PRETREATMENT OF COPPER ORE

PRIOR TO HEAP LEACHING

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

Pretreatment of copper ore prior to heap leaching includes crushing and agglomeration processes which were studied in this thesis research. Crushing is a high energy consuming process. In mining operations generally jaw and gyratory crushers are used for primary crushing and cone crushers are used for secondary crushing. During the past couple of decades High Pressure Grinding Roll (HPGR) crushers are being considered by mining companies due to lower energy consumption. In the present research copper ores (copper oxide and copper sulfide ores) were crushed by a jaw crusher and by HPGR and the products evaluated for particle damage, as well as by column leaching to determine the rate and extent of copper recovery.

X-ray computed tomography analysis and laboratory column leaching experiments on copper oxide samples revealed that products from HPGR crushing have more particle damage and higher copper recoveries when compared with products from jaw crusher crushing. As expected copper recovery increased with a decrease in particle size for the copper oxide ore. However, at smaller particle sizes (below 20 x 40 mesh) copper recovery became independent of the crushing technique.

In the case of the copper sulfide ore, copper recovery was found to be independent of the crushing technique despite the fact that more particle damage was observed in products from HPGR crushing. This unexpected behavior for the copper sulfide ore might be due to the high head grade (0.8% Cu for the copper sulfide ore and

0.3% Cu for copper oxide ore) or strong leach solution (pH of copper sulfide ore leach solution is 1.1 and pH of copper sulfide ore leach solution is 2). Column leaching results also show that about 80 to 90% of copper was recovered from the copper sulfide ore in a very short leaching time irrespective of crushing technique. As expected, copper recoveries increased with a decrease in copper sulfide particle size.

In the second portion of the thesis research the agglomeration of copper ore for heap leaching was studied. Liquid bridge agglomerates that are prepared with leach solution are not sufficiently stable and may break apart during the heap leaching operation, thus reducing permeability of the leach pad and extent of copper recovery.

In this phase of the thesis research an attempt was made to improve the quality of the agglomerates by using stucco as a binder. Agglomerate size, permeability and column leaching tests were conducted to evaluate the quality of the agglomerates. Experimental results reveal that a mixture containing 85 to 90% ore, 7 to 10% sulfuric acid solution and 3 to 5% stucco binder produces high quality stucco binder agglomerates that leach as well as, if not better than, liquid bridge agglomerates.

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CHAPTER 1

INTRODUCTION

Copper is the third most used metal by man (iron and aluminum are produced and consumed in greater quantities than copper). The critical need for copper began in 1850, with the use of electricity [1]. Given its malleability, ductility, conductivity of both heat and electricity, ability to withstand corrosion, and its esthetic characteristics, copper has established crucial importance in virtually all areas of developed and newly developing economies most notably in the areas of construction, transport, and all kinds of electrical and electronic applications [1]. Due to these revolutionary technological developments, global copper output increased 300 fold since 1850 (Table 1.1).

1.1 Copper Production Methods

Copper reserves are mostly present in the form of oxide and sulfide minerals. Copper mining is performed either underground or in open pits. Laterite ores copper oxide minerals such as cuprite and hydrous carbonates (malachite, azurite). Chalcopyrite, chalcocite, bornite, cubanite, and enargite are common examples of copper sulfide minerals[2]. Most of the copper ores contain only a very small percentage of copper minerals, and even less molybdenum and precious metals.

Table 1.1 Copper production (Adapted from reference 1).

Year	Production Kilotons	Growth (% / Year)	Main Producing Countries (%Share)		
1750	10		China (70)	Europe (30)	
1800	15	0.8	Europe (53)	China (47)	
1850	53	2.6	UK (23)		
1900	490	4.5	USA (56)	Spain (11)	
1910	890	6.1	USA (56)	Mexico (6)	
1920	960	0.8	USA (58)	Chile (10)	
1930	1540	4.8	USA (42)	Chile (14)	Canada (9)
1940	2360	4.4	USA (33)	Chile (16)	Canada (13)
1950	2490	0.5	USA (33)	Chile (15)	Zambia (11)
1960	4420	5.9	USA (22)	Zambia (13)	Chile (12)
1970	6340	3.7	USA (25)	USSR (15)	Chile (11)
1980	7740	2.1	USA (15)	Chile (14)	USSR (13)
1990	8990	1.5	Chile (18)	USA (18)	USSR (10)
2000	13230	3.9	Chile (35)	USA (8)	Peru (7)
2007	15520	2.3	Chile (36)	Peru (8)	USA (8)

The remaining minerals, of little value, are discarded. Average head grade in most of the mines is less than 1% copper. Depending on the ore type (oxide or sulfide) the copper extraction process is designed. Hydrometallurgical processes, such as heap leaching is used to extract copper from copper oxide ore and some copper sulfide ores. Subsequently copper is extracted from the leach solution by solvent extraction and electrowinning. In the case of the Pyrometallurgical process, a copper sulfide concentrate, produced by froth flotation is smelted at high temperature and refined electrolytically.

1.1.1 Hydrometallurgy

Hydrometallurgical processes are used to extract copper from low grade ores, especially copper oxide by heap leaching (Figure 1.1). Copper ore from the mine is crushed typically with jaw crushers to pass about 0.5 inch top size. This crushed ore along with acid solution is introduced into rotating agglomeration drums. In the agglomeration drums fine ore particles are bonded to coarser ore particles via liquid bridges. The agglomeration product is stacked on the heap leach pad to about 7 meters in height.

Sulfuric acid solution is introduced on the top of the heap leach pad and dissolves copper as the solution passes through the heap. Copper recovery from the heap leach pad depends on the particle size distribution, of the ore particle damage, and quality of agglomerates. About 20% of worlds annual copper production is from leaching[3]. Bioleaching and autoclave [4] leaching are also performed depending on ore type and grade in order to improve the leaching efficiency.
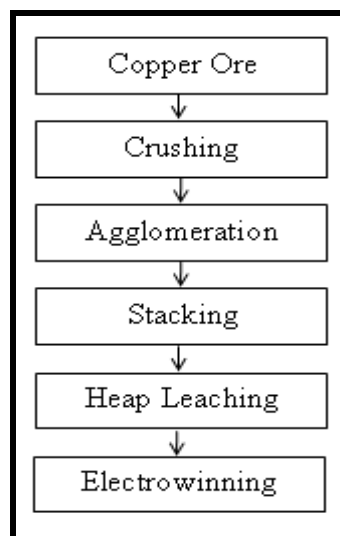
Figure 1.1 Typical hydrometallurgical process for recovery from heap leaching.

Pregnant leach solution (copper rich solution) from the leach pads is concentrated and purified by solvent extraction. During this solvent extraction stage, copper is separated from the acid solution using extractant to stabilize copper in an organic phase [5]. After stripping copper from the organic phase, copper metal is produced as cathodes during electrowinning.

1.1.2 Pyrometallurgy

About 80% of world's annual copper production is from the pyrometallurgy of copper sulfide ore [6] (Figure 1.2). Copper ore from the mine is crushed with a gyratory or jaw crusher. Discharge from crusher feeds a grinding circuit where, sag mills and ball mills further reduce the ore particles to about 75 microns in size. This slurry of fine ore particles is conditioned with chemicals to separate the copper sulfide mineral particles by flotation [7]. In About 80 to 90% of the copper is recovered during flotation.
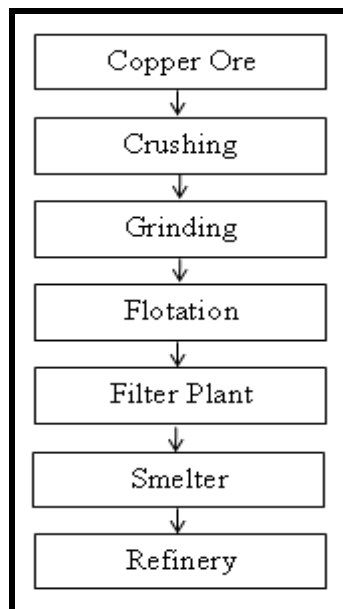
Figure 1.2 Typical pyrometallurgical process for copper recovery from sulfide ore.

The copper concentrate from flotation is sent to filtration to remove the water and to dry the concentrate. Dry concentrate is introduced into the smelting furnaces. Smelting furnace produces matte (high grade Cu/Fe sulfides). The matte is sent to the convertor where blister copper is produced. The blister copper is cast into anodes and refined electrolytically as final product.

In the present thesis research, pretreatment of copper ore prior to heap leaching (crushing and agglomeration) has been studied.

1.2 Pretreatment Stages Prior to Copper Heap Leaching

In addition to the chemistry of leach solution, crushing (particle size distribution), agglomeration, and heap structure also effect the extent and rate of copper recovery.

1.2.1 Crushing

Copper ore from the mine is reduced in size to about half inch top size by crushing. Gyratory crushers, jaw crushers and cone crushers are commonly used in the mining industry.

It has been reported that most of the energy in mineral processing operations is consumed in comminution [9]. As the copper ores are of low grade, mining companies are showing great interest in modifying the crushing circuit in order to improve the comminution efficiency and also reduce the energy consumption.

High-pressure grinding rolls (HPGR) have achieved considerable attention over the last several years given their high capacity and reduced energy consumption [21]. Particle damage and breakage in the HPGR is due to high inter particle stresses generated

when a bed of solids is compressed as it moves through the gap between two pressurized rolls [10 -16]. More detailed explanation of HPGR equipment is presented in Chapter 2.

1.2.2 Agglomeration

Run-of-mine or crushed ore is stacked on the leach pad and then the crest (top) of the heap leach pad is irrigated with leach solution that percolates by gravity through the heap. This leach solution dissolves the valuable metal and a copper rich solution discharges at the bottom [17, 18].

Copper recoveries from the heap leach pad are hindered due to the fine ore particles migration, thereby reducing the permeability of the heap leach pad [18]. To mitigate the permeability of leach pad and to improve the leaching response of the low grade ore, copper ore is agglomerated prior to heap leaching [18 - 33]. About 66% of copper mines that crush the ore perform agglomeration [18, 28]. During the agglomeration process crushed copper ore is mixed with acid solution in a rotating drum. A detailed explanation of the agglomeration process is provided in Chapter 3.

1.2.3 Heap Structure

The design of heap leach pad influences the copper recovery [19]. Construction of the heap can be classified into four categories

- Conventional or ''flat'' pads

- Dump leach system

- Valley fills

- On/off pads

Conventional leach pads are relatively flat, either graded smooth or terrain contouring on gentle alluvial fans such as in the Chilean Atacama desert, Nevada and Arizona, and the ore is stacked in relatively thin lifts (5 to 15m typically). Dump leach systems are similar or can include rolling terrain; the term ''dump'' usually means that the lifts are much thicker (up to 50m).

Valley fill systems are just that—leach ''pads'' designed in natural valleys using either a buttress dam at the bottom of the valley, or a leveling fill within the valley. On/off pads (also known as dynamic heaps) are hybrid systems. A relatively flat pad is built using a robust liner and over liner system [stacking]. Then a single lift of ore, from 4 to 10m thick, is loaded and leached. At the end of the leach cycle the spent ore is removed for disposal and the pad recharged with fresh ore. Usually loading is automated, using conveyors and stackers [19].

1.3 Research Objective

In this thesis research, experiments were done to examine the crushing and agglomeration steps in ore pretreatment prior to heap leaching. In the crusher evaluation experiments, copper ores were crushed by a traditional jaw crusher [16 - 19] and by HPGR. Particle size analysis, X-ray computed tomography analysis [20 – 25, 36], and column leaching experiments [3, 26, 27] were performed on the crushed ore to evaluate the effect of ore type, crusher type, and particle size on particle damage (microcracks), mineral exposure, and copper recovery.

In the case of agglomeration experiments, the main objective was to test the use of stucco as a binder in the agglomeration process. After obtaining promising results(good quality agglomerates) from preliminary tests, experimental variables

including the binder amount, acid solution amount, etc. were examined to establish preferred conditions for the production of quality agglomerates as determined by agglomerate size analysis, permeability test, column leaching tests, electrical conductivity test and visual inspection [17, 18, 28 to 35].

1.4 Organization of Thesis

The thesis considers two important pretreatment steps prior to heap leaching, crushing and agglomeration. After the introduction in Chapter 1, crushing conditions (jaw and HPGR) for heap leaching are evaluated and compared in Chapter 2. Since HPGR crushers have been reported to be more energy efficient, products from HPGR crushing are compared with products from the jaw crusher for both copper oxide ore and copper sulfide ore samples. Crushed ore size analysis, x-ray computed tomography analysis, and laboratory column leaching tests were performed to evaluate the effect of crushing conditions on particle damage and the leaching response.

In Chapter 3, agglomeration issues that affect the heap leaching operations are considered. The use of stucco as a binder in agglomeration for heap leaching is described in detail. Agglomerates that were formed with stucco binder are evaluated by determination of the agglomerate size distribution, permeability measurements, column leaching tests, electrical conductivity tests and visual inspection. Detailed experimental procedures, results and conclusions from the above mentioned tests are presented in Chapter 3. Finally the conclusions and future research recommendations are made in Chapter 4.

CHAPTER 2

EVALUATION OF CRUSHING AND

ASSOCIATED ISSUES

2.1 Introduction

Comminution circuits must be designed in such a way that they are both energy efficient and at the same time produce the desired particle size distribution. In the case of heap leaching, high mineral grain exposure and micro crack formation from crushing would be expected to result in increased copper recovery during heap leaching. This is because leach solution would penetrate through the micro cracks and solubilizes the mineral grains. In the present research the effect of crusher type (jaw crusher and HPGR), copper ore type (oxide, sulfide) and particle size (0.25 inch to 100 mesh) on particle damage and copper recovery were studied.

Description and the operation of jaw crushers are well known and discussed in the literature. In contrast, HPGR crushing is a relatively, new technology. It has been reported that HPGR crushers are more energy efficient and these crushers continue to be evaluated for use in the mining industry [10]. HPGR is predominantly used in the cement industry and was introduced at the mining industry for the first time in Argyle diamonds mine, Australia.

HPGR has two counter-rotating rolls (Figure 2.1). One of the rolls is fixed and other is floating. The material to be fractured is fed through the gap between the rolls and is crushed by the mechanism of interparticle breakage. The pressure for crushing is transmitted by a hydraulic system via the floating roll and is a control variable for HPGR crushing.

2.2 Sample Preparation

Figure 2.2 presents the flow sheet of sample preparation. About 450 kg of both copper oxide and copper sulfide ore samples first were crushed using a primary crusher. Crushing was done to try and achieve the same product size distribution for each crushing condition.
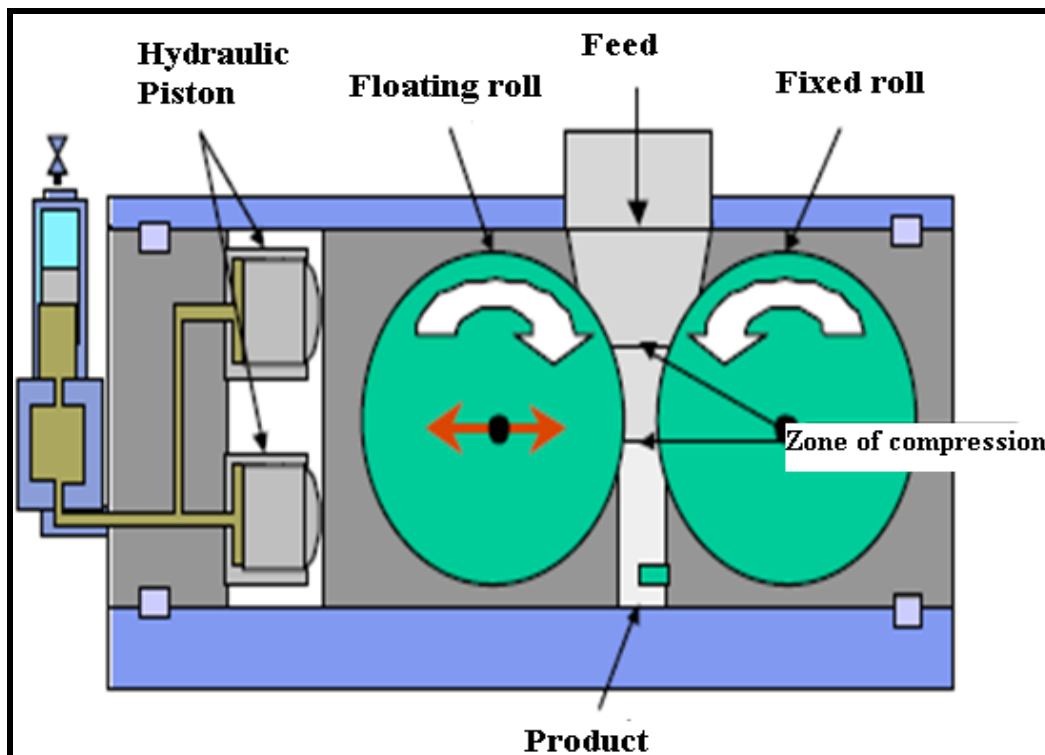
Figure 2.1 Schematic of HPGR.
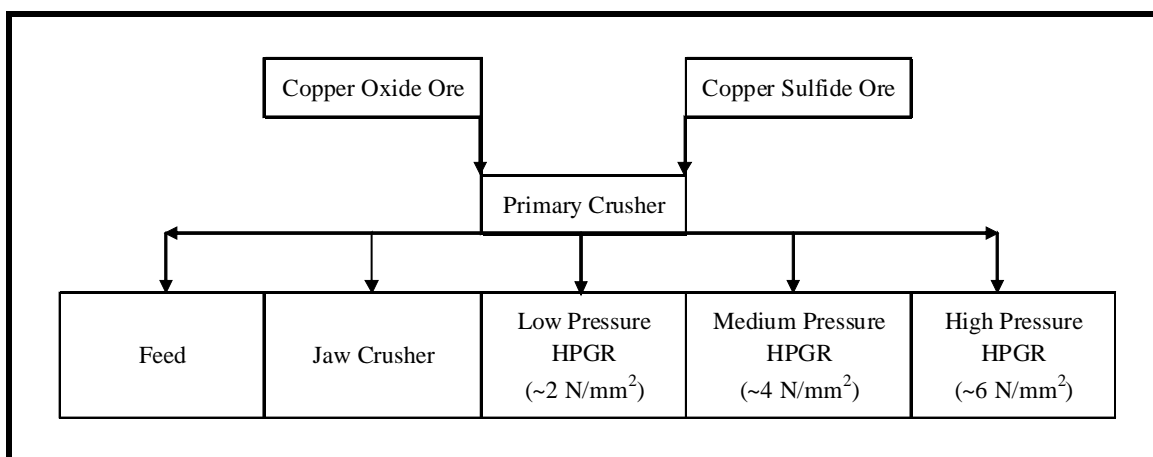
Figure 2.2 Sample preparation flow sheet.

The crushed material from each ore type was split into 5 parts (64 kg for each part). After splitting 4 parts from each ore type were crushed further. One split for subsequent crushing by the jaw crusher and the other three splits were used for HPGR crushing at different operating conditions. The 5th split from both ore types was retained and introduced as the feed sample.

These final products (5 parts from each ore type) were sent to the University of Utah from a copper mining company. Sections 2.3 to 2.6 provide a detailed discussion of experimental procedures and results. Copper head grades are about 0.3% for copper oxide ore and 0.8% for copper sulfide ore samples. Table 2.1 presents the major copper minerals in the copper ore samples that were considered in this thesis research.

Table 2.1 Major copper minerals in copper oxide ore and copper sulfide ore.

	Copper Oxide Ore	Copper Sulfide Ore
Major Copper Minerals	Chrysocolla	Chalcocite Covellite Chalcopyrite

2.3 Methods and Results

2.3.1 Particle Size Distributions of Crusher Products

Particle size analysis was the first test performed on the crushed samples. Figures 2.3 and 2.4 present the similar particle size distributions of copper oxide ore and copper sulfide ore achieved with the different crushing methods. P_{80} value from the Figures 2.3 and 2.4 is used to correlate the particle sizes obtained from different crushing methods.
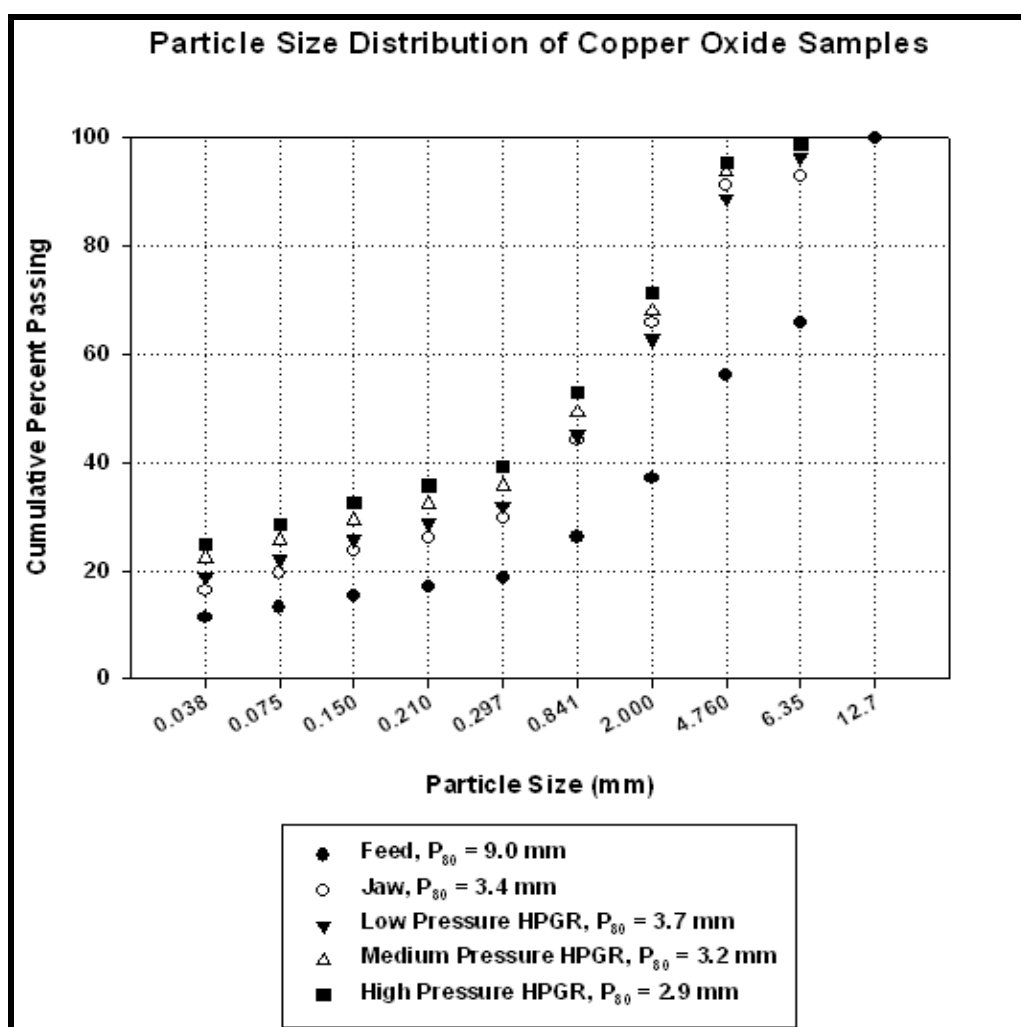
Figure 2.3 Particle size distributions of copper oxide ore samples for different crushing methods.
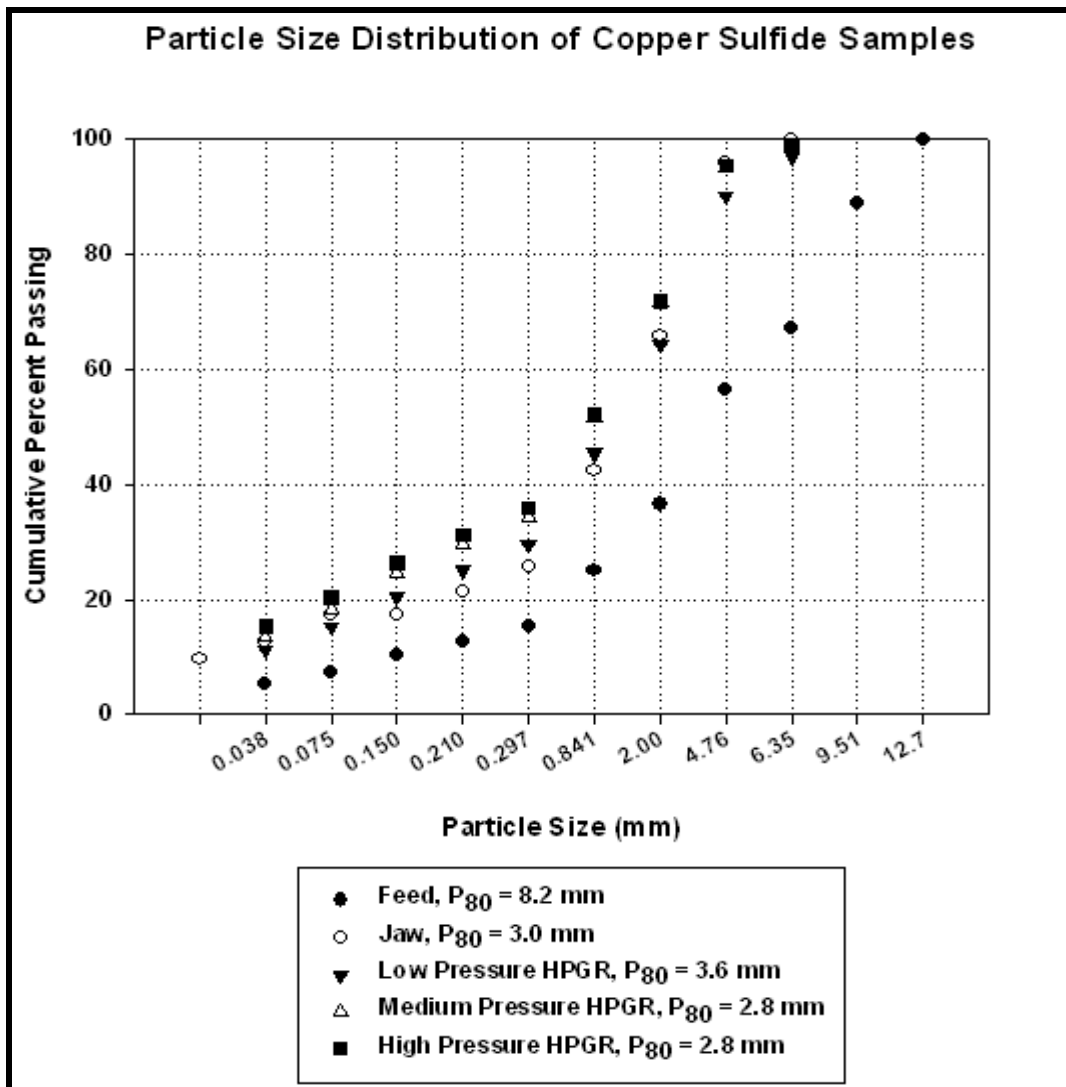
Figure 2.4 Particle size distributions of copper sulfide ore samples for
different crushing methods.

From the above Figures 2.3 and 2.4 it is clear that the high pressure HPGR
product is slightly finer than the products from the jaw crusher, low pressure HPGR, and
medium pressure HPGR. The P_{80} values for the high pressure HPGR samples are 2.9mm
and 2.8mm respectively for copper oxide ore and copper sulfide ore samples (Figures 2.3
and 2.4). Whereas the P_{80} values for the other crushing conditions generally are greater
than 3.0mm for both ore types. Another observation from the particle size distribution

data is that the copper sulfide ore appears to be softer than the copper oxide ore. Since the P_{80} values for copper sulfide samples is less when compared to the P_{80} values of copper oxide samples for all the crushing conditions (Figure 2.3 and 2.4).

Each size class of the crushed material was then examined using X-ray micro computed tomography to determine the extent of particle damage and the extent of mineral exposure.

2.3.2 Mineral Exposure and Particle Damage

As a result of particle size reduction by crushing, mineral grain exposure and particle damage (micro cracks) occurs. The amount of valuable mineral grains that are present at the surface of the ore particles influences the copper recovery values from heap leaching. Similarly micro crack formation in the particles would result in increased copper recovery from heap leaching. Both phenomena make the copper mineral grains more accessible to the leach solution and increased leaching kinetics. X-ray micro computed tomography was used to analyze the mineral exposure and particle damage.

In addition to mineral exposure analysis and particle damage, mini-column leaching tests were performed to see if cone-beam X-ray micro tomography (XMT) can be used to quantify the leaching reaction progress and the significance of surface wetting and diffusion during column leaching for unsaturated flow conditions. In this regard, copper oxide ore samples (particle size of 2.0 x 0.850 mm) from the high pressure HPGR (6 N/mm) product and the jaw crusher product were used in column leaching experiments to further evaluate the effect of particle damage due to crushing technique on leaching rate and extent of reaction. These results are reported in the section 2.3.2.5.

2.3.2.1 X-Ray Micro Computed Tomography (XMT)

X-ray micro computed tomography (XMT) had its origin in the medical services and has now been applied to nonmedical and industrial applications [20 to 25] [36]. By using XMT mineral grain exposure analysis has been performed previously, the extent of the damage in crushed products has not been evaluated previously by using XMT. In general tomography refers to the cross-sectional imaging of an object from either transmission or reflection data collected by illuminating the object from many different directions. Thus, the image from an X-ray CT scan is a cross-sectional representation of the X-ray attenuation during transmission through the object under examination. X-ray CT techniques have an inherent advantage in providing detailed images of the internal structures of opaque materials in a nondestructive manner.

Cone-beam geometry X-ray Micro Tomography (XMT) is well suited for the quantitative determination of the mass density distribution of the particles with a size of less than a few hundred microns. Rather than rotating the X-ray source and detectors during data collection, as in medical CT technology, the specimen is rotated. Instead of generating a series of two-dimensional sliced images from one dimensional projections, a three-dimensional reconstruction image array is created directly from two dimensional projections. Figure 2.5 shows a schematic diagram for the cone-beam geometry x-ray micro-CT system. X rays from a micro focus X-ray generator are partially attenuated by a specimen that is made to rotate in equal steps in a full circle about a single axis close to its center. At each rotational position, the surviving X-ray photons are detected by a planar two-dimensional array (image intensifier) large enough to contain the shadow of the specimen.
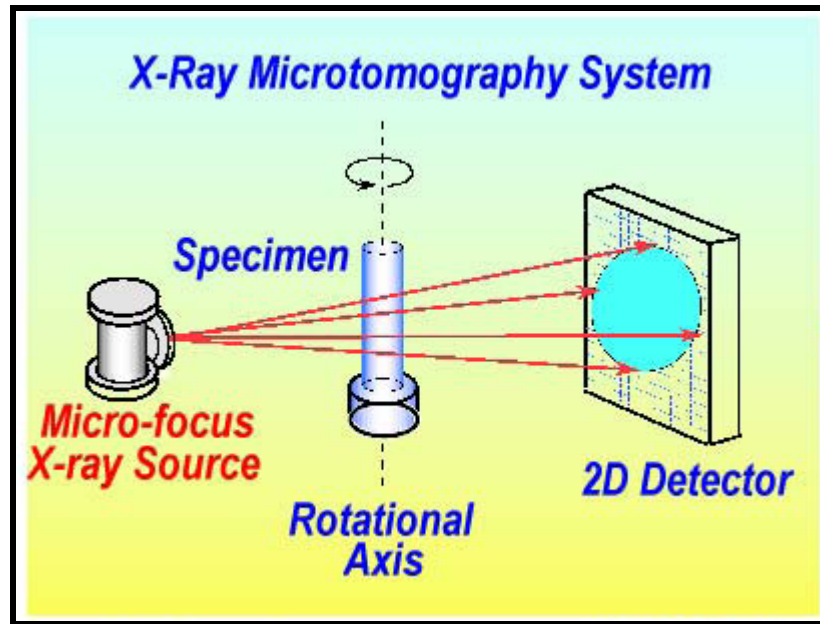
Figure 2.5 Schematic of x-ray micro computed tomography system
(Adapted from reference 20).

These two-dimensional projection images are collected using conventional video technology. The video signal is then converted to a two-dimensional digital array by an image processing system. Finally, a three-dimensional image array is reconstructed from the collected set of projection images. This reconstruction algorithm is a generalization in three dimensions of the widely used convolution-back projection method [20 to 25] [36].

2.3.2.2 Sample Preparation

A total of five particle size fractions (+6.3, 6.3 x 4.75, 4.75 x 2.0, 2.0 x 0.850, 0.850 x 0.425 mm) were scanned for each ore and for each crushing method. This corresponds to a total of 50 scans of packed particle beds using 10 and 20 μm resolution and 29 scans using 40 μm resolution. Table 2.2 summarizes the weight and number of particles used for the XMT scans.

2.3.2.3 Mineral Exposure

Particle recovery in heap leaching operations can be estimated for a specific particle size distribution, once the relationship between grain exposure and particle size is determined for the ore sample [20 to 26]. It is therefore extremely important to characterize the percentage of the exposed valuable mineral grains in the ore as a function of particle size. X-ray micro tomography (XMT) can be used for the direct determination of the percentage of exposed valuable mineral grains in multiphase particles which vary in size from 100 mm down to a few hundred microns. Voxel resolution as high as ten micrometers was achieved with in this research using the point projection CT system available in the Department of Metallurgical Engineering.

Representative samples of particles from five different size intervals were taken and put into a cylindrical container for XMT analysis. Scanning time was varied depending on the voxel resolution and the number of views. For example, for 20-micron voxel resolution and 512x512x300 data set, the scanning time is about half hour and full three dimensional reconstructions requires approximately an additional one hour. Figures 2.6 and 2.7 represent mineral exposure results for copper oxide ore and copper sulfide ore as a function of both particle size and crushing method.

Table 2.2 Copper oxide ore and copper sulfide ore samples prepared by different crushing methods for X ray computed tomography analysis.

Particle Size mm	Weight g	Number of Particles	Voxel Resolution microns	Copper Oxide %Cu	Copper Sulfide %Cu
6.30	4 to 6	10 to 20	40	0.32	0.89
6.30 x 4.75	4 to 6	20 to 40	40	0.32	0.83
4.75 x 2.00	4 to 6	70 to 90	40	0.28	0.78
2.0 x 0.85	0.3 to 0.4	100 to 200	20	0.28	0.71
0.85 x 0.42	0.06 to 0.08	>200	10	0.28	0.88
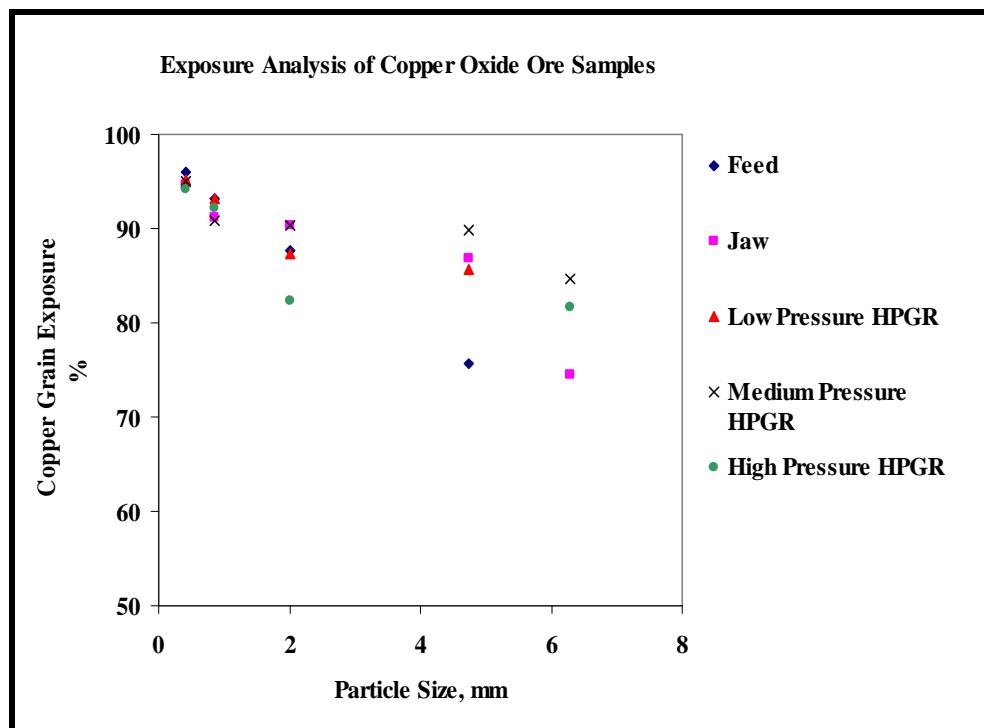
Figure 2.6 Relationship between mineral exposure and particle size (copper oxide ore).
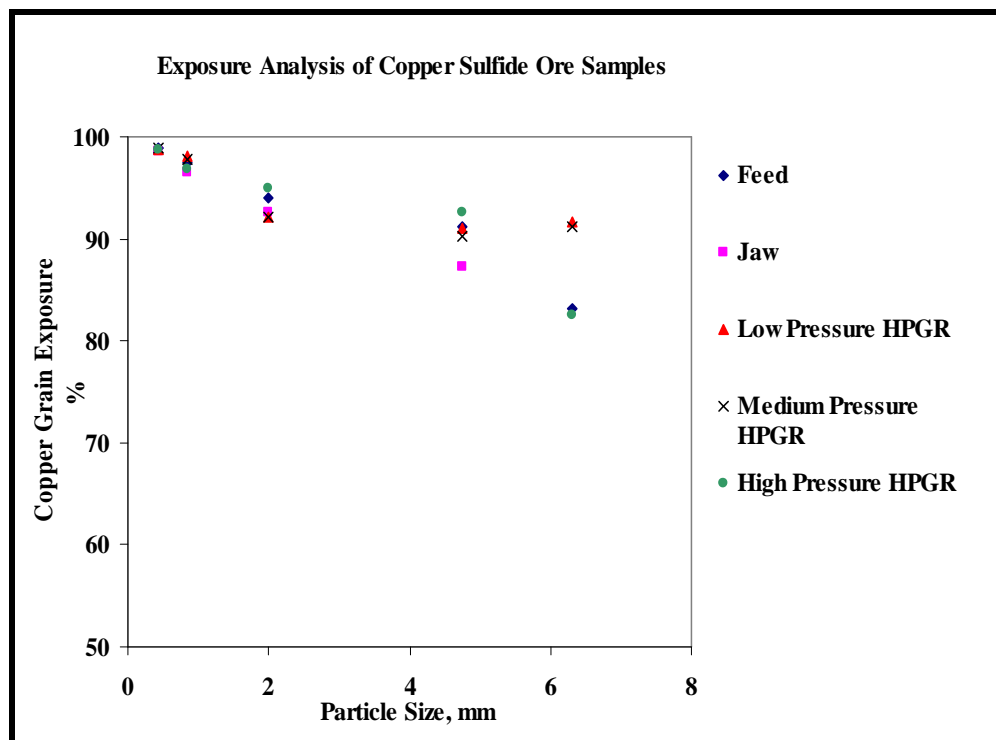
Figure 2.7 Relationship between mineral exposure and particle size (copper sulfide ore).

It is noted that more than 90% of the copper mineral grains in the copper sulfide ore sample are exposed for most of the size fractions less than 6 mm (Figure 2.7); however, only the size fractions less than 2 mm gave 90% copper mineral grain exposure in copper oxide ore samples (Figure 2.6). As expected, the copper-bearing grains of the copper oxide sample are much smaller and more disseminated inside the host rock. In addition, it is important to note that these exposure curves have a common shape which is related to the grain size distribution of the copper minerals. The relationship between the percent of grain exposed and particle size provides the basis for the prediction of copper recovery for a known particle size distribution (PSD). Combining the results of the chemical and the mineral exposure analysis, the practical recovery of copper can be estimated for a specific particle size distribution.

As expected, the exposure decreases with an increase in particle size. The slope of the curve is much more pronounced below 2.0 mm for the copper oxide sample indicating that grain the exposure can be increased significantly by increasing the amount of material in the intermediate size classes (Figure 2.6).

Grain exposure of copper oxide ore samples was less than that found for copper sulfide ore samples but exposure was affected by crusher type. Data points are spread out in copper oxide exposure data for different crushing methods (Figure 2.6). Copper oxide column leaching results show that greater recovery was generally achieved for all particle sizes prepared by HPGR high pressure crushing condition. For the copper sulfide ore samples mineral exposure was high and independent of crusher type (Figure 2.7). Exposure does not vary much with particle size and generally greater than 90%. Data points are concentrated at particular exposure values in copper sulfide for different

crushing methods (Figure 2.7).The higher copper recoveries for the sulfide ore may be expected to due to greater exposure.

2.3.2.4 Particle Damage

The effect of crusher type on particle damage was studied for both ores and all size classes. Micro crack formation during crushing should result in increased copper recovery from heap leaching. This is because the leach solution would penetrate through the micro cracks and solubilizes internal mineral grains. A total of 5 size classes and 5 crushing methods were studied to determine particle damage for both copper oxide and copper sulfide ores. In the Figures 2.8 and 2.9 the X-ray computed tomography scans of copper oxide and copper sulfide sample are presented. Micro cracks are identified with red color arrows.

Particles with cracks are counted for each ore type and crushing method and are presented in the Figures 2.10 and 2.11. The corresponding data is presented in the Appendix A. From the Figures 2.10 and 2.11 two conclusions can be made.

1. High pressure HPGR is producing more cracks than the rest of crushing method in most of the particle size classes.

2. As particle size is decreased amount of cracks is increased in copper oxide samples.

3. For high pressure HPGR copper oxide samples crack density increased from 40% to 80% as the particle size is decreased from 1/4inch to 200mesh.

4. Such trend is not clear in copper sulfide samples (about 80% of cracks are seen in all high pressure HPGR copper sulfide samples irrespective of particle size).
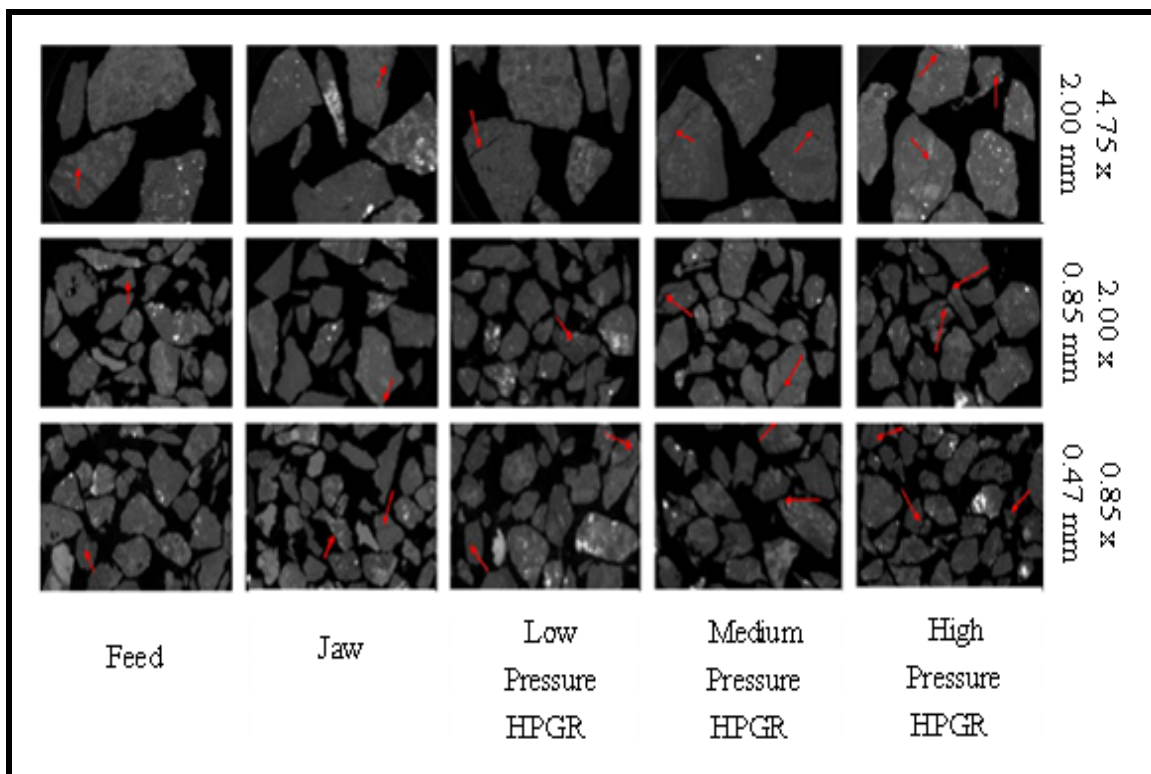
Figure 2.8 X-ray computed tomography scans for copper oxide samples.
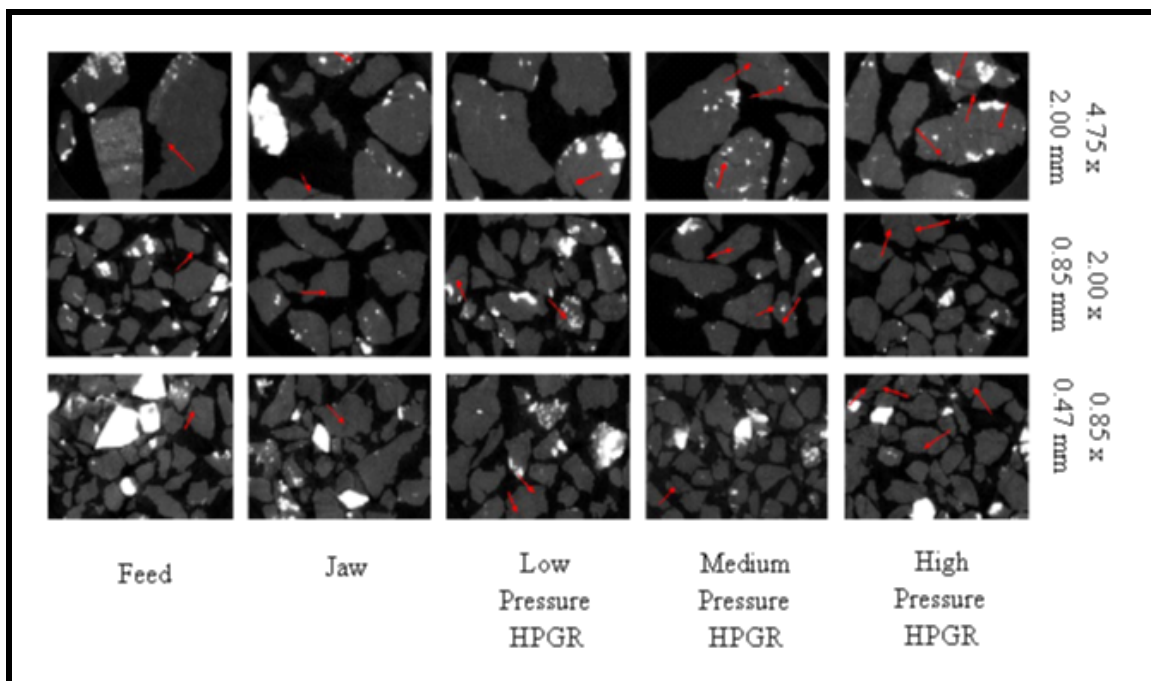
Figure 2.9 X-ray computed tomography scans for copper sulfide samples.
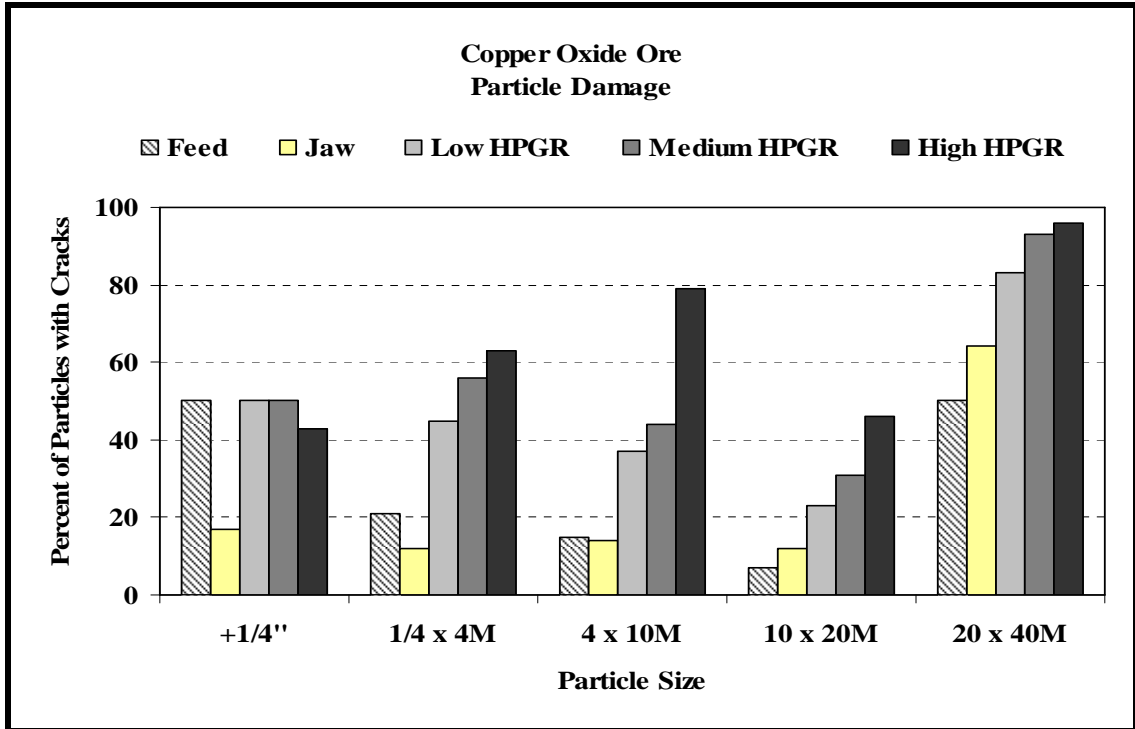
Figure 2.10 Particle damage for copper oxide samples.
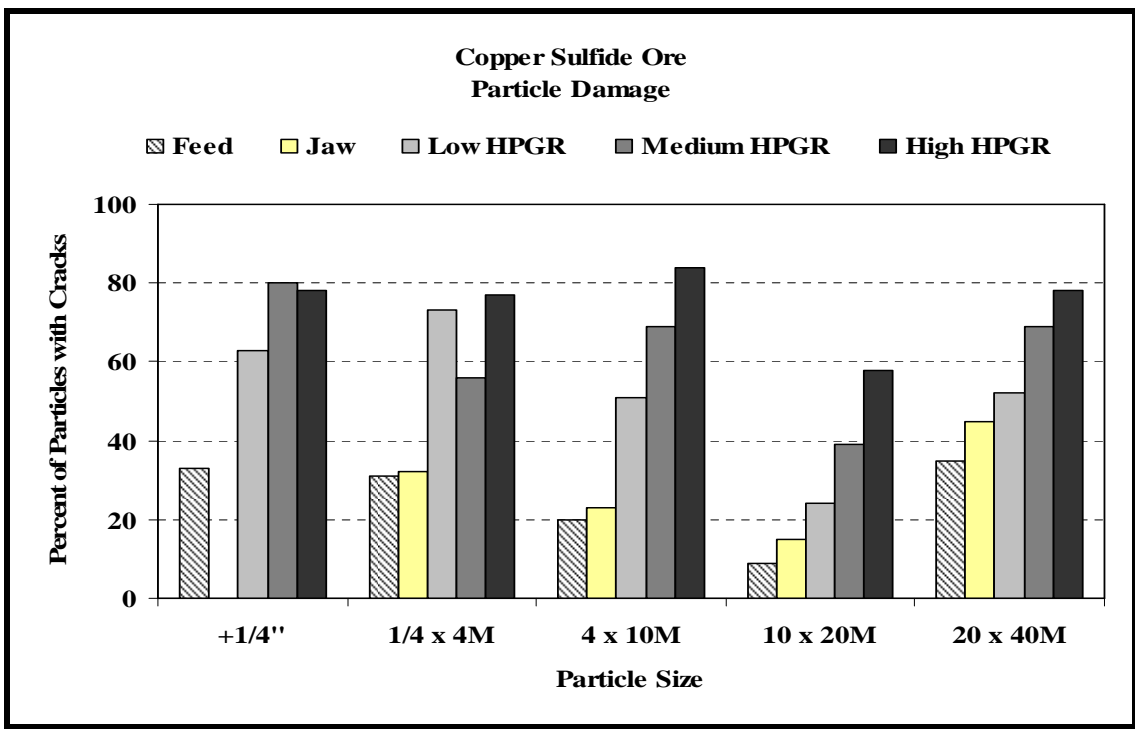
Figure 2.11 Particle damage for copper sulfide samples.

2.3.2.5 Mini Column Leaching

Ten grams each of jaw crusher product (10 x 20 mesh) and high pressure HPGR product (10 x 20 mesh) of copper oxide ore were selected to examine mini column leaching characteristics. Disappearance of chryscosocolla, pyrite, chalcopyrite and others was tracked by XMT using 40 micron voxel resolution. XMT scans were done at 2 hours, 6 hours, 1 day, 11 days and 29 days of leaching. Figure 2.12 show internal grains for high pressure HPGR and Jaw crusher products after 29 days of mini column leaching.
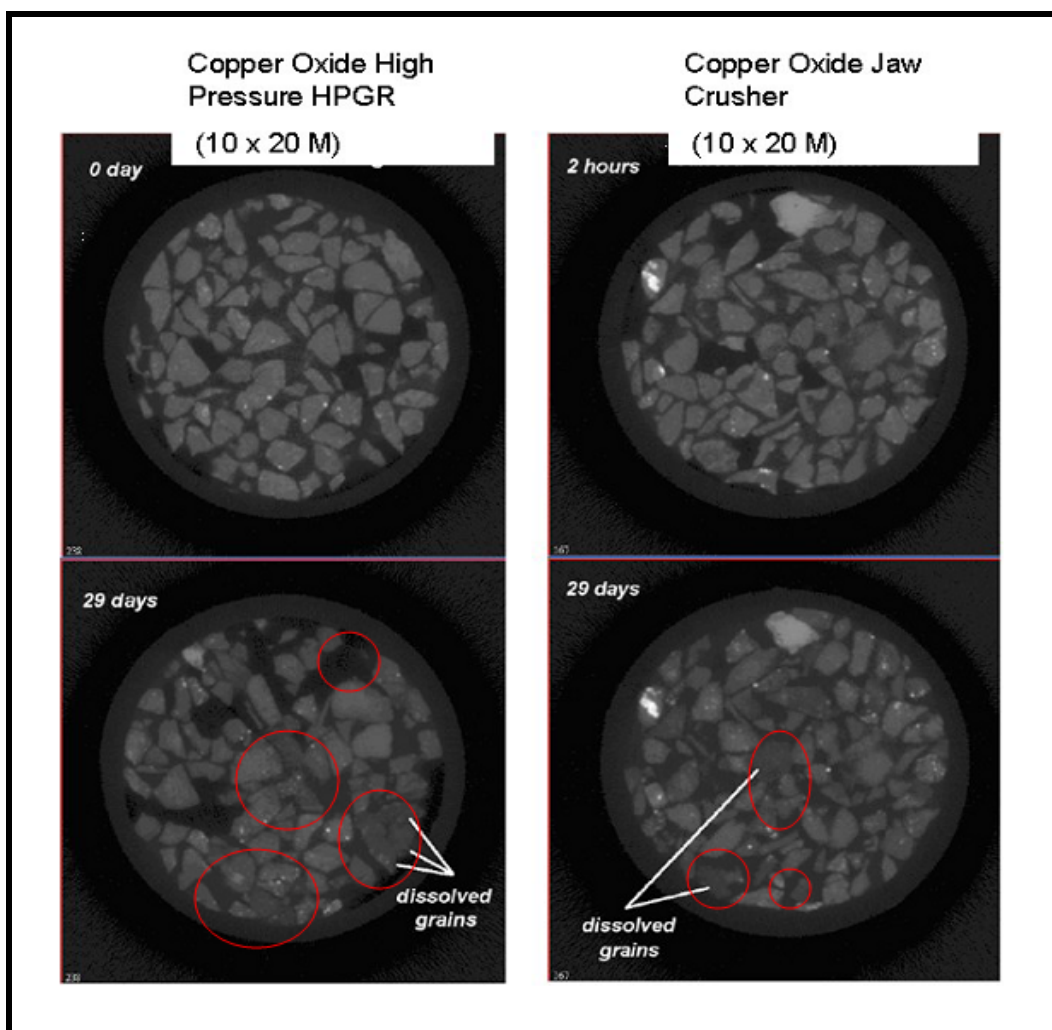
Figure 2.12 Tracking mineral grains during minicolumn leaching of copper oxide ore samples (2.0x0.85 mm), from high pressure HPGR and jaw crusher products.

Selected grains are indicated to illustrate the disappearance. Some of the grains did not dissolve due to a lack of exposure, kinetic factors associated with grain size, and decrease in crack density. The overall tend shows grains in the high pressure HPGR product dissolve to a greater extent than grains in the jaw crusher product during minicolumn leaching. Some of the dissolved copper grains are identified in red circles in the Figure 2.12.

2.3.3 Laboratory Column Leaching Experiments

After preparation and particle size analysis of the crushed products, mineral exposure, particle damage and mini column leaching tests were completed as a function of crusher type and ore type. Finally laboratory column leaching experiments were designed to better understand the effect of crusher type and ore type on the leaching response.

2.3.3.1 Sample Preparation

Copper oxide ore and copper sulfide ore samples from five different methods were size classified in to six different size fractions. Figure 2.13 gives the flow sheet of sample preparation. Sixty samples were prepared from two ore types (oxide and sulfide), five crushing techniques (fee, jaw, low pressure HPGR, medium pressure HPGR, high pressure HPGR) and six different size classes (+1/4", ¼" x 4M, 4 x 10M, 10 x 20M, 20 x 40M, 40 x 100M) (Figure 2.13). In order to validate the results, each laboratory column leaching experiment was duplicated.
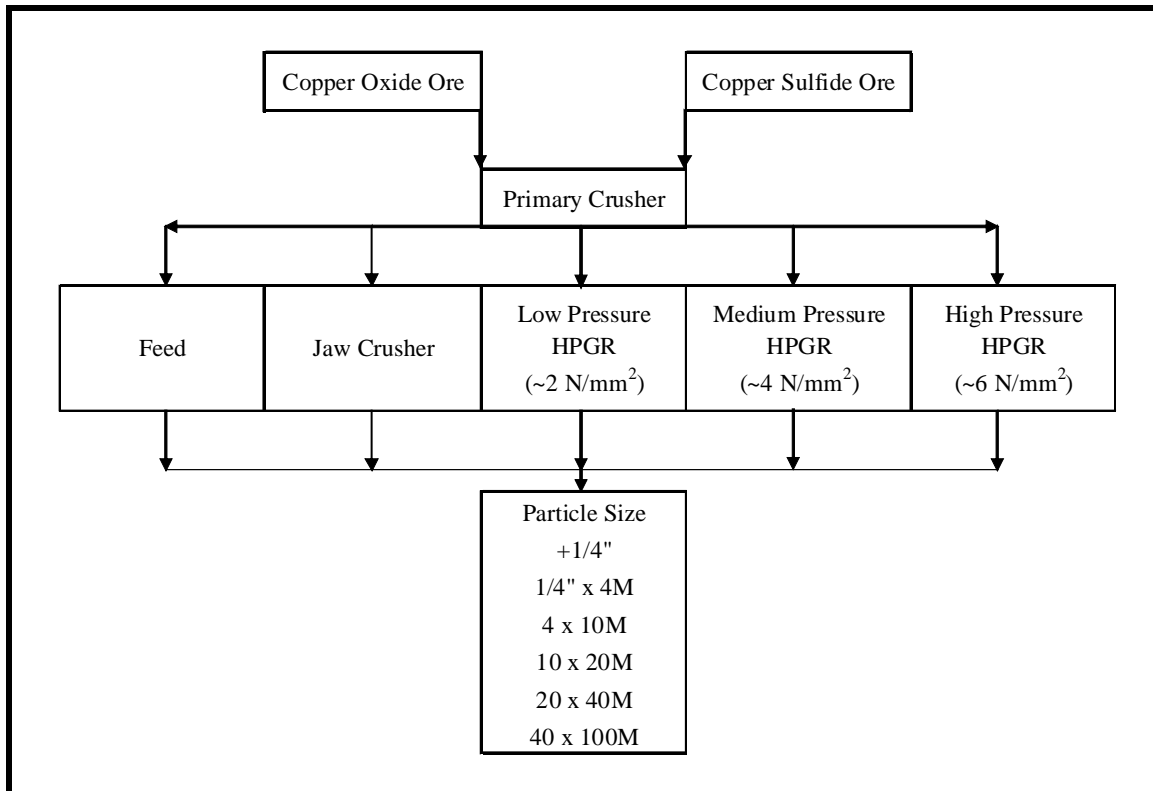
Figure 2.13 Sample preparation flow sheet for laboratory column leaching.

Forty five grams of ore material that is required for laboratory column leaching was sampled from each of the above 60 samples (Figure 2.13) by using chute riffles (Figure 2.14). The average head grade for the copper oxide ore was 0.3% Cu, and for the copper sulfide ore was 0.8% Cu. Tables 2.3 and 2.4 summarizes the head analysis of the copper oxide ore and copper sulfide, respectively, sample ore.

2.3.3.2 Experimental Procedure for Laboratory Column Leaching

Laboratory column leaching tests were carried out with a disposable syringe (60 cc volume), packed with 45 grams of sample. Columns were irrigated from the top with an intravenous (IV) system using acidic leach solutions which were provided by the

Figure 2.14 Typical chute riffles.

mining company. Two different leach solutions were used for leaching copper oxide ore and copper ore sulfide samples.

Before the experiment started, copper oxide leach solution and copper sulfide leach solutions were filtered, because they contained some particles. These solutions were used to fill the IV systems. The solutions were passed through the columns once at a 8 L/m^2/hour flow rate.

No solution recycling was done. In spite of the filtration, sometimes agglomeration occurred in which case the tubing for the IV system was blocked. To overcome this problem, flow rates for the IV systems were checked regularly. Each sample is leached for 240 hours. Pregnant leach solutions were collected at the bottom of the column on an hourly basis. Solutions were kept in disposable scintillation vials to analyze for copper concentration.

Figure 2.15 and Figure 2.16 show a schematic and photo for the column leach experiments. Each experiment was run with a duplicate to check on the reproducibility of the experimental results.

Table 2.3 Head grade for copper oxide ore samples.

Size	%Cu, Head Grade From Copper Oxide Replicate 1					%Cu, Head Grade From Copper Oxide Replicate 2				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
+1/4"	0.27	0.33	0.24	0.31	0.32	0.33	0.27	0.22	0.28	0.32
1/4 x 4M	0.26	0.26	0.25	0.26	0.32	0.27	0.34	0.29	0.25	0.3
4 x 10M	0.3	0.31	0.22	0.24	0.28	0.32	0.3	0.24	0.29	0.3
10 x 20M	0.29	0.27	0.26	0.25	0.28	0.33	0.32	0.3	0.31	0.28
20 x 40M	0.3	0.29	0.26	0.27	0.28	0.33	0.32	0.29	0.31	0.31
40 x 100M	0.35	0.32	0.3	0.31	0.31	0.37	0.33	0.32	0.34	0.36

Table 2.4 Head grade for copper sulfide ore samples.

Size	%Cu, Head Grade From Copper Sulfide Replicate 1					%Cu, Head Grade From Copper Sulfide Replicate 2				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
+1/4"	0.46	0.49	0.73	0.75	0.89	0.9	-	0.58	0.71	0.75
1/4 x 4M	0.65	0.72	0.66	0.81	0.83	0.63	0.59	0.7	0.78	0.75
4 x 10M	0.72	0.66	0.62	0.7	0.78	0.62	0.67	0.72	0.76	0.74
10 x 20M	0.7	0.62	0.61	0.64	0.71	0.72	0.72	0.68	0.78	0.77
20 x 40M	0.95	0.97	0.79	0.91	0.88	0.74	1	0.99	0.95	0.93
40 x 100M	1.02	1.03	0.93	1.04	0.99	0.83	0.8	-	1	-
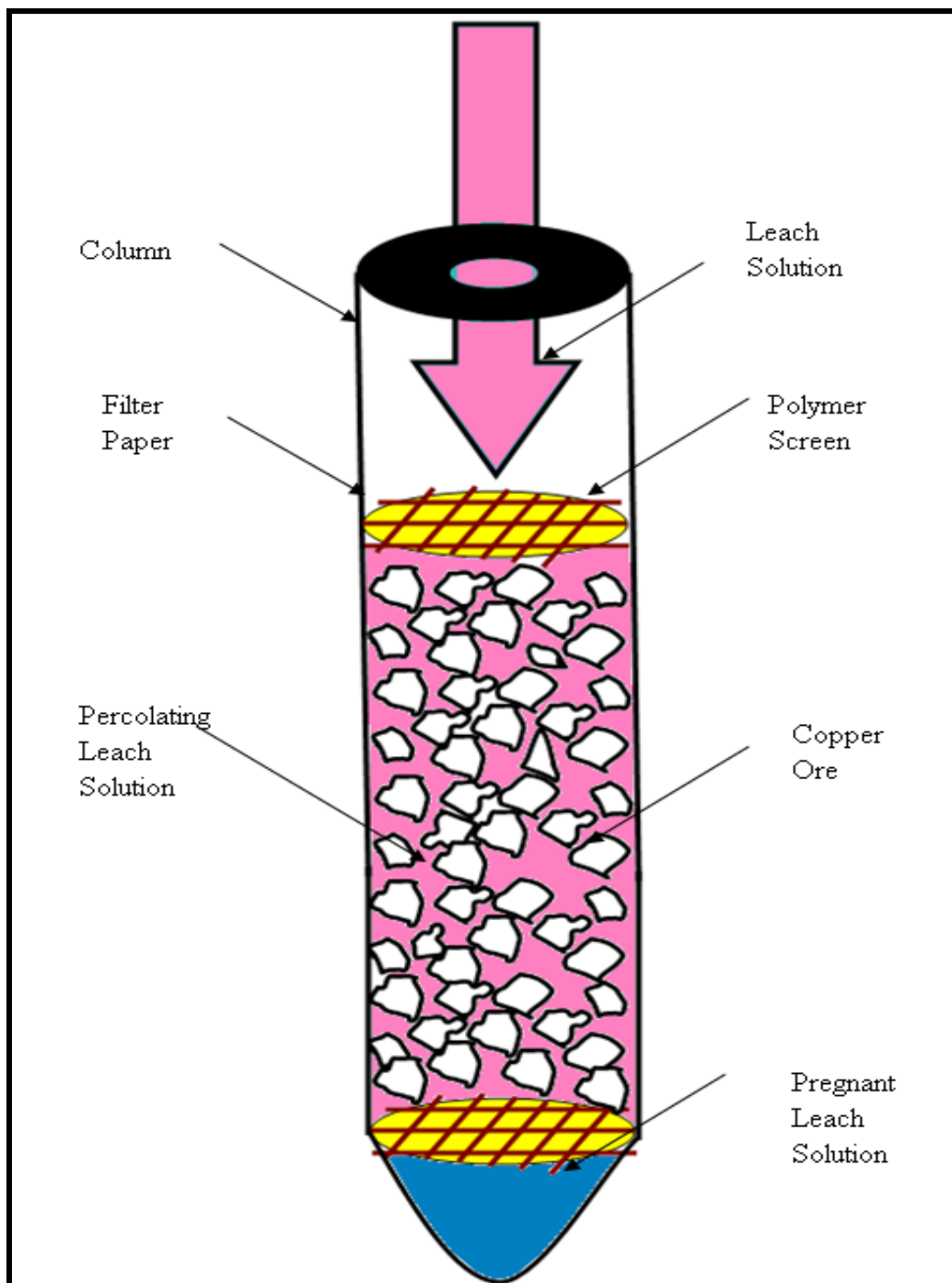
Figure 2.15 Schematic representation of laboratory column
leaching experiments.

Figure 2.16 Laboratory column leaching setup showing IV irrigation
and disposable syringe bodies containing ore samples.

Three thousand samples were collected in disposable scintillation vials. However, higher copper concentrations could not be measured directly from the (ICP) Inductively Coupled Plasma instrument. Therefore, each solution was diluted by a factor of 10 to determine the copper content in the leaching solutions. This procedure was followed for all samples.

Samples of the copper oxide leach solution and copper sulfide leach solutions were sent to the mining company to determine the copper concentration in the solutions. Also the copper concentration was determined using the ICP instrument in the Metallurgical Engineering Department at the University of Utah (U of U). The copper concentration and pH of the inlet solution are listed in Table 2.5. Analytical results from

Table 2.5 Comparison of copper concentration and initial
pH of the leach solution.

| Solution Name | Cu (g/L) | | pH |
	Results from Mining Company	Results from U of U	
Copper Oxide	0.13	0.13	2
Copper Sulfide	0.18	0.19	1.1

the mining company and from the ICP at the U of U are almost equal (Table 2.5) and demonstrate the validity of the results.

2.3.3.3 Laboratory Column Leaching Results

The inlet leach solutions contain some amount of copper (Table 2.5). The column leaching recovery was calculated for each sample as a function of time from

$$R_{Cu} = \frac{(C_t - C_o)V_t}{Copper\ Content\ of\ Feed} \tag{2.1}$$

R_{Cu} = Percent copper recovery from leaching

C_t = Copper concentration in pregnant leach solutions at time t (g/L)

C_o = Copper concentration in inlet leach solution (g/L)

V_t = Volume of pregnant leach solution at time t (V)

The detailed plots of recovery vs time are presented in Appendix B and C.

2.3.3.3.1 Copper Recovery as a Function of Particle Size and Crusher Type

Figures 2.17 to 2.19 show the copper recovery after 10 days of leaching as a function of particle size and crusher type for the copper oxide ore samples. Detailed explanation of Figures 2.17 to 2.19 is presented in Appendix B.

From the Figures 2.17 to 2.19 two conclusions can be made regarding the copper oxide ore.

1. More copper is recovered from high pressure HPGR products in most of the cases.

2. As the particle size decreases copper recovery increases from about 50 % to 80%.

These results are in correspondence with particle size analysis (Figure 2.3), mineral exposure (Figure 2.6) and particle damage (Figure 2.10). For example, P_{80} values for high pressure HPGR samples are less when compared to samples from other crushing methods (Figure 2.3).
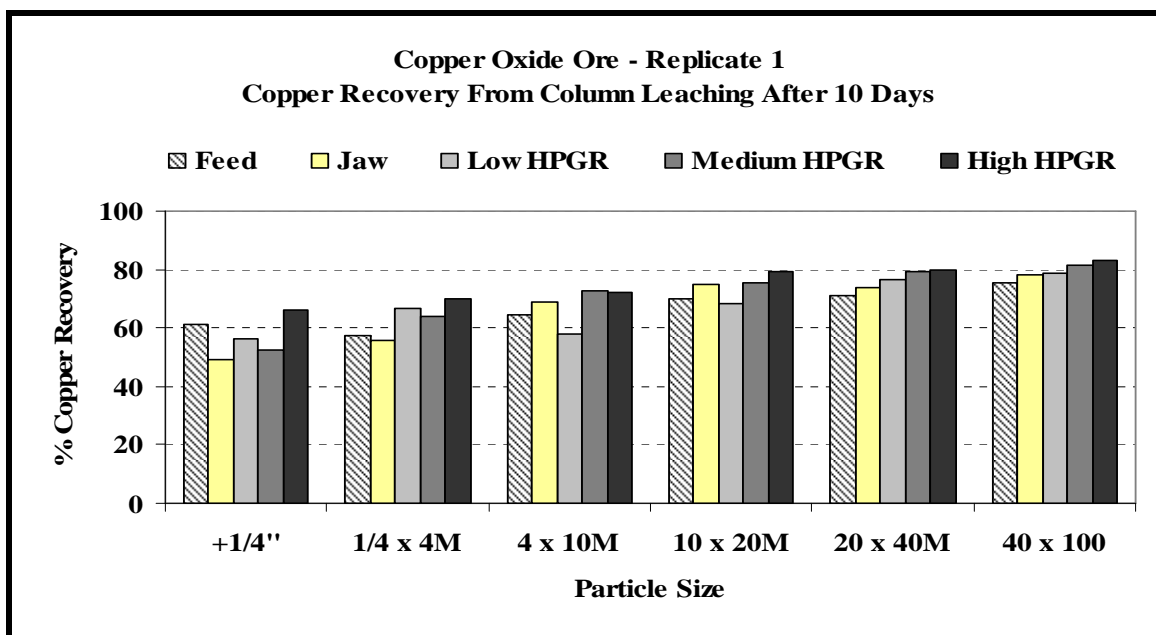
Figure 2.17 Copper recovery from copper oxide ore samples for different crushing methods and particle sizes (Replicate 1).
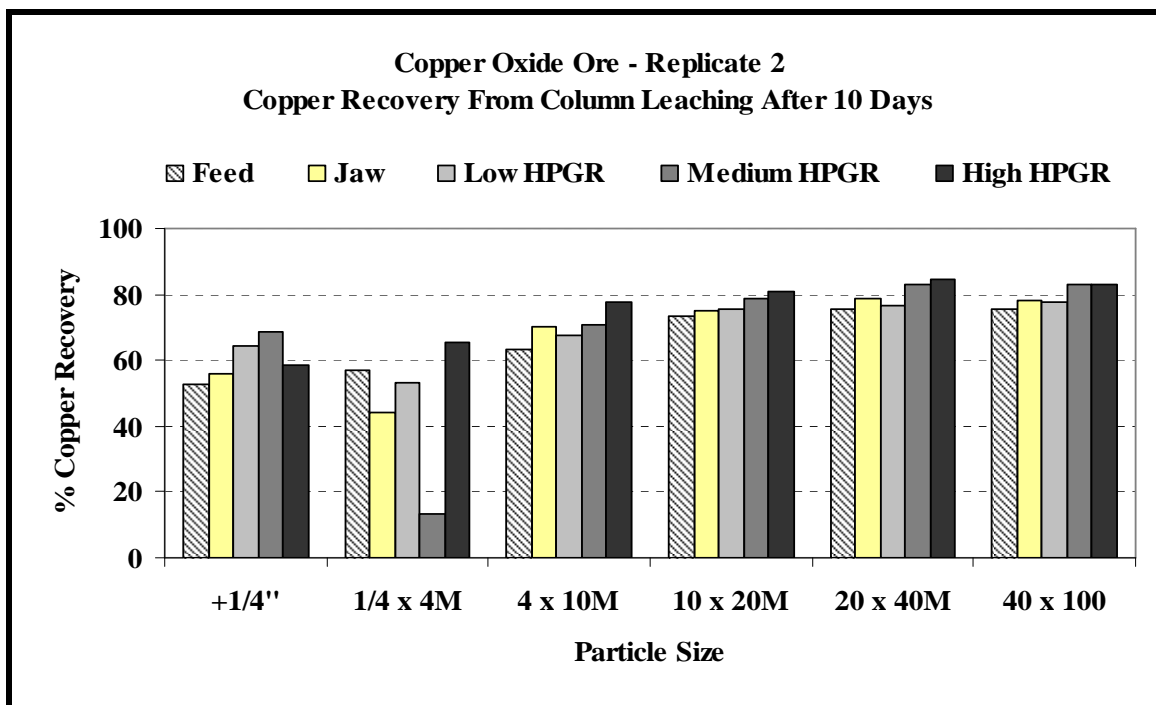
Figure 2.18 Copper recovery from copper oxide ore samples for different crushing methods and particle sizes (Replicate 2).
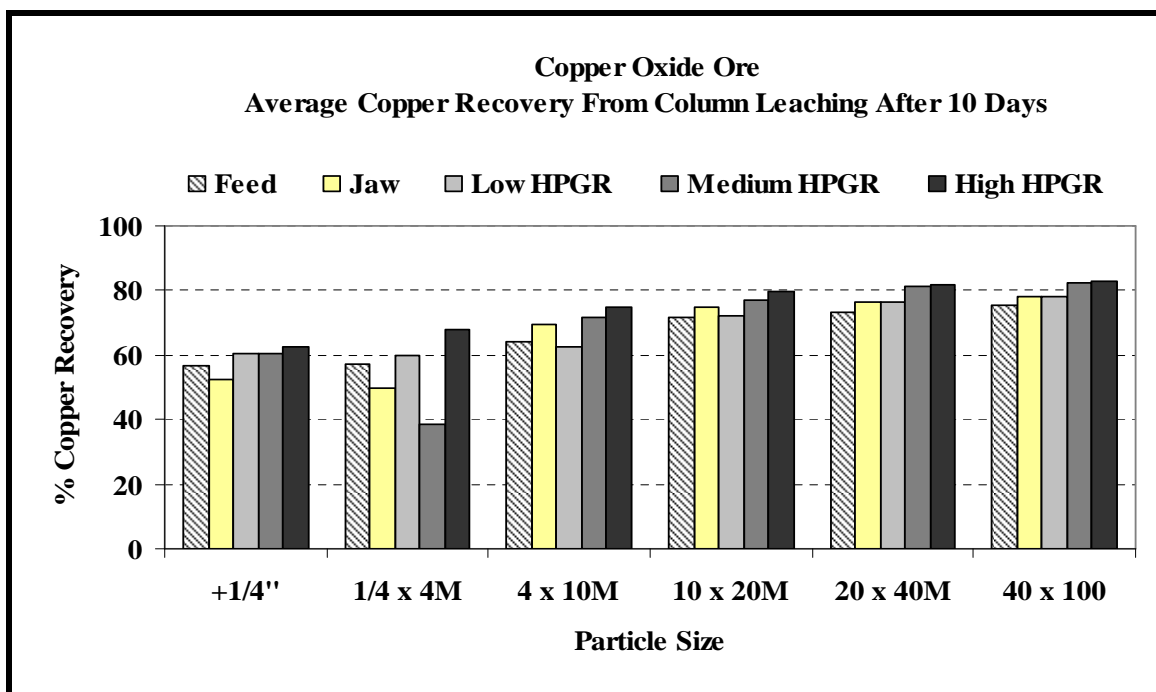
Figure 2.19 Average copper recovery from copper oxide ore samples for different crushing methods and particle sizes.

As particle size is decreased percent copper grain exposure for high pressure HPGR sample is increased from 75% at 7mm size to 95% at 0.1mm size (Figure 2.6). Similarly percent particles cracked increased from 40% to 90% for high pressure HPGR sample as the particle size is decreased from +1/4" to 20 x 40M (Figure 2.10). Figure 2.19 presents the average copper recoveries from copper oxide ore column leaching replicates 1 and 2.

Figures 2.20 to 2.22 shows the copper recoveries as a function of particle size and crusher type for copper sulfide samples. Detailed explanation of Figures 2.20 to 2.22 is presented in Appendix C. From the Figures 2.20 to 2.22 it is clear that,

1. More copper is recovered from copper sulfide ore samples than from the copper oxide ore samples, Which might be due to the higher head grade (0.8%Cu), higher exposure values (Figure 2.7) and greater particle damage (Figure 2.11) than that of copper oxide samples.
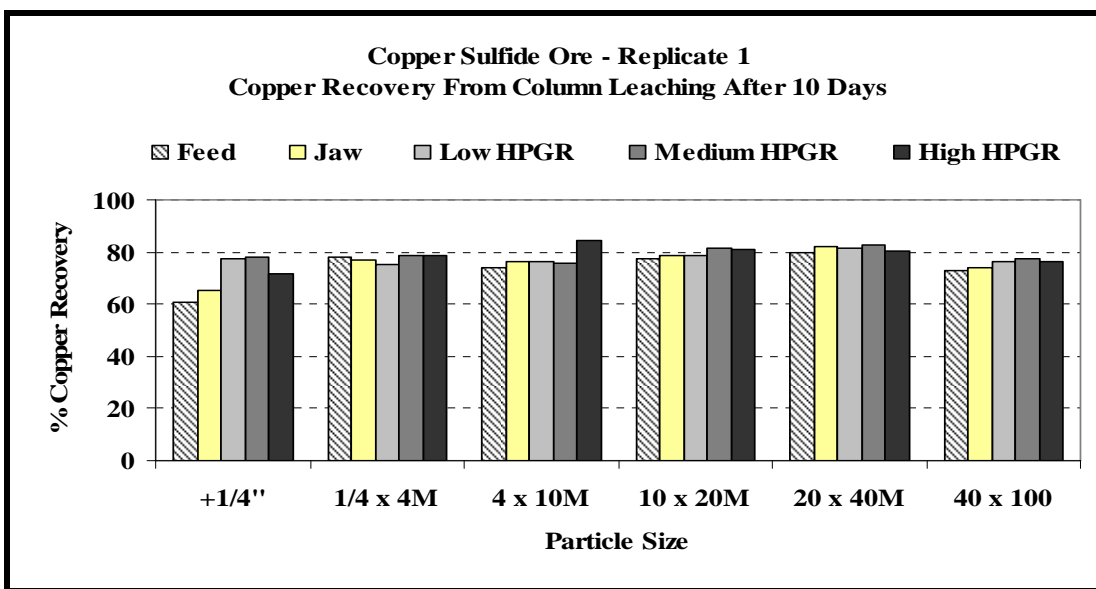
Figure 2.20 Copper recovery from copper sulfide ore samples for different crushing methods and particle sizes (Replicate 1).
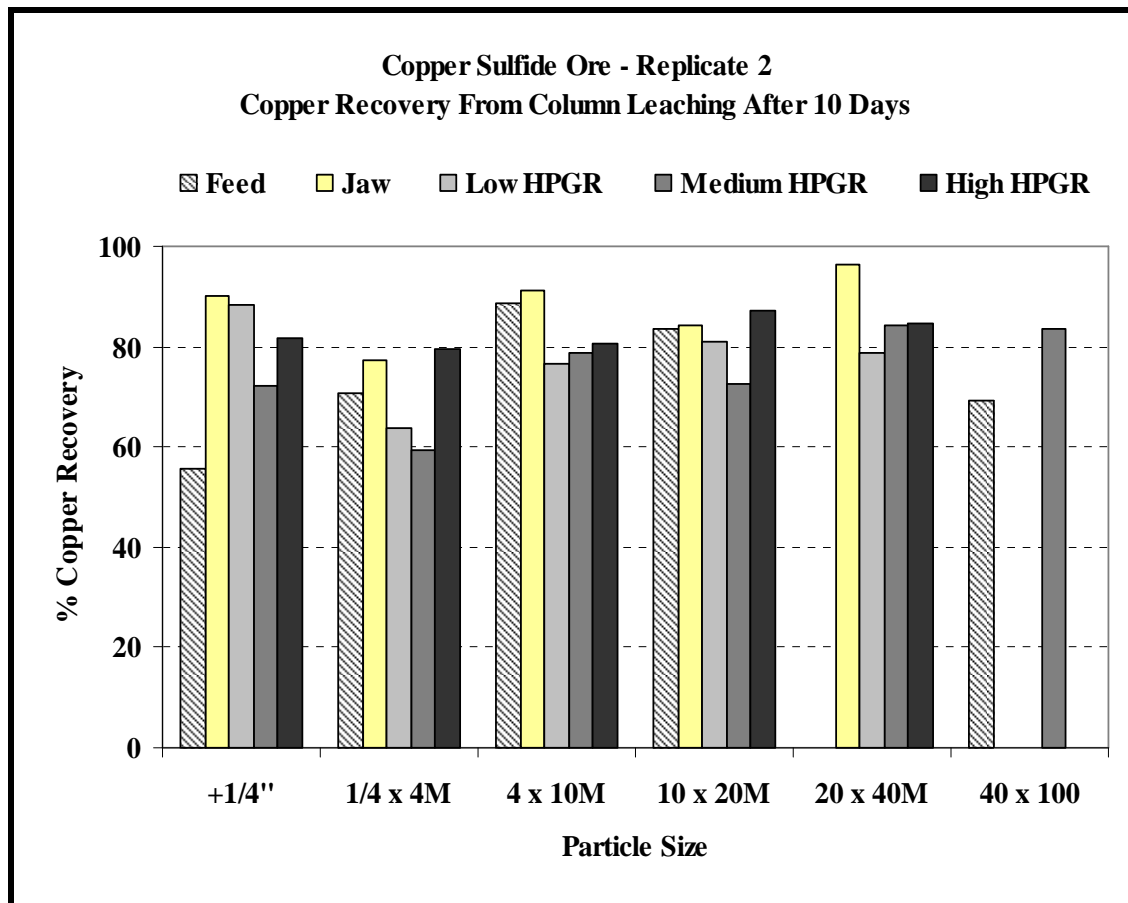
Figure 2.21 Copper recovery from copper sulfide ore samples for different crushing methods and particle sizes (Replicate 2).

2. Copper recovery tends to be independent of crushing method and also particle size.

3. This unexpected behavior might be due to the high head grades of copper sulfide samples (about 0.8%Cu). Copper oxide samples head grade is about 0.3%Cu.

4. This unexpected behavior might be due to the high head grades of copper sulfide samples (about 0.8%Cu). Copper oxide samples head grade is about 0.3%Cu.

5. Leaching solution that was used from copper sulfide ore samples is stronger than that used for copper oxide ore samples (Table 2.5). This also might effect the copper recovery response.
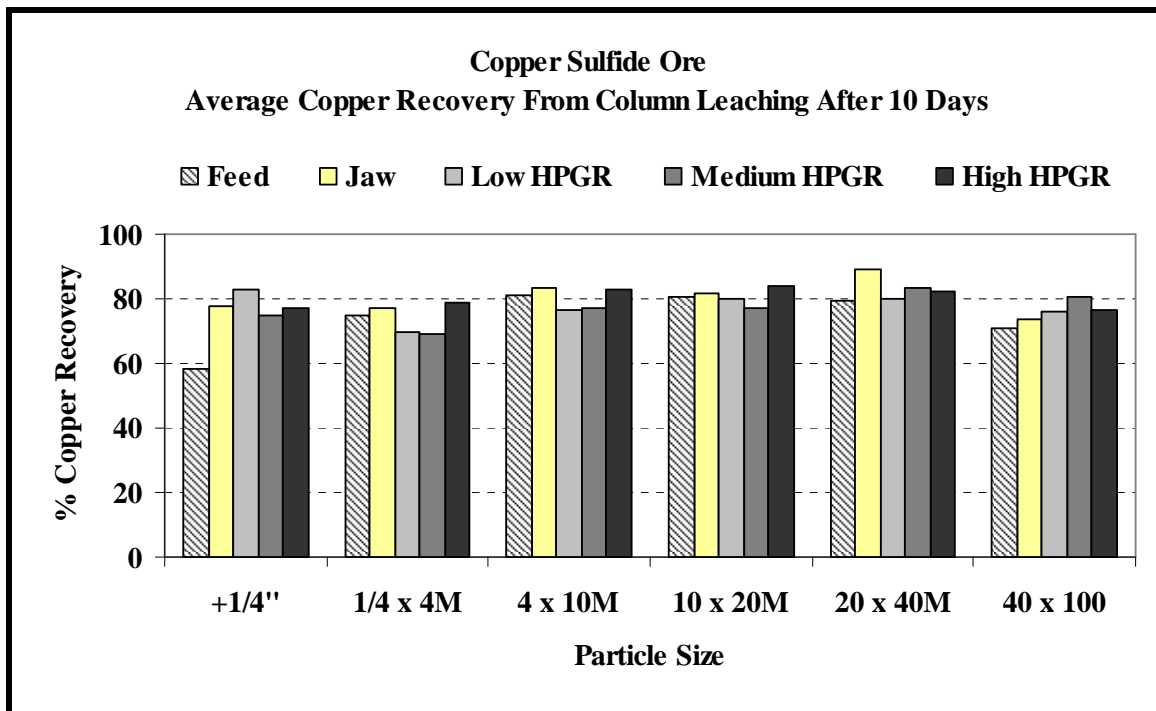
Figure 2.22 Average copper recovery from copper sulfide samples for
different crushing methods and particle sizes.

2.3.3.3.2 Comparison of Mineral Exposure and Copper Recoveries as a

Function of Particle Size for Different Crushing Conditions

In addition to replicating the laboratory column leaching experiment, comparison
has been made between copper recovery and mineral exposure to further examine the
recovery values from laboratory column leaching. Table 2.6 and Figures 2.23 to 2.32
show the comparison between copper recovery after 10 days leaching and exposure
values for copper oxide ore and copper sulfide ore samples. From the Figures 2.23 to 2.32
it is clear that copper recoveries from the different crusher samples follow the same trend
as their grain exposure values. As expected both the recovery and exposure values
increase with a decrease in particle size. Copper recovery from column leaching is less
than the exposure due to low leaching time (10 days).

Table 2.6 Percent copper recovery after 10 days leaching and
percent grain exposure for copper oxide ore and copper
sulfide ore laboratory column leaching

	Size	Copper Oxide					Copper Sulfide				
		Feed	Jaw	Low HPGR	Medium HPGR	High HPGR	Feed	Jaw	Low HPGR	Medium HPGR	High HPGR
% Cu Recovery Average	+1/4"	57	53	60	60	62	58	78	83	75	77
	1/4 x 4M	57	50	60	64	68	75	77	70	69	79
	4 x 10M	64	70	63	72	75	81	84	76	77	83
	10 x 20M	71	75	72	77	82	81	82	80	77	84
	20 x 40M	73	76	77	81	82	40	89	80	84	82
% Cu Exposure	+1/4"		74		85	82	83		92	91	83
	1/4 x 4M	76	87	86	90		91	87	91	90	93
	4 x 10M	88	90	87	90	82	94	93	92	92	95
	10 x 20M	93	91	93	91	92	97	96	98	98	97
	20 x 40M	96	95	95	95	94	99	99	99	99	99
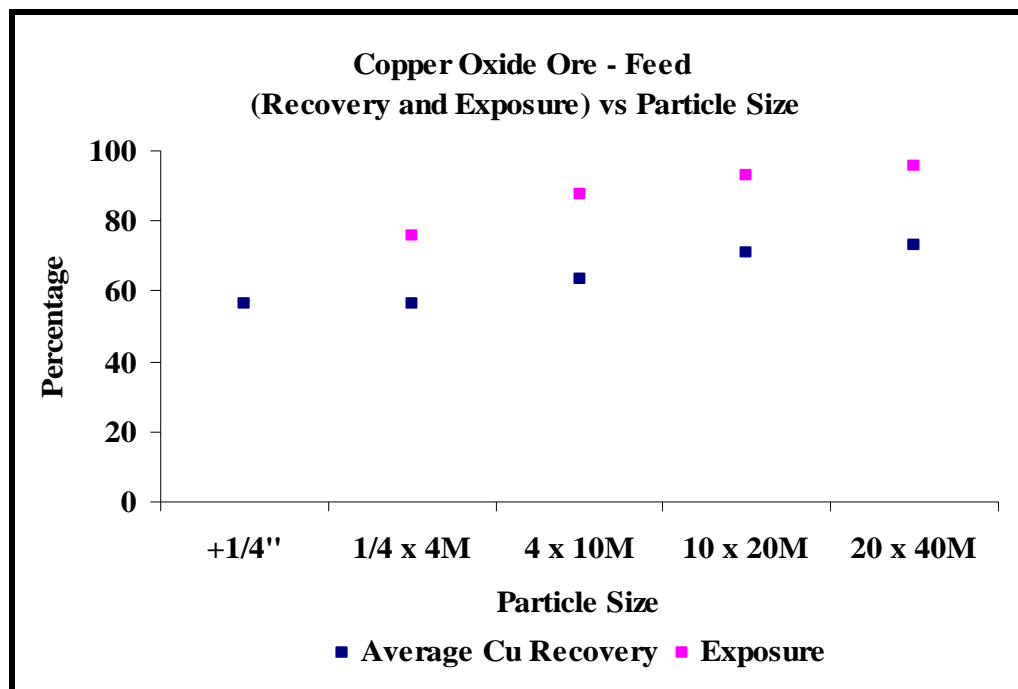
Figure 2.23 Exposure and copper recovery from laboratory column leaching after
10 days as a function of particle size for copper oxide ore feed samples.
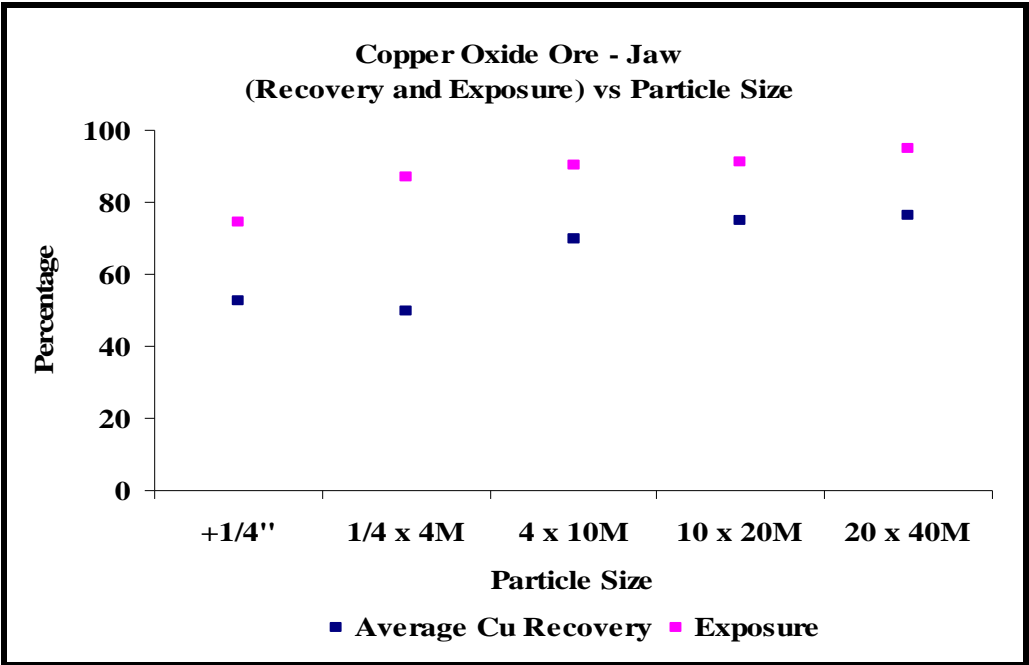
Figure 2.24 Exposure and copper recovery from laboratory column leaching after 10 days as a function of particle size for copper oxide ore samples prepared by jaw crushing.
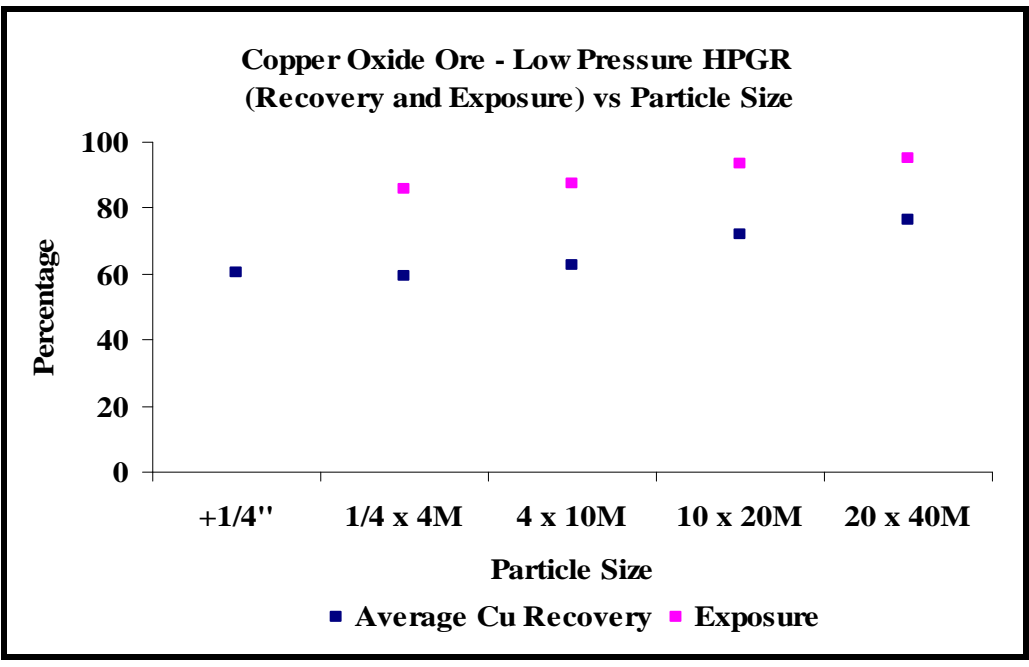
Figure 2.25 Exposure and copper recovery from laboratory column leaching after 10 days as a function of particle size for copper oxide ore samples prepared by low pressure HPGR crushing.
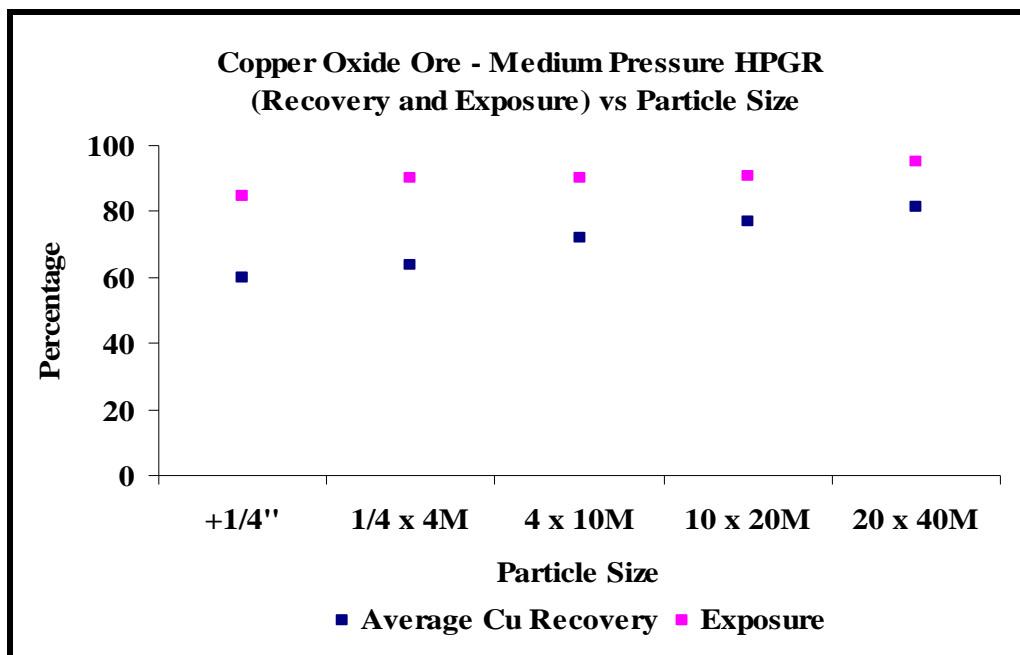
Figure 2.26 Exposure and copper recovery from laboratory column leaching after 10 days as a function of particle size for copper oxide ore samples prepared by medium pressure HPGR crushing.
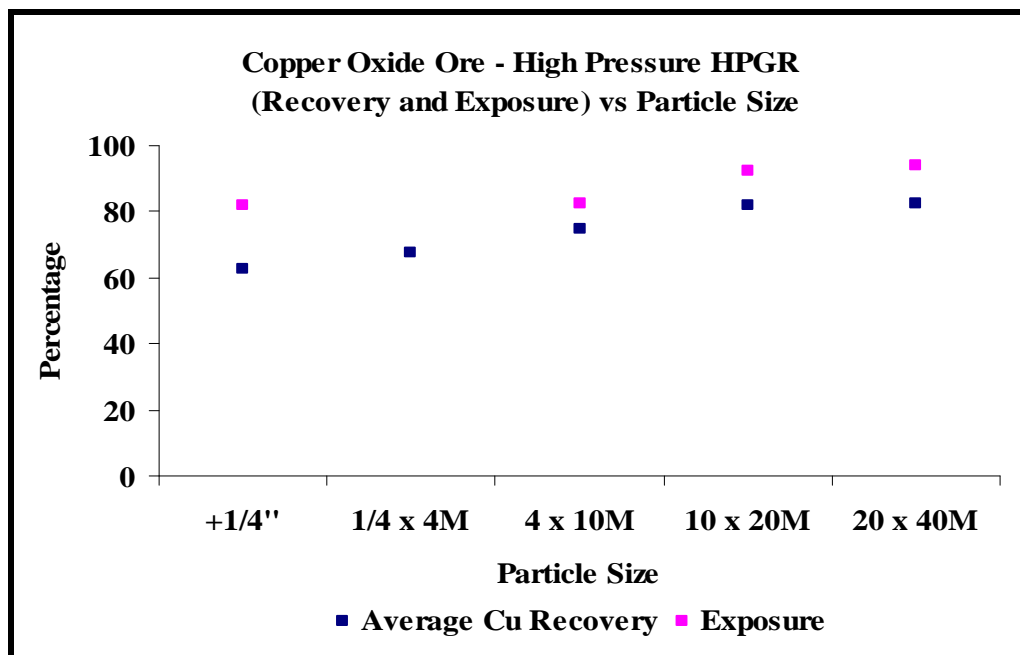
Figure 2.27 Exposure and copper recovery from laboratory column leaching after 10 days as a function of particle size for copper oxide ore samples prepared by high pressure HPGR crushing.
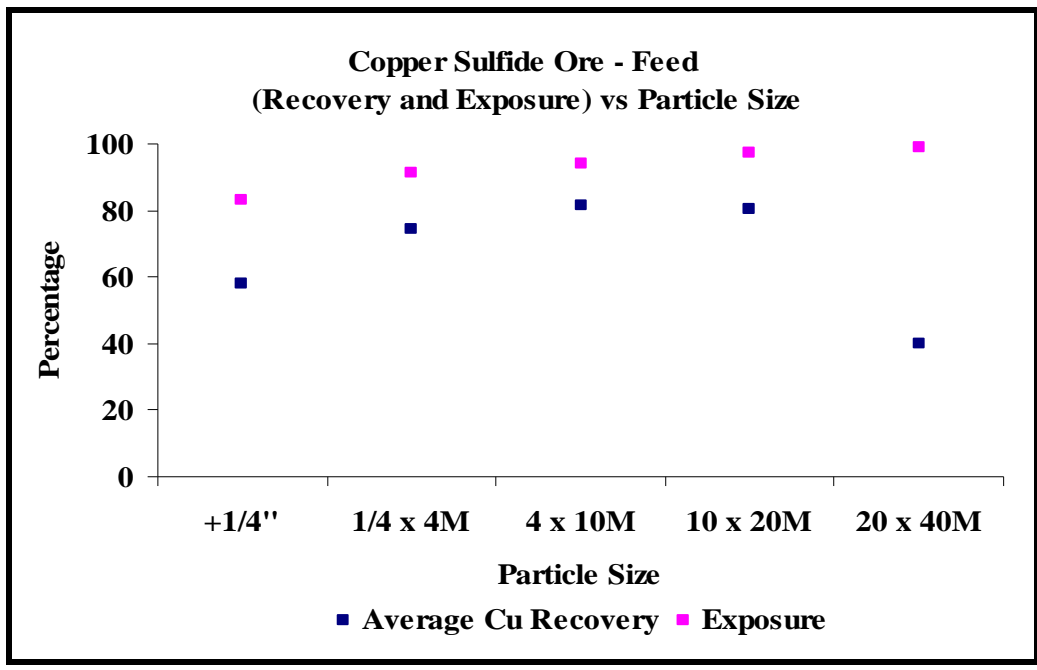
Figure 2.28 Exposure and copper recovery from laboratory column leaching after 10 days as a function of particle size for copper sulfide ore feed samples.
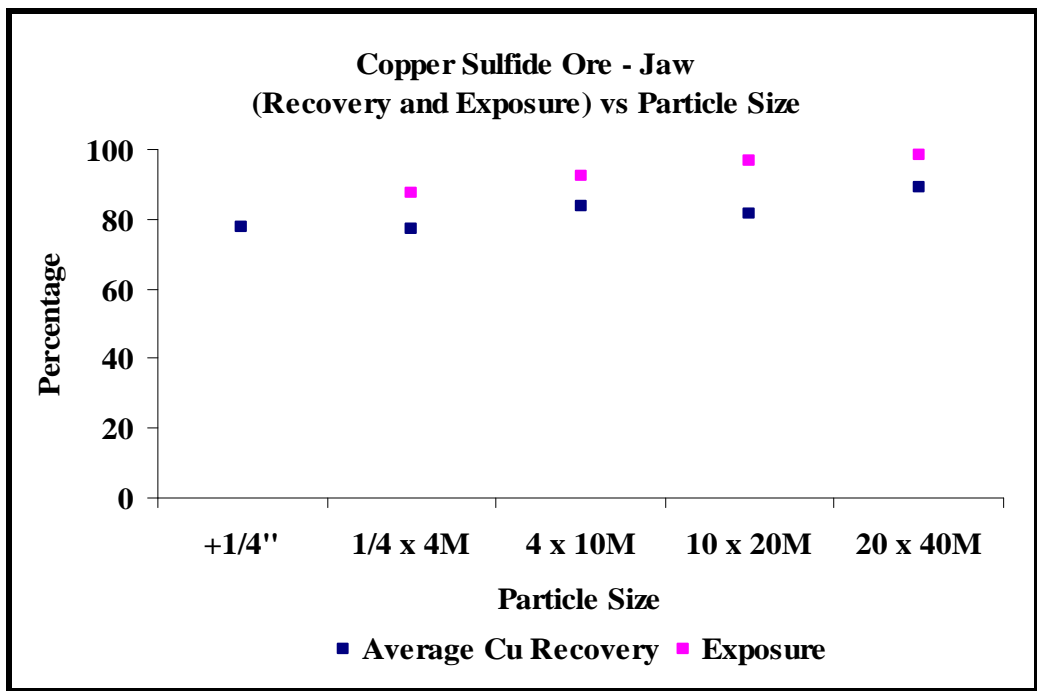
Figure 2.29 Exposure and copper recovery from laboratory column leaching after 10 days as a function of particle size for copper sulfide ore samples prepared by jaw crushing.
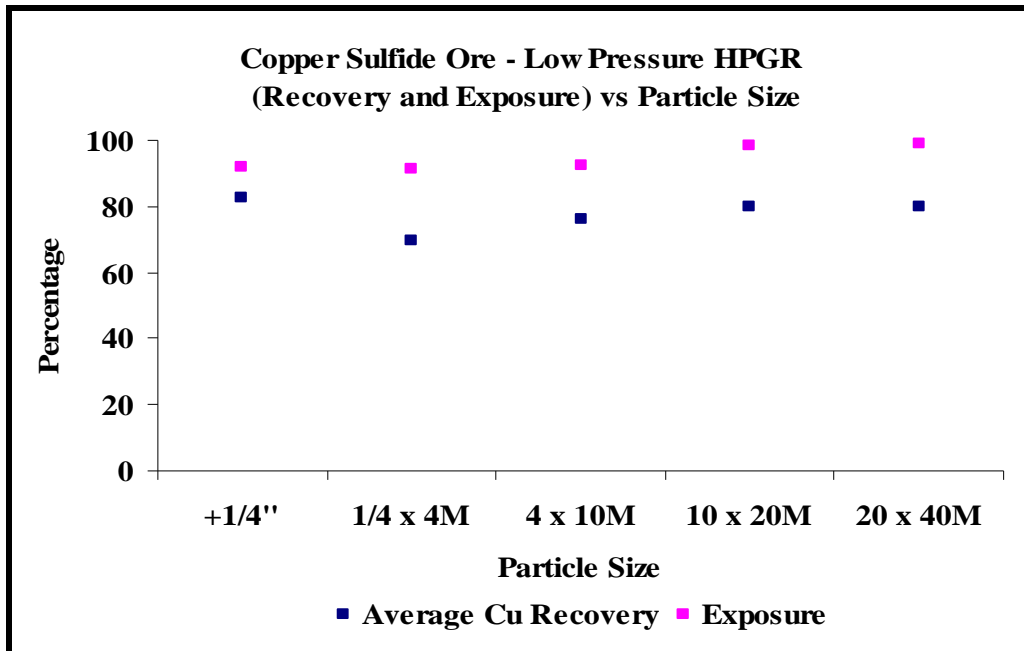
Figure 2.30 Exposure and copper recovery from laboratory column leaching after 10 days as a function of particle size for copper sulfide ore samples prepared by low pressure HPGR crushing.
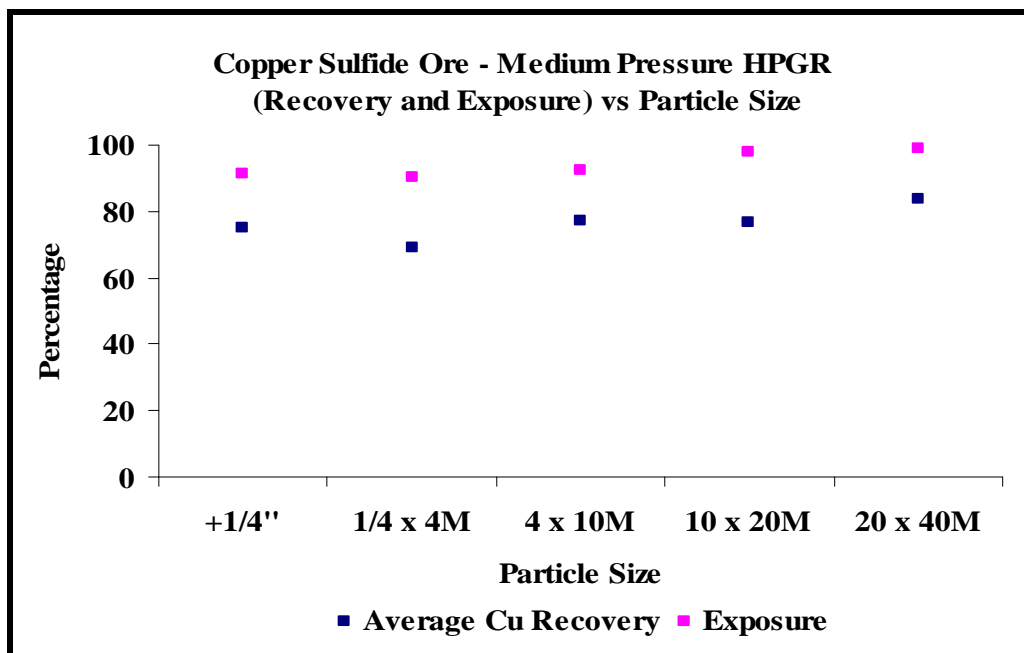
Figure 2.31 Exposure and copper recovery from laboratory column leaching after 10 days as a function of particle size for copper sulfide ore samples prepared by medium pressure HPGR crushing.
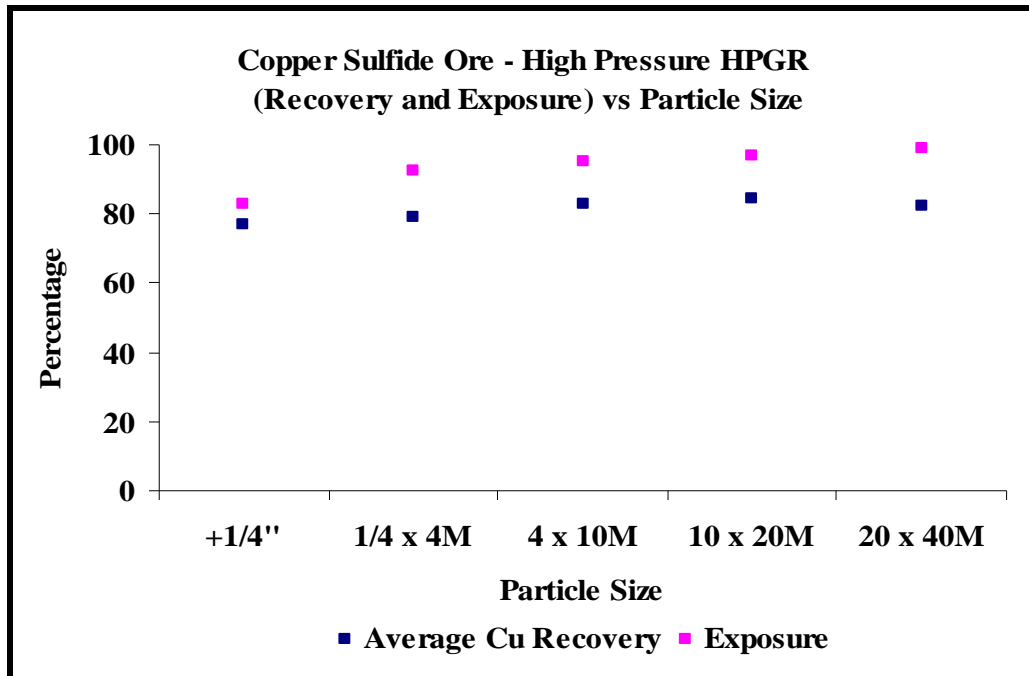
Figure 2.32 Exposure and copper recovery from laboratory column leaching after 10 days as a function of particle size for copper sulfide ore samples prepared by high pressure HPGR crushing.

2.4 Summary and Conclusions

2.4.1 Particle Size Analysis

High pressure HPGR produced a slightly finer particle size distribution when compared to other crushing methods for both copper oxide and copper sulfide samples (Figures 2.3 and 2.4). By comparing the P_{80} values, it appears that the copper sulfide ore is softer than the copper oxide ore.

2.4.2 Mineral Exposure

As expected, grain exposure decreases with an increase in particle size. Grain exposure in the copper oxide ore samples was less (85 to 90% at 2 mm) when compared

with grain exposure in the copper sulfide ore samples (95% at 2mm) but exposure was affected by crusher type. Data points are spread out in the copper oxide exposure data for different crushing methods (Figure 2.6). This trend is supported by copper oxide laboratory column leaching results, which show that greater recovery was generally achieved for all particle sizes prepared by HPGR high pressure crushing condition (Figure 2.17 to Figure 2.19).

For the copper sulfide ore samples mineral exposure was high (95% at 2mm) but independent of crusher type (Figure 2.7). Data points are concentrated at particular exposure values for the copper sulfide ore with different crushing methods (Figure 2.7).This unusual behavior account, in part, for higher copper recovery from copper sulfide ore during column leaching (Figure 2.20 to Figure 2.22).

2.4.3 Particle Damage

High pressure HPGR crushing produces more cracks than other crushing methods in most of the particle size classes (Figures 2.10 and 2.11). As particle size decreases the percentage of cracked particles increases for the copper oxide ore samples.

For high pressure HPGR copper oxide ore samples the percent of cracked particles increased from 40% to 80% as the particle size is decreased from 1/4inch to 200mesh (Figure 2.10).

Such a trend was not evident for the copper sulfide ore samples (about 80% of the particles are cracked in all high pressure HPGR copper sulfide samples irrespective of particle size) (Figure 2.11).

2.4.4 Mini Column Leaching

Figure 2.12 show internal grains for HPGR-high pressure and Jaw crusher samples which have dissolved after 29 days during minicolumn leaching. The over all trend shows that copper grains dissolve at a faster rate in the case of minicolumn leaching of high pressure HPGR products.

2.4.5 Laboratory Column Leaching

2.4.5.1 Copper Oxide Ore

Copper recoveries are high for most of the high pressure HPGR samples (Figures 2.17 to 2.19). As expected, copper recoveries increase with a decrease in particle size. Copper recovery values show the same trend as grain exposure data (Figures 2.23 to 2.27).

2.4.5.2 Copper Sulfide Ore

Copper recovery is independent of the crushing method since about 80 to 90% of copper is recovered during the initial period of leaching (Figures 2.20 to 2.22). Recovery values are higher than those for the copper oxide ore samples. This high recovery from the copper sulfide ore samples is due to the higher head grade, greater grain exposure and perhaps a more aggressive leach solution. Copper recovery values show the same trend as grain exposure data (Figures 2.28 to 2.32).

The evidence suggests that high pressure HPGR increases the leaching of copper oxide ore under the conditions considered. Whereas, the leaching of copper sulfide ore samples, under the conditions considered, is independent of crusher type despite greater

particle damage from high pressure HPGR samples. In this regards, it is expected that the effect of damage would be more significant for the copper sulfide ore if a less aggressive leach solution were used. The leach solution for the copper oxide ore was at pH 1.1, whereas the leach solution for the copper sulfide ore was at pH 2.

CHAPTER 3

BINDER FOR AGGLOMERATION IN

COPPER HEAP LEACHING

3.1 Introduction

The heap leaching method is used to recover copper from low grade ores. During copper heap leaching crushed ore is stacked in approximately 10 meter lifts. Sulfuric acid leach solution is introduced on the top of heap leach pads (Figure 3.1). As this leach solution percolates through the heap in unsaturated flow (Figure 3.2), copper is solubilized and retained in the leach solution which is collected at the toe of the heap in the Pregnant Leach Solution (PLS) pond (Figure 3.2). The percolating leach solution also causes migration of fine particles within the heap. Migrated fines may clog the natural flow channels, and form impermeable sections of the heap. When this happens, the leach solution flows around the impermeable sections in the heap, leaving these sections un-leached or partially leached, thus lowering the overall recovery [17]. To overcome the problem of fine particle migration, copper ore may be agglomerated prior to heap latching if the fine particle (-200 mesh) content is greater than 5% in the crushed material [18]. Liquid bridge agglomeration, generally employed in heap preparation is performed in revolving drums (Figures 3.3) and is thought to serve two purposes [32].

Figure 3.1 Copper heap leach pad.
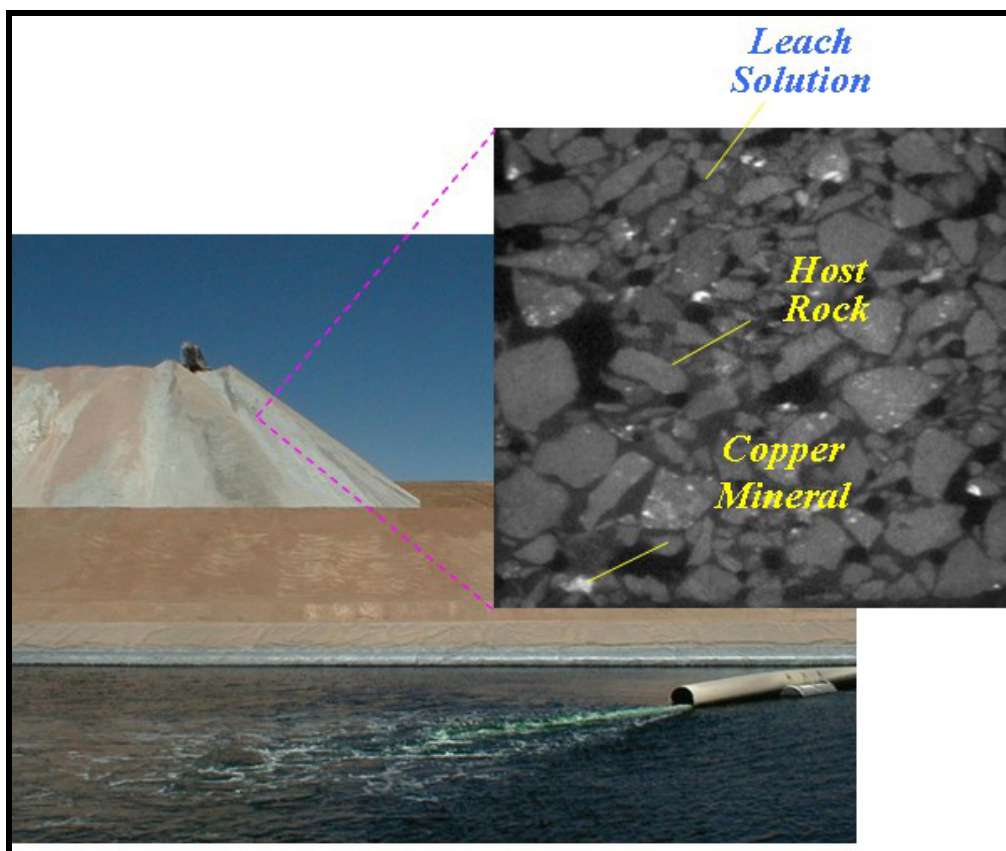
Figure 3.2 Heap leach pad with 9 m lift, CT scan showing percolation
of the leach solution in a packed bed of ore particles.

Figure 3.3 Agglomeration drums at a copper heap leach operation.

The first purpose is to take the advantage of the agglomerating liquid (acid solution, 80% water and 20% concentrated sulfuric acid) to initiate the leaching reaction and to improve the leaching response of low grade ore. The second purpose of agglomeration is to cause capillary adhesion of fine mineral particles to coarse particles through the formation of liquid bridges in order to create more permeable heap leach pads.

Liquid bridge agglomeration produces weak agglomerates and does not fully address the fine particle migration issue. The weak force of adhesion between the acid solution and ore particles can be strengthened with the use of binders [17]. S.C. Bouffard presented the nature, dosage, and chemistry of the solution and binders used for agglomeration at various copper heap leaching operations [18]. An effective binder must

not only create strong adhesion between particles but also must not hinder the copper recovery. A number of potential binders such as lignin, cellulose, methyl cellulose, tall oil, sodium silicate have been evaluated by other researchers [35]. Also in the literature it is stated that gypsum might be a possible binder to improve the permeability of the leach pads [35]. Further discussions of procedures for the use of gypsum binder were not provided, nor were any results given. In fact gypsum would not be suitable as a binder because attachment to and adhesion between particles is not expected. Such experiments in our laboratories with gypsum as binder confirmed this expectation. On the other hand the use of calcium sulfate hemihydrate (stucco) has not been considered and, although gypsum is the ultimate product of the stucco binder reaction, the nucleation and growth of the dihydrate during hydration should lead to improved agglomerate stability. Figure 3.4 presents a schematic of the anticipated agglomeration process using stucco as a binder.
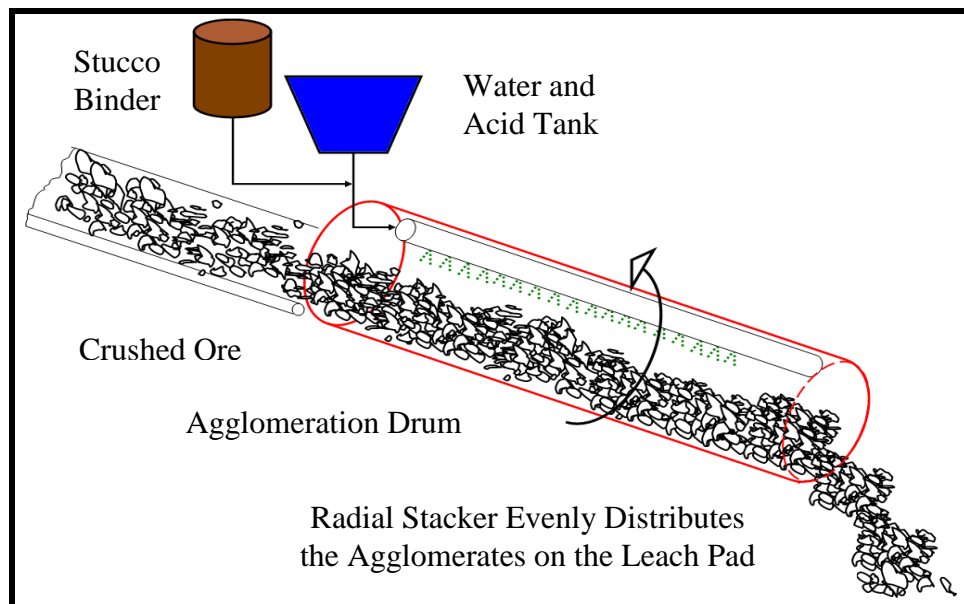
Figure 3.4 Schematic of stucco binder agglomeration process.

In this regard the objective of this part of the thesis research was to investigate the quality of agglomeration by using modified stucco as a binder. Agglomeration was done in a pilot scale plastic drum mixer with 18 pounds of crushed ore (1/2 inch x 3 mesh) and 2 pounds of fine ore particles (-200 mesh) as feed material [18]. The amount of water, acid and binder were the variables considered in these experiments.

The stability of agglomerates were evaluated by determination of the agglomerate size distribution, permeability of the packed bed of agglomerates, column leaching of agglomerates, and visual inspection [22, 30, 32]. Electrical conductivity tests were also performed with the agglomerates to determine moisture content. The success of using stucco as a binder for acid heap leaching operation is reported in this chapter and the results have been used for a provisional patent application [36].

3.2 Methods and Results

3.2.1 Experimental Procedure

A plastic drum mixer (cement mixer) that rotates at 20 RPM and with 5 degree inclination was used for agglomeration experiments (Figure 3.5). The particle size distribution of the feed material for agglomerates ranged from 0.5 inch to -200 mesh (Figure 3.6).

The copper ore sample used for agglomeration experiments was from the Zaldivar copper operations in Chile. Table 3.1 shows the copper grade and mineralogy of the ore samples. It is evident that the major mineral component is chalcocite followed by brochantite.
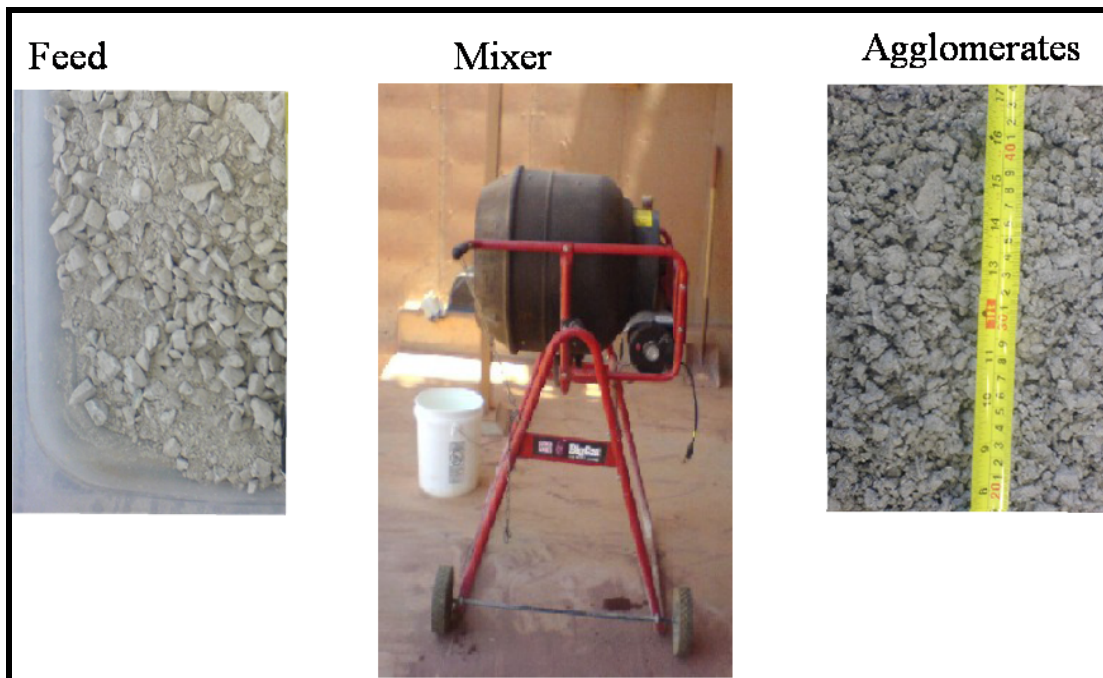
Figure 3.5 Feed, plastic drum cement mixer, agglomerates.
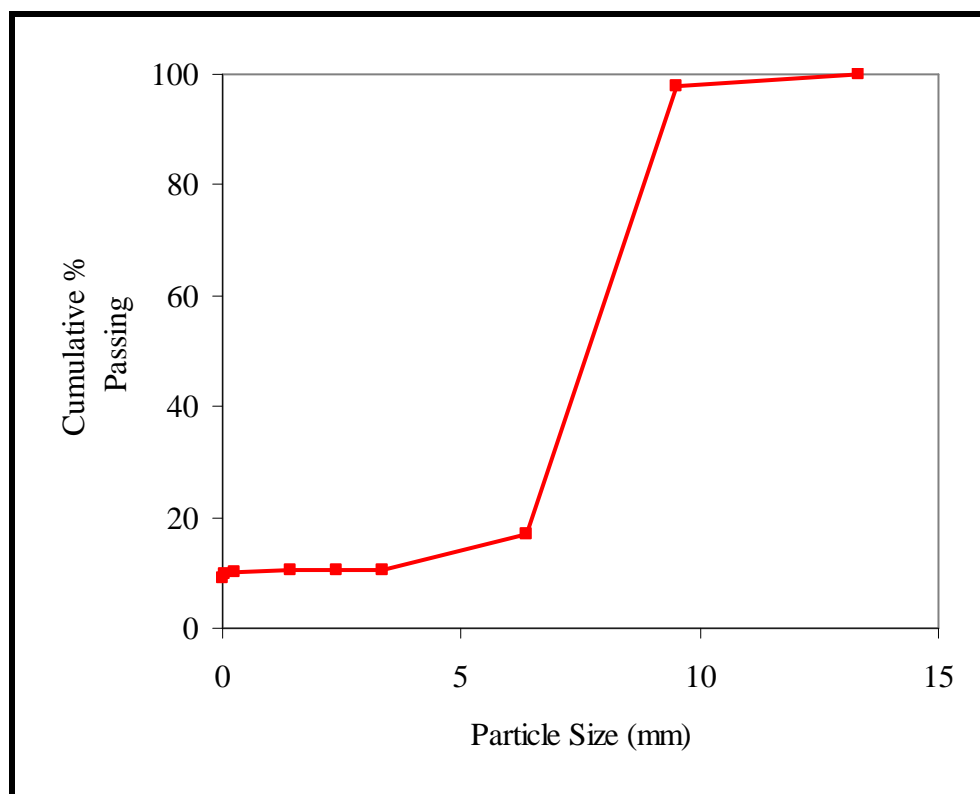
Figure 3.6 Particle size distribution of the feed.

Table 3.1 Feed sample mineralogy of the copper ore used
for agglomeration experiments.

Particla Size	Chemical Analysis Cu Head Grade	Mineralogical Analysis (100% base copper species)				
		$CuFeS_2$	Cu_2S	CuS	$CuSO_4.3Cu(OH)$	Other
mm	%	%	%	%	%	(%)
25.4 x 19.1	1.21	0.40	85.00	-	14.10	0.50
19.1 x 12.7	1.16	1.10	82.60	-	15.20	1.10
12.7 x 9.5	1.26	13.20	71.70	-	15.10	-
9.5 x 6.36	1.25	-	82.50	-	17.50	-
6.36 x 3.18	1.31	7.00	75.60	0.80	15.80	0.80
3.18 x 1.7	1.30	6.20	76.90	0.70	15.40	0.80
1.7 x 0.425	1.29	3.80	77.30	-	18.90	-
0.425 x 0.150	2.33	8.00	75.60	0.20	16.20	-
0.150 x 0.075	2.99	4.30	81.50	0.20	14.00	-
-0.75	2.67	2.40	85.00	0.40	8.70	3.50

3.2.2 Agglomerate Size Distribution

Before sieving, each sieve was cleaned and their individual weights recorded. Then the sieves were assembled in descending order of opening size. With the dried agglomerated sample on the top screen, all the sieves were shaken in a sieve shaker for three minutes. Once this procedure was completed each sieve was weighed again and the mass for each size class obtained by difference between the weight of the sieve with and without the material in that size class [30].

By the above mentioned procedure the particle size distribution of agglomerates was obtained for agglomerates prepared with 0g, 50g, 100g, 250g and 500g of stucco binder. In these experiments, the amount of acid solution (80% water and 20% concentrated sulfuric acid) and the amount feed material (20 pounds) was kept constant.

Comparison of agglomerate particle size distributions is presented in Figure 3.7. From the agglomerate size distributions two conclusions can be made. The First conclusion is that the fine particles (10% minus 200 mesh) in the feed to the agglomeration drum adhere to the coarser particles and therefore are not seen in the
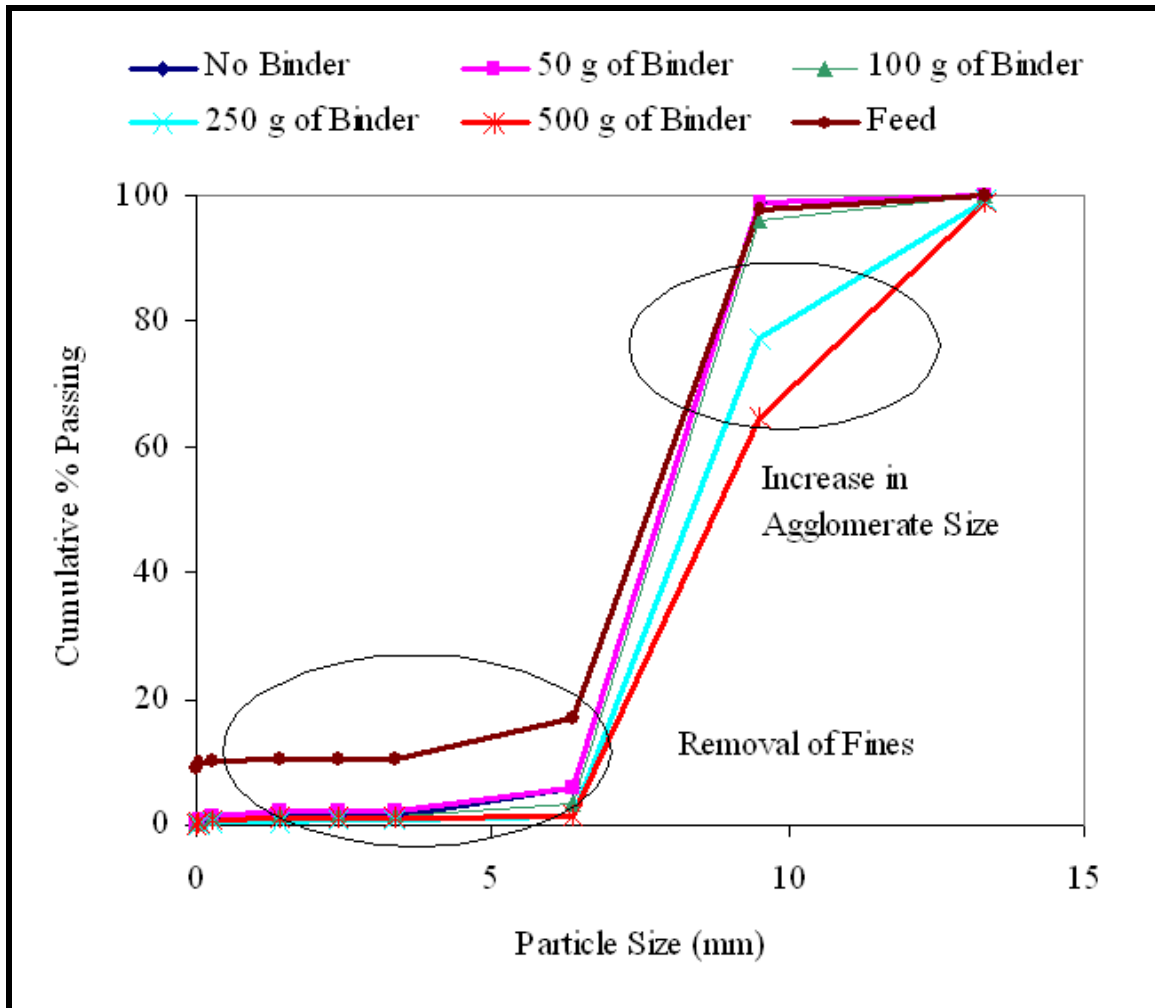
Figure 3.7 Agglomerate size distributions.

agglomerates size distributions when stucco binder is used (Figure 3.7). The Second conclusion is that the agglomerates become coarser as the amount of stucco binder amount is increased (Figure 3.7). The P_{80} value for agglomerates prepared with 0g, 50g and 100g of stucco binder is about 8.5mm and whereas the P_{80} value for agglomerates prepared with 250g and 500g of binder increases to 9.5mm and 11.0mm, respectively. This increase in agglomerate size is an indication of the effectiveness of the stucco binder and the agglomerate quality.

3.2.3 Permeability

The experimental determination of coefficient of the permeability was done by a constant head method for laminar flow through a packed bed of agglomerates (Figure 3.8). The experimental setup follows the recommendations given in ASTM D 2434 "Standard Test Method for Permeability of Granular Solids" [37].

A cylindrical column of about four inch diameter and seven inch in length was designed to hold the sample of agglomerates which is fitted between two perforated plates (about 3mm diameter holes) (Figure 3.8). Marbles are placed at the bottom and top of the agglomerates in the column to help maintain the agglomerate bed and uniform flow.

A constant head of water was maintained during the experiment. The water volume from the discharge of the column was measured at different heads for

Level maintained at constant elevation

Head change

Column with agglomerates

Water outlet
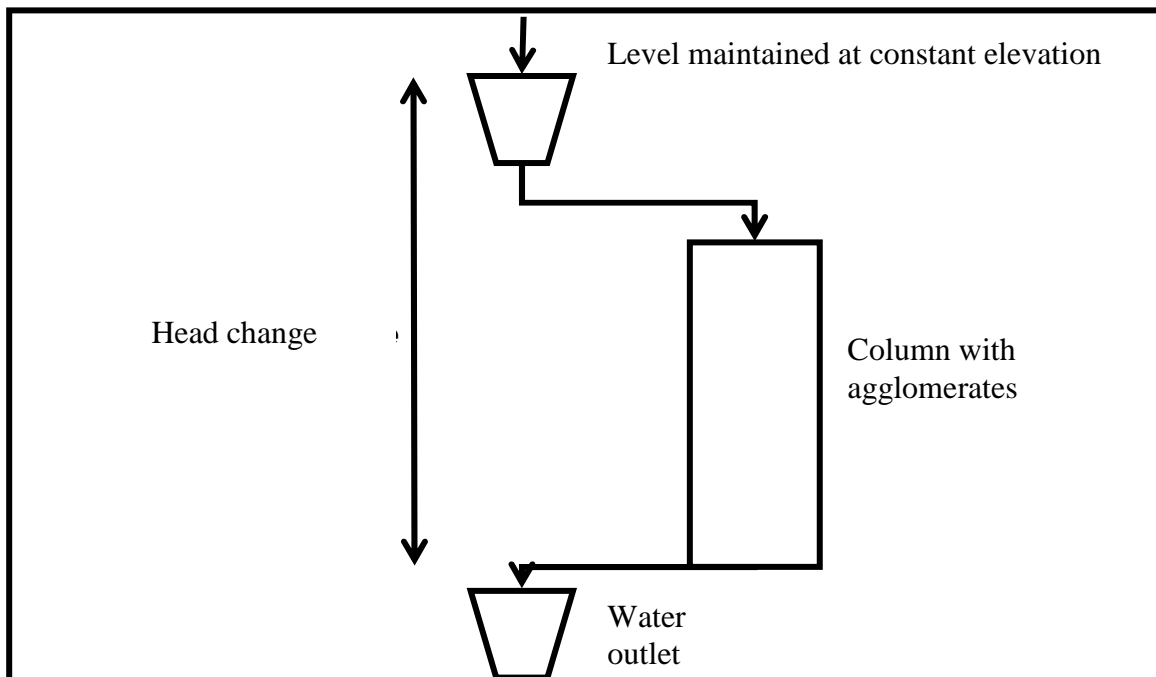
Figure 3.8 Schematic of permeability test.

permeability calculations. The coefficient of permeability is calculated from the slope of the plot of flow rate vs head change and (Figure 3.9) using Darcy's law.

Figure 3.9 presents the permeability values for the agglomerate beds prepared with different stucco binder amounts. In these experiments, the amount of acid solution (80% water and 20% concentrated sulfuric acid) and amount feed material (20 pounds) were kept constant. The results presented in Figure 3.9 clearly show that the permeability of agglomerates increases with the amount of stucco binder addition used in agglomeration process. In fact the permeability increases five times when 500 g of stucco binder is used in comparison to agglomerates prepared with 50 g of stucco binder.

Darcy's Law:

$$Q/A = (K \, \Delta P)/ \mu \, L \qquad \qquad (3.1)$$

here,

Q = Flow rate (cm^3/sec)

A = Area of column (cm^2)

K = Permeability (cm^2)

ΔP = Pressure difference = $\rho \, g \, h$

ρ = Density of water (kg/cm^3) = 0.001 (kg/cm^3)

g = Acceleration due to gravity (cm/sec^2) = 982 (cm/sec^2)

h = Head difference between solution inlet and outlet (cm)

μ = Viscosity of water (kg/(cm sec)) = 0.00001 (kg/(cm sec))

L = Length of the column that is occupied by the agglomerates (cm)
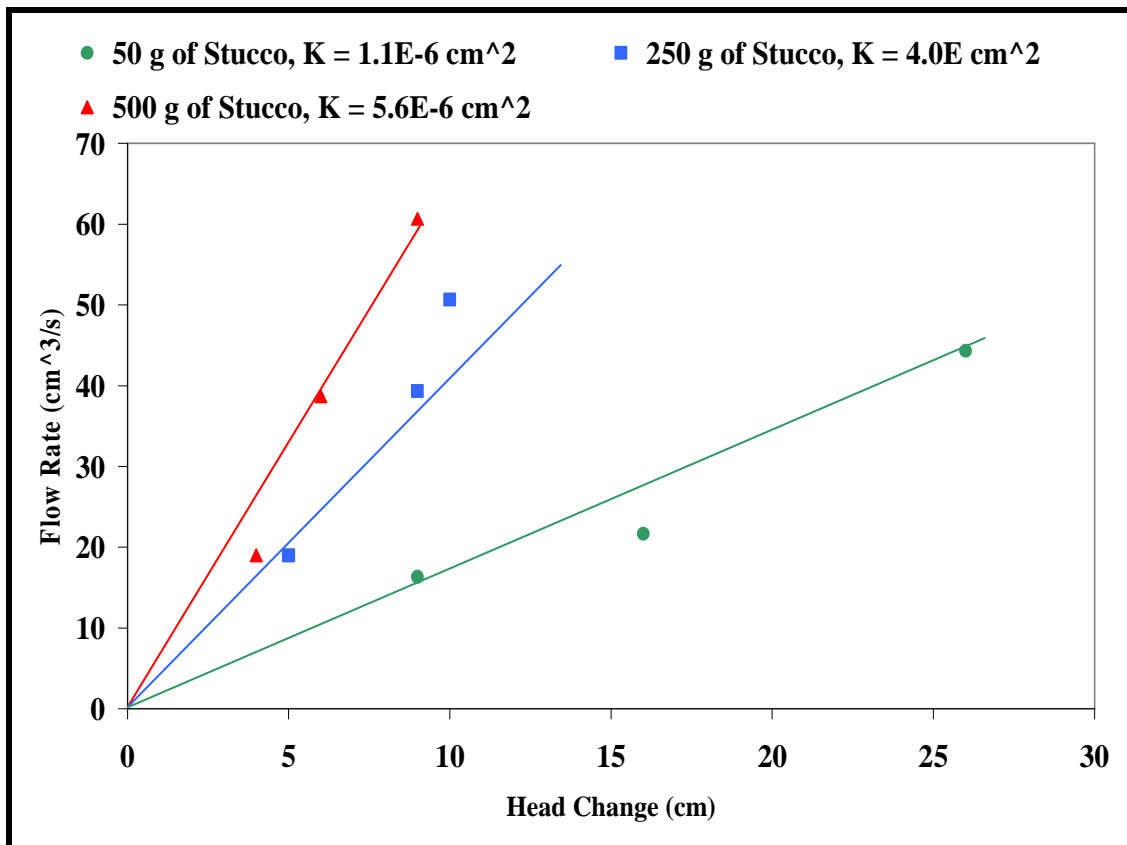
Figure 3.9 Constant head permeability test results.

From these results we can conclude that in addition to the agglomerate size, the permeability of agglomerates also increases. However, the effect of stucco binder on copper recovery must be considered.

3.2.4 Column Leaching of Agglomerates

Agglomerates prepared with 500g of stucco and 0g of stucco were loaded in columns to determine the effect of stucco binder on copper recovery during column leaching. While preparing the agglomerates, the amount of acid solution (80% water and 20% concentrated sulfuric acid) and amount feed material (20 pounds) was kept constant.

Leaching columns were 4 inch diameter and 6 feet tall. Columns were loaded with agglomerates by using a torpedo to achieve uniform distribution of the agglomerates (Figure 3.10). Cloth and polymer screens were placed over the agglomerates in the columns, so that the leach solution is distributed uniformly in the column. Marbles and a polymer screen were placed at the bottom of the columns to prevent broken agglomerates from blocking the outlet of the column. Intravenous (IV) systems were used to feed the leach solution (6 g/l sulfuric acid) into the columns at a controlled flow rate of 8 $L/m^2/hr$. Column leaching was performed for 33 days with 6 gpl sulfuric acid solution. Pregnant leach solution from column leaching was collected at regular intervals of time.

Figure 3.10 Columns loaded with agglomerates. Note the bulk density change.
The agglomerates prepared with stucco binder filled the
column to height 5 inches greater than the
height without stucco binder.

The volume of pregnant leach solution collected was also measured (Figure 3.11). Equal volumes of leach solution passed though the columns so the copper recoveries from the two columns could be compared. It is interesting to note that the flow rates are equivalent in both cases even though the permeabilities are quite different. This situation is probably due to the fact that leaching is under unsaturated flow conditions, whereas, the permeabilities measured are saturated flow permeability.

Pregnant leach solutions were analyzed using the ICP instrument to determine copper recovery from each of the two columns. Copper recovery results show that about 13 % of the copper was recovered during 33 days of leaching. In fact higher copper
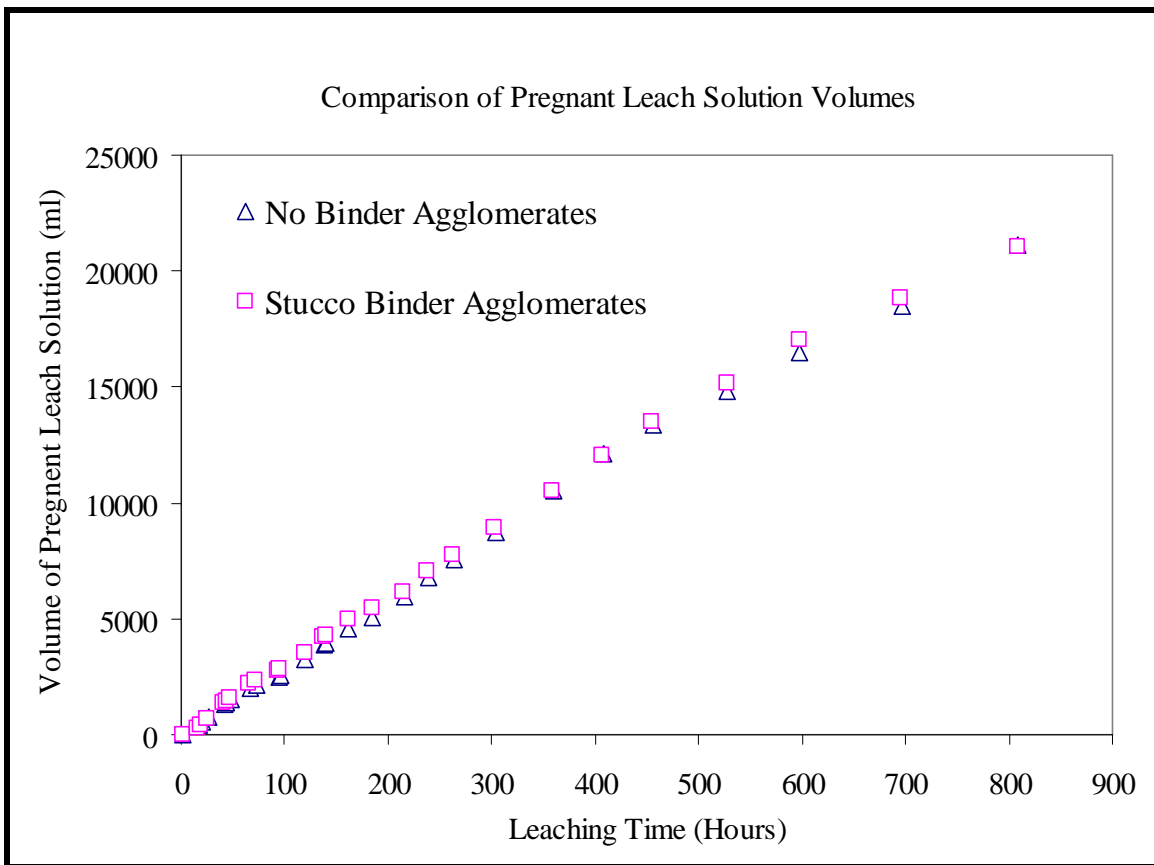
Figure 3.11 Comparison of pregnant leach solution volumes.

recovery was found for the agglomerates prepared using 500g of binder until 400 hours of leaching (Figure 3.12 and 3.13). These copper recovery results show that the stucco binder does not hinder the recoveries but in fact improves the rate of copper recovery.

Figure 3.12 shows the μ g/ml of copper in the leach solution that was measured using the ICP instrument at different leaching times. From Figure 3.12 it is clear that up to 50 hours of leaching more copper is extracted from the stucco binder agglomerated sample. Later on, not much difference is seen in the amount of copper leached from the two columns.

Figure 3.13 shows the copper recovery with respect to leaching time for each of the agglomerates. For the initial 500 hours more copper is recovered from the stucco
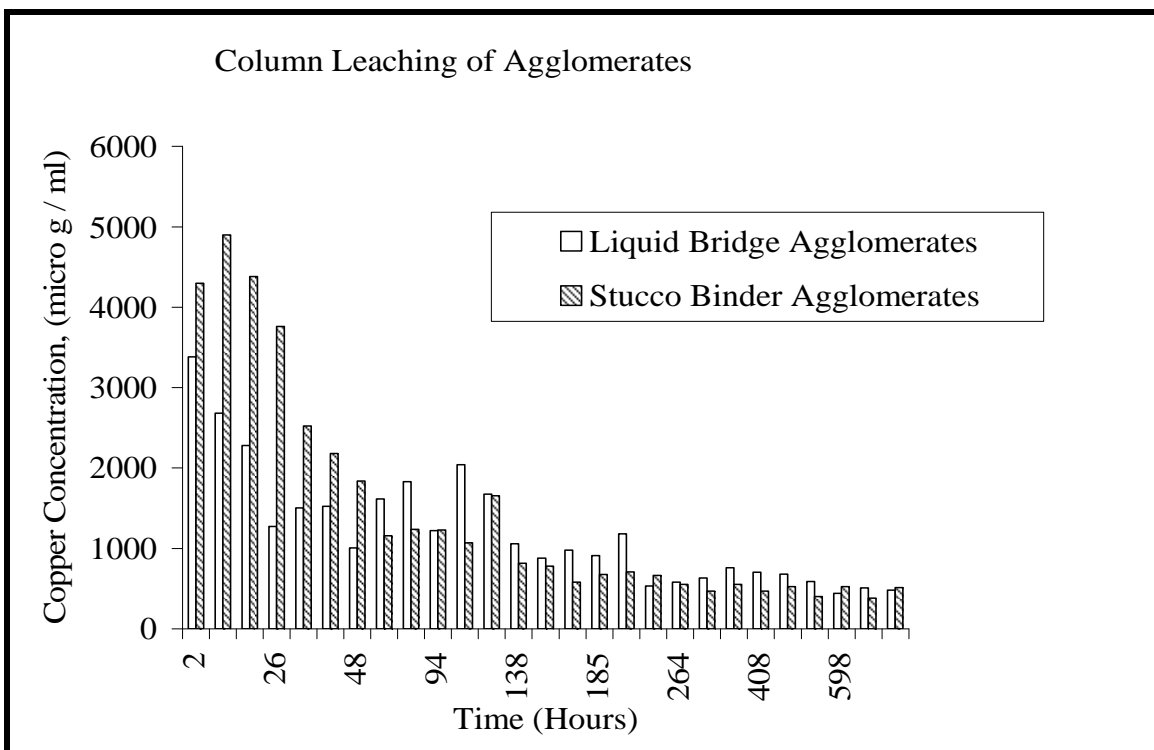
Figure 3.12 Copper concentrations in pregnant leach solution as a function
of time for column leaching of liquid bridge agglomerates and
stucco binder agglomerates.
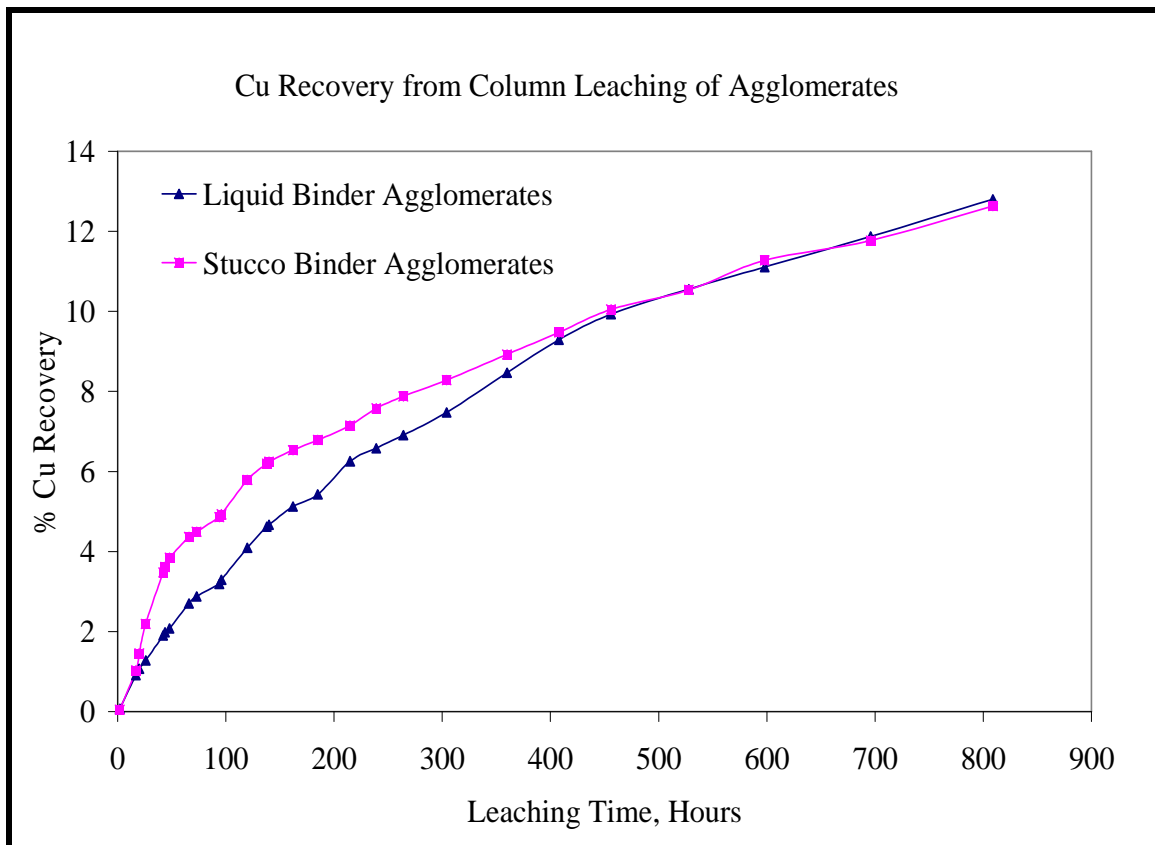
Figure 3.13 Comparison of copper recoveries from column leaching of agglomerates.

binder agglomerates and later-on there is not much difference between the recoveries. Data corresponding to Figure 3.13 are presented in Appendix D.

Previous studies in our group revealed that about 80% of the copper can be recovered from these ore samples by performing column leaching (Figure 3.14). However the leach solution chemistry must be adjusted to achieve high copper recoveries. In this thesis research the leach solution was not optimized, hence the low recovery. Because the ore contains significant chalcocite, Cu_2S, improved leaching would have been possible if an oxidant, such as ferric sulfate, had been added to the leach solution as in previous studies [38].
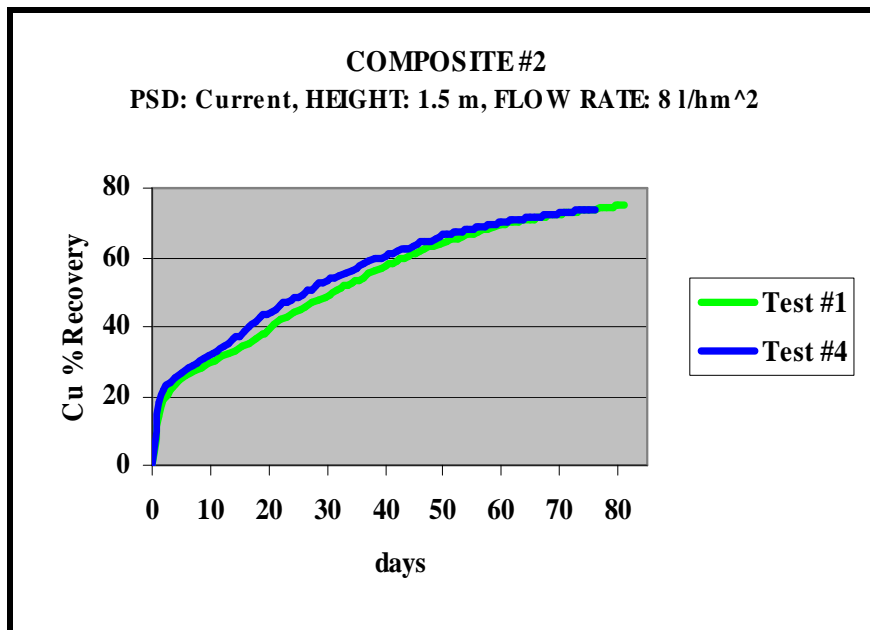
Figure 3.14 Column leaching results from previous
studies (Adapted from reference 38).

3.2.5 Electrical Conductivity Tests

Following agglomeration, the ore samples were placed into a resistance measurement device. The measurement device is shown in Figure 3.15. It consists of two equal stainless steal rectangular electrodes (length of the electrodes is equal to the length of the cylinder in which they are placed). Bolts were screwed into the two electrodes. The resistance was measured using a multimeter that is clipped to the bolts. The electrical conductivity of the packed agglomerate bed was calculated using

$$K=L/RA \tag{3.2}$$

Here K is the conductivity ($1/\Omega$ cm), L is the distance between the two electrodes (cm), R is the measured resistance (Ω) and A is the longitudinal cross
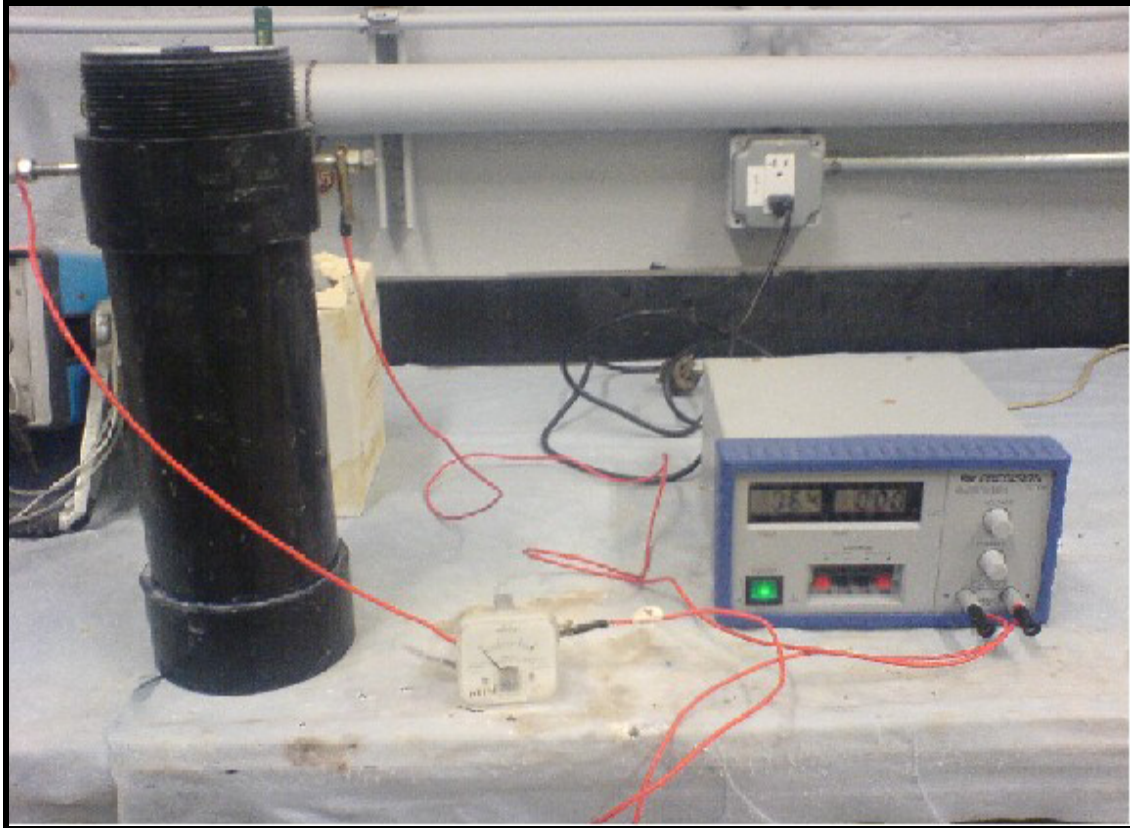
Figure 3.15 Electrical conductivity instruments.

sectional area of the electrode (cm^2). Electrical conductivity values are directly proportional the amount of moisture present in the agglomerated sample.

Figure 3.16 shows the electrical conductivity results. As expected, electrical conductivity values increase with an increase in sulfuric acid solution amount and eventually reach a constant value. This trend is identified in Figure 3.16 for no stucco addition.

Electrical conductivity values decrease with an increase in stucco binder amount for a constant sulfuric acid solution amount during agglomeration. This trend is identified in Figure 3.16 for 1000 g of sulfuric acid solution. Between the electrical conductivity values of 0.002 and 0.004 (1/ohm cm) good quality agglomerates were observed.
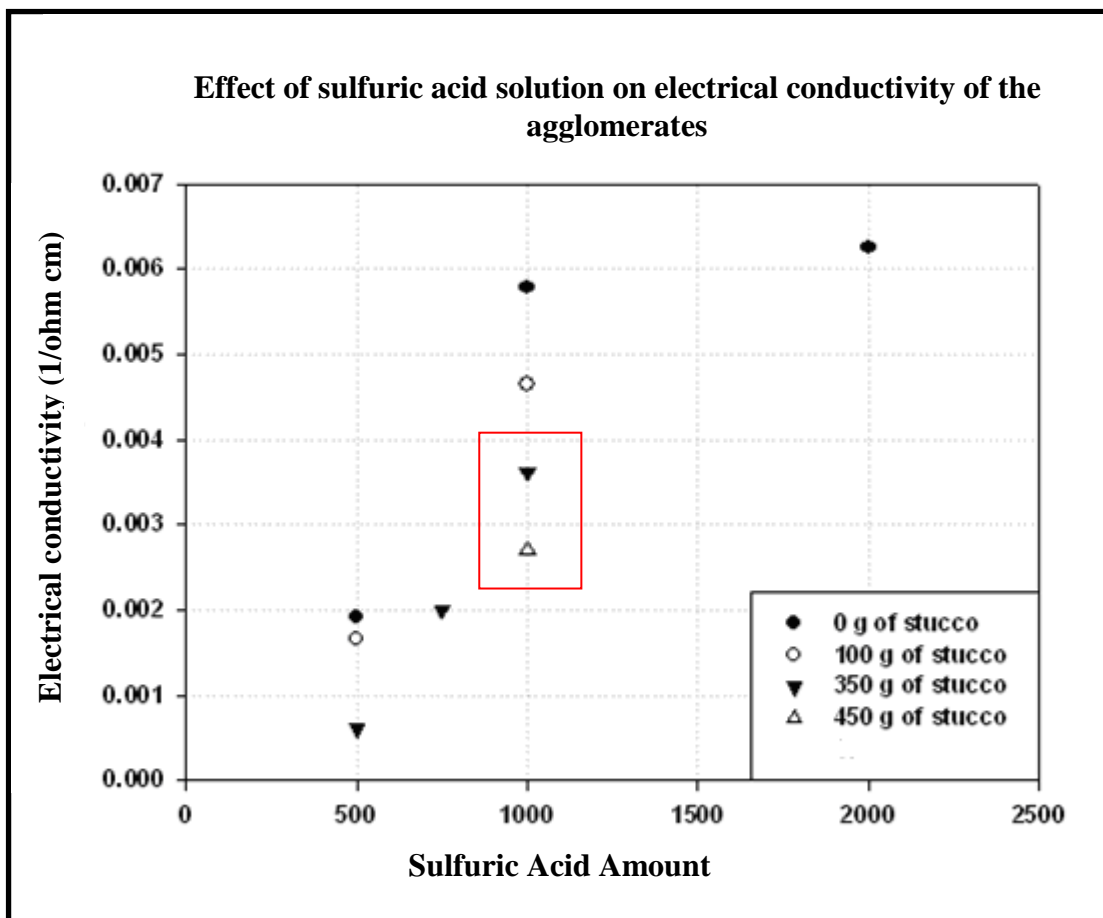
Figure 3.16 Electrical conductivity as a function of sulfuric acid solution
for different stucco binder amounts.

3.2.6 Visual Inspection

Comments on agglomerate quality can be made based on the agglomerates size, permeability, column leaching and electrical conductivity tests. Prior to the above mentioned tests, visual inspection gives a rough idea of agglomeration quality. Agglomerate color and shape varies with the acid solution chemistry amount and binder dosage. More than 75 agglomeration tests were performed, three agglomerate samples were taken under different agglomeration conditions to better illustrate the significance of visual inspection (Figure 3.17).
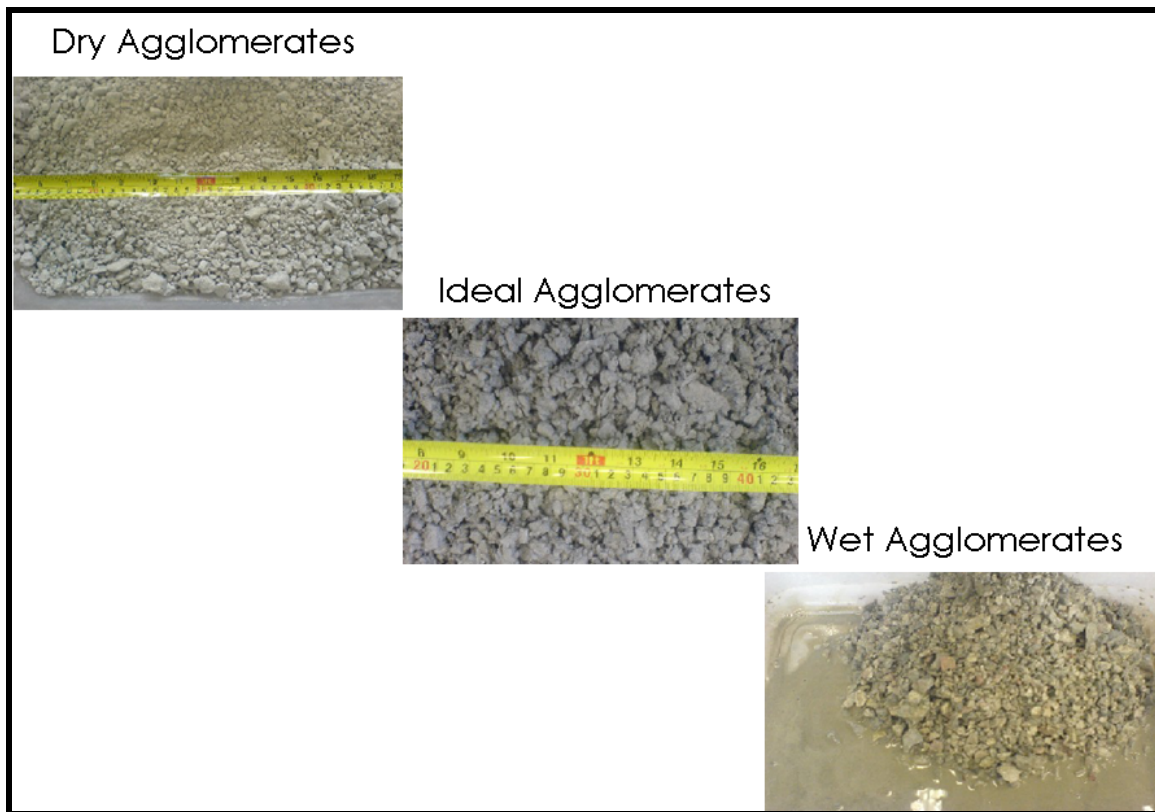
Figure 3.17 Visual inspections of agglomerates.

Good quality agglomerates were prepared with 3 to 5% f stucco binder, and 7 to 10% of acid solution. As shown by the photographs in Figure 3.17 agglomerates prepared with other combinations of binder and acid solutions were either too dry or too wet.

3.2.7 Phase Diagram Summarizing the Results

By performing agglomerate size analysis, permeability tests, column leaching tests, electrical conductivity tests, and visual inspection a phase diagram (Figure 3.18) was constructed to describe agglomerate quality as a function of sulfuric acid solution and stucco binder amounts. Good quality agglomerates were prepared with 3 to 5% stucco binder, and 7 to 10% acid solution, the region illustrated by the hatched box
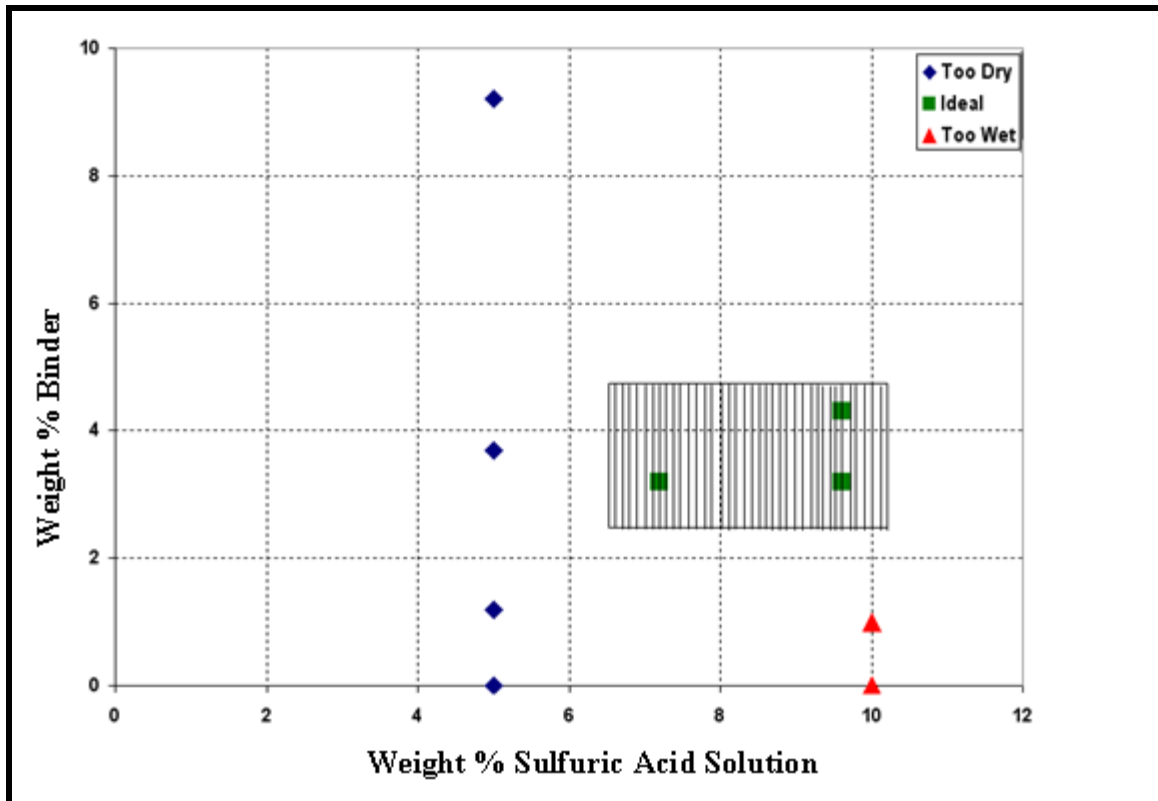
Figure 3.18- Phase diagram identifying the conditions for
high quality agglomerates.

presented in Figure 3.18. Agglomerates prepared with other combinations of binder and

sulfuric acid solution were either too dry or too wet.

3.3.7.1 Effect of Water Content

From Figure 3.7, it is clear that the agglomerates are becoming coarser when the

stucco amount is varied from 0g to 500g. In these experiments, the amount of acid

solution (80% water and 20% concentrated sulfuric acid) and amount feed material (20

pounds) were kept constant. Some experiments were done to see whether the increase in

agglomerate size is genuinely due to stucco addition or due to the water effect. Stucco

reacts with water to give gypsum.

$$CaSO_4 \, \tfrac{1}{2} H_2O + 3/2H_2O \longrightarrow CaSO_4.2H_2O \tag{3.3}$$
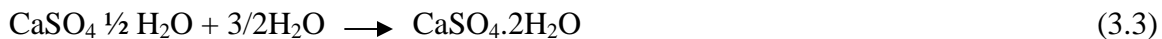
Agglomeration experiments were conducted with no stucco and by decreasing the water amount (water that is estimated to be consumed by 500g stucco to form gypsum, 3/2 mole H_2O per mole of stucco). Experimental results show that an increase in agglomerates size is only due to stucco addition but not due to the water effect (Figure 3.19). From Figure 3.19 it is clear that the agglomerates are becoming coarser as the binder amount is increased despite the decrease in water amount.
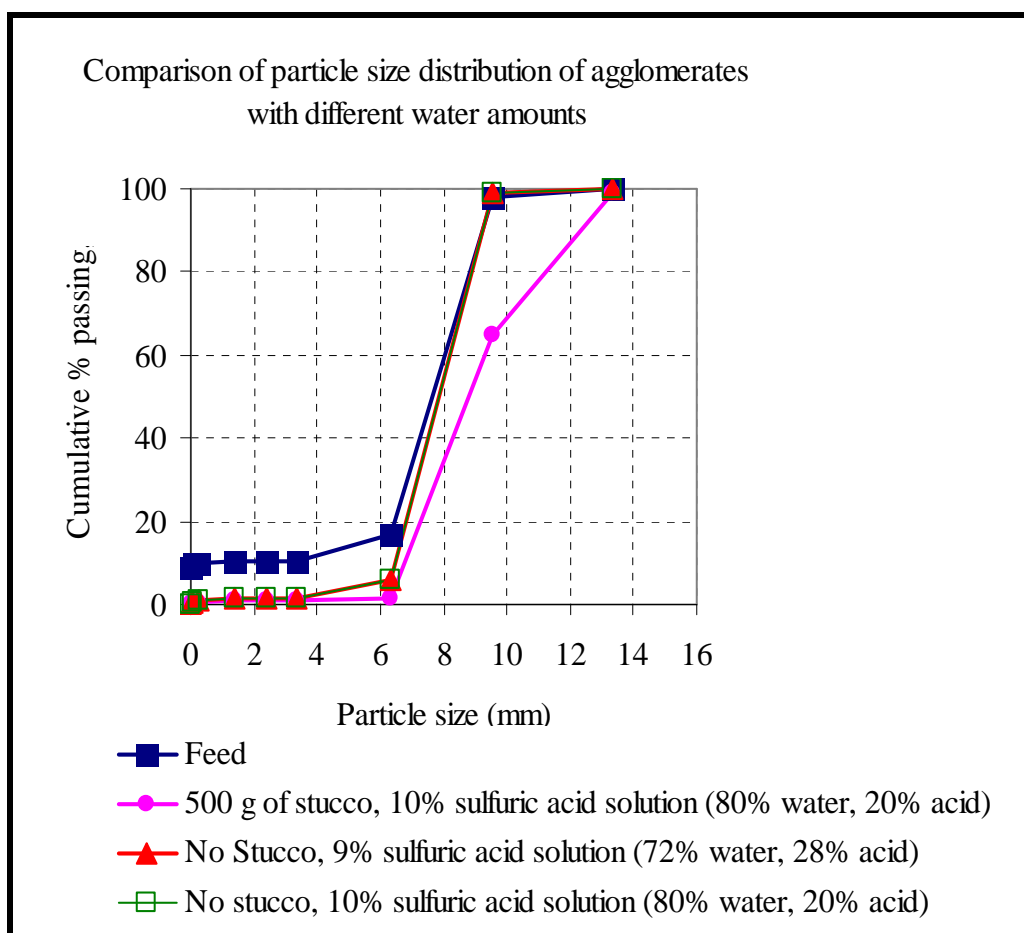
Figure 3.19 Effect of water content on agglomerate size.

3.3.7.2 Effect of Gypsum (Binder) on Agglomerate Quality

In the literature it has been suggested that gypsum could be used as binder for agglomeration [30]. So, experiments were performed by using gypsum binder to examine its effect on agglomerate quality. The gypsum binder amount and sulfuric acid solution amount were selected in correspondence to ideal agglomerates that were obtained when stucco binder is used. When stucco binder is added in the agglomeration process, some amount of water reacts with stucco to form gypsum. When gypsum binder is added there is no hydration reaction, so in order to maintain the same amounts of solution the water should be reduced according to the reaction stoichiometry.

$$CaSO_4 \text{ ½ } H_2O + 3/2H_2O \longrightarrow CaSO_4.2H_2O \tag{3.4}$$
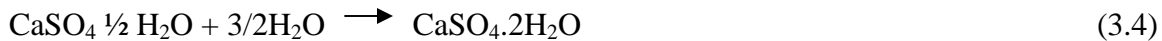
Agglomerated samples from 350g of stucco binder, 1000g of acid solution (80% water and 20% concentrated sulfuric acid) and 20 pounds of ore were compared with agglomerates from 350g of gypsum binder, 945g of acid solution and 20 pounds of ore. Figure 3.20 shows the photographs of these agglomerates. From the above Figure 3.20 it is clear that the agglomerates with gypsum binder (left) are too wet (electrical conductivity of 0.001 1/ohm cm) whereas the agglomerates with stucco binder (right) are of much better quality (electrical conductivity of 0.002 1/ohm cm).

3.3 Summary and Conclusions

Numerous binders for acid heap leaching of crushed copper ore have been suggested in literature [17, 18, 19] but none have been adopted by the mining industry.
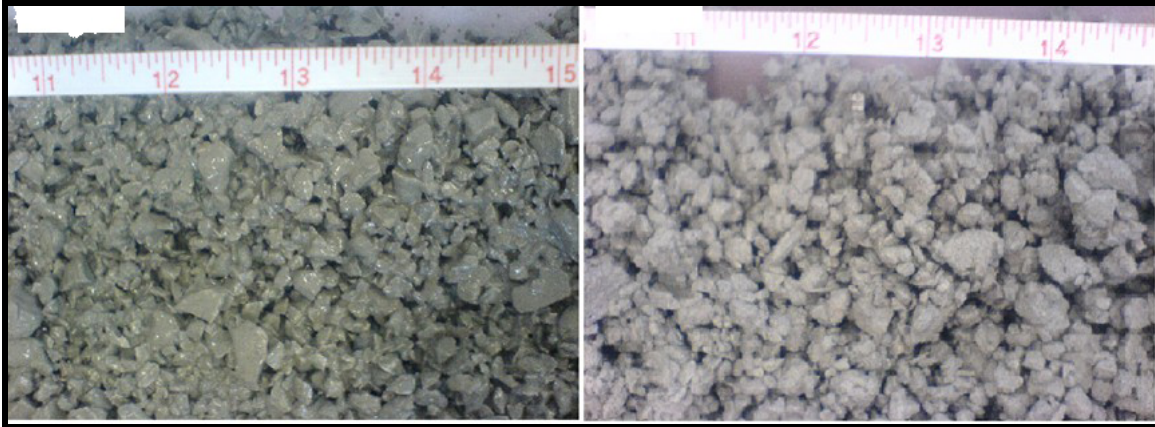
Figure 3.20 Photographs of agglomerates produced by using gypsum
(left) and stucco (right) binders.

Among the binders suggested is gypsum [30] but the effectiveness of gypsum has not
been demonstrated. In fact, our experimental results show that gypsum itself is not an
effective binder. In order to achieve binding of fine particles and the formation of stable
agglomerates, stucco (calcium sulfate hemihydrate) must be used. In this regard, stucco
serves as an effective binder because the stucco hydration reaction, which occurs during
agglomeration of the ore, immobilizes the fines binding them together with coarser ore
particles via the gypsum hydration product which forms in-situ and serves to stabilize the
agglomerates thus formed. It is expected that the ore particles both fine and coarse act as
nucleation sites for the hydration of stucco.

The quality/stability of the agglomerates is revealed from various evaluation tests,
including visual inspection and, the preferred conditions for the ore tested and its
corresponding particle size distribution has been established. For the copper ore studied
the mix for effective agglomeration should contain about 85-90% ore, 7-10% sulfuric
acid solution, and 3-5% stucco. Under these conditions the conductivity of the
agglomerates is found to be between about 0.002 and 0.004 1/(ohm cm). Of course these

preferred conditions are expected to change with ore type and particle size distribution. In this way, solution agglomeration which occurs via liquid bridges is extended by the use of stucco as a binder. Stucco hydration reactions occur within the bridges and the agglomerate structure is strengthened. As the particles are connected during agglomeration they are bound by a network of gypsum crystals, the product of the hydration reaction. The sequence of events is shown in Figure 3.21.

Figure 3.21 Sequence of events in stucco agglomeration of fine ore particles
at the surface of coarse ore particles, A) Initial mixing of
ore particles, acid solution and stucco with formation
of liquid bridge. B) Final stable agglomerate
structure formed by hydration
of stucco binder.

CHAPTER 4

CONCLUSIONS

In this thesis research, experiments were done to examine both the crushing and agglomeration steps in copper ore pretreatment prior to heap leaching.

4.1 Evaluation of Crushing

4.1.1 Particle Size Analysis

High pressure HPGR produced a slightly finer particle size distribution when compared to other crushing methods for both copper oxide and copper sulfide samples (Figures 2.3 and 2.4). By comparing the P_{80} values, it appears that the copper sulfide ore is softer than the copper oxide ore.

4.1.2 Mineral Exposure

As expected, grain exposure decreases with an increase in particle size. Grain exposure in the copper oxide ore samples was less (85 to 90% at 2 mm) when compared with grain exposure in the copper sulfide ore samples (95% at 2mm) but exposure was affected by crusher type. Data points are spread out in the copper oxide exposure data for different crushing methods (Figure 2.6). This trend is supported by copper oxide

laboratory column leaching results, which show that greater recovery was generally achieved for all particle sizes prepared by HPGR high pressure crushing condition (Figure 2.17 to Figure 2.19).

For the copper sulfide ore samples mineral exposure was high (95% at 2mm) but independent of crusher type (Figure 2.7). Data points are concentrated at particular exposure values for the copper sulfide ore with different crushing methods (Figure 2.7).This unusual behavior account, in part, for higher copper recovery from copper sulfide ore during column leaching (Figure 2.20 to Figure 2.22).

4.1.3 Particle Damage

High pressure HPGR crushing produces more cracks than other crushing methods in most of the particle size classes (Figures 2.10 and 2.11). As particle size decreases the percentage of cracked particles increases for the copper oxide ore samples. For high pressure HPGR copper oxide ore samples the percent of cracked particles increased from 40% to 80% as the particle size is decreased from 1/4inch to 200mesh (Figure 2.10). Such a trend was not evident for the copper sulfide ore samples (about 80% of the particles are cracked in all high pressure HPGR copper sulfide samples irrespective of particle size) (Figure 2.11).

4.1.4 Mini Column Leaching

Figure 2.12 show internal grains for HPGR-high pressure and Jaw crusher samples which have dissolved after 29 days during minicolumn leaching. The over all trend shows that copper grains dissolve at a faster rate in the case of minicolumn leaching of high pressure HPGR products.

4.1.5 Laboratory Column Leaching

4.1.5.1 Copper Oxide Ore

Copper recoveries are high for most of the high pressure HPGR samples (Figures 2.17 to 2.19). As expected, copper recoveries increase with a decrease in particle size. Copper recovery values show the same trend as grain exposure data (Figures 2.23 to 2.27).

4.1.5.2 Copper Sulfide Ore

Copper recovery is independent of the crushing method since about 80 to 90% of copper is recovered during the initial period of leaching (Figures 2.20 to 2.22). Recovery values are higher than those for the copper oxide ore samples. This high recovery from the copper sulfide ore samples is due to the higher head grade, greater grain exposure and perhaps a more aggressive leach solution. Copper recovery values show the same trend as grain exposure data (Figures 2.28 to 2.32).

The evidence suggests that high pressure HPGR increases the leaching of copper oxide ore under the conditions considered. Whereas, the leaching of copper sulfide ore samples, under the conditions considered, is independent of crusher type despite greater particle damage from high pressure HPGR samples. In this regards, it is expected that the effect of damage would be more significant for the copper sulfide ore if a less aggressive leach solution were used. The leach solution for the copper oxide ore was at pH 1.1, whereas the leach solution for the copper sulfide ore was at pH 2.

4.2 Binder for Agglomeration in Acid Heap Leaching

Numerous binders for acid heap leaching of crushed copper ore have been suggested in literature [17, 18, 19] but none have been adopted by the mining industry. Among the binders suggested is gypsum [30] but the effectiveness of gypsum has not been demonstrated. In fact, our experimental results show that gypsum itself is not an effective binder. In order to achieve binding of fine particles and the formation of stable agglomerates, stucco (calcium sulfate hemihydrate) must be used. In this regard, stucco serves as an effective binder because the stucco hydration reaction, which occurs during agglomeration of the ore, immobilizes the fines binding them together with coarser ore particles via the gypsum hydration product, which forms in-situ and serves to stabilize the agglomerates thus formed.

It is expected that the ore particles both fine and coarse act as nucleation sites for the hydration of stucco. The quality/stability of the agglomerates is revealed from various evaluation tests, including visual inspection and, the preferred conditions for the ore tested and its corresponding particle size distribution has been established. For the copper ore studied the mix for effective agglomeration should contain about 85-90% ore, 7-10% sulfuric acid solution, and 3-5% stucco. Under these conditions the conductivity of the agglomerates is found to be between about 0.002 and 0.004 1/(ohm cm). Of course these preferred conditions are expected to change with ore type and particle size distribution. In this way, solution agglomeration which occurs via liquid bridges is extended by the use of stucco as a binder. Stucco hydration reactions occur within the bridges and the agglomerate structure is strengthened. As the particles are connected during

agglomeration they are bound by a network of gypsum crystals, the product of the hydration reaction. The sequence of events is shown in Figure 3.21.

APPENDIX A

PARTICLE DAMAGE

Table A1 Percent of particles with cracks.

	Copper Oxide					Copper Sulfide				
Percent of Particles with Cracks										
Size	Feed	Jaw	Low HPGR	Medium HPGR	High HPGR	Feed	Jaw	Low HPGR	Medium HPGR	High HPGR
+1/4"	50	17	50	50	43	33		63	80	78
1/4 x 4M	21	12	45	56	63	31	32	73	56	77
4 x 10M	15	14	37	44	79	20	23	51	69	84
10 x 20M	7	12	23	31	46	9	15	24	39	58
20 x 40M	50	64	83	93	96	35	45	52	69	78

APPENDIX B

COLUMN LEACHING OF COPPER OXIDE ORE

Tables B1 to B12 present the copper recovery (about 240 hours of leaching) of copper oxide ore samples from replicates 1 and 2. Figures B1 to B12 correspond to the data presented in Tables B1 to B12.

Table B1 Copper recovery from copper oxide ore samples, Replicate 1 (+1/4").

Leaching Time (Hours)	Copper Oxide - Replicate 1 Percent Copper Recovery from Column Leaching (+ 1/4" Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	1	0	0
7	2	2	8	2	2
8	3	2	9	2	2
22	6	7	20	6	6
25	7	7	21	6	6
28	8	8	23	7	7
31	9	8	24	8	8
46	13	10	28	12	16
51	14	11	29	13	17
55	15	12	29	14	18
70	20	15	32	17	26
78	22	17	33	18	28
95	27	18	35	22	32
100	29	19	36	22	33
118	33	21	39	25	37
124	35	23	40	26	37
142	40	28	43	31	42
147	41	29	44	33	43
169	47	35	48	41	55
193	54	41	51	46	59
198	55	42	52	47	60
211	58	45	54	49	62
220	59	46	55	50	64
235	61	48	56	51	65
240	61	49	56	52	66

Table B2 Copper recovery from copper oxide ore samples, Replicate 1 (+1/4" x 4M).

Leaching Time (Hours)	Copper Oxide - Replicate 1 Percent Copper Recovery from Column Leaching (1/4" x 4 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	0	0	0
7	1	2	2	3	2
8	1	2	2	3	2
22	7	9	5	7	9
25	8	11	6	8	10
28	9	11	6	9	11
31	10	13	7	10	11
46	14	18	11	15	14
51	16	19	12	16	15
55	17	20	13	17	16
70	21	22	16	21	19
78	23	23	17	23	21
95	27	27	20	27	25
100	29	28	22	28	26
118	32	32	29	35	29
124	35	34	30	36	31
142	42	37	35	40	43
147	42	38	37	41	44
169	45	42	46	47	50
193	49	47	53	53	57
198	50	48	54	55	58
211	51	51	58	60	63
220	53	52	60	61	66
235	57	55	64	63	69
240	57	55	66	64	70

Table B3 Copper recovery from copper oxide ore samples, Replicate 1 (4 x 10M).

Leaching Time (Hours)	Copper Oxide - Replicate 1 Percent Copper Recovery from Column Leaching (4 x 10 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	0	0	0
2	1	1	1	1	2
4	2	2	3	3	3
6	3	2	4	3	5
8	3	3	4	5	7
22	6	6	8	13	19
24	7	6	9	14	19
26	7	7	9	14	20
28	8	7	10	15	21
30	8	8	10	16	21
46	13	10	14	22	28
48	13	10	14	23	28
54	15	11	17	24	30
70	25	14	22	30	34
79	26	16	24	32	37
97	28	32	28	42	42
100	29	33	29	43	43
121	36	45	33	48	50
143	41	57	43	56	54
151	42	58	45	57	56
167	47	59	46	60	60
175	48	60	47	61	61
191	51	62	50	64	64
215	60	64	56	68	68
240	65	69	58	73	72

Table B4 Copper recovery from copper oxide ore samples, Replicate 1 (10 x 20M).

Leaching Time (Hours)	Copper Oxide - Replicate 1 Percent Copper Recovery from Column Leaching (10 x 20 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	0	0	0
2	1	1	2	2	2
4	3	3	4	4	4
6	5	5	5	6	6
8	7	7	7	8	8
22	19	16	13	16	17
24	20	17	14	17	18
26	20	18	15	17	19
28	21	19	16	18	20
30	22	19	17	19	21
46	29	24	23	25	26
48	29	25	24	26	27
54	30	27	26	28	29
70	34	30	31	35	35
79	36	33	33	37	37
97	40	40	41	40	41
100	41	41	42	41	41
121	46	46	48	51	51
143	51	52	55	57	61
151	53	55	56	58	62
167	56	59	59	64	66
175	57	61	61	66	67
191	60	64	66	68	69
215	65	69	67	72	77
240	70	75	68	75	80

Table B5 Copper recovery from copper oxide ore samples, Replicate 1 (20 x 40).

Leaching Time (Hours)	Copper Oxide - Replicate 1 Percent Copper Recovery from Column Leaching (20 x 40 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	0	1	0
3	2	4	4	4	4
5	4	6	6	6	6
7	6	9	9	8	9
21	28	22	24	27	25
24	31	24	26	30	30
27	32	27	28	31	33
30	34	28	29	34	35
45	42	37	38	39	42
47	43	38	38	40	42
49	43	38	39	40	43
54	44	41	39	41	45
69	46	42	41	46	48
79	48	45	44	48	53
95	50	49	49	53	56
103	50	50	49	55	60
121	54	54	61	60	62
126	55	55	61	61	63
142	56	58	63	67	68
150	57	60	63	68	69
164	60	63	66	71	72
174	61	64	67	73	73
188	63	67	69	74	75
197	64	69	70	75	76
214	68	70	73	76	79
224	69	72	75	78	80
240	71	74	76	79	80

Table B6 Copper recovery from copper oxide ore samples, Replicate 1 (40 x 100M).

Leaching Time (Hours)	Copper Oxide - Replicate 1 Percent Copper Recovery from Column Leaching (40 x 100 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	0	0	0
3	2	2	3	2	2
5	3	4	6	4	4
7	4	6	8	6	7
21	12	21	21	21	18
24	14	22	24	23	20
27	15	24	26	26	21
30	16	25	27	28	22
45	22	32	36	33	27
47	23	32	36	34	28
49	23	33	37	34	28
54	24	34	39	36	30
69	28	39	42	41	35
79	31	42	44	45	38
95	36	46	49	48	42
103	38	48	51	50	45
121	44	52	55	55	50
126	45	52	56	57	52
142	50	56	60	61	57
150	53	57	62	62	58
164	57	59	65	66	62
174	59	62	67	68	64
188	62	65	70	72	69
197	65	68	72	74	72
214	68	72	75	77	77
224	71	74	76	79	79
240	75	78	79	82	83

Table B7 Copper recovery from copper oxide ore samples, Replicate 2 (+1/4").

Leaching Time (Hours)	Copper Oxide - Replicate 2 Percent Copper Recovery from Column Leaching (+ 1/4" Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	1	0	0
2	1	1	3	1	1
5	1	2	5	2	1
9	2	3	9	3	2
23	6	7	13	7	7
26	7	8	13	7	8
31	9	9	14	9	9
48	18	15	17	15	15
51	19	16	18	16	16
55	20	17	19	17	17
74	24	22	22	24	25
79	25	23	24	26	27
98	34	28	31	30	32
102	34	29	33	31	32
125	39	35	38	37	38
150	45	42	51	46	47
174	50	50	61	57	54
198	53	56	64	67	58

Table B8 Copper recovery from copper oxide ore samples, Replicate 2 (+1/4" x 4M).

Leaching Time (Hours)	Copper Oxide - Replicate 2 Percent Copper Recovery from Column Leaching (1/4" x 4 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	0	0	0
2	2	1	0	0	1
5	4	2	2	0	3
9	5	3	3	1	4
23	8	10	7	2	9
26	9	10	8	2	10
31	10	11	10	2	13
48	16	16	11	4	19
51	17	17	11	5	20
55	18	18	12	5	20
74	23	22	19	6	27
79	24	23	21	6	29
98	30	25	24	8	38
102	31	26	25	8	38
125	37	29	34	9	42
150	43	34	42	10	51
174	50	41	47	12	60
198	57	44	53	13	66

Table B9 Copper recovery from copper oxide ore samples, Replicate 2 (4 x 10M).

Leaching Time (Hours)	Copper Oxide - Replicate 2 Percent Copper Recovery from Column Leaching (4 x 10 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	0	0	0
2	1	1	1	1	1
4	2	2	3	1	2
6	3	3	4	2	3
22	8	8	14	5	13
24	9	8	15	5	14
26	9	8	15	5	15
28	10	9	16	5	16
30	11	10	16	7	18
46	20	16	23	15	26
48	21	16	23	16	26
50	21	17	24	16	26
52	22	18	24	17	28
54	23	19	24	17	28
68	30	23	28	23	37
75	34	25	28	26	38
93	35	33	32	29	40
97	36	34	32	30	42
100	37	35	33	31	43
115.4	40	38	36	34	48
124	42	39	38	37	51
140	49	42	43	43	59
148	50	43	46	48	62
166	52	44	55	51	65
169	53	45	55	52	66
190	56	51	57	59	72
210	59	62	62	64	73
218	60	65	63	66	74
234	62	69	66	70	77
242	63	71	67	71	78

Table B10 Copper recovery from copper oxide ore samples, Replicate 2 (10 x 20M).

Leaching Time (Hours)	Copper Oxide - Replicate 2 Percent Copper Recovery from Column Leaching (10 x 20 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	1	0	0	0
2	2	1	1	1	2
4	3	1	1	1	5
6	4	2	2	2	7
22	13	7	10	13	20
24	14	7	10	14	21
26	15	8	10	15	22
28	16	9	10	16	23
30	16	9	11	17	24
46	25	18	21	24	37
48	25	19	21	24	38
50	26	20	22	25	39
52	26	21	23	25	40
54	27	22	24	26	41
68	31	29	30	33	46
75	36	30	33	34	47
93	42	35	41	44	52
97	42	36	43	46	53
100	43	37	44	46	53
115.4	48	41	48	50	54
124	49	45	51	52	56
140	53	51	54	58	61
148	56	53	57	59	63
166	59	57	61	65	68
169	60	58	62	65	68
190	64	65	69	68	72
210	68	69	72	73	75
218	69	69	73	75	76
234	72	72	74	78	79
242	73	75	76	79	81

Table B11 Copper recovery from copper oxide ore samples, Replicate 2 (20 x 40M).

Leaching Time (Hours)	Copper Oxide - Replicate 2 Percent Copper Recovery from Column Leaching (20 x 40 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	0	1	1
3	1	2	2	3	2
5	2	3	2	5	4
20	13	6	3	6	10
23	15	7	4	7	12
27	18	8	5	9	18
45	26	11	13	29	27
47	27	12	14	30	28
49	28	13	14	30	29
51	28	13	15	31	30
68	35	25	24	35	36
72	36	26	25	36	37
74	37	26	25	36	37
79	39	29	27	38	39
92	41	39	30	44	43
95	41	40	31	45	43
102	43	42	34	47	46
116	46	48	42	51	52
125	49	49	45	53	55
140	52	56	50	56	61
149	54	58	53	59	64
167	59	64	59	64	70
174	60	65	62	66	71
191	64	66	68	71	73
197	64	66	69	71	74
213	69	72	72	76	77
220	71	73	73	78	79
235	74	77	75	81	82
244	76	79	77	83	84

Table B12 Copper recovery from copper oxide ore samples, Replicate 2 (40 x 100M).

Leaching Time (Hours)	Copper Oxide - Replicate 2 Percent Copper Recovery from Column Leaching (40 x 100 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	0	0	0
3	1	0	0	1	0
5	1	0	1	2	0
20	2	1	14	18	9
23	3	2	16	20	10
27	4	4	17	21	10
45	6	5	27	27	12
47	6	6	27	28	13
49	7	6	28	29	13
51	7	7	29	29	15
68	15	14	40	32	26
72	16	15	43	33	26
74	17	15	44	34	27
79	19	18	45	35	29
92	26	19	50	37	34
95	27	20	51	38	35
102	28	23	52	41	37
116	33	27	55	46	41
125	35	31	55	48	44
140	40	36	59	53	52
149	43	38	60	56	57
167	50	45	66	60	64
174	53	50	67	62	66
191	59	58	70	66	70
197	61	61	70	68	72
213	66	69	73	73	77
220	68	71	74	76	79
235	73	75	76	81	82
244	75	78	78	83	83
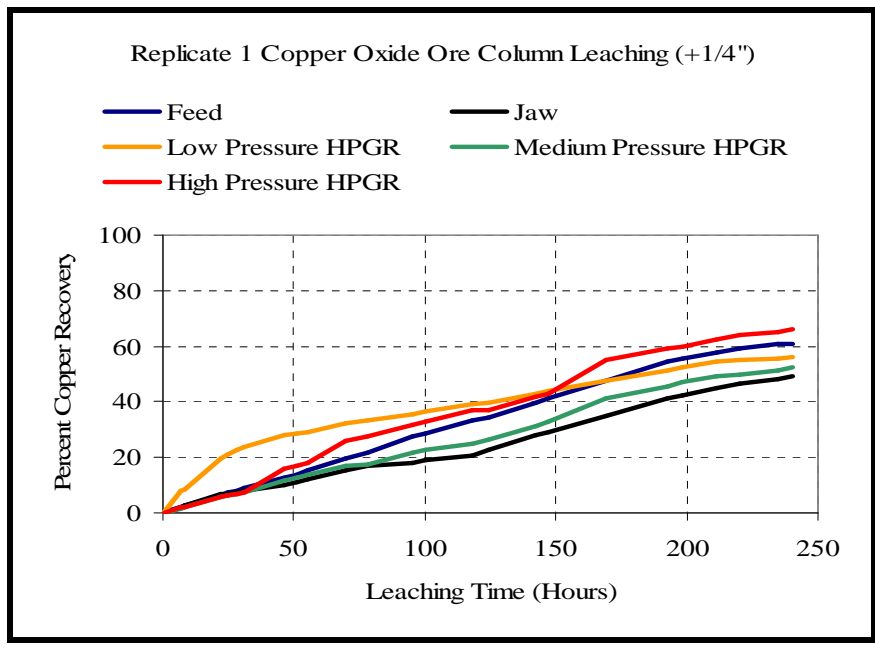
Figure B1 Copper recovery from copper oxide ore samples, +1/4" (Replicate 1) for different crushing procedures.
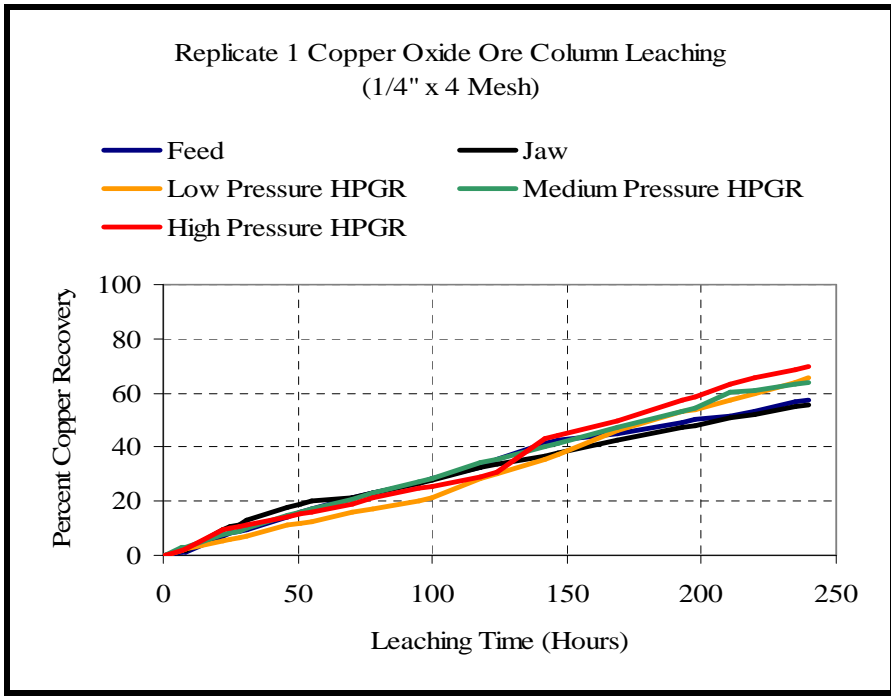
Figure B2 Copper recovery from copper oxide ore samples, 1/4" x 4M (Replicate 1) for different crushing procedures.
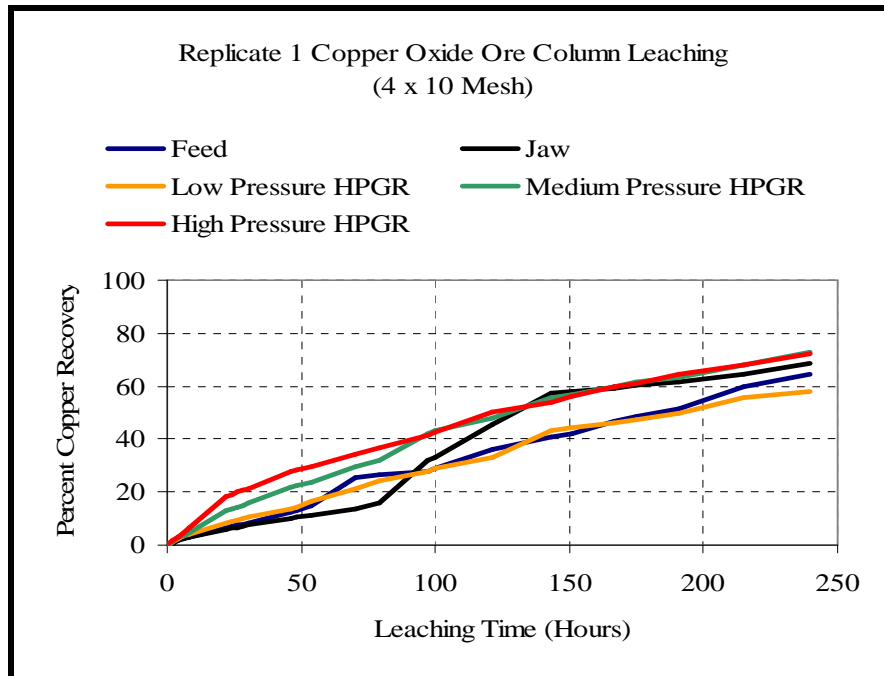
Figure B3 Copper recovery from copper oxide ore samples, 4 x 10M (Replicate 1) for different crushing procedures.
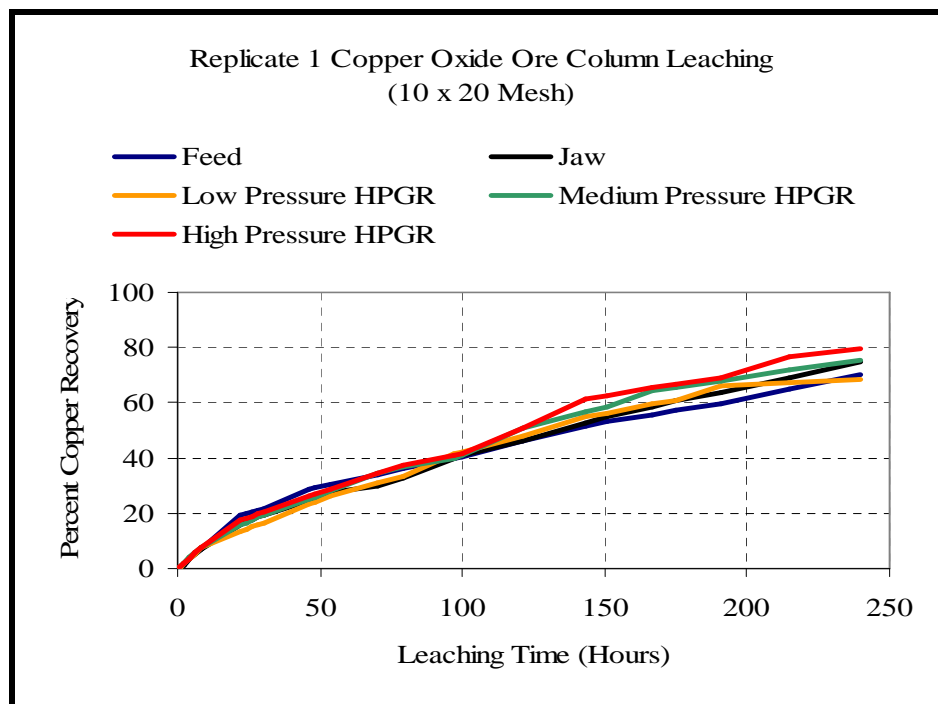
Figure B4 Copper recovery from copper oxide ore samples, +10 x 20M (Replicate 1) for different crushing procedures.
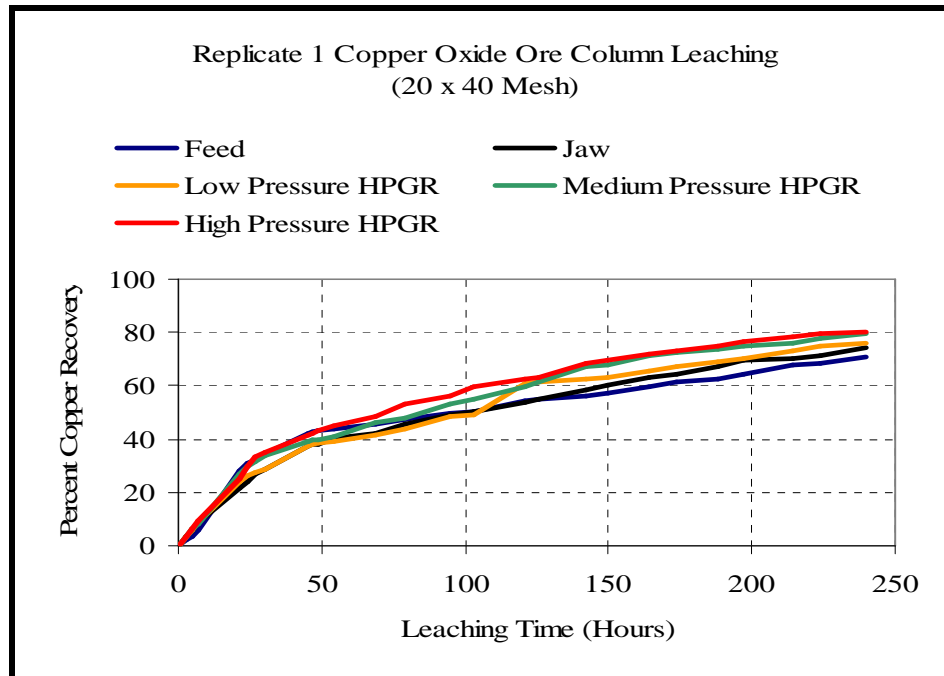
Figure B5 Copper recovery from copper oxide ore samples, 20 x 40M (Replicate 1)
for different crushing procedures.
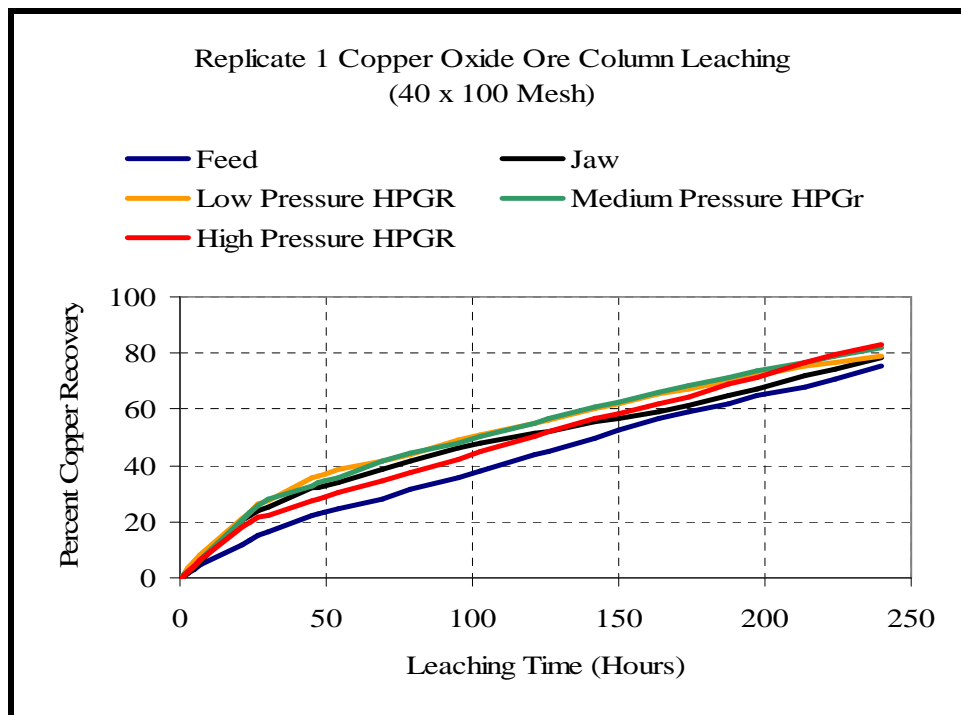
Figure B6 Copper recovery from copper oxide ore samples, 40 x 100M (Replicate 1)
for different crushing procedures.
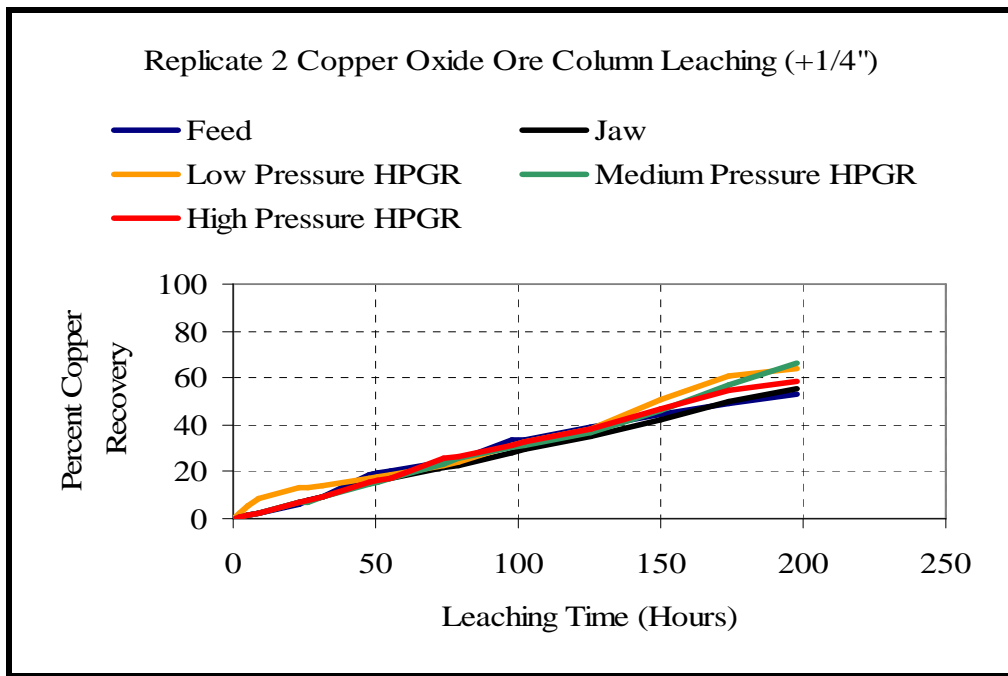
Figure B7 Copper recovery from copper oxide ore samples, +1/4" (Replicate 2)
for different crushing procedures.
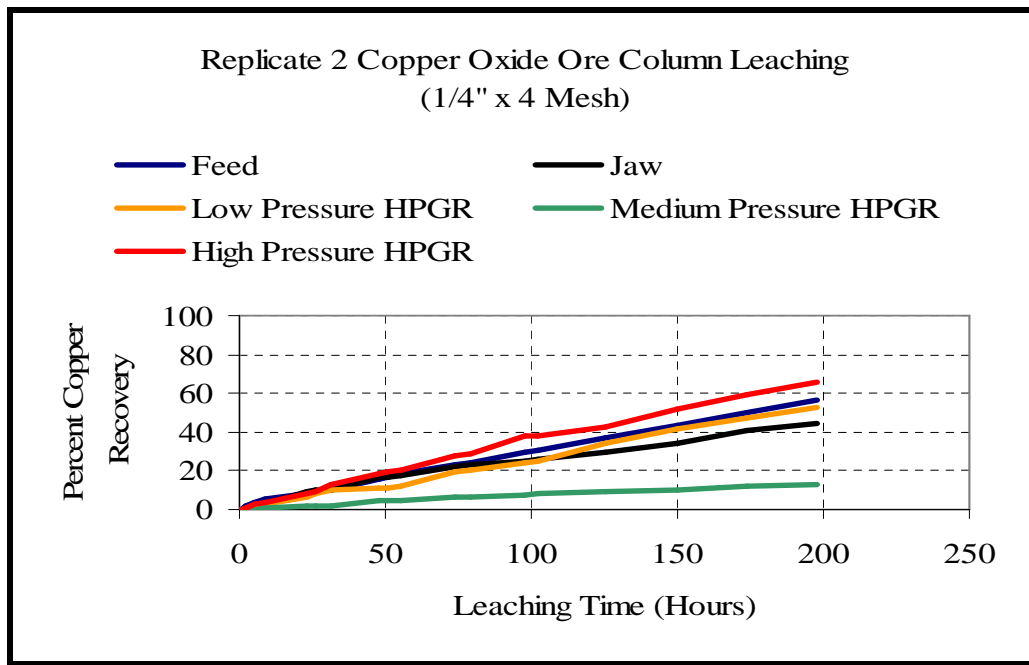
Figure B8 Copper recovery from copper oxide ore samples, 1/4" x 4M (Replicate 2)
for different crushing procedures.
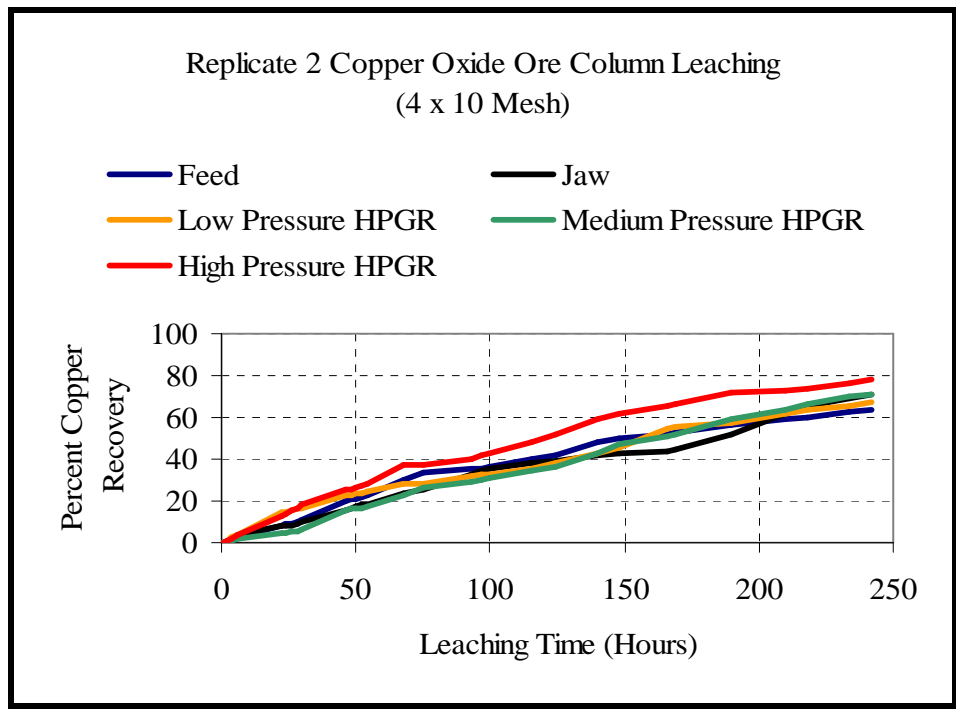
Figure B9 Copper recovery from copper oxide ore samples, 4 x 10M (Replicate 2) for different crushing procedures.
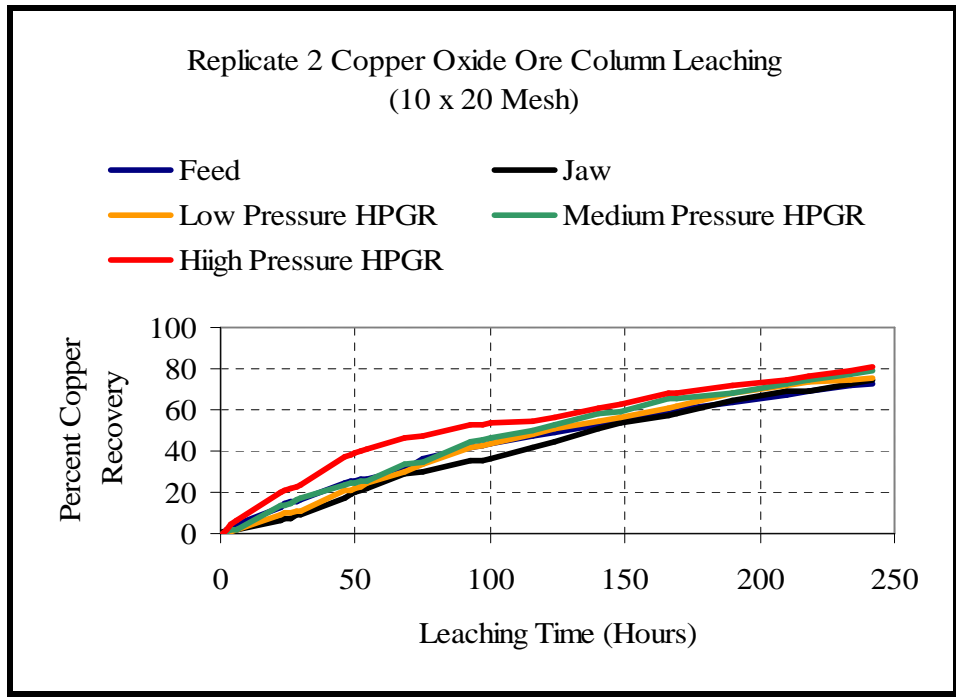
Figure B10 Copper recovery from copper oxide ore samples, 10 x 20M (Replicate 2) for different crushing procedures.
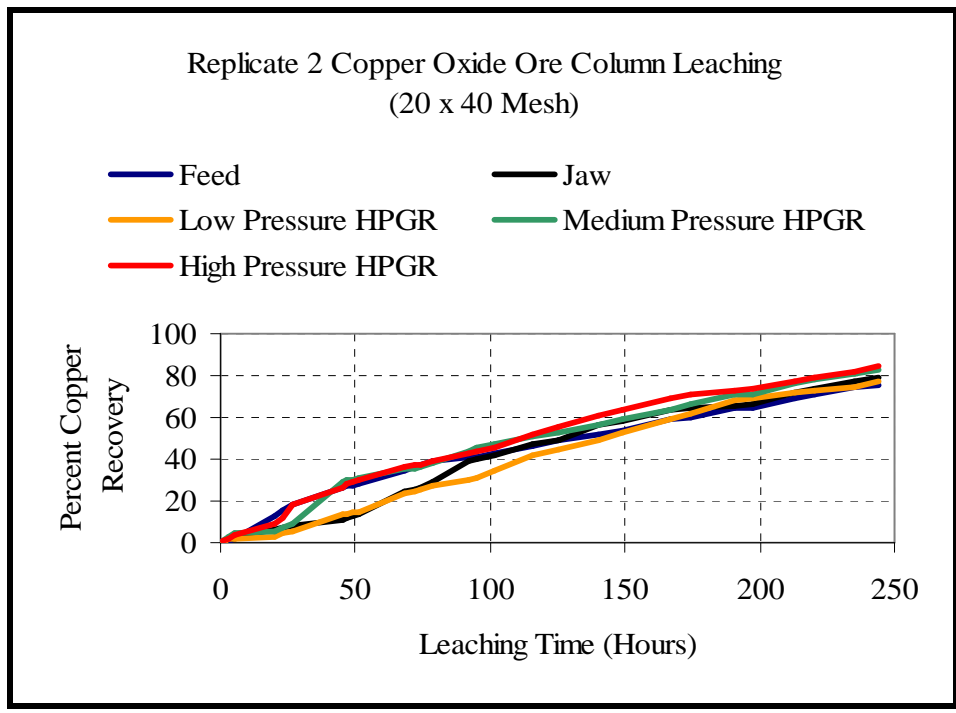
Figure B11 Copper recovery from copper oxide ore samples, 20 x 40M (Replicate 2) for different crushing procedures.
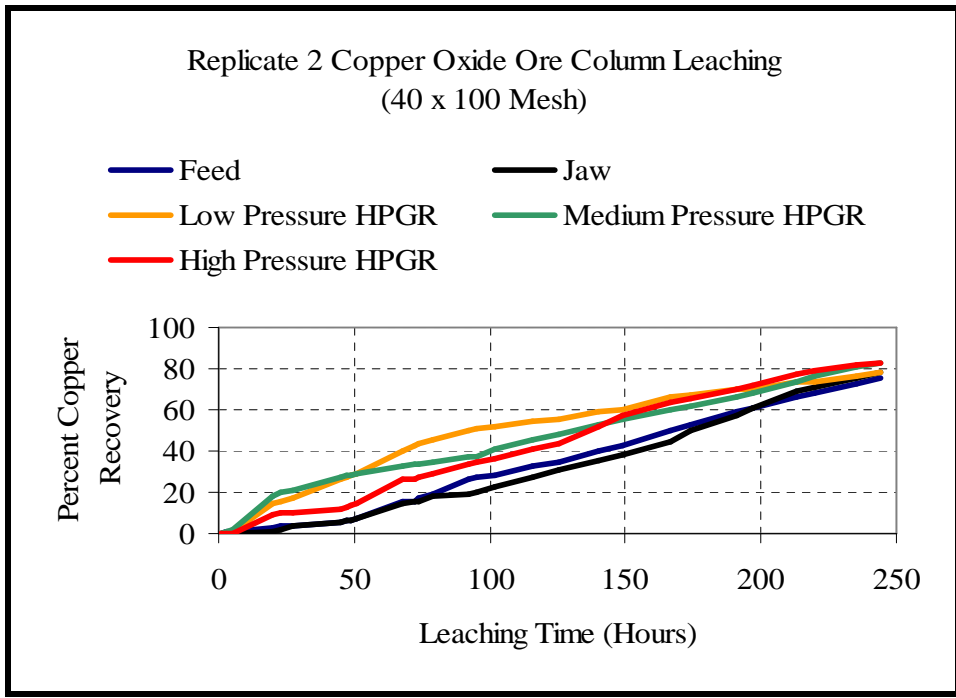
Figure B12 Copper recovery from copper oxide ore samples, 40 x 100M (Replicate 2) for different crushing procedures.

APPENDIX C

COLUMN LEACHING OF COPPER SULFIDE ORE

Table C1 to C12 present the copper recovery (about 240 hours of leaching) of copper sulfide ore samples from replicates 1 and 2. Figures C1 to C12 correspond to the data presented in Tables C1 to C12.

Table C1 Copper recovery from copper sulfide ore samples, Replicate 1 (+1/4").

Leaching Time (Hours)	Copper Sulfide - Replicate 1 Percent Copper Recovery from Column Leaching (+ 1/4" Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	1	0	1	1	1
3	2	3	3	3	3
6	3	4	5	5	4
9	5	5	6	6	6
25	12	10	13	11	12
28	13	11	14	12	14
30	14	11	14	13	14
49	24	20	21	20	22
54	26	22	23	22	23
72	31	25	30	29	30
81	33	27	32	32	33
96	34	31	35	35	39
105	37	33	37	36	41
121	44	37	40	40	44
149	48	44	48	49	51
170	50	49	55	55	56
199	55	55	67	66	63
217	57	60	72	72	67
240	61	67	77	78	71

Table C2 Copper recovery from copper sulfide ore samples, Replicate 1 (+1/4" x 4M).

Leaching Time (Hours)	Copper Sulfide - Replicate 1 Percent Copper Recovery from Column Leaching (1/4" x 4 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	0	1	0	0
3	3	2	2	1	2
6	5	4	5	3	3
9	7	5	7	4	4
25	14	12	13	8	9
28	15	13	14	9	10
30	16	14	14	10	11
49	23	25	20	16	18
54	25	27	22	18	20
72	34	36	38	33	34
81	36	39	40	34	35
96	38	41	43	36	38
105	41	43	46	38	39
121	48	45	49	40	43
149	58	49	55	46	49
170	62	54	60	55	56
199	69	66	65	62	63
217	75	72	67	68	70
240	78	77	75	79	79

Table C3 Copper recovery from copper sulfide ore samples, Replicate 1 (4 x 10M).

Leaching Time (Hours)	Copper Sulfide - Replicate 1 Percent Copper Recovery from Column Leaching (4 x 10 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	2	1	1	1	1
2	6	3	3	3	2
4	7	5	5	5	4
6	8	7	6	6	5
8	9	8	8	8	6
22	12	15	16	14	13
24	13	16	17	14	14
27	14	17	18	15	15
30	15	18	19	16	16
46	20	23	25	21	22
49	21	24	26	22	24
52	22	25	27	23	25
56	23	26	28	24	26
70	27	30	33	27	31
73	28	31	34	28	32
75	28	31	35	28	33
80	30	33	36	30	34
93	34	36	41	33	38
102	36	38	43	35	41
121	43	43	48	40	46
124	44	44	48	41	47
143	49	49	53	47	54
150	51	51	55	49	57
165	56	55	59	54	63
174	59	57	61	56	65
189	62	62	64	61	70
198	65	64	67	64	72
214	68	68	70	67	77
221	69	70	72	70	79
240	74	76	76	76	84

Table C4 Copper recovery from copper sulfide ore samples, Replicate 1 (10 x 20M).

Leaching Time (Hours)	Copper Sulfide - Replicate 1 Percent Copper Recovery from Column Leaching (10 x 20 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	2	2	2	2	1
2	7	8	7	5	4
4	10	11	9	7	6
6	11	12	11	8	7
8	12	14	12	9	8
22	18	20	17	13	13
24	19	21	18	13	13
27	20	22	19	14	14
30	21	23	20	15	15
46	25	27	25	18	19
49	25	28	25	19	20
52	26	29	26	20	20
56	27	30	27	21	22
70	30	33	31	24	26
73	31	34	32	24	27
75	31	35	33	25	28
80	32	36	34	26	29
93	35	39	37	29	32
102	37	41	40	31	34
121	42	45	45	37	39
124	43	46	46	39	40
143	49	51	52	52	48
150	52	53	54	58	52
165	58	57	58	62	56
174	60	60	60	64	59
189	64	64	65	69	64
198	66	67	67	71	67
214	70	71	72	75	73
221	72	73	74	76	75
240	78	79	79	81	81

Table C5 Copper recovery from copper sulfide ore samples, Replicate 1 (20 x 40M).

Leaching Time (Hours)	Copper Sulfide - Replicate 1 Percent Copper Recovery from Column Leaching (20 x 40 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	1	1	2	1	2
2	3	4	6	6	5
4	4	6	7	9	7
6	5	7	8	10	8
19	9	11	13	14	15
22	10	13	15	15	17
25	11	14	16	16	18
29	13	15	17	17	19
43	17	19	21	21	26
48	18	20	23	22	28
53	20	22	24	23	29
69	24	28	30	28	34
76	26	30	32	30	36
93	31	35	37	35	40
101	33	37	40	37	42
117	38	42	44	41	47
122	40	44	46	43	48
142	46	50	52	50	53
146	47	52	53	52	54
164	52	58	58	59	59
174	56	61	61	68	61
188	61	66	66	72	65
197	64	68	68	74	68
213	69	74	73	77	72
240	80	82	82	83	80

Table C6 Copper recovery from copper sulfide ore samples, Replicate 1 (40 x 100M).

Leaching Time (Hours)	Copper Sulfide - Replicate 1 Percent Copper Recovery from Column Leaching (40 x 100 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	1	1	1	1	1
2	5	5	6	4	4
4	6	7	7	5	5
6	7	8	8	6	6
19	10	11	11	10	9
22	11	12	13	11	10
25	12	13	13	12	11
29	13	14	14	13	12
43	17	17	18	17	16
48	18	19	21	18	18
53	19	20	22	19	19
69	24	25	27	24	24
76	26	27	29	26	26
93	30	32	34	31	31
101	32	34	36	33	33
117	37	39	40	38	38
122	38	41	41	40	39
142	44	46	45	46	50
146	46	47	46	47	51
164	52	52	53	53	56
174	56	55	57	56	58
188	60	59	62	61	62
197	62	61	64	64	64
213	66	66	69	68	69
240	73	74	76	77	77

Table C7 Copper recovery from copper sulfide ore samples, Replicate 2 (+1/4").

Leaching Time (Hours)	Copper Sulfide - Replicate 2 Percent Copper Recovery from Column Leaching (+ 1/4" Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0		1	0	0
3	2		4	3	2
20	8		14	17	12
25	9		16	19	15
29	11		17	22	16
31	11		18	22	17
49	18		28	30	22
54	19		29	32	25
72	27		37	33	33
82	28		38	35	37
102	32		50	42	48
106	33		51	43	49
130	35		59	51	58
151	40		65	59	66
177	46		70	64	71
199	52		76	69	76
218	54		81	70	78
240	55		88	72	82

Table C8 Copper recovery from copper sulfide ore samples, Replicate 2 (1/4" x 4M).

Leaching Time (Hours)	Copper Sulfide - Replicate 2 Percent Copper Recovery from Column Leaching (1/4" x 4 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	0	1	0	1	1
3	2	2	2	2	4
20	10	13	7	5	14
25	12	15	8	7	16
29	14	17	9	8	17
31	14	17	9	8	18
49	23	29	12	16	26
54	25	31	14	16	27
72	27	44	18	23	32
82	30	45	20	23	35
102	32	47	27	26	47
106	33	48	28	27	48
130	44	52	34	35	57
151	51	61	40	42	62
177	62	72	47	48	69
199	64	82	54	53	72
218	70	89	56	57	74
240	71	90	64	59	79

Table C9 Copper recovery from copper sulfide ore samples, Replicate 2 (4 x 10M).

Leaching Time (Hours)	Copper Sulfide - Replicate 2 Percent Copper Recovery from Column Leaching (4 x 10 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	1	1	1	1	1
3	5	4	4	4	3
6	9	7	6	7	6
8	11	9	8	8	7
23	14	19	15	16	13
25	15	20	15	17	14
28	16	21	17	18	15
31	18	22	18	19	15
48	26	29	25	25	20
51	27	30	25	27	21
55	29	31	27	28	22
58	30	32	27	29	23
71	34	37	31	35	29
73	34	37	32	35	29
77	36	38	33	36	30
82	37	40	34	37	32
98	41	44	38	45	35
105	44	46	40	47	37
122	49	51	45	53	42
125	50	52	46	53	43
144	55	53	50	55	47
153	58	54	53	56	49
176	65	62	60	65	55
191	71	67	65	67	61
201	74	70	67	69	65
215	78	74	70	72	70
223	81	76	71	73	72
243	89	77	77	79	81

Table C10 Copper recovery from copper sulfide ore samples, Replicate 2 (10 x 20M).

Leaching Time (Hours)	Copper Sulfide - Replicate 2 Percent Copper Recovery from Column Leaching (10 x 20 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	1	1	2	1	1
3	7	2	8	5	7
6	10	7	10	7	10
8	11	8	11	8	11
23	17	23	16	13	16
25	18	25	17	13	17
28	19	26	18	14	18
31	20	28	19	15	19
48	26	36	25	20	25
51	27	37	26	21	26
55	29	38	27	22	27
58	29	38	28	22	28
71	34	45	31	26	32
73	34	45	31	26	33
77	35	47	33	27	34
82	37	48	34	28	36
98	41	55	38	32	40
105	44	56	40	34	43
122	49	63	45	39	49
125	50	64	46	39	50
144	55	74	52	44	55
153	57	74	55	46	58
176	65	75	63	54	67
191	71	77	68	60	73
201	74	78	70	62	76
215	77	82	74	65	80
223	79	85	76	67	82
243	83	91	81	73	87

Table C11 Copper recovery from copper sulfide ore samples, Replicate 2 (20 x 40M).

Leaching Time (Hours)	Copper Sulfide - Replicate 2 Percent Copper Recovery from Column Leaching (20 x 40 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	2	1	1	2	4
3	9	7	8	9	7
10	14	13	12	27	23
24	20	19	17	35	25
26	20	19	17	36	26
29	21	20	18	38	27
31	22	21	18	39	27
47	28	27	21	41	32
51	29	28	23	42	33
55	31	29	24	42	34
76	42	38	33	54	39
80	43	39	34	55	40
98	50	45	37	59	44
105	52	46	38	60	46
119	56	52	41	63	48
126	58	53	44	64	50
144	64	58	52	67	54
149	66	59	53	67	55
167	71	64	57	69	59
177	75	67	59	71	61
197	83	72	64	75	66
200	84	73	65	75	67
224	90	79	72	80	74
244	101	84	79	84	85

Table C12 Copper recovery from copper sulfide ore samples, Replicate 2 (40 x 100).

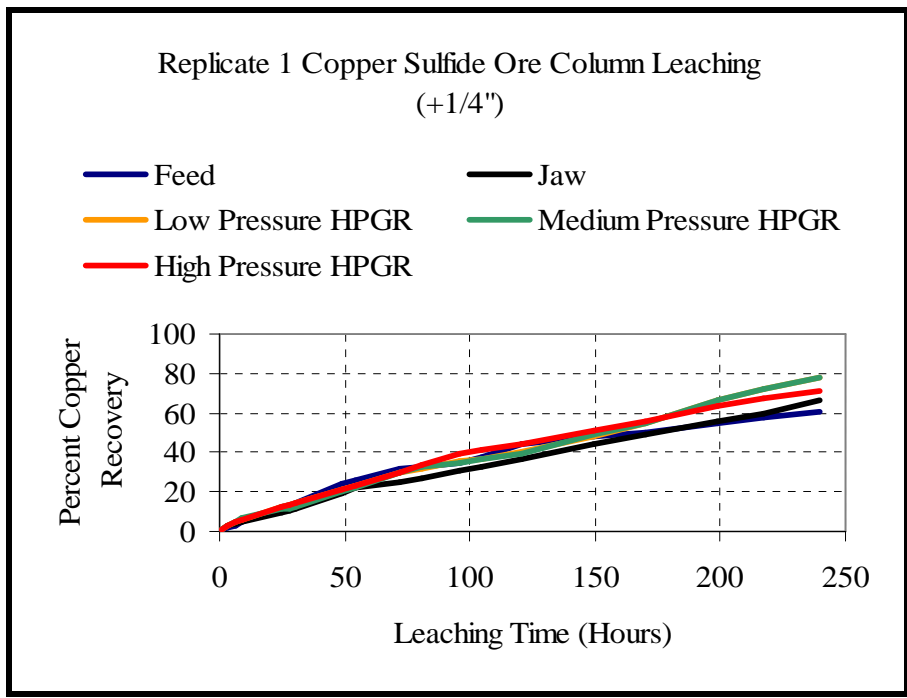| Leaching Time (Hours)	Copper Sulfide - Replicate 2 Percent Copper Recovery from Column Leaching (40 x 100 Mesh Size Fraction)				
	Feed	Jaw	Low Pressure HPGR	Medium Pressure HPGR	High Pressure HPGR
0.5	2	2		1	
3	10	11		9	
10	14	21		12	
24	18	30		14	
26	18	31		14	
29	19	33		15	
31	19	34		15	
47	24	42		19	
51	25	44		20	
55	26	46		21	
76	29	54		38	
80	30	54		39	
98	32	57		42	
105	33	58		43	
119	35	61		46	
126	36	63		48	
144	38	69		54	
149	39	70		55	
167	41	75		64	
177	42	77		66	
197	46	81		70	
200	47	82		71	
224	57	89		83	
244	69	96		84	

Figure C1 Copper recovery from copper sulfide ore samples, +1/4" (Replicate 1)
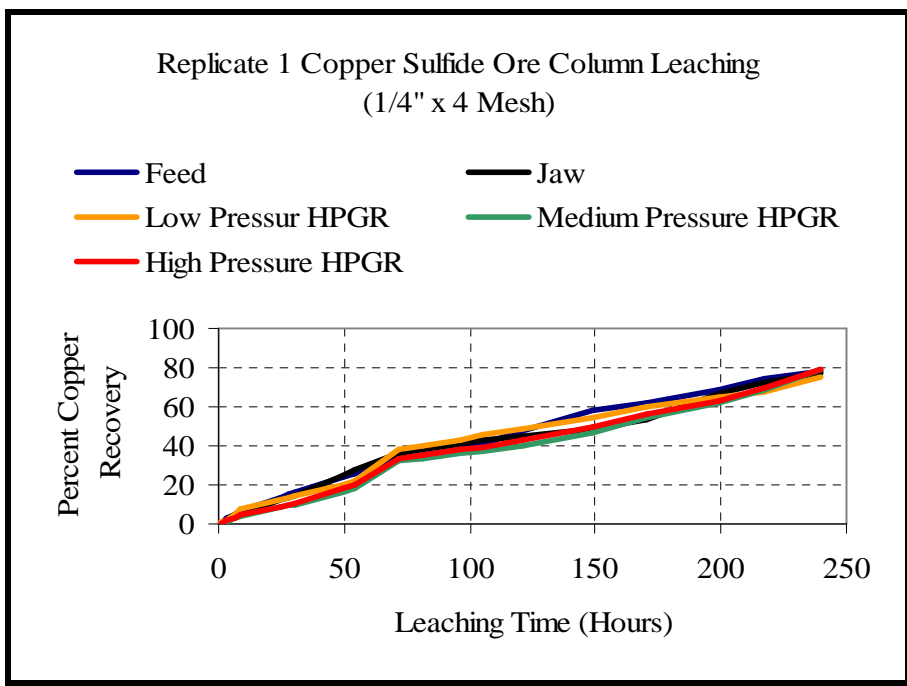for different crushing procedures.

Figure C2 Copper recovery from copper sulfide ore samples, ¼" x 4M (Replicate 1)
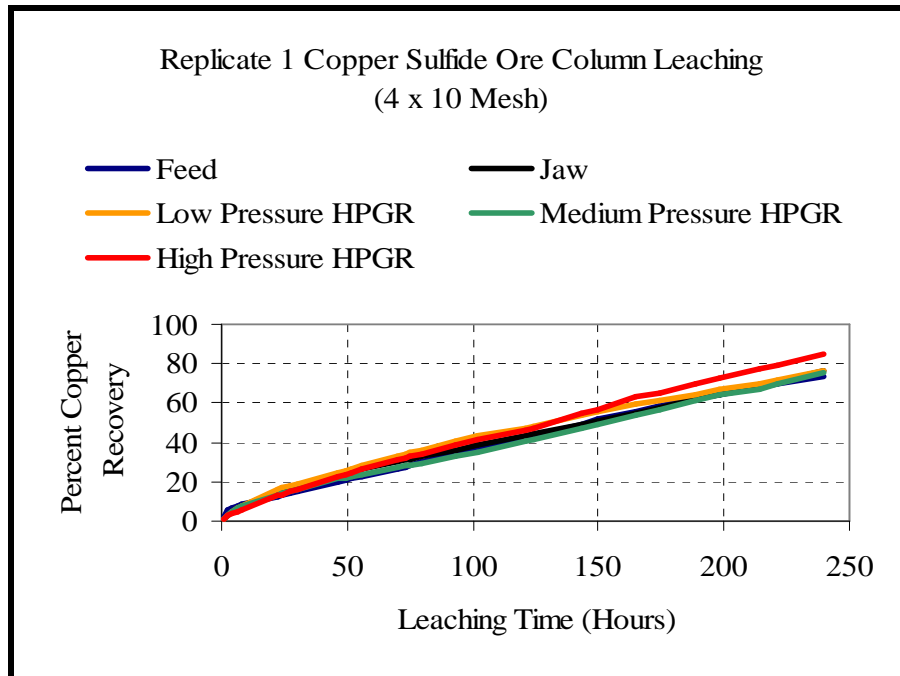for different crushing procedures.

Figure C3 Copper recovery from copper sulfide ore samples, 4 x 10M (Replicate 1)
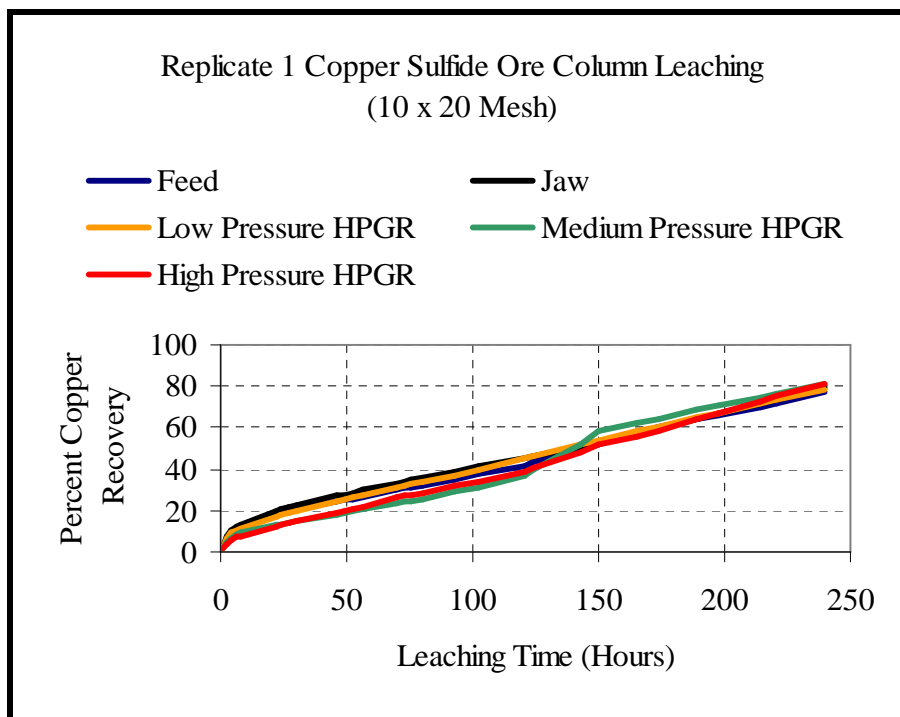for different crushing procedures.

Figure C4 Copper recovery from copper sulfide ore samples, 10 x 20M (Replicate 1)
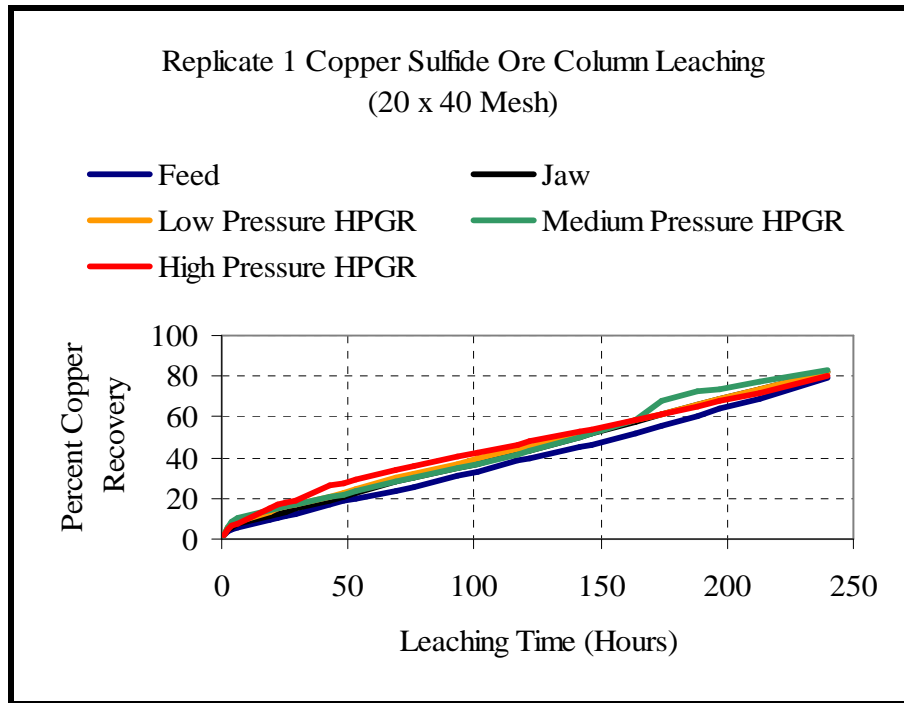for different crushing procedures.

Figure C5 Copper recovery from copper sulfide ore samples, 20 x 40M (Replicate 1) for different crushing procedures.
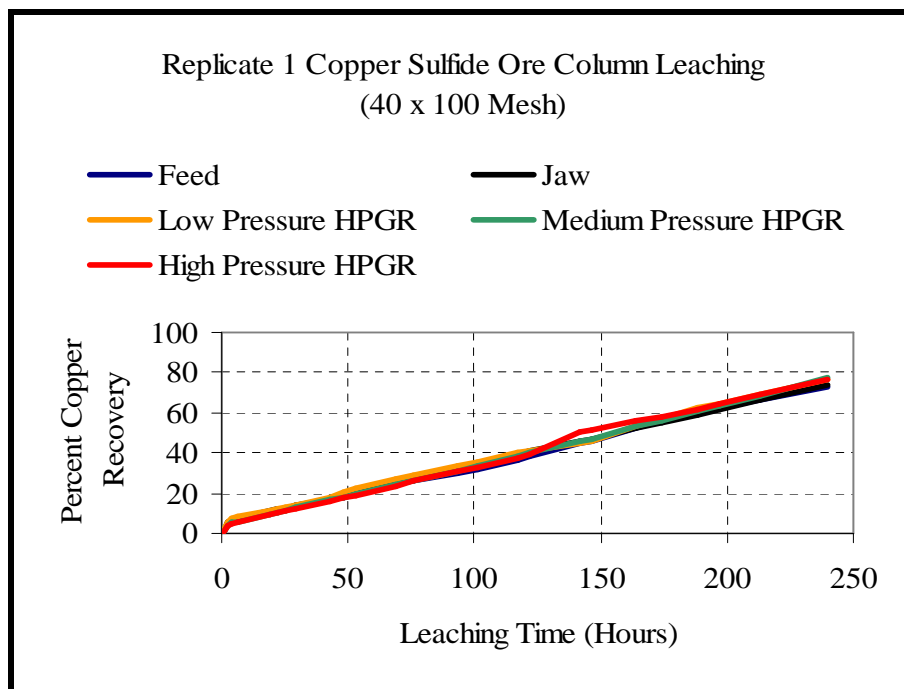

Figure C6 Copper recovery from copper sulfide ore samples, 40 x 100M (Replicate 1) for different crushing procedures.
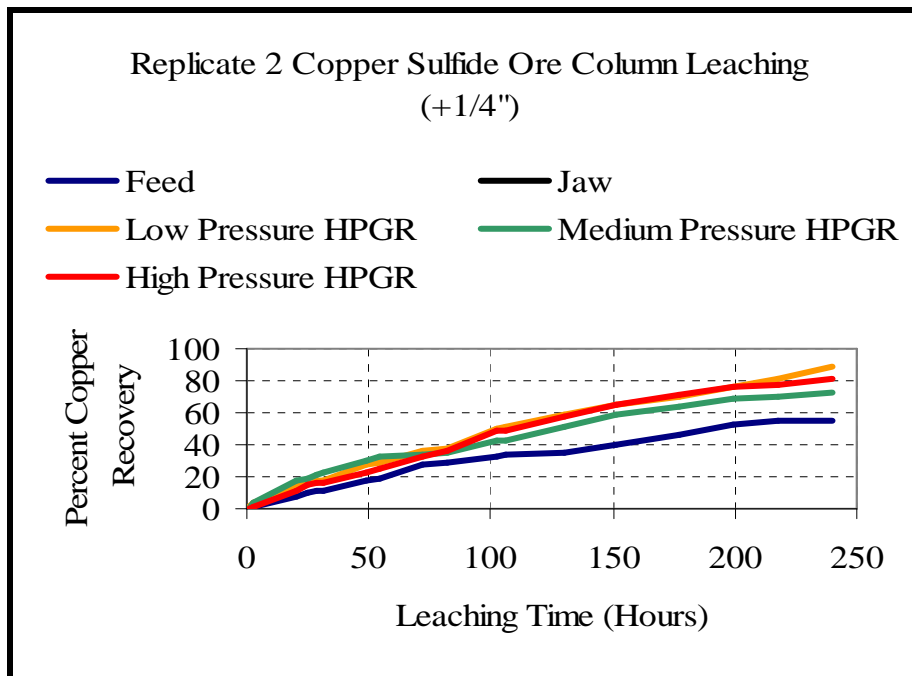
Figure C7 Copper recovery from copper sulfide ore samples, +1/4" (Replicate 2) for different crushing procedures.
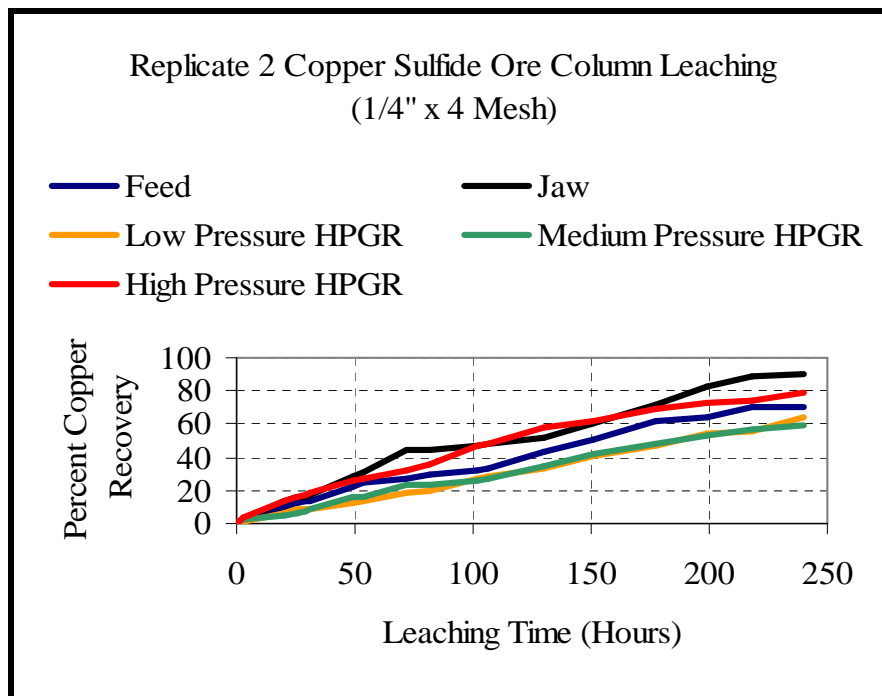

Figure C8 Copper recovery from copper sulfide ore samples, ¼" x 4M (Replicate 2) for different crushing procedures.

Figure C9 Copper recovery from copper sulfide ore samples, 4 x 10M (Replicate 2) for different crushing procedures.

Figure C10 Copper recovery from copper sulfide ore samples, 10 x 20M (Replicate 2) for different crushing procedures.
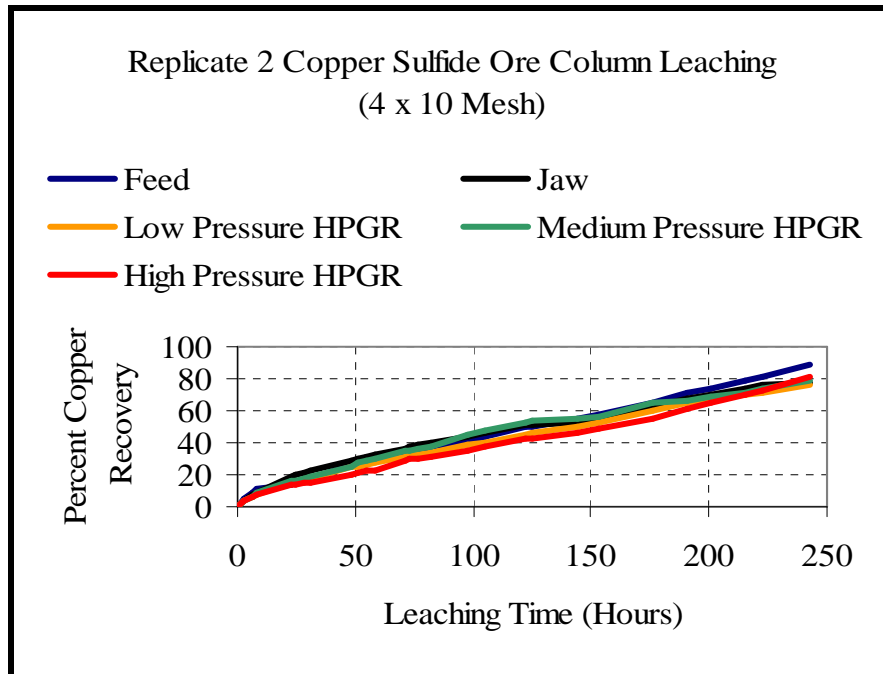
Figure C11 Copper recovery from copper sulfide ore samples, 20 x 40M (Replicate 2) for different crushing procedures.

Figure C12 Copper recovery from copper sulfide ore samples, 40 x 100M (Replicate 2) for different crushing procedures.
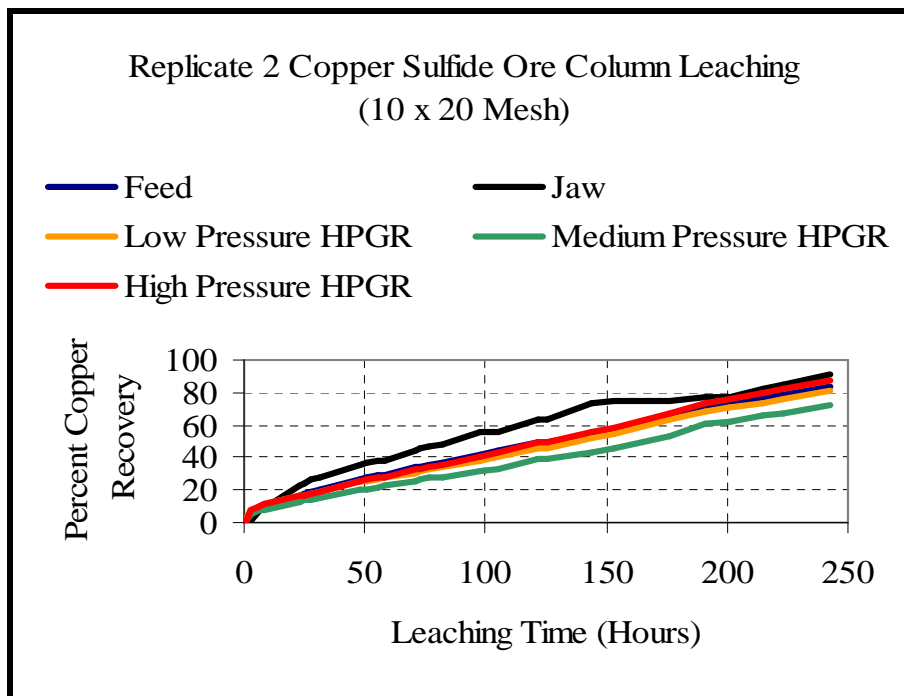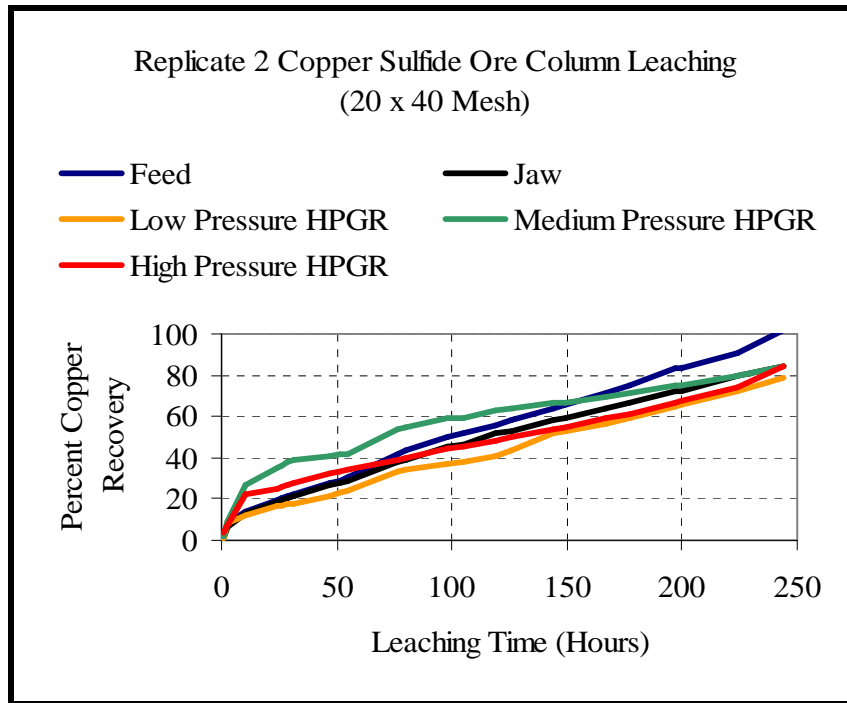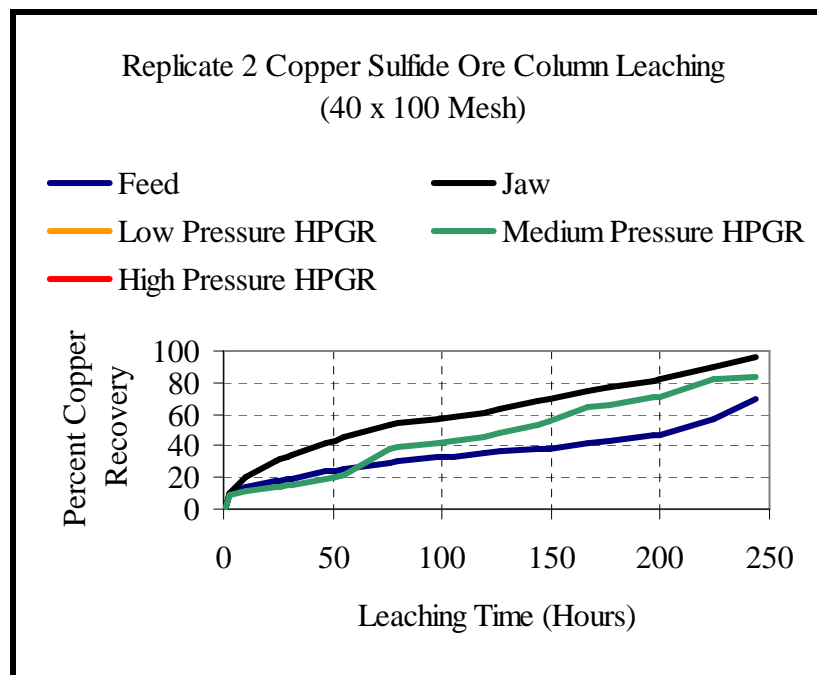
APPENDIX D

COLUMN LEACHING OF AGGLOMERATES

Table D1 presents the copper recovery values from column leaching of agglomerates with out binder and with binder. There data correspond to Figure 3.13.

Table D1- Copper recovery from column leaching of agglomerates.

Leaching Time (Hrs)	%Copper Recovery	
	No Binder Agglomerates	Stucco Binder Agglomerates
2	0.08	0.05
17	0.91	1.03
20	1.07	1.45
26	1.28	2.19
42	1.90	3.48
44	1.98	3.62
48	2.08	3.85
66	2.70	4.36
73	2.88	4.50
94	3.19	4.86
96	3.29	4.93
120	4.10	5.78
138	4.63	6.20
140	4.67	6.24
162	5.12	6.54
185	5.43	6.79
215	6.26	7.15
239	6.58	7.58
264	6.91	7.88
304	7.47	8.29
360	8.46	8.93
408	9.29	9.47
456	9.93	10.05
528	10.56	10.53
598	11.11	11.27
696	11.87	11.77
809	12.80	12.63

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