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# Treatment of Low-Grade Iron Ore Using Two Stage Wet High-Intensity Magnetic Separation Technique

Moses C. Siame, Kazutoshi Haga, Atsushi Shibayama

***Abstract***—This study investigates the removal of silica, alumina and phosphorus as impurities from Sanje iron ore using wet high-intensity magnetic separation (WHIMS). Sanje iron ore contains low-grade hematite ore found in Nampundwe area of Zambia from which iron is to be used as the feed in the steelmaking process. The chemical composition analysis using X-ray Florence spectrometer showed that Sanje low-grade ore contains 48.90 mass% of hematite ($Fe_2O_3$) with 34.18 mass% as an iron grade. The ore also contains silica ($SiO_2$) and alumina ($Al_2O_3$) of 31.10 mass% and 7.65 mass% respectively. The mineralogical analysis using X-ray diffraction spectrometer showed hematite and silica as the major mineral components of the ore while magnetite and alumina exist as minor mineral components. Mineral particle distribution analysis was done using scanning electron microscope with an X-ray energy dispersion spectrometry (SEM-EDS) and images showed that the average mineral size distribution of alumina-silicate gangue particles is in order of 100 μm and exists as iron-bearing interlocked particles. Magnetic separation was done using series L model 4 Magnetic Separator. The effect of various magnetic separation parameters such as magnetic flux density, particle size, and pulp density of the feed was studied during magnetic separation experiments. The ore with average particle size of 25 μm and pulp density of 2.5% was concentrated using pulp flow of 7 L/min. The results showed that 10 T was optimal magnetic flux density which enhanced the recovery of 93.08% of iron with 53.22 mass% grade. The gangue mineral particles containing 12 mass% silica and 3.94 mass% alumna remained in the concentrate, therefore the concentrate was further treated in the second stage WHIMS using the same parameters from the first stage. The second stage process recovered 83.41% of iron with 67.07 mass% grade. Silica was reduced to 2.14 mass% and alumina to 1.30 mass%. Accordingly, phosphorus was also reduced to 0.02 mass%. Therefore, the two stage magnetic separation process was established using these results.

***Keywords***—Sanje iron ore, magnetic separation, silica, alumina, recovery.

## I. Introduction

THE increase in demand for iron in the steelmaking industries has resulted in the processing of low-grade iron ores [1]. The low-grade iron ores usually contain more silica and alumina as gangue mineral assemblages with phosphorus and oxides of calcium and magnesium existing in small quantities [2]. Removal of silica and alumina from low-grade iron ores is considerably difficult due to the aggregation of fine silica-alumina particulates with iron oxide particles. Magnetic separation technique has therefore been known as one of the most effective iron extraction processes which are commonly used in the treatment of low-grade ore containing more and aggregated impurities [3]. Magnetic separation of iron ores is based on the principle of applying magnetic field intensity to the equipment that utilizes the difference of magnetic properties of the Iron particles and gangue mineral particles which are non-magnetic. Magnetic separation technique is described as high-intensity, medium-intensity or low-intensity depending on the relative magnitude of the magnetic field intensity applied to the equipment. Furthermore, the magnetic separation process is considered either wet or dry based on the type of the ore to be treated. [4]. Dry magnetic separation is usually done under medium magnetic intensity to treat highly paramagnetic iron ores containing minerals of chromite ($FeCr_2O_4$) or limonite ($FeO(OH)$) [5]. In other cases, dry magnetic separation using high magnetic intensity is considered when recovering iron from weakly permanent mineral particles although it usually exhibits lower production capacity as compared to dry low-intensity magnetic separation [6], [7]. Wet low-intensity magnetic separation technique is favourable for recovery of iron-containing ferromagnetic particles whilst wet high-intensity magnetic separation is ideal for low-grade ores characterized by weak magnetic mineral particles [5].

WHIMS depends on the magnetic properties of the ore particles such as magnetic susceptibility, particle size density and particle velocity in the fluids. The applied magnetic field intensity which creates magnetic field gradient in the equipment enhance the separation of magnetic particles from non-magnetic particles. [8]. Magnetic separation of iron particles in the slurry during a wet high-intensity magnetic technique is also affected by the gravitation force and hydrodynamic forces [7], therefore, separation efficiency is achieved by selection of the best magnetic separation parameters used such as particle size, pulp density, the magnetic density of the machine and pulp flow of the feed [8], [9].

This research study investigates WHIMS by considering the effect of various magnetic separation parameters such as magnetic flux density, particle size and pulp density required to produce a high-grade iron concentrate with minimal impurities.

## II. Experimental procedures

### A. Sample Preparation

Sanje ore rock samples from Nampundwe areas of Zambia were used in this study. The rock samples were crushed to less than 2 mm using P-1 Jaw crusher (Fritsch Co, Ltd) and milled to less than 200 μm using P-13 disc mill (Fritsch Co, Ltd). The

Moses C. Siame is at Akita University in the Graduate School of International Resource Science, 1-1 Gakuen-cho, Tegata Akita-shi 010-8502, Japan (e-mail: mosescharlessiame@gmail.com).

Kazutoshi Haga is the assistant professor and Atsushi Shibayama is the professor at Akita University in the Graduate School of Engineering and Resource Science, 1-1 Gakuen-cho, Tegata Akita-shi 010-8502, Japan (e-mail: khaga@gipc.akita-u.ac.jp, shibayama@gipc.akita-u.ac.jp).

milled samples were then analyzed for chemical composition using X-ray fluoresce spectrometer (XRF, ZSX Primus II Rigaku) and results tabulated as shown in Table I. The sample was then milled to less than 200 µm and screened using 5 JIS Z 8801 Sieves (IIDA Manufacturing Co, Ltd) with an aperture size of 180 µm, 150 µm, 106 µm, 63 µm and 32 µm mounted on the AS200 sieve shaker (Retsch Japan Co., Ltd). Sample particles from each sieve were then analyzed using the XRF spectrometer and mineral liberation analysis done as shown in Fig. 7. The mineralogical analysis of the ore was done using RINT Rigaku X-ray diffractometer and mineral phases identified as shown in Fig. 5. Microscopic analysis of the ore was also done using Hitachi SU-70 Scanning Electron microscopy with energy dispersion spectroscopy (SEM-EDS) and images retrieved are as shown in Fig. 6.

*B. Procedure for magnetic Separation of Sanje Ore*

All magnetic separation experiments were done using the Series L Model 4 (L-4 Machine) laboratory magnetic Separator (Eriez Manufacturing Co.) as shown in Fig. 1. The machine uses WHIMS technique to separate magnetic particles from non-magnetic particles.

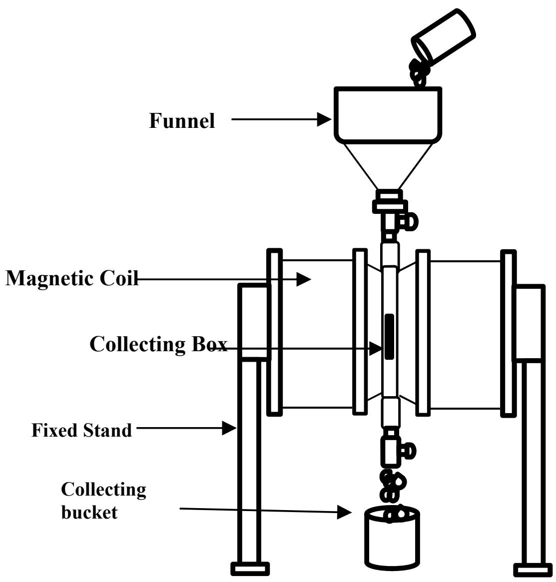


Fig. 1 Series L Model 4 WHI Magnetic separator

The L-4 Machine mainly uses compacted iron matrix mesh or pipe matrix, as shown in Figs. 4 and 5 respectively, in the collecting box as the collecting media for magnetic minerals whilst nonmagnetic particles are collected in the vessel placed at the bottom of the machine. Fig. 2 shows the relationship between current and magnetic field density of the L-4 machine. The magnetic flux density of the machine is directly proportional to the sum of current and magnetic field strength as shown in (1):

$$B \approx I + \mu_0 H \quad (1)$$

where B is magnetic density, I the current applied to the machine, H magnetic field and $\mu_0$ the magnetic permeability.

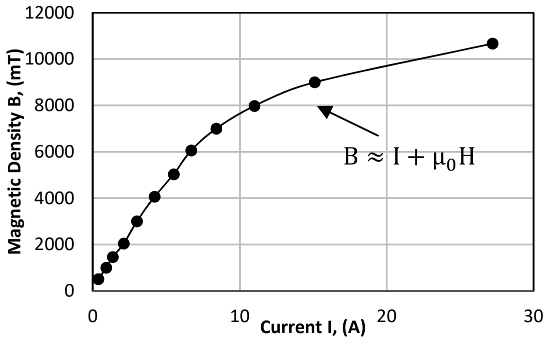


Fig. 2 Relationship between Current and Magnetic field density of the L-4 machine

*C. Procedure for Magnetic Separation of Sanje Ore*

The first stage of the experiments was to determine the optimum magnetic flux density that would correspond to high iron recovery and higher impurity removal. The voltage of the machine was adjusted and current flow to the machine increased with increase in magnetic field intensity as shown in Fig. 2. The slurry of 2% pulp density containing 25 g sample with average particle size of 25 µm was treated using magnetic field intensity of 3 T, 5 T, 7.5 T and 10 T. The slurry was fed into the machine funnel and allowed to flow at a fixed rate of 7 L/min throughout the experiments. The magnetic particles were collected in the collecting box as concentrate while the non-magnetic particles were collected as tailings in collecting bucket. Both the concentrate and tailings were dried, weighed and analyzed for chemical and mineralogical composition using XRF and XRD respectively. The percent recovery of iron was then calculated using (2):

$$\%\,Fe = \frac{C_{Fe} \times Wt_c}{(C_{Fe} \times Wt_c + T_{Fe} \times Wt_T)} \times 100 \quad (2)$$

where $C_{Fe}$ is the percentage by weight of iron in the concentrate, $Wt_c$ the wright of the concentrate, $T_{Fe}$ and percentage by weight of iron in the tailings whilst $Wt_T$ is the weight of the tailings.

*D. Effect of Pulp Density on Magnetic Separation Efficiency*

The pulp density of the slurry was adjusted to 2.5%, 5%, 7.5% and 10% using optimum magnetic flux density obtained from the first stage of the experiment. The most suitable pulp density was preferred based on the highest iron recovery and impurity removal.

*E. The Effect of Particle Size Density in Slurry on Iron Recovery*

The slurries containing different particle size fractions were prepared and treated at suitable pulp density and optimum flux density. The iron recovery and grade by mass of iron in the obtained concentrate was calculated based on respective particle fraction of the feed.

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### *F. The Efficacy of Magnetic Collectors on Iron Recovery*

After obtaining the optimum magnetic flux density and the suitable pulp density, the efficacy of the collecting equipment was investigated using the wire mesh shown in Fig. 3 and the pipe matrix in Fig. 4.

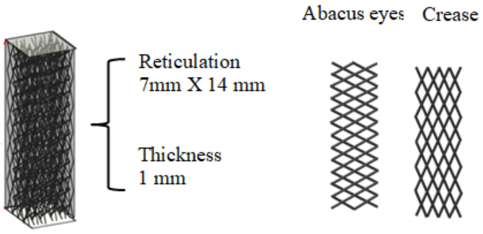


Fig. 3 Wire Mesh collector

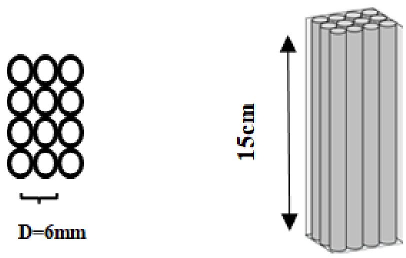


Fig. 4 Pipe matrix Collector

### *G. Two Stage Magnetic Separation*

The concentrate from the first stage magnetic separation was fed to the L-4 machine using the same optimum conditions as from the first stage i.e. magnetic flux density, pulp density and the suitable collecting matrix while pulp flow was kept constant at 7 L/m.

## III. Results and Discussion

### *A. Chemical and Mineralogical Analysis*

The chemical composition analysis using X-ray florence spectrometer showed that Sanje ore contains 48.90% mass of hematite ($Fe_2O_3$) with 34.18% mass iron grade. As shown in Table I, the ore also contains silica and alumina of 31.10% mass and 7.65% mass respectively.

TABLE I
Chemical Composition of Sanje Iron Ore

| % $Fe_2O_3$ | % Fe | % $Al_2O_3$ | % $SiO_2$ | % P | % MgO |
|---|---|---|---|---|---|
| 48.90 | 34.18 | 7.65 | 31.10 | 0.05 | 1.33 |

The mineralogical analysis results in Fig. 7 show that the major mineral components of the ore are hematite and quartz indicated by the major mineral phases while magnetite and aluminates are the minor minerals as shown by fewer mineral phases. This confirms the prominence of hematite in the Sanje iron ore.

The mineral particle distribution analysis done using SEM-EDS. Fig. 6 also shows that shows that iron mineral particles in the ore exist as free particles as well as aggregated with silica mineral particles.

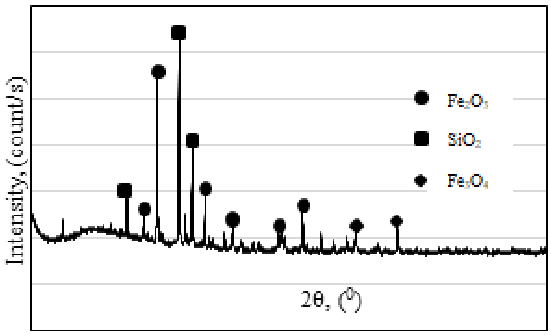


Fig. 5 XRD patterns for Sanje Iron ore

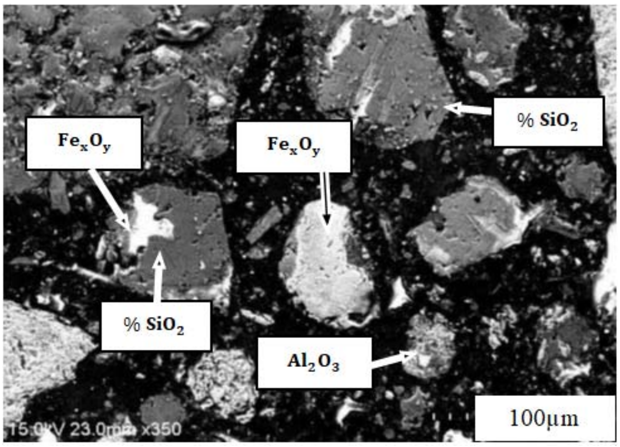


Fig. 6 SEM-EDS Pictures of Sanje ore

### *B. Mineral Liberation and Particle Size Distribution*

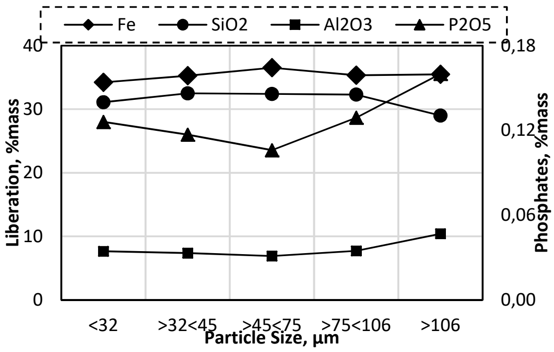


Fig. 7 Mineral Liberation graph

The grade of iron and liberation of silica shows a relatively increasing trend with a decrease in particle size until optimal liberation at particle fraction of $> 45$ µm $< 75$ µm. Alumina and phosphorous show decrease in liberation with a decrease in particle size which indicates that alumina-phosphorous gangue minerals are locked up more in coarse particles and further milling of the ore to less than 32 µm would allow further liberation. Further milling was, therefore, necessary to avoid coarser particles containing hematite-gangue aggregation to cause poor recovery efficiencies in magnetic separation [10].

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### C. Effect of Magnetic Density on Iron Recovery

Iron recovery and grade increased with increase in magnetic field density from 3000 mT to 10000 mT. As shown in Fig. 11, the magnetic field density of 5000 mT was necessary to recover 87% of iron with iron grade of 41.68% mass.

Further increase of magnetic density to 10000 mT showed a slightly higher iron grade of 49.93% mass with an optimal recovery of 89%. Alumina and silica were also reduced to 5.81% and 18.08% respectively at 1000 mT.

TABLE II
COMPOSITION OF CONCENTRATE FROM MAGNETIC SEPARATION AT VARIED MAGNETIC DENSITY

| Magnetic Density, mT | % Fe | % $Al_2O_3$ | % $SiO_2$ | % P | % Fe Recovery |
|---|---|---|---|---|---|
| 3000 | 39.26 | 3.98 | 19.78 | 0.04 | 76 |
| 5000 | 41.68 | 4.64 | 20.73 | 0.05 | 87 |
| 7500 | 43.78 | 5.81 | 18.08 | 0.04 | 89 |
| 10000 | 46.93 | 5.15 | 18.79 | 0.03 | 93 |

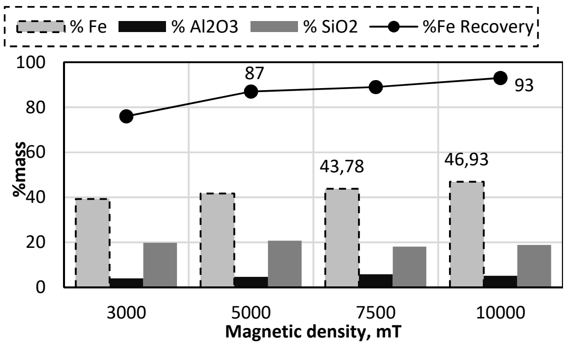


Fig. 8 Effect of Magnetic flux density on Iron recovery and Silica-Alumina removal

As shown in Fig. 8, silica was reduced to 18.79% mass at 10000 mT as compared to 19.98% mass at 3000 mT. However, this was not a case for alumina which was reduced to 3.98% mass at a lower magnetic flux density of 3000 mT and to 5.81% mass at a higher magnetic flux density of 10000 mT.

### D. Effect of Feed Pulp Density on Silica-Alumina Removal

Table III shows the results of the effect of pulp density on silica-alumina removal and iron recovery. The recovery of iron increased from 89% at a pulp density of 2% to 96% at 2.5%. As shown in Fig. 9, a further increase in pulp density shows a decreasing trend in iron recovery and silica-alumina gangue removal. The optimum pulp density was obtained at 2.5% at which 89% of iron was recovered with the grade of 49.72% mass having 4.19% mass alumina and 18.08% mass silica. The pulp density of 2.5% was the solid-liquid ratio at which the magnetic forces dominated over the liquid drag force. This entails that the magnetic attraction on iron mineral particles was stronger than both drag force and gravitational force [13]. Alternatively, higher pulp density more than 2.5% caused clogging in the collecting box and hence lower iron recovery.

TABLE III
COMPOSITION OF CONCENTRATE FROM MAGNETIC SEPARATION AT VARIED PULP DENSITY

| Pulp Density, % | % Fe | % $Al_2O_3$ | % $SiO_2$ | % P | % Fe Recovery |
|---|---|---|---|---|---|
| 2.00 | 46.93 | 5.15 | 18.79 | 0.03 | 93 |
| 2.50 | 49.72 | 4.19 | 18.08 | 0.03 | 89 |
| 5.00 | 43.70 | 5.81 | 20.02 | 0.02 | 90 |
| 7.50 | 42.01 | 5.62 | 18.80 | 0.04 | 87 |
| 10.00 | 40.26 | 6.26 | 21.70 | 0.04 | 88 |

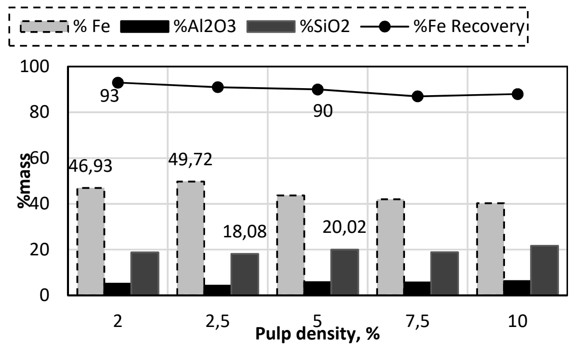


Fig. 9 Effect of feed pulp densities on Iron recovery and Silica-Alumina removal

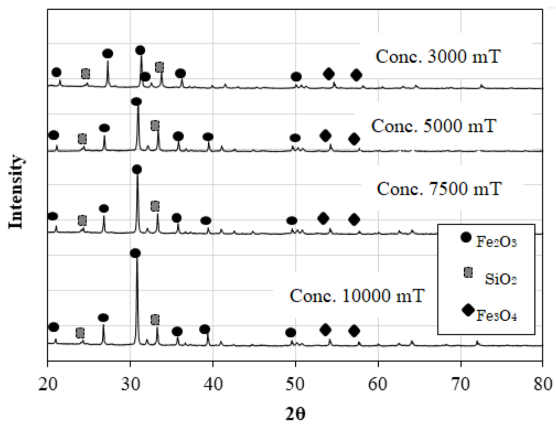


Fig. 10 XRD Mineral phase diagrams for concentrate from magnetic separation

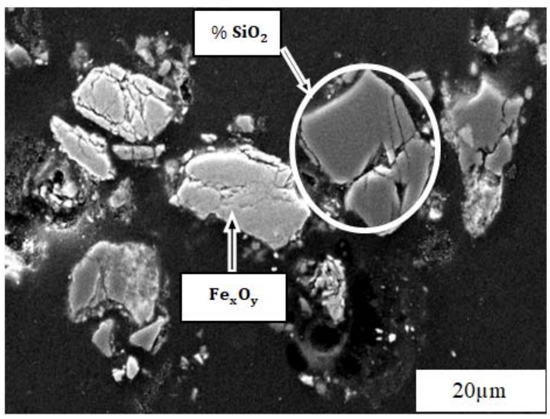


Fig. 11 SEM-EDS Pictures for concentrate from 10 T magnetic separation

The concentrate produced at optimum magnetic field density of 10 T indicates that more hematite is prominent in concentrate produced with greater magnetic field density of 7000 mT and 10000 mT than when less magnetic density was used as indicated in 3000 mT and 5000 mT. As shown from the SEM-EDS pictures in Fig. 11, the concentrate produced also shows disaggregated silica particulates which indicate that second stage magnetic separation would effectively remove the remaining free silica particles.

*E. Effect of Particle Size Density on Iron Recovery*

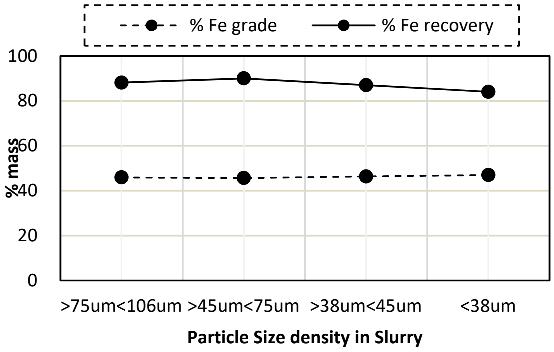


Fig. 12 Effect of particles size fractions in slurry on iron recovery

A slurry containing finer particles size of fewer than 38 micrometres showed a higher iron grade and enhanced the reduction of silica and alumina than the slurries with coarser particles. On the contrary, higher iron recovery of up to 90% was obtained from slurries with coarser particles of between 45 micrometres and 75 micrometres but contained more silica and alumina impurities. The results suggest that it was suitable to remove more impurities when the slurry having a particle size of fewer than 32 micrometres was treated.

*F. Effect of Equipment Selection on Silica and Alumina Removal*

In order to determine the suitable collecting equipment that would be used for effective separation of iron particles from gauge minerals, the efficacy of the wire mesh and the pipe matrix was investigated. Table IV shows that 89% of iron was recovered using the wire mesh and 93% for the pipe matrix. The iron grade also shows the higher content of 53.22% mass when the pipe was used as compared to the wire mesh.

TABLE IV
EFFECT OF EQUIPMENT SELECTION ON SILICA AND ALUMINA REMOVAL

| Equipment | % Fe | % $SiO_2$ | % $Al_2O_3$ | % Yield | % Fe Recovery |
|---|---|---|---|---|---|
| Wire | 49.7 | 18.08 | 4.19 | 77.22 | 89 |
| Pipe | 53.22 | 12.01 | 3.94 | 72.32 | 93 |

The lower yield of 72.32% was obtained when the pipe was used as compared to 77.22% for the wire mesh but the pipe produced a higher grade of 53.22% mass with less silica and alumina contents of 12.01% mass and 3.94% mass respectively. The results indicate that more magnetic field gradient was created in the pipe and the capturing of magnetic particles was more effective in the pipe matrix than on abacus and crease planes for the wire mesh [14]. The magnetic field gradient in the pipe matrix also dominated over the liquid drag force caused by the rate of pulp flow [15].

*G. Efficacy of Two Stage Process on Silica and Alumina Removal*

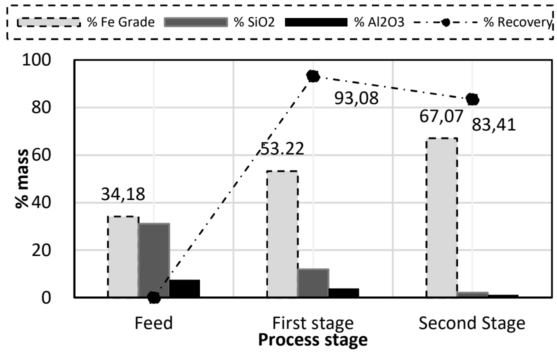


Fig. 13 Efficacy of two stage process on Silica and Alumina removal

As shown in Fig. 13, most of the silica was reduced from 12.01% mass to just 2.14% mass. The iron grade was improved drastically from 53.22% mass in the first stage magnetic separation to 67.07% mass.

## IV. CONCLUSION

To establish the best mineral processing techniques for effective removal of impurities from Sanje Iron ore, this research concludes that;

1. Sanje Iron ore is a low-grade hematite ore which contains iron-silica aggregates and their liberation requires adequate milling to fine particle fraction of less than 32 μm.
2. Effective removal of impurities from Sanje ore using WHIMS requires lower feed pulp density of 2.5% and higher magnetic field intensity of 10 T. However, higher Iron grade with minimum impurities is not attained by single magnetic separation process with just up to 53.22% mass iron grade attained with 12.01% mass silica and 3.94% mass of alumina. Phosphorous is also observed to be removed with only 0.03% mass remaining in the concentrate.
3. The two-stage magnetic separation was done to obtain the required iron grade. As shown in Fig. 13, 83.41% recovery was necessary to obtain 67.07% mass of iron grade with just 1.30% mass of alumina and 2.14% mass of silica. Phosphorous was consequently reduced to 0.01%. The proposed impurity removal process also indicates that only 9.82% of iron with 16.01% mass grade can be lost to the tailings in the first stage and just 9.67% during the second stage.
4. The two-stage impurity removal process flow is therefore proposed to upgrade low grade using WHIMS technique as shown in Fig. 14.

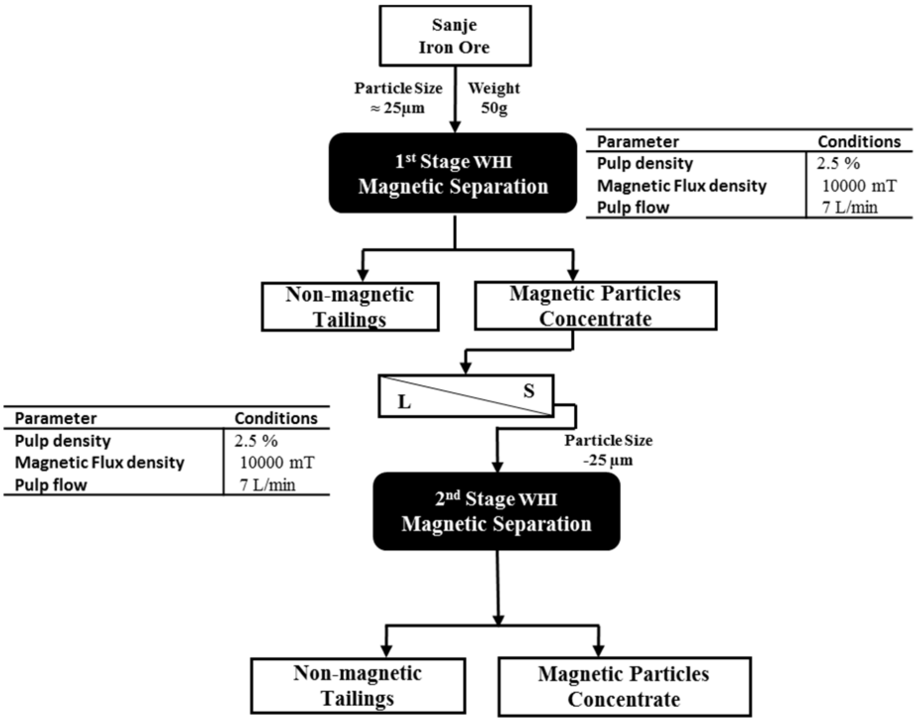


Fig. 14 Proposed impurity removal process flow chart

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