



## Reprocessing of Sangan iron ore tailings by flotation

S. Ghasemi<sup>1</sup>, A. Behnamfard<sup>1\*</sup> and R. Arjmand<sup>2</sup>

1. Department of Mining Engineering, Faculty of Engineering, University of Birjand, Birjand, Iran  
2. Opal Parsian Sangan Industrial and Mineral (OPSIM) Company, Khaf, Iran

Received 24 February 2019; received in revised form 28 March 2019; accepted 22 April 2019

### Keywords

*Iron Ore Tailing*

*Upgradation*

*Reverse Flotation*

*Anionic Collector*

*Natural Depression*

### Abstract

The Sangan processing plant consists of four consecutive low-intensity magnetic separation steps with the same magnetic field intensity of 1300 Gauss for upgradation of iron ore. Hence, the iron ore minerals with lower magnetic susceptibility or interlocked with gangue minerals have no opportunity for upgradation, and proceed to the tailing dam. Flotation is a powerful technique for upgradation of these materials, and it is the focus of this research work. A sample of 43.09% Fe and 12.1% FeO was taken from the tailings of second step of magnetic separation. The ore minerals of the sample were determined to be magnetite and hematite. A concentrate of 67% Fe and mass recovery of 50% was produced through the Davis tube test. A reverse flotation route was selected for upgradation of the sample. Fatty acid-based anionic collectors with trade names Alke and Dirol were used in the flotation experiments. The design of experiments was done by resolution IV fractional factorial design with nine factors at two levels per factor. A resolution IV design allows discrimination of all main effects and two-factor interactions. A concentrate of 53.92% Fe at a mass recovery of 60% was obtained at optimum flotation conditions of solid content 20%, pH 12, collector concentration of 1 kg/t, starch as depressant at a concentration of 5 kg/t, Alke/Dirol collector mass ratio of 30/70, conditioning time of 10 min., and concentration of Ca<sup>2+</sup> as activator 1 kg/t. In this research work, the concept of natural depression of iron minerals in the reverse flotation was introduced and evaluated.

### 1. Introduction

Annually, more than 1.5 billion tons of crude steel is produced in the world [1]. Iran is the thirteenth largest producer, and in 2017, it produced 21.2 million tons of crude steel up from 17.9 million tons in 2016 [1]. For every one ton of crude steel produced, approximately 2.5 to 3 tons of tailings will be discharged [2]. The tailings are produced during the upgradation of run of mine (ROM) iron ores and smelting of iron ore concentrate. Most of the tailing is produced during the upgradation of ROM iron ores in mineral processing plants, in which the ROM ore with iron grade of 30-40% is upgraded to a concentrate with iron grade more than 65% [2]. In the iron ore processing plants, usually the iron minerals are separated from gangue minerals during several consecutive wet

low-intensity magnetic separation steps [3, 4]. The tailings fall in the category of high risk wastes since they not only cover huge land but also pollute environment through several issues, for instance, acid mine drainage (AMD) [5-7]. Therefore, the management of tailings has a crucial importance for iron ore mineral processing plants [8]. It is usually performed in the best way by implementing the 3Rs concept [9]. The 3R strategy sets the goal of tailing reduction, reuse, and recycling [9].

In the recent years, interest in upgradation of iron ore tailings has increased worldwide. These activities are initiated not only to recover minerals but also to address various environmental issues associated with tailings [10]. Several technologies

have been employed in this regard including gravity separation, high-intensity magnetic separation, and flotation [11-14]. The gravity separation due to decreased gravitational effect and high-intensity magnetic separation due to reduced drag force have been found to be ineffective for treatment of iron tailings with fine particle sizes. However, froth flotation is a powerful technique for treatment of these materials. Therefore, it is in this regard that flotation has gained importance in treating iron ore tailings in the recent years [15, 16].

The flotation of iron ores is usually performed by reverse flotation using cationic or anionic collectors [17]. The reverse flotation using cationic collectors is the most popular flotation route for the upgradation of low-grade iron ores and iron ore tailings [18, 19]. In the reverse cationic flotation route, after depression of iron minerals by a suitable depressant such as starch at alkaline pH values, the gangue minerals are floated by a cationic collector such as dodecylamine or ether amine. The reverse flotation using cationic collectors is very sensitive to slime-sized materials, and de-sliming must be performed before the flotation process, which results in some iron loss [15]. Furthermore, the high cost of cationic collector increases the operating costs of this process and restricts its usage [17]. The reverse flotation using anionic collectors can be a suitable alternative route for the upgradation of iron ore tailings. This flotation route is not sensitive to the presence of slime-sized materials, and the anionic collectors are significantly cheaper than the cationic collectors. In reverse flotation by anionic collectors, initially, lime is added to the pulp for the pH adjustment at alkaline values and activation of silicate minerals. After that, the depression of iron minerals is performed through addition of a suitable depressant. Finally, gangue minerals are floated by an anionic collector such as fatty acids [20]. The efficient depression of iron minerals is one of the main challenges of this flotation route. The performance and operational costs of this process are highly dependent on the precise determination of the type and dosage of depressant [21-24]. In this research work, upgradation of the tailings of a magnetic separator was investigated by the reverse anionic flotation route, and the effects of various operating parameters on the process were evaluated. The main focus of this work is to find the best conditions for depression of iron minerals. Hence, the concept of natural depression of iron minerals

was introduced and evaluated.

## 2. Materials and methods

### 2.1. Reagents

Analytical reagent grade calcium nitrate tetrahydrate and sodium hydroxide were used in the flotation experiments as the activator and pH regulator, respectively. The collector used in the flotation tests included two types of Alke and Dirol collectors based on fatty acids, and the Dirol collector, in addition to the collecting effect, had a frothing effect; the collectors were provided by a local producer. Sodium silicate with a  $\text{SiO}_2/\text{Na}_2\text{O}$  ratio of 2.5 was provided from the Silicate Gostar Isfahan Co. (Iran). Corn starch was provided from a local producer, and it was used as the depressant along with sodium silicate in the flotation tests.

Analytical reagent grade HCl, phosphoric acid, sulfuric acid, tin chloride, mercuric chloride, potassium dichromate, and sodium diphenylamine sulfonate were used for analyzing the Fe and FeO contents of the samples by the titration method.

### 2.2. Iron ore sample

The Sangan iron ore mine is located in the Khorasan-Razavi Province, east of Iran. It is one of the largest iron mines in Iran and in the Middle East with an iron ore reserve more than 1.2 billion tons. The first iron ore processing plant in this area annually produces 2.6 million tons of concentrate with an iron grade of more than 65%. In this plant, the processing circuit consists of four sequential steps of low-intensity magnetic separation. The drum type magnetic separators have a diameter of 1220 mm, a length of 2400 mm, and a magnetic intensity of 1300 Gauss. The tailing of all magnetic separators are transferred to the tailing dam after thickening. The sample used in this work was taken from the tailings of the rougher wet low intensity magnetic separators (i.e., second step magnetic separation). For this purpose, a total of 7000 liters of pulp was taken using a 2.5-liter sampler in a one-month period. The pulp, after dewatering through decantation and filtering by laboratory filterpress, was dried in a laboratory oven at 90°C. After that, the sample was homogenized and used in the experiments.

### 2.3. Sample characterization

In order to determine the total iron content of the sample, an exact amount of the sample was dissolved in concentrated HCl at elevated temperatures, and then Fe(III) ions were reduced to Fe(II) ions by tin chloride. The solution volume was reached to the mark with distilled water and

sulfuric acid. The extra amount of tin chloride was neutralized by mercury chloride. After adding phosphoric acid, the total iron content of the solution was measured by titration using potassium dichromate as the titrant and sodium diphenyl sulfonate as the indicator. For the FeO analysis, a similar method with the total iron analysis was applied, by this difference that tin chloride was not added to the leach solution.

The mineralogical composition of the sample was determined on a Philips-Xpert Pro. device by conducting the X-Ray Diffraction (XRD) test. Determination of the maximum recovery of iron minerals by low-intensity magnetic separators was performed by Eriez' Davis Tube Tester Model EDT at the three different magnetic field intensities of 1420, 2340, and 3800 Gauss.

The high-resolution imaging by scanning electron microscopy (LEO, 1450 UP, Zeiss; Oberkochen, Germany) was performed to identify different phases of the sample. The identification of chemical composition of the detected phases was performed by Energy Dispersive X-Ray (EDS) analyzer (INCA ENERGY 350 accessory) connected to Scanning Electron Microscopy (SEM).

#### 2.4. Flotation tests

A certain amount of the sample was poured into the flotation cell, and the solid content was set in a pre-determined amount by adding a certain volume of water. The pulp pH was adjusted to the desired amount by adding 2 M sodium hydroxide solution. Then a certain amount of calcium nitrate salt, as the activator of gangue minerals, was added to the cell and conditioned for 3 min. Afterwards, the depressant of iron minerals (i.e. corn starch or sodium silicate) was added to the cell and conditioned for 3 min. The collector was

added to the cell, and the conditioning time was considered to be 1 or 10 min. The collector used in the flotation experiments was a mixture of Alke and Dirol collectors with mass ratios of 30/70 and 70/30. After opening the air valve, the froth phase was collected for 5 min. The flotation tailing and concentrate were dewatered, dried in an oven at 90°C, and analyzed for total Fe by the titration method.

The natural depression of iron minerals was studied through placement of a rectangular magnet with dimensions of 10\*15 cm under the flotation cell before opening the air valve. The magnetic field intensity of the magnet was measured to be 636 Gauss by Magnetic field Gaussmeter TM701 (Japan).

The effects of different operating parameters were investigated on the performance of reverse anionic flotation of the sample. The design of flotation tests was done by the Minitab 17 software package using a 2<sup>(9-4)</sup> fractional factorial design with nine factors at two levels per factor. Table 1 shows the design factors and their levels. The randomized run order of the flotation experiments and operating conditions of experimental runs are shown in Table 2.

In order to investigate the effect of natural depression of iron minerals through placement of a magnet under the flotation cell on the depressant consumption in the reverse flotation, a series of flotation tests were arranged. The first test was conducted with no presence of magnet and no depressant addition. The second flotation test was performed with magnet and without depressant addition. In the third and fourth flotation tests, the magnet was placed under the flotation cell, and the depressant was added to the flotation cell at dosages of 5 and 40 kg/t, respectively.

**Table 1. Factors and their levels for the fractional factorial design.**

Design factors	Variable levels	
	low	high
Solid content	20	40
pH	8	12
Collector concentration	1 kg/t	5 kg/t
Depressant type	Starch	Sodium silicate
Depressant concentration	5 kg/t	40 kg/t
Collector ratio	30:70	70:30
Conditioning time	1 min	10 min
Ca ion concentration	1 kg/t	5 kg/t
Magnet	No	Yes

**Table 2. The randomized run order of the experiments and the operating conditions of the experimental runs.**

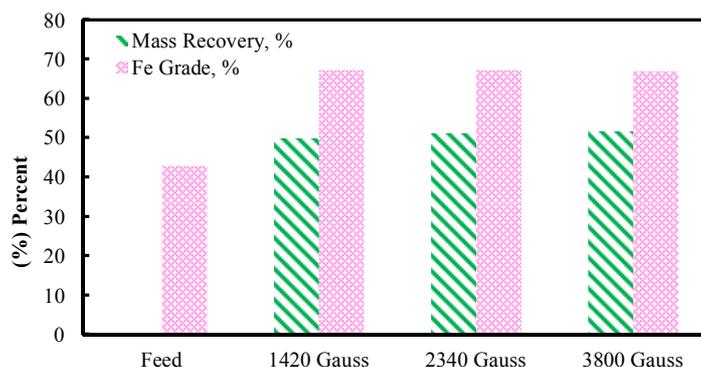
Std. Order	Run Order	Solid percent	pH	Collector conc. (kg/t)	Depressant Type	Depressant Conc. (kg/t)	Collector Ratio	Conditioning Time (min)	Activator Ca conc. (kg/t)	Magnet
2	1	40	8	1	Starch	5	70	1	1	No
9	2	20	8	1	Si	5	30	1	1	Yes
14	3	40	8	5	Si	5	70	1	5	Yes
3	4	20	12	1	Starch	5	30	10	1	No
6	5	40	8	5	Starch	5	30	10	1	Yes
10	6	40	8	1	Si	5	30	10	5	No
16	7	40	12	5	Si	5	30	1	1	No
15	8	20	12	5	Si	5	30	10	5	Yes
7	9	20	12	5	Starch	5	70	1	1	Yes
26	10	40	8	1	Si	40	70	1	1	Yes
8	11	40	12	5	Starch	5	70	10	5	No
25	12	20	8	1	Si	40	70	10	5	No
30	13	40	8	5	Si	40	30	10	1	No
28	14	40	12	1	Si	40	30	1	5	No
31	15	20	12	5	Si	40	70	1	1	No
17	16	20	8	1	Starch	40	30	1	1	No
32	17	40	12	5	Si	40	70	10	5	Yes
20	18	40	12	1	Starch	40	70	10	1	No
24	19	40	12	5	Starch	40	30	1	1	Yes
5	20	20	8	5	Starch	5	30	1	5	No
21	21	20	8	5	Starch	40	70	10	1	Yes
27	22	20	12	1	Si	40	30	10	1	Yes
23	23	20	12	5	Starch	40	30	10	5	No
19	24	20	12	1	Starch	40	70	1	5	Yes
12	25	40	12	1	Si	5	70	10	1	Yes
22	26	40	8	5	Starch	40	70	1	5	No
29	27	20	8	5	Si	40	30	1	5	Yes
18	28	40	8	1	Starch	40	30	10	5	Yes
13	29	20	8	5	Si	5	70	10	1	No
11	30	20	12	1	Si	5	70	1	5	No
4	31	40	12	1	Starch	5	30	1	5	Yes
1	32	20	8	1	Starch	5	70	10	5	Yes

### 3. Results and discussion

#### 3.1. Ore characterization

The total Fe and FeO grades of the sample were determined to be 43.09% and 12.1%, respectively. Accordingly, the amounts of magnetite (Fe<sub>3</sub>O<sub>4</sub>) and hematite (Fe<sub>2</sub>O<sub>3</sub>) were determined to be 39% and 21.26%, respectively. The particle size distribution of the sample was determined by the sieve analysis, and d80 of the sample was determined to be 66 μm. In order to investigate the maximum iron recovery by magnetic

low-intensity separators, the Davis Tube tests were performed at the three magnetic field intensities of 1420, 2340, and 3800 Gauss. Figure 1 shows the iron grade and the weight percentage of the magnetic fraction of the sample at the three different magnetic field intensities. As it could be seen, in the magnetic field intensity of 1420 Gauss, a concentrate of 67% Fe and a mass recovery of 50% were produced. Increasing the magnetic field intensity to 3800 Gauss had no significant effect on the separation process.



**Figure 1. Iron grade and mass recovery of the magnetic fraction of the Davis tube tests at three magnetic field intensities of 1420, 2340, and 3800 Gauss.**

Mineralogical composition of the sample was determined by the XRD analysis, and the spectrum was shown in Figure 2. It could be observed that the main iron mineral of the sample was magnetite, and to a lesser extent, hematite. The main gangue minerals of the sample were quartz and calcite. Furthermore, dolomite, clinochlore and dickite were present in the sample at low quantities.

Figure 3 shows the SEM image of the sample in the BSE imaging mode. In this mode, the various mineral phases are shown in terms of their densities at different brightness levels so that minerals with more specific gravity appear brighter in the SEM image. The chemical composition of the sample at specified points in

the SEM image was determined by the EDS analysis, and the results obtained were shown in Figure 3. It must be mentioned that the EDS analysis cannot detect the lightest elements, typically below the atomic number of sodium (Na). Therefore, carbon (C), nitrogen (N) and oxygen (O) cannot be detected by the EDS analysis. As it could be seen, at EDS1 and EDS2, only Fe was detected, indicating that they were iron oxide minerals (magnetite or hematite). At EDS6, sulfur was detected apart from Fe, indicating that the mineral phase of this point was pyrite. At the EDS4, EDS5, and EDS7 points, only Ca was detected, indicating that they were calcite. At EDS3, the elements Mg, Al, Fe, and S were detected.

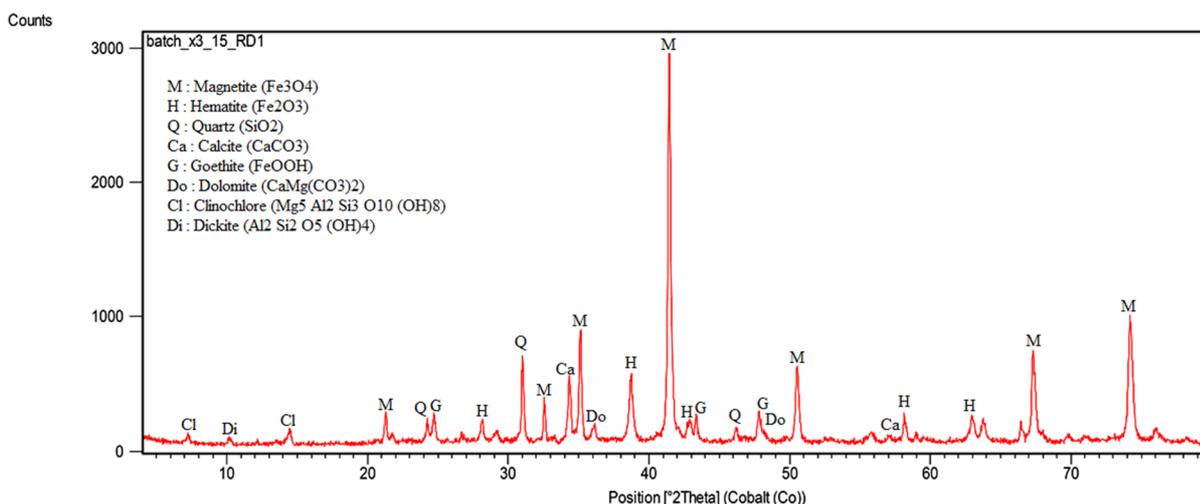


Figure 2. XRD analysis of the sample.

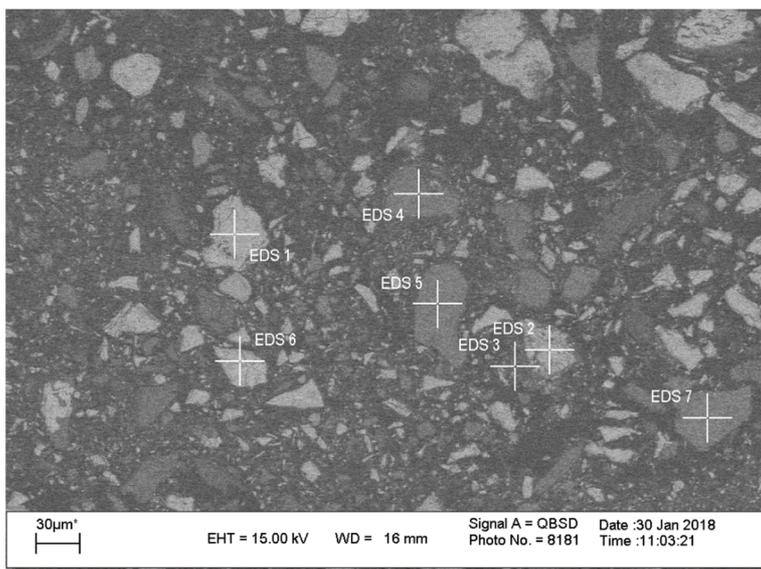


Figure 3. SEM image of the sample at the BSE imaging mode and the EDS analysis results at seven spot.

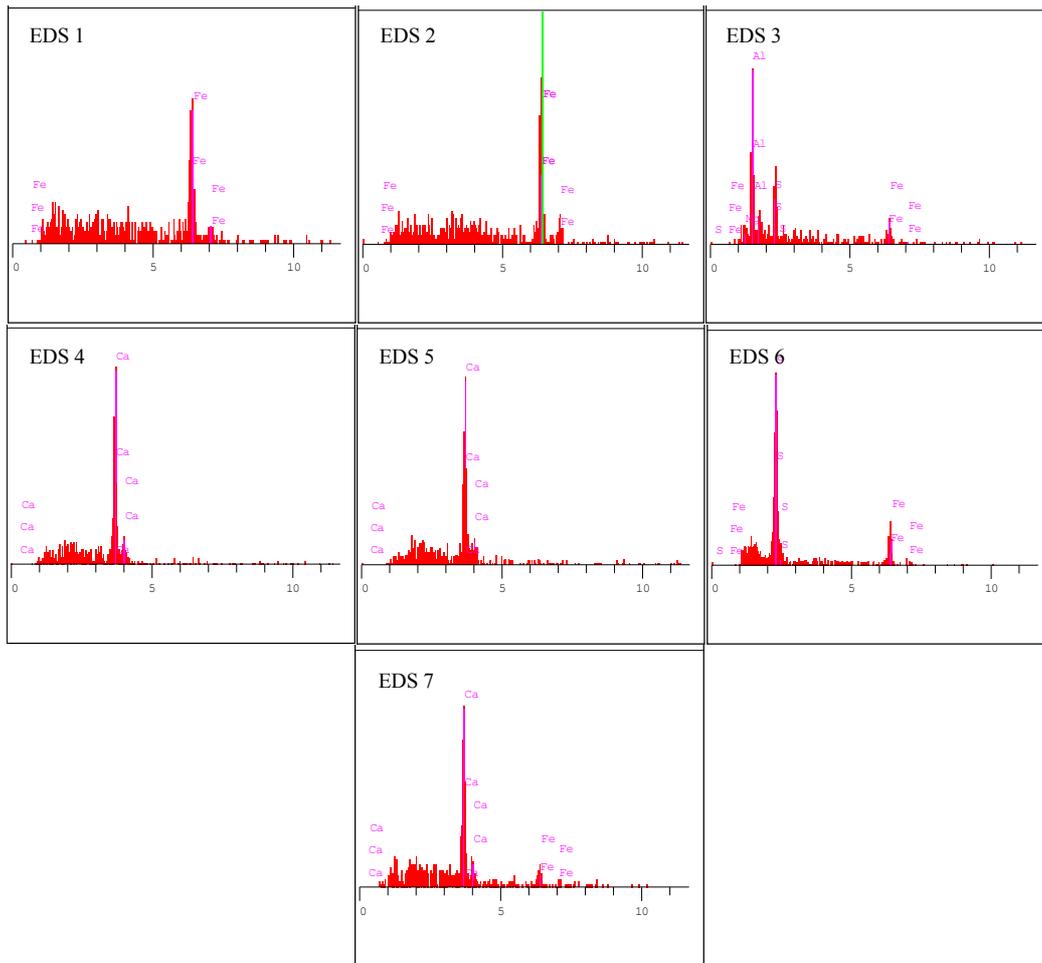


Figure 3. Continued.

### 3.2. Flotation tests

Figure 4 shows the effects of the process parameters on the iron grade of the anionic reverse flotation concentrate. It can be seen that increasing the collector concentration, pH, and conditioning time, and the presence of a magnet under the flotation cell have a positive effect on the Fe grade of the flotation concentrate. When using starch as the depressant in comparison to sodium silicate, a concentrate with a higher iron grade is obtained since starch is the sole depressant of iron minerals but sodium silicate has some depressing effects on the silicate minerals apart from iron minerals. The Fe grade of the concentrate decreases with increase in the solid content, depressant, and activator concentrations. In the flotation tests, a combination of two types of collectors Alke and Dirol with mass ratios of 30/70 and 70/30 were used. As shown in Figure 4, the Fe grade of the concentrate decreases with increase in the collector ratio from 30/70 to 70/30. Figure 5 shows the two-way interaction plots for the Fe grade of the concentrate during the anionic reverse flotation of the sample. The interaction

between the solid content and the magnet shows that in the absence of the magnet, increasing the solid content leads to a drop in the iron grade of the concentrate but in the presence of the magnet, increasing the solid content increases the Fe grade of the concentrate. The interaction between the collector concentration and the magnet shows that in the absence of the magnet, increasing the collector concentration has a negligible effect on the Fe grade of the concentrate, while in the presence of the magnet, increasing the collector concentration increases the Fe grade of the concentrate. The interaction between the activator concentration and the magnet shows that in the absence of the magnet, the Fe grade of the concentrate decreases with increase in the activator concentration, while in the presence of the magnet, increasing the activator concentration has no significant effect on the Fe grade of the concentrate. The interaction between the solid content and pH indicates that at pH 8, increasing the solid content from 20% to 40% has a low but positive effect on the Fe grade of the concentrate but the Fe grade of the concentrate decreases from

47.04% to 45.85% by increasing the solid content at pH 12. The interaction between pH and the depressant type shows that with starch, as the depressant, increasing the pH value improves the Fe grade of the concentrate (from 46.5% to 47.77%) but when using sodium silicate, it decreases with increase in the pH value (from 46.15% to 45.43%). The interaction between pH and the activator concentration shows that at a concentration of 1 kg/t of calcium ion, increasing the pH from 8 to 12 increases the Fe grade of the concentrate from 46.28% to 47.48% but at a concentration of 5 kg/t of  $\text{Ca}^{2+}$  ions, increasing pH causes a drop in the Fe grade of the concentrate from 46.28% to 45.40%. The interaction between the collector concentration and the depressant type indicates that with starch as the depressant, the Fe grade of the concentrate increases from 47.24% to 46.74% with an increase in the collector concentrate from 1 to 5 kg/t, while using sodium silicate, increasing the collector concentration leads to an increase in the Fe grade of the concentrate from 44.84% to 46.74%. The interaction between the depressant concentration and the activator concentration indicates that at a low concentration of the activator (i.e. 1 kg/t), increasing the depressant concentration from 5 kg/t to 40 kg/t leads to a decline in the Fe grade of the concentrate from 47.9% to 46.01%. However, at a high activator concentration (i.e. 5 kg/t), increasing the depressant concentration leads to an increase in the Fe grade of the concentrate from 45.68% to 46.01%.

Statistical analysis (analysis of variance, ANOVA) was conducted on the test results in order to statistically evaluate the main effects and the 2- and 3-way interactions on the Fe grade of the flotation concentrate, as shown in Table 3. As it can be seen, the P-value obtained for solid percent, collector concentration, depressant type and concentration, collector ratio, conditioning time, and activator concentration is lower than the adopted significance level (0.05). Hence, they are significant for the Fe grade of the concentrate among the main effects. However, a comparison between the F-values showed that the collector ratio had the most significant effect followed by the interaction between the collector concentration and the depressant type. On the other hand, the magnet and pH value have the least significant effects; even less than the third interaction

between the solid percent, dispersant concentration, and collector ratio. The depressant type was the third significant parameter but its interaction with the collector concentration was more significant. This emphasizes the role of interactions between the parameters in flotation.

A model was proposed by the Minitab 17 software for prediction of the Fe grade of the concentrate, as shown in Table 3. The P-value obtained for the model is lower than the adopted significance level (0.05), which confirms the model validity. Furthermore, the values obtained for  $R^2$ ,  $\text{adj-}R^2$ , and  $\text{pred-}R^2$  are very close to unity, which further confirm the validity of the proposed model for prediction of Fe grade of the concentrate at different operating conditions.

Figure 6 shows the Pareto chart of the main effects and the two-way and three-way interactions studied on the Fe grade of the flotation concentrate. As it can be seen, the collector ratio has the greatest effect on the Fe grade of the concentrate. Afterwards, the two-way interaction between the collector concentration and the depressant type and the two-way interaction between the depressant and the activator concentrations are effective on the Fe grade of the concentrate, respectively.

Figure 7 shows the normal plot of the main effects and their interactions on the Fe grade of the flotation concentrate. As it can be seen, the interaction between the collector concentration and the depressant type has the most positive effect on the Fe grade of the concentrate. The two-way interaction between the depressant and activator concentrations, the two-way interaction between the solid content and the type of depressant, and the two-way interaction between the solid content and the magnet have positive effects on the Fe grade of the flotation concentrate. Among the main effects, the conditioning time, collector concentration, and pH have positive effects on the Fe grade of the flotation concentrate, respectively.

Among the main effects and their interactions, the collector ratio, depressant type, activator concentration, two-way interaction of pH and activator concentration, two-way interaction of pH and depressant type, two-way interaction of pH and solid content, and the depressant concentration have negative effects on the Fe grade of the flotation concentrate, respectively.

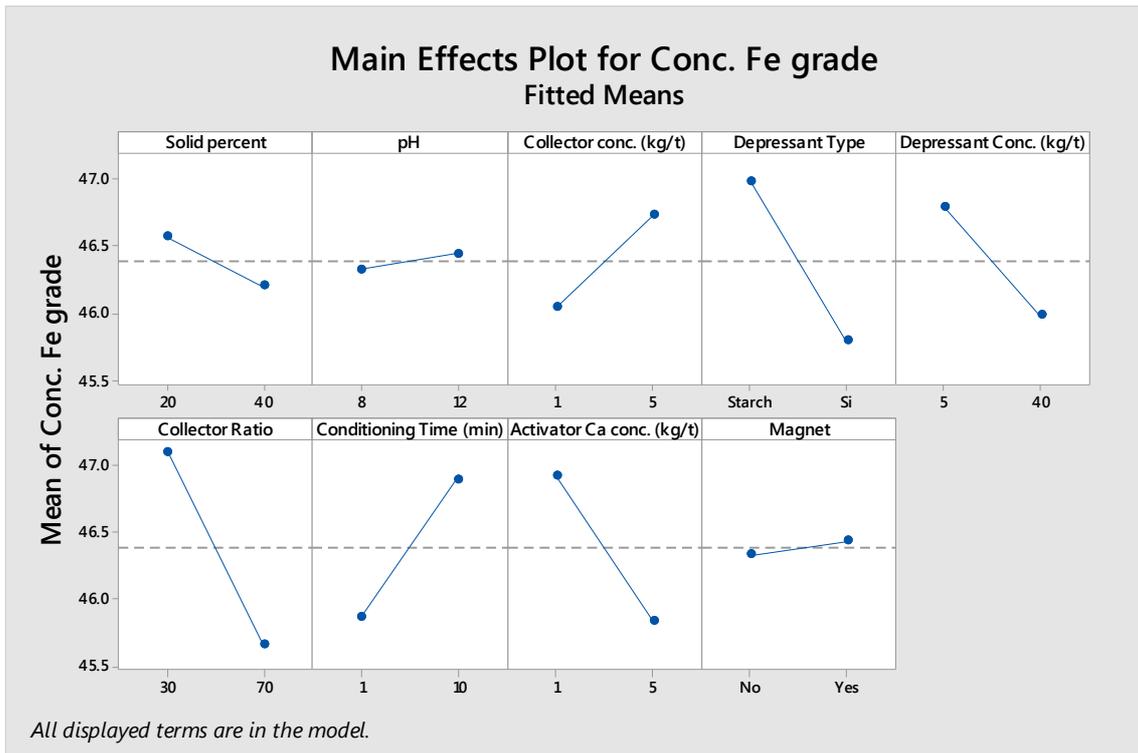


Figure 4. Main effect plots for the Fe grade of the flotation concentrate.

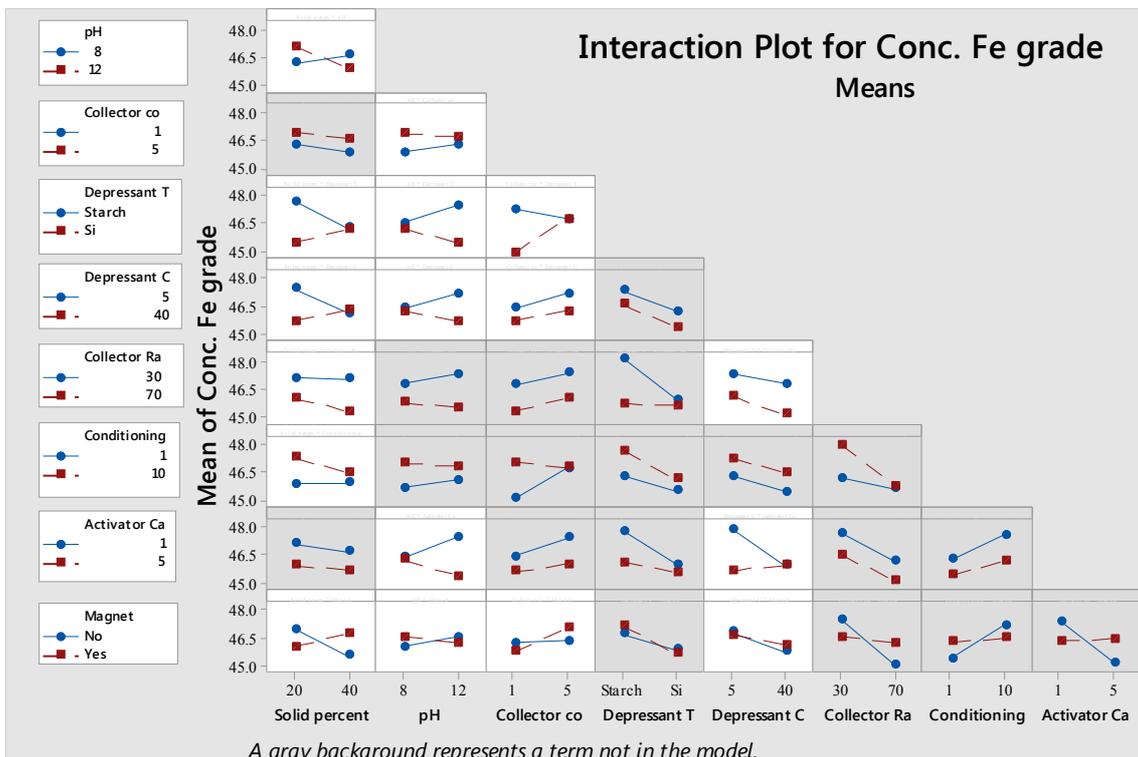


Figure 5. The two-way interaction plots for Fe grade of concentrate during the anionic reverse flotation of the sample.

**Table 3. ANOVA analysis of Fe grade of concentrate.**

Analysis of Variance						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	27	134.665	4.9876	154.43	0.000	
Linear	9	56.086	6.2318	192.95	0.000	
Solid percent	1	1.100	1.0996	34.05	0.004	
pH	1	0.105	0.1051	3.26	0.146	
Collector conc. (kg/t)	1	3.814	3.8140	118.09	0.000	
Dispersant Type	1	11.321	11.3215	350.53	0.000	
Dispersant Conc. (kg/t)	1	5.171	5.1710	160.10	0.000	
Collector Ratio	1	16.667	16.6665	516.03	0.000	
Conditioning Time (min)	1	8.390	8.3903	259.78	0.000	
Activator Ca conc. (kg/t)	1	9.423	9.4229	291.75	0.000	
Magnet	1	0.095	0.0952	2.95	0.161	
2-Way Interactions	17	78.282	4.6048	142.57	0.000	
Solid percent*pH	1	5.376	5.3755	166.44	0.000	
Solid percent*Dispersant Type	1	9.401	9.4008	291.07	0.000	
Solid percent*Dispersant Conc. (kg/t)	1	7.192	7.1917	222.67	0.000	
Solid percent*Collector Ratio	1	0.753	0.7527	23.30	0.008	
Solid percent*Conditioning Time (min)	1	1.411	1.4108	43.68	0.003	
Solid percent*Magnet	1	9.267	9.2671	286.93	0.000	
pH*Collector conc. (kg/t)	1	0.694	0.6937	21.48	0.010	
pH*Dispersant Type	1	5.606	5.6055	173.56	0.000	
pH*Dispersant Conc. (kg/t)	1	3.270	3.2698	101.24	0.001	
pH*Activator Ca conc. (kg/t)	1	7.925	7.9249	245.37	0.000	
pH*Magnet	1	1.362	1.3618	42.16	0.003	
Collector conc. (kg/t)*Dispersant Type	1	11.577	11.5766	358.43	0.000	
Collector conc. (kg/t)*Dispersant Conc. (kg/t)	1	0.146	0.1455	4.51	0.101	
Collector conc. (kg/t)*Magnet	1	3.032	3.0323	93.89	0.001	
Dispersant Conc. (kg/t)*Collector Ratio	1	0.486	0.4861	15.05	0.018	
Dispersant Conc. (kg/t)*Activator Ca conc. (kg/t)	1	10.318	10.3178	319.46	0.000	
Dispersant Conc. (kg/t)*Magnet	1	0.469	0.4694	14.53	0.019	
3-Way Interactions	1	0.297	0.2967	9.19	0.039	
Solid percent*Dispersant Conc. (kg/t)*Collector Ratio	1	0.297	0.2967	9.19	0.039	
Error	4	0.129	0.0323			
Total	31	134.794				

Model:

$$\begin{aligned}
 \text{Conc. Fe grade} = & 35.156 + 0.2204 \text{ Solid percent} + 1.3326 \text{ pH} \\
 & + 0.5841 \text{ Collector conc. (kg/t)} \\
 & - 1.030 \text{ Dispersant Type} + 0.0031 \text{ Dispersant Conc. (kg/t)} \\
 & + 0.01341 \text{ Collector Ratio} + 0.2538 \text{ Conditioning Time (min)} \\
 & + 0.6078 \text{ Activator Ca conc. (kg/t)} - 1.146 \text{ Magnet} - \\
 & 0.02049 \text{ Solid percent*pH} \\
 & + 0.05420 \text{ Solid percent*Dispersant Type} \\
 & + 0.001333 \text{ Solid percent*Dispersant Conc. (kg/t)} \\
 & - 0.001386 \text{ Solid percent*Collector Ratio} \\
 & - 0.004666 \text{ Solid percent*Conditioning Time (min)} \\
 & + 0.05381 \text{ Solid percent*Magnet} - 0.03681 \text{ pH*Collector conc. (kg/t)} \\
 & - 0.2093 \text{ pH*Dispersant Type} - 0.009133 \text{ pH*Dispersant Conc. (kg/t)} \\
 & - 0.12441 \text{ pH*Activator Ca conc. (kg/t)} - 0.1031 \text{ pH*Magnet} \\
 & + 0.3007 \text{ Collector conc. (kg/t)*Dispersant Type} \\
 & - 0.001927 \text{ Collector conc. (kg/t)*Dispersant Conc. (kg/t)} \\
 & + 0.1539 \text{ Collector conc. (kg/t)*Magnet} \\
 & - 0.001177 \text{ Dispersant Conc. (kg/t)*Collector Ratio} \\
 & + 0.016224 \text{ Dispersant Conc. (kg/t)*Activator Ca conc. (kg/t)} \\
 & + 0.00692 \text{ Dispersant Conc. (kg/t)*Magnet} \\
 & + 0.000028 \text{ Solid percent*Dispersant Conc. (kg/t)*Collector Ratio}
 \end{aligned}$$

Model Summary:

S	R-sq	R-sq(adj)	R-sq(pred)
0.179716	99.90%	99.26%	93.87%



concentrate decreases from 78.54% to 77.87% by increasing the pulp pH from 8 to 12. The collector concentration has a negative effect on the mass recovery of the concentrate, so increasing the collector concentration from 1 kg/t to 5 kg/t reduces the mass recovery of the concentrate from 83.79% to 72.55%. The mass recovery of the concentrate decreases from 83.19% to 73.15% when using starch instead of sodium silicate as the depressant. Sodium silicate has some depressing effects on the silicate minerals apart from iron minerals. As a result, the mass recovery of the concentrate of the reverse flotation increases using sodium silicate as the depressant, while the Fe grade of the concentrate decreases. The mass recovery of the concentrate increases from 77.44% to 78.9% by increasing the depressant concentration from 5 kg/t to 40 kg/t. The mass recovery of the concentrate increases from 75.27% to 81.77% by increasing the mass ratio of the Alke/Dirol collectors from 30/70 to 70/30.

Thus when the amount of the Dirol collector is higher than that for the Alke collector, a concentrate with a higher Fe grade is obtained but the mass recovery of the concentrate is reduced. Increasing the conditioning time from 1 to 10 min leads to a loss in the mass recovery of the concentrate, and it decreases from 80.02% to 76.32%. The reason for this is that by increasing the conditioning time, the opportunity for collector adsorption on the gangue mineral surfaces increases, and thus their hydrophobicity increases. The mass recovery of the concentrate increases from 76.97% to 79.55% by increasing the calcium ion concentration from 1 kg/t to 5 kg/t. Finally, the presence of a magnet under the flotation cell causes an increase in the mass recovery of the concentrate from 75.17 to 81.17%. The reason for this is that the presence of a magnet under the flotation cell attracts the iron minerals and prevents from their flotation.

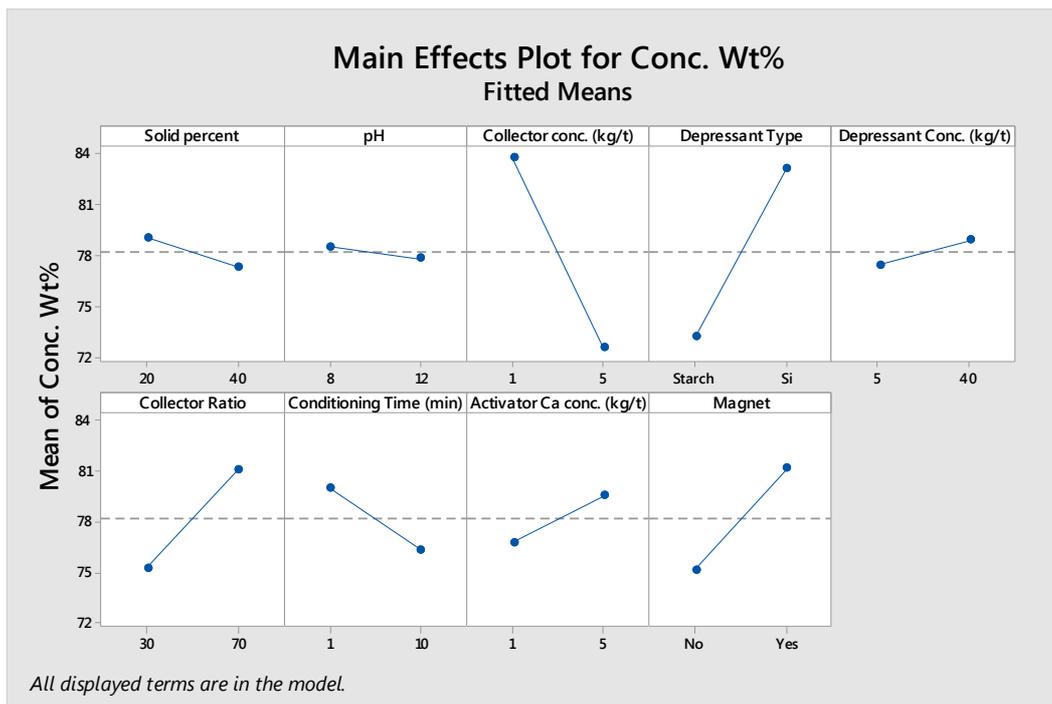


Figure 8. Main effect plots for the mass recovery of the flotation concentrate.

Figure 9 shows the two-way interaction plots for the mass recovery of the reverse flotation concentrate. The interaction between the solid content and the depressant type shows that when using sodium silicate as the depressant, increasing the solid content from 20% to 40% leads to a reduction in the mass recovery of the concentrate from 87.5% to 78.88%, while by using starch as the depressant, it increases from 70.56% to 75.74%. The interaction between the depressant

concentration and the magnet shows that in the presence of the magnet, the mass recovery of the concentrate decreases from 82.08% to 80.26% by increasing the concentration of the depressant from 5 kg/t to 40 kg/t, while in the absence of the magnet, it increases from 72.8% to 77.54%. It can be seen that in the presence of the magnet and at a low concentration of the depressant, the mass recovery of the concentrate is 82.88% but in the absence of the magnet, its amount is 72.08%. This

indicates that the presence of the magnet acts as a depressant and prevents the floatation of the iron minerals. The interaction between the depressant concentration and the conditioning time shows that at a low depressant concentration, increasing the conditioning time does not have an effect on the mass recovery of the concentrate but at a high depressant concentration (i.e. 40 kg/t), increasing the conditioning time from 1 to 10 min results in a loss in the mass recovery of the concentrate from 83.18% to 74.62%. The interaction between the pH and the magnet shows that in the absence of the magnet, increasing the pH value from 8 to 12 causes a loss in the mass recovery of the concentrate from 78.04% to 72.30% but in the presence of the magnet, it increases from 79.03% to 83.31%. The interaction between the solid content and the conditioning time shows that at a low conditioning time (i.e. 1 min), an increase in

the solid content from 20% to 40% leads to a loss in the mass recovery of the concentrate from 83.66% to 77.64% but at a high conditioning time (i.e. 10 min), it increases from 75% to 77.6%. In other words, it can be stated that at a low solid content (i.e. 20%), an increase in the conditioning time leads to a loss in the mass recovery of the concentrate but at a high solid content, increasing the conditioning time has no effect on the concentrate weight recovery. The interaction between the depressant concentration and the activator concentration indicates that in an activator concentration of 1 kg/t, the mass recovery of the concentrate increases from 74.11% to 79.46% by increasing the depressant concentration from 5 kg/t to 40 kg/t, while at an activator concentration of 5 kg/t, it decreases from 80.77 to 78.34% by increasing the depressant concentration.

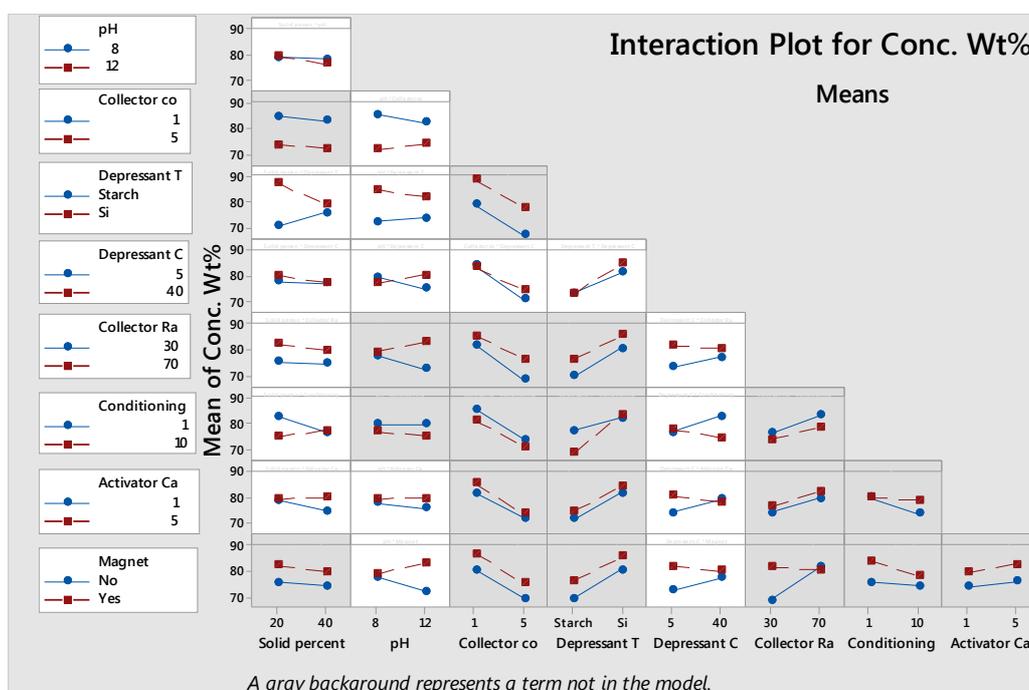


Figure 9. The two-way interaction plots for the mass recovery of the flotation concentrate during the anionic reverse flotation of the sample.

The ANOVA results for mass recovery of the concentrate are presented in Table 4. As it can be seen, the P-value obtained for the solid percent, collector concentration, depressant type and concentration, collector ratio, conditioning time, activator concentration, and magnet was lower than the adopted significance level (0.05). Therefore, these parameters had significant impacts over the mass recovery of the concentrate. The P-value obtained for pH was higher than the adopted significance level (0.05), indicating that it had an insignificant impact over the mass

recovery of the concentrate.

A model was proposed by the Minitab 17 software for prediction of the mass recovery of the concentrate, as shown in Table 4. The P-value obtained for the model is lower than the adopted significance level (0.05), which confirms the model validity. Furthermore, the values obtained for  $R^2$ ,  $adj-R^2$ , and  $pred-R^2$  are very close to unity, which further confirm the validity of the proposed model for prediction of mass recovery of the concentrate at different operating conditions.

**Table 4. ANOVA analysis of the mass recovery of the flotation concentrate.**

Analysis of Variance						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	27	4151.51	153.76	104.79	0.000	
Linear	9	2590.22	287.80	196.15	0.000	
Solid percent	1	23.72	23.72	16.17	0.016	
pH	1	4.29	4.29	2.92	0.163	
Collector conc. (kg/t)	1	1010.43	1010.43	688.65	0.000	
Depressant Type	1	806.59	806.59	549.73	0.000	
Depressant Conc. (kg/t)	1	17.10	17.10	11.66	0.027	
Collector Ratio	1	269.82	269.82	183.90	0.000	
Conditioning Time (min)	1	109.27	109.27	74.47	0.001	
Activator Ca conc. (kg/t)	1	61.15	61.15	41.68	0.003	
Magnet	1	287.84	287.84	196.18	0.000	
2-Way Interactions	17	1547.82	91.05	62.05	0.001	
Solid percent*pH	1	8.73	8.73	5.95	0.071	
Solid percent*Depressant Type	1	380.48	380.48	259.31	0.000	
Solid percent*Depressant Conc. (kg/t)	1	7.61	7.61	5.19	0.085	
Solid percent*Collector Ratio	1	8.08	8.08	5.51	0.079	
Solid percent*Conditioning Time (min)	1	152.55	152.55	103.97	0.001	
Solid percent*Activator Ca conc. (kg/t)	1	43.33	43.33	29.53	0.006	
pH*Collector conc. (kg/t)	1	51.26	51.26	34.93	0.004	
pH*Depressant Type	1	38.80	38.80	26.44	0.007	
pH*Depressant Conc. (kg/t)	1	125.17	125.17	85.31	0.001	
pH*Activator Ca conc. (kg/t)	1	10.63	10.63	7.25	0.055	
pH*Magnet	1	200.39	200.39	136.58	0.000	
Collector conc. (kg/t)*Depressant Conc. (kg/t)	1	38.45	38.45	26.21	0.007	
Depressant Type*Depressant Conc. (kg/t)	1	30.90	30.90	21.06	0.010	
Depressant Conc. (kg/t)*Collector Ratio	1	54.51	54.51	37.15	0.004	
Depressant Conc. (kg/t)*Conditioning Time (min)	1	189.74	189.74	129.32	0.000	
Depressant Conc. (kg/t)*Activator Ca conc. (kg/t)	1	121.04	121.04	82.50	0.001	
Depressant Conc. (kg/t)*Magnet	1	86.13	86.13	58.70	0.002	
3-Way Interactions	1	13.47	13.47	9.18	0.039	
Solid percent*Depressant Conc. (kg/t)*Collector Ratio	1	13.47	13.47	9.18	0.039	
Error	4	5.87	1.47			
Total	31	4157.38				

Model:

$$\begin{aligned}
 \text{Conc. Wt\%} = & 105.89 - 0.287 \text{ Solid percent} - 2.053 \text{ pH} - 6.678 \text{ Collector conc. (kg/t)} \\
 & + 19.61 \text{ Depressant Type} - 0.289 \text{ Depressant Conc. (kg/t)} + 0.1793 \text{ Collector Ratio} \\
 & - 1.171 \text{ Conditioning Time (min)} - 1.245 \text{ Activator Ca conc. (kg/t)} - 7.40 \text{ Magnet} \\
 & - 0.0261 \text{ Solid percent*pH} - 0.3448 \text{ Solid percent*Depressant Type} \\
 & + 0.00648 \text{ Solid percent*Depressant Conc. (kg/t)} \\
 & + 0.00166 \text{ Solid percent*Collector Ratio} \\
 & + 0.04852 \text{ Solid percent*Conditioning Time (min)} \\
 & + 0.0582 \text{ Solid percent*Activator Ca conc. (kg/t)} \\
 & + 0.3164 \text{ pH*Collector conc. (kg/t)} - 0.551 \text{ pH*Depressant Type} \\
 & + 0.05651 \text{ pH*Depressant Conc. (kg/t)} + 0.1441 \text{ pH*Activator Ca conc. (kg/t)} \\
 & + 1.251 \text{ pH*Magnet} + 0.03132 \text{ Collector conc. (kg/t)*Depressant Conc. (kg/t)} \\
 & + 0.0562 \text{ Depressant Type*Depressant Conc. (kg/t)} \\
 & + 0.00183 \text{ Depressant Conc. (kg/t)*Collector Ratio} \\
 & - 0.03092 \text{ Depressant Conc. (kg/t)*Conditioning Time (min)} \\
 & - 0.05557 \text{ Depressant Conc. (kg/t)*Activator Ca conc. (kg/t)} \\
 & - 0.0938 \text{ Depressant Conc. (kg/t)*Magnet} \\
 & - 0.000185 \text{ Solid percent*Depressant Conc. (kg/t)*Collector Ratio}
 \end{aligned}$$

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.21130	99.86%	98.91%	90.97%

Figure 10 shows the Pareto plot of the main effects and their interactions investigated on the mass recovery of the concentrate. As it can be

seen, the collector concentration has the greatest effect on the mass recovery of the concentrate. Afterwards, the type of depressant, two-way

interaction of the solid content and the type of depressant, the magnet, collector ratio, two-way interaction of pH and magnet, two-way interaction of the depressant concentration and the conditioning time, two-way interaction of the solid content and conditioning time, two-way interaction of pH and the concentration of depressant, two-way interaction of the depressant and activator concentration, and the conditioning time affect the process, respectively.

Figure 11 shows the normal plot of the main effects and their interactions on the mass recovery of the concentrate. As it can be seen, the depressant type has the most positive effect on the process, and then the magnet, collector ratio, the two-way interaction of pH and magnet, the two-way interaction of the solid content and the conditioning time, the two-way interaction of the pH and the depressant concentration, and activator concentration have positive effects on the mass recovery of the concentrate, respectively. The collector concentration has the most negative effect on the mass recovery of the concentrate. After that, two-way interaction of the solid content and the depressant type, two-way interaction of the depressant concentration and conditioning time, the two-way interaction of the depressant and activator concentrations, conditioning time, the two-way interaction of the depressant concentration and magnet, the two-way interaction of the depressant concentration and collector ratio, the two-way interaction of the pH and the type of depressant and solid content have negative effects on the mass recovery of the flotation concentrate, respectively.

The results of the flotation tests showed that the presence of a magnet under the flotation cell in the reverse flotation of iron ore had no significant effect on the Fe grade of the flotation concentrate, while it had a significant positive effect on the mass recovery of the flotation concentrate. In order to investigate the effect of the magnet on the amount of depressant consumption in the reverse flotation, a series of flotation tests was performed. In one test, no magnet was present and no depressant was added. In the other tests, the magnet was present but the amount of depressant was variable. The results obtained are presented in Figure 12. As it can be seen, in the absence of the magnet and the depressant, the Fe grade of the flotation tailing (i.e. froth phase) is high and the mass recovery of the concentrate is low. In the presence of the magnet and without depressant addition, the mass recovery of the concentrate increases from 70% to 80%, the Fe grade of the concentrate remains without any change, and the Fe grade of the flotation tailing decreases from 32.2% to 23.7%. In the presence of the magnet, addition of 5 kg/t of starch, as the depressant, has no significant effect on the Fe grade of the concentrate, while the mass recovery of the concentrate increases slightly from 80% to 82.75%. Further increasing the dosage of starch to 40 kg/t in the presence of the magnet has no significant effect on both of the Fe grade and mass recovery of the flotation concentrate. Therefore, the results of these tests showed that the presence of a magnet could play the role of the depressant in the reverse flotation of an iron ore.

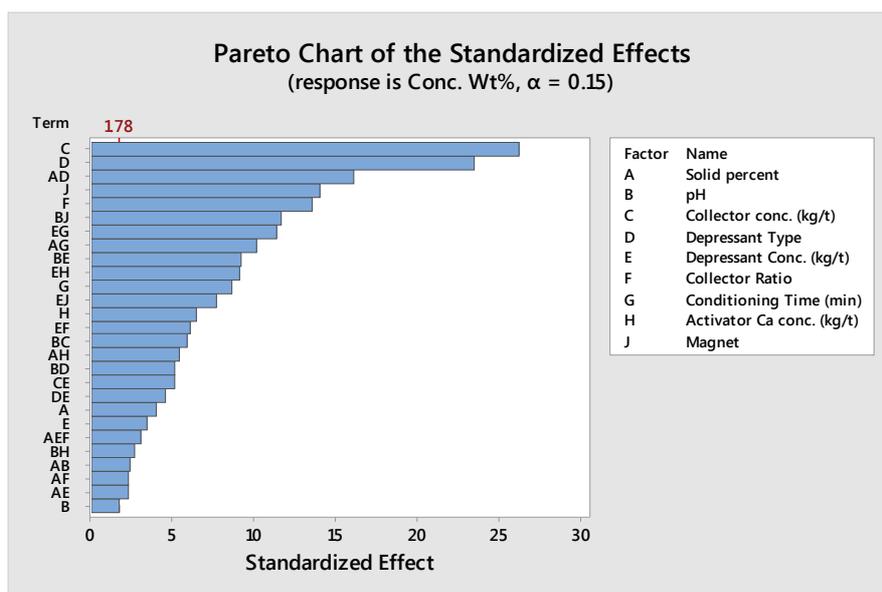


Figure 10. Pareto plot for the main effects and their interactions on the mass recovery of the flotation concentrate.

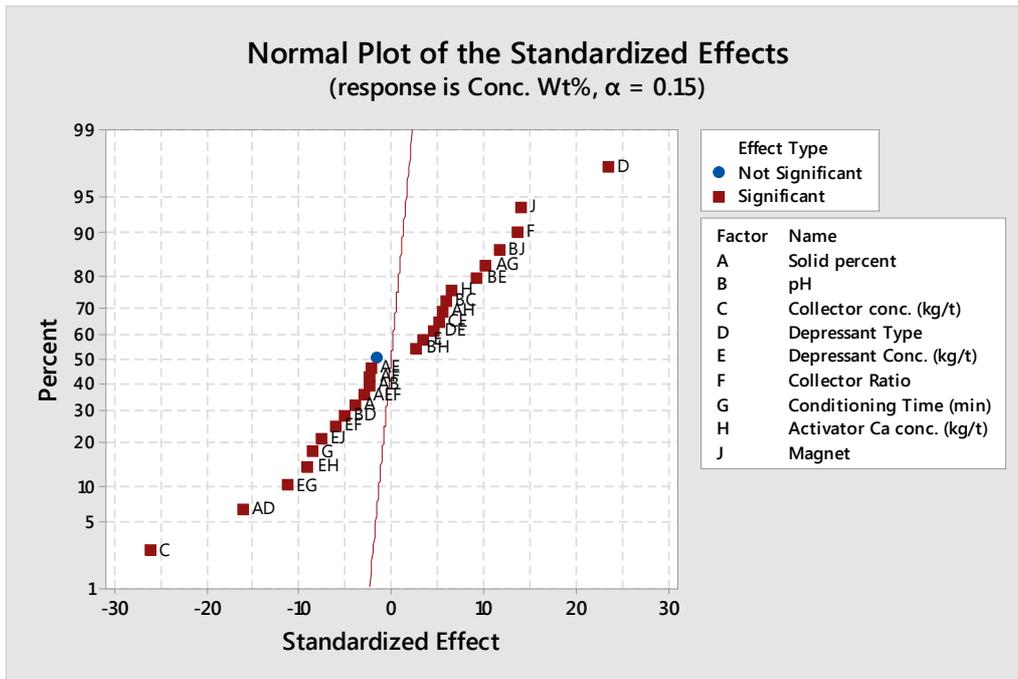


Figure 11. Normal plot for the main effects and their interactions on the mass recovery of the flotation concentrate.

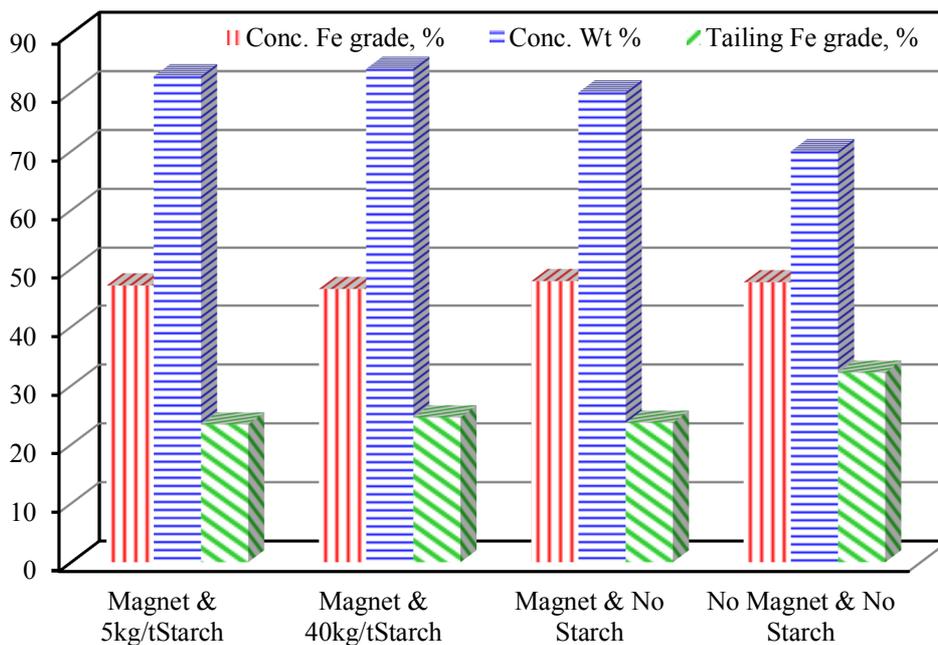


Figure 12. The effect of natural depression of iron minerals using a magnet under the flotation cell on the iron grade and mass recovery of flotation concentrate in the presence of different amounts of starch as depressant (solid content = 20%, pH = 12, collector concentration = 1 kg/t, and mass ratio of Alke/Dirol collector of 30/70, calcium ion concentration = 1 kg/t and conditioning time = 10 minutes).

#### 4. Conclusions

The upgradation of the tailings of low-intensity magnetic separators was investigated by the reverse anionic flotation. The result of the experiments showed that increasing the pH value, collector concentration, conditioning time, and presence of a magnet had positive effects on the

Fe grade of the concentrate. It decreases with increase in the solid content, depressant and activator concentrations, and Alke/Dirol collector mass ratio. When using starch as a depressant compared to sodium silicate, a concentrate with a higher Fe grade is obtained. The two-way interaction of the collector concentration and

depressant type and the effect of the collector mass ratio had the most positive and negative effects on the Fe grade of the concentrate, respectively. At the flotation test conditions of solid content of 20%, pH of 12, collector concentration of 1 kg/t, starch as the depressant at a concentration of 5 kg/t, Alke/Dirol collector mass ratio of 30/70, conditioning time of 10 min,  $\text{Ca}^{2+}$  as the activator at a concentration of 1 kg/t, and in the absence of a magnet, a concentrate with a maximum Fe grade of 53.92% and a mass recovery of 60% were obtained. The mass recovery of the concentrate increases with increase in the depressant and activator concentrations, and Alke/Dirol collector mass ratio. The mass recovery of the concentrate decreased from 83.19% to 73.15% using starch instead of sodium silicate as the depressant. The mass recovery of the concentrate increased from 75.17% to 81.17% when a magnet was placed under the flotation cell. The increase in the solid content, pH, collector concentration, and conditioning time had negative effects on the mass recovery of the concentrate. The collector concentration and depressant type had the most negative and positive effects on the mass recovery of the concentrate, respectively.

The test results showed that natural depression of iron minerals occurred in the reverse flotation of iron ores through placement of a magnet under the flotation cell. The mass recovery of the flotation concentrate increases sharply by applying this technique, while it has no significant effect on the Fe grade of the flotation concentrate. A concentrate of 47.94% of Fe and mass recovery of 80% was obtained by placement of a magnet under the flotation cell without any addition of starch as the depressant. In the presence of the magnet, addition of starch as the depressant slightly increases the mass recovery of the flotation concentrate, while it has no significant effect on the Fe grade of the concentrate. Hence, the presence of a magnet under the flotation cell could play the role of depressant in the reverse flotation process of the iron ore samples, and this flotation process could be performed without any depressant addition.

#### Acknowledgments

The authors of the paper wish to express their deep gratitude to the Iranian Mines & Mining Industries Development & Renovation organization (IMIDRO) to provide part of the project costs and Mr. Arash Tohry for providing the collectors used in the experiments.

#### References

- [1]. Basson, E. (2018). World steel in figures 2018, World steel Association, Brussels, Belgium. 7 P.
- [2]. Li, C., Sun, H., Bai, J. and Li, L. (2010). Innovative methodology for comprehensive utilization of iron ore tailings: Part 1. The recovery of iron from iron ore tailings using magnetic separation after magnetizing roasting. *J. Hazard. Mater.* 174 (1-3): 71-77.
- [3]. Svoboda, J. and Fujita, T. (2003). Recent developments in magnetic methods of material separation. *Miner. Eng.* 16 (9): 785-792.
- [4]. Ersayin, S. (2004). Low intensity magnetic separator modelling: a pseudo liberation approach. *Miner. Process. Extr. Metall.* 113 (3): 167-174.
- [5]. Das, S.K., Kumar, S. and Ramachandrarao, P. (2000). Exploitation of iron ore tailing for the development of ceramic tiles. *Waste Manag.* 20 (8): 725-729.
- [6]. Ghose, M.K. and Sen, P.K. (2001). Characteristics of iron ore tailing slime in India and its test for required pond size. *Environ. Monit. Assess.* 68 (1): 51-61.
- [7]. Dudka, S. and Adriano, D.C. (1997). Environmental impacts of metal ore mining and processing: a review. *J. Environ. Qual.* 26 (3): 590-602.
- [8]. Dold, B. (2008). Sustainability in metal mining: from exploration, over processing to mine waste management. *Rev. Environ. Sci. Biotechnol.* 7 (4): 275.
- [9]. Lottermoser, B.G. (2011). Recycling, reuse and rehabilitation of mine wastes. *Elements.* 7 (6): 405-410.
- [10]. Kumar, R. and Mandre, N.R. (2017). Recovery of iron from iron ore slimes by selective flocculation. *J. South. Afr. Inst. Min. Metall.* 117 (4): 397-400.
- [11]. Batisteli, G.M.B. and Peres, A.E.C. (2008). Residual amine in iron ore flotation. *Miner. Eng.* 21 (12-14): 873-876.
- [12]. Das, B., Prakash, S., Das, S.K. and Reddy, P.S.R. (2007). Effective beneficiation of low grade iron ore through jigging operation. *J. Miner. Mater. Char. Eng.* 7 (1): 27-37.
- [13]. Dworzanowski, M. (2012). Maximizing the recovery of fine iron ore using magnetic separation. *J. South. Afr. Inst. Min. Metall.* 112 (3): 197-202.
- [14]. Rocha, L., Caneado, R.Z.L. and Peres, A.E.C. (2010). Iron ore flotation. *Miner. Eng.* 23 (11-13): 842-845.
- [15]. Araujo, A.C., Viana, P.R.M. and Peres, A.E.C. (2005). Reagents in iron ores flotation. *Miner. Eng.* 18: 219-224.
- [16]. Thella, J.S., Mukherjee, A.K. and Srikakulapu, N.G. (2012). Processing of high alumina iron ore

slimes using classification and flotation. Powder Technol. 217: 418-426.

[17]. Ma, X., Marques, M. and Gontijo, C. (2011). Comparative studies of reverse cationic/anionic flotation of Vale iron ore. Intern. J. Miner. Process. 100: 179-183.

[18]. Filippov, L.O., Severov, V.V. and Filippova, I.V. (2014). An overview of the beneficiation of iron ores via reverse cationic flotation. Intern. J. Miner. Process. 127: 62-69.

[19]. Mhonde, N.P., Wiese, J.G. and McFadzean, B. (2017). Comparison of collector performance for a South African and a Brazilian iron ore considering mineralogical characteristics. Miner. Eng. 113: 55-67.

[20]. Quast, K. (2017). An investigation of the flotation minimum in the oleate flotation of hematite under

alkaline conditions. Miner. Eng. 113: 71-82.

[21]. Arantes, R.S. and Lima, R.M.F. (2013). Influence of sodium silicate modulus on iron ore flotation with sodium oleate. Intern. J. Miner. Process. 125: 157-160.

[22]. Lima, N.P., Valadão, G.E.S. and Peres, A.E.C. (2013). Effect of amine and starch dosages on the reverse cationic flotation of an iron ore. Miner. Eng. 45: 180-184.

[23]. Kar, B., Sahoo, H., Rath, S.S. and Das, B. (2013). Investigations on different starches as depressants for iron ore flotation. Miner. Eng. 49: 1-6.

[24]. Tohry, A. and Dehghani, A. (2016). Effect of sodium silicate on the reverse anionic flotation of a siliceous-phosphorus iron ore. Sep. Purif. Technol. 164: 28-33.

## فرآوری مجدد باطله سنگ آهن سنگان به روش فلوتاسیون

سلمان قاسمی<sup>۱</sup>، علی بهنام فرد<sup>۱\*</sup> و رضا ارجمند<sup>۲</sup>

۱- بخش مهندسی معدن، دانشکده مهندسی، دانشگاه بیرجند، ایران

۲- شرکت صنعتی و معدنی ایال پارسیان سنگان، خواف، ایران

ارسال ۲۰۱۹/۲/۲۴، پذیرش ۲۰۱۹/۴/۲

\* نویسنده مسئول مکاتبات: behnamfard@birjand.ac.ir

### چکیده:

کارخانه فرآوری سنگان شامل چهار مرحله متوالی جدایش مغناطیسی شدت پایین با شدت میدان مغناطیسی مشابه ۱۳۰۰ گوس برای پرعیارسازی کانسنگ آهن است؛ بنابراین، کانی‌های آهن‌دار با پذیرش مغناطیسی پایین‌تر یا درگیر با کانی‌های گانگ فرصتی برای جدایش پیدا نکرده و به سد باطله منتقل می‌شوند. فلوتاسیون یک تکنولوژی قدرتمند برای پرعیارسازی این کانی‌ها است و در این پژوهش مورد توجه قرار گرفته است. نمونه‌ای با عیار  $43/09\% \text{ Fe}$  و  $12/1\% \text{ FeO}$  از باطله جدایش مغناطیسی مرحله دوم این کارخانه گرفته شد. کانی‌های آهن‌دار با ارزش این نمونه منیستیت و هماتیت تعیین گردید. کنسانتره‌ای با عیار آهن  $67\%$  و بازیابی وزنی  $50\%$  توسط تست دیویس تیوب تولید گردید. از رویکرد فلوتاسیون معکوس برای پرعیارسازی این نمونه استفاده شد. کلکتورهای آنیونی از نوع اسید چرب با نام‌های تجاری Alke و Dirol در آزمایش‌های فلوتاسیون استفاده شد. طراحی آزمایش‌ها با استفاده از طرح عاملی جزئی در رزولوشن سطح IV با ۹ عامل در دو سطح برای هر عامل به انجام رسید. رزولوشن سطح IV توانایی تعیین تمامی اثرات اصلی و اندرکنش‌های دوتایی را دارد. کنسانتره‌ای با عیار آهن  $53/92\%$  با بازیابی وزنی  $60\%$  در شرایط بهینه فلوتاسیون شامل درصد جامد  $20\%$ ، pH برابر با ۱۲، غلظت کلکتور  $1 \text{ kg/t}$ ، ناشاسته به عنوان بازداشت کننده با غلظت  $5 \text{ kg/t}$ ، نسبت جرمی کلکتور Alke/Dirol برابر با  $30/70$ ، زمان آماده‌سازی ۱۰ دقیقه و یون  $\text{Ca}^{2+}$  به عنوان فعال کننده با غلظت  $1 \text{ kg/t}$  حاصل شد. در این پژوهش همچنین مفهوم بازداشت طبیعی کانی‌های آهن‌دار در فلوتاسیون معکوس معرفی و ارزیابی گردید.

**کلمات کلیدی:** باطله کانسنگ آهن، پرعیارسازی، فلوتاسیون معکوس، کلکتور آنیونی، بازداشت طبیعی.