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RESEARCH ARTICLE - CHEMICAL ENGINEERING

Optimization of Reverse Cationic Flotation of Low-Grade Iron Oxide from Fluorspar Tails Using Taguchi Method

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Abstract Due to gradual depletion of high-grade iron ores, there is a need to investigate the treatment of low-grade iron ores. Current procedures are time and cost intensive. Batch laboratory scale reverse cationic flotation was employed to concentrate low-grade Fe ore, found in fluorspar tails in the form of hematite. This study used two types of depressants (soluble starch and dextrin) and two types of amines (primary mono-amine and tertiary mono-amine). Optimisation of the process investigated parameters such as pH, collector type and dosage, depressant type and dosage, conditioning time, solids content, agitation speed and air flow rate. Owing to the high number of experiments when all possible combinations are investigated, Taguchi design of experiment method was utilised to streamline the number of experiments and optimize parameters using orthogonal array and signal–noise ratio (SN). The SN was used to determine the optimum conditions and analyse the relative significance of parameters studied. The results showed that both depressants were efficient for hematite depression; however, soluble starch produced better results when compared to Betachem 30D. Both Betacol 373 and Dodecylamine collectors were efficient as quartz collectors; however, Dodecylamine produced better results when compared to Betacol 373. Ranking of parameter using SN ratio showed that pH was the most critical parameter in obtaining higher Fe grade concentrate and the optimum pH is 10. De-slimming leads to low recoveries during reverse flotation of iron ores. The main conclusion is that Taguchi method can be used to optimise a reverse cationic flotation process of a low-grade iron ore.

Keywords Reverse cationic flotation · Taguchi method · Low-grade iron ore · Tailings

1 Introduction

The flotation process is one of the most important concentration processes of finely disseminated low-grade iron ores due to its high selectivity [1]. A lot of work has been done by numerous authors on the factors affecting flotation process [1–6]. Due to multiple parameters influencing flotation process, it is difficult to study all possible combinations of factors as it would lead to uneconomically lengthy experiments and high consumption of resources [7].

Gradual depletion of high-grade iron ores, stringent environmental laws for tailings disposal and a weak demand for iron ore, reported for South Africa in 2015 [8], have resulted in intensive exploration of cheaper ways of producing iron from ores which were regarded as low grade and uneconomical. Depending on the characteristics of the ore, the general separation methods for low-grade iron ores are gravity separation, magnetic separation and flotation [1,9,10].

The gravity method uses the difference in mineral densities, sizes and shapes to separate the targeted mineral through a fluid media. It is efficient when a marked density difference exists between the mineral and the gangue [11]. The limitation for gravity separators is that they are not efficient in the treatment of fines [11,12].

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The magnetic separation uses magnetic intensity to separate magnetic minerals from non-magnetic minerals. The use of wet high intensity magnetic separator (WHIMS) was investigated by Umadevi et al. [13] where it was found that this process was successful in achieving high-grade iron concentrate. Filippov et al. [1] suggested that wet low-intensity and WHIMS are the best methods for processing magnetite and hematite ores with a high iron content, high liberation degree of iron oxide, coarse texture and quartz as the major gangue mineral.

The flotation method utilises the difference in surface properties of the valuable minerals and the unwanted gangue. Reverse cationic flotation is the best method for concentrating iron ores and is used in all iron ore processing plants in Brazil [14]. Research done by Filippov et al. [1] showed that reverse cationic flotation of iron ores is the best concentration method when compared to reverse anionic flotation. This is due to higher process selectivity, higher flotation rate and satisfactory results when hard water is used. Although a lot of literature exist on the factors affecting flotation process [1–6], there is need to reduce the number of experiments carried out before a successful flotation process is achieved.

Design of experiments (DOE) methods are used to statistically provide a predictive knowledge of a complex, multi-variable process using fewer trials. Types of DOE methods include full factorial design, fractional factorial design and Taguchi method [15]. Taguchi method is a well-accepted technique that has been widely applied for product design and process optimization in manufacturing and engineering sectors worldwide [16–18]. It was found in 1966 by Genichi Taguchi and is based on Ronald's Fischer factorial design work. Taguchi method tests pairs of possible combinations utilising orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied [15]. This then allows a smaller number of observations required to find the main factors effecting the output. The number of minimum observations (N) required for full factorial, fractional factorial and Taguchi DOE method are given as follows:

$$\text{Full factorial doe, } N = l^k \tag{1}$$

$$\text{Fractional factorial doe, } N = l^{k-p} \tag{2}$$

$$\text{Taguchi doe, } N = 1 + k(l-1) \tag{3}$$

where l is the number of levels, k is the number of parameters, and p is the number of generators. Taguchi method is recommended for processes with intermediate number of variable (3–50), where there are few interactions between variables and only a few variables contribute significantly. The disadvantage of Taguchi method is that since it tests pairs of parameters at a time, it becomes impossible to study relationships between individual parameters.

This research investigated the use of Taguchi method as an optimisation tool for flotation of a low-grade finely disseminated iron ores. Reverse cationic flotation was explored to upgrade low-grade iron found in fluorspar tails. The analysis of obtained data was conducted using SN ratio and ANOVA [19]. Apart from being unable to study the relationships between individual parameters, Taguchi Method has proved that it can be used to predict optimum conditions for flotation of low-grade iron ores using a very minimum number of experiments.

2 Materials and Method

2.1 Materials

A sample of fluorspar tails was provided by Vergenoeg Mine, South Africa. The sample predominantly consisted of hematite with low iron grade of 48.9%Fe. Major impurities were SiO_2 (16.8%) and CaO (3.8%). The sample particle size distribution was 80% passing 155 μm with majority of the Fe-oxide occurring in the 10–70 μm size range while 81.11% of the grains were full liberated, with 3% locked Fe-oxide occurring in the <20 μm particle size fraction [20].

2.2 Reagents

The primary amine, dodecyl amine (DDA) was obtained from Merck at a purity of 98%. It was prepared to 1%ww by using deionised water and a few drops of HCl. The mixture was heated to 40 ∘C while stirring to ensure a uniform solution. The tertiary amine, Betacol 373, composed of octa-dodecane and tri-ethoxy tetradecane was obtained from Betachem as an oil in liquid form at 98% purity and 0.78g/ml density.

The depressant [soluble starch (SS)] was purchased from Merck and was prepared to 3%ww solution using deionised water. The second depressant, Betachem 30D, was received from Betachem. It was prepared to 3%ww using deionised water and heated to 40 ∘C while stirring to ensure solubility. 5% NaOH and HCl solutions were prepared using deionised water. All reagents were prepared on the day of experiments. A few drops of Dowfroth 200 were used in the flotation experiment.

2.3 Experimental Procedure

2.3.1 Design of Experiments (DOE)

Taguchi method was used for the arrangement of experiments and determination of the number of the required observations based on degrees of freedom. The method assumed no interactions existed between parameters. Minitab 17 was used for computing of Taguchi data and data analysis. The selected

Table 1 Experimental parameters and their levels (Soluble Starch-DDA system)

Parameters	Level 1	Level 2	Level 3	Level 4	Level 5
Starch dosage (g/t)	750	1000	1300	1500	2000
DDA dosage (g/t)	200	300	400	500	600
pH	4	6	8	10	12
Solids content (%)	35	40	45	50	55
Condition time (min)	3	6	10	15	20

Table 2 L25 orthogonal array matrix for Soluble Starch-DDAsystem

Exp. no.	Operating conditions				
	SD (g/t)	CD (g/t)	pH	%Solids	C/T (min)
1	750	200	4	35	3
2	750	300	6	40	6
3	750	400	8	45	10
4	750	500	10	50	15
5	750	600	12	55	20
6	1000	200	6	45	15
7	1000	300	8	50	20
8	1000	400	10	55	3
9	1000	500	12	35	6
10	1000	600	4	40	10
11	1300	200	8	55	2
12	1300	300	10	35	10
13	1300	400	12	40	15
14	1300	500	4	45	20
15	1300	600	6	50	3
16	1500	200	10	40	20
17	1500	300	12	45	3
18	1500	400	4	50	6
19	1500	500	6	55	10
20	1500	600	8	35	15
21	2000	200	12	50	10
22	2000	300	4	55	15
23	2000	400	6	35	20
24	2000	500	8	40	3
25	2000	600	10	45	6

parameters and the levels to which they were varied for the Soluble Starch and DDA system are shown in Table 1.

The selected levels were based on preliminary results obtained from previously ran experiments. Due to the five parameters and five levels, the L25 Taguchi orthogonal array matrix was used for all experiments. The experiments were conducted according to Table 2.

The output columns (Fe grade) were added into the Taguchi worksheet. The optimization was conducted studying the control factors only, with the targeted output being "higher Fe grade", where SN ratio was given as follows:

$$\frac{S}{N} = -10\log\left[\frac{\sum\left(1/y_i^2\right)}{n}\right] \quad (4)$$

Higher values of the signal-to-noise ratio (SN) identified control factor settings that minimized the effects of the noise factors thus facilitating desired output results [21]. SN ratio was also used to determine the relative importance of each factor under investigation. A confirmation test was conducted at the optimum conditions predicted by Taguchi SN ratio. Further optimization exercises were conducted until the required results were obtained. Analysis of data using ANOVA was done to identify and quantify the errors resulting from deviations on a set of results [22].

2.3.2 Flotation Experiments

All batch flotation experiments were performed using a laboratory mechanical flotation cell, Denver D12 with capacity of 2.5lt. The Denver cell is equipped with a variable speed agitator for ensuring solids are kept in suspension and for even distribution of materials. It is also fitted with an air inlet to introduce bubbles into the cell. Figure 1 shows a schematic diagram of the Denver D12 laboratory flotation cell used.

The control parameters investigated were pH, collector type and dosage, depressant type and dosage, conditioning time, solids content, agitation speed, air flow rate and effect of de-sliming. A combination of Taguchi L25, L16, L9 orthogonal arrays and full factorial designs were used throughout the project depending on the number of parameters investigated and levels to which they were varied.

The pulp was prepared to the required solids concentration (35–55%) using domestic water. It was agitated at the set speed (1200–1400 rpm) for the set conditioning time while stage wise addition of flotation reagents was done. Depressant was the first reagent added, followed by pH adjustment, then a collector and a frother. The soluble starch dosage was varied from 750 to 2000 g/t and dextrin dosage from 300 to 700 g/t. The pH was varied between 4 and 12, DDA from 200 to 600 g/t, Betacol 373 from 2500 to 8000 g/t and the conditioning time between 6 and 20 min. NaOH and HCl were used for pH adjustments. When the conditioning period had lapsed, air was introduced into the cell to start flotation. The froth was collected into the drip trays, while the system was

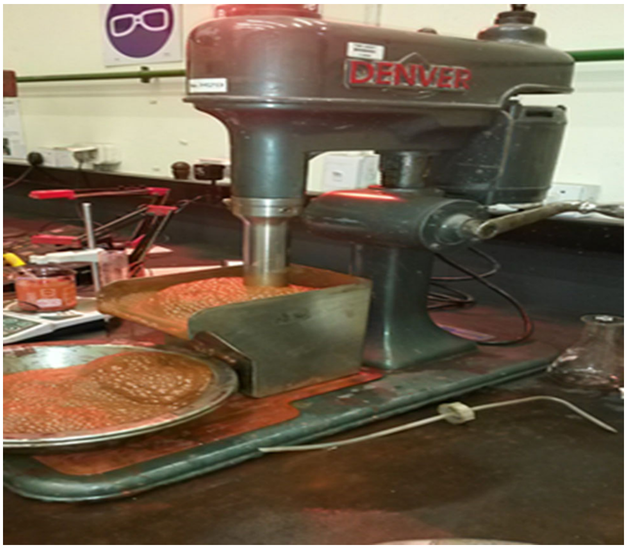

Fig. 1 Denver D12 flotation cell

kept at the required pH. Air was turned off after 2 min of flotation and agitation stopped. The floats and sinks were separately filtered, dried at 70 oC, weighed and analysed.

2.3.3 De-sliming Method

A 5 kg fluorspar tailings sample was subjected to a 20 µm vibration screen, where it was wet screened in small batches. Screening was seized when a clear run off was observed. The top and undersize were individually filtered, dried and weighed. Chemical analysis was conducted on both the −20 µm and +20 µm fractions. The −20 µm fraction was discarded and the +20 µm was used for flotation.

3 Results and Discussion

3.1 Optimum Conditions Prediction for Soluble Starch: DDA System

The L25 orthogonal array (OA) was used to measure performance of DDA and soluble starch. The effect of five parameters varied five times as shown in Table 2 was interpreted using the SN ratio for “Higher iron grade”. The results are shown in Fig. 2.

3.1.1 Soluble Starch Dosage: SN Ratio Trend

The soluble starch dosage—SN ratio trend in Fig. 2 showed that the efficiency of the process generally increased with increase in starch dosage. The highest SN ratio was predicted to be at 2000 g/t starch dosage (SD). Work done by Kar et al. [23] showed that depressing action of hematite increased with increase in starch dosage. It was noted that

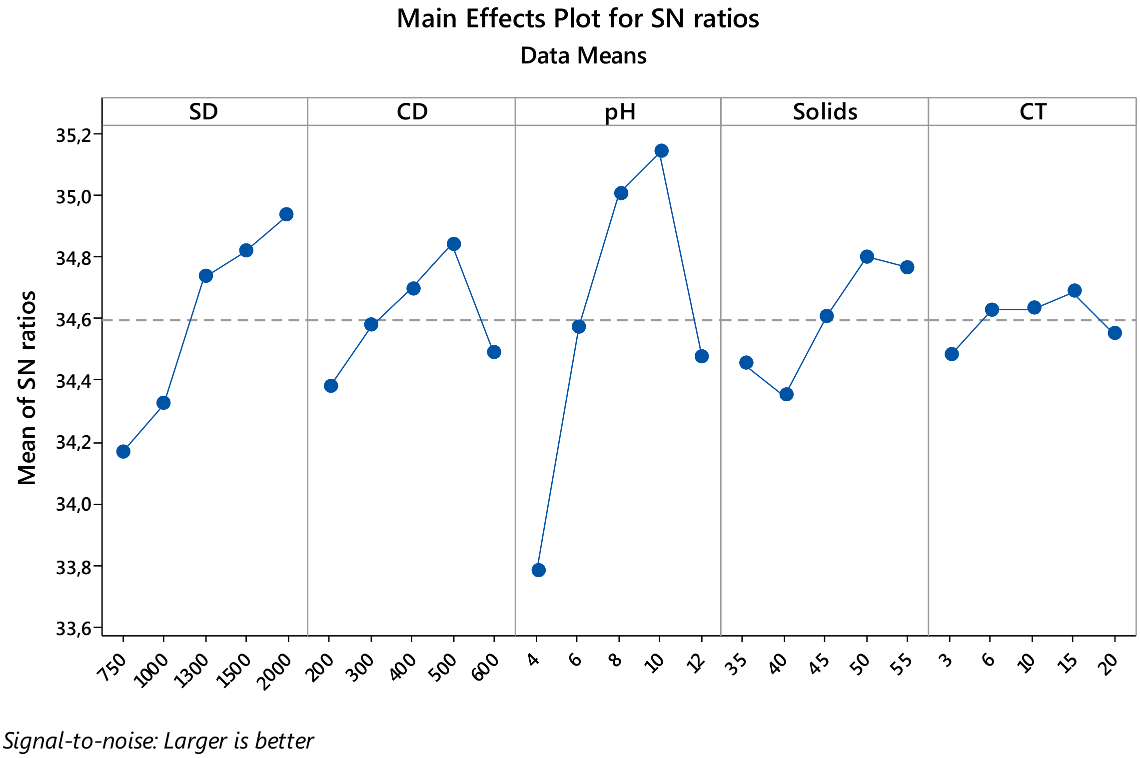

Fig. 2 SN ratio response of Soluble Starch-DDA system

the 2000 g/t soluble starch obtained as the optimum soluble starch dosage in this study is much higher than the previously recorded dosages of 400–600 g/t reported by Kar et al. and Nheta et al. [23,24]. Due to high cost of soluble starch, a decision was made not to investigate higher soluble starch dosages.

3.1.2 DDA Dosage: SN Ratio Trend

The DDA collector dosage—SN ratio trend in Fig. 2 showed that flotation performance increased with increase in collector dosage (CD) from 300 to 500 g/t after which a sudden decline was observed at 600 g/t. The floatability of quartz increases with increase in collector dosage until an optimum point is reached where a decline occurs possibly due to formation of hemi-micelles at the solid-liquid interface [1]. The optimum collector dosage of 500 g/t depicted by the SN ratio is more than that of 300 g/t shown by Nheta et al. [24] and 48 g/t suggested by Kar et al. [23]. A possible reason for a decreased system performance at higher amine dosage is that adsorption of amines on the mineral surface is pH dependent, while adsorption of starch is concentration dependent. Hence, adsorption of starch is reduced at higher amine concentration due to the formation of clathrate, thus resulting in flotation inefficiency [25].

3.1.3 Pulp pH: SN Ratio Trend

The pH—SN ratio trend in Fig. 2 showed that the efficiency of the flotation experiments increased with increase in pH and the highest SN ratio was reached at pH 10. Starch absorbs extensively on hematite and has lower affinity for quartz at higher pH, while the amine adsorbs strongly on quartz than on hematite [26]. The solution pH plays a vital role in flotation since ionic surfaces of oxide minerals are amphoteric and can take up either H^+ or an OH^- ion depending on the pH. Increase on pH intensifies the surface charge of silica, making it more negative as its point of zero charge (pH 2–3) is surpassed, hence strengthening adsorption of amines on the quartz surface. At pH 10, hematite is slightly negatively charged, since its point of zero charge is at pH 6–8; hence, hematite is not highly attracted to the amine collector around such a pH. Ma et al. [27] conducted reverse cationic flotation at pH 10.5.

The pH—SN ratio trend statistically predicts a sudden drop in system efficiency at pH >10. A similar trend was reported by Huanget al. [28], where it was observed that flotation of quartz increased gradually with increase in pH but decreased at pH >10. A decrease in system efficiency at pH >10 might be due to both hematite and quartz being highly negatively charged, hence lowering the selectivity of reagent absorption.

3.1.4 Solids Content: SN Ratio Trend

The solids—SN ratio trend shown in Fig. 2 predicted the process performance to increase with increase in solids content in the pulp until an optimum point is reached at 50% solids, after which the performance drops. A reduction in flotation efficiency at high solids content was attributed to the detachment of bubbles from particle surface, reagent starvation and reduction of bubble numbers with increase in pulp density for a given air flow rate [6].

3.1.5 Conditioning Time: SN Ratio Trend

The conditioning time—SN ratio in Fig. 2 predicted optimum Fe grade at 15 min conditioning time. This was a deviation from 5 to 6 min recommended by Mowla et al. [6] and the 6 min used by Ma et al. [27].

3.1.6 Ranking of Parameters

The parameters under investigation were ranked according to relative importance, and the results are shown in Table 3. The ranking looks at the difference between the lowest SN ratio, and the highest SN ratio as the parameter setting level is varied [29]. The parameter with the highest difference is deemed the most critical as its variation effected the most change in the output response.

The ranking of process parameter, indicated in Table 3, showed that the relative significance of the parameter was in the order of pH being the most significant parameter followed by starch dosage, collector dosage, solids content and conditioning time, respectively. This means that the system is most sensitive to pH changes. This finding is in line with literature since pH is known to be critical in flotation of iron oxides as it affects the surface charge of oxide minerals [30].

3.1.7 Confirmation Test for SS-DDA System

A confirmation test for soluble starch and DDA was conducted at predicted optimum conditions of soluble starch at 2000 g/t, DDA dosage of 500 g/t, pH 10, solids content of 50%, conditioning time of 15 min, air flow rate of 5.25 L/min and rotor speed of 1300 rpm. A concentrate assaying 61.2%Fe and 2.06%Si at 78%Fe recovery was obtained. This iron assay was below the required ≥63%Fe for pellets making.

3.2 Optimum Conditions Prediction for Betachem 30D and DDA System

Using the information attained from the soluble starch—DDA system, this investigation was conducted at parameter settings shown in Table 4 and the results shown in Fig. 3.

Table 3 Parameter ranking results using SN ratio (soluble starch: DDA system)

Level	Starch dosage	Collector dosage	*pH*	Solids content	Condition time
1	51.26	52.53	49.06	53.04	53.23
2	52.22	53.65	53.61	52.49	53.95
3	54.60	54.30	56.28	53.84	54.19
4	55.11	55.28	57.15	54.94	54.25
5	55.87	53.29	52.96	54.76	53.43
Delta	4.61	2.75	8.10	2.45	1.02
Rank	2	3	1	4	5

Table 4 Parameter settings for Betachem 30D-DDA system

Parameters	Level 1	Level 2	Level 3
Betachem 30D dosage (g/t)	300	500	700
DDA dosage (g/t)	400	500	600
pH	8	10	12
Solids content (%)	40	50	55
Condition time (min)	5	10	15
Agitation speed (rpm)	1200	1300	1400
Air rate (L/min)	3.5	5.25	7

3.2.1 Dextrin Dosage: SN Ratio Trend

Betachem 30D dosage—SN ratio trend shown in Fig. 3 shows that the optimum dextrin dosage for higher Fe grade output is at 500 g/t, which is much lower than the 2000 g/t predicted when soluble starch was used. A reduction in flotation performance with increase in Betachem 30D dosage could be due to hemicelles formation at high reagent concentration.

3.2.2 DDA Dosage: SN Ratio Trend

It was observed that the optimum DDA dosage was not reduced by the introduction of a parameter such as air rate, agitation speed and a different type of depressant. The DDA dosage—SN ratio in Fig. 3 shows an increase in flotation efficiency with increase in collector dosage with optimum dosage being 500 g/t.

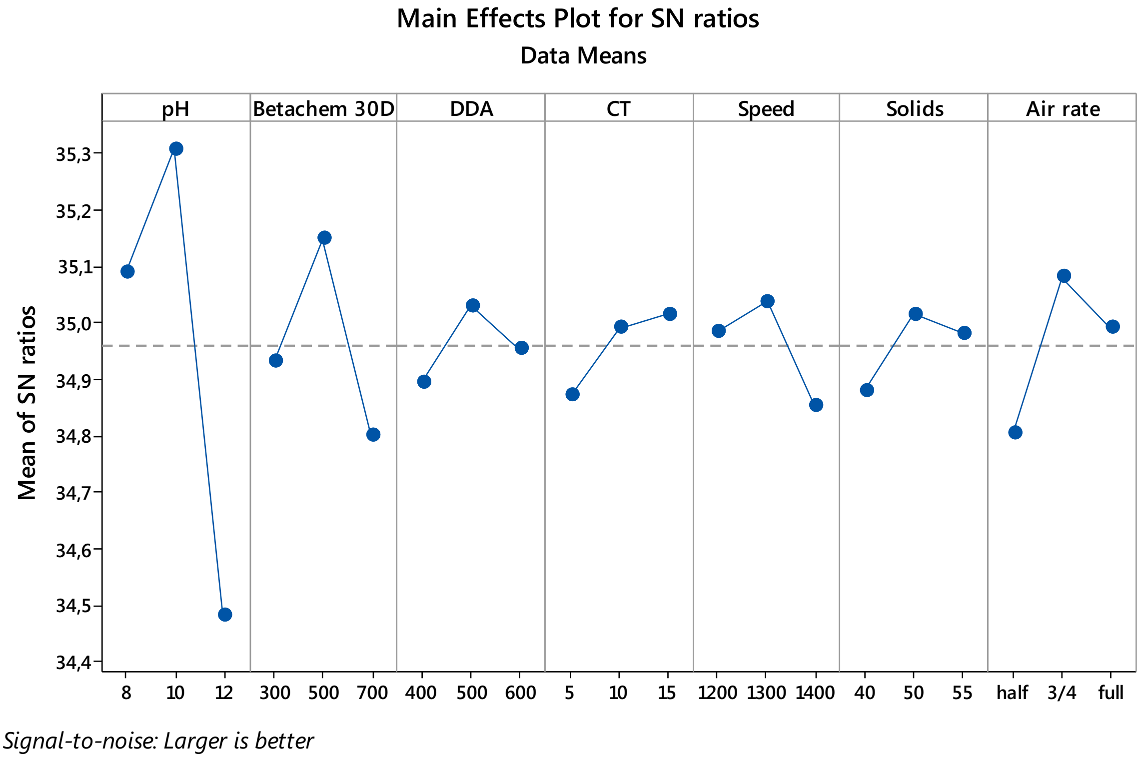

Fig. 3 SN ratio response for Betachem 30D-DDA system

3.2.3 *Air Rate and Agitation Speed: SN Ratio Trend*

The air rate—SN ration graph in Fig. 3 showed an improvement in system efficiency as air flow rate is increased from 3.5 to 5.25 L/min and a sudden drop when the air flow rate is increase to 7 L/min (half, 3/4 and Full air rate, respectively). A similar trend was observed with agitation speed—SN ratio graph where the performance is seen to increase when the agitation speed is increased from 1200 to 1300 rpm and dropped suddenly when the speed is increased to 1400 rpm. Air flow rate and agitation speed are critical for efficient performance in flotation as high air rate increase the available area for attachment of targeted mineral and the increased agitation speed increases contact opportunities of air with the target mineral. With flotation rate driven by factors; collision, adhesion and detachment, increased performance is anticipated as agitation speed is increased due to increased rate of collision and adhesion between particles and bubbles. However, at the highest impeller speed of 1400 rpm, the rate of detachment could be greater than that of collision and adhesion leading to poor flotation of quartz thus reduction in the sinks iron grade.

3.2.4 *Ranking of Parameters (Betachem 30D and DDA)*

The response of SN ratio to produce higher iron grade concentrate was used to rank the parameters according to the significance. The relative significance of the parameters showed pH to be the significant parameter followed by depressant dosage.

3.2.5 *Confirmations Tests Results for Betachem 30D: DDA System*

A confirmation test for the dextrin Betachem 30D—DDA system was conducted at predicted optimum conditions of Betachem 30D—500 g/t, DDA dosage—500 g/t, pH 10, solids content of 50%, conditioning time of 15 min, 5.25 L/min air flow rate and rotor speed of 1300 rpm. Conducting the experiment at optimum conditions showed a 63.79%Fe grade at 70% recovery.

3.3 Further Optimisation of Betachem 30D: DDA System

3.3.1 *De-sliming of Feed*

Further optimisation of Betachem 30D–DDA system was done by first de-sliming the feed followed by flotation. The aim was to explore the opportunity of reduce iron losses arising from slime coating and also reduce the reagents consumption as a result of presence of fines. The results are reflected in Fig. 4.

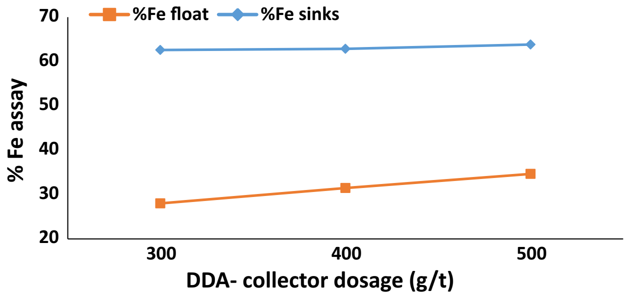

Fig. 4 Impact of de-sliming on Fe grade

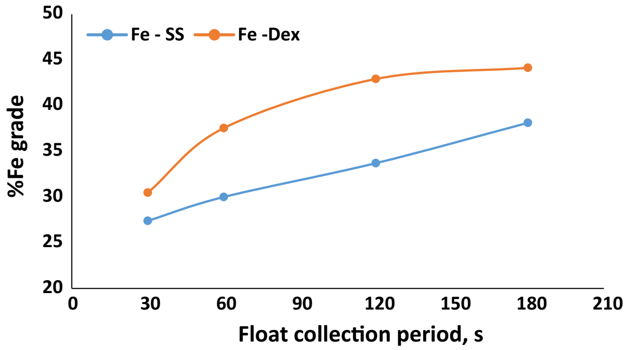

Fig. 5 Flotation kinetics of dextrin and soluble starch systems

An iron grade of 62.6% was achieved using 300 g/t collector dosage after de-sliming. The iron assay in the concentrate was seen to be increasing slightly with increase in collector dosage; however, higher losses of iron to the floats were also observed. The highest iron grade of 63.86% at 75.16% recovery was observed at 500 g/t collector dosage when de-slimed feed is used. The metal loss at 500 g/t collector dosage using de-slimed feed was 38% including the 13% loss by action of de-sliming alone. Though some reagent saving was observed with de-sliming, high metal losses were, however, observed.

3.4 Comparison Between Soluble Starch and Betachem 30D Depressants

Flotation kinetics was conducted using the tested depressants (Betachem 30D and soluble starch) with DDA as the collector. The aim was to observe depressing efficiency of the selected depressant.

The results reflected in Fig. 5 showed that both systems were good depressants of iron oxide and that the iron loss to floats increased with time. A lower concentration of iron was observed in the floats, in the first 30 s of flotation, when using soluble starch. High cost of soluble starch, however, led to the selection of the dextrin (Betachem 30D) as the better depressant.

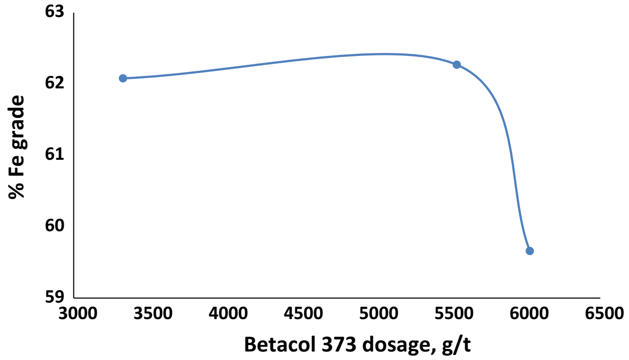

Fig. 6 Impact of collector dosage on iron grade

3.5 Optimum Conditions Prediction for Betachem 30D: Betacol 373 System

The L9 orthogonal array was selected for experimental set up and Taguchi used for analysis of results. The fixed parameters were pH 10–10.5, conditioning time 15 min, agitation speed 1300 rpm and air flow rate of 5.25 L/min. The variables were Betacol 373 dosage, Betachem 30D dosage and solids content. The optimum conditions predicted by SN ratio analysis showed that best performance for Betachem 30D–Betacol 373 was at dextrin dosage 500 g/t, Betacol 373 dosage of 3328 g/t and 35% solids content. A confirmation test was conducted at the obtained optimum conditions and a concentrate with 62.08%Fe at 69.07% recovery was achieved. Seeing that Taguchi picked the maximum setting of Betacol 373 dosage; a decision was taken to investigate further dosages.

3.6 Further Optimisation of Betachem 30D: Betacol 373 System

3.6.1 Effect of Collector Dosage Variation

The dosages 3328, 5548 and 7770 g/t were investigated with depressant (Betachem 30D) dosage fixed at 500 g/t and the results are displayed in Fig. 6.

An increase in collector dosage was observed resulting in a slight increase in iron grade until an optimum point of 5548 g/t, where after the performance suddenly dropped. The Fe grade of 62.28%Fe at a reduced recovery of 61.01% in sinks was observed at 5548 g/t. When compared to 62.08%Fe and 69.07% recovery obtained at 3328 g/t collector dosage, an increase to 62.28%Fe signals a slight improvement in results and does not justify increasing collector dosage from 3328 to 5548 g/t.

It was noted that increasing amine dosage by 9% from 5548 g/t resulted in 2.6% iron grade drop. This was in line with Lima et al 2013 findings whereby amine dosage increase contributed more to the interaction between depressant and amine dosage, hence affecting the selectivity of the process. According to Lima et al, 2013, a higher dosages of amine result in the formation of clathrate.

Table 5 Dodecylamine and Betacol 373 comparison

Description	DDA	Betacol 373
Fe in sinks	63.79%	62.08%
Si in sinks	1.76%	1.58%
Ca in sinks	0.71%	2.2%
Fe in floats	40.43%	40.07%
SiO_2	3.76%	3.39%
Al_2O_3	0.87%	0.60%
Fe recovery	70.78%	67.02%
Metal loss	29.22%	32.98%
%Mass in sinks	54.26%	53.15%
Betachem 30D dosage	500 g/t	500 g/t
Collector dosage	500 g/t	3328 g/t
pH	10 ± 0.5	10 ± 0.5
Solids content	50%	35%
Conditioning time	15 min	15 min
Agitation speed	1300 rpm	1300 rpm
Air valve opening	3/4 open	3/4 open

3.7 Comparing Cationic Amines (DDA and Betacol 373) Results

Table 5 shows comparison between the concentrates obtained at operation at optimum conditions for DDA and Betacol 373, where Betachem 30D was the used depressant.

Results tabulated in Table 5 show that both Betacol 373 and DDA reduced SiO_2 in the concentrate significantly from the feed with 16.8% to concentrates with 3.76 and 3.39%, respectively. Betacol 373 system was also able to concentrate the iron in the feed significantly from 48.9 to 62.08%Fe grade at 67.02% recovery. The alumina and phosphorus were reported at $<1\%$.

However, a system of Betachem 30D–DDA produced superior results with higher iron grade (63.79%) in concentrate, which is within the required $\geq$63%Fe. The recovery was higher at 70.78% when compared to the 67.02% obtained with use of Betacol 373. The alumina and phosphorous were at <1 wt%.

3.8 ANOVA Analysis

The Statistical Package for the Social Science (SPSS) software was used for ANOVA analysis. The following results were obtained for Soluble starch and DDA system. Hypothesis testing was done using the P value approach [31]. The

Table 6 Results for multivariate tests

Method	Value	F	Hypothesis df	Error df	Significance, P value	Partial eta squared
Pillai's trace	0.105	1.351^b	2.000	23.000	0.279	0.105
Wilks' lambda	0.895	1.351^b	2.000	23.000	0.279	0.105
Hotelling's trace	0.117	1.351^b	2.000	23.000	0.279	0.105
Roy's largest root	0.117	1.351^b	2.000	23.000	0.279	0.105

following hypothesis were made, with $\alpha = 0.05$ (Level of significance);

- Null hypothesis, H_0: There is no change in percentage of iron in sink over two repeats experiments.
- Alternative hypothesis, H_A: There is change in percentage of iron in sink over two time periods.

P value approach determines the likeliness or un-likeliness of observing a test statistic in the direction of either a null nor am alternative hypothesis. If P value is $\leq \alpha$, then the null hypothesis is rejected in favour of the alternative hypothesis. The results for the effect of %Fe in sinks are shown in Table 6, where b is a foot note denoting the exact statistics.

The P value, $P = 0.279$, was obtained. According to Ramsey, 2011 a P value >0.05 indicates weak evidence against the null hypothesis hence failure to reject null hypothesis. With $P = 0.279 > 0.05$, the null hypothesis was not rejected; hence, there was sufficient evidence to conclude that there is no change in percentage of iron in the sinks.

4 Conclusion

This paper has presented an investigation on the optimisation of reverse cationic flotation of a low-grade iron ore using Taguchi method. The confirmation tests indicated that it is possible to choose parameter combinations for flotation of iron ore using the proposed statistical technique. The relative significance of flotation parameters using SN ratio indicated that pH has the most significant effect on iron grade during reverse cationic flotation. Although de-sliming increases the grade of Fe in the sinks, it leads to very significant losses. Even though primary mono-amines are better collectors compared to tertiary mono-amines, tertiary mono-amines can achieve the same results under suitable conditions. Both starch and dextrin are good depressants of haematite. The use of Taguchi method in optimization of flotation process is effective and produces reliable results.

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