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The copper oxide heap leaching of Erdenetiin-Ovoo deposit
ore: The effect of particle size and residence time for copper
recovery

Bachelor Thesis

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Abstract

The research continued from 27th of March till 10th of August. Samples were taken from dump of Erdenetiin Ovoo porphyry copper molybdenum deposit located in Orkon aimag of Mongolia that belongs to Achit-Ikht LLC. Achit-Ikht LLC has an operation of low grade ore dumps nowadays, but there is opportunity to increase leaching efficiency by heap leaching.

The feed ore crushed in jaw crusher and divided into different fractions such as +19mm, +12.5mm, +8mm, -8mm and mixed fraction. The different fractions leached in different columns during 12 to 20 days. All experiments such as column leaching completed in processing laboratory of GMIT. The main focus of research was on particle size and leaching time, however acid curing before leaching, bed height of column and acid consumption discussed in research.

The particle size that provided highest copper concentration was mixed and -8mm fraction. But -8mm size fraction ore is not suitable for heap leaching due to low permeability. The influence of leaching time was massive for mixed and +8mm size fraction. The copper concentration after 20 days was 2 to 3 times greater than 12 days of leaching.

Key words: Copper, oxide, leaching, sulphuric acid, particle size

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1 Introduction

Copper ranks as a third most consumed metal in the world after iron and aluminum. The high grade ore resources are decreasing year by year across the world and people considering low grade ores. Approximately 80% of today's primary copper production includes ore concentration, smelting and electro-refining to convert primary copper sulfides into high purity copper cathodes. The remaining 20% of copper production involves hydrometallurgical processing of copper oxides and secondary copper sulfides, primarily in the form of a dump and a heap leaching(1).

The thesis sample is taken from Erdenetiin-Ovoo, the largest porphyry copper-molybdenum deposit in Mongolia (1.78 Gt reserve with 0.62% Cu, 0.025% Mo). It is located in northern Mongolia, about 350km northwest of capital city Ulaanbaatar. Mongolian-Russian Joint venture Erdenet open-pit copper mine has been operating in Erdenetiin-Ovoo deposit since 1978. The copper concentrate has been producing from sulfide ore and low grade waste ore of has been accumulated for over 30 years. In 2010, Achit-Ikht LLC had a long term cooperation agreement with EMC to utilize low grade waste dump ore. This is Mongolia's second modern hydrometallurgical plant that using dump leaching and built by private investors. The volume of the ore dumps is hundreds of millions of ton, and will grow during the further operation of mining. Only dump 2 ore reserve is 56 million ton. The average copper grade is 0.32%.The ore composition consists of 25% of oxide ore and 75% of sulfide ore. The average copper recovery is 30-40%(2). There is also potential to increase copper recovery and production by the heap leaching to reduce the particle size of leaching feed.

The aim of present study is to obtain optimum conditions for column leaching by testing of various parameters such as a particle size, a leaching time and acid curing on copper recovery which could be used to improve copper extraction.

2 State of knowledge

2.1. Hydrometallurgical copper extraction

2.1.1. Copper mineralogy

The primary sulphide zone locate in deep underground veins and include chalcopyrite disseminated by pyrite. The secondary sulphide enrichment minerals such as chalcocite and bornite found in weathered zone of primary deposit. The oxide enrichment zone occurs in right above the water table and contains copper oxides. The mixed oxide ores could found between secondary sulphide zone and oxide enrichment zone. This transition zone includes minerals such as chalcocite, covellite, malachite and chrysocolla. The oxide enrichment zone include copper oxides such as cuprite and tenorite, basic copper carbonates and hydroxides such as malachite, copper silicates and copper chlorides (1).Figure 1 illustrates how the oxide enrichment and secondary enrichment zones are located relative to the water table.

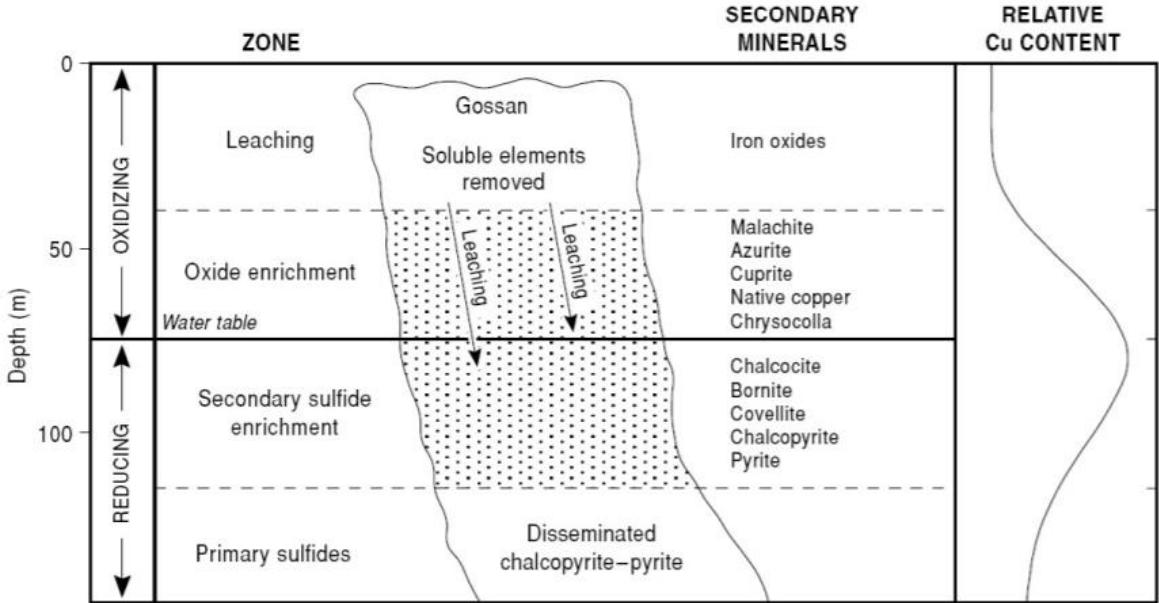


Figure 1: Copper minerals formed by weathering of a copper sulphide vein (1)

Table 1 shows a classification of copper species according to location in a vein orebody, where the mineral is disseminated within definite boundaries.

Table 1: Main mineralogical copper species by location in ore bodies (1)

Mineralized zone	Species	Composition	Copper content %
Secondary oxidised zone	Native copper	Cu	100
	Malachite	$\text{CuCO}_3 \cdot \text{Cu(OH)}_2$	57.75
	Azurite	$2\text{CuCO}_3 \cdot \text{Cu(OH)}_2$	55.3
	Chalcanthite	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	25.5
	Brochantite	$\text{CuSO}_4 \cdot 3\text{Cu(OH)}_2$	56.2
	Antlerite	$\text{CuSO}_4 \cdot 2\text{Cu(OH)}_2$	53.7
	Atacamite	$3\text{CuO} \cdot \text{CuCl} \cdot 3\text{H}_2\text{O}$	59.5
	Chrysocolla	$\text{CuO} \cdot \text{SiO}_2 \cdot \text{H}_2\text{O}$	36.2
	Cuprite	Cu_2O	88.8
	Tenorite	CuO	79.9
Secondary enrichment zone (supergene)	Chalcocite	Cu_2S	79.9
	Deginite	Cu_9S_5	78.1
	Djurleite	$\text{Cu}_{1.95-x}\text{S}$	Variable
	Covellite	CuS	66.5
Primary enrichment zone (hypogene)	Chalcopyrite	CuFeS_2	34.6
	Bornite	Cu_5FeS_4	63.3
	Enargite	Cu_3AsS_4	48.4
	Tennantite	$\text{Cu}_{12}\text{As}_4\text{S}_3$	51.6
	Tetrahedrite	$\text{Cu}_{12}\text{Sb}_4\text{S}_{13}$	45.8

The mineralogical composition information of feed ore known from Achit-Ikht LLC data. The ore minerals are determined as below and the grain size of 0.01-10mm ore sample used for analysis. From the mineralogical analysis, see Table 2, only 6-10 % is copper oxides, 2-3 % is from the copper sulphides and 31-36% is from non-cupriferous mica.

Table 2: Mineralogical composition of Erdenetiin-Ovoo deposit dump ore(3)

Mineral	Pyrite	Covellite	Chalcocite	Bornite	Chalcopyrite	Molybdenite	Titanite
%	30-35	1-2	3-5	3-5	1	0.5	0.5

2.1.2. Hydrometallurgical Copper extraction

Copper is one of the chemical elements with symbol “Cu” and atomic number is 29. The most important property of copper is high thermal and electrical conductivity(4). Approximately 1780.9 Mt copper contained in the world, with an average content of 0.49 %. The average grade of copper ores that are currently mined in the world amounts to about 0.62%, with annual production of 16 Mt/year (2). About 80% of today’s primary copper producing from copper sulphide ore by using techniques of ore concentration, smelting and electro-refining to create high purity copper cathodes. The remaining 20% of copper producing by hydrometallurgical processing of copper oxides and secondary copper sulphides, in the form of dump and heap leaching (1). The future is expected with low grade ore mining. The lower grade deposit operation is increasing year by year in the world larger mines that has already operated over 100 years, mostly in USA, Chile, Australia, as well as Serbia. As shown in figure 2, the highest grade copper ore was 5-6% in Serbia at the beginning of the 20th century. However, it dropped incessantly to less than 0.4% at the end of the century.

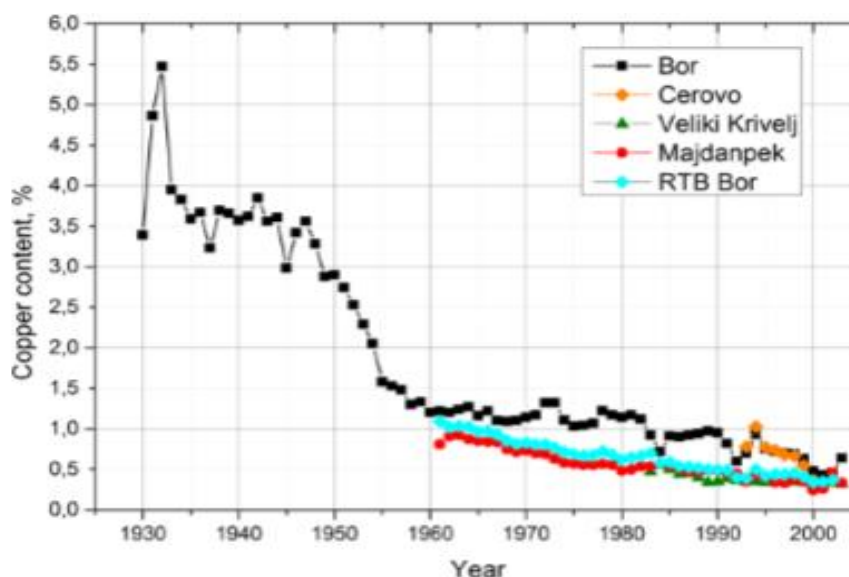


Figure 2: The copper ore grade fall during last century (5)

The figure 3 shows that the hydrometallurgical process can be briefly summarized into three separate steps:

1. Leaching of copper from ore or mine waste to produce a copper-bearing aqueous solution
2. Solvent extraction to produce a pure highly-concentrated copper electrolyte from the aqueous solution
3. Electro-winning in which the electroplating of pure copper cathodes from the electrolyte occurs(6).

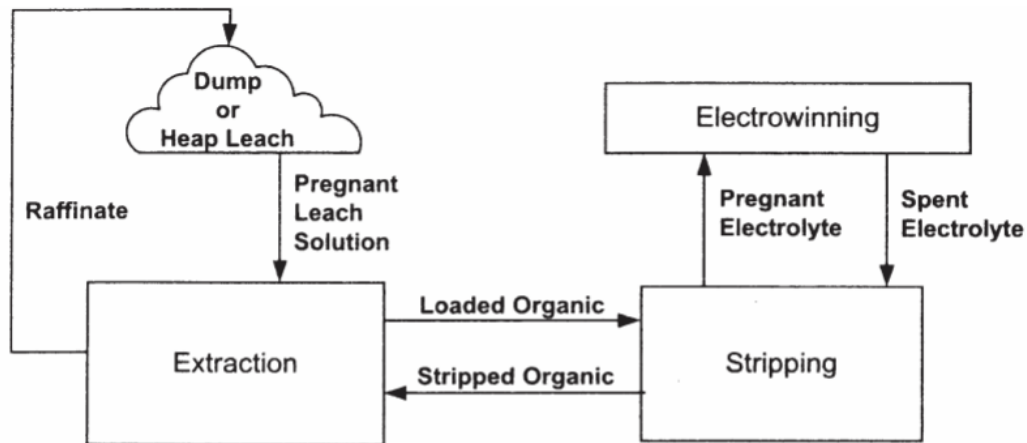


Figure 3: Conceptual leach/SX/EW flow sheet (7)

Hydrometallurgical leaching refers to the chemical and biochemical processes by which solutions transfer metal compounds from a solid phase to an aqueous solution from which the valuable metal component can then be recovered by downstream processing (6). Leaching is occasionally applied to Cu-bearing flotation tailings, mine wastes, old mines and fractured ore bodies. The leaching of mine wastes improves the efficiency with which copper is recovered from an ore body, and this process is increasing prevalence.

2.1.3. Copper leaching methods

A selection of leaching method mainly depends on mineralogy of ore, ore grade and particle size of the ore. The figure 4 shows the particle size influence for selection of leaching method.

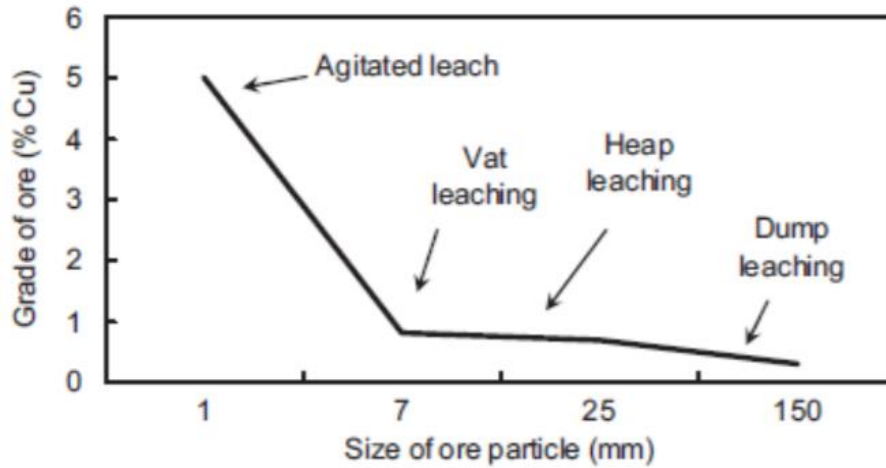


Figure 4: The selection of leaching method by the influence of particle size (2)

The leaching methods as practiced for hydrometallurgical extraction are:

- a) In-situ leaching
- b) Dump and heap leaching
- c) Vat leaching
- d) Agitation leaching.

Typical production details of these types of plants are given in Table 3.

Table 1: Details of leaching procedures (5)

Leach method	Mineralization	Cu in ore (%)	Sulphuric acid concentration in leachant, ($kg \cdot m^{-3}$)	Cu concentration in pregnant solution, ($kg \cdot m^{-3}$)
In-situ	Oxide(with some sulphide)	0.5-1	1-5	1-2
Dump	Oxide/sulphide mine wastes	0.2-1	1-5	1-2
Heap	Oxide	0.5-1	2-10	2-5
Vat	Oxide	1-2	50-100	30-40
Agitation	Oxide (concentrates)	20-30	50-100	30-50
	Roaster calcinates	30-40	50-100	30-50

In-situ, dump and heap leaching are essentially the same technique. The ore is broken to expose copper minerals at generally weak fracture interfaces and leachant is tricked by gravity between the ore pieces. The principal requirements for all three methods are an impervious base on which the pregnant leach solutions can be collected and a host rock which does not consume inordinate amounts of sulphuric acid (5).

- a) In-situ leaching involves the breaking of ore in situ by explosives with no moving of the ore by conventional mining methods. This can be practiced for low-grade surface deposits or worked-out underground mines. A technique receiving some attention is the fracturing of underground rock under hydraulic pressure (5).
- b) Dump leaching is applied to the low-copper wastes from conventional mining method, usually open-pit operations. The rock is built into large dumps and leachant is periodically distributed over the surface and allowed to trickle through the dump. Much of the copper produced from dumps is leached from sulphide minerals for which oxygen is required. The oxygen is supplied by allowing air to rise through the dumps between monthly applications of leachant (5).
- c) Heap leaching is exactly the same as dump leaching except that surface oxide ore deposits, rather than mine wastes, are broken and piled into heaps are smaller than those in dumps (~10cm) and the leaching is continuous and considerably faster. Copper recoveries from sulphide minerals which happen to be in the heaps are low due to the short (100-180 days) leaching times.
- d) Vat leaching of oxidized copper ore is carried out in order to produce directly a pregnant leach solution of sufficient copper concentration for electro-winning. As compared with in-situ, dump and heap leaching it is a high production rate method which employs concentrated.
- e) Agitation leaching is a chemical process where in the soil that is to be mixed or slurred is kept in contact for a certain period of time with fluid to be extracted. The metal solubility rate is reduces quite noticeably, and the extraction gets completed on the approach of equilibrium between the metal present in the solution and the metal contained on the surface of the soil is approached.

2.2. Copper heap leaching

Heap leaching is one of the mineral processing techniques whereby a heap of low grade ore is leached with various solvents to extract precious and base metals. Since the 1950s, it has been practiced for the extraction of copper, gold, silver, and uranium.

The ore is crushed and agglomerated before constructing a heap to achieve a uniform distribution of particles and better percolation of the solvent (9). The solid materials in the heaps are smaller than those in dumps (~10cm) and the leaching is continuous and considerably faster (10). If the ores are too fine, percolation of leach solution through the heap will be slow and drainage will be poor as well. The leach solution that comes out at the end of the leaching process is known as the pregnant leach solution, and is passed to the metal recovery/extraction stage (6). And success is measured by the degree to which target levels and rates of recovery are achieved. This distinguishes heap leaching from dump-leaching.

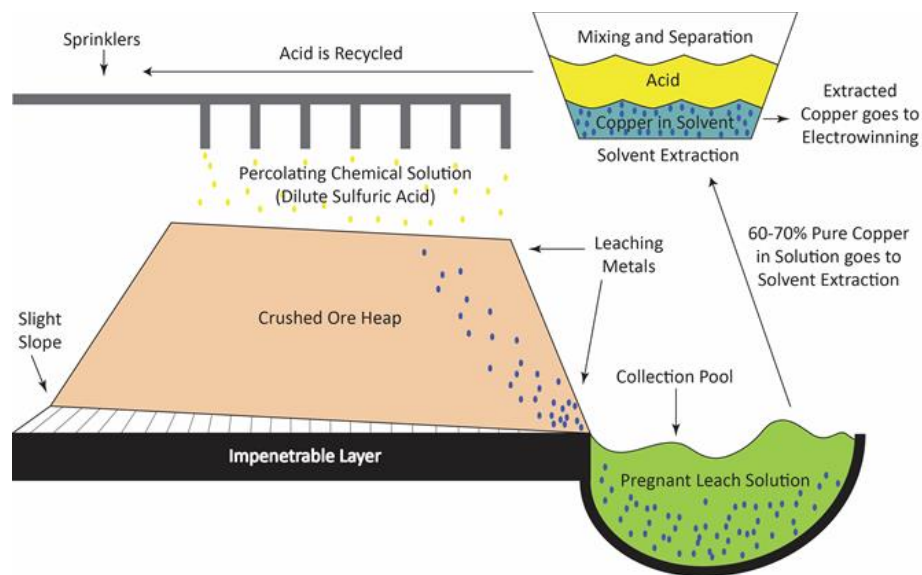


Figure 5: Cu heap leaching (8)

Advantages and disadvantages of heap leaching consists of:

Advantages:

- Low capital and operating cost
- Absence of milling step, may require crushing and agglomeration
- Simplicity of atmospheric leach processes
- Can be used to treat low-grade ores, wastes and small deposits
- Absence of liquid-solid separation step allows counter current operation
- Metal tenor may be built up recycling solution over heaps
- Simplicity in equipment and operation
- Shorter start-up times
- Less intensive environmental regulatory concerns

Disadvantages:

- Lower recoveries than mill/float or mill/leach
- Long leach cycles and hold-up
- Lengthy pilot test program
- Large footprint. (11)

The heap leaching process is simulated at laboratories by column leaching tests (9). For leaching copper, the agent of leaching can be acids, base and salt solutions. But the most typical agent is sulphuric acid. In Table 4, 5, 6 the reactions of copper oxides, sulphides and gangue minerals with sulphuric acid shown. Both of copper oxides and sulphides react with sulphuric acid and form copper sulphate and water. The oxidized ores of copper are highly soluble in dilute sulphuric acid. The actual rate of dissolution depends upon the type of leaching and condition. Copper sulphide minerals are not soluble in sulphuric acid unless oxidizing conditions provided. Copper sulphides can dissolve in iron(III) sulphate instead of sulphuric acid.

Table 2: Copper oxide leaching reactions and dissolution range for sulphuric acid(12)

Mineral	Chemical reaction	Dissolution range for sulphuric acid
Tenorite	$CuO + H_2SO_4 \rightarrow CuSO_4 + H_2O$	100%
Cuprite	$Cu_2O + 2H_2SO_4 \rightarrow CuSO_4 + Cu + 2H_2O$	70%
Copper	$Cu + Fe_2(SO_4)_3 \rightarrow CuSO_4 + FeSO_4$	-
Azurite	$Cu_3(OH)_2(CO_3)_2 + 3H_2SO_4$ $\rightarrow 3CuSO_4 + 4H_2O + 2CO_2$	100%
Malachite	$Cu_2(OH)_2CO_3 + 2H_2SO_4 \rightarrow 2CuSO_4 + 3H_2O + CO_2$	100%
Chrysocolla	$CuSiO_3 + 2H_2O + H_2SO_4 \rightarrow CuSO_4 + SiO_2 + 3H_2O$	100%
Atacamite	$2Cu_2(OH)_3Cl + 3H_2SO_4$ $\rightarrow 3CuSO_4 + CuCl_2 + 6H_2O$	100%
Brochantite	$CuSO_4 \cdot 3Cu(OH)_2 + 3H_2SO_4 \rightarrow 4CuSO_4 + 3H_2O$	-
Antlerite	$CuSO_4 \cdot 2Cu(OH)_2 + 2H_2SO_4 \rightarrow 3CuSO_4 + 4H_2O$	-

Chalcanthite	$CuSO_4 \cdot 5H_2O \rightarrow CuSO_4 + 5H_2O$	-
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Table 3: Copper sulphide leaching reactions(12)

Mineral	Chemical reaction
Chalcocite	$Cu_2S + \frac{1}{2}O_2 + H_2SO_4 \rightarrow CuS + CuSO_4 + H_2O$
Covellite	$CuS + 2O_2 \rightarrow CuSO_4$
Chalcopyrite	$CuFeS_2 + O_2 + 2H_2SO_4 \rightarrow CuSO_4 + FeSO_4 + 2S + 2H_2O$
Blaubleibender	$Cu_6S_5 + 6Fe_2(SO_4)_3 \rightarrow 6CuSO_4 + 12FeSO_4 + 5S^0$

Table 4: Important gangue leaching reactions in copper heap leaching(12)

Mineral	Chemical reaction
Pyrite	$FeS_2 + (1 - 6\beta)Fe_2(SO_4)_3 + 8\beta H_2O$ $\rightarrow (3 - 12\beta)FeSO_4 + 8\beta H_2SO_4 + (2 - 2\beta)S^0$
Calcite	$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 \cdot 2H_2O + CO_2$
Siderite	$FeCO_3 + H_2SO_4 \rightarrow FeSO_4 + CO_2 + H_2O$
Limonite	$Fe_2O_3 \cdot 3H_2O + 3H_2SO_4 \rightarrow Fe_2(SO_4)_3 + 6H_2O$

Acid curing and agglomeration are generally used prior to heap leaching of copper oxide and secondary sulphide ores to improve the copper extraction process (13). Curing is a pre-treatment in which concentrated sulphuric acid is added to a crushed ore. Typical acidic leaching solutions include hydrochloric acid, sulphuric acid and ferric sulphate.

The leaching process can cause physical and chemical interactions. Consequently, many characteristics of ore particles in the heap such as permeability, particle size distribution, porosity and acid flow parameters could change over time (9).

2.1.1 Pre-treatment of ore for heap leaching

Ore used for heap leaching exhibit different characteristics. Heap leaching, being a process that is diffusion driven, the permeability of the heap is a crucial factor that

guarantees good results. Therefore, the ore material to be subjected to heap leaching must be of the right particle size. For ore material to be subjected to heap leaching, the proportion of fines smaller than 74 μm , determines if agglomeration is needed. The composition 74 μm of fines should be about 15 % of the ore composition. Therefore agglomeration of the ore before heap leaching will reduce fine particle migration and improves permeability in the heap (12).

Acid curing

In most heap leach operations, acid curing is also another ore pre-treatment process that is carried out before subjecting the ore to heap leaching. Sulphuric acid curing involves addition of concentrated sulphuric acid into crushed ore material before heap leaching, usually added during agglomeration. The acid will react with the gangue and minerals to form sulphate crystals prior to irrigation of the heap, which easily dissolve in an acidic solution. A curing has numerous benefits which include; generation of metal salts crystals that enhance bed permeability, crack generation which enhances diffusion of solutes within the ore particles, and accelerate leaching, dehydration and carbon dioxide evolution (12). Experimental procedure of acid curing starts by crushed ore locate in agglomerating drum and wet by 8-13% of sulphuric acid during 60 seconds until it become 10% moisture. The wetted ore should rest 16-24 hours in order to improve acid reaction. The resting time could be extended, if the ore contain more clay minerals. Around 80% of total acid consumption should be used during agglomeration and acid curing, since the metal leaching and acid recycle is highest (14). After the curing period, subsequent leaching with raffinate easily dissolves the copper sulphate. The current practice of industrial heap leaching has demonstrated the advantage of acid curing.

Agglomeration

Agglomeration is a process in which fine particles are bound together to produce coarser particles. The particles get attached to each other due to capillary forces. Agglomeration reduces the leaching residence time, improves the recovery and allows leaching of fines regarded as not economically viable to process using conventional methods. Leaching efficiency improved for agglomerated than for un-agglomerated ore. Agglomerated ore had a higher recovery with the shortest possible time and lower reagent consumption as compared to unagglomerated ore. The environmental benefits of agglomeration is that good agglomerates quality reduces dust emissions.

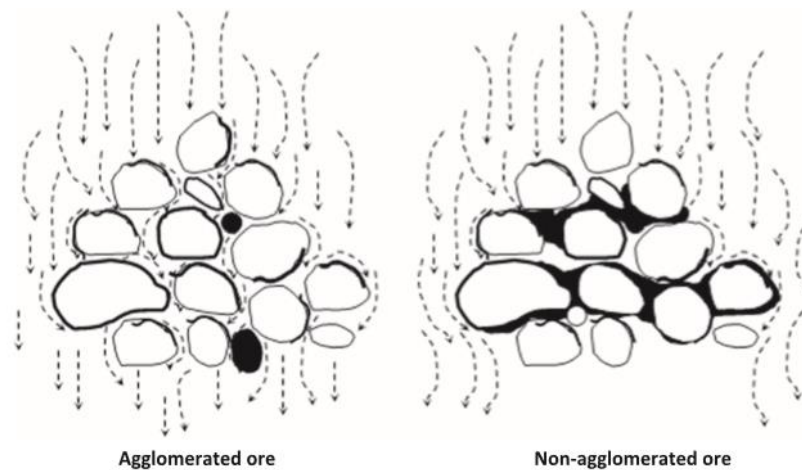


Figure 6: Comparison of solution percolation of agglomerated VS non-agglomerated ore (15)

Figure 6, shows how fine are blocking the lixiviant from percolating down the ore bed. There are more poles that enable better percolation of the within the ore bed. There have been studies carried out on the effects of various agglomeration parameters on the agglomeration process. Moisture content plays a critical in agglomerate formation and stability in the heap. Excessive moisture leads to unstable agglomerates and mud formation.

2.1.2 Variables affecting copper dissolution in heap leaching

Mineral liberation and size reduction

The most minerals have some unknown grain size distribution, texture, exposure, and spatial distribution within the ore particles, they must be initially unlocked or liberated before separation can be undertaken. In hydrometallurgical extraction of metal, the mineral grains liberation as a free grain is not necessary since the partial exposure of mineral grains may provide sufficient surface front for chemical attack by leaching solution (15). The reaction rate of leaching is directly dependent from surface area of ore due to the acid flow can cover more surface area of many fine particles than one coarser particle. Compared with other leaching types, heap leaching technology requires coarser particle size, typically from 12 to 25mm of crushed or the ore from waste dump site. The heap leach optimum particle size is determined experimentally from column tests. Usually, the sizes evaluated range from 10 to 40 mm. Generally a P80 of 6 mm or less is unacceptable (16). Use of smaller particle size is not recommended because bed permeability decreases impairing leach liquor circulation and oxygen and carbon dioxide transfer from air to the liquid phase (17).

Reagent consumption and flow rate

The main reagent consumed in copper heap leaching is sulphuric acid. Acid consumption represents 10-25 % of the operating costs of the heap leach process. A metal extraction is proportional to acid consumption and particle size has a reverse relationship with acid consumption.

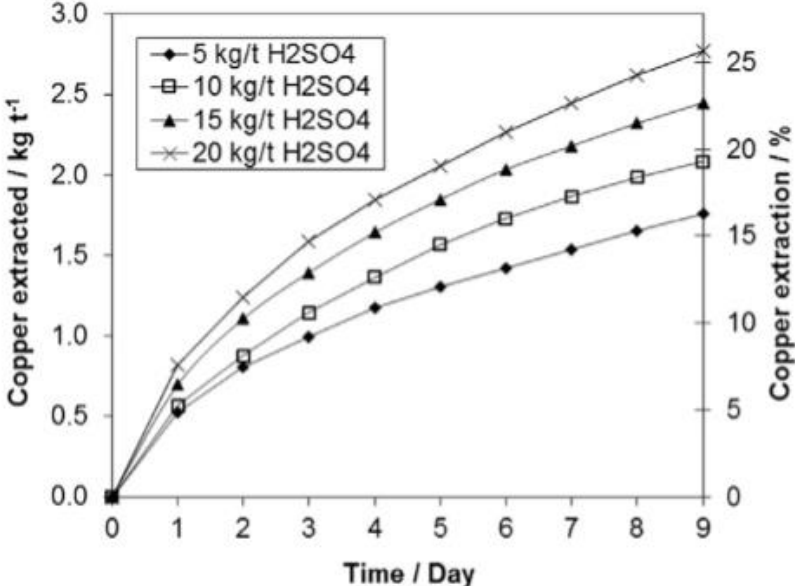


Figure 7: Copper extraction VS Leaching time

Figure 8 shows, the acid consumption and copper extraction are proportional. The peak copper extraction (~25%) provided by 20kg/t acid which is the highest amount of acid from other dosages. Also, the least copper extraction (~17%) used the least amount of acid (5kg/t) in same leaching time.

Some practical acid consumption data were founded for leaching experiment. The two companies' in Mongolia which have a hydrometallurgical operation in Erdenetiin-Ovoo deposit acid concentration and consumption informations are shown in Table 8.

Table 5: Acid consumption and concentration of Achit-Ikht and Erdmen LLC (14)

	Achit-Ikht LLC	Erdmen LLC
Acid concentration	5g/l	7.5-9g/l
Acid consumption	6-8l/h/m2	7-12l/h/m2

During the leaching process, sulphuric acid could be consumed due to wanted reactions with copper minerals, but also due to unwanted reactions with oxides and carbonates of alkaline earth (5).

Leaching time

Copper extraction is proportional to leaching time. The figure 9 shows, influence of leaching time for copper extraction with different copper mineralogy. Copper oxide ore shows extremely fast leaching rate in first days of leaching, up to 80-90% extraction achieved in first 50 days of leaching and extraction curve become stable during rest of leaching time. It is very typical that more than 90% of the total copper extracted during first one month of leaching whether oxide is mixed with sulphides or not (11). Metal extraction rates in copper secondary sulphide minerals' leaching typically show an initially fast leaching rate. The leaching up to 60-80% extraction occurred over the first few months, followed by a slower constant rate period, reaching up to 80-90% copper extraction over the following 12-24 months. For mixed zone minerals, the leaching rate is very slowly increasing day by day. Nevertheless, copper extraction reached 30-40% in three months. The primary enrichment zone has the slowest leaching rate due to its mineralogical composition (12).

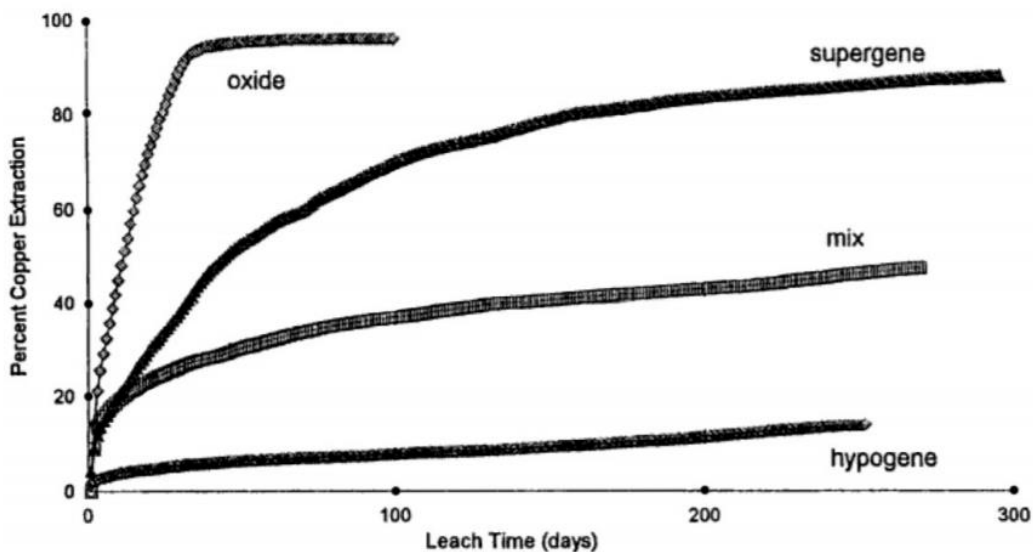


Figure 8: Influence of leaching time for copper extraction (12)

Heap bed height

There is an inverse relationship between heap height and copper extraction. If the height of the heap is lowered, the leaching extraction increases. This is due to better permeability as observed by having the lower heap height. The figure 10 shows, the relationships between Cu extraction and heap height, Cu in PLS and heap height.

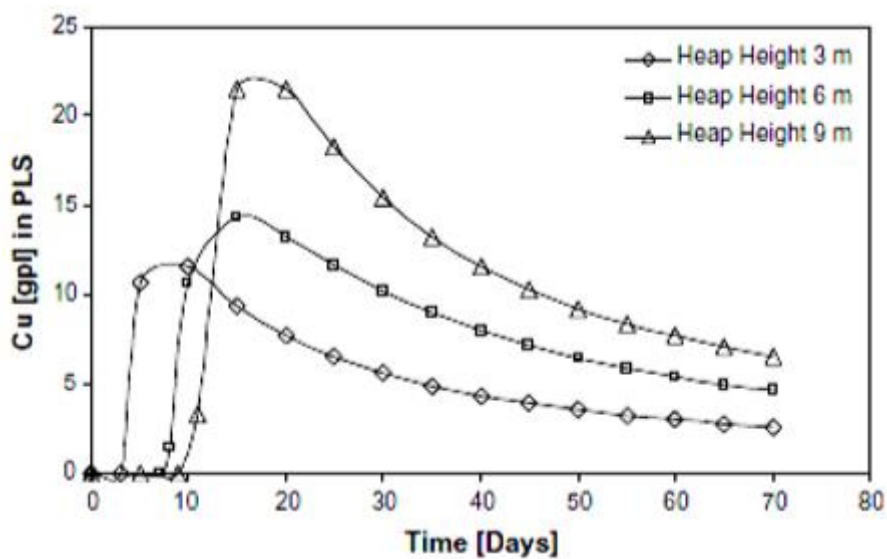
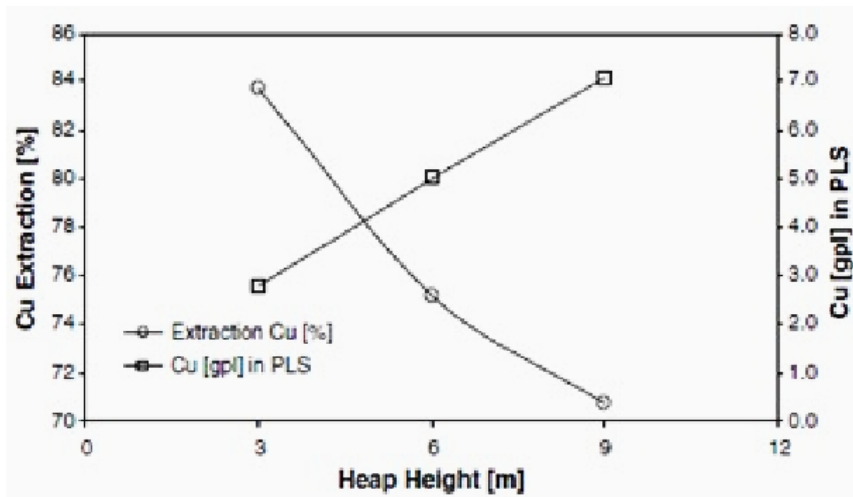


Figure 9: Cu content in PLS VS Time (12)

Furthermore, there is direct relationship between column height and copper concentration in PLS. The figure 10 shows, the heap height effect for copper concentration in PLS. The highest heap was 9m and it provided maximum copper concentrations during complete experiment.

A low temperature can be a problem. Many Nevada heap leaches report a significant recovery decrease in winter, which is offset the following summer. When a cold weather project is anticipated, column tests should be run under cold conditions. There are several reasons for a reduction in recovery rate with lower temperatures:

- Rate of reaction is slowed;
- Viscosity of water decreases;
- Lower flow rate;
- Surface tension can affect the flow of solution (10).

3 Experimental procedures

This chapter describes the materials, apparatus and experimental procedure employed in the research. It also gives the source and types of mineral samples used, leaching experiments and chemical analyses that were carried out.

3.1 Materials

3.1.1 Copper oxide ore composition

In the experiments, the oxidised copper ores were subjected to leaching. The 232kg of sample was delivered at the beginning of April, 2018. The sample was delivered from part of Erdenetiin-Ovoo deposit by Aчит-Ikht LLC. The weight of sample before and after crushing shown in Table 9. There were around 7kg of sample ore loss due to representative samples for analyses.

Table 6: The weight of sample before and after crushing

Package№	Initial weight (+38mm),kg	Weight measured after 100% crushing (-38+19mm),kg
1	48	46,955
2	37	35,255
3	34	33,29
4	41	40,215
5	39	37,588
6	33	32,225
Total	232	225,528

The copper ore contained an average amount of 0.32% of copper, generally. Unfortunately, more detailed information on the composition of the compost was not provided. However, the head assay of copper and iron, sulphur determination analysis made in Central Geological Laboratory of Mongolia. The compost particles were mostly uniform in size, and most of sample ranged from 5 to 20 cm.



Figure 10: Copper oxide ore from Erdenetiin-Ovoo deposit

Purely by observation, it was noted that both batches has slight differences in colour and smell. It is noted by Achit-Ikht LLC that the sample was taken from slope side of dump.

3.1.2 Leaching solutions used for experiments

Leach solution

The experiments were conducted using sulphuric acid-aqueous solution as a leach and acid curing solution. For acid curing, 10% sulphuric acid used. The acid solution is prepared by diluting 84.5ml of 98% concentrated sulphuric acid into 1400ml of water. For leaching, the acid solution was prepared by diluting 8g/L of 98% concentrated sulphuric acid into every 5 L of deionized water. The water was obtained from a water sink in the laboratory. The reason was to equalize the use of water in practice. The solution was then mixed thoroughly with a stirrer.

Titration solution for determination of sulphuric acid

A 1.0M sodium chloride solution and a methyl-orange are used for titration of pregnant leach solution. The 1.0M sodium chloride is prepared by diluting the standard titration solution into water and added water until the mixture became 1L. A methyl-orange solution is given from the laboratory.

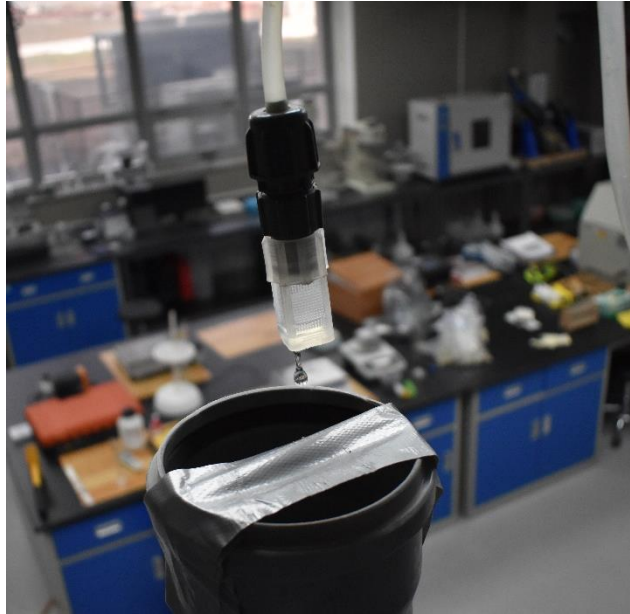


Figure 11: Sulphuric acid as a leaching solution

3.2 Apparatus and equipment

3.2.1 Jaw crusher

The serial number of 5E-JCA150*125 jaw crusher is used for size reduction of copper oxide feed ore. The maximum feed size is equal or below 100mm. The discharge size of product is 6 to 38mm. The jaw crusher used in experiment as a primary crusher. The initial feed from Erdentiin-Ovoo deposit particle size was mostly uniform, 95% of ore was 5-15cm. The ore was crushed until 100% passing 38mm by using jaw crusher. The jaw crusher maximum discharge product size was used as a 38mm size sieve.

Figure 12: Jaw crusher

3.2.2 Sieve

A many different size of sieves used for sample preparation and size analysis. Much coarser sieve meshes commonly used for experiments such as 19mm, 12.5mm and 8mm. These meshes typically



used in construction sector. Stainless steel sieve mesh has a diameter of 200mm and height of 50mm.

A mechanical sieve shaker is used for determination of fine particles ($<74\mu\text{m}$). A finer size meshes such as 2mm, 1mm, 500 μm , 125 μm , 63 μm handled in shaker. The stainless steel shaker separation is based on vibration movement and can hold up to 10 sieves in the same time. The operating time can managed from 0-99 minutes, the experiment lasts 20 minutes per sieving.



Figure 13: Mechanical sieve shaker



Figure 14: 19&12.5mm size sieves

3.2.3 Leaching column

Six polyvinyl chloride (PVC) cylindrical leaching columns measuring 200mm in diameter and 1500 mm in height were constructed. Constructions of the columns were done in processing laboratory of GMIT. PVC was selected to construct the columns due to its ready-availability, low cost, strength and its suitable size. The drawback in using PVC was that the columns are not transparent. Transparent columns can be useful for the purpose of monitoring the ongoing leaching process. The use of ready-made PVC cylinders for construction meant that the diameter of the columns was fixed during design. The column height, on the other hand, was forced to be smaller than the proposed height of 1000 mm, due to initial difficulties in securing sufficient amounts of ore. Even the column height is 1500mm, the ore was fed until 1000mm from the bottom of column. From past studies the typical height-to-diameter ratios of leaching columns were usually over 10:1. (3) However, a column height of 7.5 times the diameter can still be accepted as well. An experiment set up is shown in Figure 16.



Figure 15: PVC leaching columns

3.2.4 Leach solution feeder pump

The peristaltic six pumps (see Figure 15) was used to pump fluids into the leaching column. The pump utilizes a peristaltic motion to transfer fluid contained within the clear tubing into the leaching column. The pump itself does not come into contact with the liquid.



Figure 16: Peristaltic pump

Throughout the experiments, a pumping speed should be constant in each pump and 3L/s was set point. The time needed to transfer 2.7L of leach solution into a column packed with 14.6 kg (-8mm) of sample was about 30 – 40 minutes.

3.3 Test preparation and implementation

3.3.1 Sample preparation

The initial 232kg of sample is crushed to >38mm by jaw crusher. The jaw crusher size reduction availability was 6~38mm, therefore the control option for size reduction was on maximum. After crushing, all samples was separated into different fractions (-38mm, +19mm, +12.5mm, +8mm,-8mm) by using test sieves. Each size fraction was blended well for the representative sample for head assay analysis. Using coning and quartering sampling technique, a representative sample of 1~2kg was sampled from the bulk ore sample for chemical composition. The chemical analysis was carried out for copper (%Cu) and iron (%Fe). Coning and quartering was used as well as for particle size analysis. The screen sizes used for particle size analysis were 19 mm; 12.5 mm and 8 mm. A mix fraction is formed from the other fraction sizes as a ratio of 4.3(>19mm):1.6(>12.5mm):1.3(>8mm):2.9(<8mm) due to fractions' weight percentage after 100% <38mm crushing.

3.3.2 Moisture content determination

For moisture content determination, a 1 kg sample was dried for 24 hours at 200°C, the mass after drying was measured and the moisture content for the ore was calculated as following formula:

$$\text{Moisture content}(\%) = \frac{M(\text{wet}) - M(\text{dry})}{M(\text{dry})} \times 100$$

Where:

$M_{(\text{wet})}$: Mass of sample before drying (kg)

$M_{(\text{dry})}$: Mass of sample after drying (kg)

There were totally six packages of initial copper oxide ore sample from Erdenetiin-Ovoo deposit. However, only three packages were used for moisture determination experiment due to its safe and sealed packages during transportation. Otherwise, the experiment result could be failed. A moisture sample taken from package №: 2, 3, 5.

Table 7: The moisture content analysis result

PackageNo	Wet mass (g)	Dry mass (g)	Moisture content, (%)	Average moisture content (%)
2	1319	1266.3	4,1	3
3	1319.9	1272.4	3,7	
5	1458	1442	1,109	

3.3.3 Acid curing

The acid curing experiment was completed in only one column of leaching with >12.5mm ore. 13965gr of copper oxide ore is fed into the PVC bottle. The sealed bucket ore is rotated during 120 seconds in roll table mechanically. Then it lasted during 24 hours of acid curing. The column leaching has started right after curing.



Figure 17: 10% of sulphuric acid solution mixing with ore

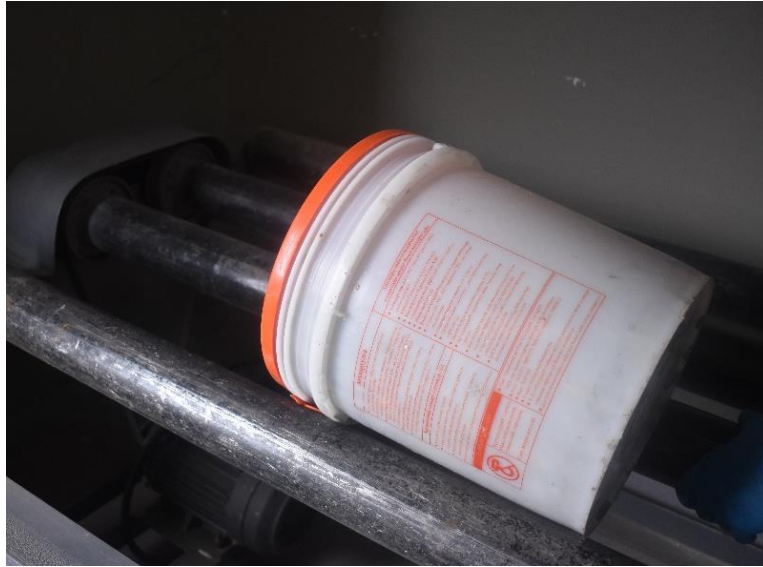


Figure 18: The ore wetted by sulphuric acid is rotating in roll table

3.3.4 Implementation of column leaching

Test of column leaching

On May 1st, 2018 very first commission of operate-ready column was occurred. The aim of the experiment was to check column and pump operation, measure the time and fluid consumption from starting until the fluid drops from the bottom of column. The normal tap water and 14.6kg of (<8mm) different type of excess ore are used. The result was obtained that first drop is dropped after 46 minutes of operation and 565ml of water dropped during one hour after the first drop. Also, the pump flow rate test was obtained constantly.

Column leaching of sample from Erdenetiin-Ovoo deposit

There were three experiment of column leaching during 48 days.

Table 8: The feed ore weight of three column leaching experiment

Column №	1 st experiment		2 nd experiment		3 rd experiment	
	Size fraction (mm)	Weight (g)	Size fraction (mm)	Weight (g)	Size fraction (mm)	Weight (g)
1	-38+19	11745	+19	12040		
2	-19+12.5	11500	+19	11855	+8	7220
3	-12.5+8	11760	+12.5	12710		

4	-8	13900	+8	12055	+12.5	13965
5	Mixed	11605	Mixed	11845		
6	-8	17130	Mixed	14160		

A first experiment started on 4th of May, 2018 at 2pm with six columns and size fractions such a >19mm, >12.5mm, >8mm, mixed fraction and two of <8mm handled. All the columns filled with ores until the bed height reached 1 meter. The first drop of PLS was dropped after 3-5 minutes on column №1&2 and 15-30 minute took for column №3&5 without any problem. However, the sulphuric acid solution was not dissolving into the ore and precipitation occurred in top of column №4&6(<8mm) due to its low flowing speed. Therefore, column 4&6's leaching was not perfect as others. The PLS was dropping into the collection bottle rarely. Therefore, <8mm sample ore did not used for column leaching but only used for mix fraction formation. The PLS collection was in every 24 hours and stored in sample glass storage (see Figure 20). The experiment taken place during 12 days and finished 17th of May, 2018.

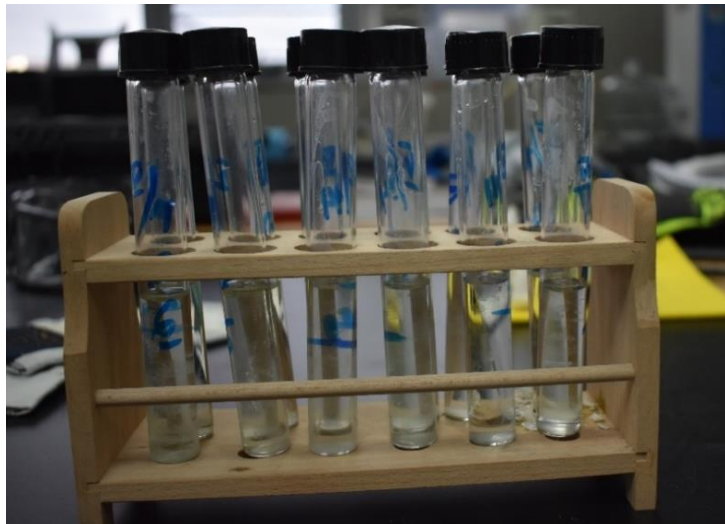


Figure 19: The pregnant leach solution sample collection

The difference between first and second experiment was the leaching time. The second experiment has continued during 20 days, started on 17th of May and ended on 5th of June. The aim of individual experiment was to identify effect of residence time for leaching. The experiment started with six columns of ore with different size fractions such as two times >19mm, >12.5mm, >8mm and two times mix fractions. Same as first experiment, all of columns filled by ore until bed height became one meter from bottom

of column. Column 1&6 operated only twelve days and rest four columns continued leaching until reached 20 days to identify the effect of leaching time.

During second experiment, a failure occurred in one of pumps and sulphuric acid supply to the top of column stopped. The reason of failure was that suction was operating without problem and pushing part of equipment broken inside of pump. The sulphuric acid was dropping from middle of pump.



Figure 20: The peristaltic pump failure and sulphuric acid drop from pump

The third experiment had only two column of leaching, >12.5mm and >8mm. The >12.5mm ore had 24 hours of acid curing before leaching and the >8mm ore filled the column only until 0.58meter from the bottom. The main focus was on effect of acid curing before leaching and effect of bed height for copper recovery.

Immediately after the leaching stage, the power supply was turned off. Since some of the fluid was still percolating through the medium, the low drainage rates were expected. The column was left for at least 24 hours had least fluid inside compared with column that immediately emptied the ore. The following figures shows the difference between ore fraction size of >19mm and mixed fraction leaching residue.



Figure 21: Mixed and >19mm size fraction leaching residues after leaching

Except for solid residue of leaching, there is also liquid residue left in the bottom of bottle. The pH of residue solution was around 1 to 2. Therefore it is not environmental to throw it away without neutralizing. By adding sodium and calcium hydroxide, the residue solution was neutralized with pH of 7~8 and the colour was dark green. Both of solid and liquid residues of leaching are landfilled and it is not harmful anymore. The figure 24 shows the liquid residue solution is in progress of neutralizing.



Figure 22: The leaching liquid residue is neutralizing by calcium hydroxide

The bottom part of leaching column was corroded after leaching experiments. The following figures are the comparison of iron part before and after leaching. The corroded parts were covered slightly with precipitates that were blue-green in colour, due to the crystallization of copper (II) salts.

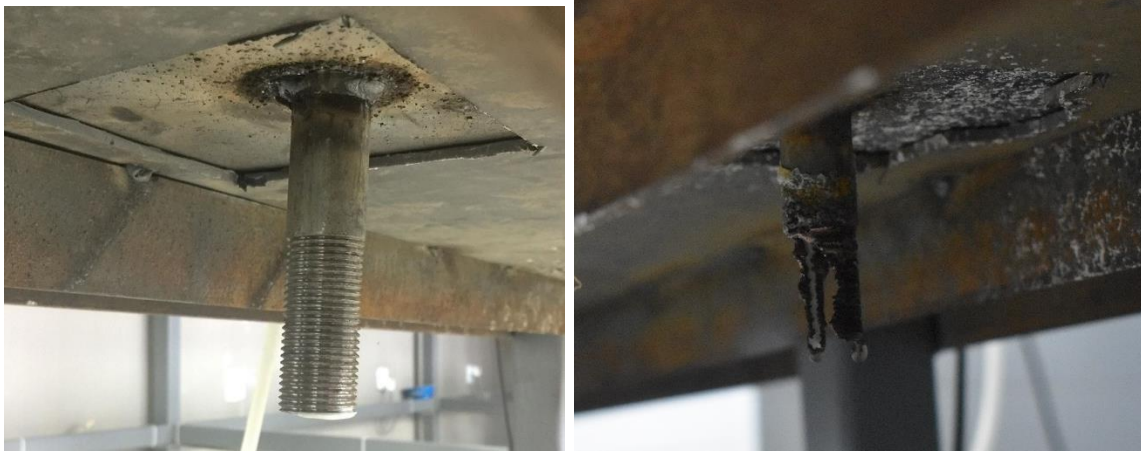


Figure 23: The bottom of leaching before and end of leaching experiment

4 Results and discussion

This chapter presents all physical observations during and after the experiments, as well as the results of tests.

4.1 Copper ore characterization

4.1.1 Chemical composition

The chemical analysis was carried out at Central Geological Laboratory of Mongolia and the following results were obtained. From the Table 9, 38mm size sieve passing ore (>19mm) has highest copper content and 19mm size sieve passing (>12.5) ore has least copper content.

Table 9: Erdenetiin-Ovoo deposit ore feed head grade assays

№	Sample (mm)	(mg/kg)	Assays (%)			
		Cu	Σ Fe	Σ S	S _{sulfide}	S _{sulfate}
1	-38	1302	-	0.98	0.33	0.65
2	+19	1518	2.42	-	-	-
3	+12.5	1059	2.22	-	-	-
4	+8	1252	2.38	-	-	-
5	-8	1484	2.69	-	-	-

4.1.2 Particle size distribution

Totally two sieving experiment have done. First particle size distribution completed with -38mm crushed ore feed with sieve sizes of 19mm, 12.5mm and 8mm. The particle size distribution curve is shown in Figure 27. The product size is usually quoted in terms of one point on the cumulative undersize curve, this often being the 80% passing size. However, the maximum cumulative percent undersize was 56.98%. Therefore P50 determined as 16mm, 50% of the particles are smaller than 16mm and 50% are larger. The weight comparison of different fraction sizes after crushing -38mm shown in Figure 28. The majority of particles(42.8%) are belonged in +19mm size fraction. And 28.8% of total particles were in 8mm size fraction. The rest of ~28% of particles are divided nearly equal into +12.5mm and +8mm fraction sizes.

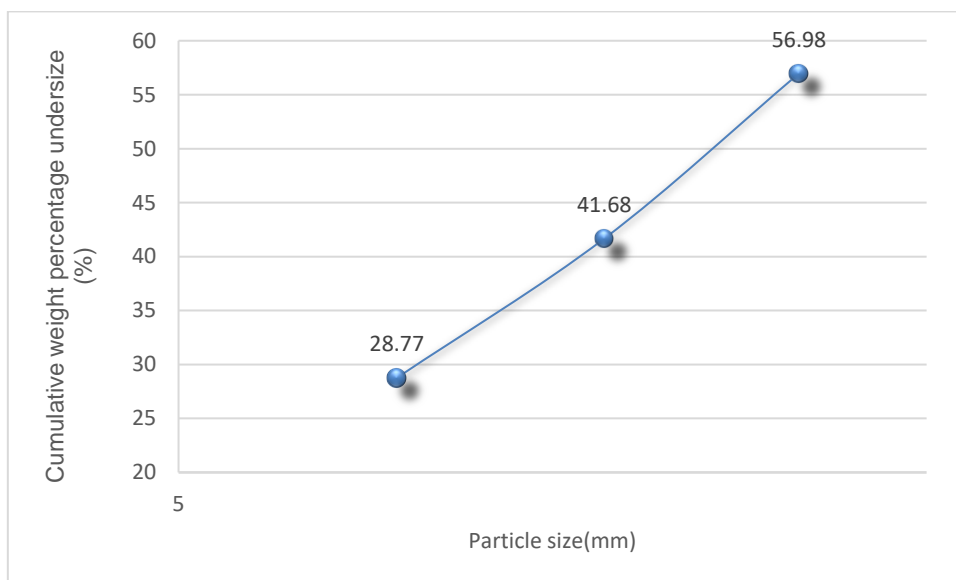


Figure 24: Particle size distribution of feed ore after crushing -38mm.

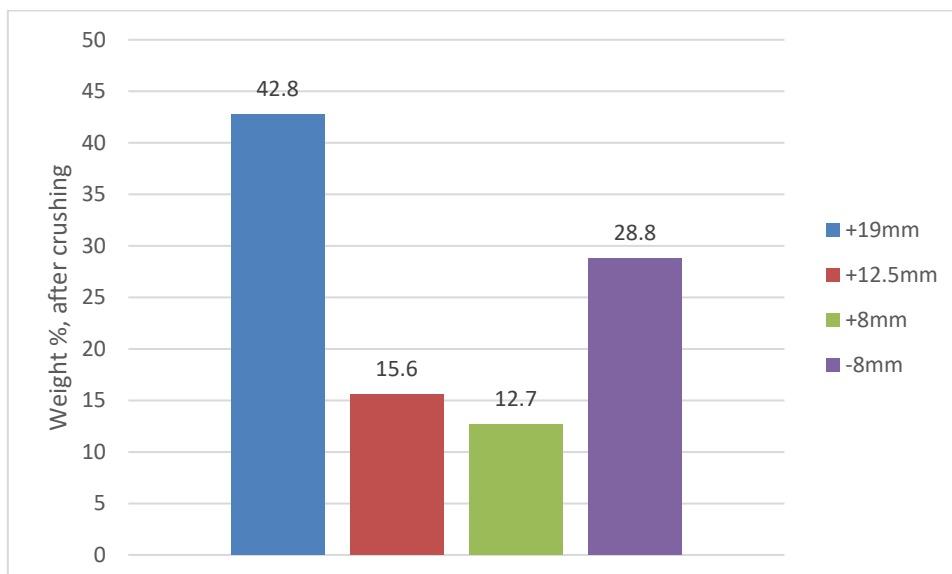


Figure 25: Weight % of feed ore after crushing -38mm

The second particle size distribution of the ore was done to determine the need for the agglomeration stage prior to agglomeration. The figure 29 shows, the particle size distribution curve for 8mm size sieve passing ore. The P25 of curve calculated as 672mm that refers to 25% of 8mm sieve size passing ore particle are less than 672mm size.

If the composition of fines of 74 μm is greater than 15 % of the ore composition, agglomeration of the ore before heap leaching is imperative. 74 μm sieve was not able in processing laboratory, however 63 μm size sieve used for determination of fines. From the figure 30, 66.51% of total particles were in +1mm fraction size and only 0.26% of 8mm size sieve passing ore was passed 63 μm sieve. Also, 2.75% was passing 125mm sieve size indicating that ore has less fine particles. Therefore agglomeration of the ore before heap leaching was not necessary.

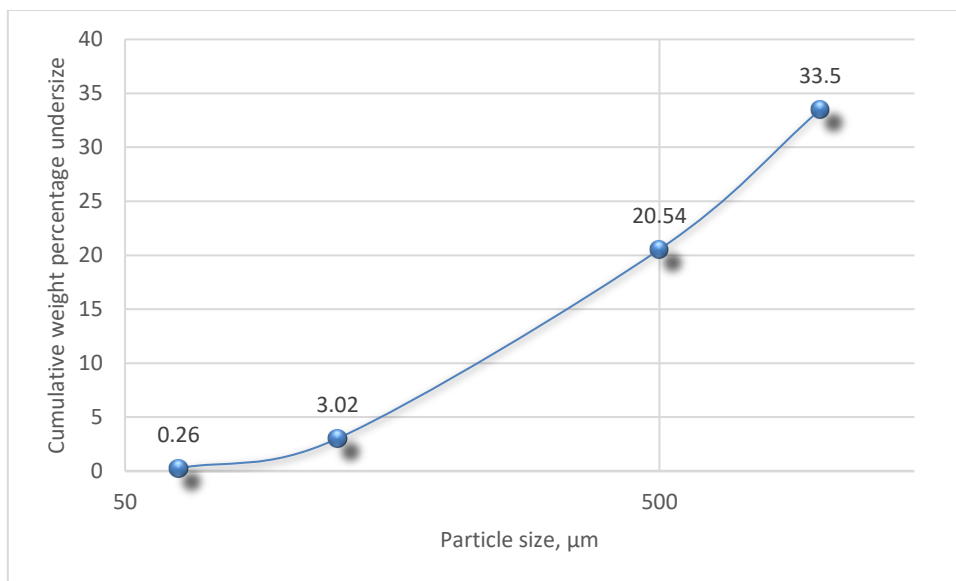


Figure 26: Particle size distribution of 8mm size sieve passing ore

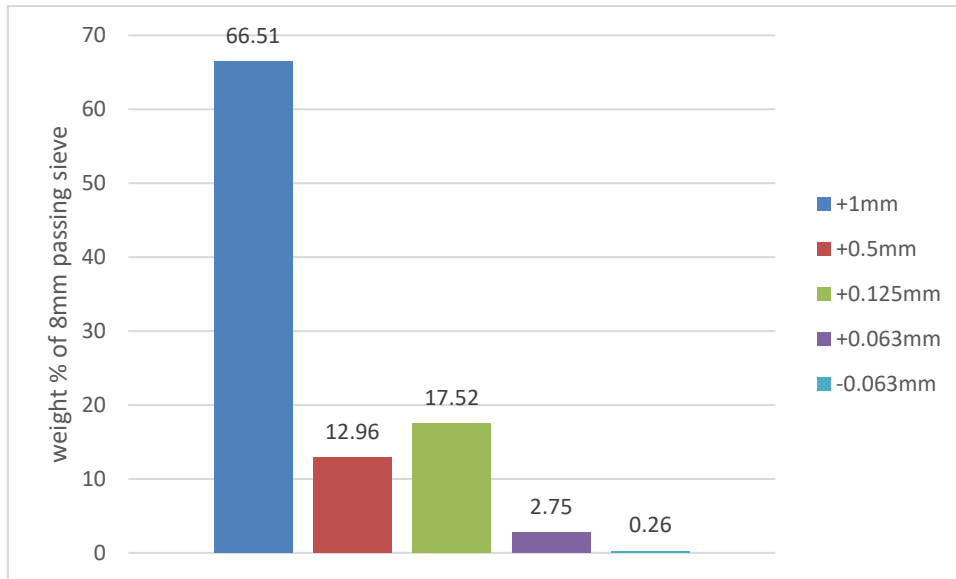


Figure 27: Weight % of 8mm size sieve passing ore

4.2 Results of leaching experiment

A column leaching test was designed to identify the influence of fraction size, leaching time, acid curing and bed height for copper concentration in pregnant leach solution using the copper oxide ore sample obtained from Achit-Ikht LLC. For all the column leaching tests carried out, the lixiviant flow rate was fixed at 3L/hr.

4.2.1 Influence of feed size for copper recovery

The particle size leaching efficiency test was carried in order to find the feed size that produce the highest leaching efficiency. The feed material was analysed for the copper contained before leaching and the copper contained after leaching at the targeted feed sizes (19 mm, 12.5 mm, 8 mm and mixed fraction). The highest copper concentration was observed at –8mm and mixed fraction size, the copper concentration decreased as the particle size increased. Fine particle size exposes the mineral to leach solution. However, in heap leaching fine particle size attracts permeability problems to the bed which will in turn lead to poor copper leaching efficiencies. From the results obtained, mix fraction was taken to be the optimum particle size.

There were totally three experiments on leaching. The first experiment was remained during 12 days with six leaching column. As shown in figure 31, the columns were filled with +19mm, +12.5mm, +8mm, mixed fraction and two times -8mm.

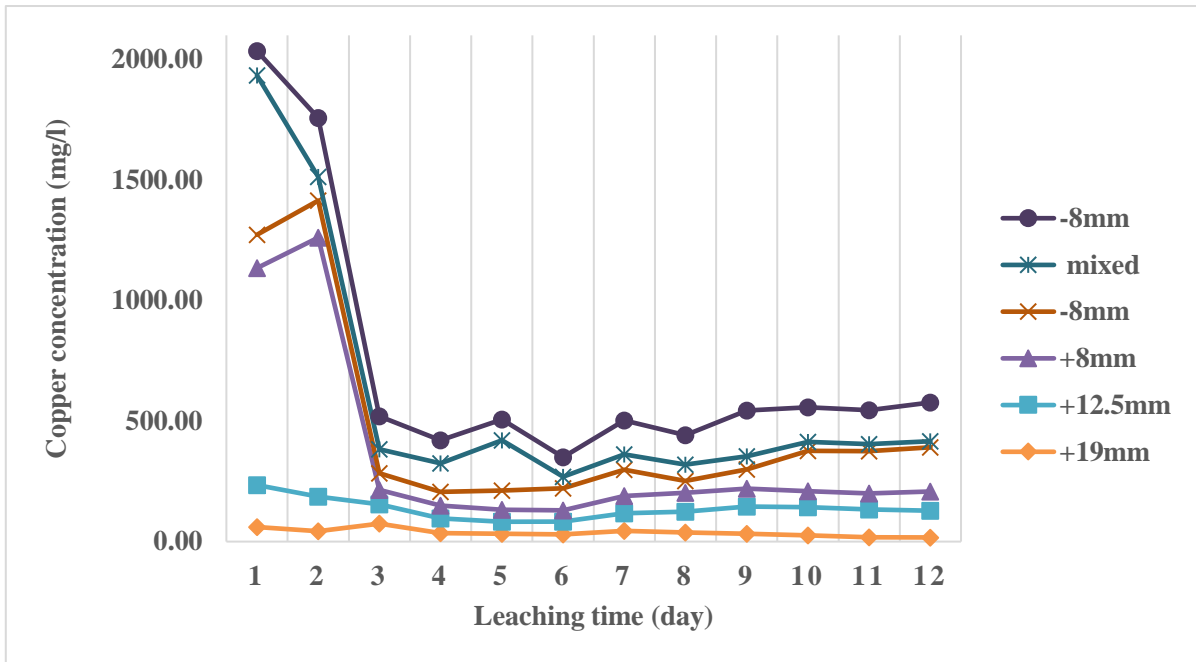


Figure 28: Effect of particle size for copper concentration

The highest copper concentration was observed at -8mm and mixed fraction sizes, 400-550mg/l of copper dissolved in twelve days. And the lowest copper extraction detected at +19mm size fraction, ~20mg/l copper dissolved in same leaching time. The fine size fractions' (+8mm,-8mm and mixed) copper concentration in pregnant leach solution dropped steeply in first three days of leaching, from 1200-2000mg/l to ~500g/l. Then the leaching rate was fluctuating slightly until 9th day of leaching. From the 9th day of leaching, the most of fractions' copper concentration are started to remaining constant. The coarser particle size fractions (+19mm and 12.5mm) leaching rate was steadily during leaching period. In copper head assay analysis, the -8mm fraction size copper concentration was lower than +19mm fraction. However, this did not have influence for result of leaching. The reason for the highest copper concentration is the -8mm particle size ore's minerals and metals have liberated and to get rid of the ore body compared with other fractions. The better liberation resulted the best copper recovery, but the leach solution was not able to flow along the ore due to low permeability of ore. This resulted that -8mm size fraction is not suitable for heap leaching of ore.

The +19mm size fraction's lowest copper recovery is due to mineral liberation as well. The +19mm and +12.5mm size fractions' particles are least liberated and permeability of ore was maximum. This concluded that only best permeability or only small grain size is not enough for good leaching result. But the mix fraction is the combination of

good permeability and perfect liberated grain size and it resulted high copper concentration.

Compared with experiment 1, the overall copper concentration of all fractions is low, around 20-500mg/l. This result associated with less acid addition during experiment.

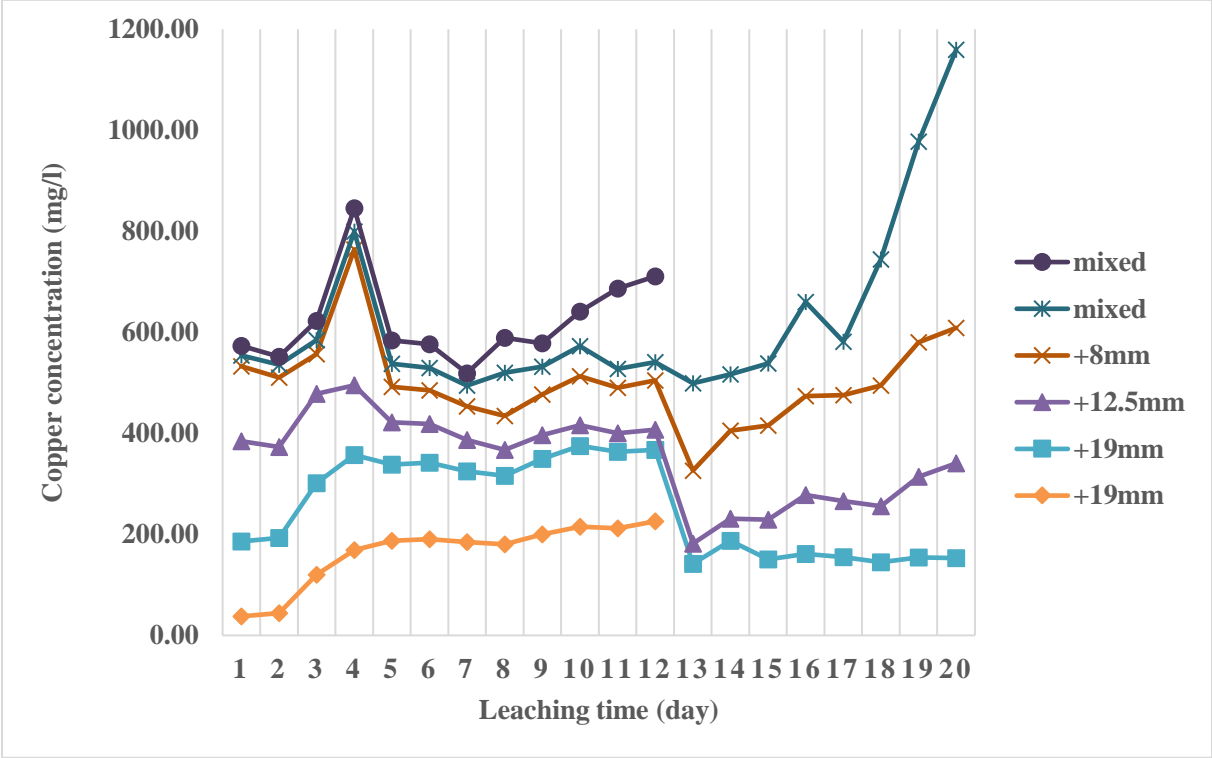


Figure 29: Effect of leaching time for copper concentration

In Figure 31, the effect of particle size and leaching time for copper concentration shown. The experiment has started with six fractions sizes such as two of +19mm, +12.5mm, +8mm and two of mixed fractions. The -8mm size fraction did not attended for second experiment since it is not suitable for heap leaching.

Matching with first experiment, the mixed fractions showed the high copper concentration result. But the sudden rise of leaching rate was not noticed in first days of leaching. The difference between 12 days and 20 days for copper concentration was massive, especially on mixed and +8mm fractions. For example, the mixed fraction copper concentration after 12 days was 36mg/l and after 20 days was 551mg.l/ the mixed fractions' copper concentration expected to increase more in longer period of leaching.

In Figure 33, the third experiment results are obtained. The third experiment has started with only two fraction sizes such as +8mm and +12.5mm. The +8mm size fraction resulted much higher copper concentration. The +8mm size fraction

permeability and leach solution flowing speed greater because of the column height was not reached 1m, it was 0.58m. The fresh acid solution ore and more copper could dissolve. The column that filled +12.5mm ore was reached 1m of column height. Nevertheless, the +12.5mm ore had acid curing before the leaching and most of oxidised copper ore copper dissolved in high concentration acid before leaching.

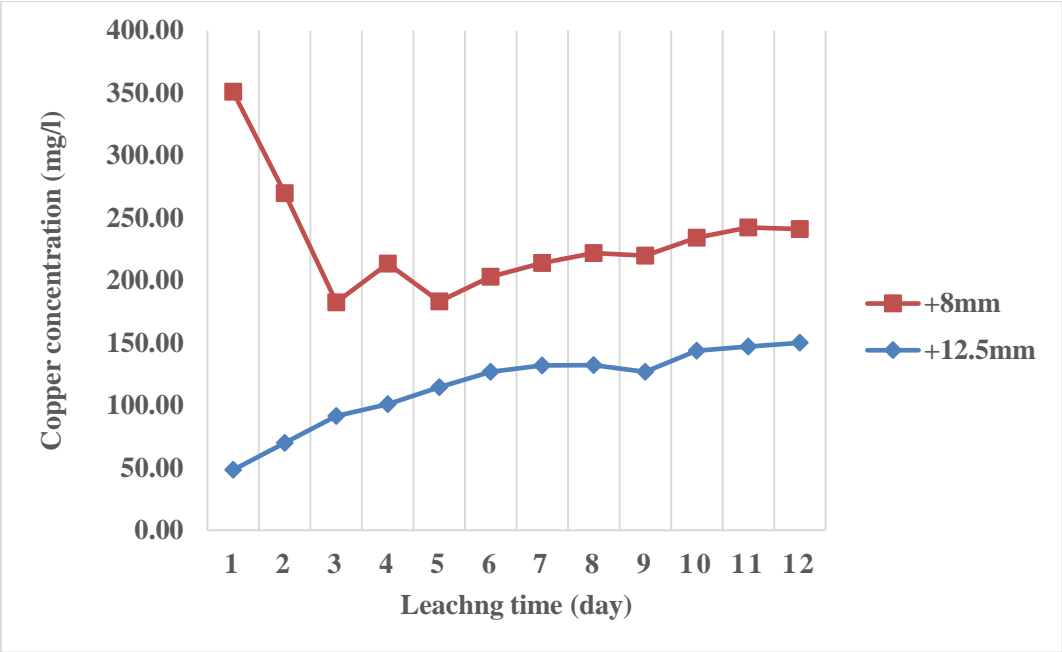


Figure 30: Effect of acid curing for copper concentration

4.2.2 Influence of leaching time for copper recovery

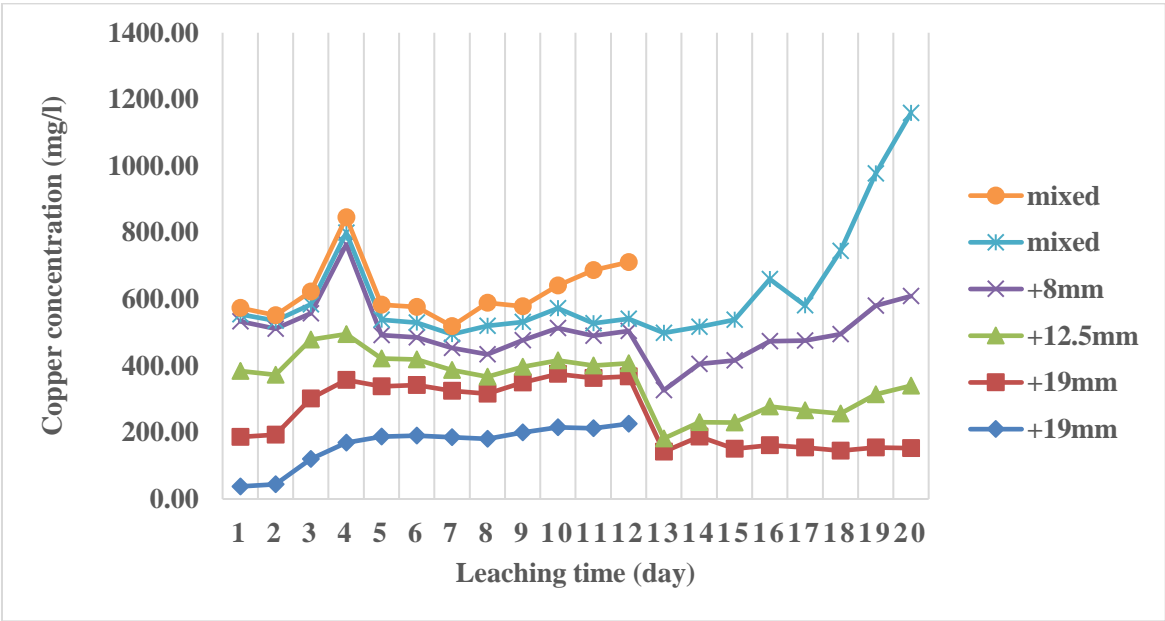


Figure 34: Effect of leaching time for copper concentration

4.2.3 Influence of acid curing for copper recovery

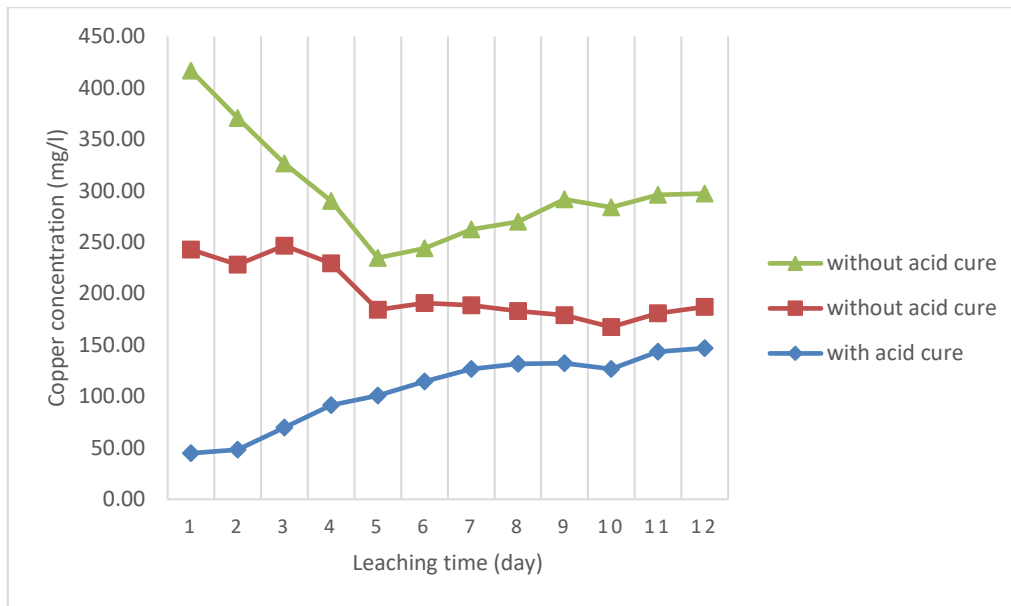


Figure 35: Effect of acid curing for copper concentration

4.2.4 Influence of bed height for copper recovery

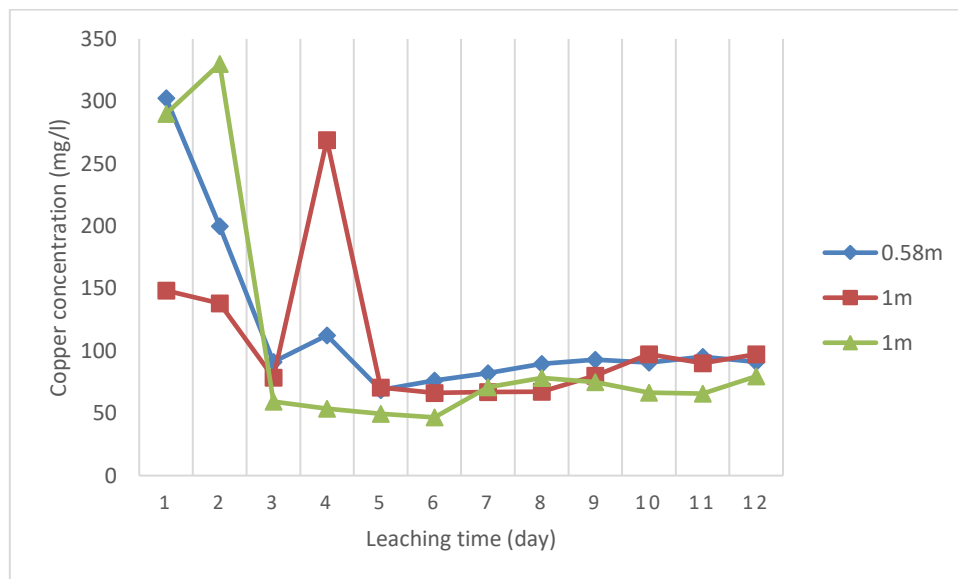


Figure 36: Effect of bed height for copper concentration in PLS

The heap height and copper extraction % have an inverse relationship, but Cu in PLS and heap height are proportional. Figure 34 shows, the influence of heap height for copper concentration in PLS. All three columns of experiment filled by +8mm particle size ore. After four days of leaching, the overall rate of leaching has stabilised. The peak copper concentration of ~350mg/l was recorded at a bed height of 1 m after leaching in first two days. There is no significant difference between three column

results. But the overall leaching rate of 0.58m ore was more constant. A lower heap height can produce better overall copper leaching efficiency, to suffer permeability problems from compaction at the base of the heap. But this experiment heaps' height difference could be not enough to see the effect.

Analysis for feed and leach residue

Particle size (mm)	Feed		Leach residue	
	Cu, (mg/kg)	Fe, %	Cu, mg/kg	Fe, %
-38+19	1518	2.42	959	
-19+12.5	1059	2.22	1052	2.03
-12.5+8	1252	2.38	1037	2.16
-8	1484	2.69	-	-
Mix	-	-	1415	2.24

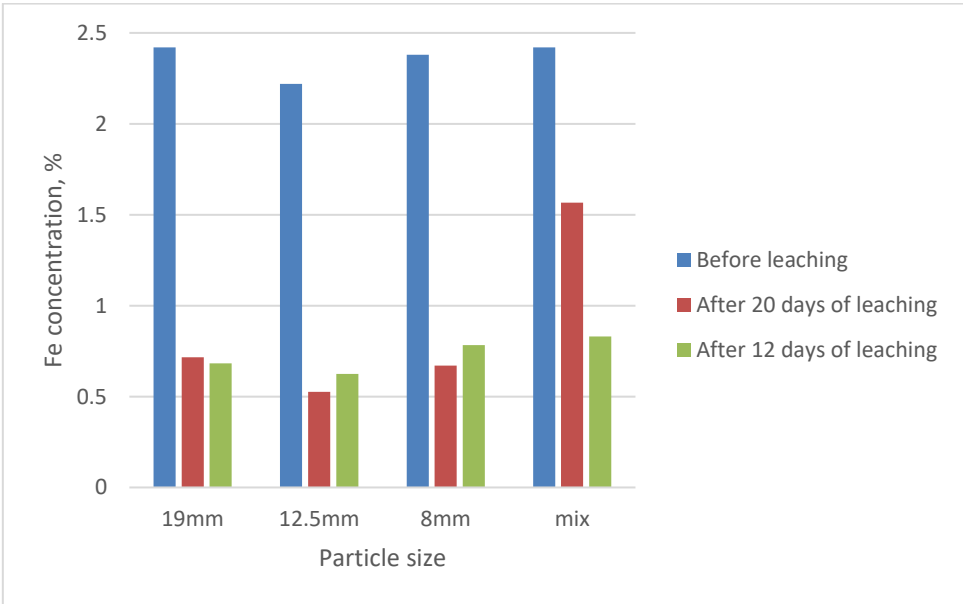


Figure 37: Fe dissolution into pregnant leach solution before and after leaching

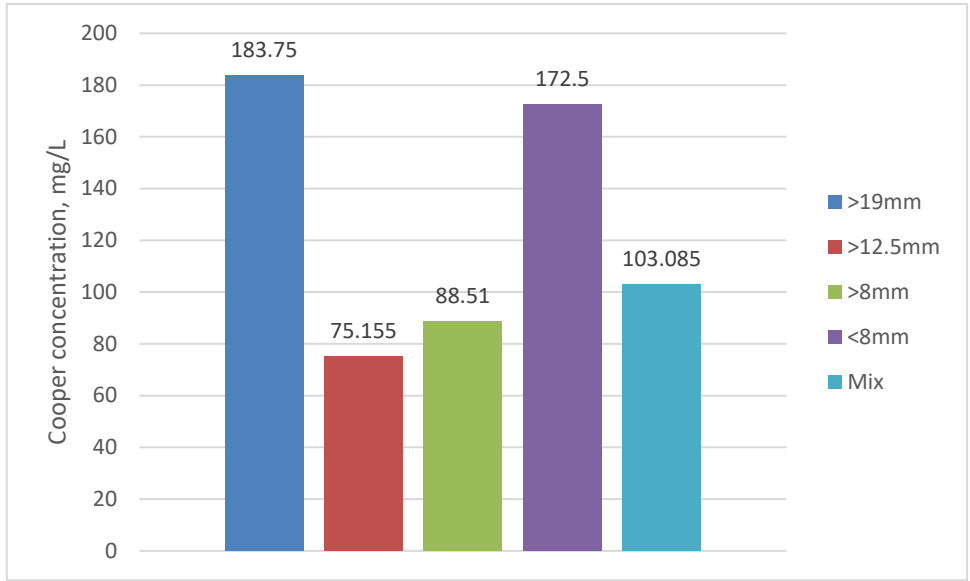


Figure 38: Average Cu concentration after 12 days

5 Conclusion and Recommendation

The leaching experiments completed during 32 days.

As shown in figure 39, the mixed fraction has resulted the highest copper concentration in pregnant leaching solution in twenty days.

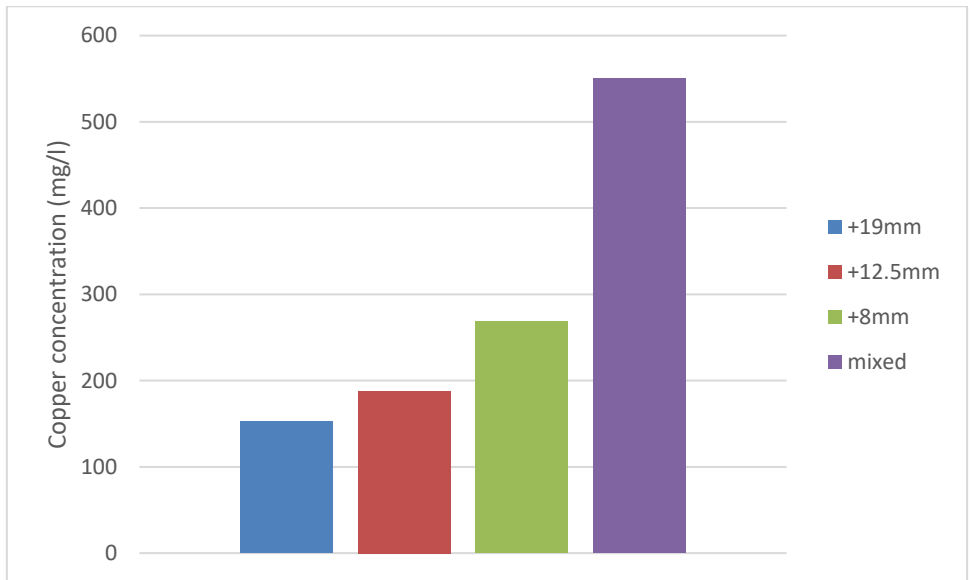


Figure 39: Copper concentration in pregnant leach solution after 20 days

The safety



6 References

1. Barriga Vilca A. Studies on the curing and leaching kinetics of mixed copper ores [Internet]. University of British Columbia; 2013 [cited 2018 Jun 12]. Available from: <https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0073850>
2. Achit-Ikht LLC website [Internet]. [cited 2018 Aug 9]. Available from: <http://achit-ikht.mn/2016/>
3. Mineralogy analysis result Achit-Ikht LLC [Internet]. [cited 2018 Aug 9]. Available from: <https://mail.google.com/mail/u/0/#inbox/164ac7a69d34f6fd?projector=1&messagePartId=0.1>
4. Copper. In: Wikipedia [Internet]. 2018 [cited 2018 Jul 25]. Available from: <https://en.wikipedia.org/w/index.php?title=Copper&oldid=851841336>
5. Leaching of low-grade copper ores: A case... (PDF Download Available) [Internet]. [cited 2018 Jun 12]. Available from: https://www.researchgate.net/publication/311916426_Leaching_of_low-grade_copper_ores_A_case_study_for_'Kraku_Bugaresku-Cementacija'_deposits_Eastern_Serbia
6. Hey L. Electrokinetic Applications in Hydrometallurgical Copper Extraction. :106.
7. Kordosky GA. Copper recovery using leach/solvent extraction/electrowinning technology: Forty years of innovation, 2.2 million tonnes of copper annually. Solvent Extr. 2002;6.
8. Hydrometallurgy lectures [Internet]. [cited 2018 Jun 12]. Available from: <https://www.dropbox.com/home/Hydrometallurgy?preview=hydro+copper.pdf>
9. Ghasemzadeh H, Sanaye Pasand M, Mollanouri Shamsi MM. Experimental study of sulfuric acid effects on hydro-mechanical properties of oxide copper heap soils. Miner Eng. 2018 Mar 1;117:100–7.

10. Manning TJ, Kappes DW. Chapter 25 - Heap Leaching of Gold and Silver Ores. In: Adams MD, editor. Gold Ore Processing (Second Edition) [Internet]. Elsevier; 2016 [cited 2018 Jun 12]. p. 413–28. Available from: <https://www.sciencedirect.com/science/article/pii/B9780444636584000256>
11. Large particle effects in chemical/biochemical heap leach processes – A review - ScienceDirect [Internet]. [cited 2018 Jun 12]. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S0892687511001178>
12. Takunda Joseph Mhandu. A HEAP LEACH FEASIBILITY STUDY FOR MIMBULA REFRACTORY COPPER ORE OF NCHANGA MINE. 2017.
13. Lu J, Dreisinger D, West-Sells P. Acid curing and agglomeration for heap leaching. Hydrometallurgy. 2017 Jan 1;167:30–5.
14. Mongolian-American joint Erdmen LLC. Leaching-Solvent Extraction-Electrowinning. In 2007.
15. Kodali P. Pretreatment of copper ore prior to heap leaching. :133.
16. Study of parameters affecting on copper... (PDF Download Available) [Internet]. [cited 2018 Jun 12]. Available from: https://www.researchgate.net/publication/299507252_Study_of_parameters_affecting_on_copper_recovery_from_oxide_ores_by_column_leaching_using_Artificial_Neural_Network
17. Petersen J. Heap leaching as a key technology for recovery of values from low-grade ores – A brief overview. Hydrometallurgy. 2015 Sep 1;165.

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Table 10: Erdenetiin-Ovoo deposit feed ore particle size distribution

Sieve size range(mm)	Sieve fractions		Nominal aperture size	Cumulative%	
	Wt(kg)	Wt%		undersize	oversize
+19	90	43.02	19	56.98	43.02
-19+12.5	32	15.3	12.5	41.68	58.32
-12.5+8	27	12.91	8	28.77	71.23
-8	60.2	28.77			
Total	209.2	100%			

Table 11: 8mm size sieve passing ore particle size distribution

Sieve size range(µm)	Sieve fractions		Nominal aperture size	Cumulative%	
	Wt(g)	Wt%		undersize	oversize
+1000	8127.5	66.5	1000	33.5	66.5
-1000+500	1584.3	12.96	500	20.54	79.46
-500+125	2141.5	17.53	125	3.02	96.98
-125+63	336.1	2.75	63	0.26	99.74
-63	31.9	0.26			

Total	12221.1	100			
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Table 12: Experiment №1, copper concentration result data

Days	Column №1	Column №2	Column №3	Column №4	Column №5	Column №6
	19mm	12.5mm	8mm	<8mm	Mix	<8
	(mg/L)					
1	60.53	174	900	138	661	101
2	43.30	143	1075	154	98.34	244
3	74.52	80	59.36	69.60	100	137
4	35.12	60.66	53.75	56.72	119	95
5	31.97	50.40	49.58	80.07	208	87.31
6	30.17	52.92	46.63	91.37	48.04	81.20
7	44.48	73.55	70.86	110	62.91	141
8	37.79	86.83	78.24	48.91	67.26	123
9	32.76	113	74.86	79.87	54.29	189
10	25.88	117	66.39	167	37.58	143
11	18.35	115	65.65	176	29.04	141
12	17.28	110	79.69	184	25.31	161

Table 13: Experiment №2, copper concentration result data

Days	Column №1	Column №2	Column №3	Column №4	Column №5	Column №6
	19mm	19mm	12.5mm	8mm	Mix	Mix
	(mg/L)					
1	37.73	149	198	148	21.48	19.13
2	43.99	149	180	138	25	15.91
3	120	182	177	78.53	27.56	37.89
4	169	188	138	269	35.38	46.19
5	187	151	83.38	70.63	45.83	45.80
6	190	152	76.43	66.30	44.79	46.59
7	185	140	62	66.9	40.81	24.51

8	181	135	51.21	67.31	85.71	69.08
9	200	150	46.84	80.15	55.08	46.79
10	215	160	40.67	97.25	59.56	68.44
11	212	151	37.20	89.99	37.48	159
12	226	142	40.01	97.33	36.17	170
13	~	142	40	145	173	~
14	~	187	43.85	174	112	~
15	~	151	78.59	187	123	~
16	~	161	117	196	186	~
17	~	155	111	210	106	~
18	~	145	111	239	250	~
19	~	154	160	266	397	~
20	~	153	188	268	551	~

Table 14: Experiment №3, copper concentration result data

Days	Column№4	Column№2
	12.5mm	8mm
	(mg/L)	
Acid cure	379	~
1	44.84	303
2	48.32	200
3	69.83	91.02
4	91.46	113
5	101	68.64
6	115	76.15
7	127	82.07
8	132	89.60
9	132	92.94
10	127	90.55
11	144	95.24
12	147	91
13	~	87.95

14	~	109.00
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Table 15: Copper concentration of >12.5mm of ore with and without acid cure before leaching

Days	12.5mm		
	with acid cure	without acid cure	without acid cure
1	44.84	198	174
2	48.32	180	143
3	69.83	177	80
4	91.46	138	60.66
5	101	83.38	50.40
6	115	76.43	52.92
7	127	62	73.55
8	132	51.21	86.83
9	132	46.84	113
10	127	40.67	117
11	144	37.20	115
12	147	40.01	110

Table 16: Copper concentration of >8mm ore in different bed heights

Days	8mm		
	0.58m	1m	1m
	(mg/L)		
1	303	148	900
2	200	138	1075
3	91.02	78.53	59.36
4	113	269	53.75
5	68.64	70.63	49.58
6	76.15	66.30	46.63
7	82.07	66.9	70.86
8	89.60	67.31	78.24
9	92.94	80.15	74.86

10	90.55	97.25	66.39
11	95.24	89.99	65.65
12	91	97.33	79.69

Table 17: Fe% in ore before and after certain times of leaching

Particle size	Initial Fe% in feed	Fe% after 12 days	Fe% after 20 days
19mm	2.42	0.68	0.72
12.5mm	2.22	0.63	0.53
8mm	2.38	0.78	0.67
Mix	2.42	0.83	1.57