Gold extraction from paleochannel ores using an aerated alkaline glycine lixiviant for consideration in heap and in-situ leaching applications

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ABSTRACT

The decreasing grades of some gold deposits combined with the increasing depths, difficult surface topography, socioeconomic and geopolitical pressures often make the processing of such deposits infeasible by conventional mining, comminution and leaching technologies. To overcome these problems, the application of in-place, in-situ, and heap leaching often represent an optimal solution that minimises the capital and operating costs associated with mining and processing operations. Non-toxic, low cost lixiviants that are stable over an extended range of pH and E_h are required to provide any practical solution to ISL. Since ISL has the inherent benefit of increased natural rock temperature and pressure, glycine-based systems can be considered to extract valuable metals. Based on earlier studies on glycine leaching of pure gold foil, this research shows that Western Australian paleochannel ores are amenable to glycine-based ISL, at elevated alkalinity. The effects of pH, temperature, free glycine, ferric ions, sodium chloride and solids percentages on the kinetics of gold extraction were assessed. More than 85% of the gold can be extracted from ore with solutions containing 15 g/L glycine at pH 12.5 in 336 hours. The presence of ferric ions did not improve the gold extraction, and most of the ferric has been precipitated from the leach solutions, implying that the chosen ferric complex was not sufficiently stable at the operating pH. The impurities dissolution during glycine leach was very low and highly selective leaching of gold over gangue was observed.

Keywords: Glycine; In situ recovery; Heap Leaching; Gold; Paleochannel

1.   Introduction

The global demand on gold derived from low grade deposits have resulted in growing volumes of fragmented, mined and processed rock masses in recent years, as well as very large tailings impoundments. The average gold grade of currently producing mines is of the order of 1 g/t and the average grade of undeveloped deposits is of about 0.7 g/t (Martens et al., 2018). Current producing and yet-to-be developed deposits keep about 85,500 t of gold, 28 % of which cannot be extracted economically utilising traditional techniques (Sebag, 2012). Given today's gold price, the estimated value of gold left in primary resources is about $1 trillion.
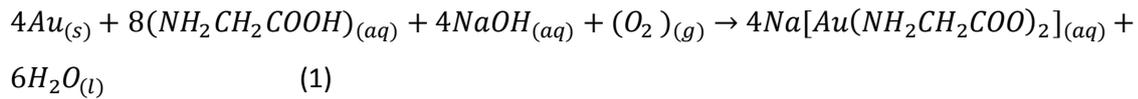
Other than the economic infeasibility of processing low grade gold ores though conventional mine-haul-mill-leach approaches, many factors may make conventional mining unjustifiable. Such factors may include difficult site access, limited access to water, restricted energy and road networks, geopolitical pressures, community concerns and difficult surface topography. The commensurate amount of waste rock and tailings that have to be stored above surface (or the cost of long hole open stoping with paste backfill for example for underground mining) is impeding conventional mining and processing approaches at low grade ores or ore bodies in environments where some of the complicating factors identified above are present. The impact of large-scale visibility, environmental footprints, and waste disposal facilities on local communities is sparking difficulties in unprecedented numbers of jurisdictions. The dissolution and subsequent recovery of valuable minerals from subsurface deposits, which is known as in-situ leaching (ISL) or in-sit recovery (ISR), is receiving renewed attention as a potentially appealing alternative that may require lower capital investment and consumes less energy (mostly haulage and comminution) compared to conventional mining technologies (Johns and Parr, 2010). The process of ISL involves the injection of reactive fluids within an orebody and their collection as a pregnant solution that is then processed to extract the valuable minerals (Karrech et al, 2018). ISL, despite making significant headway in uranium recovery, is not commercially operational for precious metals yet due to the perceived lack of cost effective, stable, low (or non) toxicity lixiviants.

Commonly available lixiviants capable to unlock precious metals from pristine rock masses are highly toxic and/or extremely harmful to adjacent ecosystems. For example, (sodium) cyanide is the most well-known, selective and cost-effective lixiviants of precious metals, but its toxicity and tendency to form by-products such as thiocyanate, cyanate, and ferrocyanide, makes its efficient recycling and reuse difficult. Less hazardous substitutes such as thiourea, thiosulfate–copper–ammonia systems and halides have been tested on natural geomaterials. In particular, iodine-iodide systems that are of lower toxicity are being investigated as potential alternatives (Karrech et al, 2018) but may be too expensive to implement. Recent research work (Eksteen and Oraby 2015; Oraby and Eksteen, 2015)

researched alternative processes that can dissolve precious metals (e.g. gold and silver) using benign reagents such as glycine. E.g. in the presence of oxidant(s) such as cupric ions, air, oxygen and hydrogen peroxide, glycine dissolves precious metals at various levels of pH and temperature. Once pumped to the surface, these metals can be subsequently adsorbed onto activated carbon (Tauetsile et al. 2018a and 2018b) in a carbon-in-column arrangement. Alkaline glycine systems proved to be conducive to gold leaching because they are non-toxic, selective over non-sulphide gangue, recyclable, and of similar or lower cost than cyanide. It is stable over a wide range of pH end Eh and non-volatile (Eksteen et al., 2018) The beneficial attributes of glycine have the potential to revolutionise the mining industry, provided that the reactive transport of pregnant solutions in thermo-porous-materials are investigated further (Karrech et al. 2018). To become fully operational, ISL mining of precious metals has to overcome other major hurdles that include the heterogeneous character of natural geomaterials, the poor infiltration of lixiviants, the mechanical deformations of host rocks, and the energy/matter exchanges. Karrech et al. (2018) modelled the lixiviant-gold-porous ore interaction during in situ recovery for an iodine-iodide system and the insights of that study is forseen to be applicable to glycine based ISR as well. Martens et al. (2012) performed reactive transport evaluations on coarse paleochannel material in pressurised columns using a iodide/triiodide lixiviant system and looked at using electrokinetic enhancement (Martens et al., 2018) by applying a voltage gradient to transport the lixiviant through the orebody.

The in situ leaching of gold was projected in the 1980s at Eastville, central Victoria. The licence of cyanide use in order to recover gold from such deposition was granted, however the approval was cancelled afterwards (O'Gorman et al. 2004). The low costs on the development, processing and infrastructure in in-situ mining/extraction compared with the conventional mining operations (Seredkin et al. 2016) made it very appealing, but the nature of the lixiviant proved to be problematic. Western Australia also has a number of naturally porous deposits where gold was deposited in paleochannels / paleoplacer deposit (Johnson and McQueen, 2001). These gold ores may have been formed by cool deposition in an existing porous structure (Stewart et al., 2017). These deposits may therefore be ideal targets for ISL (or heap leaching) due to their inherent porosity, should an appropriate lixiviant system be available.

Oraby and Eksteen (2015) have shown that the dissolution of gold from pure gold foils and up to date there is no published work was conducted to treat essentially copper-free oxide ores by solutions containing glycine as the only ligand. As copper has been shown by Eksteen and Oraby (2015) to be a catalyst for glycine leaching, the glycine based extraction of gold in the absence of any copper was foreseen to be challenging. The reaction of gold with glycine at neutral to alkaline pH can form a gold glycinate complex using a pH modifier such as caustic or lime, according Equation (1):

$$4Au_{(s)} + 8(NH_2CH_2COOH)_{(aq)} + 4NaOH_{(aq)} + (O_2)_{(g)} \rightarrow 4Na[Au(NH_2CH_2COO)_2]_{(aq)} + 6H_2O_{(l)} \qquad (1)$$

Oraby and Eksteen, 2015 have shown that glycine leaching is much slower than conventional cyanide leaching and that moderate heating is essential during the glycine leaching. In in-situ applications, heat may be supplied by the natural rock interface, geothermal or solar thermal sources at surface. In heap leach applications, economically feasible mild heating (up to 60°C) may be easily achieved by conventional solar thermal technologies, plastic sheeting, black piping and lined ponds as shown by Murray et al. (2017) for copper ores and also proposed by Mwase et al. (2014) for precious metals heap leaching. Therefore glycine based systems could be applied for gold extraction for leach modes such as in-situ, vat or heap leaching applications but is not suitable for agitated tank leaching unless strong oxidants or catalysts are used. Table 1 (Eksteen and Oraby 2015) shows the gold leach rates during the leaching of gold foils in glycine solutions which shows that gold extraction in glycine solutions is favoured by high pH. It can be seen that the gold leaching rate has been significantly increased by increasing the pH from 10.1 to 12.0.

Table 1: Gold leach rates (from pure gold foils) in glycine solutions containing 0.1 M glycine, 1% peroxide at 60 °C as a function of pH (Eksteen and Oraby, 2015).

pH	10^3 x µmol/m^2.s
6.1	3.8
10.1	4.1
11.5	55.6
12.0	104.4
12.8	181.4

Therefore, the main aim of this research work is to evaluate the application of the glycine leach process for gold extraction from essentially copper-free (Cu<0.01%) oxide (S<0.5%) ores at temperatures aligned to ISL leaching with dissolved oxygen/air as oxidant instead of hydrogen peroxide at elevated pH. The effects of glycine concentration, ferric ions, solution pH, solid contents, sodium chloride concentration and temperature are proposed for optimisation to achieve maximum gold recovery.

2. Experimental

2.1. Samples Preparation

Gold samples from a Western Australian paleochannel oxide ore have been used to conduct this research program. The samples were ground to 100% passing 75 μm to evaluate the glycine soluble gold from such ore sample at different leach conditions. The mineralogical compositions of the gold ore samples were analysed by Quantitative X-ray Diffraction (Q-XRD) technique. To calculate the final gold extraction, the feed and final leach residues were analysed for gold by fire assay and for base metals and other elements by X-ray Fluorescence (XRF) technique.

2.2.   Leaching

All experiments were carried out using solutions prepared from analytical grade reagents and deionised water. Unless specified, all experiments were conducted using a heated bottle roller in a controlled temperature incubator. The ore and glycine solutions were placed in a 2.0L plastic bottles. After pH adjustment to the targets, the slurries were rolled at 100 rpm. The lid of leach bottles has a 5 mm hole to allow for air ingress. At different sampling times, the mass of the slurry has been adjusted after monitoring the water loss by evaporation during the leaching. Solution samples of the leach solution at different times were obtained after filtration using a 0.45 μm filter paper. The solids were returned back to the leach bottle and the filtrates were analysed for gold by using atomic absorption spectrometry (AAS). The final leach filtrates were analysed for different elements by ICP-MS to determine gangue element dissolution. All the solid residues were sent in duplicates for gold analysis by fire assay.

3. Results and Discussions

Quantitative X-ray diffraction (QXRD) and X-ray fluorescence (XRF) analyses of the tested ore samples have been conducted, and the results are shown in Tables 2 and 3. The mineralogy showed that quartz is the main mineral present and kaolinite represents about 5% of the tested samples.

Table 2: Bulk mineralogical analysis of the tested paleochannel oxide ore sample

Mineral	Composition	%
Quartz	SiO_2	94
Mica group	$XY_{2-3}Z_4O_{10}(OH,F)_2$	<1
Talc	$Mg_3Si_4O_{10}(OH)_2$	<1
Kaolinite-serpentine group	$M_{2-3}Z_2O_5(OH)_4.nH_2O$	5

The elemental analysis (Table 3) confirmed the oxide nature of the ore and that Si is the main element with some presence of Fe (1%), sulfur (0.25%) and Na (0.44%) which belong to salt minerals in the ore (e.g. the S is as sulfate sulfur, not sulfide sulfur). The presence of soluble salt minerals is a good means of porosity generation during the in-situ leaching which leads to more accessibility to gold particles. The fire assay analysis showed that the feed samples contain an average gold content of 2.45 g/t.

Table 3: Elemental analysis of the tested paleochannel oxide ore sample

Sample	Au	Si	Al	Fe	Ca	Mg	S	Na	Mn	As	Cu	Ni	Pb	Zn
UNITS	ppm	%	%	%	%	%	%	%	%	%	%	%	%	%
Ore Sample	2.45	43.1	1.18	1.08	0.12	0.28	0.246	0.44	0.01	0.002	0.003	0.006	0.003	0.003

3.1. Cyanidation

A preliminary experiment was conducted determine the cyanide -soluble gold in the ore sample and to establish a baseline of leachable gold. This was done using cyanide solutions containing 500 ppm cyanide at pH 11.0. Figure 1 shows the gold is cyanide leachable and 90.1% gold extraction was achieved in 72 hours. The cyanide and lime consumptions during the cyanidation test was 0.152 and 5.33 kg/t respectively. At such a high gold recovery, fast leach rate and low reagent consumptions, cyanidation would be the best option for treating such ore. However, as cyanide in not allowed during in-situ leaching, a cyanide-free alternatives must be considered to recover precious metals.
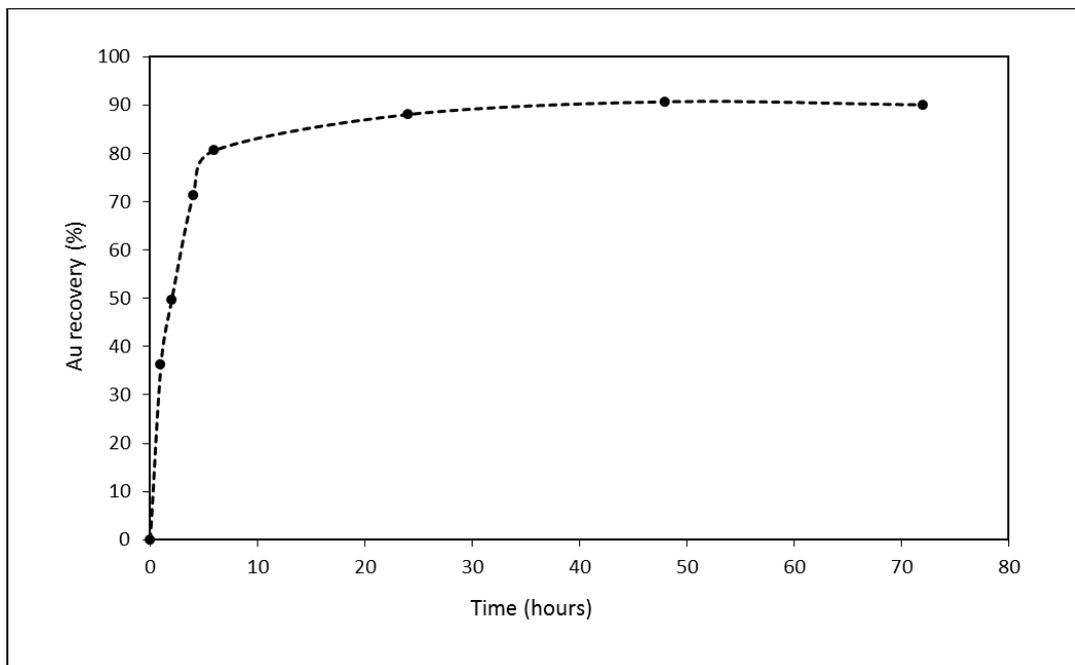

Fig. 1. Gold extraction from a free milling oxide ore by conventional cyanidation at leach conditions of 500 ppm cyanide, 30% solid content, 100% -75 μm, pH 11.0 and room temperature.

The following sections cover the optimisation of leach conditions and parameters for gold extraction by alkaline glycine solutions. The effects of glycine and oxidant concentrations, pH, solid percentages and temperature have also been studied and discussed.

3.2. Glycine leaching (GlyLeach™)

GlyLeach™ process is glycine-based hydrometallurgical process that can be used to extract copper, nickel, cobalt and zinc and other chalcophile metals from oxide, mixed oxide, supergene ores, and primary sulfide ores. Typically alkaline glycine solutions are used for leahcing, mostly in the presence of an oxidant, followed by metal recovery from solution and reagent recycling (Eksteen and Oraby, 2014) and the generalised reaction chemistry is depicted in Equation 2.

$$4\ M + 4(x+1)\ HL + 4\ NaOH + x\ O_2 \rightarrow 4\ Na[ML_{(x+1)}] + 2(x+2)\ H_2O \qquad (2)$$
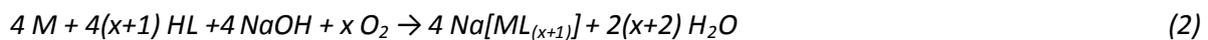
where M is precious or chalcophile metal, x represents the valence of the metal ions and L^- stands for glycine anion ($NH_2CH_2COO^-$). As glycine also dissolves and complexes copper during the leaching, the metal complexes may contribute as additional oxidants for gold leaching besides the presence of oxygen.

3.2. Effect of glycine concentration in the presence of ferric ions

As glycine is the main lixiviant for the gold leaching during the GlyLeach™ process, it is important to evaluate the effect of varying glycine concentrations on gold extraction and impurities dissolution. Fig. 2 shows the effect of glycine concentrations on gold recovery in the presence of 1.0 g/L ferric gluconate complex at pH 11.0. It is not surprising to find gold extraction increases by increasing glycine concentration. The maximum gold recovery was 24.8% after 336 hours at 37.5 g/L glycine concentration. At such concentration, glycine should be recycled back to the leach circuit after gold adsorption on activated carbon otherwise the process won't be economical.
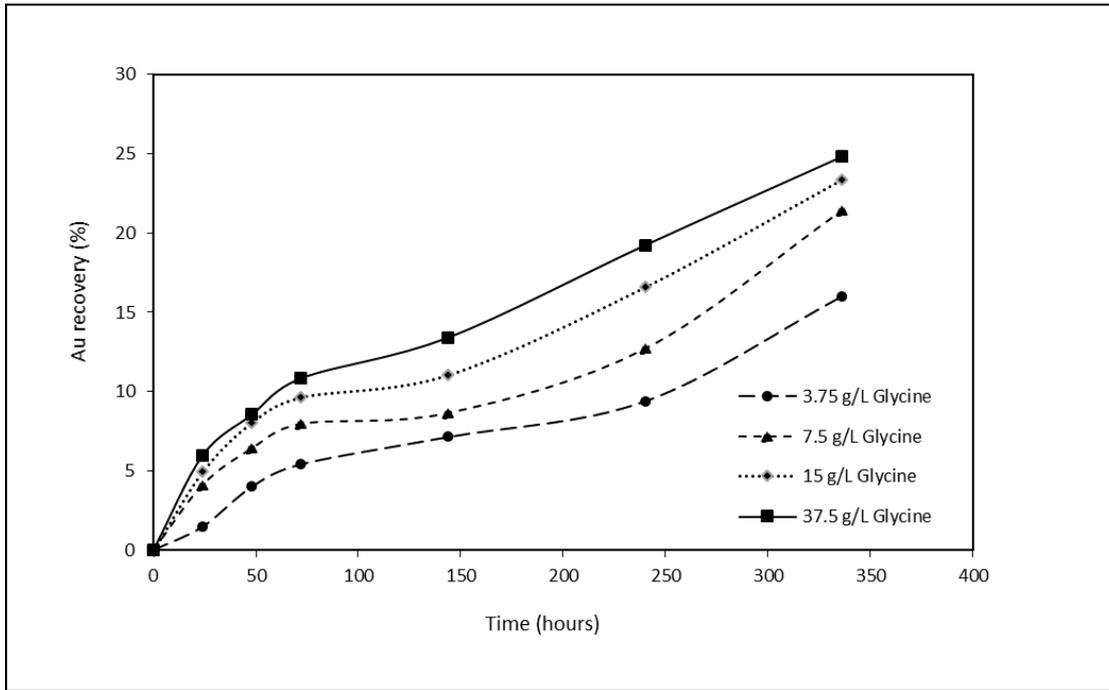
Fig. 2. Effect of glycine on gold extraction from gold oxide ore by Glyleach™ process at leach conditions of glycine, 30% solid content, 100% -75 μm, pH 11.0, 1.0 g/L Ferric and 55 ºC.

Table 4 shows the effect of glycine concentration on the impurities dissolutions. The presence of Cu and Ni glycinate complexes in the leach solutions plays as additional oxidants for the leaching of gold. The data shown in Table 4 indicates that about 40% of the ferric ions have been precipitated as most likely to iron oxides and hydroxides, which can lead to the coverage of the gold surface and partial blocking of the electrochemical reaction.

Table 4. Impurities dissolution at different glycine levels after 336 hours from gold oxide ore by Glyleach™ process (BDL = Below Detection Limit).

Sample	Cu	Co	Fe	Si	Al	Ni	Zn	As	Ca
Glycine, g/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
3.75	4.5	0.2	618	36	11.5	3.2	0.4	BDL	350
7.5	5.7	0.25	632	36	13	3.4	0.6	BDL	542
15	7.1	0.9	589	26	14	3.6	1.2	BDL	720
37.5	8.2	1.6	636	36	18	3.6	3.6	BDL	890

3.3. Effect of ferric ions concentration

In order to understand the effect of ferric concentrations on the gold dissolution, lower levels of ferric ions concentration have been tested. Fig.3 shows the effect of ferric concentration on gold dissolution in alkaline glycine solutions. Interestingly, the leaching process is much faster and overall gold recovery is higher in the absence of ferric ions. The stability of the ferric complex at the operating pH is therefore paramount. Gold extraction reaches 46.5% after 336 hours in the absence of ferric ions compared with
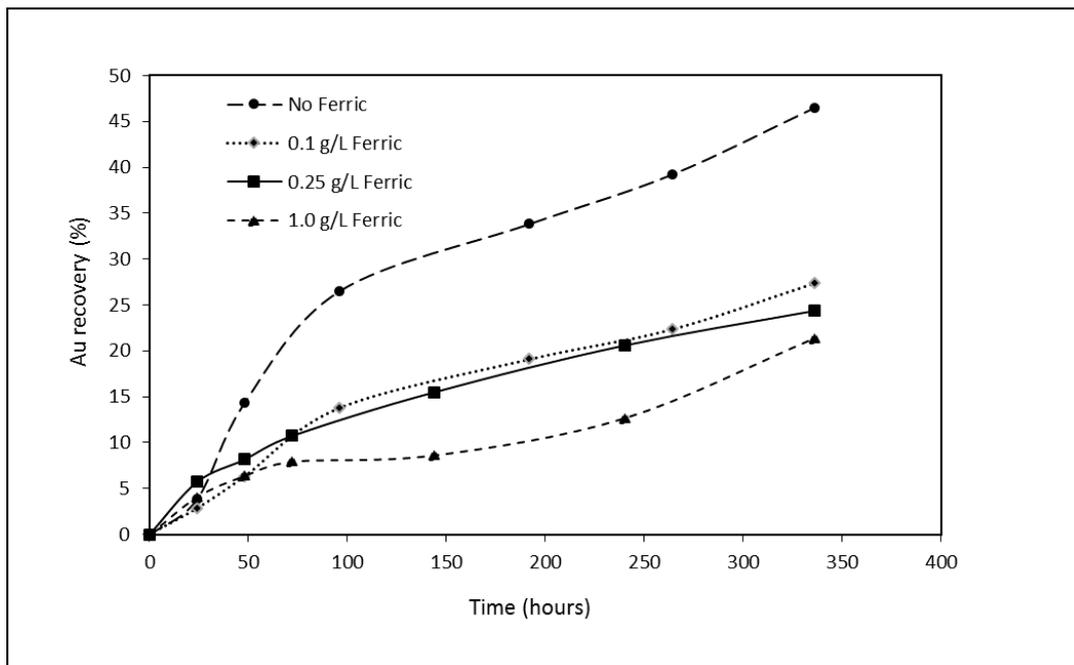
21.4% in the presence of ferric ions at 1.0 g/L.

Fig. 3. Effect of Ferric iron on gold extraction from gold oxide ore by Glyleach™ process at leach conditions of 15 g/L glycine, 30% solid content, 100% -75 μm, pH 11.0, Ferric and 55 °C.

Table 5 shows the iron analysis in the final leach solution and the mass of precipitated iron at different ferric concentrations. The results shown in Table 5 indicate that the lower gold extraction in the presence of ferric ions may result from the iron precipitation from the leach solution on the gold surface. According to this result, the rest of the leach parameters were conducted in the absence of ferric ions considering oxygen, cupric and nickel glycinate are sufficient oxidants for the reaction of gold dissolution in glycine solutions.

Table 5: Iron precipitation during the leaching at different ferric concentrations

Fe, mg/L (Initial leach solution)	Fe, mg/L (final leach solution)	Fe precipitate, mg
0	0	0
100	2.5	43.8
250	32	109
1000	589	205.5

3.4. Effect of pH

The effect of leach solution pH on gold extraction has been studied at different levels as shown in Fig. 4. It can be seen that there is a significant effect of increasing the leach pH from 10 to 11.0 and from 11 to 12. The pH adjustment was performed with calcium hydroxide/quicklime. Gold extraction increases from 22.4 to 46.5% and then to 72.2% by increasing the pH from 10 to 11 and to 12 which

corresponds to the gold leaching behaviour from pure gold foil. A leach extraction of 86% could be achieved at a pH of 12.4 after 336 hours. It is clear that a plateau of extraction was still not achieved even after 336 hours for any of the pH conditions and demonstrates that the cyanide soluble extraction can be approximated under suitable conditions. The previous research study has proven gold extraction in glycine solution favours the high pH due to the high stability of gold glycinate and the formation of hydroxide radicals at high pH. A pH of 12 was subsequently selected as the leach pH for the remainder of the study. According to Nowicka et al. (2010), the hydroxide radicals can accelerate the gold dissolution from a polished gold surface. Additionally, the cathodic reaction of oxygen reduction can generate hydrogen peroxide (Eq.3) which in consequently produces hydroxide radicals (Suess et al., 1997) according to Eqs. (4, 5 and 6).

$$4O_2 + 2H^+ + 2e \rightarrow H_2O_2 \tag{3}$$

$$H_2O_2 + OH^- \rightarrow H_2O + HOO^- \tag{4}$$

$$HOO^- + H_2O_2 \rightarrow H_2O + O_2 + H_2O \tag{5}$$
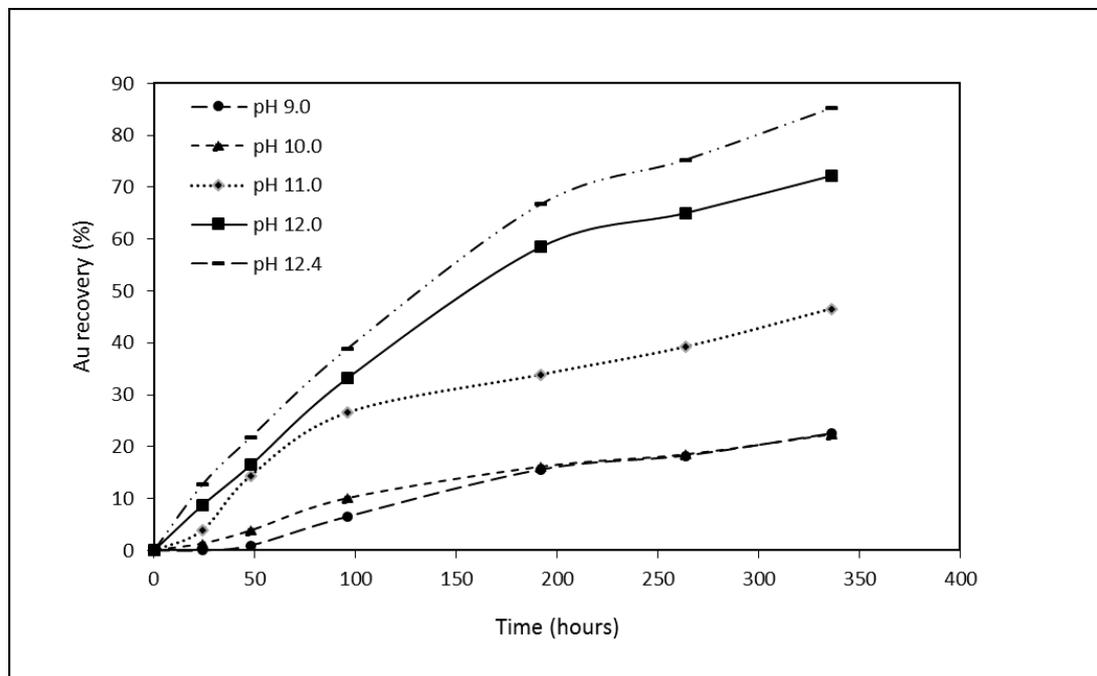
$$H_2O_2 \rightarrow 2OH^. \tag{6}$$
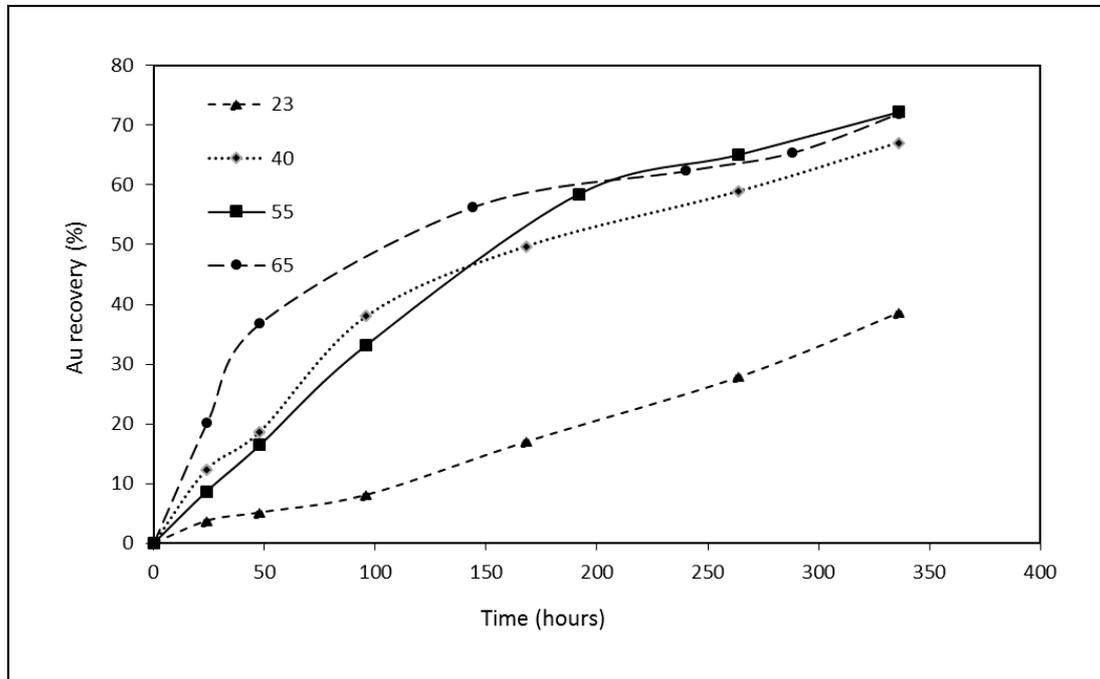

Fig. 4. Effect of pH on gold extraction from gold oxide ore by Glyleach™ process at leach conditions of 15 g/L glycine, 30% solid content, 100% -75 μm, pH, and 55°C.

3.5. Effect of temperature

According to Oraby and Eksteen (2014a and b), Oraby and Eksteen (2015) and Eksteen and Oraby (2015), temperature is a key parameter in the gold dissolution by glycine. It has been reported by Oraby and Eksteen (2015) that the activation energy of gold dissolution in alkaline glycine solution is about 50 kJ/mol. This indicates that gold dissolution with glycine is a chemically controlled reaction.

Different levels of temperature were tested to evaluate the effect of temperature on gold extraction from the tested ore. Fig. 5 shows the gold extraction at different levels of temperature, it is clearly confirmed that the temperature significantly improves the gold extraction. The gold extraction increases from 38.7% to 71.9% by increasing temperature from room temperature (23 °C) to 55 °C respectively. At 65 °C, gold dissolution was initially enhanced but after 225 hours, the gold recovery was similar to the recovery at 55 °C.

Fig. 5. Effect of temperature on gold extraction from a gold oxide ore by Glyleach™ process at leach conditions of 15 g/L glycine, 30% solid content, 100% -75 μm, pH 12.

3.6.   Effect of glycine concentration

Gold extraction at different levels of glycine concentration was tested, and the results are shown in Fig.6. It is clear that gold extraction increases by increasing the glycine concentration but the effect is not a monotonic increase in rate and yield versus concentration. I.e. the rate and extraction was less at 37.5 g/L glycine than at 15 g/L. This might indicate that appoint is reached where steric hindrance dominate and no further advantage can be unlocked by higher glycine concentrations. However, the process is not as sensitive to glycine as to pH and temperature; the maximum gold recovery was 72.1% at 15 g/L glycine for 336 hours. Gold recovery at lower glycine concentration (3.75 g/L) was 53.9% and the kinetic curve is still linear over time which confirms the continuous gold dissolution but at a slower rate. Using a lower lixiviant concentration during the in-situ leaching is recommended to minimise the risk of losing the reagent to the underground and surrounding waste rocks. A concentration of 15 g/L glycine was selected as an optimum concentration of the lixiviant for the gold extraction.
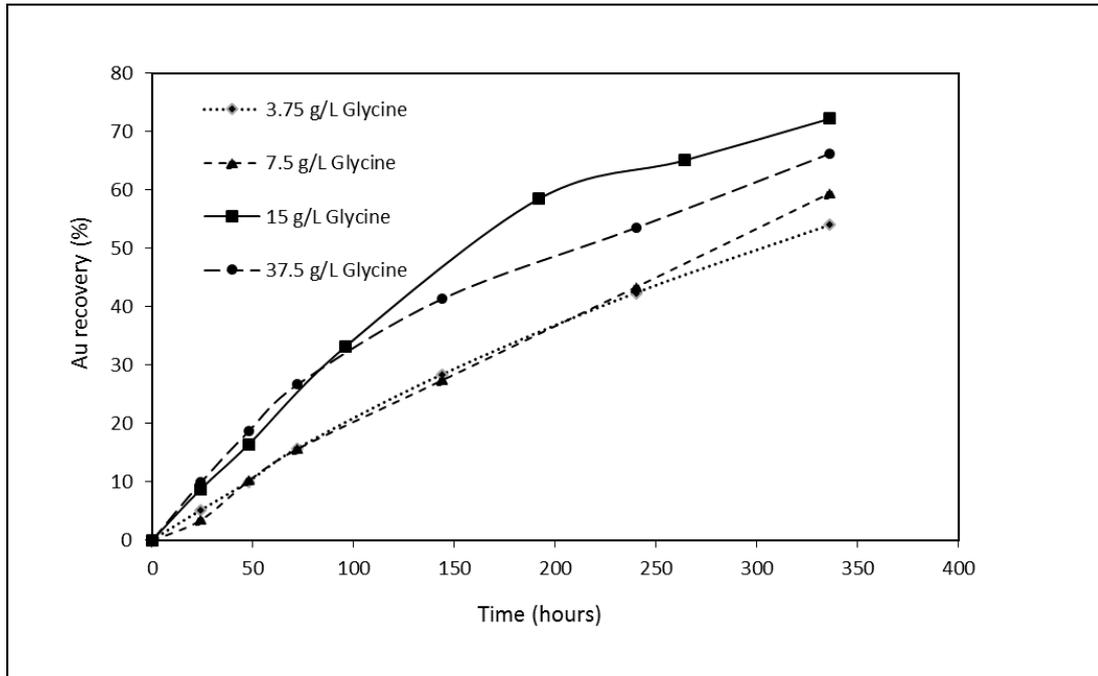
Fig. 6. Effect of glycine on gold extraction from a gold oxide ore by Glyleach™ process at leach conditions of glycine, 30% solid content, 100% -75 µm, pH 12, and 55 °C.

3.7. Effect of solid content

The effect of solid content on the gold dissolution was studied at 20, 30, 40 and 50% and the results are shown in Fig. 7. Increasing the solid content up to 40% has no effect on gold recovery, however increasing it to 50% decreases the gold recovery. It is not surprising to see the decrease in the gold recovery at high solid contents as the reagents dosages per mass of ore decreases and also the pulp density affects the diffusion of the reactants and products. The effect of solid content is not a factor during the in-situ leaching but it is an important factor for tank leach, and the percolation rate per surface area is the most important factor for heap leach applications.
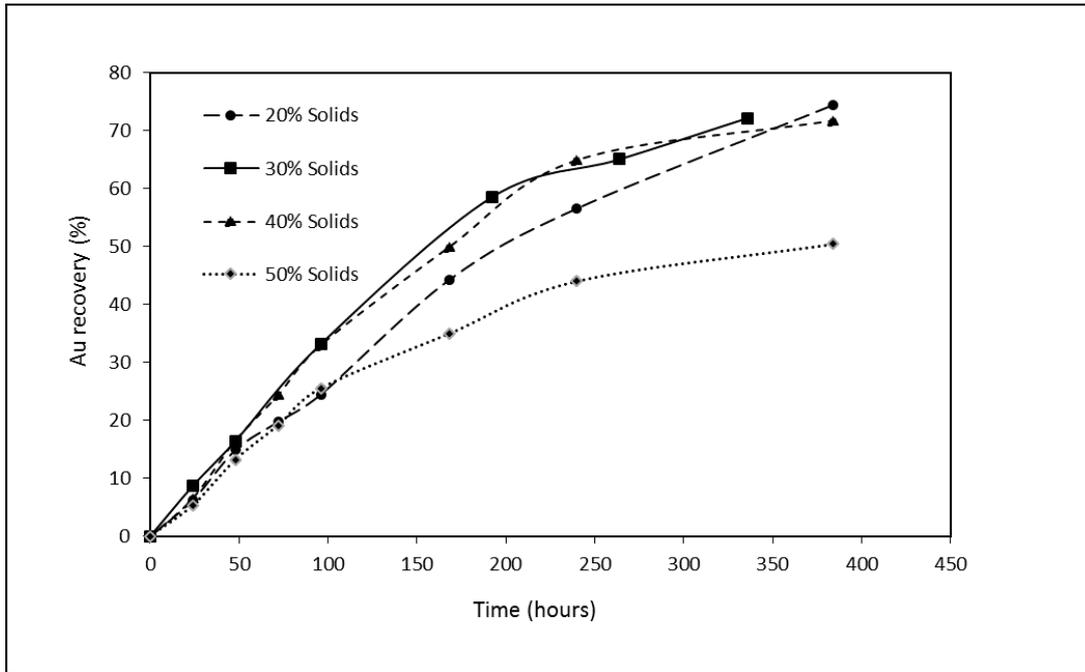
Fig. 7. Effect of on gold extraction from a gold oxide ore by Glyleach™ process at leach conditions of 15 g/L glycine, 100% -75 µm, pH 12, and 55 °C.

3.8. Effect of pH modifiers

The effects of using either lime or caustic to adjust pH to 12.0 were studied. This was conducted to investigate the possibility of using the cheapest pH modifier, lime, instead of using caustic soda to buffer the glycine in the leach solutions. The results show that lime works better than caustic and the initial gold extraction was higher during the leaching in the presence lime as a pH modifier. As the sulfur content is low in such oxide ore sample, the formation of gypsum during the leaching by utilising lime is not seen as a problem.
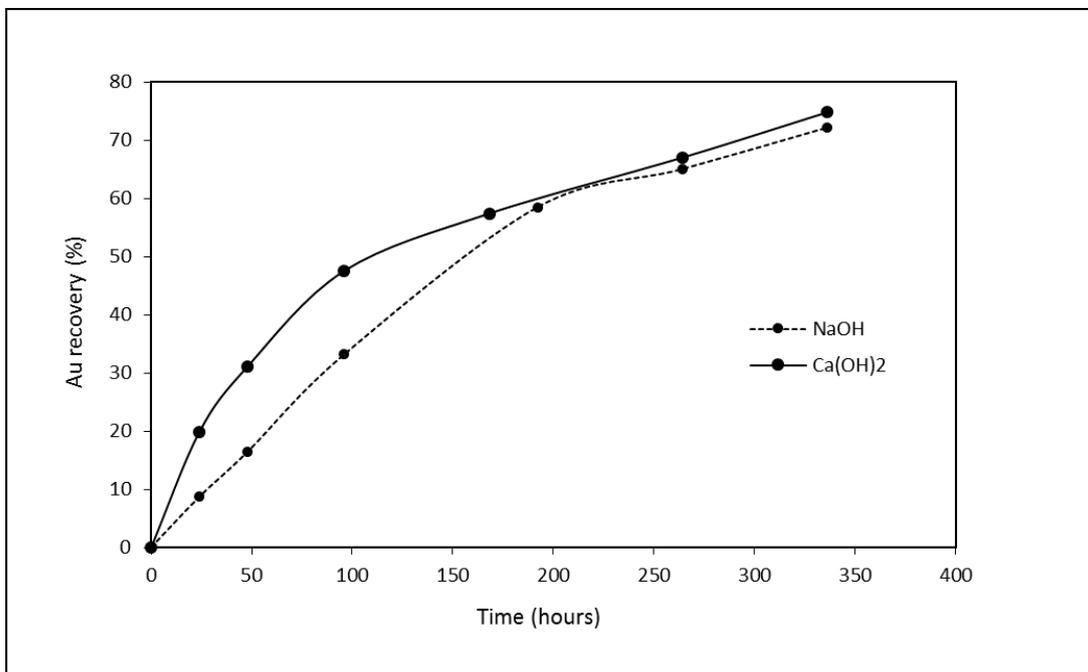
Fig. 8. Effect of pH modifiers on gold extraction from a gold oxide ore by Glyleach™ process at leach conditions of 15 g/L glycine, 30% solid content, 100% -75 µm, pH 12, and 55 °C.

3.9 Effect of sodium chloride

Leaching in the presence and absence of 0.5 M NaCl was studied to examine the effect of salts occurring in the process water and its effects on gold extraction during glycine leaching. It can be seen that the presence of salt (NaCl) has slightly improved the initial gold extraction rate and after that NaCl has a slight decelerating effect on the gold extraction rate, but the overall trend is very similar.
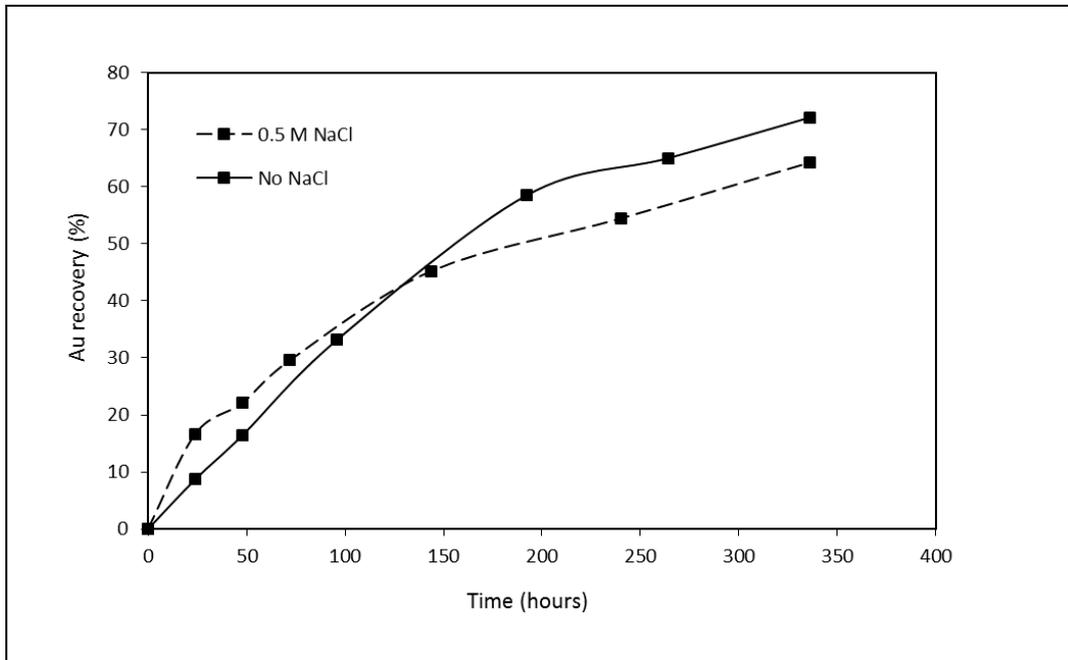

Fig. 9. Effect of sodium chloride on gold extraction from a gold oxide ore by Glyleach™ process at leach conditions of 15 g/L glycine, 30% solid content, 100% -75 µm, pH 12, and 55 °C.

3.10 Impurities Dissolution

The impurities in the final leach solutions during the glycine leaching was analysed by ICP-OES and the concentration of these impurities after 336 hours are shown in Table 6. It is interesting to see the selective dissolution of chalcophile metals (Cu, Co, Ni, Zn) dissolution over the non-chalcophile ones. Most of the elements in the final leach solutions were less than 10 ppm. The selectivity of gold dissolution over the gangue minerals makes the gold recovery by carbon adsorption easier.

Table 6: Impurities dissolution during the leaching of gold oxide ore at different leach conditions

Leach conditions				Cu	Co	Fe	Si	Al	Ni	Zn	Ca
Glycine, g/L	pH	Solids, %	Temp., C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
15	12	30	55	3	0.4	BDL	12	6	3	0.2	745
3.75	12	30	55	1	0.2	BDL	4	BDL	2.4	0.2	496
7.5	12	30	55	2	0.2	BDL	6	1	2.8	0.2	577
37.5	12	30	55	5	1.2	0.5	28	1.5	2.6	1.6	772
15	9	30	55	1	1.7	BDL	10	0.5	5.4	4.4	356
15	10	30	55	2.5	0.4	BDL	13	BDL	3.8	2.2	450
15	11	30	55	3.5	0.5	BDL	19	BDL	4.4	0.6	512
15	12.4	30	55	4.5	0.3	BDL	23	BDL	3.8	1.2	812
15	12	30	23	2.8	0.2	BDL	4	BDL	3.6	BDL	423
15	12	30	40	5.2	0.8	BDL	4	BDL	5.0	BDL	678
15	12	30	65	8.5	1.8	BDL	16	0.5	7.2	0.2	491
15	12	20	55	2.5	0.6	BDL	18	BDL	1.8	BDL	359
15	12	40	55	6	1.6	BDL	22	BDL	5.4	0.6	556
15	12	50	55	8.5	2	BDL	10	BDL	9.6	0.6	846

3.11   Optimum Leach Conditions

From the previous results, it can be observed that temperature, pH and glycine concentration are the major factors controlling the gold leaching in glycine solutions. Figures 10, 11 and 12 show the gold recovery as a function of glycine concentrations, pH and Temperature with all other conditions kept constant. The graphs were created by Design Expert software. It can be concluded that increasing temperature to 40-55 °C, pH to 12 and glycine to 10-15 g/L would be the appropriate gold leach conditions for such ore.
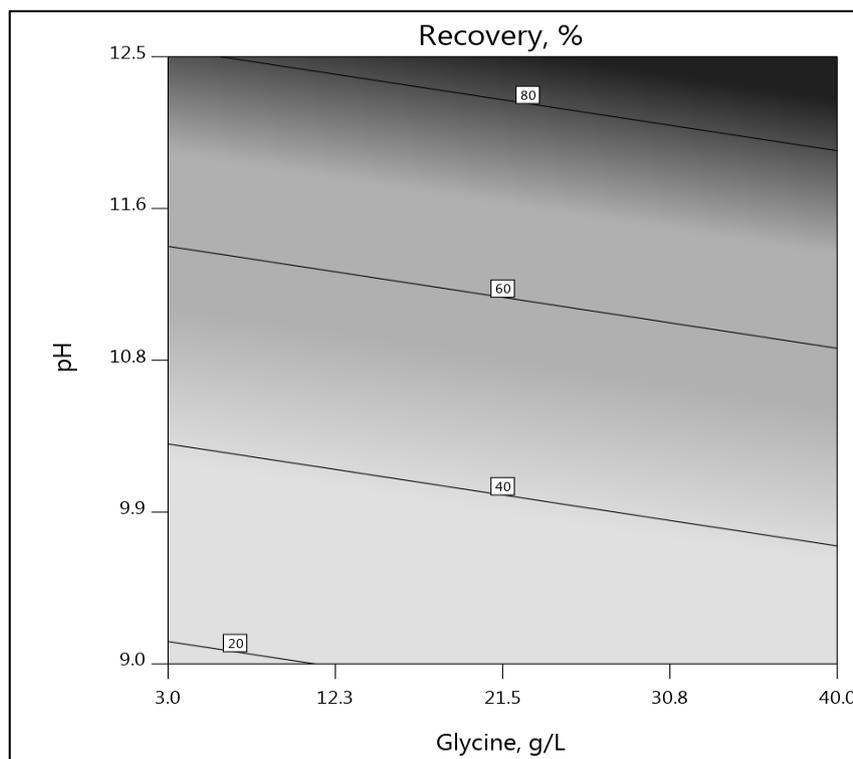

Fig. 10. The effects of glycine concentration and pH on gold extraction from a gold oxide ore by Glyleach™ process at leach conditions of 30% solid content, 100% -75 µm, 336 hours, and 55 °C.

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Fig. 10 indicates that there is minor change in gold recovery by increasing glycine concentration form 5 g/L to 40 g/L, however increasing the leach pH from pH 10.0 to pH 12.0 doubles the gold recovery from 40% to 80%.

Fig. 11 indicates that selecting glycine concentration of 15 g/L, temperature of 50 °C and pH 12.0 significantly maximises the gold extraction. As shown in Fig. 12, increasing temperature at pH 12 improves the gold extraction at different glycine levels.
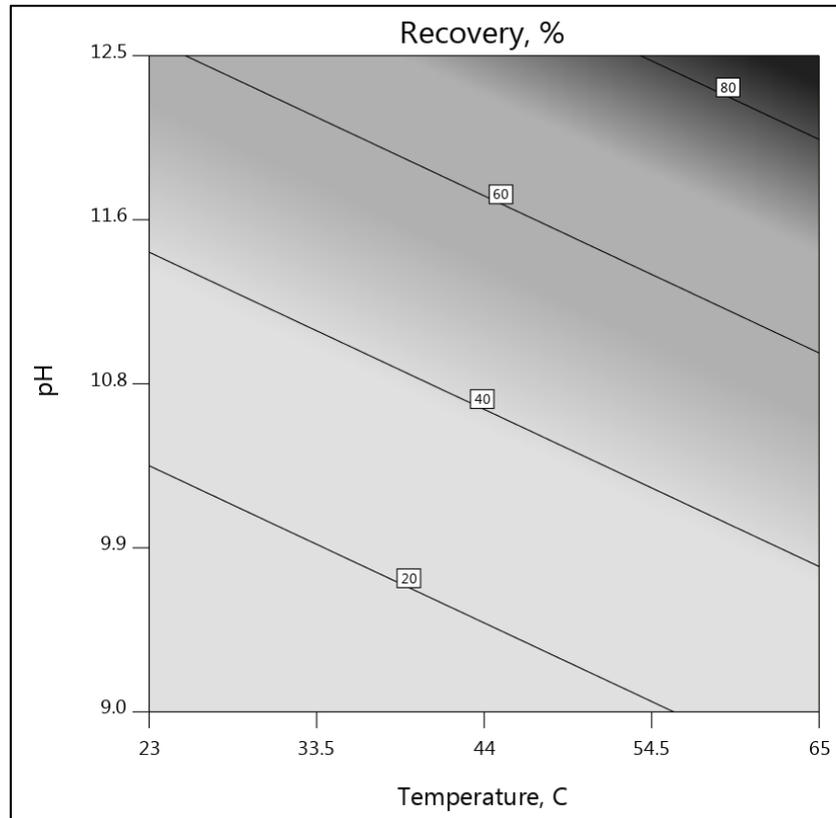

Fig. 11. The effects of temperature and pH on gold extraction from an oxide ore by Glyleach™ process at leach conditions of 30% solid content, 100% -75 μm, 336 hours and 15 g/L glycine.
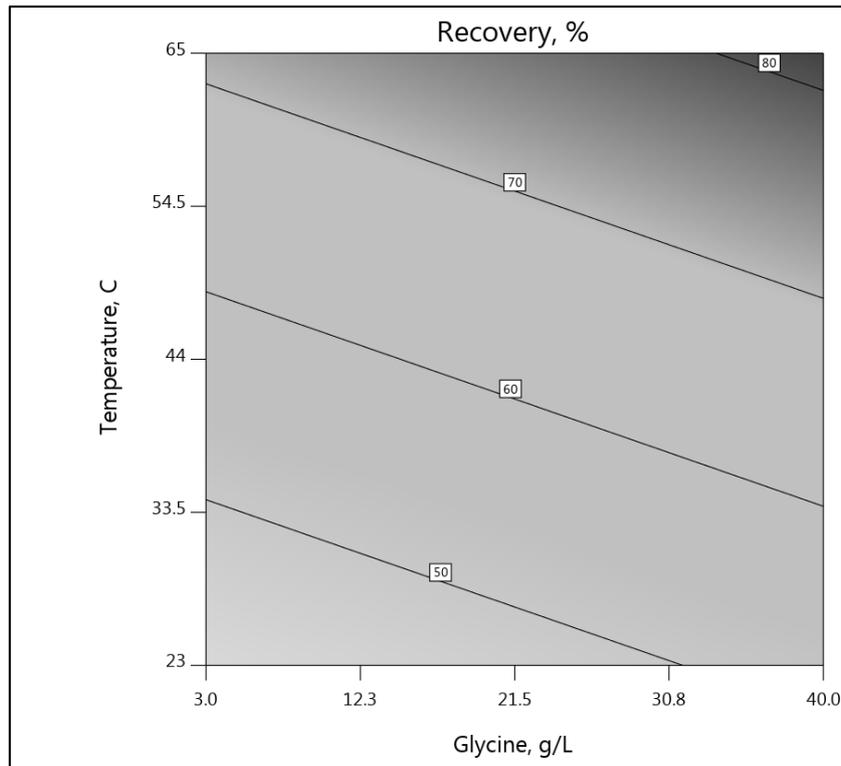
Fig. 12. The effects of temperature and glycine concentration on gold extraction from an oxide ore by Glyleach™ process at leach conditions of 30% solid content, 100% -75 μm, 336 hours, and pH 12.

4.   Conclusions

An alkaline glycine leaching research study for a free milling gold ore has been conducted to evaluate the amenability of such gold leaching from oxide ores for the application of heap, vat and in-situ leaching modes. The study shows that glycine-based gold leach rate is slow; it was found to be 1/20th of the gold leach rate by cyanidation at room temperature in the absence of catalysts and at similar pH. Such leach rates make it difficult to apply glycine alone (in the absence of catalysts) for agitated tank leach mode. In this study, different parameters have been evaluated to increase the gold leach rate and overall gold recovery from a free milling oxide ore. The effects of glycine concentration, leach pH, temperature, ferric ions and sodium chloride have been studied. The results showed that the glycine concentration, pH and temperature have significant roles in increasing the gold leach rate and the overall gold recovery. Increasing the temperature significantly improves the gold extraction which indicates that the gold leaching in alkaline glycine solutions is a chemically controlled reaction. In the case of in situ leaching, rock temperatures may be naturally elevated, providing the source of thermal energy. In the case of heap leaching, the use of solar ponds, solar thermal heating combined with plastic sheeting may provide cost-effective ways to raise the temperature of the fluid within the heap, as has been shown by Murray, Platzer, & Petersen (2017). In particular, temperatures of 55°C, as used in this paper, is not too difficult to achieve (particularly in Australia) with solar thermal heating in

appropriate climates. Increasing glycine concentration enhances the gold extraction, however for in-situ leaching application using lower reagent concentration is preferable to decrease the risk of losing the leach reagent to the surrounding gangue rocks. The research study shows that the leach solution pH has significantly improved the gold extraction and leaching at pH 12.0 or higher is recommended to increase the kinetics of gold extraction. The proposed flowsheet for glycine leaching consists mainly from leaching followed by gold recovery by carbon in column (CIC) and recycling glycine solution to the leaching step.

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6. References

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