Development of a physical separation pre-concentration process for the extraction of Rare Earth bearing ore

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Dates:
Received: 29 May 2024
Accepted: 2 July 2024
Published: October 2024

How to cite:
Mokgomola, T., Marape, G., Singh, A., and Bisaka, K. 2024. Development of a physical separation pre-concentration process for the extraction of Rare Earth bearing ore. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 124, no.10, pp. 567–574

DOI ID:
http://dx.doi.org/10.17159/2411-9717/695/2024

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This paper is based on a presentation given at the Southern African Rare Earths 2nd International Conference 2024, 19-20 June 2024, Swakopmund Hotel and Entertainment Centre, Swakopmund, Namibia

Abstract

This paper investigated the pre-concentration amenability of sovite (carbonatite) ore to enhance the grade of rare earth elements (REE) bearing minerals by rejecting calcite, and to improve total rare earth elements (TREE) recovery using gravity and magnetic separation. A high proportion of calcite affects downstream processes like leaching due to high acid consumption. Multiple flowsheets combining gravity and magnetic separation were employed to target > 60% TREEs recovery to the final concentrate and > 60% calcite rejection to the tailings. Head analysis of the feed showed the sample's main constituents as Fe (15.61%), Ca (16.04%), SiO_2 (7.13%), and lastly TREEs (1.12%). Mineralogy liberation data at 2mm top size indicated poor liberation of TREEs, with the majority of minerals displaying < 30% mass greater than 80% liberated. Grain size distribution data showed that the majority of REE minerals are fine grained and report to the < 20 µm size class. Calcite liberation mineralogy showed < 60% mass greater than 80% liberation.A combination of a single-stage shaking table with a wet high intensity magnetic separator at a magnetic intensity of 7520 G was found to be the optimum flowsheet. For a shaking table feed with P_{80} of 150 µm followed by tails regrind to P_{80} of 45 µm as feed to wet high intensity magnetic separator, the overall mass balance results showed that 60.5% TREEs are recovered to the concentrate while 63.0% calcite is rejected to the tails. However, due to the fine-grained nature of TREEs, no flowsheet improved their grade.

Keywords

Sovite, total rare earth elements (TREEs), calcite, wet high intensity magnetic separation (WHIMS), low intensity magnetic separation (LIMS), shaking table (ST)

Introduction

In recent years, worldwide investment in the recovery of rare earth elements (REE) has been financed due to their increasing use in modern high technology industries. REEs are included in a growing list of critical raw materials (Berger et al., 2014; Sager and Wiche, 2024). REE's primary recovery from value bearing ores is costly due to low concentrations within the ore. According to Sager and Wiche (2024), the concentration of REEs in the earth's crust ranges from 66 mg/kg (Ce) to 0.3 mg/kg (Lu). For the extraction of REEs minerals for valuable and raw material to be feasible, various REEs beneficiation processes have been established and others are currently being explored to upgrade and recover REEs at optimum costs.

Rare earth elements (REEs) are comprised of seventeen chemical elements in the periodic table. Among the seventeen, fifteen of them are lanthanides and the other two are yttrium and scandium, which occur in the same ore deposits as lanthanides and exhibit the same chemical properties (Hoshino, et al., 2016; Sager and Wiche, 2024). Yttrium was the first REE discovered by chemist Johan Gadolin in 1794 and promethium was the last REE discovered approximately 150 years later in 1947. REEs are found within other minerals in the earth's crust, as they do not occur individually (Hoshino et al., 2016). REEs are critical raw materials for modern technologies ranging from cellphones, magnets, and LED lights to wind turbines due to their properties like magnetic, catalytic, and phosphorescent properties (Frances, 2021).

In this paper, the mineral of interest is sovite ore originating from Southern Africa. The ore is carbonatite or calcite rich, thus making calcite the main gangue mineral. According to Frances (2021), the majority of operational REEs mines are carbonatite-related deposits. This paper thus focuses on the rejection of calcite to improve the recovery of REEs, which is important in the mining industry.

This paper aims to provide an economically viable route to recover REEs and reject calcite from sovite ore using gravity and magnetic separation techniques according to the properties of the valuable and the gangue minerals within the ore. To achieve this, ore characterization using elemental chemical analysis followed by bulk modal mineralogy using AutoSEM technology was conducted.

Gravity separation methods are the most commonly used beneficiation methods employed to exploit the density differences between valuable minerals and the gangue within a given ore. The method uses the differential settling velocity between particles. This settling velocity is governed by particle weight, buoyancy and drag force (Roy, 2009; Murthy and Tripathy, 2020). It is the oldest beneficiation technique and is widely used due to the associated low costs, simple operating procedures, and its eco-friendly nature. The most popular gravity separation units used for wet processes are shaking tables, jig, and spirals (Roy, 2009).

Gravity separation units are selected based on particle size and the capacity of the unit. Gravity separators provide peak performance when operated in optimum conditions and the right feed particle size range for a given material. The biggest challenge for most gravity separation methods has been fine and ultrafine particles (Murthy and Tripathy, 2020). For this paper, due to limitations in feed mass, a flowing film gravity concentrator such as the Wilfley shaking table was utilized. Tabling of ores is efficient when the differences in specific gravity between the minerals is high (Roy, 2009).

Magnetic separation methods are employed to exploit the differences in magnetic properties of minerals within a given ore. This technique uses magnetism to separate materials that respond more strongly to a magnetic force from materials that exhibit a weak response. It is a newer process when compared with gravity separation but old when compared with froth floatation methods.

Selection of a magnetic separation unit or mechanism is based on the magnetic properties of the given mineral. Some materials are ferromagnetic, paramagnetic and others diamagnetic. Ferromagnetic materials require a low magnetic intensity for separation, whilst paramagnetic materials require a high magnetic intensity to be susceptible to the magnetic forces. According to Cohen (1986), only four elements namely cobalt, iron, gadolinium, and nickel are ferromagnetic but seven REEs are strongly paramagnetic.

Most minerals are weakly paramagnetic or diamagnetic and their magnetic susceptibilities are constant and show straight-line relationships to the strength of the magnetic field exerted on them. Paramagnetic minerals have a higher magnetic permeability compared to their surrounding media making it easier for the particle to move in the direction of the field strength due to high field density within the particle. On the other hand, diamagnetic minerals have lower magnetic permeability than the surrounding media (Cohen, 1986). In this research, both low and high magnetic intensity (LIMS and WHIMS) separators were used to determine the optimum flowsheet for REE recovery whilst rejecting calcite.

Methodology

Figures 1 to Figure 3 shows the schematic diagrams of flowsheets used for the procedures of characterization and the different possible combinations of magnetic and gravity separation flowsheets.

Head and mineralogy

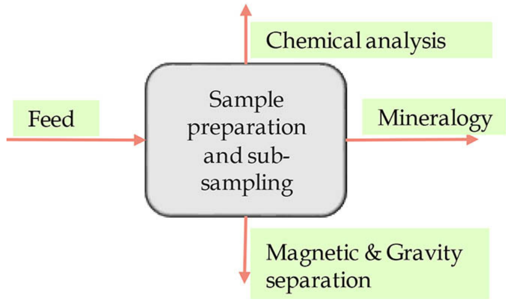

Figure 1—Characterization schematic diagram

Sample receipt and preparation

Approximately 280kg of sovite feed sample was delivered for testwork purposes. The sample was at a top size of 1/4 core pieces, so roughly 10 mm x 10 cm pieces and dry upon receipt. The sample was weighed, blended, stage crushed using Jaw and cone to 100% passing 20 mm, and then subsampled using cross-cut method for coarser sizes for various tests according to the scope of the testwork. The subsamples were stage crushed to 100% passing 2 mm for mineralogy, 100% passing 1mm for particle size distribution and head analysis and 2 mm for ball milling to P_{80} = 300 µm, 150 µm, 106 µm, 53 µm and 45 µm. The finer fractions, that is, -2 mm, samples, were subsampled using the rotary splitter.

Elemental chemical analysis on the sovite ore was done using ICP base metal, and REE solid digestion methods to determine the grade of calcite, REE, and Fe. Mineralogical analysis on the sample was carried out using quantitative X-ray diffraction (qXRD), scanning electron microscopy (SEM), and automated scanning electron microscope (AutoSEM) analysis. The purpose of the

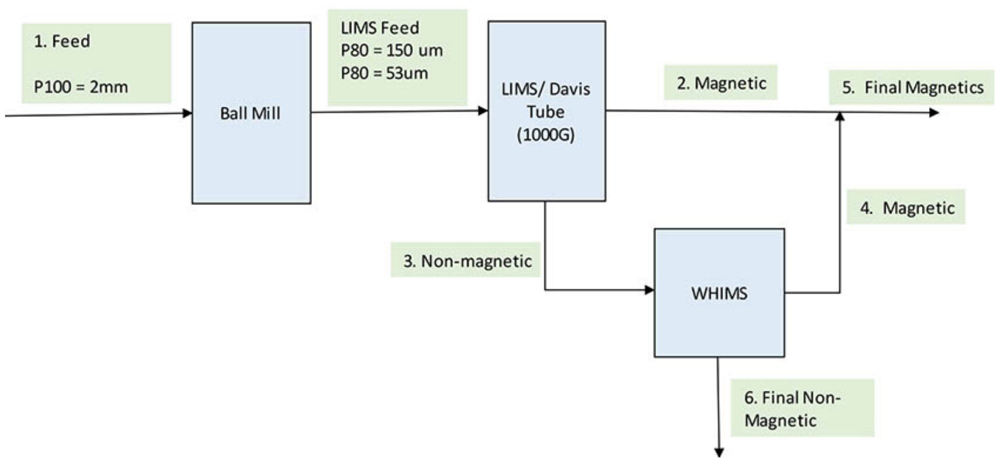

Figure 2—Typical magnetic separation schematic diagram

investigation was to establish the presence, identity, and relative abundance of minerals as well as to obtain information on REE minerals in terms of their mode of occurrence, relative abundance, REE deportment, and grain size, liberation at a top size of 100% passing 1.18 mm, mineral associations and bulk modal mineralogy.

Magnetic separation

Figure 2 shows a typical magnetic separation flowsheet comprising of Ball mill, LIMS and WHIMS.

Davis tube testwork

To determine the percentage of ferromagnetic material in the sample, magnetic separation was conducted using an electromagnet Davis tube as depicted in Figure 2. The separation occurs by exploiting the high susceptibility of ferrous material in the sample to magnetic forces. The sample was fed at P_{80} of 53 µm and tested at a magnetic field intensity of 1000 G. The non-magnetic products were sent to the WHIMS equipment.

Laboratory Wet LIMS and WHIMS Testwork

As per Figure 2, laboratory wet LIMS testwork, using a permanent magnet at a magnetic field intensity of 1000 G, was conducted on the feed at P_{80} of 150µm to recover ferrous material in the feed before WHIMS testwork.

The non-magnetic material was subjected to WHIMS at four intensities (2000 G, 4000 G, 6000 G, and 7520 G) to determine the intensity that will reject calcite and improve the grade of REE. This testwork was conducted five (5) times across multiple flowsheet combinations with shaking table tails and slimes as feed (Figure 3), and the Davis tube and LIMS non-magnetic streams as feed (Figure 2).

Laboratory dry LIMS

The roasted feed at a P_{80} of 150 µm was subjected to dry magnetic separation using laboratory high-intensity induced-roll lift type magnetic separator at seven magnetic intensities (800 G, 850 G, 870 G, 900 G, 920 G, 950 G, and 1000 G). The sample contained hematite, thus roasting of the sample at 1000°C increased the magnetic susceptibility for low intensity dry magnetic separation.

Combined gravity separation and magnetic separation testwork

Figure 3 shows the schematic diagram used for the combination of shaking table with magnetic separation.

Shaking table testwork

The shaking table test was conducted six times across multiple flowsheets for calcite rejection using the density difference between REE, Fe, and Ca. The shaking table consists of a slightly inclined deck that exposes particles to gravitational, vibrational, and flow water forces allowing the particles to separate due to their difference in density, shape, and size. The shaking table produced nine (9) products namely four concentrates, two middlings, two tails, and one slimes stream. Shaking table was conducted at P100 of 1.18 mm, P_{80} of 300 µm, 150 µm (three times) and 106µm (Scavenger in a flowsheet). The tails from shaking table at P100 = 1.18 mm, were subjected to WHIMS to form flowsheet 7 as shown in Table II. The slimes and tails of these tests were milled to P_{80} of 45 µm for magnetic separation using WHIMS, with the exception of WHIMS on shaking table tests tails at P100 = 1.18 mm.

Results and discussion

Head analysis and mineralogical evaluation

Table I shows the chemical composition of the sovite ore. It is observed that the REE collectively constitutes 1.12% of the sovite ore. The %Fe was higher than expected at 15.61% with %Ca at

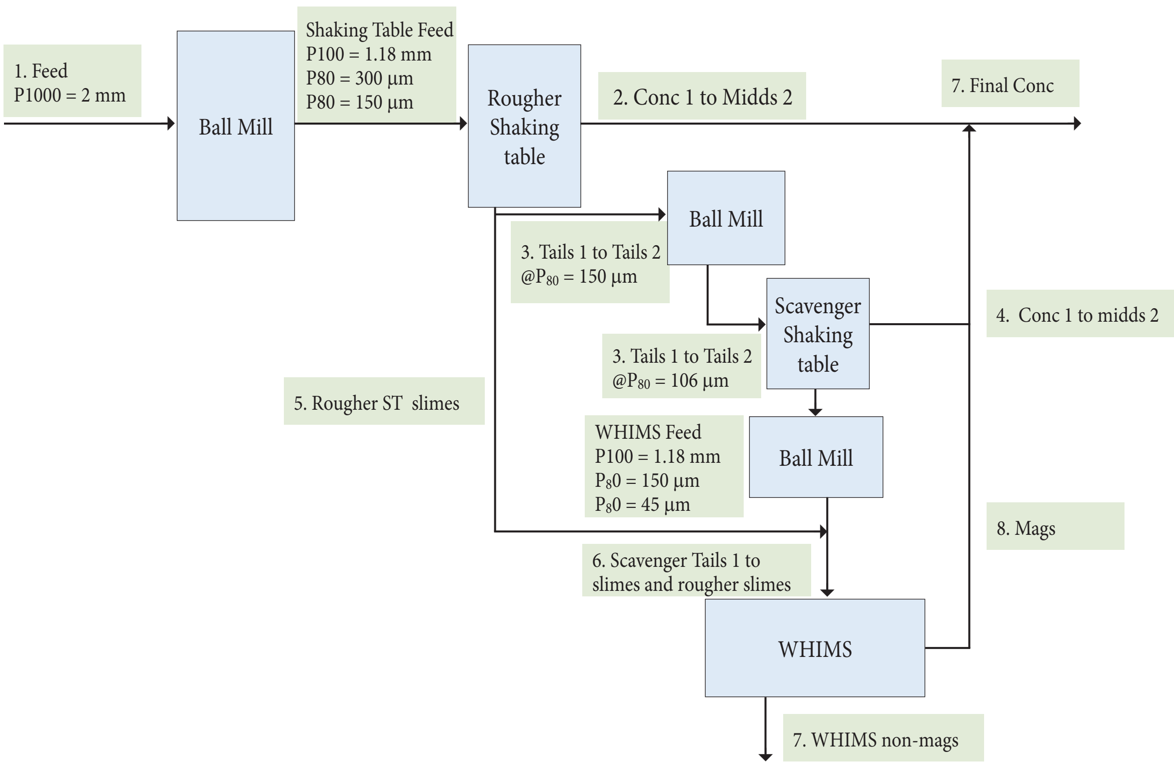

Figure 3—Schematic diagram of shaking table and WHIMS

Table I

Sovite ore head grade

	Grade (%)									
	Fe	Ca	$CaCO_3$	MgO	MnO	SiO_2	TREE	Th	U	C
Head 1	15.62	15.92	39.81	4.08	4.05	7.01	1.15	0.05	0.00	8.13
Head 2	15.59	16.15	40.38	4.13	4.06	7.25	1.09	0.05	0.00	8.17
Head average	15.61	16.04	40.10	4.10	4.06	7.13	1.12	0.05	0.00	8.15

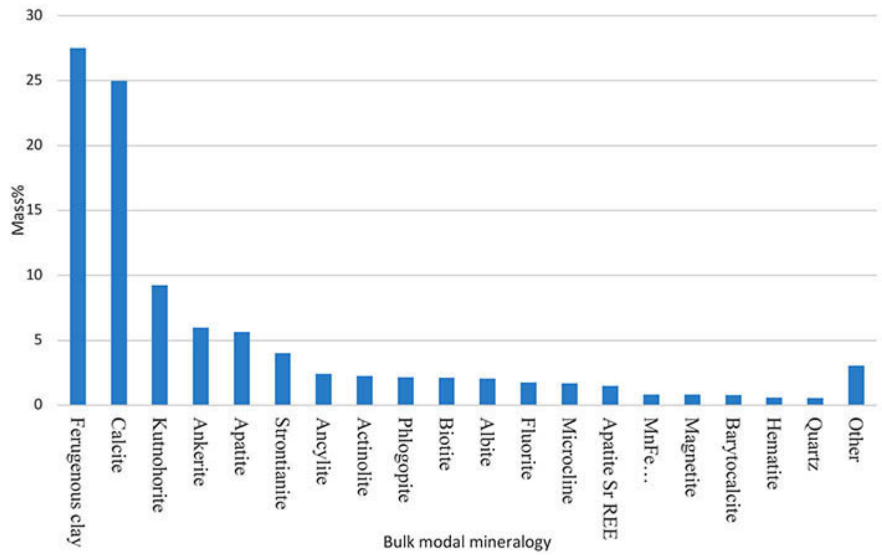

Figure 4—Bulk modal mineralogy

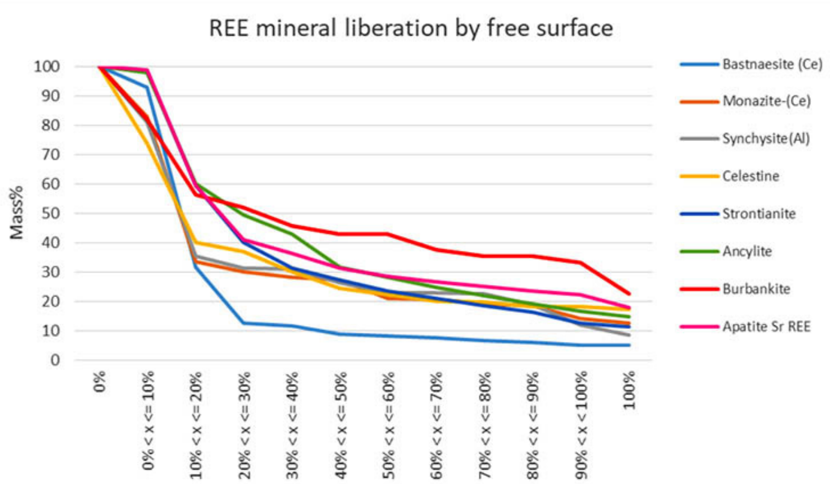

Figure 5—REEs minerals cumulative liberation by free surface

16.04% (40.10% $CaCO_3$). Bulk mineralogy of the samples (Figure 4) shows that the ore predominantly consists of ferruginous clay, calcite and kutnohorite.

REEs and calcite minerals liberation and grain size distribution

Liberation characteristics of cumulative REE and calcite minerals by free surface and particle composition are presented in Figure 5 to Figure 8. Liberation classification by particle composition is based on area percent of the mineral of interest (e.g., TREE) over the total area of a particle. Liberation classification by free surface is based on the degree to which valuable minerals within the ore have a free surface after crushing, making them accessible for separation and concentration processes. Liberation classes are defined in 12 groups ranging from 0% to 100% area, in 10% intervals and reported by cumulative liberation by area. Results in each class are cumulated from 100% liberated to 0 % liberated.

With the exception of burbankite, the majority of REE minerals display poor liberation by both particle composition and free surface liberation with the majority of minerals displaying <30% mass greater than 80% liberated.

Calcite displayed <60% mass greater than 80% liberation by both particle composition and free surface liberation.

Grain size distribution

Size is reported in equivalent circle diameter (ECD), which is the diameter of a circle of equivalent area to that of the grain, in microns. Grain sizes are based on the average horizontal intercept through a grain and are measured on a two dimensional surface. The grain sizes of the minerals of interest are divided into size classes using ECD and presented in mass percentage. Grain size distribution is presented in Figure 9.

With the exception of bastnaesite (Ce), strontianite, and ancylite, the majority of REE minerals are finer grained and report to the <20 µm size class.

Overall comparison of flowsheet options

Due to multiple flowsheets used to generate an optimum flowsheet for calcite rejection and REEs recovery, the feed, concentrate, and tails of each flowsheet are presented in Table II and discussed in the following paragraphs.

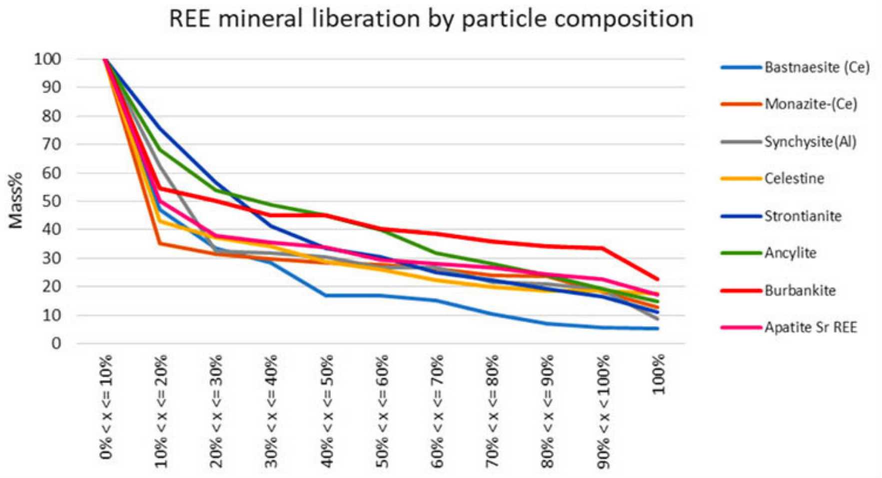

Figure 6—REE minerals cumulative liberation by particle composition

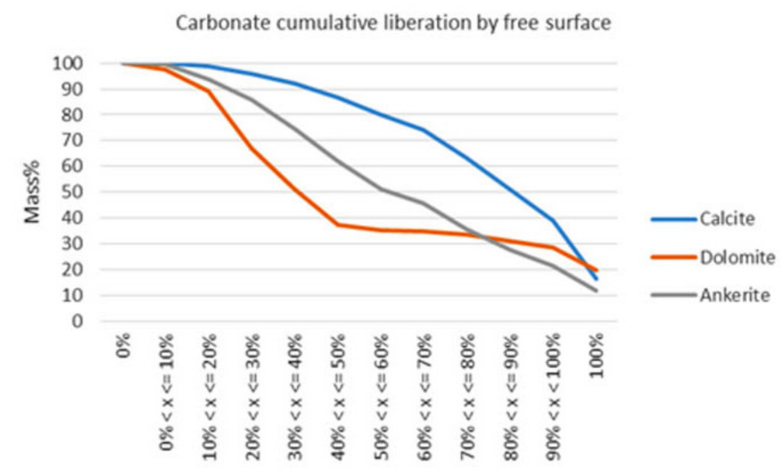

Figure 7—Carbonate mineral cumulative liberation by free surface

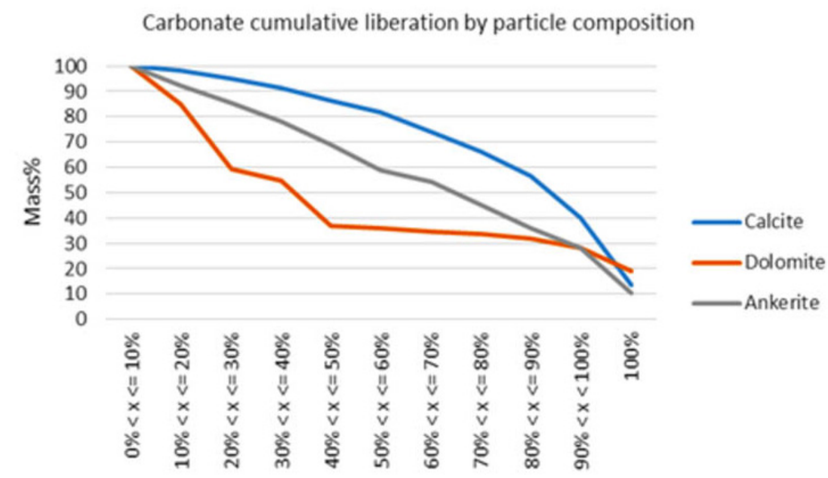

Figure 8—Carbonate mineral cumulative liberation by particle composition

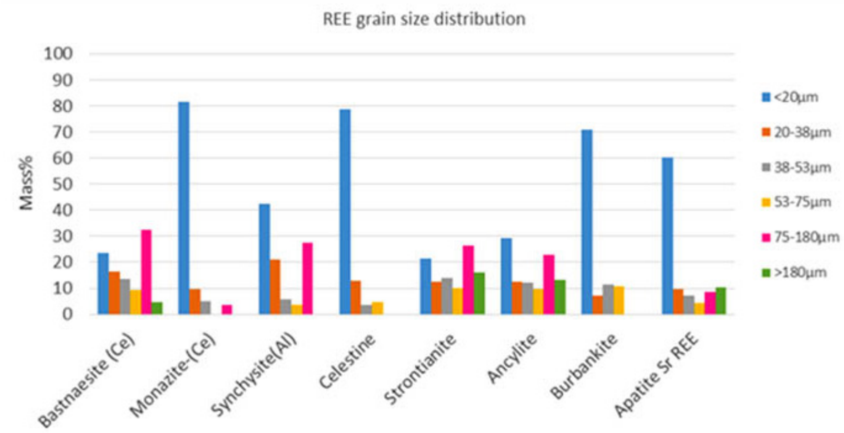

Figure 9—REE minerals grain size distribution

Table II presents the Davis tube and WHIMS results at magnetic field intensities of 1000 G and 7520 G, respectively at a feed grind of P_{80} 53 µm (Flowsheet 1). Davis tube was conducted to determine the fraction of ferrous material in the sample, and only 1.6% by mass reported to the magnetic stream suggesting the feed was predominantly paramagnetic. The overall mass balance results showed that at a WHIMS magnetic intensity of 7520 G, Ca rejection to the non-magnetic stream was 24.1% Ca not meeting target specification. At this intensity, about 12.3% TREE is lost to the waste stream at a grade of 1.00%. This flowsheet could not be optimized due to failure to reject Ca to the non-magnetic stream. A high proportion of calcite affects downstream processes such as leaching leading to high acid consumption (Thomas, 2021). To solve this problem gravity separation and roasting of the feed at at 1 000°C to increase the magnetic susceptibility for low intensity dry magnetic separation was recommended. According to Corte et al. (2019), roasting reduces a paramagnetic material such as hematite to ferromagnetic magnetite, allowing it to be recovered by wet low magnetic separation.

Flowsheets 2 to 4 in Table II shows the results of gravity separation on the shaking table for three size fractions. Ca rejection to the tails and slimes ranges from 79.7% to 84.1%. Rejection to the tails increased with decreasing feed particle size. Similar to the Ca trend, the TREE recovery to tails and slimes is observed to increase with decreasing particle size ranging from 64.3% to 68.7%. As a result, it was recommended to grind the tails and slimes to a P_{80} 45 µm and process it through the WHIMS at 4 magnetic intensities to generate a gravity and magnetic separation flowsheet. The recommended shaking table feed grind for the combination flowsheet was P_{80} = 150 µm.

Flowsheets 5 and 6 show the results of gravity separation in conjunction with WHIMS. Flowsheet 6 has two gravity separation stages with the second shaking table (scavenger) fed at 80% passing 106µm (tails of rougher shaking table). The overall mass balance results of single stage shaking table and WHIMS (Flowsheet 5) showed that 60.5% TREEs are recovered to the concentrate while 63.0% Ca is rejected to the tails. In order to boost the rejection of Ca to the tails, a two-stage shaking table including the regrind of the rougher shaking table tails to 80% passing 106µm was recommended and the tails and slimes of the scavenger stage were fed through WHIMS magnetic separation. The overall recovery of Ca to the tails increased by 4% whilst the TREEs lost to the tails increased by 9%. Flowsheets 6 and 5 had slightly similar TREE concentrate grades of 1.94% and 1.03% respectively. Since there is an increase in losses of TREEs to the tails in Flowsheet 6, Flowsheet 5 is recommended.

Flowsheet 7 combined shaking table and WHIMS using a coarse fraction, P100 = 1.18 mm, to observe if it will be different to the fine fraction Flowsheet. The results showed that 55.4% Ca can be rejected to the tails, which is lower than the rejection observed with a finer fraction. TREEs loss to the tails was 37.9%, lower than the losses observed with the finer fraction. From these combinations of gravity and WHIMS, a single stage gravity separation at a finer grind of P_{80} = 150 µm is recommended due to the highest rejection of Ca to the tails.

A roasted feed, at P_{80} = 150 µm, which increased the magnetic susceptibility of the feed was fed through LIMS +WHIMS (Flowsheet 8) and through a dry magnetic separator (Flowsheet 9) to observe if Ca can be rejected and if TREE recovery will be improved. For wet LIMS+WHIMS, the results showed that only 33.2% of Ca would be rejected to the non-magnetic stream. Compared to the non-roast feed, which rejected only 24% Ca at a finer fraction of P_{80} 53 µm (Flowsheet 1) the roasted feed performed better.

Dry magnetic separation using laboratory high-intensity induced-roll lift type magnetic separator at seven magnetic intensities on demagnetized roasted feed at a grind of P_{80} 150 µm achieved the lowest Ca rejection compared to all Flowsheets at 19.9% Ca to the tails. This process is therefore not feasible.

According to the mineralogy of the feed, the majority of REE minerals display poor liberation with the majority of minerals displaying <30% mass greater than 80% liberated and the majority of the grains lies in the <20 µm size fraction. This means that the REEs in the sample are fine-grained, indicating that the concentrate grade from gravity and magnetic separation methods could not be improved. Gravity and magnetic separation in combination were successful in pre-concentrating the feed by rejecting 60% Ca to the tails. According to Bidari and Aghazadeh (2017), the presence of calcite during leaching slows down the leaching rate by developing a surface layer. During leaching, calcite reacts quickly in acid and consequently, causing a decrease in pH and precipitation of secondary minerals (Thomas, 2021). Mineralogy indicated that the majority of the calcium bearing gangue is calcite, followed by kutnohorite and ankerite and therefore pre-concentration will thus reduce acid consumption during the leaching process.

Table II

Overall mass balance of multiple flowsheets tested

Flowsheet number	Flow sheet description	Stream name	Overall yield (%)	TREE grade (%)	Ca grade (%)	TREE recovery (%)	Ca recovery (%)
1	P_{80} = 53 µm Davis Tube +WHIMS	Davis tube feed measured Davis tube feed calculated Overall mags Overall non-mags	100.0 100.0 84.9 15.1	1.12 1.23 1.27 1.00	16.04 15.39 13.76 24.56	100.0 100.0 87.7 12.3	100.0 100.0 75.9 24.1
2	P100 = 1.18 mm ST	-1.18mm ST feed measured -1.18mm ST feed calculated ST conc ST tails + slimes	100.0 100.0 32.1 67.9	1.12 1.08 1.20 1.02	16.04 15.42 9.77 18.08	100.0 100.0 35.7 64.3	100.0 100.0 20.3 79.7
3	P_{80} = 300 µm ST	300 ST feed measured 300 ST feed calculated ST Conc ST tails + slimes	100.0 100.0 30.1 69.9	1.12 1.13 1.29 1.06	16.04 15.25 9.31 17.81	100.0 100.0 34.3 65.7	100.0 100.0 18.3 81.7
4	P_{80} = 150 µm ST	150 ST feed measured 150 ST feed calculated ST conc ST tails+ slimes	100.0 100.0 28.8 71.2	1.12 1.10 1.19 1.06	16.04 16.99 9.38 20.06	100.0 100.0 31.3 68.7	100.0 100.0 15.9 84.1
5	P_{80} =150 µm ST + P_{80} = 45 µm WHIMS	ST feed measured ST feed calculated Overall conc Overall tails	100.0 100.0 54.2 45.8	0.83 0.84 0.94 0.73	16.04 15.95 10.90 21.91	100.0 100.0 60.5 39.5	100.0 100.0 37.0 63.0
6	P_{80} =150 µm ST + P_{80} = 106 µm ST + P_{80} = 45 µm WHIMS	ST feed measured ST feed calculated Overall conc Overall tails	100.0 100.0 51.3 48.7	0.78 0.92 1.03 0.92	16.15 15.88 10.30 21.88	100.0 100.0 57.2 48.8	100.0 100.0 33.3 67.2
7	P100 = 1.18 mm ST + P100 = 1.18 mm WHIMS	ST feed measured ST feed calculated Overall conc Overall tails	100.0 100.0 63.2 36.8	1.12 1.08 1.06 1.11	16.04 15.17 10.70 22.85	100.0 100.0 62.1 37.9	100.0 100.0 44.6 55.4
8	Roast feed P_{80} = 150 µm WLIMS +WHIMS	LIMS feed measured LIMS feed calculated Overall mags Overall non-mags	100.0 100.0 69.5 30.5	1.12 1.03 0.91 1.31	22.33 19.41 18.64 21.16	100.0 100.0 61.2 38.8	100.0 100.0 66.8 33.2
9	P_{80} = 150 µm demagnetizing coil +dry LIMS	LIMS feed measured LIMS feed calculated Mags Non-mags	100.0 100.0 82.7 17.3	1.09 1.02 0.99 1.15	23.92 22.90 22.18 26.33	100.0 100.0 80.4 19.6	100.0 100.0 80.1 19.9

Conclusions

- Multiple flowsheets were investigated to determine the potential for calcite rejection whilst improving the TREE recovery.
- The mineralogy of the sample showed that the TREE bearing minerals are fine grained and reported to the <20 µm size class. Liberation showed that <30% by mass of the TREE bearing minerals are 80% liberated.
- A single stage gravity separation shaking table in conjunction with WHIMS at feed grind of P_{80} 150 µm was found to be the optimum flowsheet amongst the flowsheets tested. The flowsheet showed that 60.5% TREE are recovered to the concentrate while 63.0% Ca is rejected to the tails.
- Removal of >60% of the calcite should improve the feasibility of downstream extraction of the REE.
- The flowsheets tested could not improve the grade of TREE because they are fine grained.
- At a pilot scale, we recommend the use of fine spiral processing technology or falcon concentrator to investigate gravity concentration of a finer feed at P_{80} < 150 µm.
- Due to the fine nature of the REE-bearing minerals, it is recommended to employ a multi-gravity separator. The benefits of multi-gravity over shaking table and spirals is that they tend to hone in on the -30 µm fraction, whilst shaking tables and spirals tend to misplace the slimes.

References

Berger, A., Janots, E., Gnos, E., Frei, R., Bernier, F., 2014. Rare earth element mineralogy and geochemistry in a laterite profile from Madagascar. *Applied Geochemistry*, pp. 218–228.

Bidari, E., Aghazadeh, V. 2017. Pyrite oxidation in the presence of calcite and dolomite: Alkaline leaching, chemical modeling and surface characterization. *Transactions of Nonferrous Metals Society of China*, vol. 28, no. 7, pp. 1433–1443.

Cohen, H.E. 1986. Magnetic Separation. Wills, B.A., Barley, R.W. (eds) Mineral Processing at a Crossroads. Dans: *Mineral Processing at a Crossroads*. London: Springer, pp. 287–286.

Corte, C.D., Bergmann, C., Woollacott, L. 2019. Improving the separation efficiency of Southern African haematite from slimes through selective flocculation coupled with magnetic separation. *The Southern African Insitute of Mining and Metallurgy*, pp. 963–972.

Frances, W. 2021. *Encyclopedia of Geology* (Second Edition). London: Elsevier.

Hoshino, M., Sanematsu, K., Watanabe, Y. 2016. Chapter 279 - REE Mineralogy and Resources. *Handbook on the Physics and Chemistry of Rare Earths*, pp. 129–291.

Murthy, Y.R., Tripathy, S. 2020. Process optimization of a chrome ore gravity concentration plant for sustainable development. *Journal of the Southern African Institute of Mining and Metallurgy*, pp. 261–268.

Roy, S. 2009. Recovery Improvement of Fine Iron Ore Particles by Multi Gravity. *The Open Mineral Processing Journal*, pp. 17–30.

Sager, M., Wiche, O. 2024. Rare Earth Elements (REE): Origins, Dispersion, and Environmental Implications—A Comprehensive Review. *Environments*, vol. 11, no. 2, pp. 1–3.

Thomas, M. 2021. Understanding gangue acid consumption in copper sulfide heap leaching: Predicting the impact of carbonates, silicates and secondary precipitates. *Minerals Engineering*, pp. 1–10. ◆