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THE EFFICIENCY OF MECHANIZED MINERAL PROCESSING TECHNIQUES TO RECOVER TIN AND TANTALUM ORES. CASE STUDY: NYAMATETE CONCESSION, RWANDA

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ABSTRACT

Mining activities have resulted in a large volume of tailings containing a certain proportion of lost minerals, making them a potential reprocessing opportunity, and information on tailings and mineral reprocessing is often scarce. In this study, a conceptual framework was established and used to produce meaningful information and knowledge from the tailings of the Nyamatete mine at HABATU Mining Company Limited (an ASM in Rwanda). Tailings particles were investigated based on the observed lithology to determine their distribution over the tailing dams, and a site-specific sampling approach and procedure were established. Sieving the collected samples, particle size analysis, and chemical analysis using XRF were chosen as methods for tailings characterization. Raw materials such as SnO_2, minor Ta_2O_5, and Nb_2O_5 and elements of environmental importance such as Mn, Co, and as were observed but in small quantities are largely predominant in quartz vein, have been discovered in Nyamatete tailings. The comminution and gravity separation by mechanical reprocessing facilities improved Cassiterite recovery by 43.9 % compared to the artisanal processing method. SnO_2 recovery of 19.4 % and 29.9 % with grades of 63.224 % and 76.6 % were obtained in pegmatite and quartz tailings respectively. According to a scoping study, the Habatu tailings have an appropriate grade, the valuable content occurs in a recoverable grain-size range, and the total ore amount scales with the required input for the reprocessing equipment. Tailings reprocessing with mechanized reprocessing equipment is advantageous because it improves efficiency while also treating the material with previously unknown quantities of ore, thereby significantly increasing the total recovery of processed Run of Mine.

Keywords: Artisanal processing; Cassiterite; Coltan; Mechanized processing; Tailings.

1 INTRODUCTION

Cassiterite (SnO_2) and Coltan ($(Nb, Ta)_2O_5$) are the most common principal ores of tin and tantalum minerals discovered in Rwanda and are usually associated with granitic intrusion in the Kibaran belts northeast. Accumulations of these ores may be primary or secondary. The primary formation of tin and tantalum is hard rock without weathering from the source rock, (quartz veins mostly hosting tin), whereas the secondary formation is weathered rock, either in situ, (pegmatite veins mostly hosting both tin and tantalum, or transported from the source rock by stream or river) to form eluvial and alluvial deposits [1]. These deposits are mined using underground mining methods, mostly vein mining, and processed using artisanal processing methods, which include panning, ground sluicing, and semi-mechanized processing methods that lead to the loss of more than 50 % of economically valuable minerals in tailings [2]. In historical times, the mining of minerals generated millions of tons of waste rock and mining tailings, which were released into the environment through structures such as dumps, embankments, piles, dams, and other variations. These materials are unwanted by-products of mining where successive mineral processing operation suffered, and mining tailings have particular characteristics which depend

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on the processing technology and original ore deposit [3]. The reprocessing of tailings has been an option used for the remediation and rehabilitation of affected mine sites. Additionally, the economic interests in metals recovering are justified by its price increase and risk of critical supply. The potential recovery of metals can be a benefit for land and local communities' redevelopment [3].

Heizmann & Liebetrau (2017) [2] found that tailings contain significant amounts of ores in a recent study on the efficiency of artisanal and small-scale mining in Rwanda, and recommended reprocessing of these tailings as a proper way of managing tailings and optimizing the recovery of the ores at the site. Another study on the economic impact of artisanal and small-scale mining in Rwanda concluded that tailings reprocessing is required to recover lost ores in tailings and boost production and income [4]. Zyl (2016) estimated that approximately 75 significant tailing reprocessing projects for copper, diamond, and gold reclamation are now underway around the world [5].

The recovery of lost ores, as well as the restoration of contaminated landscapes, and the establishment of a financial system to reduce waste and utilize resources may all be aided by the utilization of extractive waste [5]. Indeed, the reprocessing of tailings decreases waste generation and utilization of undiscovered resources: by repurposing the residual part, the number of current tailings may be reduced, reducing the requirement to extract new resources and lowering the demand for new tailings formation [6].

Figueiredo et al. (2019) [3] studied the design optimization of tailings reprocessing: tungsten and zinc recovery in Portugal based on structural maximization, consisting of setting the structure of the equipment arrangement and parametric maximization that is expressed by determining set values of design variables, corresponding to design parameters. It is important to investigate the full potential of mine tailings processing technologies to encourage the recycling of resources and the growth of the economy and the ecosystem as a whole [7, 8]. Tailings reprocessing is an option that may be considered to meet the concepts of current mineral industry challenges: sustainability and the circular economy [3].

Nyamatete concession, as one of the artisanal and small-scale mines that dominate Rwanda's mining sector, is characterized by minimal capital and low technology operation employing artisanal processing methods like panning and ground sluicing that have released tens of thousands of tons of mining waste mining and tailings including certain ore minerals due to their inefficiency [2]. Although those processing methods have been seen to be the most cost-effective, it is difficult to separate fine and ultrafine Cassiterite and coltan ores from gangue minerals. There are no studies that have been done to determine the number of lost ores in artisanal and small-scale mining tailings in terms of quantity and quality for commercial exploitation across the country [9]. Conducting this research has increased interest in tailings enhancing the reprocessing activity at the mine site resulting in optimization of mineral recovery. These advancements in processing have the potential to create a positive cycle of environmental preservation as tailing will be collected in one location and will be easier to handle, as well as the recycling of water from the processing facility, resulting in safer working conditions. This research is aimed at assessing the recovery of Tin and Tantalum ore minerals left in tailings that are applicable for the Nyamatete concession implementation of sustainable reprocessing. Specifically, it determines the recovery rate of the traditional processing method and the chemical composition of the tailings to quantify the ore lost in tailings hence proposing the recovery method.

2 BACKGROUND OF THE STUDY AREA

The Nyamatete mine is situated in the Eastern Province of Rwanda and is currently exploited by HABATU Mining Company Ltd in the Rwamagana District (Figure 1). The study area is located approximately 50 km from Kigali, near the shore of Lake Mugesera. The concession has a perimeter of 2475 ha of which about 60 ha is currently being exploited. The topography around the mine consists of several flat hills (plateau), while the valleys in between are quite wide and flat. A tin geochemical anomaly was discovered in 1983-1984 by the UNDP-sponsored geological and mining exploration program (GPM). Furthermore, since 2013, when the company was awarded the license to extract coltan, Cassiterite, and wolfram, mining activities have been carried out by HABATU MINING COMPANY, while exploration has proceeded to identify new mineralized zones in the perimeter. Cassiterite was discovered in pegmatite and quartz veins, as well as in eluvium. Pegmatite and quartz veins are frequently found in concordance with the host rocks' bedding, although they can also be found as cross-cutting veins (disconcordant veins) [10].

As the reason for low-grade regional metamorphism, the deposit's pegmatite has been extensively compressed and recrystallized add the feldspars been replaced with kaolin. Because of its toughness, only quartz has survived the weathering. Quartz tailings samples were obtained at Site 1. Quartzite dominates as the host rock for mineralized quartz veins, with lesser intercalations of metapelites rocks. The quartzite includes just a limited quantity of other minerals, mostly feldspar, detrital muscovite, biotite and sulfides in addition to quartz [10].

Cassiterite (SnO_2) and minor coltan $(Nb, Ta)_2O_5$ are the primary minerals which are found in quartz veins and pegmatite veins. Quartz, mica (primarily white mica), iron oxide, and quartzite are the most common gangue minerals. As a result, the Cassiterite and coltan-bearing rocks were separated and dumped outside the tunnel dug to reach the subsurface mineral deposit, resulting in multiple waste dumps around the area. The tailing dumps in the Nyamatete concession, on the other hand, are the largest and easiest to reach. Ground sluicing and panning were employed to process ores as illustrated in Figure 3.

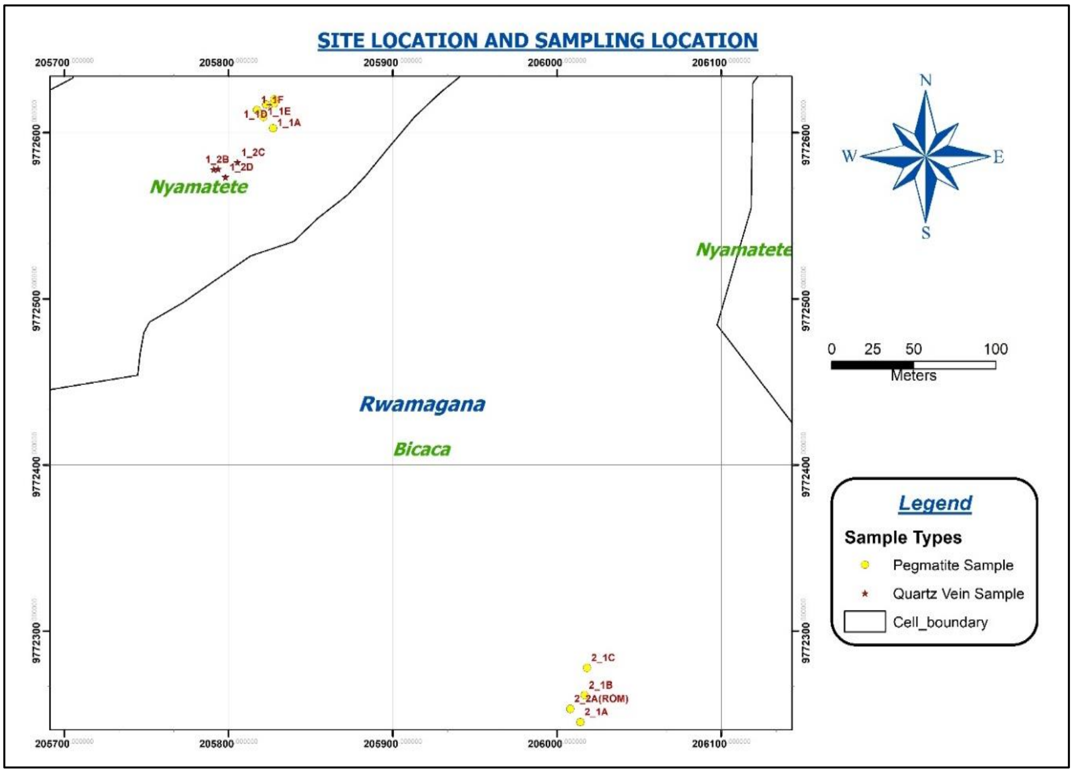

Figure 1. *The geographical location of Nyamatete Concession. Yellow dots and indigo stars show pegmatite and quartz vein sampling points respectively*

3 METHODS AND MATERIALS

Two weeks of field survey was conducted in the Eastern province; one at HABATU mining company for sample collection and another week in Piran Resource limited company for analysis. The flowsheet of the research method is shown in Figure 2 below.

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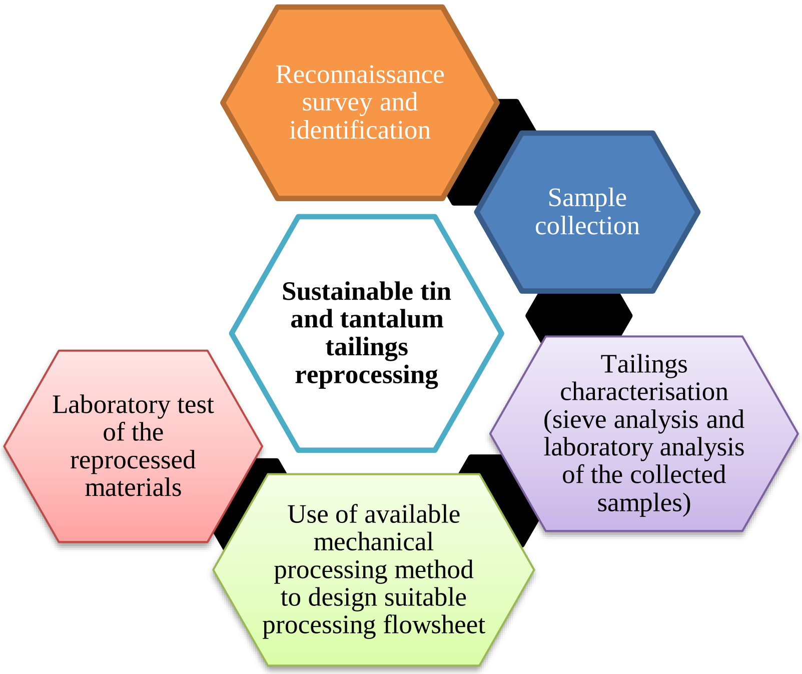

Figure 2. *Conceptual framework of this research*

At HABATU mine, we visited the site, observed the run of mine and mineral handling and we collected samples for analysis. In this research, geological hammer for sampling, Geographic Positioning System (GPS) for taking geographical locations, plastic sample bags for sample collection, pickaxes, spade, sieve sample, sample splitter, sample pulverizer, jaw crusher, two roll crushers, and shaking table were used.

Samples were collected by cone and quartering of run of mine and tailings and tested chemically and physically. Furthermore, the sample was put through various mechanical processing equipment to study the viability of reprocessing. The concentrate and tailings from such processing plants were tested using XRF to determine their efficiency. Furthermore, the artisanal processing method (Figure 3) was compared with the proposed mechanical processing method proposed by this research (Figure 5).

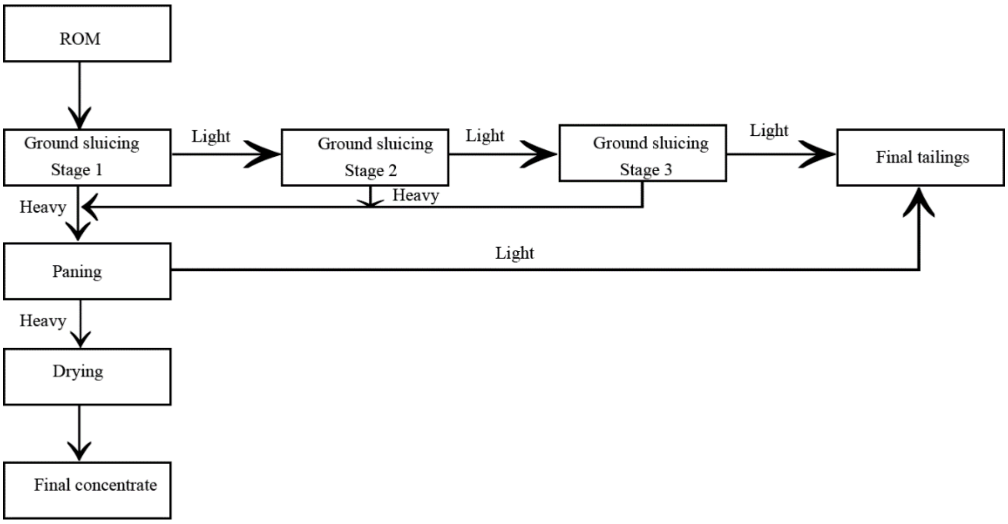

Figure 3. *Flowsheet of artisanal processing method currently used at Habatu mining company*

3.1 Sampling and Sample Preparation

Multi-increment (gridding) sampling was used to sample HABATU mining company tailing dams and ROM which entails collecting increments from different portions of the tailing dam and mixing them to get a bulk sample. To be sampled for analysis, two productive sites were chosen. One is still operational, while the other has ceased operations but still has enough tailings to be analyzed. Three types of samples were taken: a pegmatite run-of-mine sample, pegmatite tailings sample, and quartz tailings sample. Each tailing dam to be sampled had an area of 40 to 50m and a depth of 6m. The tailings dam was divided into at least 30 cells of roughly equal surface area. Among 30 cells each of 8.25m to 8m, only 5 cells were chosen for sample collection.

Figure 4. *Tailing dams at Habatu mining company*

To avoid any errors induced by surficial pollution such as rainfall, humidity, and temperature, the tailings from 2cm below the surface were discarded. Increments of roughly equal mass (at least 200kg) are collected from 2cm to the bottom to the maximum of 5m of the cell with a spade and pickaxe (Table 1).

Table 1. *Quantity of samples collected for the test*

Sample	Description	Total mass (kg)	Mechanical test	Sieve test	Chemical test
Site 1B	Quartz vein	208kg	200kg	2kg	2kg
Site 2 and 1A	Pegmatite vein	408kg	400kg	4kg	4kg
ROM	Pegmatite vein	24kg	20kg	2kg	2kg

This method was chosen to clearly understand each layer's characteristics in each hole. Particles of any size were included during the collection procedure and wet samples were air-dried in each case, the bulk sample from each dam was mixed on a smooth flat surface to obtain homogeneous samples and weighted to be 1 ton. After that, the sample was coned and quartered four times to get a representative sample for analytical tests. Using this method, the team created one representative sample of 4:1 ratio of the bulk sample.

3.2 Analytical Methods

Three main artisanal processing tests such as sieve (grain size distribution), physical separation (mechanical processing), and chemical test (Figure 5) were performed to determine the quantity and quality of ore mineral lost in tailings and propose a suitable processing method.

3.2.1 Artisanal Processing Method

Artisanal processing test was conducted using linear ground sluicing, made up of three sluicing ponds to process 21000kg of run-of-mine (Figure 3). Once the sluicing process was completed, panning was used to improve the grade of the concentrate by removing the remaining gauges.

3.2.2 Sieve Test (Grain size distribution test)

Sieve samples were tested using two sieves, one with 2 mm and the other with 1 mm diameter, to acquire three distinct portions of the samples (the coarse fraction (greater than 2 millimeters), the fine fraction (between 1 millimeter and 2 millimeters), and very fine (<1 mm)). Because of the diverse mineralogical backgrounds of the investigated deposits, the samples reveal variable grain size attributes. To create a homogeneous tailings mixture, each fraction sample was mixed, coned and quartered to create a representative sample for the chemical test.

3.2.3 Mechanical Test (physical separation)

Mechanical processing tests were carried out at Piran Resources' processing plant in Rwamagana. This plant served as the foundation for a full processing setup, along with a preliminary stage with various size reduction machines, a shaking table, and a magnetic separator. Before sorting, the fractioned sample was subjected to multiple comminution and screening steps. The dressing action was done on a single shaking table. A water distributor was used to keep the flow of water on the table constant. The feed was separated into concentrate, middlings, and tailings tanks by the slope of the table, the flow of water, and the constant vibration of the table.

3.2.4 Chemical Test

The quantitative and qualitative metal concentrations in both ROM and tailings samples were determined using mounted X-ray fluorescence (XRF). A 2 kg sample to be tested was pulverized up to 38 micrometers and split to get 200 grams. This test aimed to track the amount of SnO_2 and Ta_2O_3 in the samples and detect any chemical contaminants that could be present.

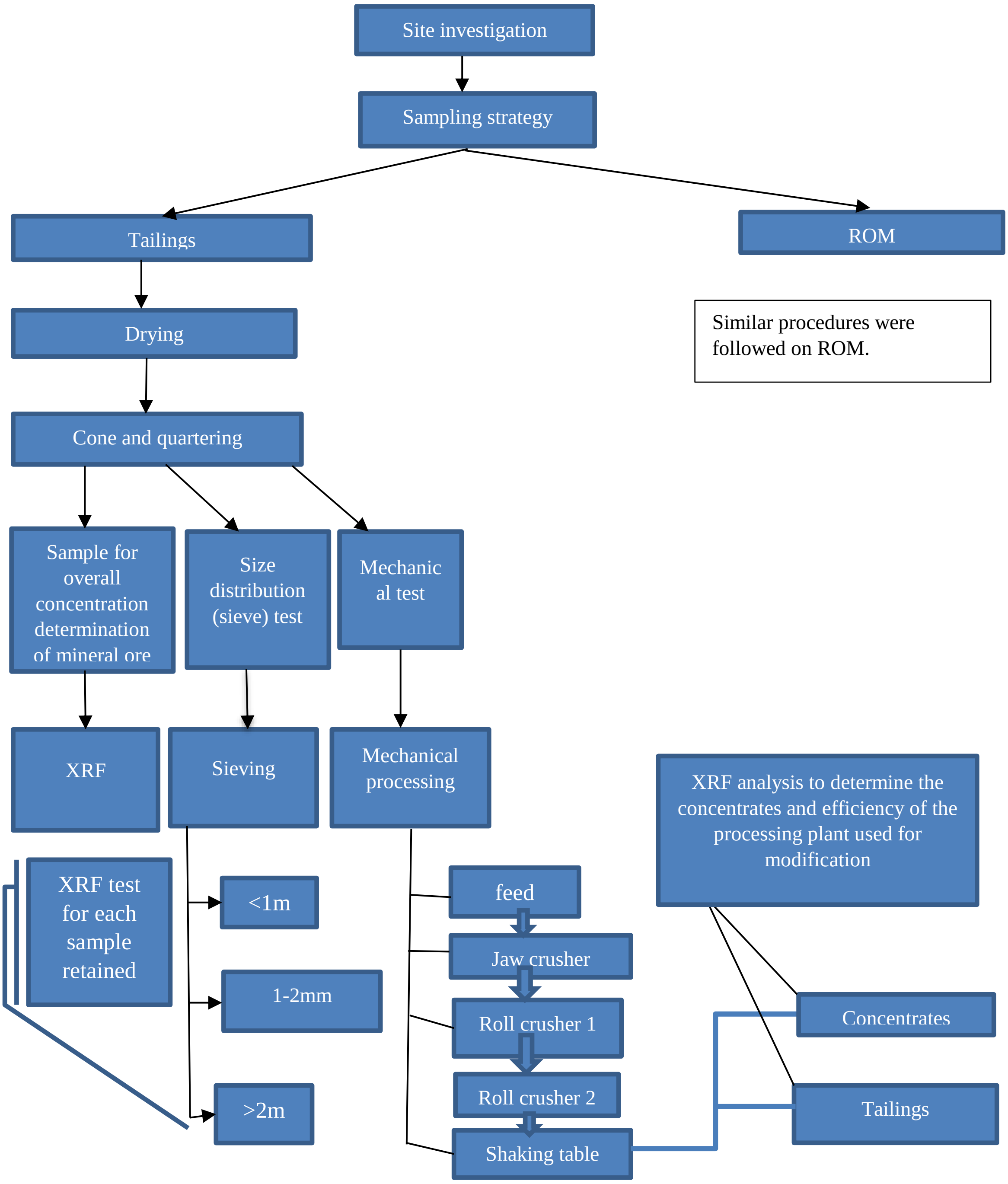

Figure 5. *The proposed flowsheet of tin recovery used in this research*

4 RESULTS AND DISCUSSION

4.1 Sieve Test (Grain size distribution)

The general grain size distribution features of the sampled ROM and tailings from quartz and pegmatite veins are shown in Table 2. The grain-size distributions in the sub-samples differ significantly. Approximately 67.5 % of the ROM is found in a fraction less than 2 mm, which is nearly equivalent to its tailings, which contain 68.75 %. This was due to varying degrees of weathering; and only 40 % of quartz tailings fall into this category. The quartz vein tailings sample was found to contain a proportion of coarse grain-size compositions, occupying 60 % of the fraction greater than 2 mm due to its high resistance to weathering. The other samples, on the other hand, comprise 32.5 % and 31.5 % of ROM and pegmatite tailings, respectively.

Table 2. *Grain size distribution properties of the sampled ROM and tailings*

Subsamples	**Total mass**	**> 2mm**	**1mm–2mm**	**< 1mm**
ROM	2 kg	0.65 kg = 32.5 %	0.4 kg = 20 %	0.95 kg = 47.5 %
Tailings from pegmatite vein (mixed coltan and Cassiterite from site 1A and 2)	4 kg	1.25 kg = 31.25 %	0.95 kg = 23.75 %	1.8 kg = 45 %
Tailings from quartz vein (Cassiterite from site 1B)	2 kg	1.2 kg = 60 %	0.6 kg = 30 %	0.2 kg = 10 %

4.2 Chemical tests result in overall samples

The results from the chemical tests were found to contain an average SnO_2 content of 0.302 % and a Ta_2O_5 with concentration of 0.023 % in pegmatite run-of-mine. In Quartz tailings an average SnO_2 content of 0.385 % and a Ta_2O_5 concentration of 0.063 % were found while pegmatite tailings contain a SnO_2 content of 0.224 % and a Ta_2O_5 concentration of 0.059 %. Ta_2O_5 concentration was found to be low and may not be economical for extraction.

4.2.1 Chemical analysis of sieve samples

All grain-size fractions of the above-mentioned sieve results (Table 2) were chemically tested and analyzed using Microsoft excel. Figure 6 illustrates the variation of the relevant target minerals in various particle sizes distribution. The grain-size fraction is depicted on the x-axis. The percentages of SnO_2 and Ta_2O_5 ore minerals contained in each fraction concerning the total mineral of interest contained in samples of a run of mine are shown in brown, yellow and brown dots, respectively. At the primary y-axis, the distribution is quantified. The brown and blue columns represent the target mineral grade (SnO_2 and Ta_2O_5, respectively) in every portion corresponding to a secondary y-axis.

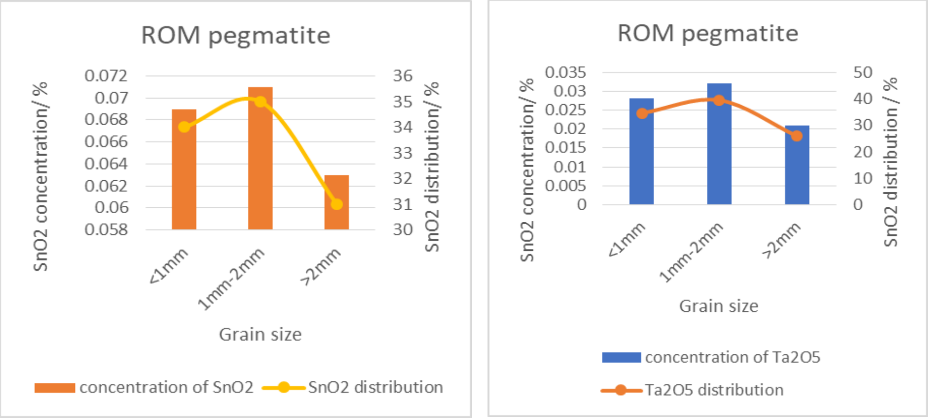

Figure 6. *Grain size distribution properties of the sampled ROM and their target mineral composition*

Figure 7 represents the target mineral distribution where the highest concentrations of the target in pegmatite run-of-mine samples were found in fractions ranging from 1mm to 2mm. This is because the pegmatite has weathered, and concentrations are larger at the size that is smaller because they offer a much more particular area. This graph shows a share of 34 % of the total sample of SnO_2 in the fraction less than 1mm while for the fraction between 1mm and 2mm it shares rises by 1 % to 35 %. The lowest peak of SnO_2 is found at the coarse fraction (>2mm) of 31 %. Similarly, the greatest peak of Ta_2O_5 is discovered in the portion between 1-2 millimeters and has a 39.5 %. For the fraction, less than 1 mm Ta_2O_5 has the same share of the total sample similar to SnO_2 which is 34 % while for the coarse fraction it has the lowest peak of 25 %. In general, it was observed that SnO_2 is 4.5 % greater than Ta_2O_5 at size fractions ranging from 1mm to 2mm, the same share in a fraction less than 1mm and 5 %, for the coarse fraction size. For the pegmatite tailings the target minerals were found to be distributed unusually. Most of the target mineral (41 % SnO_2) was discovered in fractions less than 1 mm. This is because smaller sizes have higher concentrations of ore minerals due to weathering. After all, they provide more specific part and the artisanal ground sluicing method used do not capture thin particles which make them lost in tailings. The graph shows the share of 34 % of the total sample of SnO_2 in the fraction less than 1mm while for the fraction between 1mm and 2mm and coarse fraction, it shows an equal share of 33 %.

The greatest peak of Ta_2O_5 is found in the fraction less than 1mm and was 40.7 %. Ta_2O_5 has the same share of 37.3 % for the fraction of between 1 and 2 mm and the lowest peak of 22 % for the coarse fraction. In general, it was observed that SnO_2 is 0.3 % and 11 % greater than Ta_2O_5 at size fractions ranging from less than 1 mm and greater than 2 mm respectively, while Ta_2O_5 is 7.3 % greater than SnO_2 at the fraction between 1mm and 2 mm.

In general, the concentration of the target minerals was observed to be found in the fine fractions less than 1 mm and coarse grain sizes greater than 2 mm. This is due to the processing methods of ground sluicing and panning, which have a low efficiency of recovering fine grains and a lack of appropriate comminution to recover interlocked minerals in large-sized rocks. Distinct distribution of the target mineral was detected in the quartz vein tailings. The majority of the target mineral was discovered in portions less than 1 mm and greater than 2 mm. According to the study, the tiny granules under 1 mm account for 41.3 % of the SnO2.

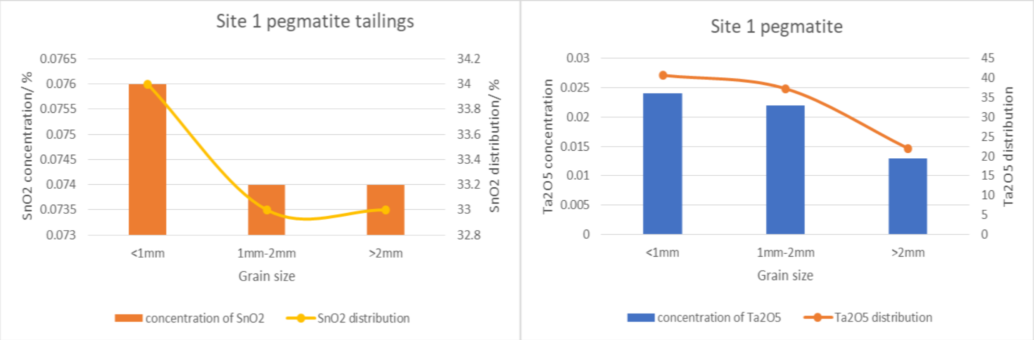

Figure 7. *Grain size distribution properties of the sampled pegmatite tailings and their target mineral composition*

In a fraction between 1mm and 2mm, approximately 24.4 % of the total SnO2 was obtained. Above 2 mm, 34.3 % is enclosed. The fine fractions below 1mm contain 41.3 % of the target minerals. It was observed that the target mineral concentration is strong for fractions less than 1 mm and larger than 2 mm. This demonstrates that the processing method utilized is inadequate in terms of comminution and separation, resulting in the retention of thin particles. The largest distribution (41.2 %) of Ta_2O_5 was found at fractions bigger than 2 mm. This is because minerals are trapped in large-sized quartz and are left in tailings owing to inadequate communication. The Ta_2O_5 share in the fractions between 1 and 2 mm is 39.7 %, while the lowest share is 19.1 % in the fractions smaller than 1 mm. In general, SnO2 distribution is 22.2 % bigger than Ta_2O_5 distribution at sieves smaller than 1 mm, while Ta_2O_5 shares are 14.7 % and 6.91 % more than SnO_2 shares at sieves 1 mm to 2 mm and larger than 2 mm, respectively.

4.3 Artisanal and mechanical processing result

The artisanal processing method and mechanical method were tested, and the results presented in Table 3.

Table 3. *Recovery mass from mineral processing*

Processing method	Item	Total feed	Recovery mass
Artisanal processing method	ROM (pegmatite vein)	21000 kg	35 kg
Mechanical processing method	ROM (pegmatite vein)	20 kg	60g
	Pegmatite tailings	400 kg	275g
	Quartz tailings	200 kg	300g

Table 3 shows the results from different processing methods used. Artisanal dressing method was used to process 21000 kg of ROM only 35 kg were recovered, about 20 kg of ROM used in mechanical processing test that recovered 60 g of concentrate, this show that using mechanical processing method 63 kg can be recovered from 21000 kg of ROM. Quartz tailings were found to have a lot of ore left in tailings compared to pegmatite due to the lack of comminution.

Equations 1 was used to calculate the mineral recovery of the mechanical method and artisanal processing method from tailings and ROM of pegmatite veins (Table 4). The chemical analysis revealed the concentrate grade and concentration, as well as feed values.

The formula for calculating percentage recovery is as follows:

$$R = 100\frac{Cc}{Ff} \qquad (1)$$

where R = percentage recovery, C = weight recovered of concentrate, c = assay of concentrate, F = weight of concentrate, and f = assay of concentrate.

Table 4. *Comparison of artisanal processing and mechanical processing method*

Processing method	Findings	SnO_2 grade (%)	SnO_2 recovery (%)	Additional recovery (%)
Artisanal processing (ROM)	Concentrate	81.353	44.8	
	Tails pegmatite	0.224		
Mechanical processing (ROM)	Concentrate	89.304	88.7	43.9
	Tails	0.04		

The recovery rate of both the mechanical processing method and the artisanal method is shown in Table 4. As seen artisanal processing has a low recovery of SnO_2 of 44.8 % leaving above 50 % in tailings. The reason for this loss may be due to inefficient processing methods used that do not recover fine grain ore, most of lost ore in tailings was discovered in grain sizes smaller than 1 mm. Furthermore, target minerals in grain size greater than 2 mm were found in tailings and were lost due to inadequate comminution. The mechanical processing method has the highest recovery of 88.7 % with an additional recovery of 43.9 % compared to the artisanal processing method. Therefore, the mechanical processing method can be used to recover lost ore from artisanal tailings.

Table 5. *Performance of mechanical reprocessing of tailings*

Item	Results	SnO_2 grade (%)	SnO_2 recovery (%)
Pegmatite tailings	Concentrate	63.244	19.4
	Tails	0.023	
Quartz tailings	Concentrate	76.635	29.9
	Tails	0.049	

As shown in Table 5, the mechanical processing method was used to recover lost target minerals (SnO_2) in the artisanal processing method. Under comminution and gravity separation, SnO_2 recovery of 19.4% and 29.9% with a grade of 63.224 % and 76.6 % were obtained in pegmatite and quartz tailings respectively. Despite the absence of choices for optimum process water flow calibration and shaking table inclination, mechanical processing used, was shown to be more efficient than traditional artisanal processing. It successfully recovered non-magnetic minerals from tailings.

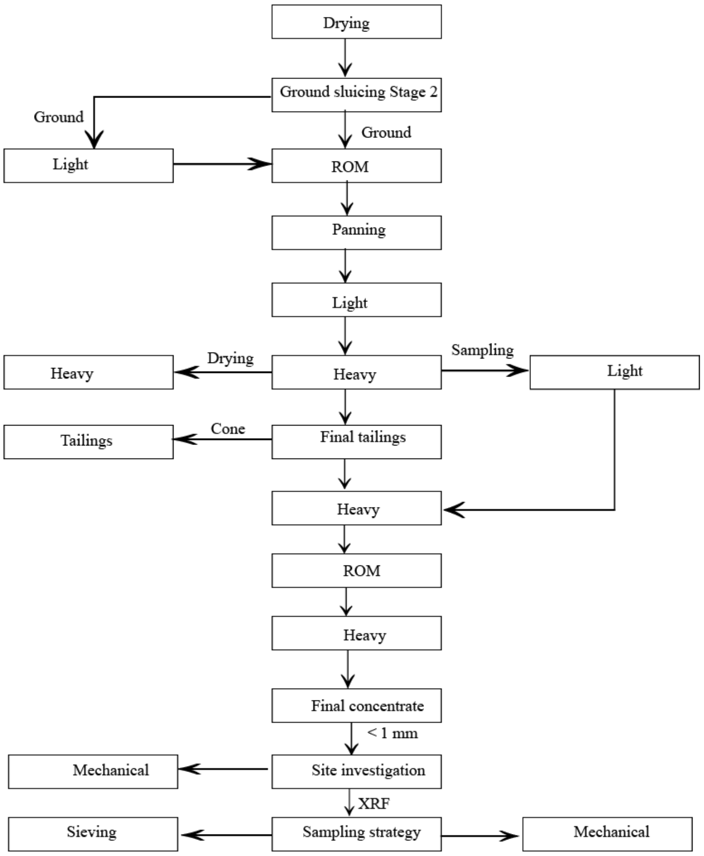

Figure 8. *Suitable flow sheet of tailings reprocessing*

The estimated 17,158 tons of tailings at the Nyamatete concession contain 25,737 kg of SnO_2 and 203.4 kg of Ta_2O_5 from quartz tailings. The estimated 87,527 tons of tailings at the Nyamatete concession include 60,175 kg of SnO_2 and 309.3 kg of Ta_2O_5 from pegmatite tailings. Quartz tailings are notably exceptional due to artisanal processing's poor comminution, as evidenced by the fact that 60 % of the target mineral is found in fractions larger than 2 mm and contains concentrate. This shows that proper comminution was required to liberate the target mineral. Furthermore, because the grade of 2.6 % and 0.288 % Ta_2O_5 were not economical; the separation from SnO_2, using a magnetic separator was not required. Therefore, a mechanized mineral processing technique to Recover Tin and Tantalum ores should be employed to increase the productivity.

5 CONCLUSION

This research focused on the possibility of tailings processing at the Habatu Mining Company limited and the influence of the ore body's characteristics on existing tailings processing procedures, such as ground sluicing and panning. On the other side, a conceptual framework was established and used to systematically produce important information and knowledge regarding Nyamatete concession tailings dams in Rwanda's Rwamagana area. The goal of the conceptual framework was to determine the amount of lost ore in tailings and create effective and efficient ways for recovering minerals from tailings while leaving a stable and ecologically friendly residue. All research hypothesis was answered from the tests and their analysis. The target minerals were found to be lost in tailings due to the nature of the host rock, ore characteristics, and the artisanal processing method used. Data on the ore's mineralogical characteristics, as well as the size and geometry of the ore body, must be obtained. Various mechanical handling schemes should be evaluated before investing in a processing facility, the mechanical processing plant used had several limitations, including the fact that it was designed to recover coarse ore, had only a single shaking table, lacked calibration, and a blinding machine. This could be enhanced using a series of shakers with varying degrees of capacity to keep size up to fine grains, as well as a grinding mill for adequate comminution, which is likely to be a good strategy that resulted in the proposed more precise processing plant. Different processing methods rely on exact size distribution to function successfully, hence the grain size distribution of the treated material has a considerable impact on the processing method. A feed with a slim grain size distribution, for example, is much more likely to achieve a high recovery rate. Therefore, multiple screening and comminution processes are required before sorting if the feed contains a variety of grain size distributions.

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