g/L glycine concentration, the copper adsorption suppression though observed is not remarkable. This result may be because at high glycine concentration,  $Cu(Gly)_3^-$  which has a less affinity for carbon than  $Cu(Gly)_2$  is formed. At concentrations of 5 g/L glycine and beyond, copper may be present as  $Cu(Gly)_3^-$  hence no effect of glycine beyond 5 g/L glycine concentration. According to Table 1, the model parameter  $k$  is slightly higher at 5 g/L glycine for gold. Generally, the adsorption rate is quite insensitive and doesn't depend much on

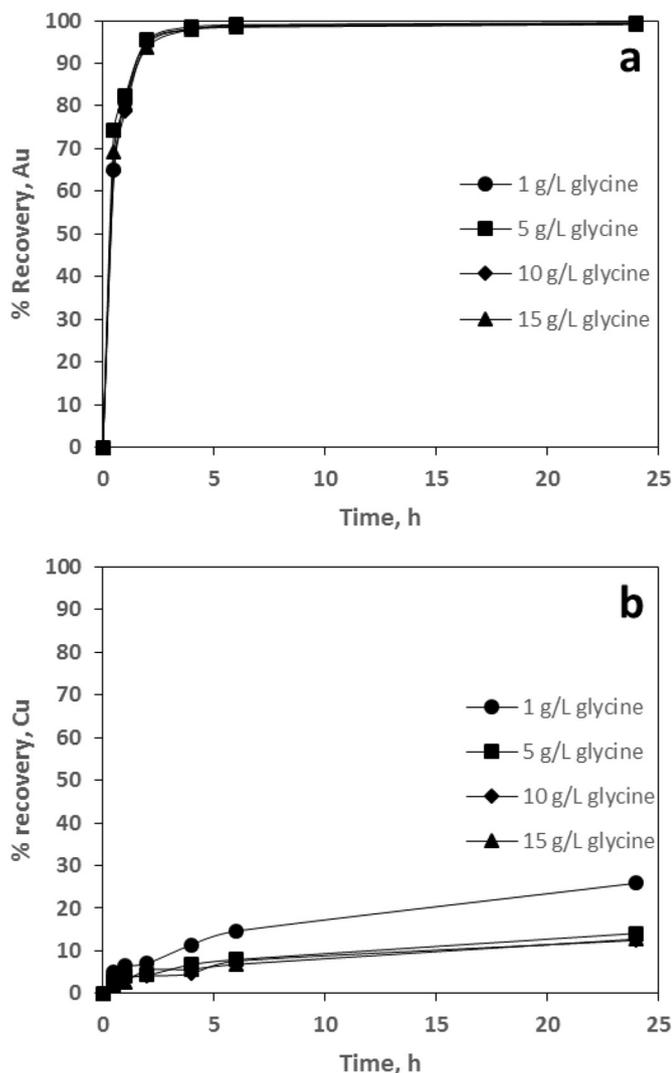


Fig. 1. Adsorption of Au (a) and Cu (b) in glycine solutions at different glycine concentrations ([Au] 2 ppm, [Cu] 40 ppm, pH 11, [Carbon] 2 g/L, 23 °C, 24 h contact time).

Table 1  
Fleming Kinetic model constants for Au and Cu at different free glycine concentration.

Glycine Conc (g/L)	$k$ ( $h^{-1}$ )		$n$		$R^2$	
	Au	Cu	Au	Cu	Au	Cu
1	2696.8	34.5	1.7	0.4	0.99	0.92
5	3491.1	20.4	1.6	0.4	0.97	0.92
10	2509.9	18.3	1.6	0.2	0.98	0.94
15	2756.3	16.0	1.5	0.6	0.98	0.91

solution concentration of glycine for gold. For copper, increased glycine concentration decreases the adsorption rate. Another reason why there is less copper recovered at high glycine concentrations.

### 3.3. Effect of solution pH

Adsorption kinetic curves of gold and copper are shown in Fig. 2(a) and (b). The adsorption kinetics were studied at pH 9, 10, 11 and 12. As can be seen, almost 100% of the gold and < 10% of the copper was adsorbed (recovered) in 6 h for all pH values. Extending the adsorption time increases copper adsorption but does nothing to gold adsorption.

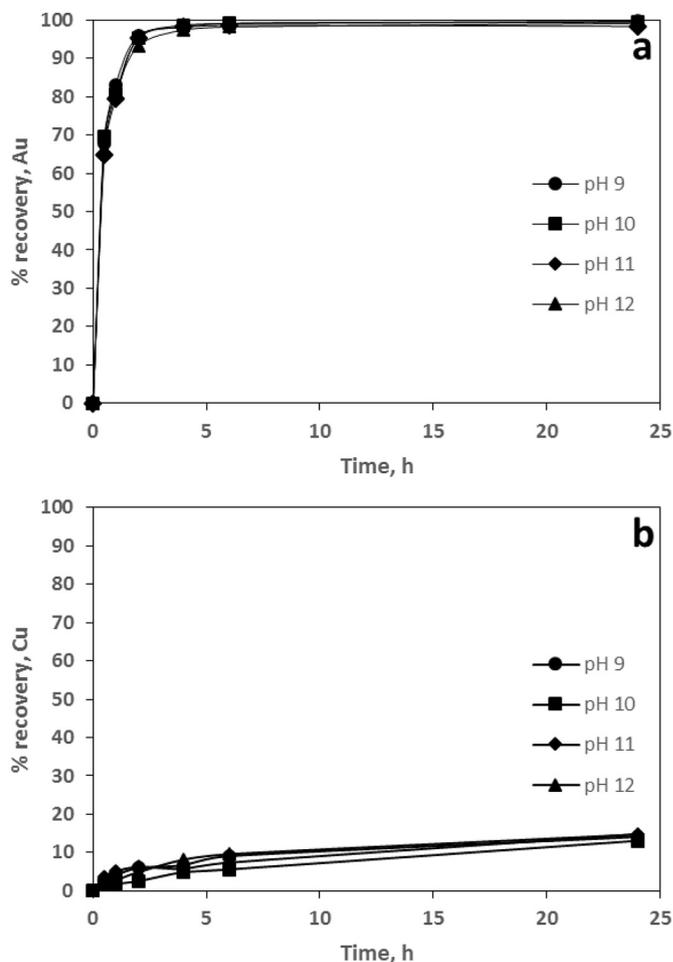


Fig. 2. Adsorption of Au (a) and Cu (b) in glycine solutions at different pH levels ([Au] 2 ppm, [Cu] 40 ppm, [Glycine] 5 g/L, [Carbon] 2 g/L, 23 °C, 24 h contact time).

Table 2  
Fleming Kinetic model constants for Au and Cu at different solution pHs.

pH	$k$ ( $h^{-1}$ )		$n$		$R^2$	
	Au	Cu	Au	Cu	Au	Cu
9	3111.2	21.5	1.6	0.4	0.98	0.96
10	3078.6	10.9	1.7	0.5	0.97	0.91
11	2657.5	25.4	1.7	0.2	0.98	0.75
12	2494.0	16.5	1.4	0.7	0.99	0.98

This suggests focus should be on short adsorption times, which is ideal for carbon-in-pulp systems which run with big leach tanks reactors but small adsorption times. As can be inferred from Table 2, the initial rate constant  $k$  for gold decreases with increasing pH. This is to be expected as an increase in pH means an increase in hydroxide ions and hence increased competition for active adsorption sites which are known to strongly adsorb onto activated carbons (Davidson, 1974). The pH for all experiments was adjusted by addition of sodium hydroxide.

### 3.4. Effect of initial gold concentration

Fig. 3 shows the effect of initial gold concentration on the competitive adsorption of gold and copper glycines onto activated carbon. From Fig. 3(a), it is apparent that, in all cases, after 4 h, the rate of gold loading slowed down considerably. Almost 100% gold was recovered within 6 h for 2, 4 and 8 ppm initial gold concentrations implying gold

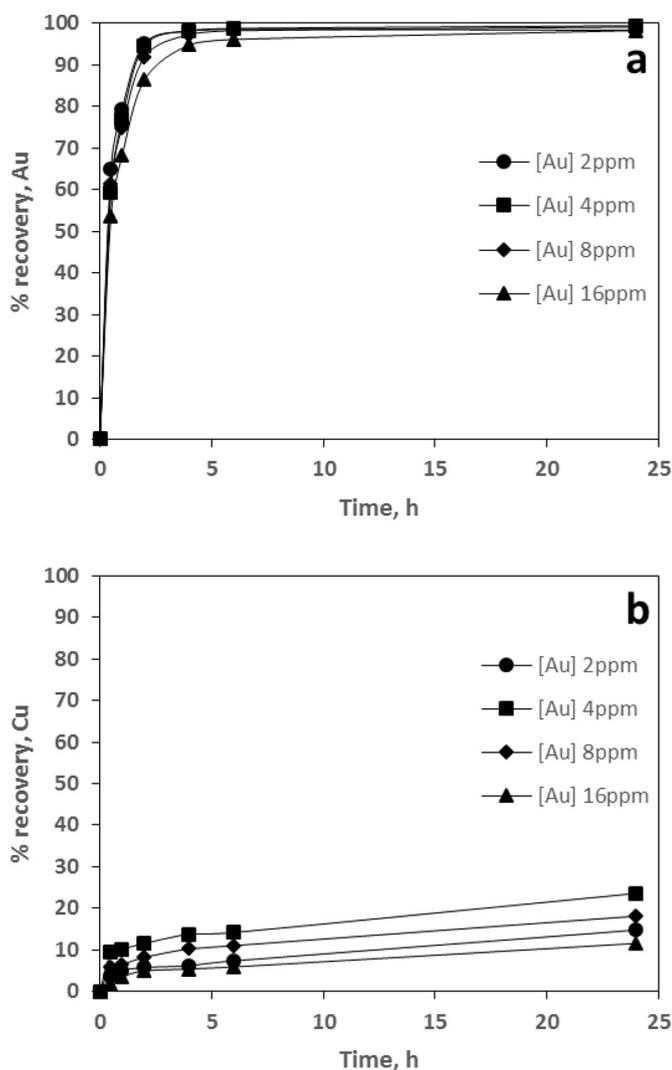


Fig. 3. Adsorption of Au (a) and Cu (b) in glycine solutions at various initial gold concentrations ([Cu] 40 ppm, [Glycine] 5 g/L, [Carbon] 2 g/L, pH 11, 23 °C, 24 h contact time).

Table 3  
Fleming Kinetic model constants for Au and Cu for different initial gold concentrations.

Initial Au Conc (ppm)	$k$ ( $h^{-1}$ )		$n$		$R^2$	
	Au	Cu	Au	Cu	Au	Cu
2	2657.5	25.2	1.7	0.3	0.98	0.90
4	2281.0	59.7	1.8	0.2	0.99	0.97
8	2000.8	37.6	1.6	0.3	0.98	0.98
16	1324.2	15.9	1.4	0.6	0.99	0.89

recovery is independent of initial gold concentration at gold concentrations of 8 ppm and below. There is no obvious trend with copper adsorption as seen in Fig. 3(b). At 2 ppm gold, the copper adsorption is low. Highest copper is recovered at an initial gold concentration of 4 ppm. At 16 ppm, the copper recovery is lowest. This may be explained by increased competition between copper and gold at high gold concentrations. Since activated carbon has a higher affinity for gold than copper glycinate complexes, increasing the gold concentration increases the rate of ion exchange mechanism between copper glycinate and gold glycinate. Copper glycinate is adsorbed and then replaced by

gold glycinate which activated carbon has a high affinity for. As can be seen from Table 3, the initial rate of adsorption for gold decreases with increasing gold concentration. This is counter intuitive as normally for cyanide systems, it has been observed that the initial adsorption rate is bigger at higher gold concentrations (Marsden and House, 2006).

### 3.5. Effect of initial copper concentration

Different copper concentrations of 0, 20, 40, 80 and 800 ppm with 2 ppm Au were used for adsorption tests. According to the results, presented in Fig. 4(a) gold adsorption, in terms of overall recovery is independent of copper concentration. Increased copper concentration increases the initial rate of adsorption,  $k$ , for gold with a maximum rate observed at a copper concentration of 40 ppm which was taken as the optimum concentration for all experiments (Table 4). A high copper system does not necessarily increase overall copper recovery as can be seen from Fig. 4(b). It is however interesting to see that the copper adsorption at 800 ppm Cu is lower than at 20, 40 and 80 ppm Cu. This is an added advantage of the glycine system from a selectivity point of view. Increased copper concentration increases the initial rate of adsorption for copper glycinate complexes.

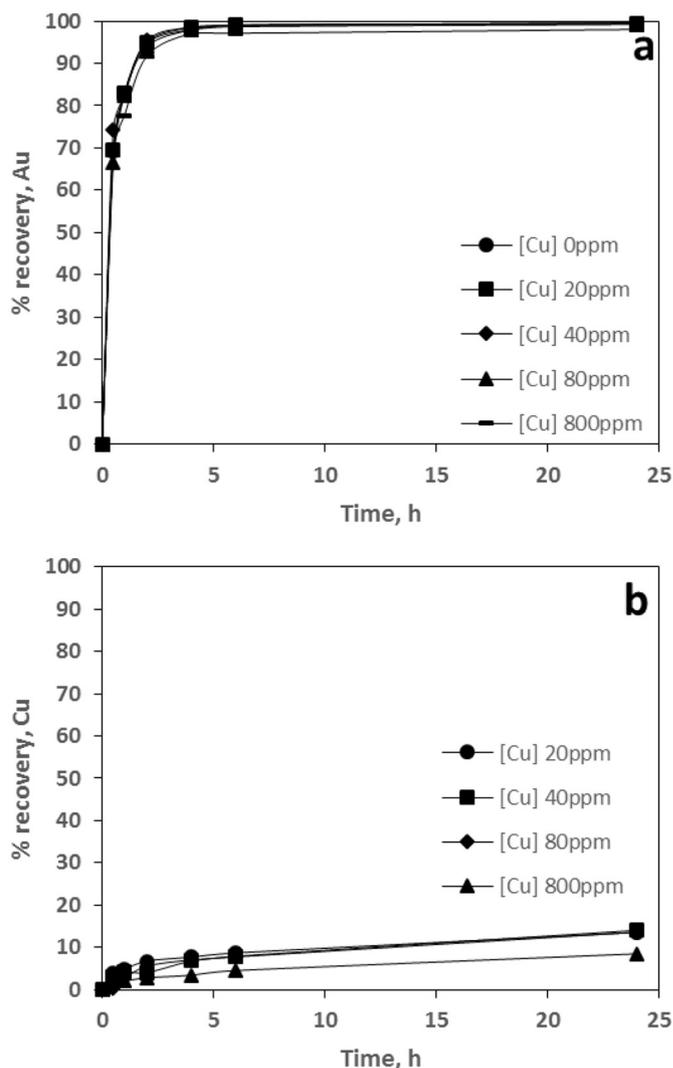


Fig. 4. Adsorption of Au (a) and Cu (b) in glycine solutions at various initial copper concentrations ([Au] 2 ppm, [Glycine] 5 g/L, [Carbon] 2 g/L, pH 11, 23 °C, 24 h contact time).

**Table 4**  
Fleming Kinetic model constants for Au and Cu at different initial copper concentrations.

Initial Cu Conc (ppm)	$k$ ( $\text{h}^{-1}$ )		$n$		$R^2$	
	Au	Cu	Au	Cu	Au	Cu
0	2985.5	–	1.5	–	0.99	–
20	3145.9	26.9	1.7	0.4	0.99	0.98
40	3491.1	20.5	1.6	0.4	0.97	0.85
80	2731.4	9.1	1.5	1.3	0.99	0.88
800	2351.3	11.7	1.3	0.3	0.97	0.98

3.6. Effect of carbon concentration

The rate of loading and overall metals recovery was measured at various carbon concentrations between 2 and 12 g/L (See Table 5). The results shown in Fig. 5(a) indicate that, overall gold recovery is independent of the carbon concentration in solution. The carbon concentration however has a marked effect of the initial gold adsorption rate. Increasing the carbon concentration increases the surface area of the carbon making more active sites available to adsorb metal complexes thereby increasing the rate of adsorption significantly as can be seen from  $k$  values in Table 5. An interesting result is observed at 12 g/L carbon, where the initial gold adsorption rate is exponentially higher than for lower carbon concentrations studied. Notably, the corresponding  $R^2$  for this carbon concentration is quite low (0.6). This might be an indication of the limitation of the model used, suggesting that 12 g/L carbon concentration is probably in the range outside what the Fleming  $k,n$  model can fit. A more complex model structure might be suitable for high carbon concentrations. Since the gold glycine complex is strongly adsorbed onto carbon, preg-robbing ores, which naturally contain carbonaceous material, are not suited for the glycine leach system. The carbon found in preg-robbing ores tends to be very fine resulting in increased surface area and re-adsorption of the gold complex from solution and hence reduction in the overall gold recovery. For copper glycinates, the reverse is true. The initial copper adsorption rate decreases as you increase the carbon concentration. However the overall adsorption increases with increasing carbon concentration. This implies a shorter residence time is appropriate for glycine adsorption system. For a residence time of 3 h for example, as shown by the data in Fig. 5(a) and (b), over 99% gold is recovered while < 8% copper was adsorbed.

**Table 5**  
Fleming Kinetic model constants for Au and Cu at different carbon concentrations.

Carbon concentration (g/L)	$k$ ( $\text{h}^{-1}$ )		$n$		$R^2$	
	Au	Cu	Au	Cu	Au	Cu
2	2657.5	25.2	1.7	0.3	0.98	0.90
4	4749.8	17.2	1.8	0.6	0.99	0.95
8	72,614.1	14.3	3.1	0.7	0.87	0.98
12	374,069.4	19.0	1.7	0.6	0.60	0.99

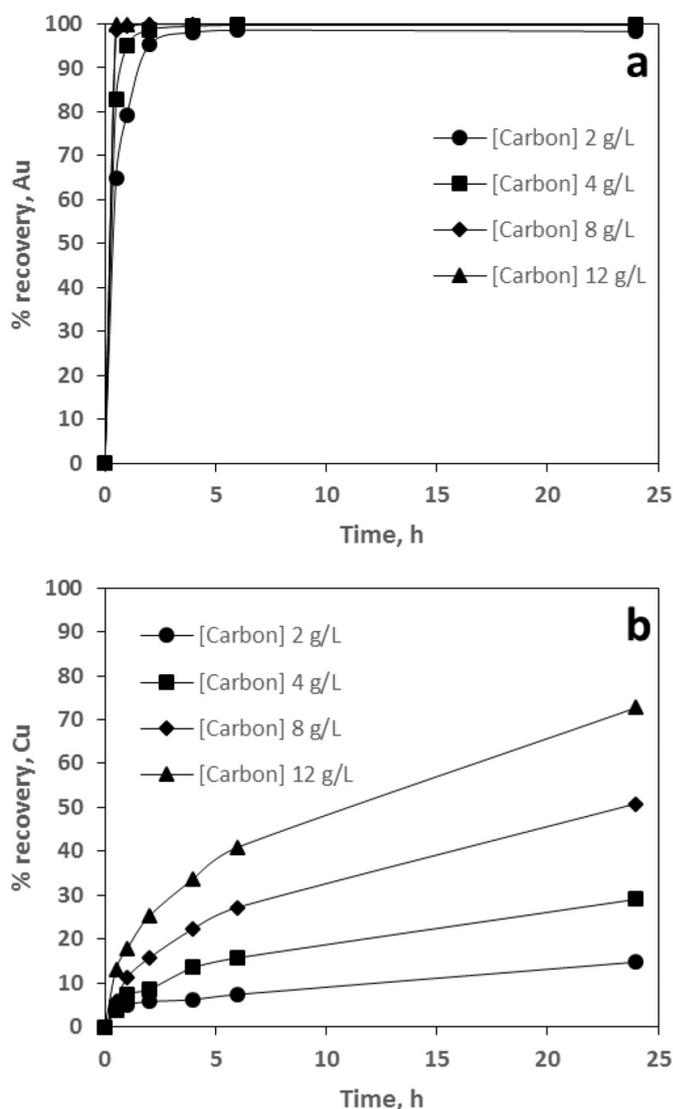


Fig. 5. Adsorption of Au (a) and Cu (b) in glycine solutions at different carbon concentrations ([Au] 2 ppm, [Cu] 40 ppm, [Glycine] 5 g/L, pH 11, 23 °C, 24 h contact time).

3.7. Effect of  $\text{Ca}^{2+}$

The initial rate of metals extraction and overall recovery were determined from solutions of varying ionic strength by addition of the  $\text{Ca}^{2+}$  ion as  $\text{CaCl}_2$ . The results are given in Fig. 6 and Table 6. Table 6 shows that a higher ionic strength neither affects the adsorption rate nor the overall gold recovery in alkaline glycine significantly. The effect on the loading capacity is more pronounced than for the loading rate. When the calcium concentration is increased to a certain level, it causes carbon fouling which reduces metal adsorption.

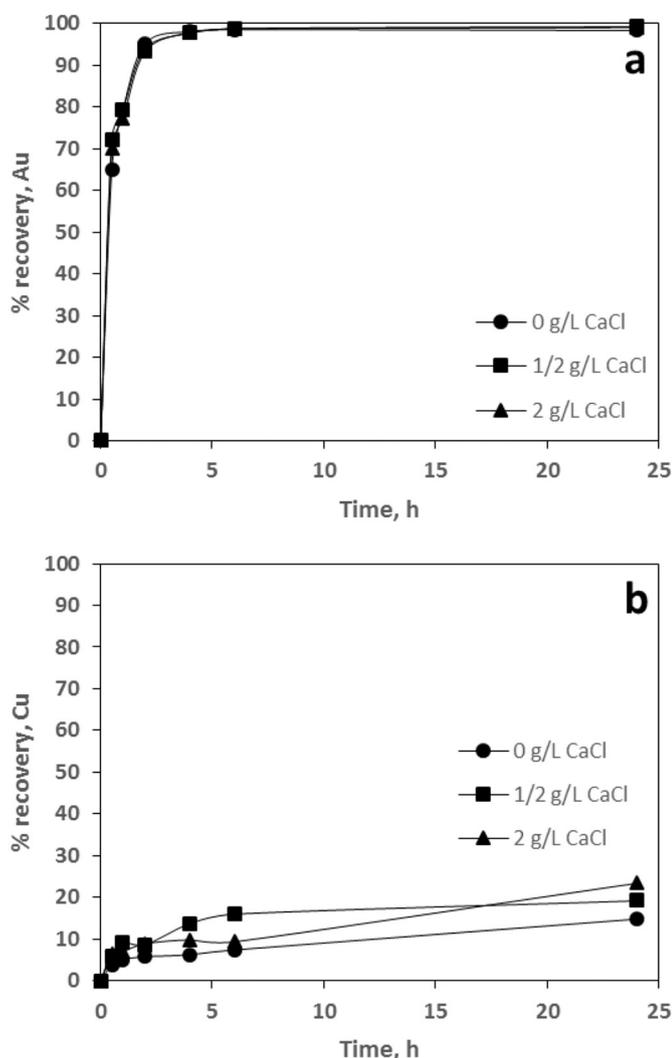


Fig. 6. Adsorption of Au (a) and Cu (b) in glycine solutions at different concentrations of calcium chloride ([Au] 2 ppm, [Cu] 40 ppm, [Glycine] 5 g/L, [Carbon] 2 g/L, pH 11, 23 °C, 24 h contact time).

Table 6

Fleming Kinetic model constants for Au and Cu at different free calcium chloride concentrations.

CaCl <sub>2</sub> Conc (g/L)	<i>k</i> (h <sup>-1</sup> )		<i>n</i>		<i>R</i> <sup>2</sup>	
	Au	Cu	Au	Cu	Au	Cu
0.0	2845.7	25.2	1.4	0.3	0.9616	0.90
0.5	2594.5	44.2	1.5	0.4	0.9549	0.86
2.0	2657.5	40.9	1.7	0.2	0.9799	0.96

#### 4. Conclusions

The data of Au and Cu adsorption recoveries for 24 h adsorption time were modelled by the Fleming *k<sub>n</sub>* adsorption kinetic model. The model was applicable for all cases except the high carbon concentration of 12 g/L. It was shown that the overall gold recovery was insensitive to variation of solution pH, free glycine concentration, carbon concentration, initial Au and Cu concentrations as well as ionic strength of the solution. Over 99% gold was recovered in 24 h for all studied parameters. Copper recoveries increased with increasing carbon concentration with 14.8%, 29.1%, 50.7% and 72.7% copper recovered at carbon concentrations of 2, 4, 8 and 12 g/L respectively. This

observation would seem to indicate that in a gold-copper glycinate system, low carbon concentrations with residence times up to 6 h should be used to ensure that gold adsorption is maximised while copper co-adsorption is minimised. Other studied parameters did not have a marked effect on the percentage copper recovery. The effect of studied parameters on the initial rate of adsorption *k*, are summarised below:

- Increasing pH decreases the initial adsorption rate of gold glycinate complexes. The highest adsorption rate for copper (25.4 h<sup>-1</sup>) occurred at pH 11.
- The highest initial gold adsorption rate of 3491.1 h<sup>-1</sup> was observed at 5 g/L glycine. Increasing free glycine concentration decreased the initial rate of adsorption for copper complexes.
- The initial rate constant for gold is independent of the ionic strength of the solution. However for copper, an increase in the ionic strength of the solution almost doubled the initial adsorption rate. The copper rate constants were 25.2 h<sup>-1</sup> and 44.2 h<sup>-1</sup> for solutions containing 0 g/L and 0.5 g/L CaCl<sub>2</sub> respectively.
- The increasing initial gold concentration in solution decreased the initial gold adsorption rate. The rate value at a gold concentration of 16 ppm was 1324 h<sup>-1</sup> which is half the rate at 2 ppm gold concentration which is 2658 h<sup>-1</sup>. For copper, a maximum adsorption rate (59.7 h<sup>-1</sup>) was noted an initial gold concentration of 4 ppm.
- Increasing the carbon concentration increases the initial gold adsorption rate but decreases the initial adsorption rate for copper.
- Low copper concentrations of 20 and 40 ppm increases the gold adsorption rate. When copper is present in concentrations above 80 ppm, the initial gold adsorption rate is lower than that of a free copper system.
- Based on the results, the suggested operating parameters for gold adsorption from an alkaline glycine media containing 2 ppm Au and 40 ppm copper are 5 g/L glycine concentration, pH of around 10, with 2 to 4 g/L carbon.

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#### References

Boehm, H.P., 1994. Some aspects of the surface chemistry of carbon blacks and other carbons. *Carbon* 32 (5), 759–769.

Dahya, A.S., King, D.J., 1983. Developments in carbon-in-pulp technology for gold recovery. *Can. Inst. Min. Metall. Petrol.* 76 (857), 55–61.

Daud, W.M.A.W., Ali, W.S.W., 2004. Comparison on pore development of activated carbon produced from palm shell and coconut shell. *Bioresour. Technol.* 93 (1), 63–69.

Davidson, R., 1974. The mechanism of gold adsorption on activated charcoal. *J. South. Afr. Inst. Min. Metall.* 75 (4), 67–76.

Demopoulos, G.P., Cheng, T.C., 2004. A case study of CIP tails slurry treatment: comparison of cyanide recovery to cyanide destruction. *Eur. J. Miner. Process. Environ. Prot.* 4 (1), 1–9.

Eksteen, J.J., Oraby, E.A., 2015. The leaching and adsorption of gold using low concentration amino acids and hydrogen peroxide: effect of catalytic ions, sulphide minerals and amino acid type. *Miner. Eng.* 70, 36–42.

Eksteen, J.J., Oraby, E.A., Tanda, B.C., 2017a. A conceptual process for copper extraction from chalcopyrite in alkaline glycinate solutions. *Miner. Eng.* 108, 53–66.

Eksteen, J.J., Oraby, E.A., Tanda, B.C., Tauetsile, P.J., Bezuidenhout, G.A., Newton T. Trask, F., Bryan, I., 2017b. Towards industrial implementation of Glycine-based leach and adsorption Technologies for Gold-Copper Ores. *Can. Metall. Q.*, 1–6, <https://doi.org/10.1080/00084433.2017.1391736>

Fleming, M., 1984. The absorption of gold cyanide onto activated carbon. III. Factors Influencing the Rate of Loading and the Equilibrium Capacity. *J. South. Afr. Inst. Min. Metall.* 84 (4), 85–93.

Hashimoto, K., Miura, K., Yoshikawa, F., Imai, I., 1979. Change in pore structure of carbonaceous materials during activation and adsorption performance of activated carbon. *Indus. Eng. Chem. Proc. Desgn. Develop.* 18 (1), 72–80.

Jones, W.G., Klauber, C., Linge, H.G., 1989. Fundamental aspects of gold cyanide adsorption on activated carbon. In: *World Gold '89 – Society for Mining Metallurgy and Exploration*, pp. 278–281.

Laxen, P.A., 1984. Carbon-in-pulp processes in South Africa. *Hydrometallurgy* 13 (2),

- 169–192.
- Marsden, J., House, I., 2006. *The Chemistry of Gold Extraction*. Ellis Horwood Limited, England.
- Mattson, J.S., Mark, H.B., 1971. *Activated Carbon: Surface Chemistry and Adsorption from Solution*. Marcel Dekker Incorporated, USA.
- McDougall, D.J., Hancock, R.D., Nicol, M.J., Wellington, O.L., Copperthwaite, R.G., 1980. The mechanism of the adsorption of gold cyanide on activated carbon. *Journal of the South African Institute of Mining and Metallurgy* 80 (9), 344–356.
- Nicol, G., 1984. The absorption of gold cyanide onto activated carbon. I. The kinetics of absorption from pulps. *J. South. Afr. Inst. Min. Metall.* 84 (2), 50–54.
- Oraby, E.A., Eksteen, J.J., 2014. The selective leaching of copper from a gold–copper concentrate in glycine solutions. *Hydrometallurgy* 150, 14–19.
- Oraby, E.A., Eksteen, J.J., 2015. The leaching of gold, silver and their alloys in alkaline glycine–peroxide solutions and their adsorption on carbon. *Hydrometallurgy* 152, 199–203.
- Otake, Y., Jenkins, R.G., 1993. Characterization of oxygen-containing surface complexes created on a microporous carbon by air and nitric acid treatment. *Carbon* 31 (1), 109–121.
- Puri, B.R., 1970. Surface complexes on carbons. *Chem. Phys. Carbon* 6, 191–282.
- Le Roux, J.D., Bryson, A.W., Young, B.D., 1991. A comparison of several kinetic models for the adsorption of gold cyanide onto activated carbon. *J. South African Inst. Min. Metall.* 91 (3), 95–103.
- Shafeeyan, M.S., Daud, W.M.A.W., Houshmand, A., Shamiri, A., 2010. A review on surface modification of activated carbon for carbon dioxide adsorption. *J. Anal. Appl. Pyrolysis* 89 (2), 143–151.
- Stange, W., 1999. The process design of gold leaching and carbon-in-pulp circuits. *J. South. Afr. Inst. Min. Metall.* 99 (1), 13–25.
- Tanda, B.C., Eksteen, J.J., Oraby, E.A., 2017. An investigation into the leaching behaviour of copper oxide minerals in aqueous alkaline glycine solutions. *Hydrometallurgy* 167, 153–162.
- Tauetsile, P.J., Oraby, E.A., Eksteen, J.J., 2018. Adsorption Behaviour of Copper and Gold Glycinates in Alkaline Media onto Activated Carbon. In: Part 1: Isotherms. Revised paper under review, *Hydrometallurgy*.