Influence of pH Modifiers and Pulp Density on Pulp Rheology and Carbon-in-Leach Gold Recovery

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Abstract

Gold beneficiation is capital intensive and has several challenges along the recovery route, thus, several methods are sought after to optimise the recovery. Process chemistry needs to be controlled, and pulp density is one of the key parameters that affect leaching and adsorption of gold onto activated carbon. The carbon needs to be distributed uniformly in the pulp to have effective contact with the pregnant solution. In cyanidation systems, pH modifiers such as lime, caustic soda and caustic potash are utilised to raise the pH above 10.5 to ensure the presence of free cyanide in solution for gold complexing. Even though lime is cheap and commonly used, it has the potential to influence rheology, thus affecting carbon movement and recovery relative to the other pH modifiers. In this paper, the rheological properties of slurries conditioned with lime, caustic soda and caustic potash at varying pulp densities of 45%, 50% and 55% were analysed to determine their effects on pulp density, slurry flow and gold recovery. In terms of fluid flow, the pulp conditioned with lime had the highest resistance to flow, and hence the poorest rheology. Recoveries for all the set-ups were observed to increase with decreasing pulp densities, with lime giving a relatively higher average recovery (93.30%) than caustic soda (91.02%) and caustic potash (90.82%). When the pulp densities were matched with specific gravities (S.G), the dispersion of activated carbon within the pulps of various densities indicated S.G. of 1.4 as the optimum for even distribution of carbon in the pulp.

Keywords: pH Modifiers Pulp Density, Rheology, Cyanidation, Adsorption

1 Introduction

The branch of physics known as slurry rheology is concerned with the deformation and flow of matter. (Barnes *et al.,* 1989; Muster *et al.,* 1995; Mingzhao *et al.,* 2004). Grinding, adsorption, leaching, solid-liquid separation, mixing, cycloning, pumping, and screening are just a few of the rheology-dependent process units (Basnayaka *et al.,* 2017). Mineral slurries' rheological behavior has a significant impact on their processing and engineering. Rheological behavior has a controlling influence on solid-solid and solid-liquid separations, in addition to controlling the transportation of slurries around processing circuits (e.g. flow in pipes and through pipes). Rheology aids in pump sizing and has a significant impact on the project economics of a full-scale plant. The optimum slurry viscosity facilitates in determining mill performance and mill power requirements (Mingzhao *et al.,* 2004). Rheology has been used extensively to investigate particle-particle interactions in oxide mineral, clay mineral, and coal slurries, providing information on the state of aggregation induced by changes in pH, electrolyte concentration, and the addition of various processing reagents (Mezei, 2003; Basnayaka *et al.*, 2017).

During cyanidation process, various pH modifiers such as lime, sodium hydroxide and potassium hydroxide are utilised. Among the above-mentioned pH modifiers, lime is said to be the traditional pH modifier because of its economic value. Lime has several functions in cyanidation process, most notably, it maintains proper pH in the cyanide solution, thereby keeping it in the liquid phase and also preventing the formation of hydrogen cyanide gas (Habashi, 1999; Marsden and House, 2006). However, lime has adverse effects on leaching circuit; hence its dependence to an excessive degree can be problematic. From Davidson (2007), calcium ions from lime passivate the surfaces of activated carbon, thereby reducing adsorption and affecting elution process. Calcium ions form a highly insoluble complex with gold on the surface of carbon. Due to the insoluble nature of calcium aurocyanide, it does not easily elute and thus fouls regenerated carbon. This reduces carbon activity which further impacts metal recovery negatively (Mardsen and House, 2006).

$2Au(s) + Ca^{2+}\ 4CN^{-} + H_2O + 0.5O_2 = Ca[Au(CN)_2]_2 + 2OH^{-}$

Sodium hydroxide and potassium hydroxide on the other hand are expensive and corrosive. They are known simply as caustic soda and caustic potash respectively. Aside these major disadvantages in comparison with lime, they have many advantages as a pH modifier such as; high solubility, good rheological behavior and effectiveness in the neutralisation of strong or weak acids. Their use as deflocculants have been proven to be a possible mitigation measure to siltation (Mardsen and House, 2006). However, the reactions of silica with potassium hydroxide as well as with sodium hydroxide form gelatinous precipitates which cannot be separated from the particles. These gels have the ability to passivate the mineral surfaces and prevent leaching of gold (Mardsen and House, 2006).

Though the recovery of gold from cyanide-leached pulps and solutions could be done by several techniques, carbon adsorption is mainly used because of its well-established kinetics, economic viability, efficiency and readily release of adsorbed gold during elution (Bailey, 1987; Marsden and House, 2006). For adsorption to be efficient, certain parameters such as specific gravity, pulp density, pH of the adsorption medium, temperature, the nature of activated carbon used and degree of agitation must be established (Marsden and House, 2006; Staunton *et al.*, 2010).

In mineral processing, the amount of solids in a pulp has a marked effect on grinding, leaching and adsorption, and thus overall recovery. Too high pulp density in grinding can act as a cushion and absorb impact forces between media and ore particles, hence reducing the efficiency of grinding. Also, when the pulp is too dilute, particles coat the surfaces of the steel balls poorly, hence reducing contact between particles and grinding media (Wills, 2006). Pulp density also determines the mass transfer and the contact between lixiviants and ore particles during leaching. High pulp density limits lixiviant contact with gold particles. On the other hand, very low pulp density waste reagents needed to condition pulp (Shrithammavut, 2008). Furthermore, adsorption of gold ions onto activated carbon depends on uniform dispersion of the carbon within the slurry, and this is influenced by the pulp density and specific gravity, and thus the rheology.

This paper set out to analyse the influence of pulp rheology, pH modifiers and the rippling effect of pulp density and its corresponding specific gravity on suspension of activated carbon and gold adsorption on gold recovery. This was achieved by conducting rheology tests of slurries conditioned with lime, caustic soda and caustic potash differently at varying pulp densities and also by determining carbon distribution at different pulp densities.

2 Materials, Methods Used

2.1 Materials, Equipment and Sample Preparation

Gold ore samples were obtained from a Mine in southern Ghana treating free-milling gold ore. Reagent grade cyanide, caustic soda, caustic potash and lime; nitric acid, hydrochloric acid, silver nitrate and rhodonine were all obtained from the Minerals laboratory of the University of Mines and Technology (UMaT), Tarkwa, Ghana. Major equipment used included: Metso Jaw, Metso Cone Denver Roll crusher, Cascading ball mill, Varian AA240FS Fast Sequential Atomic Absorption Spectrometer, Ametek Rheometer and KRUPS Turbomix, and these were all available at the Central laboratory of UMaT.

A total sample of 20 kg was crushed several times using the Metso Jaw crusher, once with the Metso Cone crusher and twice again using the Denver Roll crusher.

2.2 Grindability Test of Crushed Samples

Three (3) kg sample was used for grindability analysis on the samples to determine the optimum time required to mill to 80% passing 106 µm. From the roll-crushed sample, 100 g from the 3 kg sample was screened using 106 µm screen to determine the percentage passing at time zero of milling. The sample was milled for 10 minutes and screened using 106 µm to determine the percentage passing at that time. The procedure was repeated after 15 minutes of milling. The percentages passing 106 µm were plotted against the grinding times, and the optimum time required to achieve 80% passing 106 µm was estimated from the straight line and used to grind the rest of the samples.

2.3 Sample Conditioning and Rheological Analysis

The test was conducted for lime, caustic soda and caustic potash at 45%, 50% and 55% solids (pulp) density. Granulated caustic soda and caustic potash were added to 45%, 50% and 55% pulps to condition them to a pH of 11. Likewise, lime was added to 45%, 50% and 55% pulp to condition to a pH of 11. The various modifier weight required to raise the pH to 11 for the various pulp densities were recorded, and the rheologies measured.

Rheological analysis was conducted for all the samples with Dial readings recorded for 600, 300, 200, 100, 60, 30, 20, 10, 6, 3, 2 and 1 revolutions per minute. Results obtained were recorded, and inference drawn from them.

2.4 Bottle Roll Test

After conditioning, 300 ppm sodium cyanide was added to each of the samples, and activated carbon concentration of 10 g/L was used for the leaching and adsorption process.

The pulps at the various solid densities were bottle-rolled for 48 hours, and samples were taken after 2, 4, 8, 12, 24 and 48 hours. The loaded carbon was separated from the pulp after leaching and the samples were filtered for AAS analysis to determine the concentration of gold in the liquid tailings after carbon adsorption. Titration was conducted after each sampling to top up cyanide in order to maintain the concentration, and the pH was also checked to maintain a constant value. After 48 hours, the tailings were washed thoroughly and dried, after which 50 g of sample was taken from each of the nine samples for acid digestion. The concentrations of gold in solution were determined by the Varian AA240FS Fast Sequential Atomic Absorption Spectrometer

2.5 Acid Digestion of Tailings Samples

A 50-g sample was taken from each of the dried tailings via Jones riffle sampler into a beaker. Hydrochloric acid (75 ml) and nitric acid (25 ml) were added respectively to the samples in the beaker, after which they were heated for 10 minutes using an electric hot plate and then allowed to cool. After cooling, the solutions were filtered and the concentration of gold in tailings determined by the Varian AA240FS Fast Sequential Atomic Absorption Spectrometer

2.6 Behavior of Carbon in the Pulp

A heavy medium (4-methyl-2-pentanone and tetrabromoethane) with specific gravity equivalent to the different pulp densities were prepared. Equal concentrations of carbon were added to the solutions, and the behavior of carbon in each of the medium was observed. The S.G of the pulp and that of the heavy medium can be determined by the use of the Marcy scale or Equation 1:

$$S.G = \frac{1}{\left[\frac{\%solids}{Ore_{S.G}}\right] + [1 - \%solids]} \quad (1)$$

The experiment was repeated with subsequent portions of the ore at pulp densities of 45, 50 and 55, but at the same concentration of regents.

2.7 Analysis of Data

Solution samples from the leaching and aqua-regia digestion experiment were analysed for gold using Varian AA240FS Fast Sequential Atomic Absorption Spectrometer, with cathode lamp as light source for gold and mixture of air–acetylene as the flame atomizer gas. Standard calibration curves were prepared using gold solutions of known concentrations. The recoveries were calculated using Equation 2. Graphs of leaching times against recoveries were then plotted from the results obtained.

$$\text{Recovery (\%)} = \frac{\text{(Head grade - (Au in solution@48 hrs + Au in Tailings))}}{\text{Head grade}} \times 100$$

(2)

3 Results and Discussions

This paper set out to analyze the influence of pulp rheology, pH modifiers, pulp density and its corresponding specific gravity on suspension of activated carbon and gold adsorption, and the rippling effect on overall gold recovery. The rheology test was conducted for pulp densities of 45%, 50% and 55% at 600, 300, 200, 100, 60, 30, 20, 10, 6, 3, 2 and 1 revolutions per minute. The various pulps were then conditioned with lime, caustic soda and caustic potash to see their effects on rheology. The leaching test work was exposed to the same experimental conditions with a cyanide strength of 300 mg/L, a pH of 11, activated carbon concentration of 10 g/L and pulp densities of 45%, 50% and 55% for 2, 4, 8, 12, 24 and 48 hours. Samples were taken at the time interval stated above and the concentration of gold in solution determined using the Varian AA240FF Atomic Absorption Spectrometer.

3.1 Analysis of Rheology of Pulp Densities with no pH Modification (Control)

The rheological analysis of pulp densities with no pH modification is depicted in Fig. 1. The viscosity of the pulp is given by the slope of the graph of shear stress against shear rate (s^{-1}) (Pa).

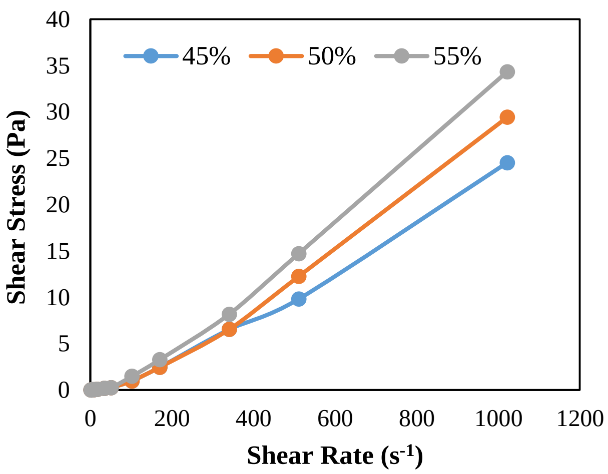

Fig. 1 Rheological Analysis of Pulp Densities with no pH Modification

From Fig. 1, the viscosity observed (slope of graph) in the 55% solids pulp was the steepest, with that of the 45% solids pulp being the least. The yield stress which represents the threshold amount of stress to initiate flow (Mangesana *et al.*, 2008; Baawuah *et al.*, 2014; Jaensson *et al.*, 2018) decreased in the order of 55%, 50% and 45% pulp density (mass concentration). This is because fluids with higher mass concentrations require higher shear stress to initiate flow due to particle-particle interactions which causes sliming of the pulp as the particle size for the test was relatively fine (D_{80} of 106 μm).

3.2 Effect of Lime on Rheology and Gold Recovery

The effect of lime on rheology and gold recovery are presented in Fig. 2 (a) and (b). In rheology, the particle size distribution of the solids forming slurry plays a major role on the rheological behavior of the slurry. Also, slurry viscosity is highly influenced by solids density. From Fig. 2a, it was observed that viscosity increased with increase in solid concentration and also, pulp densities with better rheological properties had better recovery.

Gold recoveries from slurries conditioned with lime at pulp densities of 45%, 50% and 55% is depicted in Fig. 2b. From Fig. 2b, recovery increased with increase in time and also decreasing pulp density. The recoveries obtained from 45% and 50% pulp were relatively higher as compared with 55%. The higher recoveries were as a result of increased diffusion of oxygen in the pulp and auro-cyanide complexes across the boundary layer into the bulk solution due to low percent solids (Marsden and House, 2006). However, with the low recovery recorded for the relatively higher pulp density (55% solids), the resistivity of the pulp to agitation was high and, as such, the contact between the gold in solution and the cyanide as well as mass transport of auro-cyanide complexes across the boundary-layer by diffusion was reduced. This caused a relatively higher tailings grade of 0.25 g/t for the 55% solids pulp.

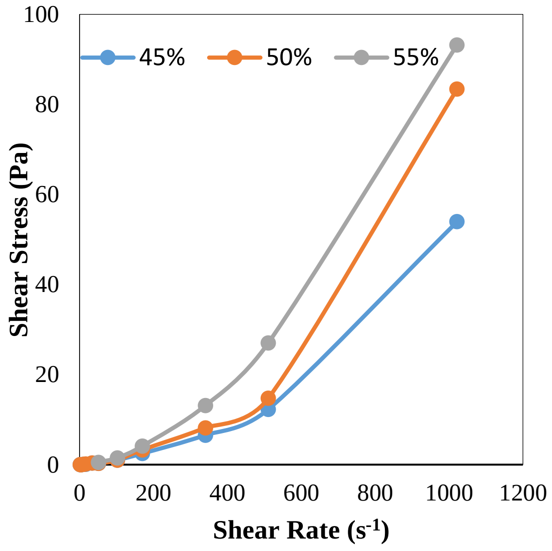

Fig. 2a Rheological Analysis of Pulp Densities Conditioned with Lime

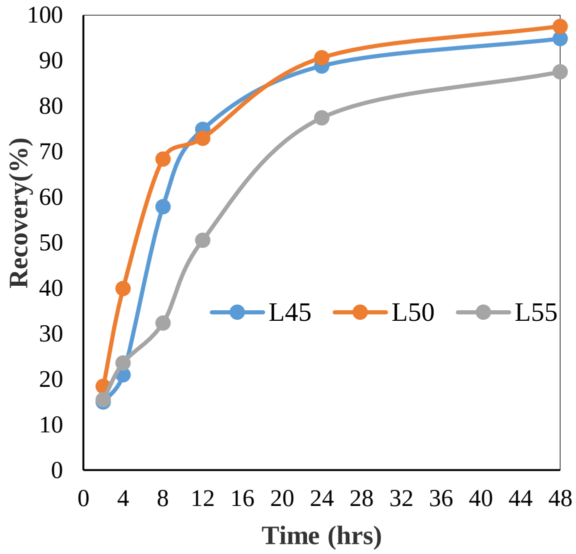

Fig. 2b Gold Recoveries from Slurries Conditioned with Lime at Different Pulp Densities

3.3 Effect of Caustic Soda on Rheology and Gold Recovery

The rheological analysis of slurries conditioned with caustic soda is shown in Fig. 3a. From the rheological analysis, it was observed that 45% solids gave the best rheological property followed by 50% and then 55%. This is because high viscosity fluids need more shear stress and a higher initial input energy to initiate flow as compared to low viscosity fluids.

Caustic soda was used as a pH modifier to condition the three pulps to a pH of 11. Caustic, unlike lime, has a high pH decay profile because it is very soluble in water. Gold recoveries from slurries conditioned with caustic soda are presented in Fig. 3b. From the graph it can be observed that solid concentration had the same effect as lime, hence the order of recovery. Pulp density of 55% had a relatively low recovery even though it had faster kinetics out of the three tests after 12 hours. This is because, initial dissolution of gold and complexing of aurocyanide ions is faster due to the abundance of gold-bearing solids. However, as leaching progresses, the solution becomes saturated due to lower solution to solids ratio. Therefore, dissolution of gold slowly reaches equilibrium, and thus the lower recovery.

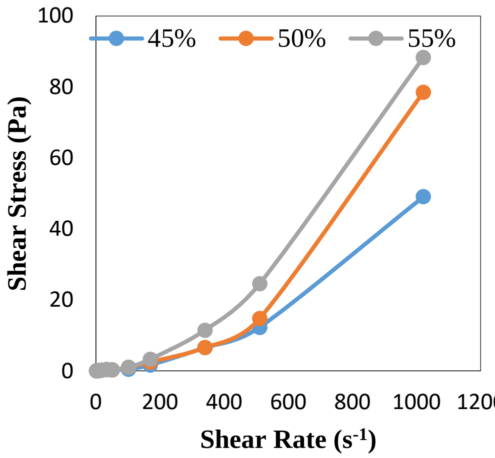

Fig. 3a Rheological Analysis of Pulp Densities Conditioned with Caustic Soda

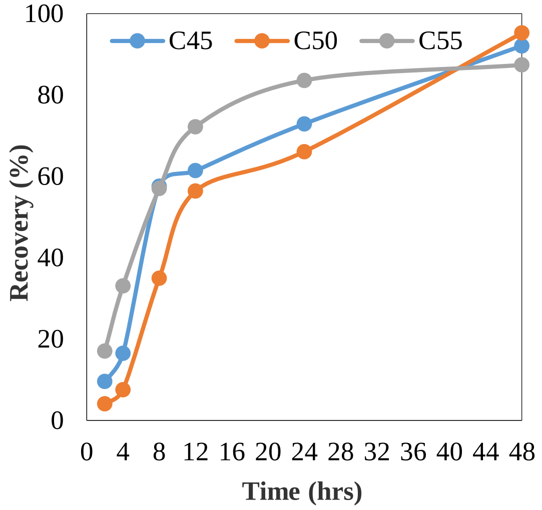

Fig. 3b Gold Recoveries from Slurries Conditioned with Caustic Soda at Different Pulp Densities

3.4 Effect of Potash on Rheology and Gold Recovery

The effect of caustic potash on rheology and gold recoveries are expressed in Fig. 4 (a) and (b). From Fig. 4a, it was observed that 45% had the best rheological property followed by 50% and 55%. The same trend was observed with lime and caustic soda.

Caustic potash was also used as a pH modifier to condition the three pulps to a pH of 11. Caustic potash, which is used in many of the same applications as caustic soda, is a strong base and it dissolves readily in water giving off much heat and forming a strong alkaline. Gold recoveries from slurries conditioned with caustic potash are presented in Fig. 4b and from the figure, it can be seen that solid concentration had the same effect as lime and caustic soda, thus resulting in a lower recovery in 55% pulp density sample.

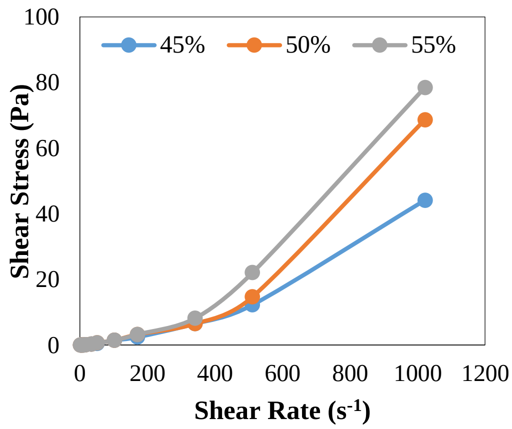

Fig. 4a Rheological Analysis of Pulp Densities Conditioned with Caustic Potash

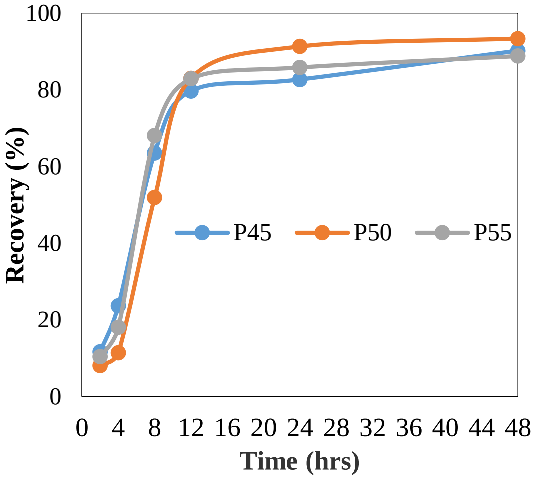

Fig. 4b Gold Recoveries from Slurries Conditioned with Caustic Potash at Different Pulp Densities

3.5 Comparison between the control Pulp and the pH Modified Pulp

A comparison between the viscosities of the unmodified pulp against the pH-modified pulp is portrayed in Fig. 5. The experiment was duplicated, and the graph depicts the average results. From Fig. 5, it can be witnessed that pH modifiers have the ability to alter the rheological behavior of pulp.

Lime can act as a flocculant/coagulant in most solid-liquid systems and has the ability to increase settling rate of particles as the calcium ions bridge particles together, increasing settling velocity which in turn increases viscosity and the yield stress (Mardsen and House, 2006). Sodium hydroxide and Potassium hydroxide on the other hand form gelatinous precipitates with silica which can bridge particles together thereby increasing viscosity and thus changing rheological properties of the system (Shi *et al.*, 2001; Mardsen and House, 2006).

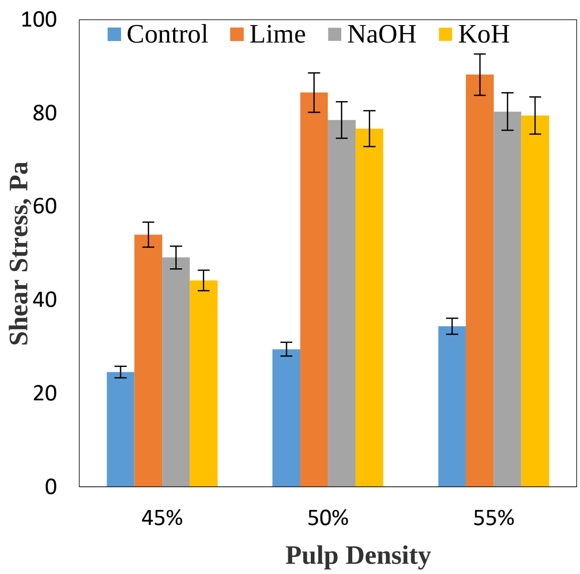

Fig. 5 Comparison between the Control Pulp and the pH-Modified Pulp

3.6 Effects of Pulp Rheology and pH Modifiers on Gold Recovery

The effects of pulp rheology and pH modifiers on gold recovery are presented in Fig. 6 (a) and (b). The tests were carried out in pairs to ensure uniformity, and the average findings are shown in the graphs. From Fig. 6a it can be noted that sodium hydroxide and potassium hydroxide had a better rheological behavior as compared to lime. This can be attributed to the fact that the calcium ions in lime bridge particles together, increasing settling velocity which in turn increases viscosity and the yield stress (Mardsen and House, 2006). However, lime had the highest gold recovery as compared with sodium hydroxide and potassium hydroxide as depicted in Fig. 6b. This may be due to the fact that, the reactions of silica and potassium hydroxide as well as with sodium hydroxide form gelatinous precipitates which cannot be separated from the particles, passivating the mineral surfaces and preventing leaching of gold (Mardsen and House, 2006). Also, potassium hydroxide and sodium hydroxide may have rapid decay profile, which implies the rate at which their concentrations reduce in a system is faster than lime, hence, the pH drop may reach points below 10 quicker and cause cyanide to hydrolyse more to form hydrogen cyanide gas, thus reducing the amount of free cyanide present as compared to lime (Mardsen and House, 2006; Shrithammavut, 2008).

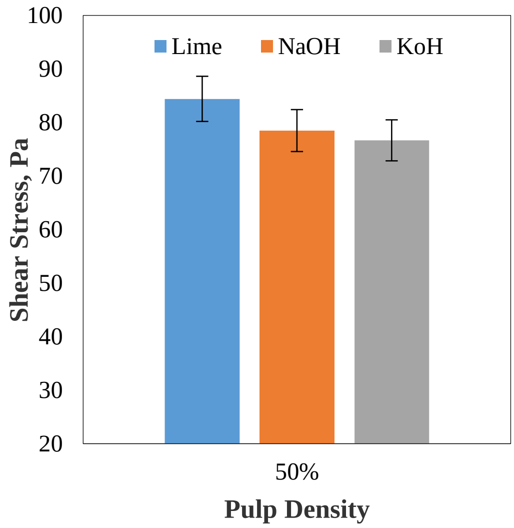

Fig. 6a Rheological Behavior at 50% Pulp

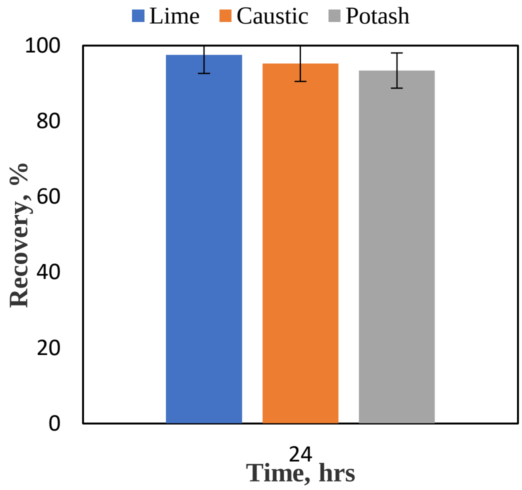

Fig. 6b Gold Recovery at 50% pulp

3.7 Effects of Pulp Density on Dispersion of Carbon

The effect of pulp densities and its corresponding specific gravities on suspension of activated carbon and gold adsorption was studied. Fig. 7 exhibits the results on how activated carbon is dispersed in a heavy medium at different S.G.

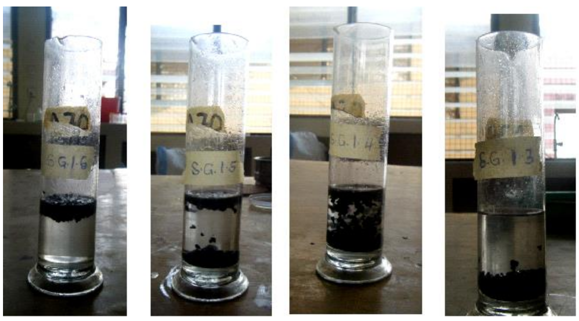

Fig. 7 Effect of Pulp Density on Dispersion of Carbon

The heavy media used in this experiment were prepared from 4-methyl-2-pentanone and to different S.G. From Fig. 7, it was perceived that at S.G of 1.6, all the carbon floated on the media and this was due to the fact that the S.G. of wet carbon is less than 1.6. At S.G of 1.4, greater percentage of the carbon suspended in the medium giving it a uniform dispersion in the medium, and this is because the S.G of the medium and that of the wet carbon are equal, aiding the suspension. Finally, at S.G. of 1.3, all the carbon sank to the bottom of the medium as the S.G. of the carbon was higher than that of the medium.

3.8 Effects of Pulp Density on Gold Adsorption

The effect of pulp density on gold adsorption is displayed in Fig. 8. From Fig 8, it was observed that as the pulp density increased, the recovery also increased to about 97 % at 50 % solids, beyond which the recovery decreased with increasing pulp density to a minimum value of 87 % at 55% solids.

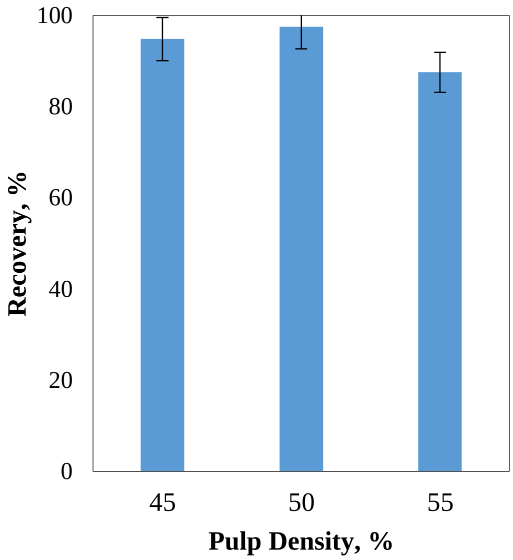

Fig. 8 Effect of Pulp Density on Gold Adsorption.

The lower recovery recorded for 45 % pulp was due to the lower specific gravities of the pulp, less than 1.4 for the wet carbon, thus causing the carbon to sink to the bottom. In a similar manner, when this specific gravity is attained in adsorption tanks in processing plants, the carbon will sink to the bottom. This will reduce the carbon to gold solution contact due to uneven dispersion of carbon in the pulp, a situation which may occur even if the right concentration of carbon is charged into the tanks.

The higher recovery recorded at 50% solids is due to the fact that, the S.G of the pulp was equal to that of the wet carbon, and as such, the carbon was evenly dispersed in the pulp due to suspension. This greatly enhanced carbon to solution contact required for efficient adsorption.

Also, the decreasing recovery recorded at 55% solids is because the S.G of the pulp was higher than that of the carbon and as a result the carbon floated on the pulp. Consequently, there was inefficiency in carbon to solution contact with negative implications on adsorption.

4 Conclusions

The goal of this paper was to look into the effects of pH modifiers and pulp density on pulp rheology, and the rippling effect of specific gravity on activated carbon suspension and overall gold recovery in a CIL system. The following conclusions were drawn based on the findings and discussion: pH modifiers have the ability to change the viscosity and rheological properties of pulps; 45% pulp had the best rheological property followed by 50% and 55%. This is because high viscosity fluids need more shear stress and a higher initial input energy before the fluid can flow as compared with low viscosity fluids. Viscosity increased with increase in solid concentration and also, pulp densities with relatively better rheological properties had better recovery. The average recovery for all was found to increase with decreasing solid concentration, with lime having the highest average recovery of 93.30% as against 91.02% and 90.82% respective recoveries for caustic soda and caustic potash.

Also, for evenly dispersion of carbon in the pulp, the optimum pulp density of 50%, which is equivalent to S.G. of 1.45 should be used. This resulted in efficient adsorption, and corresponding gold recovery rate of 97%. A change in pulp density above or below 50% solids had a negative impact on adsorption, and resulted in lower gold recovery efficiency.

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