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Statistical analysis and concentration of iron ore using Longi LGS 500 WHIMS

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ABSTRACT

A Longi LGS 500 wet high intensity magnetic separator (WHIMS) was used to concentrate a fine, low grade South African hematite ore. The ore was prepared into different size fractions and was subjected to changes in pulp density, magnetic field intensity and pulsation frequency which followed a 3^3 full factorial matrix. The concentrate mass yield and Fe grade were selected as the dependent responses to the changes. The analysis of variance (ANOVA) shows that the variables investigated are significant to the material's response to magnetic separation. This significance was in the order of magnetic field intensity followed by pulsation frequency and then pulp density. It was also noted that a single stage magnetic separation has a potential to upgrade a feed (−75 μm and 40% Fe) to a 55% Fe grade, as the pulsation frequency increases. In addition, the model predictions and actual data were in good agreement, reporting regression coefficients within acceptable ranges.

1. Introduction

The production of iron ore is largely used to meet the increase in the global demand for steel and pig iron. An estimated 1.5 billion tons of steel were produced globally in 2011 of which 683 million tons was produced in China [1]. The increased rate in world steel production, driven largely by construction growth in China and Middle East, has resulted in demand for high grade iron ore. The escalating economic growth within these regions has resulted in the exploration of more mineral ore deposits. The conventional method for processing iron ore is by crushing the run of mine (ROM) material to <40 mm size fraction followed by scrubbing and/or wet screening at 10 mm to generate −40+10 mm fraction [2]. The −10+0.15 and −0.15 mm size fractions are usually classified as fines and slimes, respectively. The slimes generated have been traditionally regarded as waste and usually dumped into slime ponds. The rejection of these slimes is considered a loss and additionally harmful to the environment. In many instances, most of these fines are generated from mechanised mining operations with millions of tonnes reporting to tailing dumps in South Africa. Therefore, given the unused value in these materials, along with the findings by Mohanty et al., where iron ore slimes are found to have high aluminium content with valuable Fe grade in ranges >50%, it was paramount to exploit alternative beneficiation techniques to further increase the yields and quality of the fine fractions of iron ore in South Africa [2].

Numerous magnetic separation techniques (dry or wet) have been developed over the years to meet the requirement of the mineral processing industry for the concentration of different ores. This is based on parameters such as the magnetic susceptibility differences in particles, the generation of higher magnetic field and the design of the separator [3–10]. In addition, researchers have also used both wet high and low magnetic separators for treating different minerals possessing different magnetic properties [11]. In this research study, a new magnetic separation technique as reported in the ASIA Miner report and developed in China, was used for the beneficiation of low grade hematite ore [12]. The equipment relies on its high intensity magnetic capability designed to attract materials with weakly magnetic attributes. It is composed of a corrosion resistant stainless steel matrixes, constituting of about 12% to 18% Cr content. The higher the chromium content, the more resistant the matrixes are to corrosion. It also has a water cooling system passing between the coils, which aids in reducing heat generated during runs.

The equipment was designed based on magnetic jigging principles similar to a SLon, where the pulsation mechanisms assist in improving separation efficiency. This is achieved by agitating the pulp and keeping the particles loose in order to minimise particle entrapment thus creating more surfaces for collecting particles.

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Theoretically, this principle allows the separation of mixtures with small differences in density and small difference in magnetic susceptibility. Through the application of this new technique, the extraction of valuable particles from previously discarded fines and slimes dumps which previously were found not to be cost-effectively viable for beneficiation, could become a feasible option. In addition, the fines generated during the mining of iron ore could be beneficiated further to generate direct reduce iron (DRI) feed material while other minerals like coal, manganese and chromite found with gangue minerals containing iron phases could also be separated using this approach [13]. With all the aforementioned positive attributes of this WHIMS technique and no data reported using the Longi magnetic separator in beneficiating South African iron ore, it needs to determine the separation capabilities of this separator based on an estimated 450 million tons of slimes generated and dumped annually in South Africa. The research aims to determine the optimum process conditions on the Sishen iron ore for maximum achievable grade and recovery and to analyse the influence of variables on the material using a statistical approach.

2. Experimental

2.1. Material

A low grade iron ore material was acquired from Sishen Mine, Northern Cape in South Africa for the purpose of this study. The material was received at −32+8 mm size fraction and was ground using a high pressure grinding roll (HPGR) to generate sample <1.18 mm size fraction. The ground material was then blended using a combination of a riffle splitter and a rotary splitter to maintain homogeneity and to obtain representative sub-samples. The SEM-energy dispersive X ray spectroscopy (EDS) detector system and back scattered electron (BSE) images show that the sample (<1.18 mm) is predominantly Fe oxide in a form of hematite with silicates as main gangue minerals as presented in Fig. 1, while the particle size distribution analyses on each of the sizes as shown in Table 1 was analysed for elemental composition using X ray fluorescence (XRF). The result obtained from the sizing indicated that the majority of the mass is distributed within the 850 and 150 μm fraction. The remaining material was screened at 106 and 75 μm using the Sweco vibrating sieve to generate −1000+106, −106+75 and −75 μm size fractions. A head grade was then determined from the individual size fractions and was calculated to be 43.54% Fe, 14.49% SiO_2 and 13.66% Al_2O_3. The sizing results showed an evenly distributed Fe grade, ranging between 41% Fe and 44% Fe.

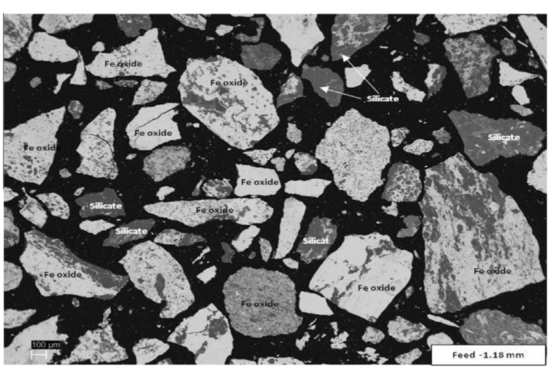

Fig. 1. BSE image from the −1.18 mm feed.

2.2. Test procedures

A wet-high intensity magnetic separator (WHIMS), in a form of Longi LGS 500, was used for this study. It is semi-continuous pilot scale equipment, constituting of a 500 mm diameter rotating rotor with replaceable matrixes. It also consists of a collecting point for the magnetic particles, a pulsating mechanism to keep particle loose from the matrix and the wash water system to wash off the particles and keep the matrix clean. The throughput of the separator ranges between 0.05 and 0.25 ton per hour, and slurry density within 10% to 40% solids. For this study, each of the sized material was individually treated in 10 kg batches on the Longi LGS 500 WHIMS, and the effective separation performance of the separator was determined by varying the following set parameters, i.e. pulp density, magnetic field intensity and pulsating frequency. The matrixes were set at a distance of 2 mm, rotor standard speed of 4 r/min, and constant wash water and feed rate. The pulp was prepared at 20%, 25% and 30%, and allowed to be agitated for 5 min before being fed into the separator. Varying magnetic field of 1000, 5500 and 10,000 G were tested, along with pulsating frequency of 6, 12 and 25.2 Hz. The pulsator assists in keeping particles loose and prevents the clogging of the matrix as a result of the back and forth motion from the frequency converter. As the ring rotates, the attached magnetic particles were collected from the pulp and vigorously washed off into the concentrate holding plate and non-magnetic particles are released from the matrix into a separate collector. For each test, three products were collected, i.e., the magnetic, middlings and non-magnetic, they were individually filtered and oven dried at 105 °C. Once dried, all products were blended, sub-sampled in preparation for chemical analyses.

3. Results and discussion

Three different size fractions (1000+106, −106+75 and −75 μm) of hematite ore were used and the influence of pulp density,

Table 1
Particle size distribution and composition of the −1.18 mm feed material.

Sieve screen (μm)	Mass (%)	Cum mass (%)	Passing (%)	Grade (%)		
				Total Fe	SiO_2	Al_2O_3
+1180	0.06	0.06	100.00	41.43	15.10	15.20
−1180+850	4.72	4.78	99.94	43.75	14.45	14.50
−850+600	19.99	24.77	95.22	44.63	13.80	13.10
−600+425	16.40	41.18	75.23	44.18	13.60	13.90
−425+300	14.19	55.37	58.82	44.15	13.40	13.80
−300+212	10.76	66.13	44.63	44.16	13.70	13.90
−212+150	14.65	80.78	33.87	43.62	14.40	13.60
−150+106	3.01	83.80	19.22	41.51	15.70	13.70
−106+75	6.33	90.12	16.20	41.51	17.10	13.40
−75+53	3.14	93.26	9.88	40.30	18.60	13.60
−53	6.74	100	6.74	40.43	17.60	13.90
Head grade	100			43.54	14.49	13.66

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magnetic field intensity and pulsation frequency was evaluated for effective separation of the Longi LGS 500. The results from each parameter are discussed in the sections below and the data from the product's grade and yield validated by using analysis of variance (ANOVA).

3.1. Effects of pulp density

As stated by Joseph, any variation in pulp density will alter the velocity at which particles are introduced to the magnetic separator and therefore may be expected to alter the process efficiency during separation [14]. As pulp density decreases below a threshold value, the pulp velocity increases, causing a rapid flow through the rotating rotor, thus reducing particle capture and recovery capabilities of the magnetically induced particles. The pulp density increases above the known threshold value, the particles tend to overcrowd the matrix and reduce the recovery capability of the matrix [14]. In this study, the effect of varying pulp density was investigated while the magnetic field and pulsation frequency were kept constant at 2800 G and 12 Hz. The results were in agreement with the authors' findings and were promising where comparing mass yield concentrate and Fe grade was concerned. It could be that at a low pulp density of 20%, particles move freely with less inter-particles forces. This eliminates formation of coagulate. Also, when the magnetic particles attached on the matrix, they were easily washed off the matrix to create more surface area for incoming particles to attach which resulted in high mass yields concentrates and Fe recoveries. As the pulp density increased from 20% to 25% and 30%, there was a decrease in Fe recovery. This could have been as a result of increased overcrowding on the matrix. In such instances, there is a limited surface area for the incoming magnetic particles to attach, thus reducing the overall Fe recovery. It can be noted that, with the decrease in the particle recovery, the quality of the product was not affected, remaining within the same ranges of 50% Fe to 52% Fe as shown in Figs. 2–4. This further proves the decrease in surface area was the main reason for the decrease in overall mass yield concentrate and Fe recovery. This was the trend in all three size fractions −1000+106, −106+75 and −75 μm. Thus, for high Fe recoveries and relatively good Fe grades, the tests could be conducted at <30% pulp density.

3.2. Effects of magnetic field strength

The principle of magnetism states that, the higher the magnetic field intensity, the higher the probability of a particle to be captured [15]. In other words, the efficiency of a magnetic separator for effective removal of non-magnetic particles from magnetic particles depends on the intensity and magnetic flux generated, along with the matrix type used. The investigations on the effect of varying the current to generate magnetic field intensity from 1000 to 5500 and 10,000 G were conducted. The pulp density and pulsation frequency were kept constant at 30% and 12 Hz respectively. The variation of the magnetic field intensity was shown to have a major effect on the quality of the product. From a separation efficiency point of view, an increase in magnetic field intensity had a positive effect on the mass yield concentrate and recovery. However, the increase in magnetic field intensity had a negative effect on the product quality. This was noted for all three size fractions as shown

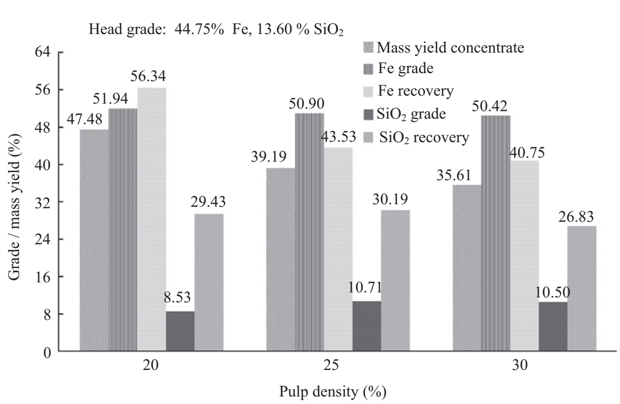

Fig. 2. Effects of changes in pulp density for −1000+106 μm size fraction.

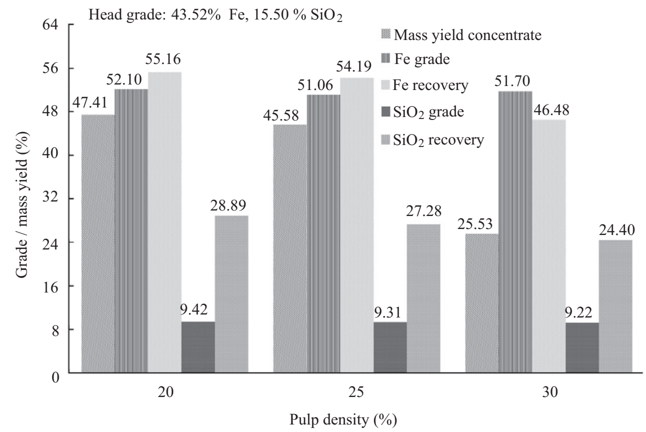

Fig. 3. Effects of changes in pulp density for −106+75 μm size fraction.

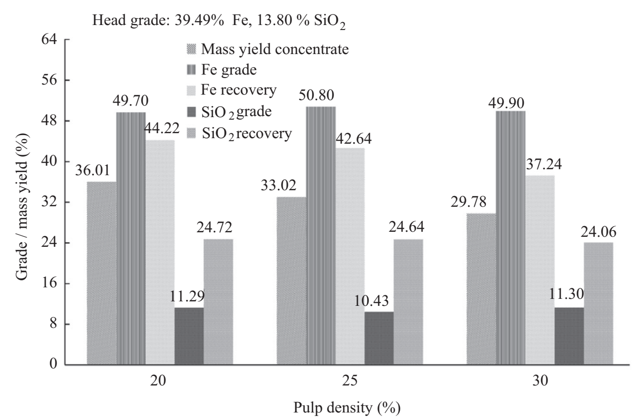

Fig. 4. Effects of changes in pulp density for −75 μm size fraction.

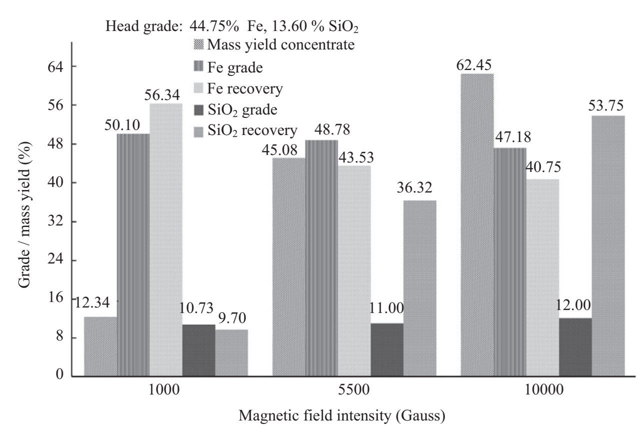

Fig. 5. Effects of changes in magnetic field intensity for −1000+106 μm size fraction.

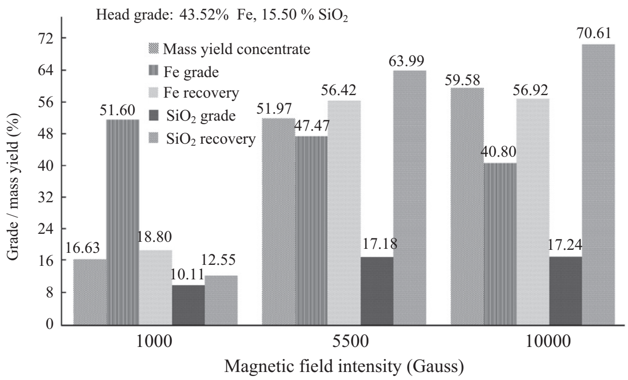

Fig. 6. Effects of changes in magnetic field intensity for −106+75 μm size fraction.

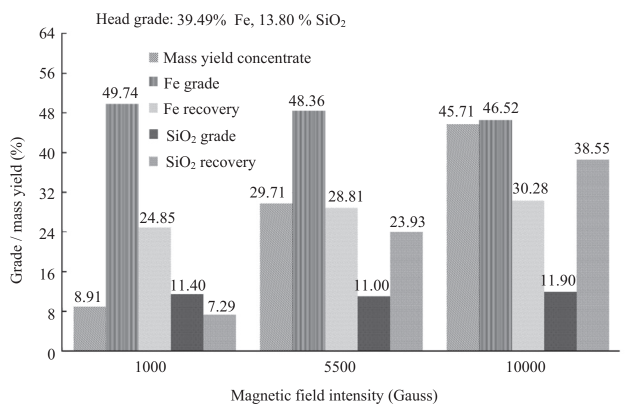

Fig. 7. Effects of changes in magnetic field intensity for −75 μm size fraction.

in Figs. 5–7, whereby the mass yield concentrate and SiO_2 content increased with increase magnetic field intensity. It could have been as a result of both the high and weakly susceptible particles were pulled towards the matrix's surface area. At the same time, this increase in magnetic field intensity could have created enough force for the magnetic particles to form coagulates as they attach on the matrix. During this process, the finely sized non-magnetic particles mechanically entrapped are then released from the coagulates when the rotating rotor moved away from the highly magnetised separating zone to where the magnetic field is lowest. These non-magnetic particles would have been released into the magnetic stream launder, thus increasing the mass yield to concentrate, at the same time diluting the product grade.

Based on the results attained, it would appear that to achieve high Fe recoveries, high magnetic field intensity of 10,000 G needs to be applied, however, this would compromise the product quality due to accumulated diluting gangue minerals. At such magnetic field intensity, this process could be used as a primary rejection stage for downstream cleaning stages. Alternatively, to achieve a reasonably good Fe grade of >50% Fe with <10% SiO_2, an intensity of 1000 G needs to be applied, but this would compromise the overall Fe recoveries to <20%. The results do show that Longi LGS 500 WHIMS has matrix capabilities to generate enough force to facilitate particle capture.

3.3. Effects of pulsation frequency

In order to reduce particle entrapment, clogging of the matrix and to improve product quality, the pulsation mechanism of the Longi LGS 500 magnetic separator was used. Its effect is such that, as the pulsating frequency increases, the competing forces

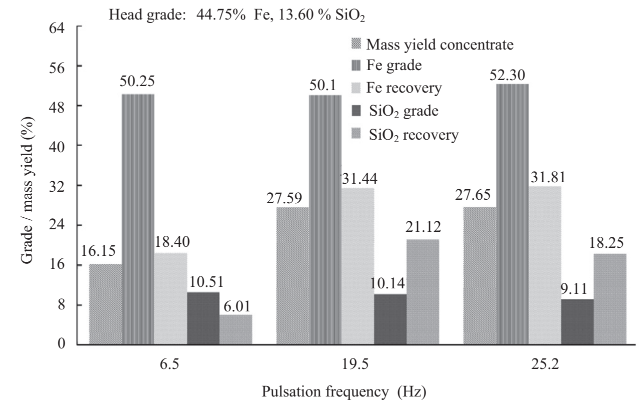

Fig. 8. Effects of changes in pulsation frequency for −1000+106 μm size fraction.

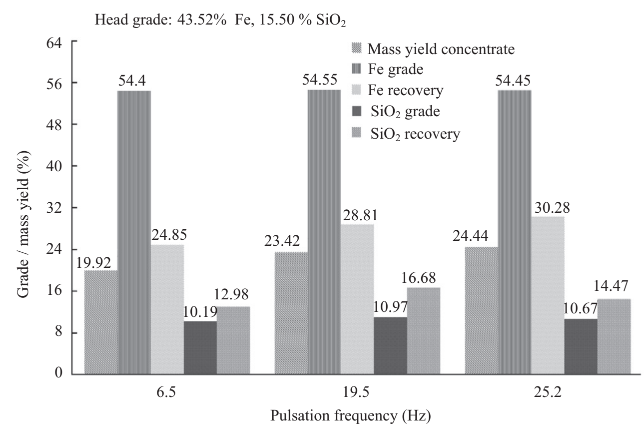

Fig. 9. Effects of changes in pulsation frequency for −106+75 μm size fraction.

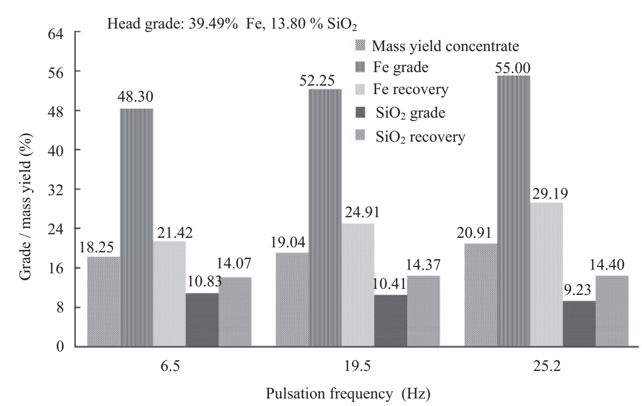

Fig. 10. Effects of changes in pulsation frequency for −75 μm size fraction.

(hydrodynamic and drag forces) acting upon the non-magnetic particles increase. This effect prevents entrapment of fine sized non-magnetic particles within the magnetic coagulates [3]. The current investigations were conducted by varying the pulsation frequency from 6.5 to 19.5 and 25.2 Hz, while magnetic field intensity and pulp density were kept constant at 2800 G and 30% pulp density. The results from the three size fractions treated show that the pulsation frequency has a positive effect on the overall quality of the product. High mass yields concentrate with a maximum achievable Fe grade of 55% Fe (Figs. 8–10) with low gangue contents were achieved in all three size fractions. It could be that as the pulsation frequency increased, the pulp was agitated resulting

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Table 2
Independent variables and (3^3) full factorial design.

Level	X_1 (%)	X_2 (G)	X_3 (Hz)
(a) Variable			
Low	20	1000	6.5
Medium	25	5500	19.5
High	30	10,000	25.2
Input	X_1 (%)	X_2 (G)	X_3 (Hz)
(b) Full factorial design 33			
1	0.20	2800	12.0
2	0.25	2800	12.0
3	0.30	2800	12.0
1	0.30	1000	12.0
2	0.30	5500	12.0
3	0.30	10,000	12.0
1	0.30	2800	6.5
2	0.30	2800	19.5
3	0.30	2800	25.2

Table 3
Analysis of variance (ANOVA) outputs on the interaction of variables.

Group	Count	SOS	Average	Variance
(a) Anova output of mass yield concentrates (%)				
Column 1: X_1	27	1807.06	66.93	133.61
Column 2: X_2	27	508.63	18.84	167.33
Column 3: X_3	27	86.59	3.21	4.55
Column 4: X_1X_2	27	81.23	3.01	40.83
Column 5: X_1X_3	27	46.24	1.71	1.86
Column 6: X_2X_3	27	151.71	5.62	78.89
Column 7: $X_1X_2X_3$	27	144.69	5.36	78.16
(b) ANOVA output of Fe grade (%)				
Column 1: X_1	27	26.59	0.98	21.80
Column 2: X_2	27	74.97	2.78	9.78
Column 3: X_3	27	87.23	3.23	4.32
Column 4: X_1X_2	27	263.34	9.75	51.09
Column 5: X_1X_3	27	79.27	2.94	1.32
Column 6: X_2X_3	27	407.59	15.10	95.81
Column 7: $X_1X_2X_3$	27	391.92	14.52	102.82

in an upwards and downward movements of particles within the separation zone. This created an adequate distance between particle and rotor together with the number of times the particles interacted with the rotor. During such process, selectivity is increased and eliminating the entrapment of the non-magnetic particles, hence improved mass yield concentrates as the pulsation frequency was increased.

Therefore, the high pulsation frequency is necessary for releasing non-magnetic particles from the matrix and thereby for keeping the matrix clean and facilitating good quality products. It was also evident that a high pulsation frequency of 25.2 Hz, 30% pulp density and 2800 G were the optimum conditions for achieving good Fe grade and overall product recovery.

3.4. Statistical analysis: analysis of variance (ANOVA)

The method of analysing data using analysis of variance (ANOVA) is widely used in mineral processing for evaluating the significance of the variables used during investigations [15,16]. The ANOVA outputs were obtained from a Microsoft office, Excel 2010 spreadsheet, using data from twenty-seven (27) test runs on the iron material at three size fractions. The test runs were based on the full factorial design 3^3 following an equation shown below.

$$N = 2^z \tag{1}$$

where N is the number of investigations; and z the number of variables.

The effects of the three variables at three levels (Table 2) were investigated namely: (X_1) pulp density (%), (X_2) magnetic field intensity (G) and (X_3) pulsation frequency (Hz). The estimated coefficients from the mathematical model together with the ANOVA outputs are discussed in Sections 3.5 and 3.6 below.

3.5. Interaction effects

Tables 3 and 4 show ANOVA outputs and the discussion were based on the null hypothesis, which makes comparison of the mean between groups and mean within a group. The hypothesis suggests that there is no difference between the two means, i.e. effects of the variables are the same and the decisions on whether to accept or reject the hypothesis were based on the ratio between F value and F critical. If the F value is $<F$ critical, then the null hypothesis will be accepted, and the opposite is true. If F value $>F$ critical, the null hypothesis will be rejected. The results show that of the three variables, X_2 with the largest positive sum of all square value in the mass yield concentrate, followed by X_3. X_3 has a more significant effect while X_1 reported a negative sum of square value but reported as an absolute value, suggesting the least effect. Thus, as the parameters X_2 and X_3 increased, the mass yield concentrate and Fe grade also increased. The opposite was true for X_1, whereby an increase in parameters had a negative impact on the mass yield concentrates with Fe grade remaining relatively within the same ranges. The order of significant effect was $X_2 > X_3 > X_1$ and $X_2X_3 > X_1X_2 > X_1X_3 > X_1X_2X_3$.

To achieve good product quality using Longi LGS 500 for low grade hematite material at three size fractions, a balance between the main parameters X_2 and X_3 would be required. The X_2X_3 was shown to have the most effect compared to X_1X_2, X_1X_3 and the more complex $X_1X_2X_3$, further supporting the fact that the two variables were the main parameters for achieving optimum separation. Thus, a balance could be at a low magnetic field intensity allowing for recovery of the highly susceptible particles free of the gangue and at a high pulsation frequency ensuring that all the non-magnetic particles are not attached to the matrix or even entrapped within the non-selective coagulates.

Table 4
Analysis of variance (ANOVA) for linear model of Fe ore mass yield and grade.

Source of variation	SOS	df	MS	F value	P-value	F critical
(a) Output data for mass yield concentrate						
Between groups	12261.45	6.00	21102.07	292.37	0.00	2.15
Within groups	13136.10	182.00	72.18			
Total	139748.54	188.00				
(b) Output data for Fe grade						
Between groups	14533.46	6	2422.24	59.09	0	2.15
Within groups	7460.39	182	40.99			
Total	2199.85	188.0				

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Table 5
Regression coefficients from the actual and modelled data.

Size fraction (μm)	Regression coefficient (R^2)
(a) Mass yield concentrate (%)	
−1000+106	0.90
−106+75	0.87
−75	0.86
(b) Fe grade (%)	
−1000+106	0.84
−106+75	0.84
−75	0.96

Table summarises the ANOVA outputs for mass yield concentrates and the grade of the Fe ore, from which the sum of all squares (SOS), degree of freedom (df), mean square (MS), *F* value, probability (*P*) value and *F* critical were determined and conclusions drawn. The *P* value gives an indication of the significance of variables in predicting the responses to individual and interactive effects [16,17].

The results reported low *P* values at <0.05 indicating that the model is significant at 95% confidence level. Based on these results, the variables were considered significant for the magnetic separation process.

3.6. Mathematical model

The mathematical model used is a linear regression equation as shown in Eq. (2), to determine how well the model fits to the actual data. A Microsoft 2010 excel was used for determining this relationship, mainly for mass yield concentrate and Fe grades. In general, the smaller the difference between the model and the actual values, the higher the regression coefficient i.e. *R* squared (R^2), and the better the fit and closer to 100%.

$$Y = a_o + a_1X_1 + a_2X_2 + a_3X_3 + a_4X_1X_2 + a_5X_1X_3 + a_6X_2X_3 + a_7X_1X_2X_3 \quad (2)$$

where *Y* is the Fe grade or mass yield for the magnetic stream; and *X* the independent variable.

Table 5 shows correlations between the modelled outputs and the actual values for the mass yield and the Fe grade. The results obtained further confirmed that X_2 reported the highest positive values, indicating that it has the most significant effect. The X_2X_3 interaction was found to have contributed the most positive value to the modelled value. The responses reported coefficients of 0.90, 0.87, and 0.86 for mass yields concentrates and 0.84, 0.84, 0.96 for Fe grade −1000+106, −106+75 and −75 μm fractions respectively, further suggesting the significance of the model. The authors Joglekar and May suggested a good R^2 fit should at least be 0.80 [18]. The results could be further supported by the results attained by Aziz et al., who reported R^2 of 0.93 for manganese recovery and 0.94 for iron recovery [19]. Again the result by Tripathy et al., the R^2 was reported at 0.94 for chromite grade and 0.93 for chromite recovery [20].

3.7. Summary

The WHIMS investigations were conducted on three size fractions constituting of slightly different mineral Fe and SiO_2 associations. The results showed that the Longi LGS 500 possesses great capabilities for beneficiating the material, even at wide size ranges, for example the −75 μm size fraction reported up to 55%. The analysis of variance together with the regression model was applied to validate the effects of the three variables investigated. From the model outputs, the null hypothesis qualified to be rejected indicating that the effects of the parameters were significant to the mass yield concentrate and Fe grade responses, particularly magnetic field intensity and pulsation frequency. In addition, the regression coefficients from the modelled and actual values were in good correlation and were reported to be in the range of 0.84 to 0.96.

4. Conclusions

The effects of varying the pulp solids, magnetic field intensity and pulsation frequency provide detailed beneficiation capabilities of the newly developed Longi LGS 500 WHIMS on a low grade iron ore material prepared to three different size fractions. From the research investigations, the following conclusions were drawn:

(1) It was observed that the Longi LGS 500 is potentially good for beneficiating low grade iron ore fines, and the back scattered electron (BSE) images showed that the ore is predominantly Fe oxide in a form of hematite with silicates as main gangue minerals.
(2) It was noted that the increase in pulp density from 20% to 25% and 30% had a negative effect on the mass yield of concentrate. At pulp solids >20%, the matrix was overloaded resulting in the concentrate mass yields concentrate and Fe recoveries decreasing with no significant effects on the Fe grade.
(3) The changes in magnetic intensity from 1000 to 10,000 G increased the mass yield of the concentrates, while the pulsation mechanism, on the other hand, positively affected the overall quality of the product, more so on the −75 μm size fraction. An increase from 6.5 to 19.5 and 25.5 Hz showed an increase in both the mass yield concentrates and Fe grade.
(4) The interactions between parameters were shown to be essential, and most notable was between X_2X_3 having the most effect, followed by X_1X_3 then $X_1X_2X_3$. These results supported the fact that of the two variables investigated, the X_2 and the X_3 had a major individual effect on this particular iron sample.
(5) The optimum conditions for iron ore could be achieved at 20%, 2800 G and a pulsation of 25.2 Hz.

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