DRY BENEFICIATION OF LOW-GRADE IRON ORE FINES USING A TRIBO-ELECTRIC BELT SEPARATOR

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ST Equipment & Technology LLC (STET) has developed a novel processing system based on tribo-electrostatic belt separation that provides the mineral processing industry a means to beneficiate fine materials with an energy-efficient and entirely dry technology. In contrast to other electrostatic separation processes that are typically limited to particles >75µm in size, the STET triboelectric belt separator is suited for separation of very fine (<1µm) to moderately coarse (500µm) particles, with very high throughput. The STET tribo-electrostatic technology has been used to process and commercially separate a wide range of industrial minerals and other dry granular powders. Here, bench-scale results are presented on the beneficiation of low-grade Fe ore fines using STET belt separation process. Bench-scale testing demonstrated the capability of the STET technology to simultaneously recover Fe and reject SiO_2 from itabirite ore with a D50 of 60µm and ultrafine Fe ore tailings with a D50 of 20µm. The STET technology is presented as an alternative to beneficiate Fe ore fines that could not be successfully treated via traditional flowsheet circuits due to their granulometry and mineralogy.

1.0 Introduction

Iron ore is the fourth most common element in earth's crust [1]. Iron is essential to steel manufacturing and therefore an essential material for global economic development [1-2]. Iron is also widely used in construction and the manufacturing of vehicles [3]. Most of iron ore resources are composed of metamorphosed banded iron formations (BIF) in which iron is commonly found in the form of oxides, hydroxides and to a lesser extent carbonates [4-5]. A particular type of iron formations with higher carbonate contents are dolomitic itabirites which are a product of the dolomitization and metamorphism of BIF deposits [6]. The largest iron ore deposits in the world can be found in Australia, China, Canada, Ukraine, India and Brazil [5].

The chemical composition of iron ores has an apparent wide range in chemical composition especially for Fe content and associated gangue minerals [1]. Major iron minerals associated with most of the iron ores are hematite, goethite, limonite and magnetite [1,5]. The main contaminants in iron ores are SiO_2 and Al_2O_3 [1,5,7]. The typical silica and alumina bearing minerals present in iron ores are quartz, kaolinite, gibbsite, diaspore and corundum. Of these it is often observed that quartz is the mean silica bearing mineral and kaolinite and gibbsite are the two-main alumina bearing minerals [7].

Iron ore extraction is mainly performed through open pit mining operations, resulting in significant tailings generation [2]. The iron ore production system usually involves three stages: mining, processing and pelletizing activities. Of these, processing ensures that an adequate iron grade and chemistry is achieved prior to the pelletizing stage. Processing includes crushing, classification, milling and concentration aiming at increasing the iron content while reducing the amount of gangue minerals [1-2]. Each mineral deposit has its own unique characteristics with respect to iron and gangue bearing minerals, and therefore it requires a different concentration technique [7].

Magnetic separation is typically used in the beneficiation of high grade iron ores where the dominant iron minerals are ferro and paramagnetic [1,5]. Wet and dry low-intensity magnetic separation (LIMS) techniques are used to process ores with strong magnetic properties such as magnetite while wet high-intensity magnetic separation is used to separate the Fe-bearing minerals with weak magnetic properties such as hematite from gangue minerals. Iron ores such goethite and limonite are commonly found in tailings and does not separate very well by either technique [1,5]. Magnetic methods present challenges in terms of their low capacities and in terms of the requirement for the iron ore to be susceptible to magnetic fields [5].

Flotation, on the other hand, is used to reduce the content of impurities in low-grade iron ores [1-2,5]. Iron ores can be concentrated either by direct anionic flotation of iron oxides or reverse cationic flotation of silica, however reverse cationic flotation remains the most popular flotation route used in the iron industry [5,7]. The use of flotation its limited by the cost of reagents, the presence of silica and alumina-rich slimes and the presence of carbonate minerals [7-8]. Moreover, flotation requires waste water treatment and the use of downstream dewatering for dry final applications [1].

The use of flotation for the concentration of iron also involves desliming as floating in the presence of fines results in decreased efficiency and high reagent costs [5,7]. Desliming is particularly critical for the removal of alumina as the separation of gibbsite from hematite or goethite by any surface-active agents is quite difficult [7]. Most of alumina bearing minerals occurs in the finer size range (<20um) allowing for its removal through desliming. Overall, a high concentration of fines (<20um) and

alumina increases the required cationic collector dose and decreases selectivity dramatically [5,7].

Moreover, the presence of carbonate minerals – such as in dolomitic itabirites- can also deteriorate flotation selectivity between iron minerals and quartz as iron ores containing carbonates such as dolomite do not float very selectively. Dissolved carbonates species adsorb on the quartz surfaces harming the selectivity of flotation [8]. Flotation can be reasonably effective in upgrading low-grade iron ores, but it is strongly dependent on the ore mineralogy [1-3,5]. Flotation of iron ores containing high alumina content will be possible via desliming at the expense of the overall iron recovery [7], while flotation of iron ores containing carbonate minerals will be challenging and possibly not feasible [8].

Modern processing circuits of Fe-bearing minerals may include both flotation and magnetic concentration steps [1,5]. For instance, magnetic concentration can be used on the fines stream from the desliming stage prior to flotation and on the flotation rejects. The incorporation of low and high intensity magnetic concentrators allows for an increase in the overall iron recovery in the processing circuit by recovering a fraction of the ferro and paramagnetic iron minerals such as magnetite and hematite [1]. Goethite is typically the main component of many iron plant reject streams due to its weak magnetic properties [9]. In the absence of further downstream processing for the reject streams from magnetic concentration and flotation, the fine rejects will end up disposed in a tailings dam [2]. Tailings disposal and processing have become crucial for environmental preservation and recovery of iron valuables, respectively, and therefore the processing of iron ore tailings in the mining industry has grown in importance [10].

Clearly, the processing of tailings from traditional iron beneficiation circuits and the processing of dolomitic itabirite is challenging via traditional desliming-flotation-magnetic concentration flowsheets due to their mineralogy and granulometry, and therefore alternative beneficiation technologies such as tribo-electrostatic separation which is less restrictive in terms of the ore mineralogy and that allows for the processing of fines may be of interest.

Tribo-electrostatic separation utilizes electrical charge differences between materials produced by surface contact or triboelectric charging. In simplistic ways, when two materials are in contact, the material with a higher affinity for electron gains electrons thus charges negative, while material with lower electron affinity charges positive. In principle, low-grade iron ore fines and dolomitic itabirites that are not processable by means of conventional flotation and/or magnetic separation could be upgraded by exploiting the differential charging property of their minerals [11].

Here we present STET tribo-electrostatic belt separation as a possible beneficiation route to concentrate ultrafine iron ore tailings and to beneficiate dolomitic itabirite mineral. The STET process provides the mineral processing industry with a unique water-free capability to process dry feed. The environmentally friendly process can eliminate the need for wet processing, downstream waste water treatment and required drying of final material. In addition, The STET process requires little pre-treatment of the mineral and operates at high capacity – up to 40 tones per hour. Energy consumption is less than 2 kilowatt-hours per ton of material processed.

2.0 Experimental

2.1 Materials

Two fine low-grade iron ores were used in this series of tests. The first ore consisted of an ultrafine Fe ore tailings sample with a D50 of 20 µm and the second sample of an itabirite iron ore sample with a D50 of 60 µm. Both samples present challenges during their beneficiation and cannot be efficiently processed through traditional desliming-flotation-magnetic concentration circuits due to their granulometry and mineralogy. Both samples were obtained from mining operations in Brazil.

The first sample was obtained from an existing desliming-flotation-magnetic concentration circuit. The sample was collected from a tailings dam, then dried, homogenized and packed. The second sample is from an itabirite iron formation in Brazil. The sample was crushed and sorted by size and the fine fraction obtained from the classification stage later underwent several stages of desliming until a D98 of 150 µm was achieved. The sample was then dried, homogenized and packed.

Particle size distributions (PSD) were determined using a laser diffraction particle size analyzer, a Malvern's Mastersizer 3000 E. Both samples were also characterized by Loss-on-ignition(LOI), XRF and XRD. The loss on ignition (LOI) was determined by placing 4 grams of sample in a 1000 ℃ furnace for 60 minutes and reporting the LOI on an as received basis. The chemical composition analysis was completed using a wavelength dispersive X-ray Fluorescence (WD-XRF) instrument and the main crystalline phases were investigated by XRD technique.

The chemical composition and LOI for the tailings sample (Tailings), and for the itabirite iron formation sample (Itabirite), is shown in Table 1 and particle size distributions for both samples are shown in Fig 1. For the tailings sample the main Fe recoverable phases are goethite and hematite, and the main gangue mineral is quartz (Fig 4). For the itabirite sample the main Fe recoverable phases are hematite, and the main gangue minerals are quartz and dolomite (Fig 4).

Table 1. Result of chemical analysis for major elements in tailings and Itabirite samples.

Sample	Grade (wt%)							
	Fe	SiO$_2$	Al$_2$O$_3$	MnO	MgO	CaO	LOI**	Others
Tailings	30.3	47.4	4.3	1.0	*	*	3.4	13.4
Itabirite	47.6	23.0	0.7	0.2	1.5	2.2	4.0	21.0

* <0.1 wt.%.
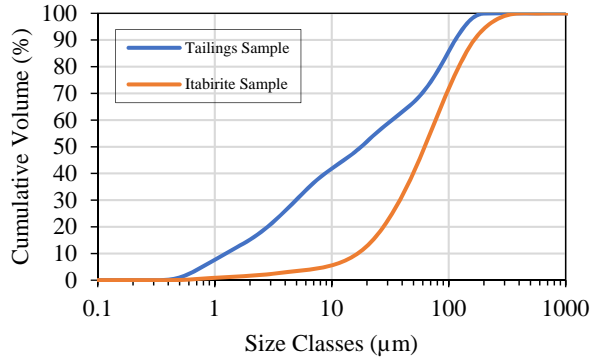** LOI$_{1000}$: Loss on Ignition at 1000 C

Figure 1 – Particle Size Distributions

2.2 Methods

A series of experiments were designed to investigate the effect of different parameters on iron movement in both iron samples using STET proprietary tribo-electrostatic belt separator technology. Experiments were conducted using a bench-scale tribo-electrostatic belt separator, hereafter referred as 'benchtop separator'. Bench-scale testing is the first phase of a three-phase technology implementation process (See Table 2) including bench-scale evaluation, pilot-scale testing and commercial-scale implementation. The benchtop separator is used for screening for evidence of tribo-electrostatic charging and to determine if a material is a good candidate for electrostatic beneficiation. The main differences between each piece of equipment are presented in Table 2. While the equipment used within each phase differs in size, the operation principle is fundamentally the same.

Table 2. Three-phase implementation process using STET tribo-electrostatic belt separator technology

Phase	Used for:	Electrode Dimensions (W x L) cm	Type of Process/
1- Bench Scale Evaluation	Qualitative Evaluation	5*250	Batch
2- Pilot Scale Testing	Quantitative Evaluation	15*610	Batch
3- Commercial Scale Implementation	Commercial Production	107 *610	Continuous

2.2.1 STET Operation Principle

The operation principle of the separator relies on tribo-electrostatic charging. In the tribo-electrostatic belt separator (Figures 2 and 3), material is fed into the narrow gap 0.9 – 1.5 cm between two parallel planar electrodes. The particles are triboelectrically charged by interparticle contact. The positively charged mineral(s) and the negatively charged mineral(s) are attracted to opposite electrodes. Inside the separator particles are swept up by a continuous moving open-mesh belt and conveyed in opposite directions. The belt is made of plastic material and

moves the particles adjacent to each electrode toward opposite ends of the separator. The counter current flow of the separating particles and continual triboelectric charging by particle-particle collisions provides for a multistage separation and results in excellent purity and recovery in a single-pass unit. The triboelectric belt separator technology has been used to separate a wide range of materials including mixtures of glassy aluminosilicates/carbon (fly ash), calcite/quartz, talc/magnesite, and barite/quartz.

Overall, the separator design is relatively simple with the belt and associated rollers as the only moving parts. The electrodes are stationary and composed of an appropriately durable material. The separator electrode length is approximately 6 meters (20 ft.) and the width 1.25 meters (4 ft.) for full size commercial units. The high belt speed enables very high throughputs, up to 40 tons per hour for full size commercial units. The power consumption is less than 2 kilowatt-hours per ton of material processed with most of the power consumed by two motors driving the belt.
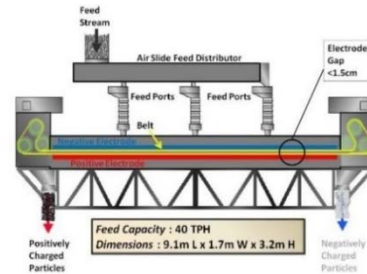

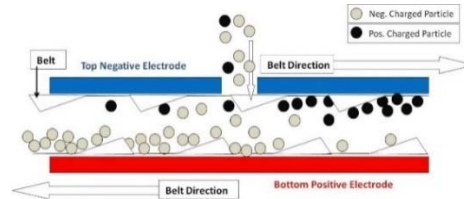Figure 2 – Schematic of triboelectric belt separator

Figure 3 - Detail of separation zone

As can be seen in Table 2, the main difference between the benchtop separator and pilot-scale and commercial-scale separators is that the length of the benchtop separator is approximately 0.4 times the length of pilot-scale and commercial-scale units. As the separator efficiency is a function of the electrode length, bench-scale testing cannot be used as a substitute for pilot-scale testing. Pilot-scale testing is necessary to determine the extent of the separation that the STET process can achieve, and to determine if STET process can meet the product targets under given feed rates. Instead, the benchtop separator is used to rule out candidate materials that are unlikely to demonstrate any significant separation at the pilot-scale level. Results obtained on the bench-scale will be non-optimized, and the separation observed is less than which would be observed on a commercial sized STET separator.

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Testing at the pilot plant is necessary prior to commercial scale deployment, however, testing at the bench-scale is encouraged as the first phase of the implementation process for any given material. Furthermore, in cases in which material availability is limited, the benchtop separator provides a useful tool for the screening of potential successful projects (i.e., projects in which customer and industry quality targets can be met using STET technology).

2.2.2 Bench-scale testing

Standard process trials were performed around the specific goal to increase Fe concentration and to reduce the concentration of gangue minerals. Different variables were explored to maximize iron movement and to determine the direction of movement of different minerals. The direction of movement observed during benchtop testing is indicative of the direction of movement at the pilot plant and commercial scale.

The variables investigated included relative humidity (RH), temperature, electrode polarity, belt speed and applied voltage. Of these, RH and temperature alone can have a large effect on differential tribo-charging and therefore on separation results. Hence, optimum RH and temperature conditions were determined before investigating the effect of the remaining variables. Two polarity levels were explored: i) top electrode polarity positive and ii) top electrode polarity negative. For the STET separator, under a given polarity arrangement and under optimum RH and temperature conditions, belt speed is the primary control handle for optimizing product grade and mass recovery. Testing on the bench separator helps shed light on the effect of certain operational variables on tribo-electrostatic charging for a given mineral sample, and therefore obtained results and trends may be used, to certain degree, to narrow down the number of variables and experiments to be performed at the pilot plant scale. Table 3 lists the range of separation conditions used as part of phase 1 evaluation process for the tailings and itabirite samples.

Table 3 lists the range of separation conditions

Parameter	Units	Range of Values	
		Tailings	**Itabirite**
Top Electrode Polarity	-	Positive-Negative	Positive-Negative
Electrode Voltage	-kV/+kV	4-5	4-5
Feed Relative Humidity (RH)	%	1-30.7	2-39.6
Feed Temperature	°F (°C)	71-90 (21.7-32.2)	70-87 (21.1-30.6)
Belt Speed	Fps (m/s)	10-45 (3.0-13.7)	10-45 (3.0-13.7)
Electrode Gap	Inches (mm)	0.400 (10.2 mm)	0.400 (10.2 mm)

Tests were conducted on the benchtop separator under batch conditions, with feed samples of 1.5 lbs. per test. A flush run using 1 lb. of material was introduced in between tests to ensure that any possible carryover effect from the previous condition was not considered. Before testing was started material was homogenized and sample bags containing both run and flush material were prepared. At the beginning of each experiment the temperature and relative humidity (RH) was measured using a Vaisala HM41 hand-held Humidity and Temperature probe. The range of temperature and RH across all experiments was 70-90 °F (21.1-32.2 (°C)) and 1-39.6%, respectively. To test a lower RH and/or higher temperature, feed and flush samples were kept in a drying oven at 100 °C for times between 30-60 minutes. In contrast, higher RH values were attained by adding small amounts of waters to the material, followed by homogenization. After RH and temperature was measured on each feed sample, the next step was to set electrode polarity, belt speed and voltage to the desired level. Gap values were kept constant at 0.4 inches (10.2 mm) during the testing campaigns for the tailings and itabirite samples.

Prior to each test, a small feed sub-sample containing approximately 20g was collected (designated as 'Feed'). Upon setting all operation variables, the material was fed into the benchtop separator using an electric vibratory feeder through the center of the benchtop separator. Samples were collected at the end of each experiment and the weights of product end 1 (designated as 'E1') and product end 2 (designated as 'E2') were determined using a legal-for-trade counting scale. Following each test, small sub-samples containing approximately 20 g of E1 and E2 were also collected. Mass yields to E1 and E2 are described by:

$$\gamma_{E1} = \frac{W_{E1}}{W_{E1}+W_{E2}} \tag{1a}$$

$$\gamma_{E2} = \frac{W_{E2}}{W_{E1}+W_{E2}} \tag{1b}$$

where γ_{E1} and γ_{E2} are the mass yields to E1 and E2, respectively; and W_{E1} and W_{E2} are the sample weights collected to the separator products E1 and E2, respectively. For both samples, Fe concentration was increased to product E2.

For each set of sub-samples (i.e., Feed, E1 and E2) LOI and main oxides composition by XRF was determined. Fe contents were determined from the Fe_2O_3 values. For the tailings sample LOI will directly relate to the content of goethite in the sample as the functional hydroxyl groups in goethite will oxidize into $H_2O_{(g)}$ [10]. Contrary, for the itabirite sample LOI will directly relate to the contain of carbonates in the sample, as calcium and magnesium carbonates will decompose into their main oxides resulting in the release of $CO_{2(g)}$ and sub sequential sample loss weight. XRF beads were prepared by mixing 0.6 grams of mineral sample with 5.4 grams of lithium tetraborate, which was selected due to the chemical composition of both tailings and itabirite samples. XRF analysis were normalized for LOI.

Finally, Fe recovery (ϵ_{Fe}) to product (E2) and SiO_2 rejection (φ_{Si}) were calculated. ϵ_{Fe} is the percentage of Fe recovered in the concentrate to that of the original feed sample and φ_{SiO_2} is the percentage of SiO_2 removed from the original feed sample. ϵ_{Fe} and φ_{Si} are described by:

$$\epsilon_{Fe} = \frac{\bar{C}_{Fe,E2}*\gamma_{E2}}{\bar{C}_{Fe,E1}*\gamma_{E2}+\bar{C}_{Fe,E2}*\gamma_{E2}} \tag{2}$$

4

$$\varphi_{SiO_2} = \frac{\bar{C}_{SiO_2,E1}*\,\gamma_{E1}}{\bar{C}_{SiO_2,E1}*\,\gamma_{E1} + \bar{C}_{SiO_2,E2}*\,\gamma_{E1}} \qquad (3)$$

where $\bar{C}_{i,(Feed,E1,E2)}$ is the normalized concentration percentage for the sub-sample's i component (e.g., Fe, SiO_2).

3.0 Results and Discussion

3.1. Samples Mineralogy

The XRD pattern showing major mineral phases for the tailings and itabirite samples are shown in Fig 4. For the tailings sample the main Fe recoverable phases are goethite, hematite and magnetite, and the main gangue mineral is quartz (Fig 4). For the itabirite sample the main Fe recoverable phases are hematite and magnetite and the main gangue minerals are quartz and dolomite. Magnetite appears in trace concentrations in both samples. Pure hematite, goethite, and magnetite contain 69.94%, 62.85%, 72.36% Fe, respectively.
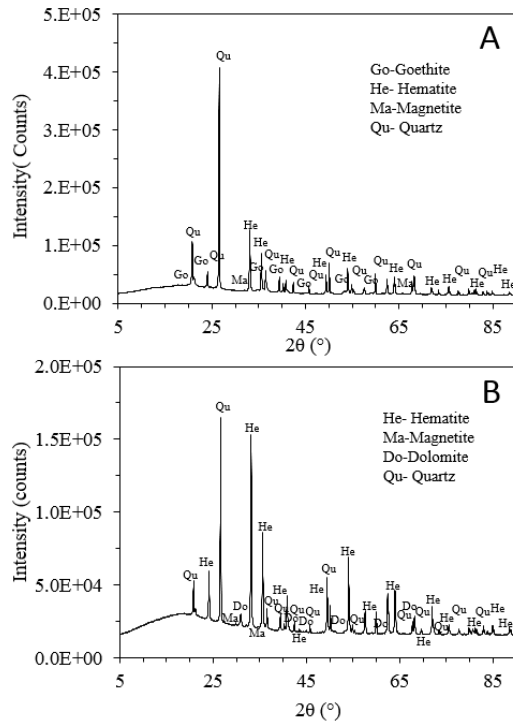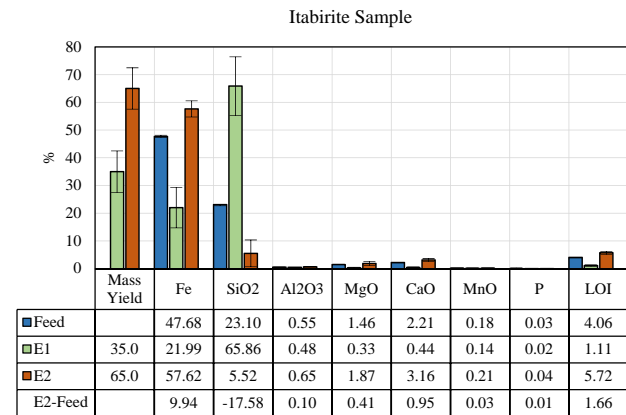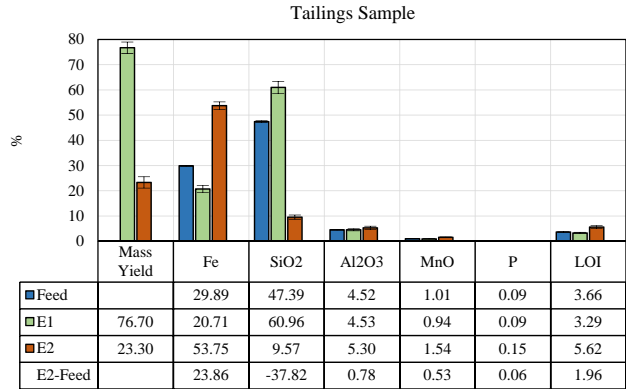

Fig.4. XRD patterns. A – Tailings sample, B – Itabirite sample

3.2 Bench-scale experiments

A series of test runs were performed on each mineral sample aimed at maximizing Fe and decreasing SiO_2 content. Species concentrating to E1 will be indicative of a negative charging behavior while species concentration to E2 to a positive charging behavior. Higher belt speeds were favorable to the processing of the tailings sample; however, the effect of this variable alone was found to be less significant for the itabirite sample.

Average results for the tailings and itabirite samples are presented in Fig 5, which were calculated from 6 and 4 experiments, respectively. Fig 5 presents average mass yield and chemistry for feed and products E1 and E2. In addition, each plot presents the improvement or decrease in concentration (E2- Feed) for each sample component (e.g., Fe, SiO_2). Positive values are

	Mass Yield	Fe	SiO2	Al2O3	MnO	P	LOI
Feed		29.89	47.39	4.52	1.01	0.09	3.66
E1	76.70	20.71	60.96	4.53	0.94	0.09	3.29
E2	23.30	53.75	9.57	5.30	1.54	0.15	5.62
E2-Feed		23.86	-37.82	0.78	0.53	0.06	1.96

	Mass Yield	Fe	SiO2	Al2O3	MgO	CaO	MnO	P	LOI
Feed		47.68	23.10	0.55	1.46	2.21	0.18	0.03	4.06
E1	35.0	21.99	65.86	0.48	0.33	0.44	0.14	0.02	1.11
E2	65.0	57.62	5.52	0.65	1.87	3.16	0.21	0.04	5.72
E2-Feed		9.94	-17.58	0.10	0.41	0.95	0.03	0.01	1.66

associated to an increase in concentration to E2, while negative values are associated to a decrease in concentration to E2.

Fig.5. Average mass yields and chemistry for Feed, E1 and E2 products. Error bars represent 95% confidence intervals.

For the tailings sample Fe content was increased from 29.89% to 53.75%, on average, at a mass yield (γ_{E2}) – or global mass recovery - of 23.30%. This corresponds to Fe recovery (ϵ_{Fe}) and silica rejection (φ_{SiO_2}) values of 44.17% and 95.44%, respectively. The LOI content was increased from 3.66% to 5.62% which indicates that the increase in Fe content is related to an increase in goethite content (Fig 5).

For the itabirite sample Fe content was increased from 47.68% to 57.62%, on average, at a mass yield (γ_{E2}) of 65.0%. This corresponds to Fe recovery (ϵ_{Fe}) and silica rejection (φ_{SiO_2}) values of 82.95% and 86.53%, respectively. The LOI, MgO and CaO contents were increased from 4.06% to 5.72%, 1.46 to 1.87% and from 2.21 to 3.16%, respectively, which indicates that dolomite is moving in the same direction as Fe-bearing minerals (Fig 5).

For both samples, Al_2O_3, MnO and P seem to be charging in the same direction as Fe-bearing minerals (Fig 5). While it is desired to decrease the concentration of these three species, the combined concentration of SiO_2, Al_2O_3, MnO and P is decreasing for both samples, and therefore the total effect achieved using the benchtop separator is an enhancement in the product Fe grade and a decrease in the contaminants concentration.

Overall, benchtop testing demonstrated evidence of effective charging and separation of iron and silica particles. The promising laboratory scale results suggest that pilot scale tests including first and second passes should be performed.

3.3 Discussion

The experimental data suggests that the STET separator resulted in an important increase in Fe content while simultaneously reducing SiO_2 content.

Having demonstrated that triboelectrostatic separation can result in a significant increase in Fe content, a discussion on the significance of the results, on the maximum achievable Fe contents and on the feed requirements of the technology is needed.

To start, it is important to discuss the apparent charging behavior of mineral species in both samples. For the tailings sample the main components were Fe oxides and quartz and experimental results demonstrated that Fe oxides concentrated to E2 while quartz concentrated to E1. In simplistic ways, it could be said that Fe oxide particles acquired a positive charge and that quartz particles acquired a negative charge. This behavior is consistent with the triboelectrostatic nature of both minerals as shown by Ferguson (2010) [12]. Table 4 shows the apparent triboelectric series for selected minerals based on inductive separation, and it shows that quartz is located at the bottom of the charging series while goethite, magnetite and hematite are located higher up in the series. Minerals at the top of the series will tend to charge positive, while minerals at the bottom will tend to acquire a negative charge.

On the other hand, for the itabirite sample the main components were hematite, quartz and dolomite and experimental results indicated that Fe oxides and dolomite concentrated to E2 while quartz concentrated to E1. This indicates that hematite particles and dolomite acquired a positive charge while quartz particles acquired a negative charge. As can be seen in Table 4, carbonates are located at the top of the tribo-electrostatic series, which indicates that carbonate particles tend to acquire a positive charge, and in consequence to be concentrated to E2. Both dolomite and hematite were concentrated in the same direction, indicating that the overall effect for hematite particles in the presence of quartz and dolomite was to acquire a positive charge.

The direction of movement of the mineralogical species in each sample is of paramount interest, as it will determine the maximum achievable Fe grade that can be obtained by means of a single pass using the tribo-electrostatic belt separator technology.

For the tailings and itabirite samples the maximum achievable Fe content will be determined by three factors: i) The amount of Fe in Fe-bearing minerals; ii) the minimum quartz (SiO_2) content that can be achieved and; iii) The number of contaminants moving in the same direction as Fe-bearing minerals. For the tailings sample the main contaminants moving in the same direction of Fe-bearing minerals are Al_2O_3, MnO bearing minerals, while for the itabirite sample the main contaminants are CaO, MgO, Al_2O_3 bearing minerals.

Mineral Name	Charge acquired (apparent)
Apatite	+++++++
Carbonates	++++
Monazite	++++
Titanomagnetite	.
Ilmenite	.
Rutile	.
Leucoxene	.
Magnetite/hematite	.
Spinels	.
Garnet	.
Staurolite	.
Altered ilmenite	-
Goethite	-
Zircon	--
Epidote	--
Tremolite	--
Hydrous silicates	--
Aluminosilicates	--
Tourmaline	--
Actinolite	--
Pyroxene	---
Titanite	----
Feldspar	----
Quartz	-------

Table 4. Apparent triboelectric series for selected minerals based on inductive separation. Modified from D.N Ferguson (2010) [12].

For the tailings sample, the Fe content was measured at 29.89%. XRD data indicates that the predominant phase is goethite, followed by hematite, and therefore the maximum achievable Fe content if a clean separation was possible would be between 62.85% and 69.94% (which are the Fe contents of pure goethite and hematite, respectively). Now, a clean separation is not possible as Al_2O_3, MnO and P-bearing minerals are moving in the same direction as the Fe-bearing minerals, and therefore any increase in Fe content will also result in an increase of these contaminants. Then, to increase the Fe content, the amount of quartz to E2 will need to be significantly decreased to the point it offsets the movement of Al_2O_3, MnO and P to product (E2). As shown in Table 4, quartz has a strong tendency to acquire a negative charge, and therefore in the absence of other minerals having an apparent negative charging behavior it will be possible to considerably decrease its content to product (E2) by means of a first pass using the triboelectrostatic belt separator technology.

For instance, if we assume that all the Fe content in the tailings sample is associated to goethite (FeO(OH)), and that the only gangue oxides are SiO_2, Al_2O_3 and MnO, then Fe content to product would be given by:

$$Fe(\%) = \big(100 - SiO_2 - (Al_2O_3 + MnO)\big) * 0.6285 \qquad (4)$$

where, 0.6285 is the percentage of Fe in pure goethite. Eq.4 depicts the competing mechanism that takes place to concentrate Fe as $Al_2O_3 + MnO$ increases while SiO_2 decreases.

For the itabirite sample the Fe content was measured at 47.68%. XRD data indicates that the predominant phase is hematite and therefore the maximum achievable Fe content if a clean separation was possible would be close to 69.94% (which is the Fe content of pure hematite). As it was discussed for the tailings sample a clean separation won't be possible as CaO, MgO, Al_2O_3 bearing minerals are moving in the same direction as hematite, and therefore to increase Fe content SiO_2 content must be reduced. Assuming that the entirety of the Fe content in this sample is associated to hematite (Fe_2O_3) and that the only oxides contained in gangue minerals are SiO_2, CaO, MgO, Al_2O_3 and MnO; then Fe content in the product would be given by:

$$Fe(\%) = \big(100 - SiO_2 - (CaO + MgO + Al_2O_3 + MnO + LOI)\big) * 0.6994 \qquad (5)$$

where, 0.6994 is the percentage of Fe in pure hematite. It must be noticed that Eq.5 includes LOI, while Eq.4 does not. For the itabirite sample, the LOI is associated to the presence of carbonates while for the tailings sample it is associated to Fe-bearing minerals.

Evidently, for both tailings and itabirite samples it is possible to significantly increase the Fe content by reducing the content of SiO_2; however, as shown in Eq.4 and Eq.5, the maximum achievable Fe content will be limited by the direction of movement and the concentration of oxides associated to gangue minerals.

In principle, the concentration of Fe in both samples could be further increased by means of a second pass on the STET separator in which CaO, MgO, Al_2O_3 and MnO bearing minerals could be separated from Fe-bearing minerals. Such separation would be possible if most of quartz in the sample was removed during a first pass. In the absence of quartz, some of the remaining gangue minerals should in theory charge in the opposite direction of goethite, hematite and magnetite, which would result in increased Fe content. For instance, for the itabirite sample and based in the location of dolomite and hematite in the triboelectrostatic series (See Table 4), dolomite/hematite separation should be possible as dolomite has a strong tendency to charge positive in relation to hematite.

Having discussed on the maximum achievable Fe contents a discussion on the feed requirements for the technology is needed. The STET tribo-electrostatic belt separator requires the feed material to be dry and finely ground. Very small amounts of moisture can have a large effect on differential tribo-charging and therefore the feed moisture should be decreased to <0.5 wt.%. In addition, the feed material should be ground sufficiently fine to liberate gangue materials and should be at least 100% passing mesh 30 (600 um). At least for the tailings sample, the material would have to be dewatered followed by a thermal drying stage, while for the itabirite sample grinding coupled with, or follow by, thermal drying would be necessary prior to beneficiation with the STET separator.

The tailings sample was obtained from an existing desliming-flotation-magnetic concentration circuit and collected directly from a tailings dam. Typical paste moistures from tailings should be around 20-30% and therefore the tailings would need to be dried by means of liquid-solid separation (dewatering) followed by thermal drying and deagglomeration. The use of mechanical dewatering prior to drying is encouraged as mechanical methods have relative low energy consumption per unit of liquid removed in comparison to thermal methods. About 9.05 Btu are required per pound of water eliminated by means of filtration while thermal drying, on the other hand, requires around 1800 Btu per pound of water evaporated [13]. The costs associated with the processing of iron tailings will ultimately depend on the minimum achievable moisture during dewatering and on the energetic costs associated with drying.

The itabirite sample was obtained directly from an itabirite iron formation and therefore to process this sample the material would need to undergo crushing and milling followed by thermal drying and deagglomeration. One possible option is the use of hot air swept roller mills, in which dual grinding and drying could be achieved in a single step. The costs associated with the processing of itabirite ore will depend on the feed moisture, feed granulometry and on the energetic costs associated to milling and drying.

For both samples deagglomeration is necessary after the material have been dried to ensure particles are liberated from one another. Deagglomeration can be performed in conjunction to the thermal drying stage, allowing for efficient heat transfer and energy savings.

4.0 Conclusions

The bench-scale results presented here demonstrates strong evidence of charging and separation of Fe-bearing minerals from quartz using triboelectrostatic belt separation.

For the tailings sample Fe content was increased from 29.89% to 53.75%, on average, at a mass yield of 23.30%, which corresponds to Fe recovery and silica rejection values of 44.17% and 95.44%, respectively. For the itabirite sample Fe content was increased from 47.68 % to 57.62%, on average, at a mass yield of 65.0%, which corresponds to Fe recovery and silica rejection values of 82.95% and 86.53%, respectively. These results were completed on a separator that is smaller and less efficient than the STET commercial separator.

Experimental findings indicate that for both tailings and itabirite samples the maximum achievable Fe content will depend on the minimum achievable quartz content. In addition, achieving

higher Fe grades may be possible by means of a second pass on the STET belt separator.

The results of this study demonstrated that low-grade iron ore fines can be upgraded by means of STET tribo-electrostatic belt separator. Further work at the pilot plant scale is recommended to determine the iron concentrate grade and recovery that can be achieved. Based on experience, the product recovery and/or grade will significantly improve at pilot scale processing, as compared to the bench-scale test device utilized during these iron ore trials. The STET tribo-electrostatic separation process may offer significant advantages over conventional processing methods for iron ore fines.

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