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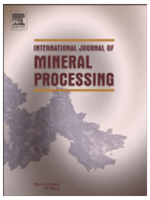

Polyacrylamide as an agglomeration additive for copper heap leaching

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ABSTRACT

Heap leaching has significant challenges associated with permeability. Low permeability decreases recovery rates and recovery. It is believed that low heap permeability is caused by the migration of fine particles. This fines migration clogs the natural flow path of leach solutions, forcing it to flow around some regions of the heap, leaving them un-leached. Binders show significant promise in this application because they will increase agglomerate strength leading to a reduction in fines migration. However, most binders have been used without any systematic reasoning. Using a novel soak test, systematic studies have been completed on a wide range of binders. A non-ionic polyacrylamide was found to reduce fines migration as much as 93%. It is believed that this binder was successful due to electrostatic attraction, hydrogen bonding, and physical bonding.

1. Introduction

Heap leaching is a method used to recover precious metals such as gold and copper from low grade ores. In copper heap leaching, the ore is stacked in approximately 6.1 m (20 ft) 'lifts' and an acidic leach solution (raffinate) is sprayed on the top of the heap. As the raffinate percolates through the heap, the copper is solubilized and retained in the liquid phase. The flowing liquid can also cause migration of fine particles within the ore bed. The migration of fines clogs the natural flow channels, and forms impermeable layers within the heap which the raffinate cannot penetrate easily. When this happens, solution flows around sections of the heap, leaving them un-leached or only partially leached, which lowers overall recovery. Agglomeration is one method which is being used to resolve this problem. Agglomeration causes the smaller particles to adhere to the surfaces of the coarser ore particles, which prevents fines from migrating. However, current practice is to agglomerate the ore by moistening it with raffinate. This procedure does not bind particles together very strongly, resulting in agglomerate breakdown, which causes fines migration. Binders are a potential solution to this problem since they will form stronger, more stable agglomerates which will resist breakdown. Not only should an effective binder have a strong affinity for the particle surfaces, it also must withstand the extreme acid environment which is found in a heap. In the past, in other heap leaching operations, binders were added without any systematic reasoning. The majority of common binders do not perform well in acid, and so it was necessary to carry out systematic studies to discover what qualities are needed in the selection of acid-resistant agglomeration binders.

In order to determine if a given binder could improve agglomerate stability in acidic solutions, it was necessary to develop a reproducible, quantitative testing method where the agglomerates could be subjected to an acidic environment as would be experienced in a leach heap. The soak test was developed to do this. With use of this testing procedure, a variety of binders for agglomeration could be compared to determine which type produced the best results. Once a binder had been determined, it was important to investigate how and why it was working.

2. Theory

Attraction forces are forces which can act between ore particles and a binder, giving an agglomerate strength. Attraction forces between solid particles are mainly molecular, electrostatic, and magnetic (Lewandowski and Kawatra, in press; Pietsch, 2002). At small distances the effect of these forces can be great, although they decrease quickly with distance. These forces may also enhance the forces due to the other binding mechanisms, such as adhesion and cohesion forces, solid bridges, surface tension, or capillary pressure.

Molecular forces include (i) van der Waals forces, (ii) valence forces, and (iii) non-valence association.

i. van der Waals forces are physical forces of attraction and repulsion existing between molecules which occur due to polarization induced in each particle by the presence of others. Drying induces van der Waals interactions, causing the polymer chains to become irreversibly adsorbed to the ore.
ii. Valence forces arise when the bonds between atoms or molecules are broken, creating new surfaces with unsatisfied valences. If the newly created surface area is large, the valences themselves may recombine if newly created surfaces come close to each other.
iii. Non-valence association includes hydrogen bonding. Hydrogen bonding is an attraction interaction between an electronegative atom and a hydrogen atom (hydrogen bond donor) which is bonded to another electronegative atom (hydrogen bond acceptor), shown in Fig. 1. The hydrogen bond acceptor does not

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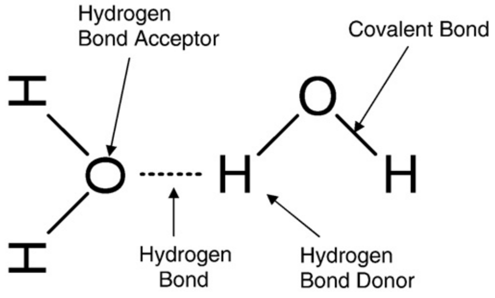

Fig. 1. An example of hydrogen bonding between two water molecules.

need to be attached to a hydrogen atom. The electronegative atom is almost always fluorine, oxygen, or nitrogen. Hydrogen bonds are typically stronger than van der Waals forces, but they are weaker than covalent or ionic bonds. Due to the fact that hydrogen bonds are stronger than van der Waals forces, it was expected that hydrogen bonding would be occurring between the binder and ore surfaces would lead to more stable agglomerates. The strengths of hydrogen bonds vary depending on the bond donor and bond acceptor atoms, as shown in Table 1.

If a binder has hydrogen bond donor sites, it will increase the ability for hydrogen bonding to take place between the ore and polymer, giving additional strength to the agglomerate. If a binder does not have any donor sites, hydrogen bonding cannot take place, leaving the agglomerates with lower strength than those with binders which have donor sites.

Electrostatic forces may exist due to unsatisfied electrostatic fields. When surfaces are immersed in water, ion exchange with the liquid causes electrical double layers to form. One way binders would be attracted to the surfaces of the particles is through electrostatic attraction (Nasser and James, 2006). It was probable that cationic binders will become more strongly ionized when subjected to acid (Zhou and Franks, 2006). This allows them to be attracted to the negatively charged ore surfaces, neutralizing the surface charges of the ore particles. When anionic polymers are subjected to acid, their charges are neutralized, leaving them unable to attach to the ore by electrostatic attraction.

Magnetic forces act similarly to electrostatic forces. This mechanism is limited to particles which possess magnetic properties, and are not applicable to this study.

Experiments were to be conducted to determine what types of binder produced the most stable agglomerates. They would also be used to conclude if either hydrogen bonding or electrostatic attraction could be the reason for the improved agglomerate stability.

3. Experimental

3.1. Materials

Two hundred pounds of a low grade chalcocite ore (Cu_2S) which was rich in silica (SiO_2) was received from a copper processing operation. The ore consisted of approximately 0.25% Cu_2S and 42% SiO_2. The ore was crushed to 85% passing 0.635 cm (1/4 in.) in order to be a suitable size for agglomeration tests. Identical samples were needed for experiments that had size distributions and compositions that were as nearly identical as possible. A consistent size distribution was particularly important, since the primary benefit of agglomeration was control of migration of fines, which was dependent on the quantity of fines present. Samples were produced by screening the entire ore sample received from the mine into five size fractions, given in Table 2. Each size fraction was divided into subsamples using a rotary splitter, and the individual subsamples were weighed to ensure that they were all of identical weights. Experimental samples were prepared by combining one subsample from each of the five size fractions. The resulting experimental samples then had size distributions identical to that of the original ore sample. The composition of the sample was analyzed using X-ray diffraction (XRD), near infrared spectroscopy (NIR), and ocular microscopy (OM), to determine the various minerals within the sample. The majority of the sample was found to be silica with trace amounts of copper-bearing minerals, such as chalcocite, covellite, and chalcopyrite. The mineralogical analysis is given in Table 3.

Table 1
Examples of hydrogen bonds and their corresponding strength (Emsley, 1980).

Hydrogen bond type		Bond strength
F–H….F	Stronger	155 kJ/mol
O–H….N	↓	29 kJ/mol
O–H….O	↓	21 kJ/mol
N–H….N	↓	13 kJ/mol
N–H….O	Weaker	8 kJ/mol

(–) Indicates a covalent bond.
(….) Indicates a hydrogen bond.

Table 2
Size distribution of copper ore used in experiments.

Ore size fraction	% size fraction
+1/4 in. (+6350 μm)	1.3% ± 0.0%
−1/4 in. to +4 mesh (−6350 to +4750 μm)	15.2% ± 0.1%
−4 mesh to +6 mesh (−4750 to +3350 μm)	15.9% ± 0.1%
−6 mesh to +10 mesh(−3350 to +1700 μm)	20.6% ± 0.1%
−10 mesh (−1700 μm)	47.0% ± 0.4%

Table 3
Mineralogy results of copper ore sample.

Mineral	wt.%	Method
Pyrite	1.2	XRD
Quartz	42	XRD
Muscovite	22	NIR
K-feldspar	21	XRD
Plagioclase	5	XRD
Kaolinite	4	NIR
Swelling clay	3	NIR
Biotite	1	NIR
Chlorite	0.5	NIR
Chalcocite/covellite	0.25	OM
Chalcopyrite	Trace	OM

The average weight of each experimental sample was 500 g. The size distribution of the samples used is given in Table 2.

A limited number of experiments were also performed with a pyrrhotite ore (FeS). This ore was predominately pyrrhotite, and did not contain much gangue material. Approximately 3000 g of pyrrhotite was crushed and rotary split into uniform samples. The average weight of each experimental sample was 500 g. The size distribution of pyrrhotite samples used is given in Table 4.

Table 4
Size distribution of pyrrhotite ore used in experiments.

Ore size fraction	% size fraction
+1/4 in. (+6350 μm)	1.6% ± 0.0%
−1/4 in. to +4 mesh (−6350 to +4750 μm)	6.2% ± 0.3%
−4 mesh to +6 mesh (−4750 to +3350 μm)	13.0% ± 0.5%
−6 mesh to +10 mesh (−3350 to +1700 μm)	33.5% ± 0.2%
−10 mesh (−1700 μm)	45.7% ± 0.2%