Particle Damage and Exposure Analysis in HPGR Crushing of Selected Copper Ores for Column Leaching

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Abstract

In mining operations, jaw and gyratory crushers are generally used for primary crushing, and cone crushers are used for secondary crushing. During the past decade, however, High-Pressure Grinding Rolls (HPGR) are being considered due to potential processing benefits such as energy savings, improved exposure/liberation and particle weakening. At this time there is no detailed quantification of particle damage and downstream benefits from HPGR crushing are uncertain. In the present research, copper ores (copper oxide ore and copper sulfide ore) were crushed by a jaw crusher and by HPGR and the products were evaluated for particle damage and copper grain exposure by X-ray computed tomography. Column leaching was done to determine the rate and extent of copper recovery.

X-ray computed tomography analysis and laboratory column leaching experiments for copper oxide ore revealed that products from HPGR crushing have more particle damage and higher copper recoveries when compared with products of the same size class from jaw crusher crushing. Generally the copper recovery from column leaching of the oxide ore was found to be dependent on the extent of grain exposure, which increases with a decrease in particle size.

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 and strong leach solution. Column leaching results also show that about 80 to 90% of the copper was recovered from the copper sulfide ore in a relatively short leaching time irrespective of crushing technique. As expected, copper recoveries improved with a decrease in the particle size of the copper sulfide ore as exposure of copper mineral grains increased.

Keywords: High-pressure Grinding Rolls, X-Ray Tomography, Particle Damage, Exposure Analysis and Column Leaching.

1. **Introduction**

With the advent of high-pressure grinding rolls (HPGR) in the 1980's, the comminution process efficiency improved to some extent in terms of energy savings. In HPGR, particle breakage is the result of high inter-particle stresses generated when a bed of solids is compressed moving through the narrow gap created between two pressurized rolls. As a result of higher inter-particle stresses a much greater proportion of fines are created in the HPGR product when compared to the product from conventional crushing. It has taken many years for high-pressure grinding rolls to make inroads into the mineral industry. Initially HPGR was used for diamond liberation, followed by preparation of iron ore for pelletizing and eventually into hard rock mining applications such as copper, gold and platinum (Batterham, 2011).

In the last decade, HPGR has gained more importance and popularity since it is reported to offer numerous metallurgical benefits such as energy savings (Schonert 1988; Dunne et al, 1996; Battersby et al, 1992; Fuerstenau and Kapur, 1995; Daniel 2007), particle weakening and preferential damage of coarse particles (Tavares, 2007), same degree of liberation at a coarser size (Apling and Bwalya (1997), better liberation of minerals (diamond) and, preferential comminution where induced micro fissures follow grain boundaries causing higher reactivity of the product to the micro fissures (Battersby et al (1992; Dunne et al., 1996).

HPGR crushing skews the product particle size distribution to the finer size, which is reported to manifest itself in improved leaching and pre-concentration performance (Dunne et al, 1996). Although there is significant work published regarding energy savings and improvements in efficiency of the comminution process due to HPGR, not much has been reported regarding the downstream benefits of HPGR comminution. Considering the strict environmental regulations, new mining operations (Copper, Gold and Nickel) are implementing hydrometallurgical operations such as heap leaching to recover the metal from lean/low grade ores rather than the conventional flotation-smelting approach. It should be emphasized that comminution will play a more significant role in these operations, considering that the valuable minerals need to be dissolved completely. In the case of heap leaching, it is expected that high mineral grain exposure and micro-crack formation from efficient crushing will result in increased metal

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recovery. This is because leach solution would penetrate through the micro cracks and solubilise the mineral grains.

Intuitively, it is understood that energy utilization in size reduction must affect the ore properties related to mineralization and grain boundaries. In some cases HPGR promotes particle micro-fractures, micro-cracks in the crushed ore improving the metal recovery in subsequent heap leach operations and reducing downstream mill energy requirements (Michaelis, 2005; Daniel, 2007).

The reported metallurgical benefits of high-pressure grinding rolls include increased liberation in cement (Celik and Oner, 2006), an increased gold cyanide leach recovery (Dunne et al, 1996), faster leach kinetics for copper ore (Baum et al., 1996), process enhancement for diamond recovery (Battersby et al., 1993), enhanced levels of liberation at coarser sizes for lead-zinc ore (Apling and Bwalya (1997), improved cassiterite concentration (Clark and Wills, 1989) and the presence of micro-cracks and higher porosity for sphalerite particles Ghorbani (2011). Recently, (Baum and Ausburn, 2011) reported pertinent contributions of HPGR technology to copper column leaching such as higher rock matrix fracturing, grain boundary liberation of sulfides, accessibility of fine-grained disseminated and fracture-located sulfides, and faster leach kinetics as compared with conventional crushing with a 2-10% increase in copper recovery depending on the mineralization.

In contrast it has been reported (Vizcarra and Wightman, 2008; Vizcarra et al., 2010) that particle-bed breakage mechanisms (such as HPGR) do not enhance the liberation properties of metalliferous ores such as copper-gold sulfide ores and copper porphyry ores. Hence, the liberation of valuable minerals from particle bed breakage using HPGR is uncertain and will be dependent on the nature/texture of the feed material.

One of the reasons for this uncertainty regarding the effectiveness of HPGR may be inadequate information regarding the particle damage and quantification of preferential liberation. In the past, image analysis of narrow size fractions of HPGR product was accomplished by Celik and Oner (2006) using optical microscopy for cement, by Daniel (2007) using Mineral Liberation Analysis (MLA) for lead-zinc, chromite and bauxite ores, and by Baum and Ausburn (2007) using optical microscopy and mercury porosimetry for copper ore. All the authors (Celik and Oner, 2006; Daniel, 2007; and Baum and Ausburn, 2011) reported improved liberation with HPGR due to microcracking/micro-fractures but detailed quantitative information regarding particle damage, exposure analysis, and liberation analysis has not been reported.

It is very difficult to quantify how damage (micro-cracks) and grain boundary fracture produced from HPGR crushing affects the downstream processes such as heap leaching and flotation, which further relates to the metal recovery. In a recent work on the same lines, HPGR was found to increase the extent of platinum liberation although no improvement was reported in the flotation performance, which may be due to the production of very fine particles (Chapman et al., 2011).

It is quite obvious, that if an ore from the same deposit source is subjected to comminution by two different methods, such that the product particle size distribution is quite similar, and subsequent downstream treatment demonstrates substantial differences in recovery, then there is reason to believe that preferential exposure/liberation has occurred and the comminution mechanism has an effect on the downstream process such as heap leaching.

Hence, in this study, investigation of the effect of crusher type (jaw crusher and HPGR), copper ore type (oxide, sulfide) and particle size (6.35 mm to 0.150 mm) on particle damage and copper recoveries were studied using similar feed size distributions.

2. Experimental Materials and Procedures

2.1. Ore Characteristics and Preparation

The initial sample preparation was carried out and about 450 kg of both copper oxide and copper sulfide ore samples which were prepared using a primary crusher. The crushing was done to achieve a similar feed particle size distribution for each crushing condition. The flow sheet for sample preparation plan and crushing experiments are shown in Figure 1. The crushed material from each ore type was split into five parts (64 kg for each part). After splitting, four parts from each ore type were further crushed. 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 used as the feed sample. The final products (five parts from each ore type) were used for subsequent damage analysis and column leaching. The copper head grades for copper oxide ore and copper sulfide ore samples were 0.3% and 0.8% respectively. The copper grade did not vary significantly with respect to particle size as shown in Table 1. The copper oxide ore contains mainly chrysocolla whereas the copper sulfide ore contains chalcocite, covellite and chalcopyrite.

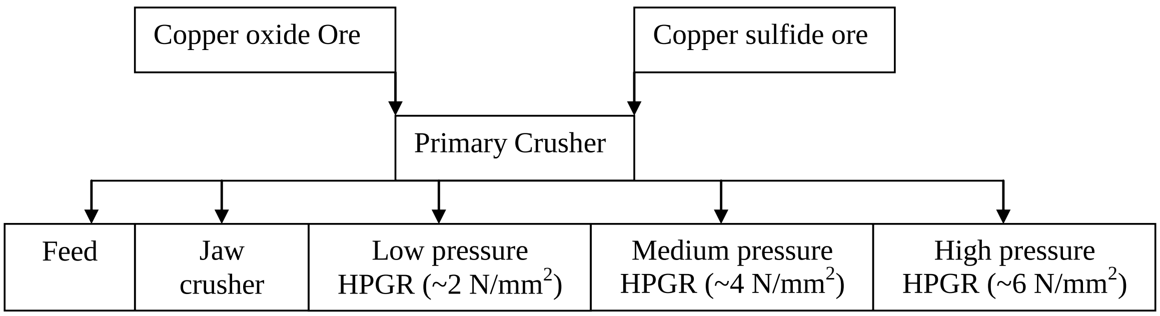

Figure 1. Sample preparation flow sheet.

Table 1: Copper head grades of copper oxide and copper sulfide ore samples for different size classes

Particle Size (mm)	Copper Oxide (%Cu)	Copper Sulfide (%Cu)
+ 6.30	0.32	0.89
6.30 x 4.75	0.32	0.83
4.75 x 2.00	0.28	0.78
2.0 x 0.85	0.28	0.71
0.85 x 0.42	0.28	0.88

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2.2. Particle Size Distribution of Crusher Products

The particle size distributions for both the copper oxide and copper sulfide crushed samples are shown in Figures 2 and 3. It was found that very similar particle size distribution of copper oxide ore and copper sulfide ore could be achieved with the different crushing methods. The P_{80} values obtained from particle size distribution (PSD) plots were used to characterize the PSD's obtained from different crushing methods.

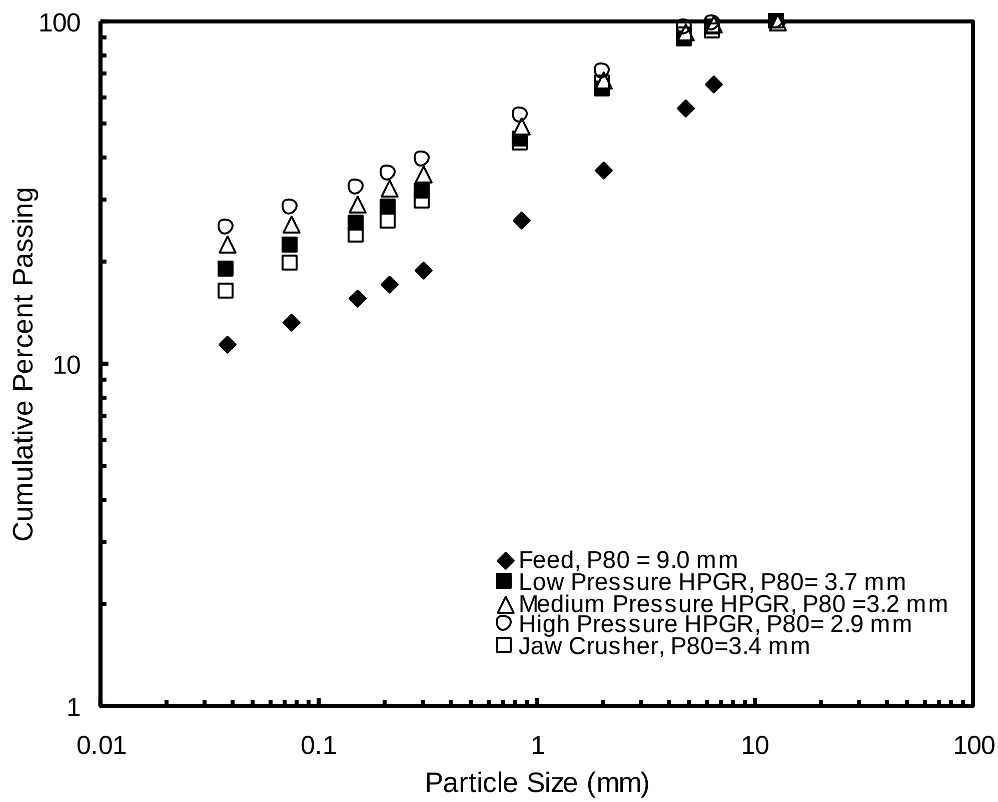

Figure 2. Particle size distributions of copper oxide ore samples obtained from different crushing methods.

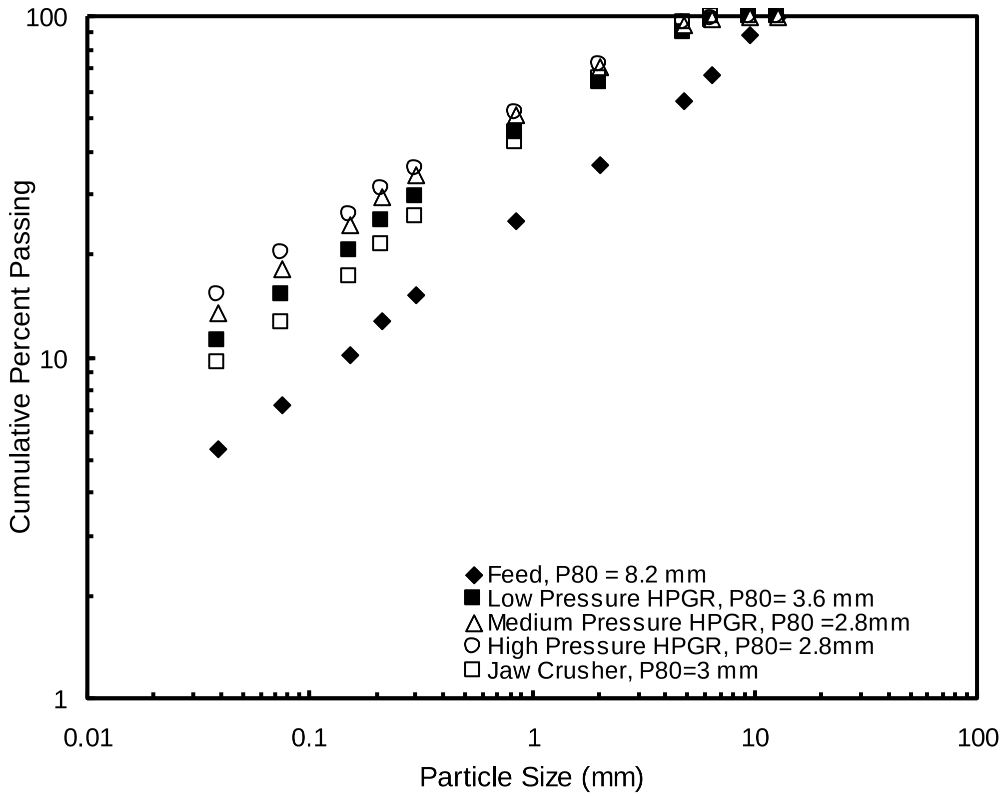

Figure 3. Particle size distributions of copper sulfide ore samples obtained from different crushing methods.

It is clear from Figures 2 and 3 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 whereas the P_{80} values for the other crushing conditions generally are greater than 3.0mm for both ore types. Also, based on the P_{80} values from the particle size distribution data, the copper sulfide ore appears to be softer than the copper oxide ore.

2.3. X-Ray Micro Computed Tomography (XMT)

X-ray computed tomography had its origin in the medical field with millimeter resolution and now the technique for 3D visualization has been extended with micro resolution. During the past decade X-ray micro computed tomography analysis has been developed for use in the coal and mineral industries. (Miller et al., 2003; Miller and Lin, 2004; Miller., J. D. and Lin. C. L., 2004, Garcia et al., 2008; Videla et al., 2007; Lin and Miller, 2005). In general X-ray tomography refers to the 3D imaging of an object from transmission data (projections) collected by illuminating the object from many different directions. X-ray CT techniques have the 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 multiphase particle properties in 3D with a size of less than a few hundred microns. Further details are mentioned elsewhere (Miller et al., 2003; Garcia et al., 2008; Videla et. al., 2007; Lin and Miller, 2005). Most recently, in 2009, the resolution has been extended to 1 micron with the XMT-400 from Xradia (Miller et al., 2009).

As a result of particle size reduction by crushing, mineral grains are exposed and particle damage (micro-cracks) occurs. The number of valuable mineral grains available at the surface of the ore particles influences the copper recovery values from heap leaching. Similarly the formation of micro-cracks is expected to increase copper recovery during heap leaching. Both phenomena make the copper mineral grains more accessible to the leach solution and should increase the leaching kinetics.

In this paper, the extent of particle damage is evaluated for the first time using micro XMT and mineral grain exposure analysis is used as described previously (Miller et al., 2003). Each size class of the crushed material obtained from sample preparation was examined using X-ray micro computed tomography to determine the extent of particle damage and the extent of mineral exposure.

A total of five particle size classes (+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 which corresponds to a total of 50 scans of packed particle beds using 10 and 20 micron resolution and 29 scans using 40 micron resolution. The weight and number of particles used for the XMT scans are summarized in Table 2.

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Table 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)
+ 6.30	4 to 6	10 to 20	40
6.30 x 4.75	4 to 6	20 to 40	40
4.75 x 2.00	4 to 6	70 to 90	40
2.0 x 0.85	0.3 to 0.4	100 to 200	20
0.85 x 0.42	0.06 to 0.08	>200	10

3. Mineral Exposure

Copper 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 (Miller et al., 2003; Garcia et al., 2008). 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 40 mm down to a few hundred microns. Voxel resolution as high as ten micrometers was achieved in this study using the point projection CT system available. Representative samples of particles from the five different size classes 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, in the case of 20-micron voxel resolution and a 512x512x300 data set, the scanning time was about 30 minutes and a full three dimensional reconstruction requires approximately an additional hour. The mineral exposure results for copper oxide ore and copper sulfide ore as a function of both particle size and crushing method are shown in Figures 4 and 5.

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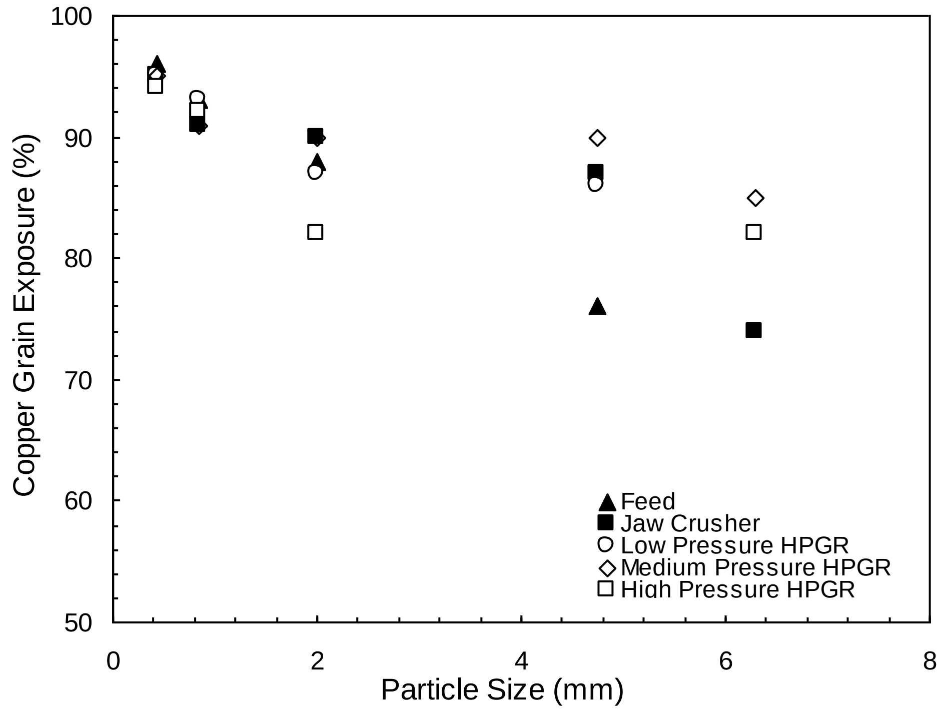

Figure 4. Relationship between mineral exposure and particle size (copper oxide ore).

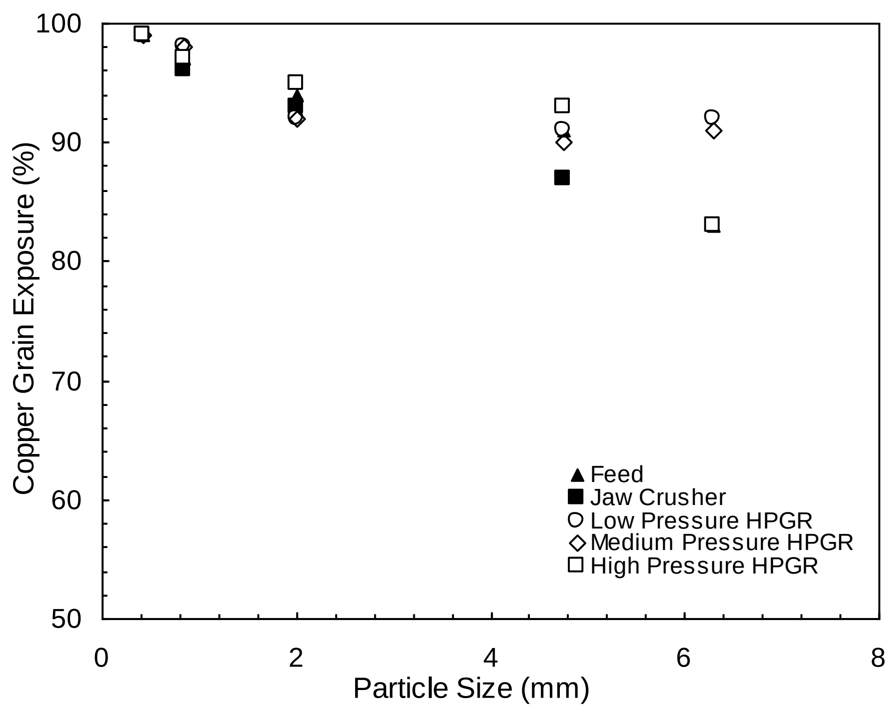

Figure 5. Relationship between mineral exposure and particle size (copper sulfide ore).

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It can be observed that good exposure is achieved in both cases. More than 90% of the copper mineral grains in the copper sulfide ore sample were exposed for particles less than 6 mm in size (Figure 5). However, only particles less than 2 mm in size gave a 90% exposure for the copper oxide ore samples (Figure 4). 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) (Miller et al., 2003). Combining the results of chemical analysis and the mineral exposure analysis, the practical recovery of copper can be estimated for specific particle size distributions. As expected, the exposure decreases with an increase in particle size. The slope of the curve is much more pronounced below 2 mm for the copper oxide sample indicating that grain exposure can be increased significantly by increasing the amount of material in the intermediate size classes (Figure 4).

It can be seen from both Figures 4 and 5, that grain exposure for the copper oxide samples and copper sulfide samples was affected by crusher type. In both cases, grain exposure for particles crushed by HPGR generally was greater when compared to particles of the same size crushed by the jaw crusher. However, no strict pressure trend was observed for HPGR crushing.

The difference in exposure characteristics between the copper sulfide and copper oxide samples exists because of the difference in texture, different grain size, which is evident from X-ray computed tomography images (Figures 6 and 7).

As can be seen from the exposure analysis plots (Figures 4 and 5), an overall trend can be observed; that is, with an increase in grain size (the copper sulfide ore sample has a larger grain size than the copper oxide ore sample, compare Figures 6 and 7) the grain exposure increases which confirms the results from earlier studies (Garcia et al., 2006). However, a distinct trend with respect to crushing techniques is not clear especially for the copper oxide ore. Exposure for large particle size classes (4.75 mm and 6.30 mm) is uncertain due to sampling statistics. Only ten to forty (10-40) particles were scanned for these particle size classes.

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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 is expected to result in increased copper recovery during heap leaching because the leach solution would penetrate through the micro cracks and solubilise the internal mineral grains. A total of five size classes and five crushing methods were investigated to determine the particle damage for both copper oxide and copper sulfide ores. The X-ray computed tomography scans of copper oxide and copper sulfide sample are shown in Figures 6 and 7, and the micro-cracks are identified with red arrows.

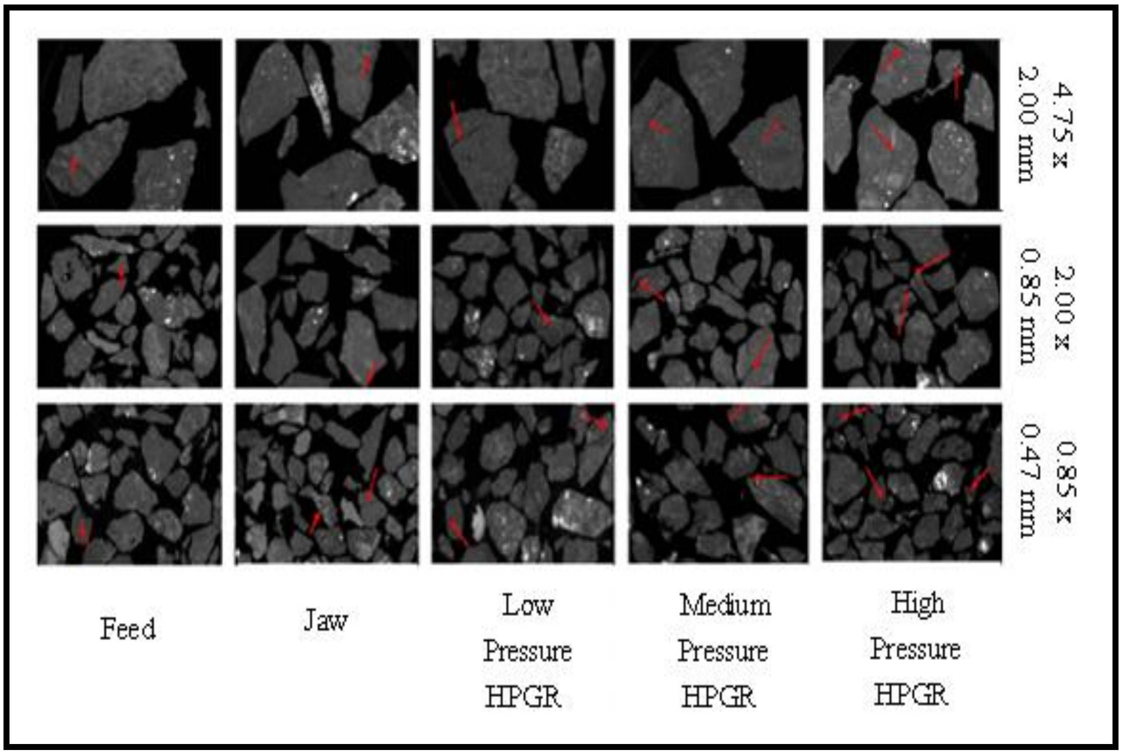

Figure 6. X-ray computed tomography scans for copper oxide samples.

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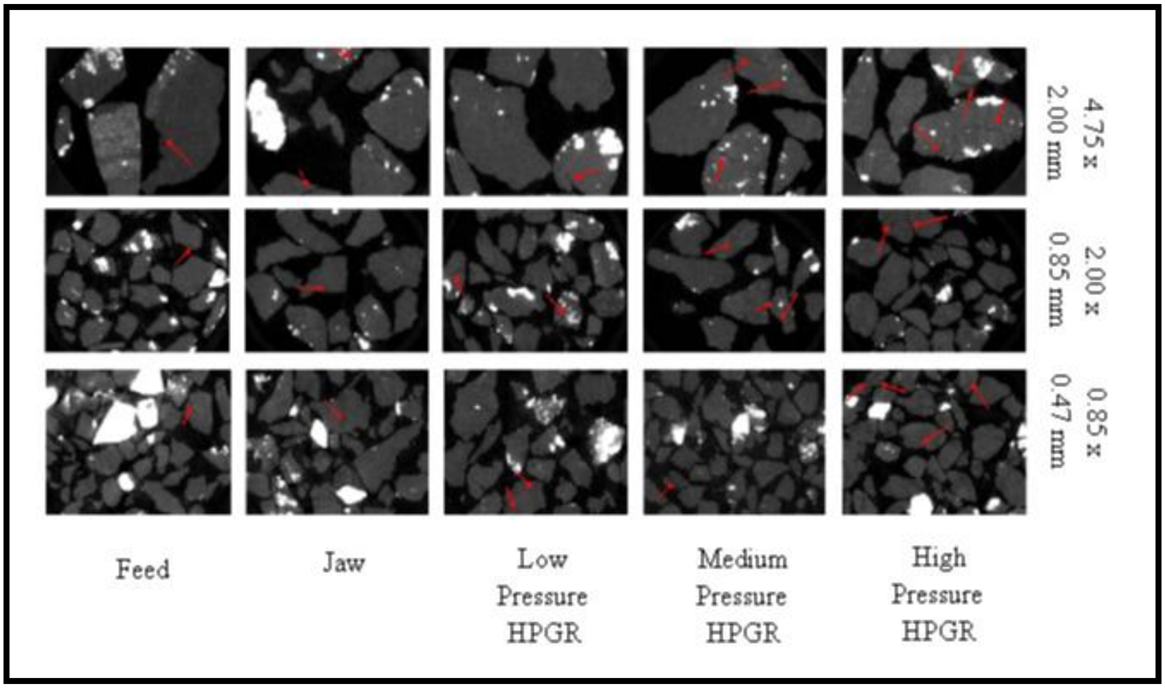

Figure 7. X-ray computed tomography scans for copper sulfide samples.

The particles with cracks were counted for each ore type and each crushing method. Damage for the copper oxide ore is shown by the fraction of particles damaged (fraction of particles with cracks) in Figure 8. A similar plot for the copper sulfide ore is shown in Figure 9. It can be concluded that high-pressure HPGR produces more cracks than the other crushing methods for most of the particle size classes as shown in Figures 8 and 9. As the particle size is decreased, the fraction of cracked particles is increased in the case of the copper oxide ore. Also, for high-pressure HPGR copper oxide samples the percent of particles damaged increased from 40% to 80% as the particle size decreased from 6.35mm to 0.074mm. Such a trend is not clear in the case of the copper sulfide ore (about 80% of the particles are cracked for high-pressure HPGR crushing except the 2.00x0.850mm). The extent of damage in terms of the percent of particles cracked for different crushing techniques for 4.75 x 2.00 mm particles is given in Table 3.

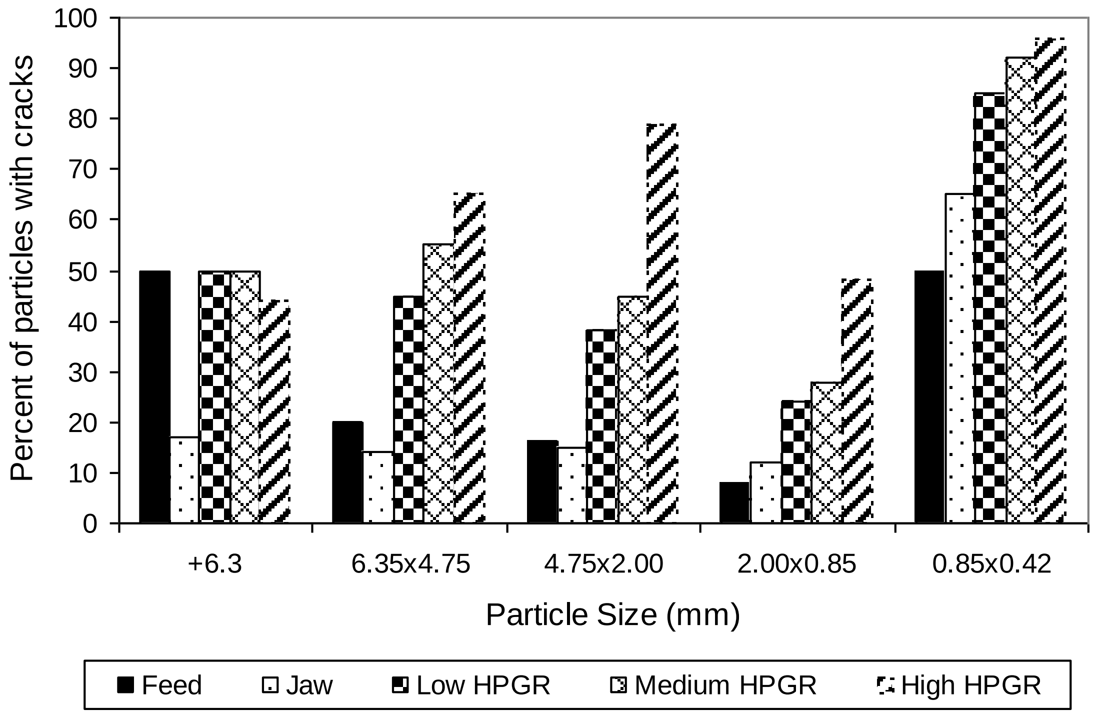

Figure 8. Particle damage for copper oxide samples.

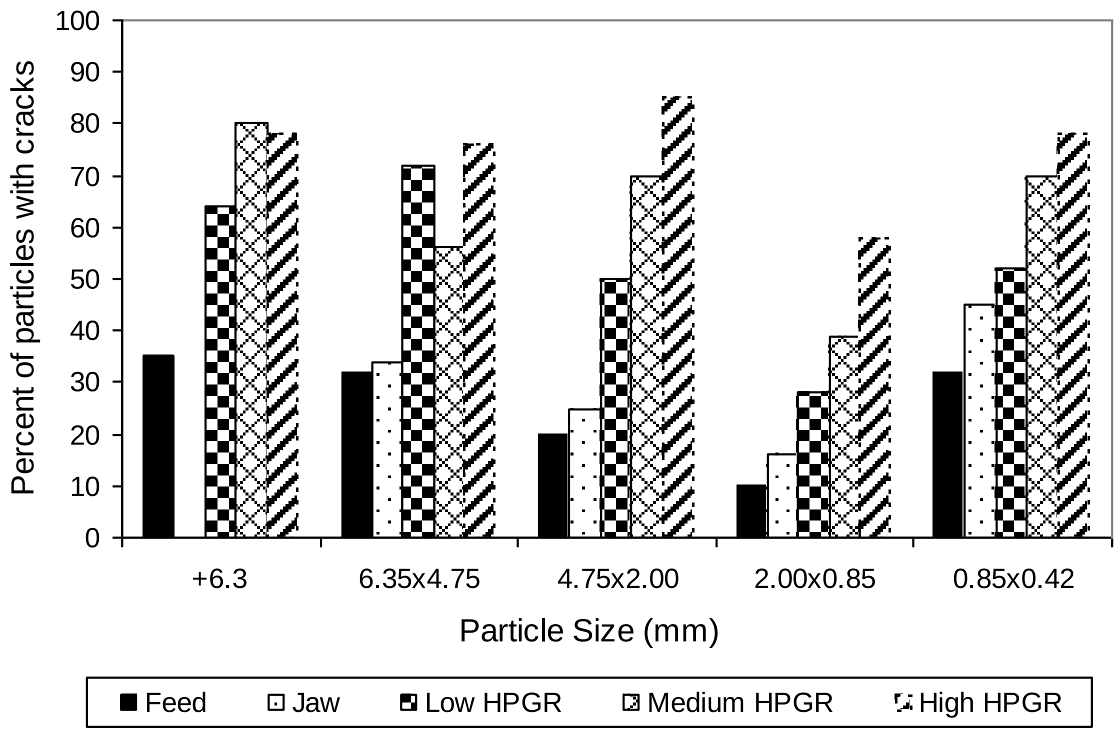

Figure 9. Particle damage for copper sulfide samples.

Table 3: Percent of particles (4.75 x 2.00 mm) for different crushing methods (voxel resolution=40 microns)

Crushing Method	Extent of Damage (% of Particles Cracked)	
	Copper Oxide Ore Sample	Copper Sulfide Ore Sample
Feed	14	20
Jaw Crusher	14	23
Low Pressure HPGR	37	51
Medium Pressure HPGR	44	69
High Pressure HPGR	79	84

It must be recognized that damage analysis was limited to large cracks due to voxel resolution. Hence, only cracks of size greater than 40 microns were detected. The authors believe with the use of the high resolution Micro XMT-400, the cracks/damage can be explained in greater detail. From initial Micro XMT-400 analysis of HPGR products damage can be described in terms of the specific crack surface area. Preliminary results are shown in Table 4.

Table 4: Crack information for damaged particle of copper oxide ore using Micro XMT-400

Particle volume (mm^3)	Total surface area of cracks	Specific crack surface area (mm^2/mm^3)
0.2752	2.7646	10.0471

With the use of Micro XMT-400, valuable information regarding particle damage, number of micro-cracks, size of cracks, and surface area of cracks, can be determined and correlated with energy for breakage. Future research will involve the use of Micro XMT-400 to investigate these issues.

5. COLUMN LEACHING

The products of both the crushed ores evaluated for particle damage were also assessed using column leaching to determine the rate and extent of copper recovery. The leaching

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experiments were conducted in two parts namely mini-column leaching and laboratory column leaching. The following section deals with both the parts in detail.

5.1. Mini-column Leaching

The mini-column leaching tests were performed to investigate 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 2.00 x 0.85 mm) from the high-pressure HPGR (6 N/mm^2) crushing and from jaw crusher crushing were used in column leaching experiments to further evaluate the effect of particle damage (due to the crushing technique) on the leaching rate and the extent of reaction.

Ten grams each of the jaw crusher product (2.00 x 0.85 mm) and the high-pressure HPGR product (2.00 x 0.85 mm) for the copper oxide ore were sampled to examine the mini-column leaching characteristics. The leaching was evaluated by the disappearance of chrysocolla, pyrite, chalcopyrite and other grains as determined by XMT using 40 micron voxel resolution. The XMT scans were done at 2 hours, 6 hours, 1 day, 11 days and 29 days of leaching. The internal grains for the high-pressure HPGR and the jaw crusher products after 29 days of mini-column leaching are shown in Figure 10.

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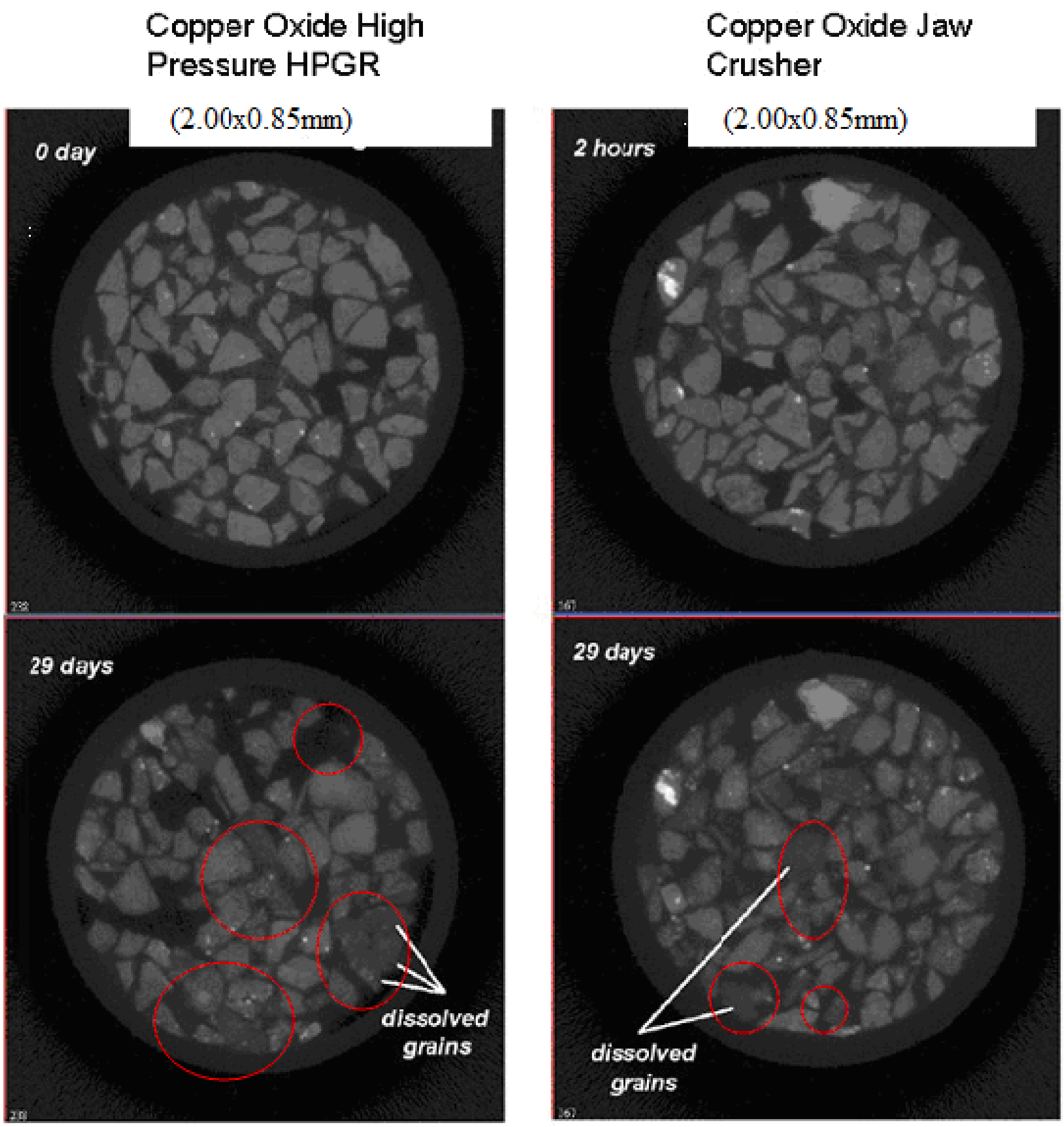

Figure 10. Tracking mineral grains during mini-column leaching of 2.00x0.85 mm copper oxide ore samples (2.00x0.85 mm) from high-pressure HPGR and jaw crusher products.

Dissolution of copper grains for the copper oxide samples (2.00x0.85 mm) are illustrated from XMT scans as indicated by the red circles in Figure 10. In some cases it appears that the grains did not dissolve due to a lack of exposure and/or a decrease in crack density. The results suggest that grains in the high-pressure HPGR product dissolve to a greater extent than grains in the jaw crusher product during mini-column leaching.

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5.2. Laboratory Column Leaching

The laboratory column leaching experiments were designed to better understand the effect of crusher type and ore type on the leaching response.

5.2.1 Sample Preparation

Copper oxide ore and copper sulfide ore samples crushed were size classified into six different size fractions. Sixty samples were prepared from two ore types (oxide and sulfide), five crushing techniques (feed, jaw, low-pressure HPGR, medium-pressure HPGR and high-pressure HPGR) and six different size classes (+6.35mm, 6.35x4.75mm, 4.75x2.00mm, 2.00x0.85mm, 0.85x0.420mm, 0.420x0.149mm) as shown in Figure 1. In order to validate the results, each laboratory column leaching experiment was done twice. Each laboratory column leaching experiment required forty five grams of ore material which was sampled from each of the sixty samples by using chute riffles. The head analysis of the copper oxide ore and copper sulfide ore are summarized in Table 1.

5.2.2 Experimental Procedure for Laboratory Column Leaching

The laboratory column leaching tests were carried out with a disposable syringe (60 cc volume) which was packed with 45 grams of sample. Columns were irrigated from the top with an intravenous (IV) system using acidic leach solutions provided by the industry. Two different leach solutions were used. One solution for leaching copper oxide ore and one solution for leaching copper sulfide ore samples. Before the start of each experiment, the copper oxide leach solution and the copper sulfide leach solutions were filtered to eliminate any suspended particles. These solutions were used to fill the IV systems and were passed through the columns once at flow rate of 8 L/m^2/hour. The solutions were not recycled. Each crushed ore sample was leached for 240 hours (10 days) and the pregnant leach solutions were collected at the bottom of the column on an hourly basis. Solutions were kept in disposable scintillation vials to be analyzed for copper concentration. The schematic and experimental set up for the column leach experiments are shown in Figure 11. Each experiment was run in duplicate to check on the reproducibility of the experimental results.

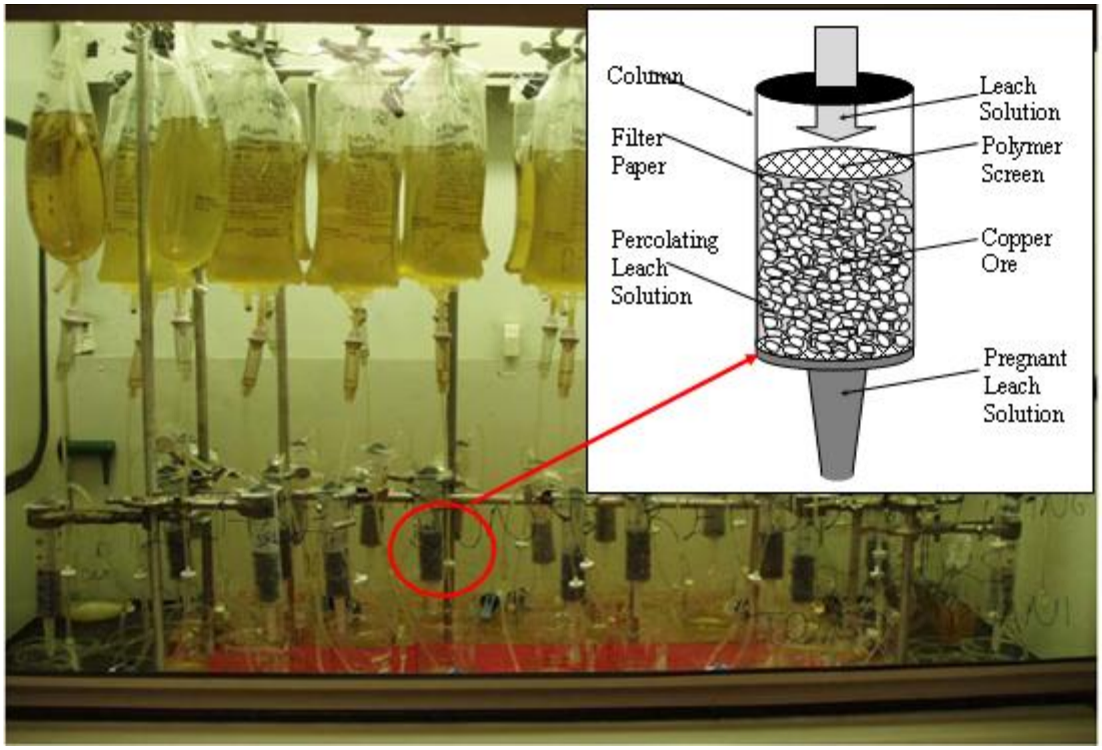

Figure 11. Schematic representation of the laboratory column leaching and photograph of Laboratory column leaching experiments (unsaturated flow) showing IV irrigation and disposable syringe bodies containing ore samples.

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

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5.2.3 Laboratory Column Leaching Results

The column leaching recovery was calculated for each sample as a function of time as shown in equation 1.

$$R_{Cu} = \frac{(C_t - C_o)V_t}{Copper\ Content\ of\ Feed} \tag{1}$$

where R_{Cu} is percent copper recovery from leaching, C_t is copper concentration in pregnant leach solutions at time t (g/L), C_o is copper concentration in the inlet leach solution (g/L) and V_t is volume of pregnant leach solution at time t (ml)

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

The average copper recovery from two replicates after 10 days of leaching as a function of particle size and crusher type for the copper oxide ore samples is shown in Figure 12. It can be concluded from Figure 12 that more copper is recovered from the high-pressure HPGR products in most of the cases. Also, as the particle size decreases copper recovery increases from about 50% to 80%. These results are in correspondence with particle size analysis (Figure 2), mineral exposure analysis (Figure 4) and particle damage (Figure 8). For example, P_{80} values for high-pressure HPGR samples are less when compared to samples from other crushing methods (Figure 2).

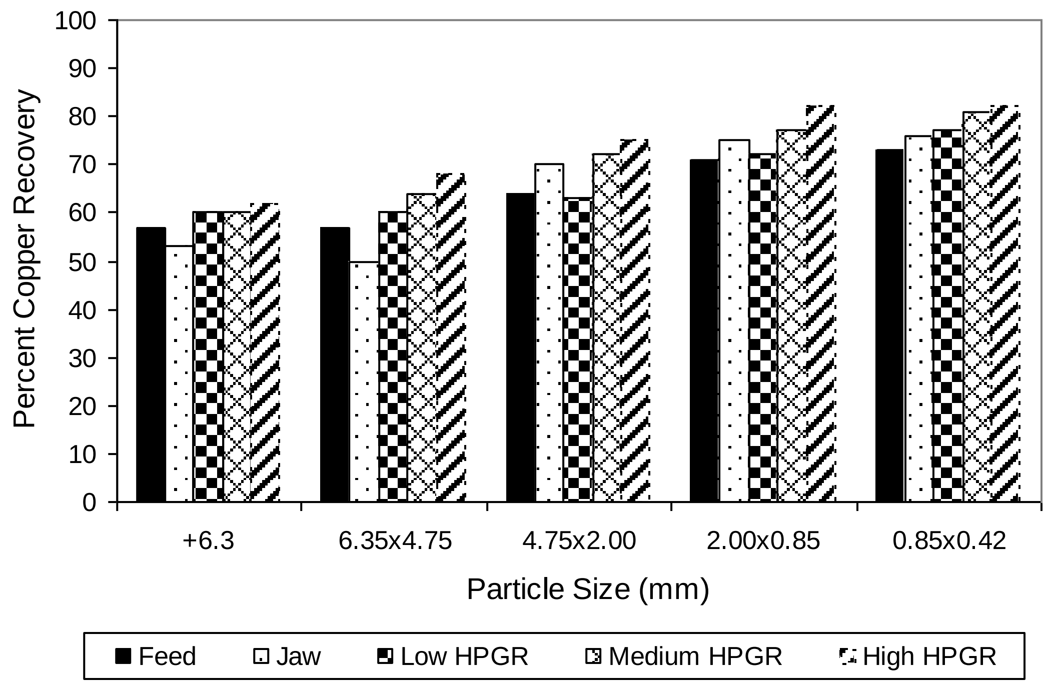

Figure 12. Average copper recoveries from copper oxide ore samples for different crushing methods and particle sizes.

As the particle size is decreased the percent copper grain exposure for the high-pressure HPGR sample is increased from 75% at the 7mm size to 95% at the 0.1mm size (Figure 4). Similarly the percent of damaged particles increased from 40% to 90% for the high-pressure HPGR sample as the particle size decreased from +6.35 mm to 0.85x0.42mm (Figure 8).

The average copper recovery from two replicates after 10 days of leaching as a function of particle size and crusher type for the copper sulfide ore samples is shown in Figure 13. It can be seen from Figure 13 that more copper is recovered from copper sulfide ore samples than from the copper oxide ore samples, which may be due to the higher head grade (0.8%Cu), higher exposure values (Figure 5) and greater particle damage (Figure 9) than that observed for the copper oxide ore samples.

Copper recovery for the sulfide ore tends to be independent of crushing method and also particle size. This unexpected behavior might be due to the high head grades for the copper sulfide ore samples (about 0.8%Cu). Also, the leaching solution used for the copper sulfide ore samples was stronger than that used for copper oxide ore samples. The leach solution for the copper sulfide ore had a pH of 2.0 whereas the pH for the oxide ore was 1.1. Of course the pH and leach solution composition is expected to affect the copper recovery.

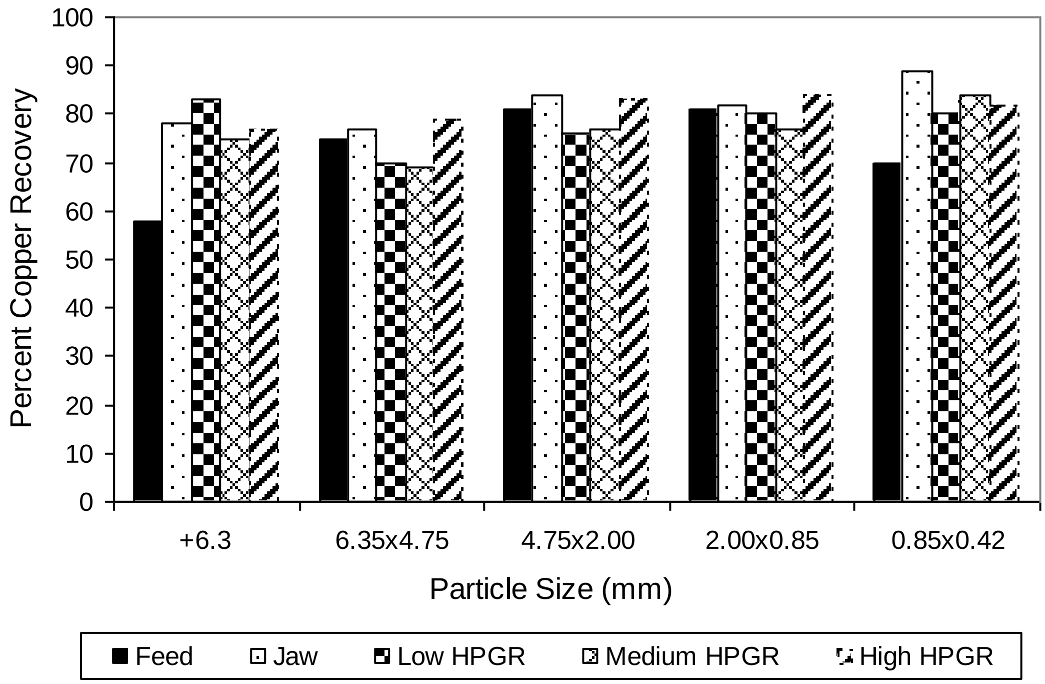

Figure 13 Average copper recoveries from copper sulfide samples for different crushing methods and particle sizes.

5.2.5 Comparison of Mineral Exposure and Copper Recoveries as a function of Particle Size for Different Crushing Conditions

Comparison was made between copper recovery and mineral exposure to further examine the significance of exposure on recovery from laboratory column leaching. The comparison between copper recovery after 10 days leaching and exposure values for copper oxide ore and copper sulfide ore samples is made in Table 5. It is evident from Table 5 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

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increase with a decrease in particle size. Copper recovery from column leaching is less than that suggested from exposure analysis due to a low leaching time (10 days).

Table 5. Percent copper recovery after 10 days leaching and percent grain exposure for copper oxide ore and copper sulfide ore laboratory column leaching

		Copper Oxide					Copper Sulfide				
	Size (mm)	Feed	Jaw	Low HPGR	Medium HPGR	High HPGR	Feed	Jaw	Low HPGR	Medium HPGR	High HPGR
%Copper Recovery Average	+6.3	57	53	60	60	62	58	78	83	75	77
	6.35x4.75	57	50	60	64	68	75	77	70	69	79
	4.75x2.00	64	70	63	72	75	81	84	76	77	83
	2.00x0.85	71	75	72	77	82	81	82	80	77	84
	0.85x0.42	73	76	77	81	82	70	89	80	84	82
%Copper Exposure	+6.3		74		85	82	83		92	91	83
	6.35x4.75	76	87	86	90		91	87	91	90	93
	4.75x2.00	88	90	87	90	82	94	93	92	92	95
	2.00x0.85	93	91	93	92	92	97	96	98	98	97
	0.85x0.42	96	95	95	95	94	99	99	99	99	99

6. Summary and Conclusions

6.1 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 and 3). Based on the P_{80} values, it appears that the copper sulfide ore is softer than the copper oxide ore.

6.2 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. This trend is supported by copper oxide laboratory column leaching results,

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which show that greater recovery was generally achieved for all particle sizes prepared by HPGR high-pressure crushing conditions (Figure 12) whereas for the copper sulfide ore samples mineral exposure was high (95% at 2mm) but was independent of the crusher type (Figure 5). The data points were concentrated at particular exposure values for the copper sulfide ore with different crushing methods (Figure 5). This unusual behavior due to large grain size of the copper sulfide samples accounts, in part, for higher copper recovery from copper sulfide ore during column leaching (Figure 13).

6.3 Particle Damage

High-pressure HPGR crushing produces more internal cracks than other crushing methods in most of the particle size classes (Figures 8 and 9). As the 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 6.35 to 0.074mm except for 2.00x0.85mm (Figure 8). Such a trend was not evident for the copper sulfide ore samples (about 80% of the particles were cracked in all high-pressure HPGR crushing copper sulfide samples irrespective of particle size) (Figure 9). It was found that damage analysis of large cracks was limited by voxel resolution. Future research will involve the use of Micro XMT-400 to investigate these issues.

6.4 Mini-column Leaching

The grains from the copper oxide ore samples prepared by high-pressure HPGR and jaw crusher crushing dissolved after 29 days during mini-column leaching experiments. X-ray micro tomography results shown in Figure 10 suggest that copper grains dissolve at a faster rate in the case of high-pressure HPGR products.

6.5 Laboratory Column Leaching

For the copper oxide samples, copper recoveries were high for most of the high-pressure HPGR samples (Figure 12). As expected, copper recoveries increase with a decrease in particle size. Copper recovery values show the same trend as grain exposure data as shown in Table 5. For the copper sulfide ore, copper recovery was independent of the crushing method since about 80 to 90% of copper is recovered during the initial period of leaching (Figure 13). Recovery values were higher than those for the copper oxide ore samples and apparently due to the higher head grade, greater grain exposure and perhaps a more aggressive leach solution. The copper recovery values show the same trend as grain exposure data (Table 5). The evidence suggests that high-pressure HPGR increases the leaching capacity 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 regard, it is expected that the effect of damage would be more significant for the copper sulfide ore if a less aggressive leach solution was used.

The above 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 for high-pressure HPGR samples. 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.

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