GERMAN - MONGOLIAN INSTITUTE
FOR RESOURCES AND TECHNOLOGY

The present work was submitted to the Faculty of Engineering

Reprocessing of tailing from Erdenet mine: Optimization of the P80 grind size for the flotation

Bachelor Thesis

by

Dugar Davaajargal

Supervisor 1	**Prof. Dr. Battsengel Baatar**
Supervisor 2	**MSc. Munkhjargal Chimeddorj**
Advisor	**Dr. Narangarav Terbish**

Ulaanbaatar, 05/22/2022

Statutory Declaration

Davaajargal, Dugar	153569008599
Last Name, First Name	Student ID Number

I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

Reprocessing of tailing from Erdenet mine: Optimization of the P80 grind size for the flotation

I did not use any sources other than those stated. In case the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

Ulaanbaatar, Mongolia
2022.05.22
Place, Date

Signature

Abstract

This thesis paper is carried out as an extended part of the “Adriana” project. The study of the possibility of reprocessing the tailings from Erdenet copper and molybdenum mining company by the mechanical flotation process is investigated. Regarding the historical data of the EMC LLC, the copper content in the tailing was above 0.1% due to operational activity and lack of technology in previous years.

Within this thesis work, grinding times for the P80 grind sizes of 75, 54 and 38 µm are determined. Also, flotation tests on these various sizes with an initial F80 feed size of 122 µm are carried out. From the experimental work, the optimal P80 grind size for flotation is identified as 54 µm with a recovery of 36.97% and a grade of 1.18%. Sustainable development could be achieved in a self-financing way by reprocessing tailings.

For further research work on reprocessing the tailings from EMC LLC, this study work will be helpful to a certain extent, and more studies on operational and technological advancement are needed.

Acknowledgment

I am very thankful to my supervisors, Prof. Dr. Battsengel and MSc. Munkhjargal who guided me throughout my thesis work also gave me the wonderful opportunity to be a part of the “Adriana” project which is related to my thesis work. Throughout the project, I learned so many things, and a lot of opportunities were given to me, for which I am grateful.

My next thanks go to Mr. Baasandorj, the process laboratory assistant; Ms. Narangarav, the project coordinator and advisor; and Ms. Ankhchimeg, a member of my project team. With their help and motivation, I have done my thesis work without any hardship.

I am also honored to be a part of the German-Mongolian Institute for Technology as a raw material and processing engineer. This was a great chance for me to develop myself as a good engineer with the help of my classmates, professors and staff who motivated, supported as well as believed in me. Without their existence, I would not have come here. That’s why I would like to express my utmost gratitude to them.

Last but not least, I am very thankful to my friends and family members who got my back in hard times and kept inspiring me that I could be a better version of myself.

List of figures

List of tables

Table of Contents

1 Introduction

Adriana project which consists of partners such as GEOS Ingenieurgesellschaft mbH, GMIT, Dimap-Spectral GmbH,Martin-Luther University Halle-Wittenberg, EMC and EiT. The task of GMIT is to determine the possibility of reprocessing tailing from Erdenet mining. (1)

The Adriana project focuses on airborne remote sensing of copper tailing. The project aims to investigate how innovative methods of remote sensing can contribute to exploration of the recycling potential of tailings and comparable anthropogenic deposits also to what extent these methods complement conventional exploration and reservoir modeling methods. In order to determine the usable valuable potential of tailings deposits using examples of the copper tailings of Erdenet mine, innovative airborne remote sensing methods will be applied and results will be used for 3D resource modeling with existing historical operational data and conventional exploration results.

Moreover, treatment technology for copper tailings from Erdenet mine will be tested and developed in this study. In conclusion, the use of innovative methods is more effective and economical assessments will be faster and more effective.

1.1 Significance of copper

The demand for copper has been increasing over the years because of its significant properties such as excellent electrical as well as thermal conductivity, ductility, malleability and resistance to corrosion. Before the 20th century, copper was used for jewelry, utensils and weapons etc. But after mass adaptation to electricity, the demand for copper increased drastically (Figure 1). (2) The copper demand will increase in the future because the main usage of copper is for civilization which is guaranteed by technological advancement.

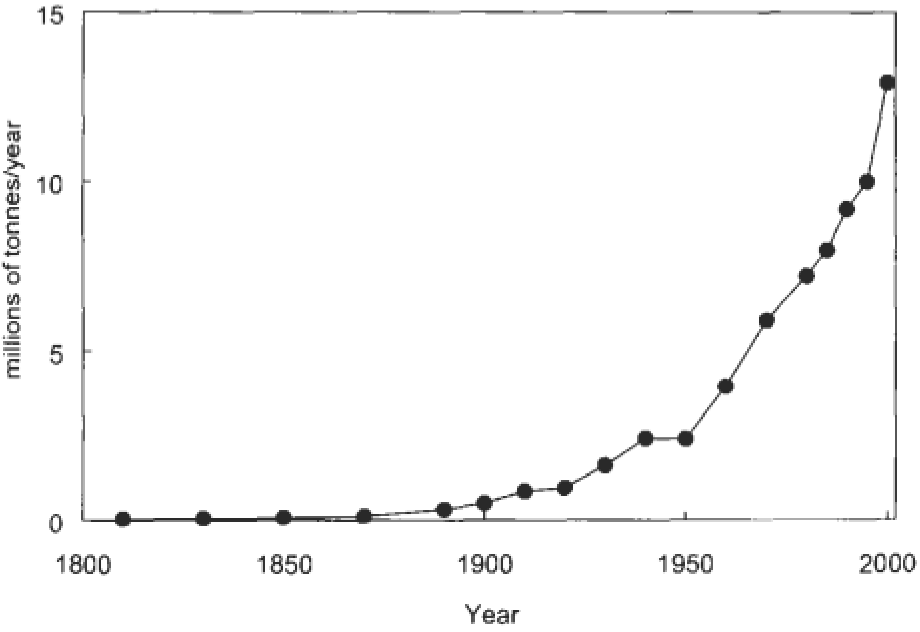


Figure 1: World mine production of copper in the 19th and 20th centuries

Because of the increase in humanity's population, conventional energy production from coal is causing so many greenhouse gas emissions, which is causing climate change. This change is directly related to natural disasters and it is harmful to the survival of natural species and humankind.

Therefore, the European Union came up with a climate target plan until 2030 by reducing the greenhouse gases by 55%. (3) To implement this new law, a lot of renewable energy systems need to be built for climate change mitigation. This renewable energy equipment requires plenty of materials, especially copper. (4) This ensures the increase in demand for copper products in the future which is a good opportunity for the Mongolian economy which is directly related to the export of products from the mine.

According to the mining ministry's reports for 2021, mining products accounted for 93.3% of total exports and 28.9% of the national budget.(5) Copper alone accounted for

63% of total mine tax. Based on this information, it can be said that Mongolia's main economic factors depend on copper mining and exporting. In (Figure 2) to (Figure 3), the trend of demand and price for copper are shown. (6, 7) The increasing trend can be seen in both figures. Hence to meet this requirement, more appropriate and sustainable mining operations and plans are needed.

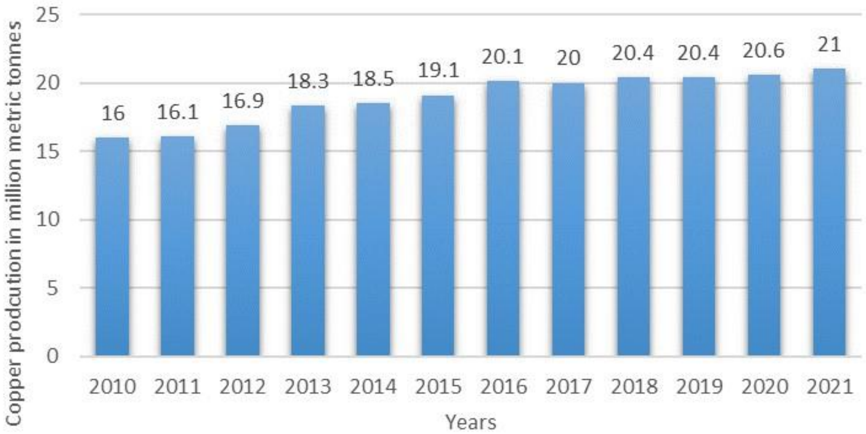


Figure 2: The copper production worldwide

Figure 3: The copper price for the last 5 years

1.2 Copper reserves

According to the U.S. Geological Survey in 2014, the global proven copper resource was about 2.1 billion tons and it was expected to increase to 3.5 billion tons due to exploration. (8) According to the U.S. Bureau of Resources survey in 2021, the global total reserves were 880 million tons.

From the copper reserve table (Figure 4) which shows the copper reserves by countries, Chile has the largest copper reserves of 200 million tons followed by Australia, Peru, Russia and Mexico etc.

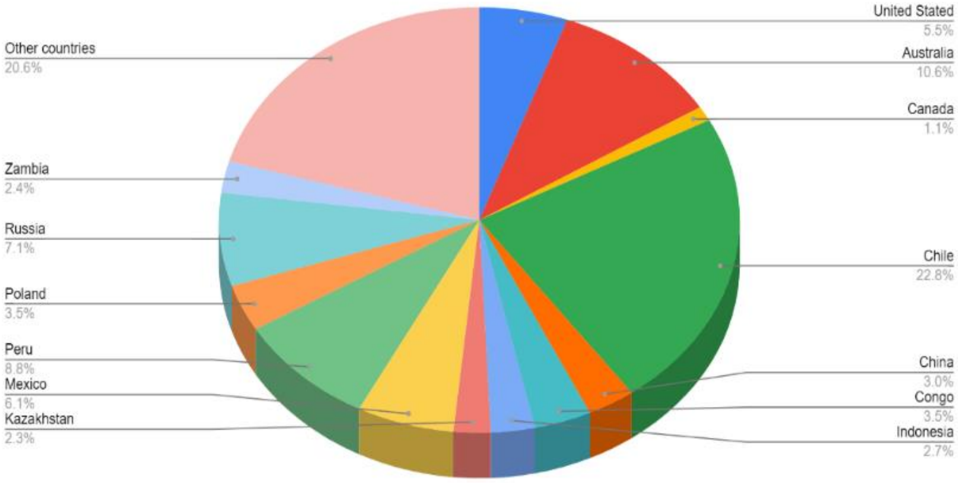


Figure 4: Copper reserves by country in 2021

Mongolian copper reserves are 57 million tons, according to the Ministry of Economy and Development. (9) Copper deposits include Oyu tolgoi's 37 million tons, Tsagaan suvarga's 10.6 million tons, and Erdenet's 1.2 billion tons, as shown in (Figure 5)

Figure 5: Mongolian reserves

1.3 Copper ore minerals

Copper ore with an average copper content of 0.4% is mined from open pits and average copper content down to 1% is mined from underground mines. The main copper mineral types include primary sulfide minerals, secondary sulfide minerals, native copper, carbonates, hydroxy-silicates, oxides and sulfates etc. (10) In (Table 1), the commercial copper minerals are shown. In ores, copper minerals occur at lower concentrations and the remaining minerals consist of oxide rock such as andesite or granite with small amounts of iron minerals.

Table 1: Commercial copper minerals

Principle commercial copper minerals			
Type	Common minerals	Chemical formulas	Theoritical Cu content (%)
Primary sulfide minerals			
Hypogene sulfides	Chalcopyrite	$CuFeS_2$	34.6
	Bornite	Cu_5FeS_4	63.3
Secondary sulfides			
Supergene sulfides	Chalcocite	Cu_2S	79.9
	Covellite	CuS	66.5
	Digenite	$Cu_{1.8}S$	78.1
Native copper	Metal	Cu	100
Carbonates	Malachite	$CuCO_3*Cu(OH)_2$	57.5
	Azurite	$(CuCo_3)_2*Cu(OH)_2$	55.3
Hydro-silicates	Chrysocolla	$CuO*SiO_2*2H_2O$	36.2
Oxides	Cuprite	Cu_2O	88.8
	Tenorite	CuO	79.9
Sulfates	Antlerite	$CuSO_4*2Cu(OH)_2$	53.7
	Brochantite	$CuSO_4*3Cu(OH)_2$	56.2

1.4 Objective of the study

1.4.1 General objective

The main purpose of this study is to investigate the real possibility of reprocessing the tailings from EMC LLC by the mechanical flotation process based on treating samples by size reduction and comparing results.

The simplest solution to tailings and overburden is reclamation by planting plants on surfaces. Instead of this method, a study of the tailings about its characteristics, historical data assessment and possibility of reprocessing methods should be conducted so that valuable minerals can be extracted from the waste materials. By doing this, the tailings will be recycled and reprocessed in a self-financing way. The increase in copper prices is also the reason why those valuable copper minerals in tailings are of interest.

1.4.2 Specific objective

- Determination of the grinding time on P80 grind sizes
- Determination of optimal P80 grind size for the froth flotation
- Compare flotation experiment results to determine the best flotation condition.

1.4.3 Expected outcomes

The expected outcomes from the thesis work include:

1. With sample preparation prior flotation by size reduction using rod mill, the gangue minerals and the valuable copper minerals will be separated and liberated. Flotation will be more efficient with reduced particle size.
2. After each size reduction, grades and recoveries will be increased.

2 Literature review

This section covers the necessary research works, books, websites, and materials for the context of this study. With descriptions and explanations of the literature review, the study work will be more understandable and easy to catch up with the concept.

2.1 Erdenet copper molebdenym mining

Erdenet is one of Mongolia's largest mining companies and is vital to the Mongolian economy. The Erdenet Mining Corporation was established in 1978 in accordance with an agreement between the governments of Mongolia and the former Soviet Union. The Erdenet mine annually produces 530,000 tons of copper concentrate and 4,300 tons of molybdenum concentrate. (11) Erdenet mine is located in the city of Erdenet, Orkhon province which is 340 km away from UB city and 140 km away from the Russian borderline. (12)

The Erdenet processing plant operates a complex two-phase Cu-Mo dressing process. The flowsheet (Figure 6) includes three sequential stages such as bulk concentration where Cu-Mo concentrate with Cu content of 15-17% and Mo content of 0.4-0.5% and final concentration stage where production of Cu-Mo concentrate containing copper content of not less than 23.5%, lastly molybdenum concentration with production of Mo content of not less than 47%. Middlings from rougher molybdenum flotation is copper concentrate. Because of the three-stage sequential process, there are three tailings where each content of Cu-Mo is different. (13)

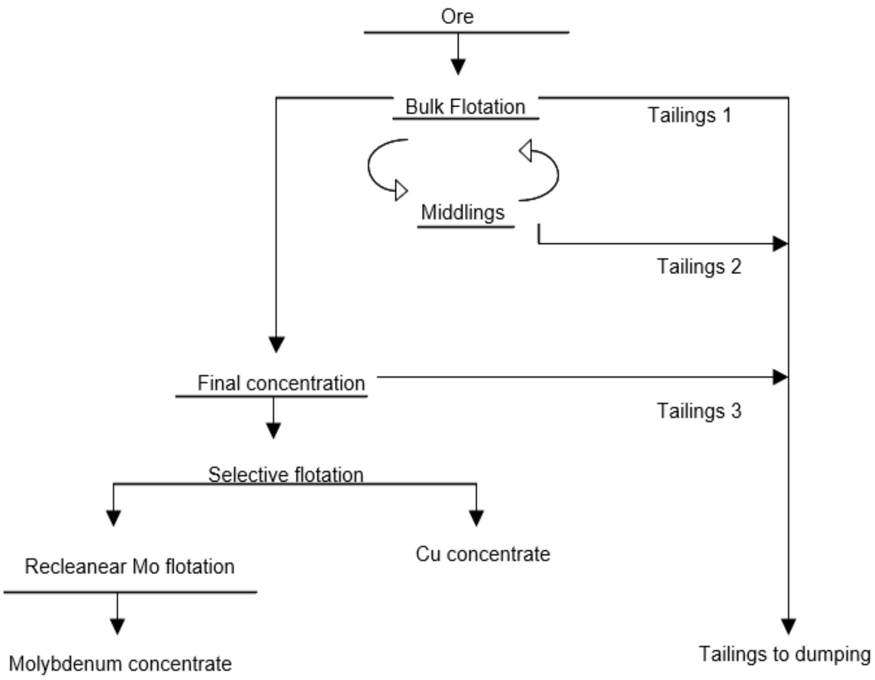


Figure 6: Flowsheet of Erdenet Mining Corporate

2.2 Tailing storage facility of Erdenet mine

The tailing storage facility of Erdenet which is part of the mining activity, was developed by a former Soviet design institute in mid-1970. The tailing storage facility was selected based on its geo-morphological advantage with an upstream embankment design using a nearby valley (Figure 7) and single a discharge point, meaning it is the most advantageous and cheapest option. (11)

Figure 7: Upstream embankment design with valley and surrounding mountains of Erdenet mine

Due to the height difference between the concentrator and the tailing storage facility, there is no need for a pump and the tailing which has a 30 to 70% solids to water slurry ratio that can be discharged with natural flow. A third-party engineering company (MechnaBor Engineering) is responsible for its maintenance, auditing and yearly construction planning and upgrading.

From the key technical specifications (Table.3), in 2015 the facility was in its middle of the depositional phase, but 7 years have passed since then, thus the capacity can be close to its designated capacity. The tailings from flotation are stored in a storage facility of Erdenet which has an overall area of 18.6 km^2 and a capacity of 1700 million m^3.

Table 2: Key specifications of the tailing storage facility at Erdenet mine in 2015

TSF operational specifications	Current status
Overall area	~18.6 km^2
Embankment area	1.4 km^2
Sand deposited area	13.73 km^2
Lake area	27 million meters^3
Contained water	3.48 km^2
Total sand volume	718 million meter^3
Design capacity	1700 million meter^3
Current embankment level	1300m RL
Design embankment level	1320m RL

The existing tailing storage facility design has many adverse effects on the environment such as white dust, excessive water loss, ground and surface water contamination, dam wall seepage and leachates etc. The Erdenet mine is located near the Erdenet city (Figure 8). That’s why the extreme pollutants from mining activity will be harmful to surrounding residents and animals. Also, the release of white dust into the air will cause degradation of the surface.

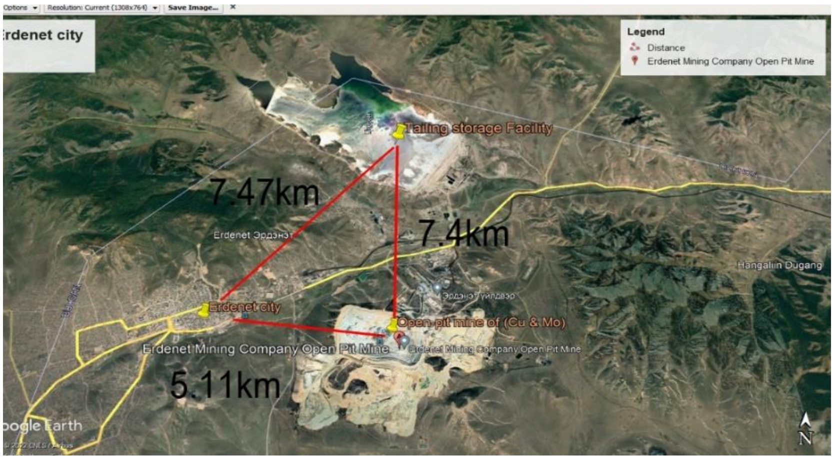


Figure 8: Distances between tailing to the city and open-pit mine

According to Erdenet’s process plant‘s historical data from 1978 to 2019, the total accumulated tailings is approximately 870 million tons and the metal copper in it is about 971 thousand tons which is large compared to the Bor flotation tailings with over 100 years of history in Siberia.

The head grade of Erdenetiin Ovoo copper and molybdenum deposit of Erdenet mine has decreased from about 0.9 to 0.48% (Figure 9). From this, it can be assumed that the exploitable copper ore is close to its end in the near future. Hence, geological research on new copper deposits should be done to extend the life-cycle of the mining activity.

Moreover, copper content in the tailing (Figure 10) has decreased from approximately 0.42 to 0.06% between 1978 and 2019. During these years, operational and technical aspects have improved and therefore, the recovery of copper has been kept despite the decrease in head grade of the ore. Also, in the beginning of mining activity, the copper content in tailings was quite high where for commercial importance, the typical copper ore contains a copper content of 0.3 to 2%. As a result, the tailings from the Erdenet mine can be expected to contain a certain amount of copper metals of interest that can satisfy the industry's copper demand for a limited time as a secondary reserve.

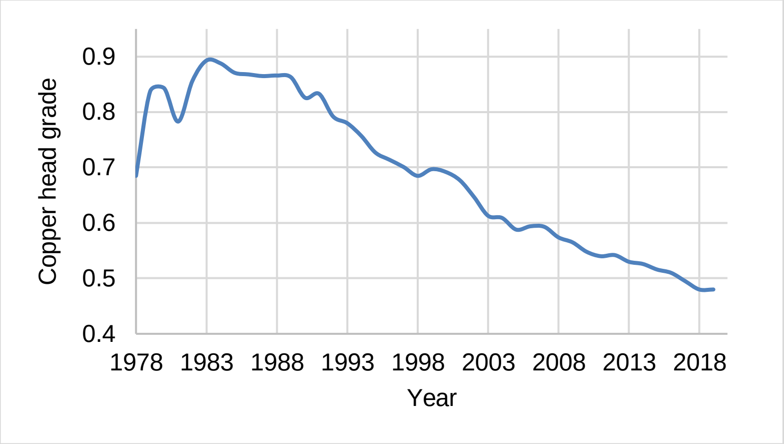


Figure 9: Historical data about Erdenet mine's copper head grade

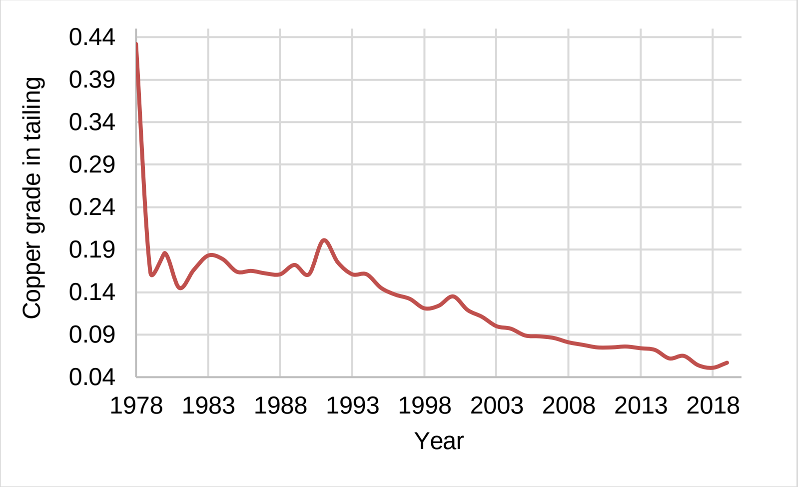


Figure 10: Historical data about Erdenet mine's copper grade in the tailings

2.3 Reprocessing of mine waste

Raw materials are crucial for modern ways of living where no new resources are explored but a lot of waste is produced from mining activities which is harmful to the environment. The increase in the price and demand of raw materials can be a good reason to focus on the waste from mines.

Mining waste is leftover material from exploration, mining and processing of substances according to legislation on mines. Based on the extraction method, the mining waste can be divided into different groups such as waste rocks, waste or tailings, slags etc. The old waste deposits can be considered as significant reserves for valuable metals because they were not exploited and economically recoverable metals may remain. But site documentation and applicable methods to recover these metals are not well defined. Also, the cut-off grade which economically differentiates the usable ore from low grade waste rock, may vary in the future regarding the improvement and advancement of more suitable technologies as well as methods. (14)

To mention the reprocessing of mine waste, such as from copper mine in Uganda, cobalt was recovered from pyrite waste using a bioleaching process in the 90s. (15) According to a study in 2005, lead was recovered from lead-zinc mining waste using a multi-gravity separator. (16) A nickel grade of 0.8% from a nickeliferous pyrrhotite focus study. (17) Biological recovery of nickel from tailings test work. (18) And last but not least, study of the recovery of Cu and Ag etc. (19)

To reprocess mining waste, research on identification and characterization, as well as modeling mining waste behavior, are critical for determining the potential for recycling and reuse. Also, innovation and improvement in the processing method for the recovery of metals in mining waste are needed.

2.4 Reuse of tailings as construction materials

The consumption of raw materials such as cement, gypsum, sand and stones is increasing due to infrastructure development. Sustainability in the future depends on environmental conservation and technological innovation and development. Therefore, the use of increasing mine waste which has accumulated over the years, as raw materials for construction materials, can be an alternative solution to the environment and sustainability.

Global mine operations produce 20-25 billion tons of solid waste and 5-7 billion tons of tailings every year. The disposal of tailings generally includes direct disposal in rivers, seas or in cells, confinement and dams in a slurry form containing 25-30% solids. Generally, copper tailings are rich in Si, Ca, Al, Mg, Fe and also have a certain amount of metals and metalloids such as Pb, As, Co, Cu, Zn, V, and Cr etc. Acid mine drainage can be caused by the sulfide minerals in tailings.

Based on its physical and chemical properties, tailing is suitable for the production of various engineering applications such as bricks, ceramics, aggregates, and cementitious binders etc. However, the problems associated with usage, revolve around heavy metal leaching and acid mine drainage. Moreover, the use of tailings as a civil engineering application extended to such as cemented backfill, soil stabilization, landfills and embankments etc.

The use of mine tailings as construction materials has the potential to not only reduce the demand on the existing natural resources as well as provide an effective and environmentally friendly way of disposal of mine tailings with caution of leaching of heavy metals and acid mine drainage. However, the risks can be minimized by treating tailings with alkali activation, hydration and chemical bonding. (20)

Figure 11: Furniture made of mine tailings in Portugal

2.5 Common oxide copper tailings reprocessing methods

The increase in copper demand and copper production leads to an increase in the discharge of copper tailings as well. The physical form of copper tailing is similar to sand but it has a more complex mineral composition that may contain certain amounts of valuable minerals that can’t be recovered by conventional processing methods.

The general copper tailings consist of minerals such as quartz, feldspar, calcspar, mica, copper pyrite, and pyrrhotite etc. And copper tailings have a large number of valuable elements such as Si, Ca, Al and Fe.

Copper tailings contain a certain number of valuable elements that can be reprocessed to satisfy the demand in current industrialization to a certain level which will require more suitable and innovative technologies. Different mineral processing methods are needed for different tailing characteristics and types. There are two types of common reprocessing methods for oxide copper tailings: vulcanization flotation and leaching. (21)

2.5.1 Vulcanization flotation of oxide copper tailings

The main principle of the vulcanization flotation process is to conduct flotation with a xanthate collector while sulfidizing ground ore with sodium sulfide which adsorbs HS- and S2- by forming a copper sulfide layer as cover. This allows the xanthate collector to adsorb on the surface of oxidized minerals as well as on sulfide minerals.

Due to the large amount of copper tailings, a lot of chemicals will be wasted because of the size using this processing method. Therefore, to avoid wasting chemicals and increase concentrate grade, pre-enrichment is important for discarding waste materials from valuable minerals.

The reprocessing of copper tailings by the vulcanization flotation method can be used for large scale oxide copper tailings to acquire high copper grade concentrates. Nevertheless it will require high technical operations as well as large investments.

2.5.2 Leaching oxide copper tailings

The copper tailings leaching process includes converting the solid phase of copper into a liquid phase and the extraction of copper from the solution. Based on which leaching agent is used, the leaching process can be divided into acid leaching, ammonia leaching, bacterial leaching and electrochemical leaching. The two common leaching methods for oxide copper tailings are described below:

1. Acid leaching: Using diluted sulfuric acid as a leaching reagent for processing oxide copper tailings which are mainly composed of acidic gangue, has the advantages of a high copper leaching rate and a low cost of leaching agent as well as simple operation. This method is suitable for simple copper oxide ore.
2. Ammonia leaching: This method is suitable for leaching copper tailings with higher alkaline gangue content and more silt where tailings can be reduced and roasted before leaching. The ammonia leaching method has high selectivity for metallic copper and alkaline gangue components but it will require high equipment and energy consumption.

2.6 Case study of reprocessing old copper flotation tailings waste of Serbia

According to the study, reprocessing old flotation copper tailings which are located near to Bor town, has been exploited for a hundred years and mining wastes including mining and flotation tailings, have accumulated to about 650 million tons containing 750 thousand tons of copper metal. (22)

The purpose of this study is to investigate the possibility of recycling Bor copper tailings which have negative effects on the environment. Instead of just simple reclamation, it recovers valuable minerals from waste materials by recycling. Therefore, it is an economically sufficient and environmentally friendly way of treating tailings.

The tailings consist of an average copper content of 0.3 %, gold 0.8 g/t, silver 2.4 g/ton and sulfur 12.7 %. The main reprocessing stages consist of excavation, repulping, attrition, bulk flotation and selective flotation. The new tailings will be returned to the closed open pit.

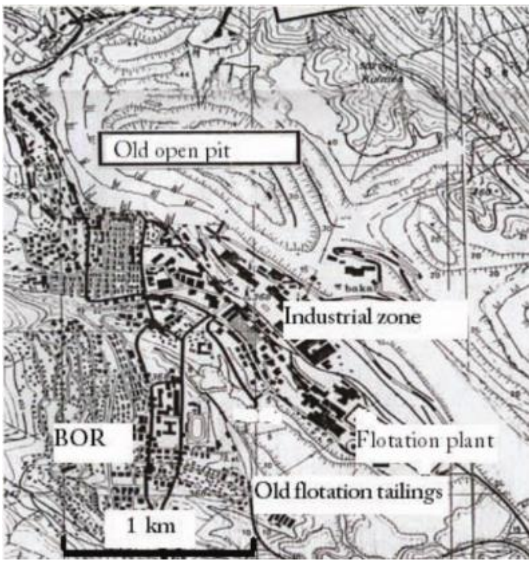


Figure 12: Distance between tailings and town

Sample characteristics consist of moisture content of 7.33 %, density of 2.92 $kg/m^{3,}$ pH 3.85, sulfide copper minerals of 0.41 %, oxidized copper minerals of 0.401 %. From the quantitative mineralogical investigation, the main copper minerals were chalcocite, cornite, covellite, chalcopyrite and enargite.

In the batch flotation test, the experiments were carried out with variable parameters such as pH, collectors and solid/liquid ratio etc. Sample preparations consisted of ball mill grinding, attrition in an attrition machine and without size reduction. Attrition of samples before flotation led to the best results which is cheaper than grinding and offers better bulk sulfide flotation. The best results were achieved by size reduction by attrition, collector PIBX (Potassium Isobutyl Xanthate), pH of 10 with copper recovery of over 97 %.

Within this study work, the real possibility of reprocessing of copper tailings is investigated. By reprocessing copper tailings, it gives solutions to ecological problems such as removing and recycling old tailings and the new desulfured tailings will fill the closed open pit, extending the life-cycle of the mine activity through employment etc.

2.7 Froth flotation of sulfide copper ores

For direct smelting of copper ore which typically has a copper content of 0.3-2%, is economically too low. Therefore, prior processing of copper sulfide ores by froth flotation to about copper content of 22-45% concentrate is important because heating and melting unprocessed ores will require large amounts of energy as well as furnace capacity. (23)

The basic principle of froth flotation is to adjust the surface of copper minerals using reagents such as collectors, frothers, modifiers, activators, depressants etc., from hydrophilic (water loving) to hydrophobic so that valuable minerals will be separated from gangue minerals by being adsorbed on the surface of the froth and then collected on the surface of the slurry. This process is important for the production of the copper industry.

2.7.1 Collectors

The collectors adjust the surface of copper minerals by attaching its heteropolar molecules where polar charged ends are connected to the mineral’s surface leaving nonpolar end as extention so that it becomes water repellent. Commercial collectors are usually blended with each other and per ton of ore feed about 10 to 50 g/t of collectors are used.

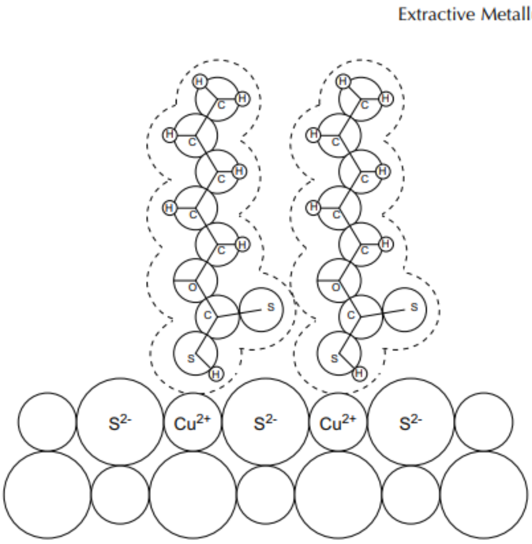


Figure 13: Sketch of amyl xanthate ions to covellite

2.7.2 Modifiers

Separation of sulfide minerals is a complicated process. Thus, by modifying the surface of non-copper sulfide minerals with OH- hydroxyl ions, these minerals will be depressed where collectors will be attached to only copper minerals, allowing them to float.

By adding lime, the concentration of hydroxyl ions is adjusted while varying the basicity of the slurry. An example of how floatability changes on sulfide minerals based on varying pH and collector dosage is shown in (Figure 14). From this, it can be observed that sulfide minerals such as pyrite and galena are depressed between pH values of 7.5 to 10.5 and only copper minerals will float.

Even though adding lime depresses other sulfide minerals, excess addition of depressing agents must be prevented due to its inclusive depressing of copper sulfide minerals.

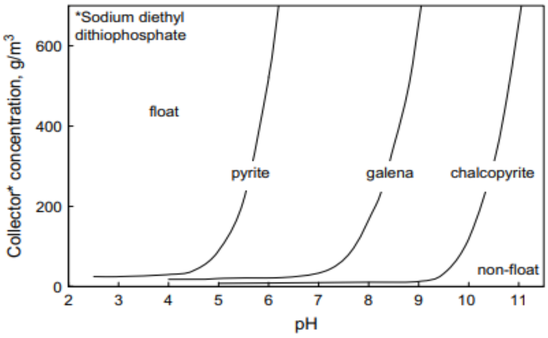


Figure 14: Effect of collector concentration and pH on the floatability

2.7.3 Frothers

The main purpose of frothers is to create strong but short-lived bubbles which could hold copper minerals on top of the cell and burst the moment they overflow the cell. Common frothers include branched chain alcohols such as natural pine oil, synthetic methyl isobutyl carbinol, polyglycols and other blends etc.

Froths are stabilized when the polar charge of the frother is absorbed in water, whereas the other non-polar branch forms a cross-linked network in air (Figure 15). In addition, the branched chain of nonpolar ends should not be too long to make the froth short lived. The surface area of the bubbles decreases as frothers are added, causing mineral particles to be attached to a more relative surface.

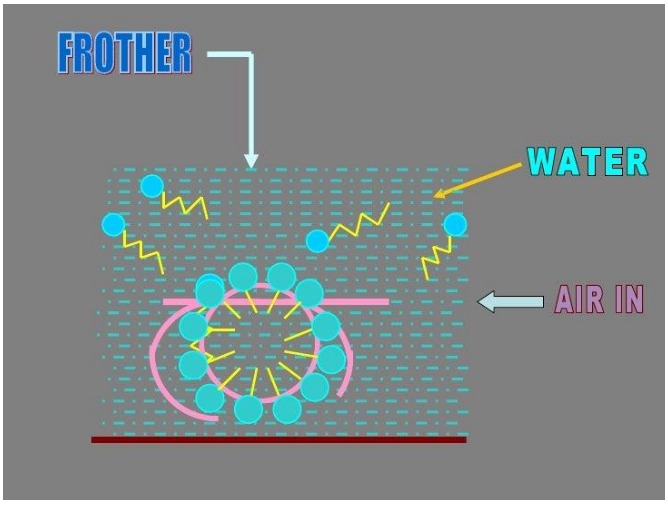
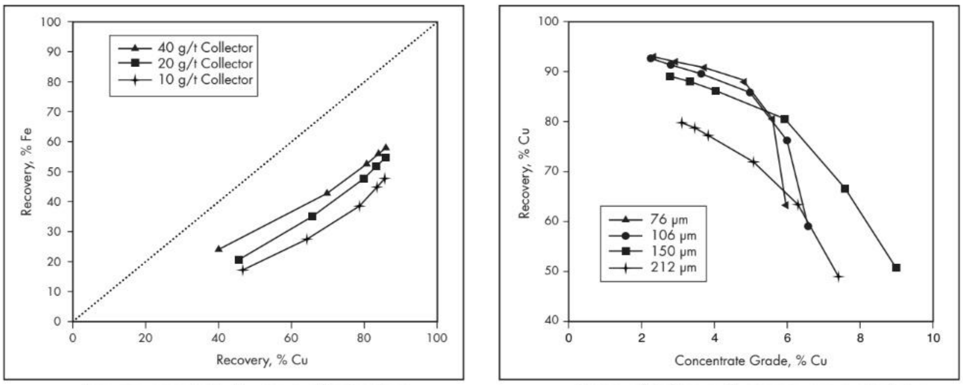


Figure 15: Scheme of frother

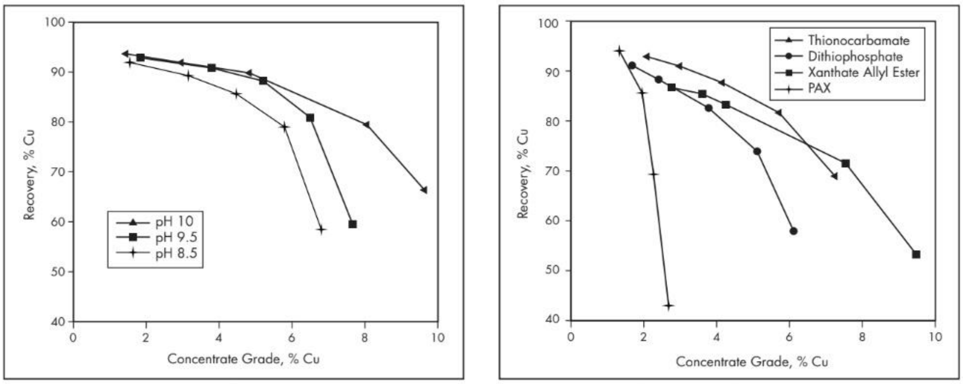
2.8 Flowsheet development test work

To develop a flotation flowsheet, first of all, batch kinetic flotation tests should be conducted based on P80 sizes ranging from typically 75, 106, 150 and 212 µm. Narrower sizes can be used afterwards. The optimum grind size is found based on the economic evaluation since the metals recovered at each grind size must be compared to the capital and economic costs. (24)

After determining the optimum grind size, the optimum reagent regime from different reagent types and their doses is found from grade-recovery curves (Figure 16). From the comparison of grade-recovery curves, optimum parameters such as pH, grind size and collector type are found respectively. The better copper floatability and selectivity over the gangue regarding curve is plotted on the top and right side of the other curves. Finally, if possible, a simple flotation flowsheet should be designed with repeated cycles so that the performance of the process can be checked regularly.



Iron–copper selectivity versus collector dose **Copper flotation performance versus grind size**



Copper flotation performance versus pH **Copper flotation performance versus collector type**

Figure 16: Example flotation test results for flowsheet development

2.8.1 Basic copper flotation flowsheet

In most plants, a simple flowsheet for treating low grade, low complexity copper ores is used (Figure 17). High recovery of copper is concentrated in the rougher flotation stage at a coarse grind size. Then the rougher concentrate is reground and is fed to the cleaner circuit. (19)

The first cleaner tailings are scavenged in a cleaner-scavenger stage and tailings from the scavenger circuit are sent to final tailings. Also, the concentrates from the first cleaner circuit can be further cleaned with one or two more cleaner stages, whereas the tailings from each stage are recycled to the previous stages.

In addition, not returning final tailings as feed to the rougher circuit has the advantage of avoiding fine-sized recirculation of middlings and weakly activated pyrite particles between the cleaner-scavenger and rougher stages which will cause an unstable rougher circuit with reduced residence time. Moreover, the fine reground particles from final tailings will affect the hydrodynamics of rougher flotation’s froth.

This simple flotation flowsheet is used for concentrators such as Chuquicamata, 'isputada, Escondida, Esperanza, LosBronces, Los Pelambres, and Ministro Hales (all in Chile); Antapaccay, Constancia, and /as Bambas (all in Peru);Alumbrera (Argentina); Bagdad, Metcalf, and Ray (all in theUnited States); Boddington (Australia); Sossego (Brazil);Grasberg (Indonesia); Lumwana (Zambia); and Oyu Tolgoi (Mongolia) etc.

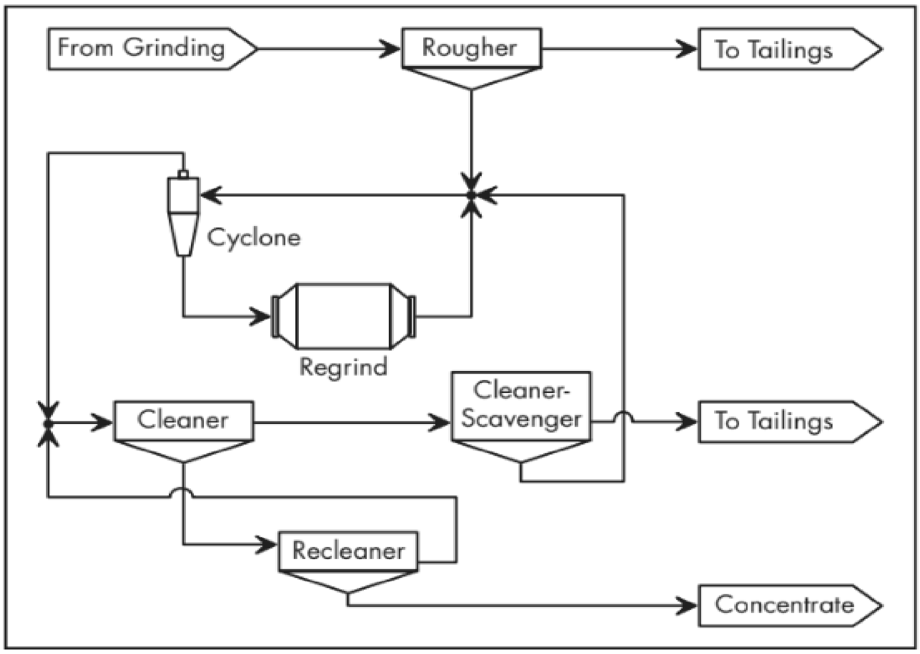


Figure 17: An example of a simple copper flotation flowsheet

2.9 Gind size and liberation of copper minerals

In a copper mine, the copper ore is ground in subsequent stages of comminution such as blasting, crushing and wet grinding to liberate copper minerals from gangue so that copper is collected in concentrate by the flotation process (Figure 18). The particle size of the ore is reduced to about 0.1 m from blasting to crushers and product size of nearly 0.01 m goes to wet grinding to produce a particle size of approximately 100 µm. The fineness of the final ore will be determined by the number of times it passes through the grinding mills. (18)

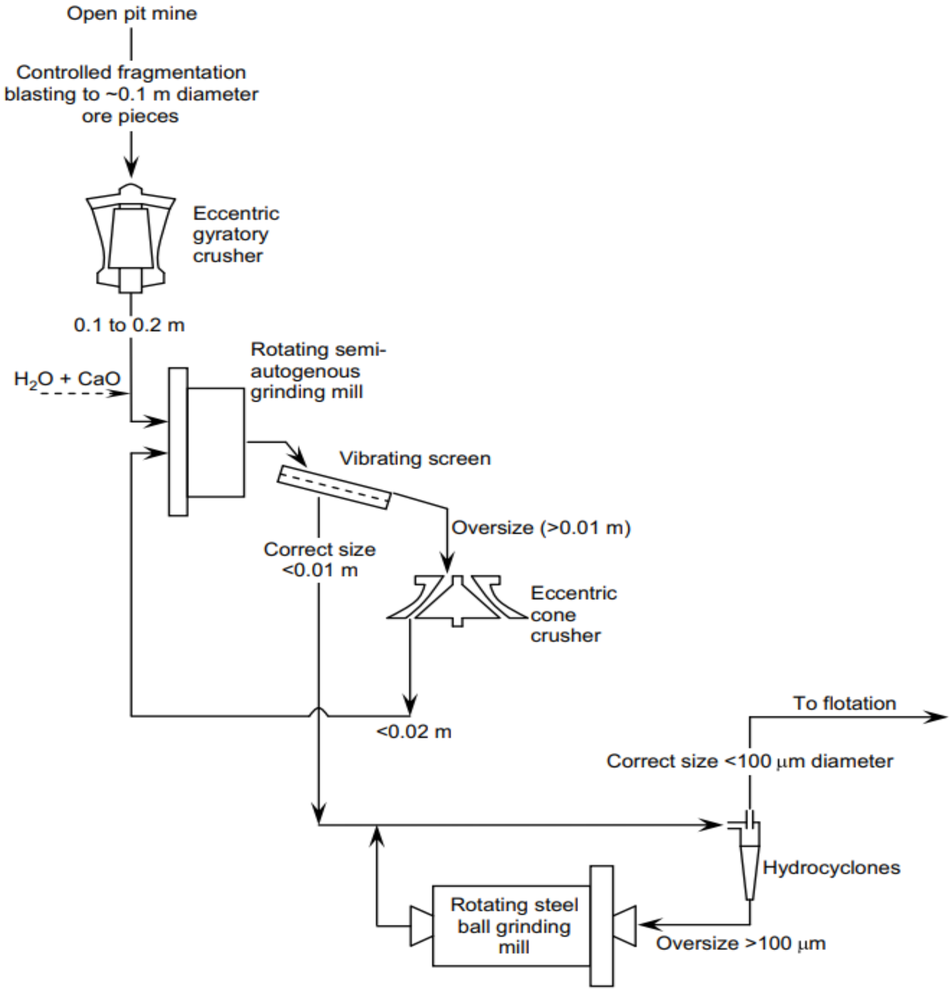


Figure 18: An example of a copper comminution process

Then, in the flotation circuit, coarse-sized ore particles are pre-concentrated before being reground concentrates reported to the cleaner stage. By doing this, the volume of the ores to be size reduced is decreased due to the comminution process consuming a large amount of energy. In addition, tailings with coarse size have advantages such as reduced costs of tailing storage as well as underground backfill costs and minimized water consumption with the following capital and operating costs associated with the comminution process.

In the process stage of flotation, too fine or too coarse size of particles must be avoided because at too coarse size the copper minerals are locked with gangue minerals which prevents flotation and too fine grind size disturbs the contact between valuable copper minerals and bubbles as well as fine copper minerals may agglomerate with pyrite minerals, thus an intermediate size is preferred.

From the example of grind size effects on copper recovery and corresponding copper content in the tailings (Figure 19), it can be seen that the recovery increases with the reducing particle size of the ore, resulting in a decrease in copper content in the tailings. The optimum grind size can be seen from 75 to 37 µm with recovery between 95-99% with a following copper content in tailings of around 0.25 to 0.12%.

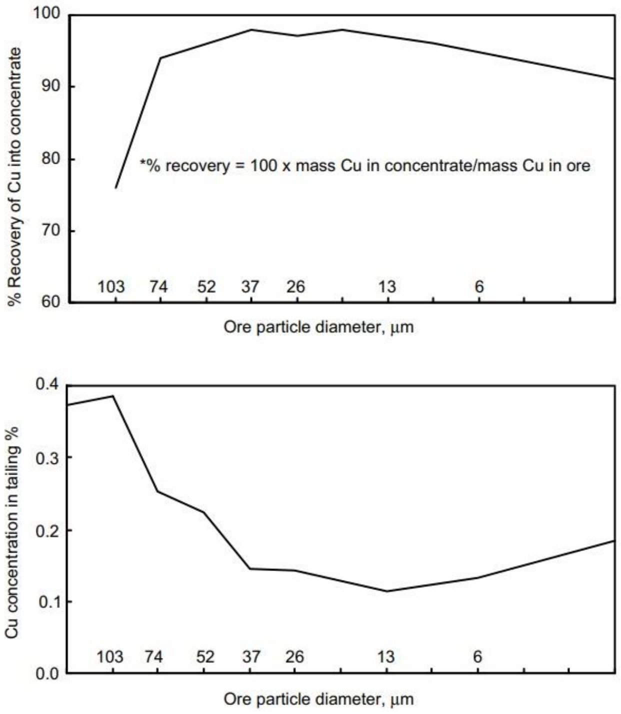


Figure 19: Example flotation results of copper recovery and copper content in tailings regarding ore grind size

3 Methods

This section includes the necessary description of used apparatus and equipment, methods and sample characteristics for the flotation test work. To conduct flotation test work, basic flowsheet and flotation parameters are also mentioned.

3.1 Apparatus and Equipment

3.1.1 Automatic precise divider for mineral ore sample dividing

To mix and divide large amounts of samples in the laboratory, the automatic divider is used for preparing subsamples for further research and test work (Figure 20). Compared to a human hand-operated riffle sample splitter, it has fewer errors and the machine is sealed, so there is no dust emission.

The tailing samples from Erdenet mine were mixed 5 times and divided using an automatic sample divider into around 5 kg subsamples.

Figure 20: Automatic precise sample divider

3.1.2 Riffle sample splitter

The riffle sample splitter is suitable for mixing and dividing small amounts of samples. With cross arranged chutes, the sample is divided into 2 equal sized subsamples.

The basic principle of sample preparation consists of sample A being divided into B and C parts and B is again divided into D, E and C is divided into F and G. Then these subsamples are cross mixed with each other such as a mixture of D and G as well as E and G. This mixing process is repeated at least 4 to 5 times for proper sample mixing.

Figure 21: Sample splitter

The 5 kg tailing samples from Erdenet mine are mixed and divided using this riffle sample divider to prepare 1 kg subsamples for further test work.

3.1.3 Rod mill

As the name implies, the rod mill consists of iron or steel rods inside the container and with each given grinding time, the sample is ground to a finer particle size where valuable minerals and gangue materials are liberated from each other (Figure 22). Furthermore, because the grinding process is carried out in wet conditions with 60 to 75 percent solids by mass, no dust is emitted.


Figure 22: Rod mill

In addition, samples used in this test work are ground using a rod mill with a solids to water ratio of 60.6 to 39.4% to determine the particle size distribution and P80 grind sizes for the flotation test work. Prior to the flotation stage, samples are ground with the addition of 0.6g of lime to depress the pyrite minerals so that only copper sulfide minerals can float.

3.1.4 Wet sieve analysis

To determine the particle size distributions of the samples such as F80 and P80, wet sieve analysis is conducted (Figure 23). The wet sieve consists of successive sieves with decreasing size downwards, using water flow and constant vibration. After some time, the sample is classified according to their particle sizes while the coarse particles are retained on top and the finer particles of the sample pass through the sieve. The operation of water conditioning prevents dust emission.


Figure 23:Wet sieve

The feed particle size distribution of samples in this thesis work is determined using sieve sizes of 250, 212, 150, 100, 75, 54, 38.5 μm. Then, to determine P80 grind sizes for the flotation test, sieve sizes of 75, 54, 38.5 μm are used.

3.1.5 X-ray fluorescence spectroscopy

The elemental analysis is conducted using X-ray fluorescence in short XRF in a non-destructive way (Figure 24). Samples are excited using an X-ray source and it is measured by the handheld XRF which determines the fluorescent X-rays. This is a good quantitative and qualitative analyzer which has a standard error of less than 0.03%. Because each element is detected based on its production of unique fluorescent X-rays.

Figure 24: XRF analysis

Copper, iron and molybdenum contents of samples are analyzed using XRF but only the content of copper is mentioned in the Appendix due to the main focus being copper. In addition, the content of copper in concentrates and tailings is determined to plot recovery-grade curves for comparing results to achieve the optimal one.

3.1.6 Flotation machine

In this thesis work, the flotation test work was conducted using the Denver model D12 laboratory flotation machine which is well known and the world leader in froth flotation testing (Figure 25). The flotation machine consists of a stainless steel standpipe with an air control valve and various types of cells, impellers and diffusers.

With given flotation parameters, all rougher and scavenger stage flotation is carried out to test the possibility of reprocessing of copper tailings from Erdenet mine. (25)

Figure 25: Denver flotation machine

3.1.7 Laboratory pressure filter

A laboratory pressure filter is used for dewatering samples for test work. The filter consists of a cylindrical base as a pulp container, a yoke with a closing handler which secures the lid, drain grooves, a steel screen on bottom the of the container and cloth and paper filters.

Under increasing pressure using air inside the insulated volume, the water within the pulp is pumped through the filters, leaving a solid mass. This squeezed leftover is called cake.

Figure 26: Pressure Filter

The new tailings from flotation in this test work are filtered for dewatering or recovering the excess water which is later used for slurry preparation. Because this water has adjusted pH and certain amounts of reagents.

3.1.8 Laboratory drying oven

Drying ovens can be used in laboratories for various tasks such as evaporation, sterilization, temperature testing and for incubating temperature sensitive experiments. Drying is a delicate process as the drying too fast or too slow or unevenly can ruin the process.

Figure 27: Drying oven

In this study test work, a drying oven with a temperature of 103 °C is used to evaporate the wet sieved samples and concentrate including tailings from flotation. After drying, XRF elemental analysis is conducted on each sample to find out the copper content.

3.2 Origin of the tailings sample

In 2016, the tailing samples from Erdenet mine's tailing storage facility were collected by Geomin drillings from 11 different locations which are classified as accessible in winter and summer (Figure 28). The tailing samples are differentiated by their depth which is ranging from a minimum of 0 to a maximum of 88m. The names of the samples include W1, W3-W7, S2, S3, S5, S6 and F4 which in total 64 samples plus each sample weighs around 5 kg, resulting in a total of 308 kg.

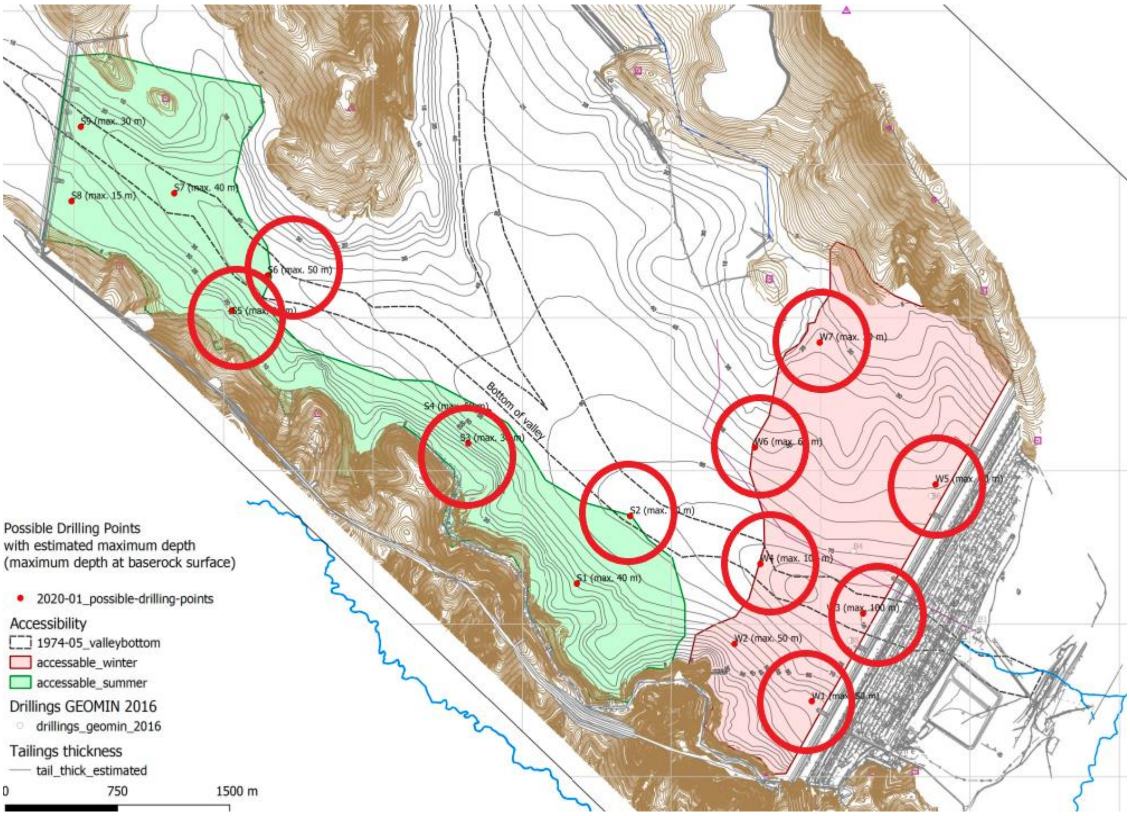


Figure 28: Location of the tailing samples

3.3 Sample preparation

Sample preparation of the tailings from Erdenet mine consists of stages such as drying (due to sample-containing moisture content of 1-6%), XRF analysis, sample mixing and dividing and grinding (Figure 28). The samples are classified into three types such as from depth 10 to 88 m, 10 to 40 m and 40-88 m since 0 to 10 m is not used in this test work because it is assumed to have low copper content which ranged from 0.04 to 0.07% whereas other samples ranged from 0.07 to 0.23%. Therefore, three composites were made: C_{10-88}, C_{10-40} as well as C_{40-88} and the average copper contents of these samples is shown in (Table 3).

From the table, it can be seen that the copper contents in these samples don‘t differ much, thus composite C_{10-88} is used for the test work as representing the whole copper tailings. Also, results of XRF analysis of the tailing samples are attached in the appendix.

Table 3: Result of XRF analysis of samples

Number	Sample name	Copper grade (%)
1	Composite 10-88m	0.108
2	Composite 10-40m	0.0945
3	Composite 40-88m	0.1245

In addition, according to the study “Leaching of copper tailings“ which was conducted by Erdenet’s institute “Erdenet tsogtsolbor”, chemical analysis of composite sample C_{10-88} is shown below. From this, it can be seen that the tailings sample contains about 36.44% of oxidized copper mineral. Hence, the use of sulfidizer is suggested to recover more copper minerals.

Table 4: Chemical analysis of samples

Parameters	Content of element, %			Total, Cu%
	Primary copper mineral	Secondary copper mineral	Oxidized copper mineral	
Cu% of composite 10-88m	0.035	0.04	0.043	0.118
Copper fraction	29.66	33.9	36.44	100

3.4 Grinding time determination

Before the batch flotation kinetic test, grinding time for each grind size is determined by the grind calibration curve which shows the relationship between the P80 grind sizes versus time (Figure 29). The sample is ground either by rod or ball mills, then the discharge will be sieve analyzed to find P80 at each grinding to plot the curve. The grind calibration curve controls P80 grind size by predicting and from the curve, if we need a grind size of 100 μm, it can be seen that the sample must be ground for 30 minutes. (26)

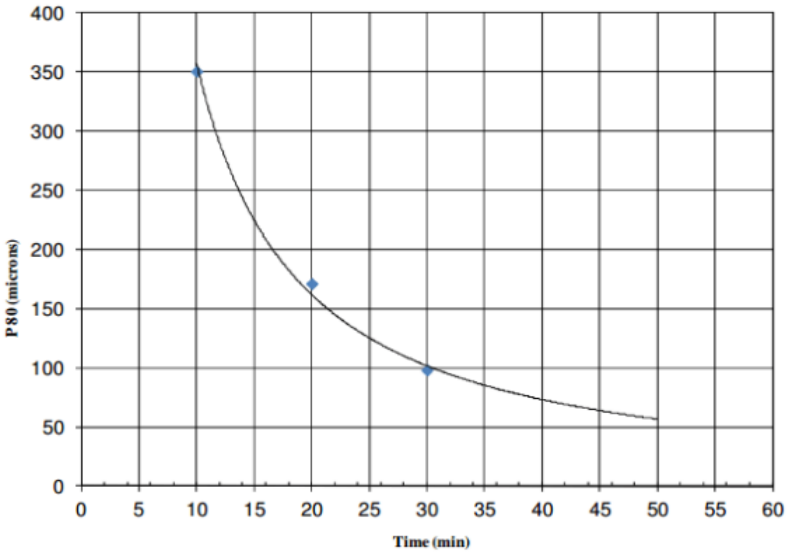


Figure 29: Grind calibration curve

Regarding the test work of the tailings, the sample's pulp density consists of 61% solids, that is from 1 kg of solid mass with an added 650 ml of water. A rod mill is used for size reduction of the sample. However, the determined P80 grind sizes in this test work did not follow this exact method to find grinding time. Instead, each discharge is screen analyzed using only the needed size sieve. To be more clear, if determination of grinding time of P80 grind size of 38.5 μm is needed, only sieve size of 38.5 μm is used for wet screen analysis whether 80 % of the particles passes through or not. Hence, grinding time is determined from the grinding time versus the passing percent of the particles.

The reason why this method was applied in this test work was because of the fine particles of the tailing samples which contained other wastes similar to dried and worn out plants, that affected the mass. Also, wet screen analysis of these fine sized tailing samples required so much physical strength and time. The other reason for using this shortcut method was to save time and be more efficient due to the fact that a lot of experiments needed to be done before the deadline. Therefore, the main goal was to just find P80 grind sizes and each grind size was double checked to prove whether 80% passed or not.

3.5 Batch flotation test

After finding optimum parameters from the previous experiments for the flotation such as reagents regime, air flow rate and rotor speed (Table 5), the batch flotation test was conducted on samples with P80 grind sizes of 75, 54, 38.5 μm and primary sample P80 size of 122 μm. The goal of this test is to find the optimum grind size for the flotation by comparing results from conducted experiments on grade vs. recovery curve.

The flotation tests were performed in a Denver flotation machine with self-aeration. The ground sample was mixed with process water and conditioned in a 2.5-liter flotation cell at an impeller speed of 1100 rpm. The pH value is adjusted to 10.5 using lime before adding the reagent. The reagents were added according to predetermined quantities. At the end of 2 minutes of conditioning in rougher and 1 minute in scavenger stage flotation, air is introduced from the bottom of the cell and froth flotation is continued for 8 minutes. The froth and tailings were collected separately and after filtering and drying, weighing as well as XRF elemental analysis were performed for plotting grade and recovery curves for further analysis.

Firstly, 0.6g of limestone is added to the sample in milling to depress pyrite minerals. After that, the first stage of rougher flotation is conducted two times on each size. The kinetics of flotation consists of 3 minutes in the rougher stage, 3 and 2 minutes in the scavenger stage. In total, three concentrates were collected in 8 minutes. And the interval time of the mass pull is 10 seconds. Finally, the process flowsheet of the experiment is shown below (Figure 30).

Table 5: Flotation parameters

		Stage 1	Stage 2
		Rougher flotation	Scavenger flotation
Collector (g/t)	Monfloth 03	6	3
	Bica 901	3	1
Frother (g/t)	MIBC	15	5
Sulfidizer (g/t)	NaSH	-	1
Condition time (min)		2min	1min
pH		10.5	
Rotor speed (rpm)		1100	
Air supply (m3/hour)		0.4	

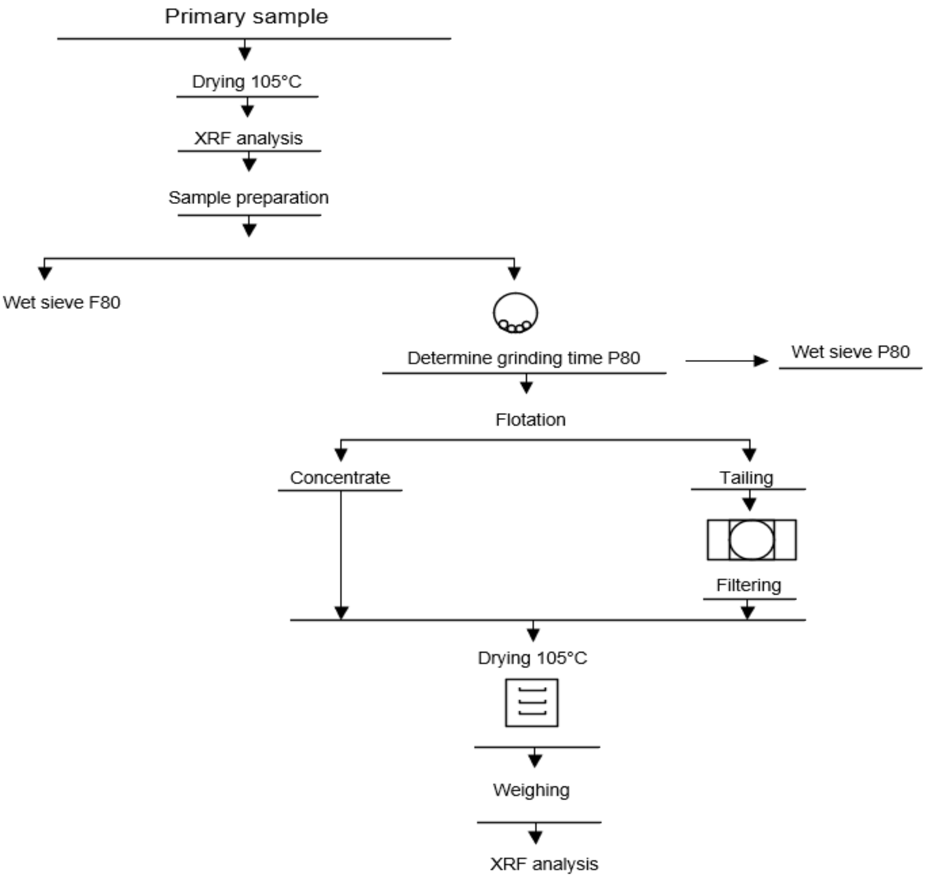


Figure 30: Process flowsheet of test work

4 Results and discussions

This section introduces and discusses the results of each experiment, such as particle size analysis, grinding time determination, and flotation test.

4.1 Particle size distribution of coposite sample 10-88m

Tailings samples are wet screened using sieves with sizes of 250, 212, 150, 100, 75, 54 and 38.5 μm to find the F80 feed size. From the particle size distribution curve (Figure 31), it can be observed that the F80 size is 122 μm. Due to the agglomeration of fine particles and waste plants in the samples, the mass varied, thus making the curve not smooth.

Then XRF analysis is conducted on the retained mass of the sieves so that the copper distribution in each fraction is known (Figure 32). From the curve, it can be seen that the total copper in these sizes is about 35% which means the remaining 65% of the copper minerals are in particles which pass through the sieve size of 38.5 μm.

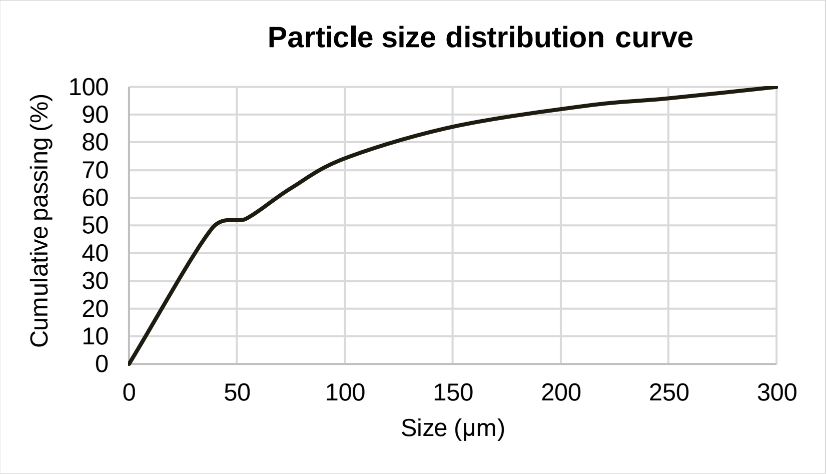


Figure 31: Particle size distribution curve of the sample

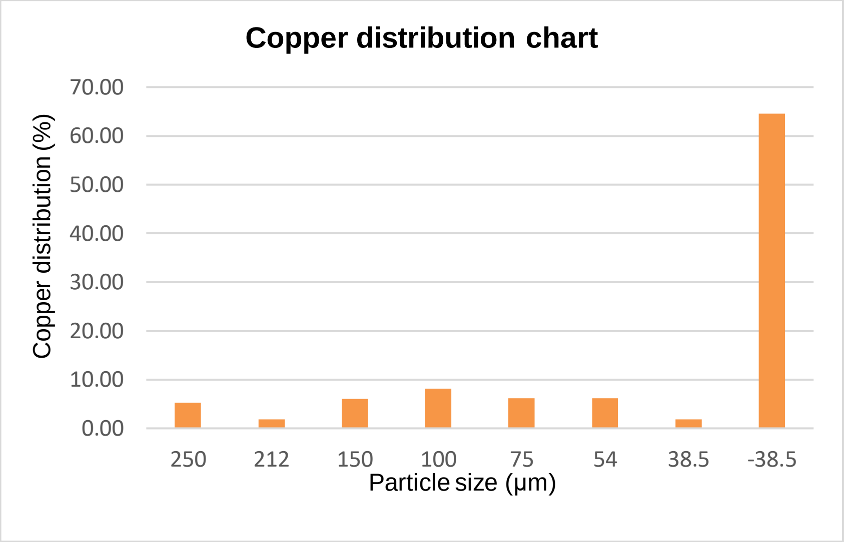


Figure 32: Copper distribution along particle size

4.2 Grinding time determination

From the example graph of grinding time determination (Figure 33), it can be observed that the P80 grind size of 75 µm is found at a grinding time of 186 seconds. The passing percentage of ground sample and grinding time have almost an linear relationship where increase in grinding time results in passing percent to follow upward.

The main focus was finding P80 sizes, thus grinding time to achieve each grind size such as 75, 54 and 38.5 µm was found (Figure 34). The grinding calibration curve is plotted based on the P80 sizes and grinding time. For example, it can be seen from the curve that achieving a grind size of 60 µm needs a grinding time of 600 seconds. The other grind sizes can be found using this curve which is limited by the P80 size of 38.5 µm.

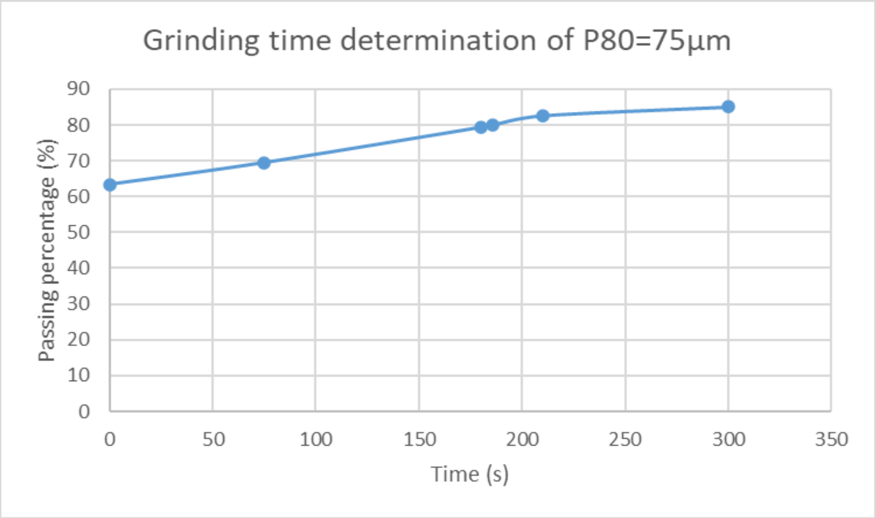


Figure 33: An example of determining grinding time for a P80 grind size of 75 µm

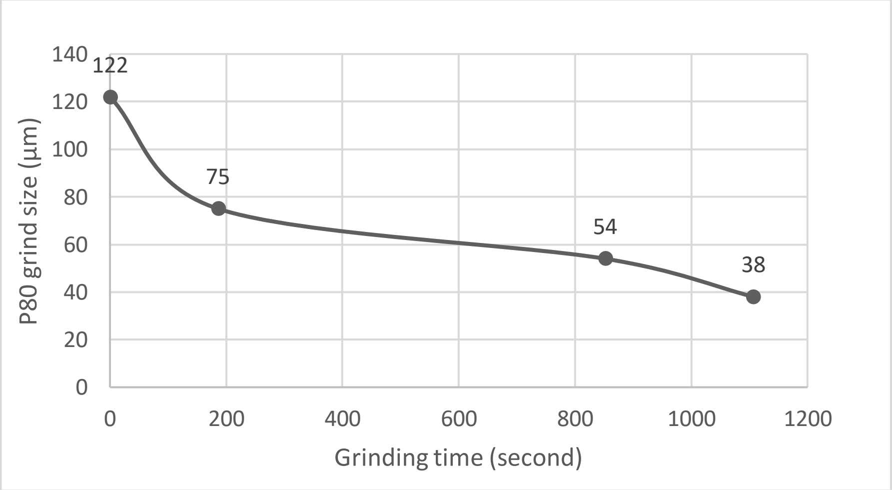


Figure 34: Grinding calibration curve of reduced sizes

4.3 Flotation test work

Based on the results of flotation, copper recovery-grade curves are plotted. From the graph (Figure 35), it can be seen that the best result corresponds to the flotation test conducted on a P80 grind size of 54 µm because it is placed on the top and right side compared to other curves. From the more detailed graphic (Figure 36), it can be seen that the flotation tests conducted on a grind size of 54 µm achieved copper recovery of 36.97% and a grade of 1.18%.

Also, from the graph which shows the relationship between grinding time, recovery and copper content in the tailing (Figure 37), it can be observed that the optimum grinding time of the tailings is 852 seconds where it has almost maximum copper recovery and the lowest copper content in the tailing.

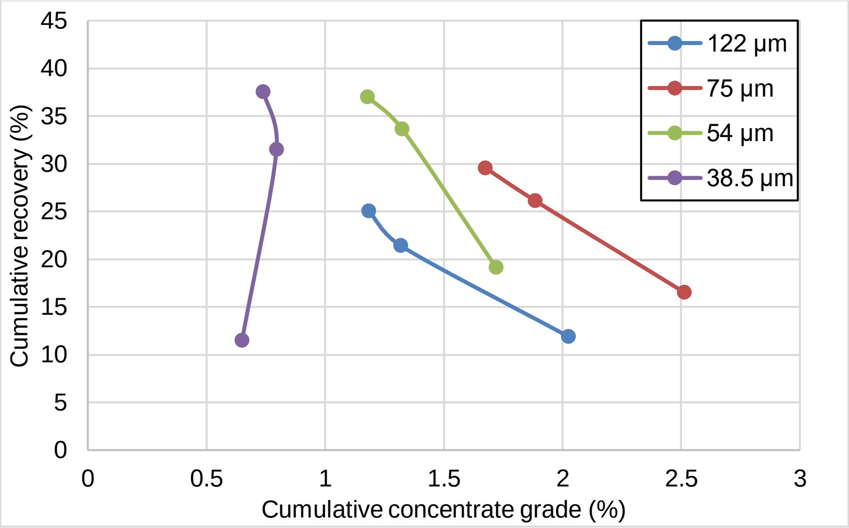


Figure 35: Copper grade-recovery curve

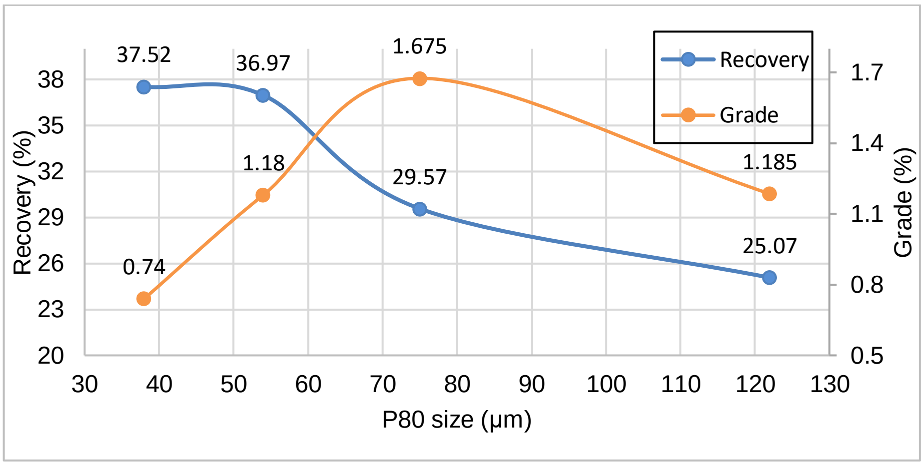


Figure 36: Grind size effect on grade and recovery

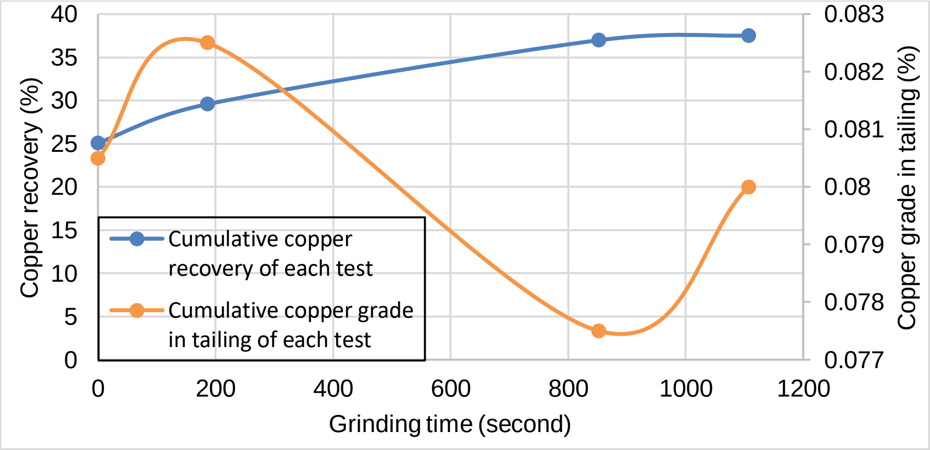


Figure 37: Effect of grinding time on recovery and copper content of the tailings

Based on the optimum result, the reprocessing flowsheet can be designed with stages of rod mill grinding and flotation (Figure 38).

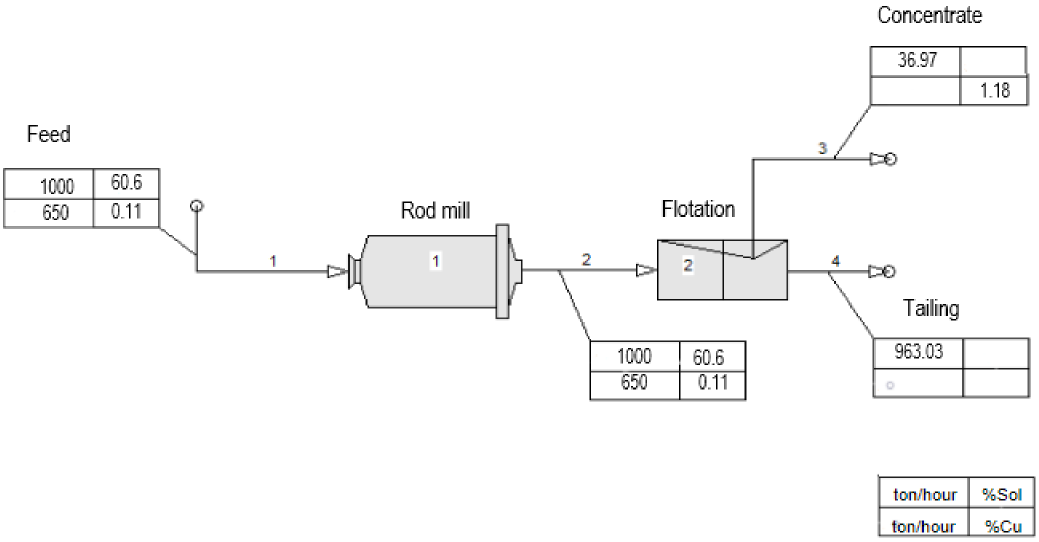


Figure 38: Process flowsheet of reprocessing copper tailing from Erdenet mine

5 Conclusion

The optimization of P80 grind size for Erdenet mine tailings was studied for approximately 6 months, from September 30th to March 30th. The purpose of this study work was to investigate the real possibility of reprocessing the copper tailings from Erdenet mine using batch flotation tests. The optimum result corresponded to a grinding time of 1107 seconds with a P80 grind size of 54 µm and copper recovery of 36.97% as well as a grade of 1.18%.

The goals of this study work are fulfilled and the expected outcome is that after each grinding, the valuable minerals will be liberated, thus increasing the grade and recovery. However, the grade decreased from the second test which might have happened due to very fine particles that agglomerate with each other and prevent copper minerals from floating.

Copper tailings in Erdenet have great potential for being a secondary reserve. But within this study work, 36.97% of the copper mineral was recovered from the tailings sample. Also, to meet the demand for raw materials in the future, these secondary reserves will be of interest due to the fact that no size reduction, digging, and transportation is needed and tailings can be recycled in a self financing way. Therefore, more suitable reprocessing methods that can recover valuable minerals are needed.

6 References

1. ADRIANA – Remote sensing detection of industrial recyclables in mine tailings . Bundesministerium für Bildung und Forschung/ Federal Ministry of Education and Research (BMBF) Division Resources, Circular Economy; Geosciences 53170 Bonn, Germany. 2019.
2. Davenport.W.G KingMSchlesingerMBiswasAK. Extractive_Metallurgy_of_Copper_-_G._W._DAVENPORT [Internet]. 4th ed. [Accessed 2022 March 07]. Available from: https://mmu2.uctm.edu/depts/mcm/E-library/Extractive_Metallurgy_of_Copper_-_G._W._DAVENPORT.pdf
3. 2030 Climate Target Plan. Directorate-General for Climate Action.
4. Moreno-Leiva S, Haas J, Junne T, Valencia F, Godin H, Kracht W, et al. Renewable energy in copper production: A review on systems design and methodological approaches. Journal of Cleaner Production. 2020 Feb;246:118978.
5. ЭРДЭС БАЯЛГИЙН САЛБАРЫН СТАТИСТИК МЭДЭЭЛЭЛ [Internet]. [Accessed 2022 March 22]. Available from: https://mmhi.gov.mn/wp-content/uploads/2022/03/1642591435475764-1-12-%D1%81%D0%B0%D1%80.pdf
6. Copper Prices for the Last 5 Years [Internet]. [cited 2022 May 22]. Available from: https://www.dailymetalprice.com/metalpricecharts.php?c=cu&u=mt&d=1200&msclkid=79c6a79fbb3d11eca07138af89fd6375
7. Total copper mine production worldwide from 2010 to 2021 [Internet]. [Accessed 2022 April 10]. Available from: https://www.statista.com/statistics/254839/copper-production-by-country/#:~:text=The%20total%20worldwide%20copper%20mine%20production%20amounted%20to,metric%20tons%20in%202010.%20Copper%3A%20an%20essential%20metal?msclkid=f8981798bb3511eca4ab6df8f0ec2480
8. U.S. Geological Survey, Mineral Commodity Summaries of copper, January 2021 [Internet]. [Accessed 2022 March 15]. Available from: https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-copper.pdf?msclkid=ca2ac421bb5b11ec8a104b040dfdba9b

9. Metals and Mining Abundant natural resources and minerals [Internet]. [Accessed 2022 April 12]. Available from: https://investmongolia.gov.mn/metals-and-mining/

10. Schlesinger, Mark E. Extractive Metallurgy of Copper.

11. Myagmarsuren D, Davaatseren T, Vladimir K. Dealing with mine closure planning liabilities, opportunities and lessons learned. In: Proceedings of the 11th International Conference on Mine Closure. Australian Centre for Geomechanics, Perth; 2016. p. 381–8.

12. Erdenet Mining Corporation [Internet]. [Accessed 2022 March 25]. Available from: https://www.erdenetmc.mn/en/about

13. Nazarov.Yu.P ZiminAVGegegtS. POTENTIAL ENHANCEMENT OF COMPREHENSIVE COPPER–MOLYBDENUM ORE DRESSING BY PARTIAL INVOLVEMENT OF TAILINGS. [Accessed 2022 March 16]; Available from: file:///C:/Users/Owner/Documents/Thesis%20related/Nazarov%20Potential%20Enhancement%20of%20Cu-Mo%20Ore%20by%20Partial%20Involvement%20of%20Tailings%20-%20Copy.pdf

14. Bellenfant G, Guezennec AG, Bodénan F, Cassard D. Mine Closure [Internet]. 2013. Available from: www.acg.uwa.edu.au

15. Morin D., Battaglia F. and Ollivier P. (1993) Study of the bioleaching of a cobaltiferous pyritic concentrate, Proceedings of the "International Biohydrometallurgy Symposium". Jackson Hole, Wyoming, Etats-Unis. "Biohydrometallurgical Technologies", pp. 147-156

16. Goktepe F. (2005) Treatment of lead mine waste by a Mozley multi-gravity separator (MGS), Journal of Environmental Management 76, pp. 277–281

17. Peek E., Barnes A. and Tuzun A. (2011) Nickeliferous pyrrhotite – ‘‘Waste or resource?’’, Minerals Engineering 24 (7), pp. 625–637.

18. Fosso-Kankeu E., Mulaba-Bafubiandi A.F., Mamba B.B. and Barnard T.G. (2011) Assessing the effectiveness of a biological recovery of nickel from tailing dumps, Minerals Engineering 24(5), pp. 470–472.

19. Kamradt A., Borg G. Schaefer J., Kruse S., Fiedler M., Romm P., Schippers A., Gorny R., Du Bois M., Bieligk C., Liebetrau N., Nell S., Friedrich B., Morgenroth H., Wotruba H. and Merkel C. (2012) An Integrated Process for Innovative

Extraction of Metals from Kupferschiefer Mine Dumps, Germany. Chemie Ingenieur Technik 84 (10), pp. 1694-1703.

20. Surya.M NapoleanaACAntoniosK. Recycling Mine Tailings for a Sustainable Future Built Environment. In: Energy and sustainable futures. p. 163–9.

21. Common Copper Tailings Reprocessing Methods [Internet]. [Accessed 2022 March 28]. Available from: https://www.xinhaimining.com/newo/998.html

22. Markovic.Z NenadMVDraganM. Old copper flotation tailings waste reprocessing. 2010 [Accessed 2022 March 21]; Available from: https://www.researchgate.net/publication/289040497_Old_copper_flotation_tailings_waste_reprocessing

23. Schlesinger, Mark E. Extractive Metallurgy of Copper.

24. Robert.C KomarKCAY, editor. Mineral processing & extractive metallurgy handbook.

25. DENVER D12 LABORATORY FLOTATION MACHINE [Internet]. [Accessed 2022 March 16]. Available from: https://www.911metallurgist.com/equipment/denver-d12-laboratory-flotation-machine/

26. Grind Calibration Curve -Laboratory Test. [Accessed 2022 March 30]; Available from: https://www.911metallurgist.com/blog/grind-calibration-curve

7 Appendices

Appendix 1

Table 6: Weight of tailings samples from Erdenet

№	Sample name	Sample description	Depth	Weight (gramm)	Depth interval (m)
1	W1-0-10	W1	0 to 10	5048.7	10
2	W1-10-20		10 to 20	5232.7	10
3	W1-20-30		20 to 30	5032.9	10
4	W1-30-40		30 to 40	5039.7	10
5	W1-40-50		40 to 50	5021.3	10
6	W1-50-60		50 to 60	5034.4	10
7	W1-60-70		60 to 70	3018.7	10
8	W1-70-80		70 to 80	5035.1	10
9	W1-80-88		80 to 88	5021.8	10
10	W3-0-10	W3	0 to 10	5028.4	10
11	W3-10-15		10 to 15	3044.8	10
12	W3-25-29.8		25 to 29.8	2513.2	10
13	W3-29.8-40		29.8 to 40	5116.8	10
14	W3-40-50.2		40 to 50.2	5019.4	10
15	W3-50.2-60		50.2-60		10
16	W3-60-70		60 to 70	5119.8	10
17	W3-70-79.5		70 to 79.5	5006.7	10
18	W3-79.5-84.5		79.5 to 84.5	1116.4	10
19	W4-0-10	W4	0 to 10	5015.5	10

20	W4-10-20		10 to 20	5020	10
21	W4-20-30		20 to 30	5019.2	10
22	W4-30-40		30 to 40	5030.9	10
23	W4-40-50		40 to 50	5024.3	10
24	W4-50-60		50 to 60	5201.5	10
25	W4-60-70		60 to 70	5142.5	10
26	W4-70-80		70 to 80	5028	10
27	W5-0-10.9	W5	0 to 10.9	5036	10
28	W5-10.9-20		10.9 to 20	5009	10
29	W5-20-30		20 to 30	5010.7	10
30	W5-30-39.5		30 to 39.5	5020.4	10
31	W5-39.5-50		39.5 to 50	5032.9	10
32	W5-50-60.7		50 to 60.7	5064.6	10
33	W6-0-10	W6	0 to 10	5107.7	10
34	W6-10-20		10 to 20	5055.9	10
35	W6-20-30		20 to 30	5221.8	10
36	W6-30-40		30 to 40	5036.7	10
37	W7-0-10	W7	0 to 10	5577.9	10
38	W7-10-20		10 to 20	5289.5	10
39	S2-0-10	S2	0 to 10	5007.5	10
40	S2-10-20		10 to 20	5014.8	10
41	S2-20-30		20 to 30	5030.9	10
42	S2-30-40		30 to 40	5022.7	10
43	S2-40-50		40 to 50	5012.3	10

44	S2-50-60		50 to 60	5006.5	10
45	S2-60-64		60 to 64	2536.3	10
46	S3-0-10	S3	0 to 10	4993	10
47	S3-10-20		10 to 20	5014.7	10
48	S3-20-26		20 to 26	5003.8	10
49	S5-0-10	S5	0 to 10	5071.9	10
50	S5-10-20		10 to 20	5875.6	10
51	S5-20-30		20 to 30	5006.5	10
52	S5-30-40		30 to 40	4996.2	10
53	S5-40-50		40 to 50	3519.3	10
54	S5-50-60		50 to 60	5124.5	10
55	S6-0-10	S6	0 to 10	5186.1	10
56	S6-10-20		10 to 20	4991	10
57	S6-20-30		20 to 30	5032.5	10
58	S6-30-40		30 to 40	5077	10
59	S6-40-50		40 to 50	5034	10
60	S6-50-60		50 to 60	5129.9	10
61	S6-60-70		60 to 70	5032.2	10
62	F4-0-13.3	F4	0 to 13.3	6069.2	13.3
63	F4-19.3-41.3		19.3 to 41.3	6217.8	22
64	F4-41.3-55.3		41.3 to 55.3	6008.3	12
			Total weight	308,410.3	

Appendix 2

Table 7: Result of XRF analysis of the tailings samples

№	Sample name	Test №	Copper grade (%)	Test №	Copper grade (%)	Average Copper grade (%)
1	W1-0-10	2798	0.066	2799	0.064	0.065
2	W1-10-20	2812	0.092	2814	0.095	0.0935
3	W1-20-30	2810	0.118	2811	0.111	0.1145
4	W1-30-40	2816	0.115	2818	0.113	0.114
5	W1-40-50	2791	0.113	2792	0.111	0.112
6	W1-50-60	2830	0.151	2831	0.148	0.1495
7	W1-60-70	2832	0.123	2833	0.126	0.1245
8	W1-70-80	2828	0.103	2829	0.09	0.0965
9	W1-80-88	2824	0.076	2826	0.079	0.0775
10	W3-0-10	2883	0.065	2884	0.059	0.062
11	W3-10-15	2879	0.09	2880	0.083	0.0865
12	W3-25-29.8	2885	0.13	2886	0.12	0.125
13	W3-29.8-40	2867	0.071	2868	0.085	0.078
14	W3-40-50.2	2863	0.144	2864	0.096	0.12
15	W3-50-60	2865	0.082	2866	0.074	0.078
16	W3-60-70	2881	0.124	2882	0.117	0.1205
17	W3-70-79.5	2861	0.118	2862	0.117	0.1175
18	W3-79.5-84.5	2871	0.205	2872	0.244	0.2245
19	W4-0-10	2778	0.041	2780	0.035	0.038
20	W4-10-20	2787	0.058	2788	0.057	0.0575
21	W4-20-30	2801	0.082	2802	0.085	0.0835
22	W4-30-40	2776	0.129	2777	0.126	0.1275
23	W4-40-50	2789	0.176	2790	0.164	0.17
24	W4-50-60	2796	0.178	2797	0.175	0.1765
25	W4-60-70	2761	0.174	2762	0.181	0.1775
26	W4-70-80	2783	0.095	2782	0.103	0.099

27	W5-0-10.9	2770	0.069	2771	0.076	0.0725
28	W5-10.9-20	2821	0.113	2822	0.096	0.1045
29	W5-20-30	2803	0.069	2805	0.072	0.0705
30	W5-30-39.5	2772	0.103	2775	0.102	0.1025
31	W5-39.5-50	2819	0.184	2820	0.171	0.1775
32	W5-50-60.7	2806	0.159	2808	0.165	0.162
33	W6-0-10	2869	0.047	2870	0.056	0.0515
34	W6-10-20	2891	0.079	2892	0.08	0.0795
35	W6-20-30	2887	0.157	2888	0.114	0.1355
36	W6-30-40	2893	0.145	2894	0.15	0.1475
37	W7-0-10	2889	0.058	2890	0.056	0.057
38	W7-10-20	2895	0.076	2896	0.079	0.0775
39	S2-0-10	2838	0.042	2839	0.034	0.038
40	S2-10-20	2899	0.058	2900	0.058	0.058
41	S2-20-30	2897	0.096	2898	0.085	0.0905
42	S2-30-40	2836	0.077	2837	0.076	0.0765
43	S2-40-50	2906	0.133	2907	0.124	0.1285
44	S2-50-60	2902	0.229	2903	0.236	0.2325
45	S2-60-64	2904	0.198	2905	0.193	0.1955
46	S3-0-10	2763	0.041	2764	0.047	0.044
47	S3-10-20	2793	0.091	2794	0.084	0.0875
48	S3-20-26	2767	0.071	2769	0.073	0.072
49	S5-0-10	2834	0.051	2835	0.052	0.0515
50	S5-10-20	2853	0.062	2854	0.056	0.059
51	S5-20-30	2877	0.084	2878	0.099	0.0915
52	S5-30-40	2842	0.094	2844	0.09	0.092
53	S5-40-50	2848	0.057	2849	0.056	0.0565
54	S5-50-60	2855	0.086	2856	0.087	0.0865
55	S6-0-10	2873	0.057	2874	0.056	0.0565
56	S6-10-20	2840	0.061	2841	0.059	0.06
57	S6-20-30	2845	0.067	2846	0.069	0.068
58	S6-30-40	2850	0.086	2852	0.091	0.0885

59	S6-40-50	2875	0.19	2876	0.149	0.1695
60	S6-50-60	2857	0.17	2858	0.163	0.1665
61	S6-60-70	2859	0.215	2860	0.18	0.1975
62	F4-0-13.3	2765	0.04	2766	0.045	0.0425
63	F4-19.3-41.3	2757	0.068	2759	0.064	0.066
64	F4-41.3-55.3	2784	0.081	2786	0.084	0.0825

Appendix 3

Table 8: Results of the flotation test works of different P80 grind sizes

Sample name	Test №	Mass (%)				Mass in percent (%)			
		C1	C2	C3	Tailing	C1	C2	C3	Tailing
P80-122	1	5.4	11.1	6.1	977.4	0.54	1.11	0.61	97.74
P80-122	2	7	10.5	4.3	978.2	0.70	1.05	0.43	97.82
P80-75	3	8.8	10.5	6	974.7	0.88	1.05	0.60	97.47
P80-75	4	6.5	6.8	3.2	983.5	0.65	0.68	0.32	98.35
P80-54	5	13.8	16.4	7.5	962.3	1.38	1.64	0.75	96.23
P80-54	6	12.6	17.4	6.4	963.6	1.26	1.74	0.64	96.36
P80-38.5	7	28.9	22.5	12.1	936.5	2.89	2.25	1.21	93.65
P80-38.5	8	13.4	30.9	14.6	941.1	1.34	3.09	1.46	94.11

Appendix 4

Table 9: Flotation results of different P80 grind sizes continued, part 2

Sample name	Cumulative mass (%)			Copper grade (%)				Copper head grade (%)
	C1	C2	C3	C1	C2	C3	Tailing	
P80-122	0.54	1.65	2.26	2.11	0.903	0.692	0.082	0.11
P80-122	0.70	1.75	2.18	1.94	0.95	0.82	0.079	0.10
P80-75	0.88	1.93	2.53	2.25	1.15	0.71	0.083	0.12
P80-75	0.65	1.33	1.65	2.78	1.48	1.13	0.082	0.11
P80-54	1.38	3.02	3.77	1.63	0.949	0.579	0.076	0.12
P80-54	1.26	3.00	3.64	1.81	1.08	0.558	0.079	0.12
P80-38.5	2.89	5.14	6.35	0.65	0.874	0.548	0.078	0.12
P80-38.5	1.34	4.43	5.89	0.65	0.922	0.54	0.082	0.12

Appendix 5

Table 10: Flotation results of different P80 grind sizes continued, part 3

Sample name	Copper recovery (%)				Cumulative copper recovery (%)			Cumulatice copper grade (%)		
	C1	C2	C3	Tailing	C1	C2	C3	C1	C2	C3
P80-122	10.77	9.48	3.99	75.76	10.77	20.25	24.24	2.11	1.30	1.13
P80-122	13.02	9.52	3.36	74.10	13.02	22.54	25.90	1.94	1.34	1.24
P80-75	16.92	10.32	3.65	69.11	16.92	27.23	30.89	2.25	1.65	1.43
P80-75	16.08	8.95	3.22	71.75	16.08	25.03	28.25	2.78	2.12	1.92
P80-54	19.47	13.47	3.76	63.30	19.47	32.94	36.70	1.63	1.26	1.12
P80-54	18.80	15.49	2.94	62.76	18.80	34.30	37.24	1.81	1.39	1.24
P80-38.5	15.90	16.65	5.61	61.84	15.9	32.55	38.16	0.65	0.75	0.71
P80-38.5	7.12	23.30	6.45	63.12	7.12	30.43	36.88	0.65	0.84	0.77

Appendix 6

Figure 39: Overall activities