Bioresource Technology 100 (2009) 1931–1936

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Technological assessment of a mining-waste dump at the Dexing copper mine, China, for possible conversion to an in situ bioleaching operation

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ARTICLE INFO

Article history:
Received 26 August 2008
Received in revised form 14 October 2008
Accepted 14 October 2008
Available online 25 November 2008

Keywords:
Waste rock dump
Bioleaching
Dexing copper mine

ABSTRACT

In order to extract copper metal from the waste dump of Dexing copper mine and resolve the environmental problems caused by acidic water and heavy metals, a dump bioleaching plant was designed based on a series of experimental investigations. The investigation shown that the low-grade of the dump, refractoriness of chalcopyrite, leakage of pad, small *Acidithiobacillus* population and low dump permeability are the main factors that contribute to the challenges faced by the plant. Stability of the high and steep slope of the dump is the other hidden danger to which much attention is not paid. To evaluate the potential unstability of the dump, the leaching process, ore surface erosion, particle size, chemical elements and mechanical properties of the waste rock in DCM were investigated through experiment in this paper.

1. Introduction

Mining of metals invariably leaves its mark on the environment, producing large amounts of waste rock which is generally pilled up into large dumps on the land surface (Johnson, 2006). A mining waste rock dump (WRD) can be considered as a potential source of pollution system, which after rainfall produce leachate discharges loaded with acid mining drainage (AMD) (Sainz et al., 2002). The pyritic materials are transformed into sulphates with the water percolating through the WRD, accompanied with an increment of acidity. The process starts with the direct oxidation of pyrite followed by indirect oxidation with ferric ions. Chemical oxidation can be catalyzed by *Acidithiobacillus*. Along with the pyrite reactions, there may be further associated reactions, due to the presence of other metallic sulphides. As a result of these reactions, acidic metalliferous water flowed out of the WRD and discharged into local streams and rivers (Gidarakos et al., 2008). Another most significant negative impacts induced by an increase in the acid level within a dump structure is the increase of pore acid pressure which in turn increases the potential of a dump-slide that may endanger the mine environment.

Negative environmental aspects of WRD are those that are most firmly embedded in the general psyche (Fernandes and Franklin, 2001). Some abandoned mines have been subjected to minor or major reclamation schemes, designed to reduce deleterious impacts on the local environment, to enhance the surrounding area aesthetically and possibly to allow the derelict site to be redeveloped. And in some cases, it is economically feasible to re-process dump that were produced at a time when it contained large amount of low-grade waste rocks, in order to recover metals. The Rio Tinto mine in Spain was probably the most famous example, producing copper from dump leaching operations as long ago as the 1700s. But it was not until the late 1940s that a link was established between the bacterium *Acidithiobacillus ferrooxidans* and acid generation in mines. After that discovery, commercial exploitation of the phenomenon accelerated. The use of the technology was largely confined to copper dump leach operations during the early decades of development, however, with applied researchers investigating operating conditions in the dumps, the level of understanding increased substantially over succeeding years.

Dump bioleaching is a mineral processing technology whereby large piles of crushed or run-of-mine rock are leached with *Acidithiobacillus*-containing solution that extracts valuable minerals. Kennecott Copper has successfully used the bioleaching process since the 1950s, and other mining operations around the world followed Kennecott's lead (Brierley and Brierley, 2001; Kinnunen et al., 2006). Presently, bioleaching has developed into a key hydrometallurgical technology, in conjunction with solvent extraction and electrowinning, for the recovery of base metals, including most notably copper from both oxides and secondary sulphides (Zhou et al., 2009), and more recently, nickel and zinc (Mishra et al., 2008; Zhao et al., 2008; Mousavi et al., 2008).

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doi:10.1016/j.biortech.2008.10.021

2. Methods

2.1. Description of the mine site and surrounding area

Dexing copper mine (DCM), situated in Jiangxi Province of China, is 200 km away from provincial capital city Nanchang. Mining production of DCM started in 1965 by underground mining. The open pit operation started in 1971, and currently produces some 36 million tonnes of crude ore annually, which positions among the largest open pit copper mine in Asia. Six-hundred-million tonnes of sulfidic over-burden and waste rock, containing small but valuable quantities of copper and other metals have accumulated since the commercial production of the mine and were transported by truck from open pit of DCM to the dump site. The dump was built along the upstream valley of the Dawu River, to take advantage of natural slopes for maintaining the stability of pile and for facilitating the drainage of water (Mishra et al., 2008). The WRD occupied an area of approximately 7,570,000 m^2.

The WRD became the source of acid mine drainage waters, resulting form the reaction of *Acidithiobacillus*, air, water and minerals within the dump. The surrounding environment, such as river and soil, was negatively influenced by the heavy metals carried by the acid AMD. Dump leaching refers to the leaching of large, amorphous, and heterogeneous waste dumps or stockpiles which have accumulated over the life of the mine. It seeks to reduce pollution by potential contaminants, and seeks to reduce the potential for contamination of the wider environment by controlling the migration of potential pollutants and isolating the source of pollution (Shayestehfar et al., 2007).

The total weight of the copper metal within the WRD in Dexing exceeds 1.2 million tonnes. The exploitation of waste rock by traditional method was not economical, but dump leaching has the advantages of low investment, better working conditions, and lower energy consumption (Wu et al., 2007). In order to extract copper metal from those secondary resources and eliminate the environmental pollution in this area, dump leaching experiments using acidity and *Acidithiobacillus*-containing mine water was first started in 1979. In 1984, the first 1000 t scale heap bioleaching experimental investigation was started. In 1987, a heap bioleaching recovery of copper from chalcopyrite of 16.59% was achieved from the waste rock containing only 0.121% copper. As shown in Table 1, the recovery of heap leaching operation at a scale of 1000t copper-containing waste rocks was improved to 30% (Yang et al., 2002; Liu et al., 2004).

Based on the experimental results from these joint investigations, the feasibility study of Dexing dump bioleaching plant was fulfilled on August 1993. The primary design was finished on April 1994, and the plant with anticipated annual production of 2000 t cathode copper was put in use on October 1997. The dump was not inoculated with the leaching *Acidithiobacillus*. The leach solution percolated through the leach dump, and the pregnant leaching solution (PLS, its elemental composite was shown in Table 2) was collected in a reservoir at the foot of the dump. The copper was removed from solution by solvent extraction (Extractant Lix984N was used), in which the copper was concentrated by transferring it from the aqueous leaching solution to an organic solution. The barren was then recycled to the top of the dump.

Table 1
The two 1000 t scale heap bioleaching experiments in DCM.

Time	Grade of original waste ores			Solution		Recovery (%)
	Cu (%)	Fe (%)	S (%)	Cu (g/L)	Fe/Cu	
1987	0.121	4.48	3.77	1	12	16.59
1991	0.279	4.47	3.04	1.5	4	30

Table 2
The concentration of elemental composition of PLS (g/L).

Component	Cu^{2+}	Fe^{2+}	Fe^{3+}	CaO	MgO	Al_2O_3	SiO_2
Concentration	0.30	0.892	0.258	0.76	6.2	2.09	0.17

2.2. Main challenges faced by the operation

Because of the construction methods employed by the DCM and the volume of the solid material treated, dump leaching is a crude operation. The placement of the dump in a natural valley can impede the flow of air to the interior of the pile. The large size of some of the rocks limits contact among the metal-sulfide minerals, the oxidizing solution and the *Acidithiobacillus*. During the dumps construction large ore haulers compact the surface, creating impermeable zones in the pile. At present, there are several setbacks faced by the dump of DCM, the annual production of copper metal is less than 800 t, far from what is anticipated. Recovery is less than 10% per year and the Cu^{2+} concentration of PLS is 0.3–0.45 g/L. The main factors that contribute to the situation of the leaching operation are as follows:

(1) *Low-grade of the dump:* The ores, with grade between 0.1% and 0.279%, ought to be dumped separately from waste rocks. The Cu^{2+} concentration of the PLS would be 1 g/L by handling the higher grade ores. But in fact, all the ores, waste rocks and clay were mixed together during early dumping stage, and the average grade of the dump was 0.08%, which leads to the low Cu^{2+} concentration of the PLS.

(2) *Refractoriness of chalcopyrite:* DCM is a sulphide ore deposit, the content of chalcopyrite ($CuFeS_2$) within the waste rocks increase as the mining level of the open pit goes down. The ore contains 0.45% primary copper sulfide, 0.028% secondary copper sulfide, 0.0068% free copper oxide and 0.0052% bonded copper oxide. Bioleaching processes are particularly suitable for the treatment of secondary copper sulphides but are very inefficient for attacking chalcopyrite, due to the refractory nature of this mineral to chemical and biological leaching (Finzgar et al., 2006; Rodriguez et al., 2003).

(3) *Poor permeability of the dump:* According to the experience of successful leaching dumps, the optimum height of the dump is 10–20 m. The dump of DCM was not used for leaching originally. In 1997, when the dump leaching was put into use, the height of the dump was about 120 m above the ground. Besides the height of dump, the anisotropy, clay, weathering of rock also contributed to the poor permeability of the dump.

(4) *Small bacterium population:* In order to investigate the action of *Acidithiobacillus* on leaching, three experiments under different conditions were been conducted in shake flasks by DCM and Central South University. The results shown that the solution without *Acidithiobacillus* or iron extracted only small amount of copper from the waste ores, but the recovery of ores treated by the inoculated solution reached 44%. So the activity of *Acidithiobacillus* is critical to the bioleaching by accelerating the bioleaching process of Dexing dump. The population of *Acidithiobacillus* distributed within the area of DCM is small, usually below 1.0×10^4 cells/mL.

(5) *Leakage of pad:* The dump of DCM was originally used for storing waste rock. Trucks were used to dump the waste rocks. The bottom of the dump was poorly prepared without any elastic pad. Plenty of solution leaked from the bottom of the dump and pool, and the amount of the solution within the pool did not increase even in the rainy season.

2.3. Stability evaluation of the dump

Besides the above challenges, stability of the high-steep slope is a clear and present to which sufficient attention has not been paid (Catalan et al., 2002). The height of the dump is now approaching 150 m, and the inclination of the dump slope is about 70°. The mechanical properties of the waste rock would deteriorate further under the continuous attack of leaching and weathering, and the piles may become locally saturated from solution irrigation, the potential for liquefaction also exists (Majdi et al., 2007). The failure of the dump could result in a catastrophic failure (Sloot et al., 2007).

In order to evaluate the stability of DCM dump, a serial of experiment was conducted to investigate the leaching process, ore surface erosion, particle size, chemical elements and mechanical properties of the waste rock in DCM (Abed et al., 2008).

2.4. Samples

The samples, obtained from the dump of DCM, were dried, screened and grouped into different size fractions (obtained by a laboratory-scale process screening). Two granulometric fractions were employed, fine and coarse groups. Eighteen kilogram ores were selected from each group. The particle size distributions of the samples were measured by screen analysis. The fine group samples has a particle size distribution of P20 (interpolated 20% passing) of 0.8 mm, P40 of 2.2 mm, P60 of 3.0 mm, P80 of 4.8 mm and P100 of 10 mm, and the coarse group has a particle size distribution of P20 of 6.2 mm, P40 of 8.8 mm, P60 of 9.9 mm, P80 of 13.0 mm and P100 of 30.0 mm. Chemical analyses shown the sample contained 0.49%Cu, 4.66%Fe, 2.32%S, 0.03%Mo, 0.015%As, 60.75%SiO_2, 13.80%Al_2O_3, 3.36%CaO and 2.80%MgO. Primary copper sulphide is mainly of copper and clayish matrix such as silicate and aluminate is uppermost matrix, whose absorption ability for heavy metal and *Acidithiobacillus* is relatively strong (Wu et al., in press). The unleached samples were analyzed by ICP-AES without grinding, the result shown that Si, Al, K, Fe, Cu, S, Mg and Ca were the main elements of the samples, while silicate and aluminate was the uppermost matrix.

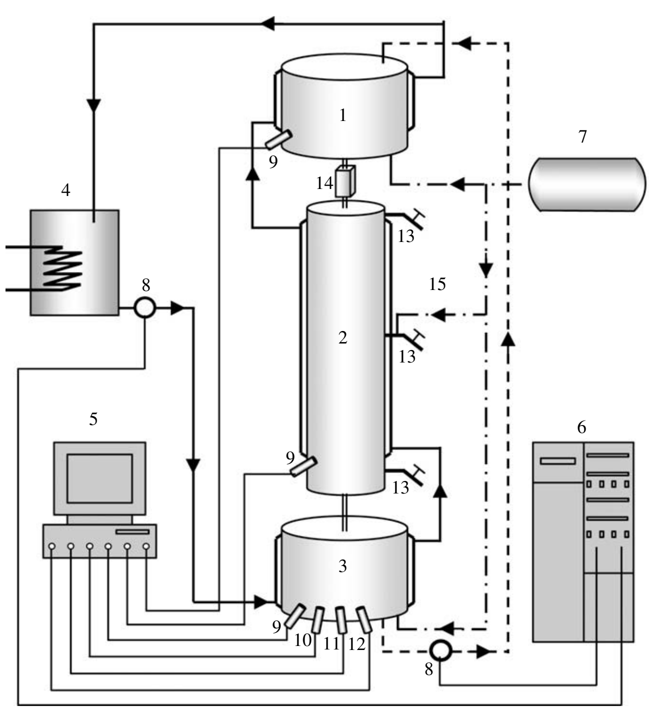

Fig. 1. Schematic of the novel bioleaching apparatus. 1-raised barrel, 2-column, 3-collecting barrel, 4-heating tank, 5-datum collection, 6-control cabinet, 7-air compressor, 8-peristaltic pump, 9-temperature sensor, 10-pH electrode, 11-dissolved oxygen sensor, 12-redox potential sensor, 13-solution outlet, 14-flow meter, 15-gas flow meter, ——▶—— water circulation, - - -▶- - - solution circulation, —·—▶·— aeration system.

2.5. Microorganism and cultivation

The microorganism used throughout the experiment, dominated by *A. Ferrooxidans*, *A. thiooxidans* and *Leptospirillum ferrooxidans*, was from the solution pool of DCM. The microorganism was grown and maintained in 9 K medium (Silverman and Lundgren, 1959), containing (per liter of distilled water) 3.0 g of $(NH_4)_2SO_4$, 0.5 g of $MgSO_4 \cdot 7H_2O$, 0.10 g/L KCl, 0.5 g of K_2HPO_4, 0.01 g of $Ca(NO_3)_2$ and 44.22 g of $FeSO_4 \cdot 7H_2O$; the pH was adjusted to 2.0 with H_2SO_4. The number of *Acidithiobacillus* in leachate was counted by direct examination using a light microscope together with a hemocytometer.

2.6. Experimental apparatus

Fig. 1 shown the novel bioleaching apparatus, mainly consisted by leaching systems, computer, control cabinet, air compressor, operation platform and hot water tank. All parts of the apparatus contacted with solution were fabricated from 316L stainless steel.

The circulation of solution, hot water and air in the experiment are described as below:

(1) The circulation of solution: The solution was circulated within the raised barrel (30 L), column (130 mm in internal diameter, and 1000 mm high), collective barrel (30 L), and the pump was controlled by a control cabinet.
(2) The circulation of hot water: The water in the heating tank was pumped into the jacket of collecting barrel, column and raised barrel to warm up the leaching system.
(3) Aerated system: The compressed air from the air compressor was distributed into the raised barrel, column, and collective barrel respectively, so that the *Acidithiobacillus* growth and bioleaching process can be enhanced (Hector, 2001). The velocity of the air flow was controlled by a gas flowmeter.

2.7. Experimental procedure

Coarse and fine samples were loaded in the both sides of the column separately. Distilled–ion exchanged water and the cultivated microorganism were used to prepare the solution, the volume of which was 15 L, and the pH was adjusted to 2.0 with H_2SO_4. The solution was irrigated with its rate adjusted by the flowmeter, approximately 30 L/m^2 h. pH increased at the end of each circulation, and H_2SO_4 were added to adjust it to 2.0 again before the next circulation began. The whole leaching process lasted for 63 days (one day for each circulation).

2.8. Analytical procedure

Copper concentrations in leaching liquors were determined by Atomic absorption spectroscopy (AAS). The surface of samples from both groups was examined using the Scanning electron microscope (SEM) before and after leaching treatment, the SEM was coupled to Energy dispersive X-ray spectrometry (EDS). The pH of solution was monitored at room temperature with a pH meter and calibrated with a pH buffer. For all the experiments, chemical grade reagents and distilled water were used, with the exception of the chemical analysis in which double distilled water was used.

3. Result and discussion

3.1. Extraction process analysis

During the leaching process, acid was consumed by the reaction with minerals and alkaline gangue. The pH of the solution was 2.0 at the beginning of each circulation, and increased after its reaction with the ores inside the column. At the end of each circulation, solution pH was adjusted to 2.0, so that enough acid was provided for leaching reaction, keeping acid environment for the *Acidithiobacillus*l.

The acid was consumed rapidly by the copper oxide, secondary copper sulfide and alkaline gangue at the beginning of leaching process. So the solution pH increased at the end of circulation. The experimental result shown that the pH value increased sharply initially (10 days), afterward the pH increased slightly for every circulation, because the acid could only be consumed by penetrating into the inner part of ore particles by diffusing process the speed of which was relatively slow.

The experiment also shown that the beginning of the leaching stage, the copper concentration increased slowly even though the acid was consumed rapidly, because the acid was neutralized by various acid-consuming reactions, for example, the leaching of carbonate minerals and silicate minerals (Mousavi et al., 2006). Little acid was account for the copper extraction during the initial leaching stage.

3.2. Change of rock size and dump subsidence

The depth of the ore in column decreased sharply at the beginning of leaching, while the height became steady during the later leaching period. The factors accounted for the ores subsidence during leaching process are as follows:

(1) Same of the fine ores were dissolved or carried out of the column by solution.
(2) The bounded water layer formed once the ore particles were wetted. Attractions between the particles increased under the effect of electric double layer, ionic layer and tension of solution surface. So the distance between ore particles decreased.

The size distribution of leached residues is shown in Fig. 2. Comparing with the size distribution of samples before leaching, Fig. 2 shown that the leaching process results in a considerably finer particle size distribution. The content of fine residues in both coarse and fine materials increased after leaching due to the precipitation which turned to small particles once dried.

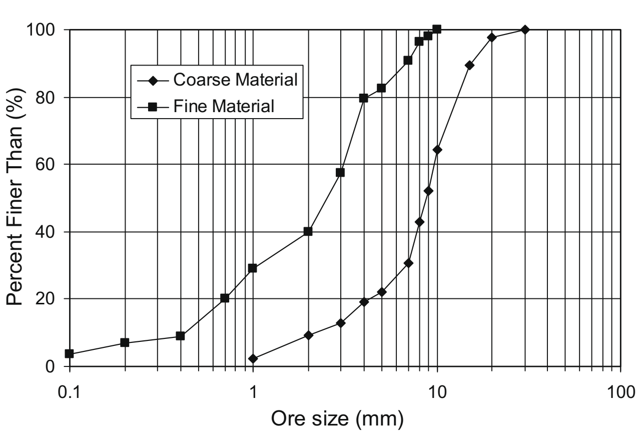

Fig. 2. Particle size distribution of the leached residues.

3.3. Effect of leaching on waste rock

The surface morphology of waste rock is the indication of its chemical degradation. In order to study the surface morphology of the residues after leaching, six groups of leached residues were selected from top, middle, bottom part of both fine and coarse regions. The samples were subjected to SEM analysis.

The SEM images shown that unleached ore surface appeared to be relatively smoother. The corrosion of the leached residue surface area is obviously. The SEM images of the residue surface showed a complex porous like structures, because the minerals on the surface were dissolved by the acid and bacteria. Fractures and cracks were developed, so that the solution can penetrate into the inner part of the ores and leached inside minerals.

Comparing SEM images of coarse residue from different part of the column, we can see the corrosion state of coarse residues in various depth location of the column. The top residue was degraded seriously, while the corrosion of middle residues was lighter than that of top residue. The appearance of fracture is visible in the SME image of bottom residue surface. Precipitation of clay, elemental sulfide and jarosite formed on the bottom residue surface, and the fractures were induced when the leached residue was dried. From the morphological analyzing, we can conclude that the erosion and extraction were decreased with the increase of column depth. This observation consists with the result of extraction analysis.

Comparison between fine residues from different part of the column reveals the obvious correlation between corrosion extent and location depth. The unleached ore surface was smooth. The SEM images of middle fine residue shown the effect of leaching attack and presents some large and deep pores that were probably occupied by acid soluble minerals before leaching process (Veglio et al., 2001). Clearly, the sulfide surface appeared very rough, showing a large area of irregular erosions. The surface of middle and bottom residue was much smoother than that of top residue, indicating a lesser extent of erosion.

3.4. Change of chemical element of waste rock surface

The ore surface was attacked by the acid solution and *Acidithiobacillus* during the leaching process. In order to investigate the chemical element of leached residues, samples were selected from top, middle and bottom part of the column. The leached residues were analyzed by ICP-AES without grinding. The content of Cu, Si, Mg and K of the leached residue's surface was reduced comparing with that of ores before leaching. There were two reasons account for this phenomenon. One is due to the dissolution of minerals which contain those elements. The other reason is that the leached residue surface was covered by the precipitation of sulfur and jarosite. The content of Al, Fe, S and Ca on the surface of leached residue (located in bottom of column) was increased, because the minerals which contain those elements were dissolved by the acid solution and prone to precipitate on the ore surface when the pH value increased.

3.5. Mechanical behaviour of waste rock material

The waste rock was degraded significantly by the solution and *Acidithiobacillus*. In order to investigate the mechanical properties of the rock during the leaching process, waste rocks obtained from DCM were divided into four groups randomly, and leached for 0, 15, 30 and 45 days, respectively. Tensile stress, shear strength and cohesion were investigated for each group. The experiment result shown that the tensile strength and shear strength decreased with increasing leaching time. The acid and *Acidithiobacillus* reacted with the mineral, gangue and matrix on the rock surface, and rare reaction happened inside the waste rock at the beginning of the leaching. So the tensile and shear strength decreased slightly initially. During the middle stage of leaching, large quantities of the minerals inside the rock reacted with the solution, so the strength dropped sharply. During the last stage of leaching, it's hard for the acid to access to the inner reactant of the rock, and the leaching reaction became less extensive. So the tensile and shear strength changed slightly.

At the beginning of leaching, the solution penetrated into the cracks and pores, so the cohesion between the particles inside the rock increased slightly. But under the continuous attack of acid and *Acidithiobacillus*, the cohesion decreased gradually with increasing leaching time.

3.6. Particle crushing due to high confining pressure

For very high WRD one could expect that the high confining stresses could influence in some way the main geotechnical characteristic of typical waste rock material such as: shear strength, deformability and permeability. The probable crushing of rock particles producing finer material could also play a major role in the final behaviour of the waste rock mass.

The high pressures associated with the weight of the materials stockpiled in waste rock dumps with heights over 100 m induce particle crushing, modifying the initial grain size distribution of the material and leading to an increase in the amount of sands and fines in the granular matrix. To evaluate this phenomenon, Bard et al. conducted a systematic post-test grain size analysis in the waste rock obtained from a copper mine in Chile (Vlenzuela et al., 2008). The result shown that, with the increasing of final effective stress, the rock crushing is manifested. The size of the initial particle became much smaller, so the content of fine grains increased.

3.7. Liquefaction potential of the dump

Liquefaction typically occurs when saturated, loose granular material contracts, or collapses, under some shear strain triggering event (Thiel and Smith, 2004). In order for static liquefaction to occur, a number of conditions must be satisfied. The material must have high enough sand and fines content to sustain pore pressures. The structure must be loose enough to contract during applied shear stresses. The void space must be saturated or nearly so. In addition there must be a triggering mechanism. Liquefaction can be initiated either by static or dynamic loads. However, for waste rock structures, static liquefaction (no earthquake) is a far more common trigger mechanism and has led to a number of the largest facility failures in the mining industry.

Low density of the loosened material within the DCM dump slope in combination with its grain size in the range of fine to medium, leads to an inherently unstable slope. Waste dumps constructed under seemingly dry conditions over strong, free-draining foundation would not appear to be exposed to liquefaction flow sliding. However, when the irrigation rate is high or during the rainy season, some parts of the dump could become saturated. Under these circumstances, it takes only a modest shear strain to potentially trigger liquefaction. This strain exists presently in the form of the steep dump slopes but could also come from a minor dynamic loading as, for instance, a wave caused by the dump trucks (trucks having a capacity of 154 tonnes are used to transport the waste rock in DCM) or blasting (low energy explosion, by loading a small amount of dynamite into drilling holes, is used to assist in loosening the rock material and improve the permeability of dump), to cause a local increase of pore water pressure. Subsequently, a loss of contact between the grains occurs and the effective stress is reduced. This local liquefaction is able to extend quickly, which could result in the failure of whole dump.

4. Conclusion

In order to cope with the environmental pollution caused by the WRD and DCM has set up a dump leaching plant to recover the second resource economically. But a number of challenges have been faced by the dump of DCM. The investigation shown that low grade of waste rock, refractoriness of chalcopyrite, small sprinkling area, leakage of pad, low oxidation ability of *Acidithiobacillus* and low permeability are the main factors contributing to the challenges. In order to improve the copper production of the leaching plant, several measures have been exercised by DCM, such as separate ores from rocks, loose the dump, strip the dump surface, improve the oxidation ability of *Acidithiobacillus* and optimize operating procedure.

Besides those challenges, stability of the high-steep slope is a very clear and present concern as a catastrophic failure of this dump appears probable. Leaching behavior, surface morphology, mechanical properties, size and chemical elements of the waste rock before and after leaching were investigated through experiment. The result shown that, under the attack of acid and bacterium, the Cu^{2+} released from the waste rock constantly, and the rock erosion deteriorated with the increasing of leaching time and dump height. Normal stress, shear strength and cohesion decreased sharply during the leaching procession. The deterioration of the rock properties and/or static or dynamic liquefaction could result in the failure of the dump. Particle crushing under the pressure of high rock dump is another factor related to the stability of the dump, so increased attention is required to the stability issues for these dumps.

Acknowledgements

The authors would like to acknowledge the financial support for this work provided by the National Key Fundamental Research and Development Program of China (2004CB619205), China Science Fund for Distinguished Group (50621063, 50774011), and the State Scholarship Fund of China Scholarship Council (2007U47082).

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