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MINERALOGICAL AND SEPARATION CHARACTERISTICS OF IRON ORE FINES FROM BELLARY – HOSPET, INDIA WITH SPECIAL EMPHASIS ON BENEFICIATION BY FLOTATION

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Abstract

The depletion of high grade iron ore and increased generation of fines during mining and handling and demand for high grade iron ore fines for pellet making and export has necessitated the processing of low to medium grade fines. Physical separation methods were found to be inadequate to process fine sized ores due to reduced selectivity of separation. An attempt has been made to understand the intricate associations between different mineral phases of iron ore fines from Bellary-Hospet area, India from XRD, as well as Electron microscopy studies. XRD studies indicated that hematite and goethite are the iron bearing minerals in order of abundance and quartz and kaolinite form the gangue. EPMA studies on these ores show the presence of gibbsite as the only alumina bearing phase and apatite as phosphorous bearing mineral. Traces of alumina, present as solid solution in the iron oxide minerals has also contributed Al_2O_3 to the ores. Electron microscope studies indicated that gibbsite grains are in the range of 10 to 50 microns and are intimately associated with the iron oxide phases. Particle Size Analysis and Heavy Medium Separation (HMS) tests on different size fractions provided the insight into the liberation and separation characteristics of the material. d_{80} of the material was found to be 40.5 microns. 20.6% by weight of the material can

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be treated as fairly liberated and obtained as a concentrate assaying 66.29% Fe, 2.15% SiO_2 and 1.17% Al_2O_3 from the feed assaying 60.43% Fe, 6.88% SiO_2 and 3.26% Al_2O_3. This defines the lower bench mark for theoretical recovery and grade of the concentrate. Further, scope exists for increase in recovery of iron values from the partially liberated particles without diluting the concentrate grade in terms of allowable limits of alumina (not more than 2.5%) for pellet making. Considering all these factors, flotation appears to be the only industrially viable process to recover these iron values with acceptable grade, recovery and alumina in the concentrate.

Key words: *Iron ores, EPMA, HMS, Liberation, Flotation.*

1. Introduction

The Government of India highlighted Processing and utilization of iron ore fines as a pre-requisite to meet the domestic raw material requirements for the projected 110 million tonnes of domestic steel production by the year 2019-20 in the National Steel Policy announced in November 2005 [1]. This would require 190 million tonnes of iron ore. The policy lays emphasis in encouraging investments in adding value to iron ore fines. It was indicated that 60% of the iron ore produced in India comes in the form of fines during the course of mining operations itself. Further, 10-12% lumps become fines while handling, loading / unloading (particularly in Bellary – Hospet sector where the ore is soft and friable) and while converting them into calibrated lump ore (CLO) for sponge / pig iron plants / exports. Also, as mining depths increase, the ores are becoming softer and increased moisture content resulting in lower grade ores which need to be processed for their optimal utilization. The fines (especially ultrafines or concentrate; <150μm) can only be made into pellets suitable to blast furnace / COREX charge and they should conform to stringent and consistent specifications.

The iron ore deposits of Bellary – Hospet sector are considered to be one of the richest iron ore deposits next to those in Orissa, Bihar and Chattisgarh. The ore bearing terrain is just south of the Bellary-Hospet railway line and comprises of Ramandurg, Kumaraswamy, Donimalai, Timmappanagudi and Devadarigudda sections along the eastern and western ranges of Sandur hills. The principle ore bearing minerals of normative composition averaged over a number of deposits of this area are hematite 70-75%, goethite/limonite 15-20% and martite 5-15% are highly oxidized. Some of the salient features of these ores are

- relatively soft nature which generate excess fines during mining, handling and processing, at times, beyond acceptable limits for subsequent processes
- high alumina content
- intrinsic association of alumina with iron bearing minerals at -25μm rendering selective recovery of iron values almost impossible at this size range.

The typical chemical composition of these ores is given in the following Table 1.

Table 1. *Typical chemical composition of ore*

Constituent	Weight,%
Fe	55.0-69.0
SiO_2	0.2-10.0
Al_2O_3	0.9-15.0
TiO_2	0.2-1.2
MnO	0.1-2.1
P	0.02-0.16
S	0.005-0.05
CaO	0.05-0.2
MgO	0.03-2.1
H_2O	2.0-12.0

M/s JSW Steel Limited, one of the leading producers of Steel in India outsources iron ore fines for its beneficiation plant from the above mentioned eastern and western ranges of Sandur hills. It has been established that the ore from different sources vary widely in mineralogy, chemical composition, particle size distribution and response to washability for reduction of alumina. Accordingly they have been classified as preferred, tolerable and not amenable for processing. Based on this, necessary caution is being exercised while procuring the iron ore fines for their beneficiation plant. A 3.0 Mtpa beneficiation plant has been in operation with the primary objective of reducing alumina in iron ore fines. It has two parallel streams, each with a rated capacity of 300 tph. The unit operations in each stream (Fig. 1) comprise of wet screening, classification of undersize of wet screening by a set of screw classifiers followed by 2-stage hydro-cycloning of screw classifiers' overflow at 20-microns cut-point. The underflow of 2-stage hydro-cycloning forms the concentrate which is fed to the pellet plant after dewatering by horizontal belt filter. The oversize material from screen and screw classifier fines are stock piled in the raw material yard for their usage in the downstream processes. Analysis of the plant performance data over a period of one year provided the following information.

- Screen oversize (64.04% Fe & 2.31% Al_2O_3) and screw classifier fines (64.70% Fe & 2.04% Al_2O_3) were of good quality to be utilized in the downstream processes
- Screw classifier overflow (59.84% Fe & 4.16% Al_2O_3) is being subjected to 2-stage hydrocycloning to obtain a concentrate (63.43% Fe & 2.32% Al_2O_3) with weight recovery of 45%.

Since the cut-point of hydro-cyclones was at 20μm, relatively lower diameter cyclones in a cluster with parallel feeding were being used. This often resulted in choking of the spigots, at times, by extraneous material reporting along with the slurry, leading to sub-optimum performance with loss of iron values into cyclone overflow and thereafter into tailings. Earlier studies [2, 3] on Goan iron ores of India indicated that slilica and alumina could be reduced by cationic reverse flotation of fine iron ore concentrate as a value addition step.

As a prelude to the detailed investigation into preventing the metal losses, studies were undertaken to understand the mineralogical and separation characteristics of this screw classifier overflow with a view to design a process for maximizing the recovery of iron values at equivalent or better grade as compared to that from existing practice.

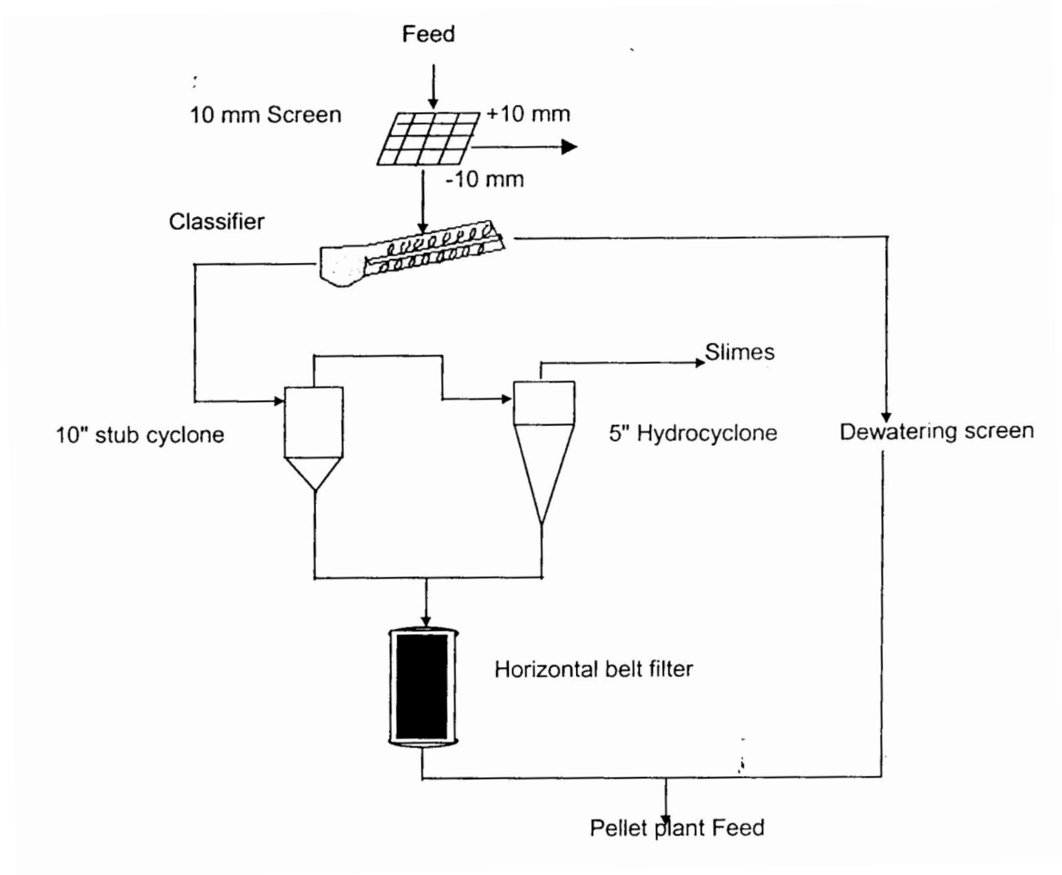

Figure 1. *Typical flow diagram of one stream*

2. Mineralogical characterization

2.1 XRD Studies

XRD analysis of the as received sample (screw classifier overflow) revealed (Fig.2 and Table 2) that the major iron bearing opaque minerals are **hematite** (JCPDS No.33-664) followed by **goethite** (JCPDS No.29-713). The silicate gangue minerals identified are quartz (SiO_2, JCPDS No.33-1161) and kaolinite {$Al_2Si_2O_5(OH)_4$, JCPDS No.14-0164}.

One of the more important findings of earlier investigations is that alumina in Indian iron ore slimes occurs in the form of two distinct mineral constituents namely, gibbsite (hydrated aluminium oxides) and kaolinite (and other clay minerals in minor quantities). In the present sample under investigation, kaolinite is the predominant alumina bearing phase, making its separation from iron bearing mineral phases easier by flotation as against the one in which alumina is present in gibbsite form [4].

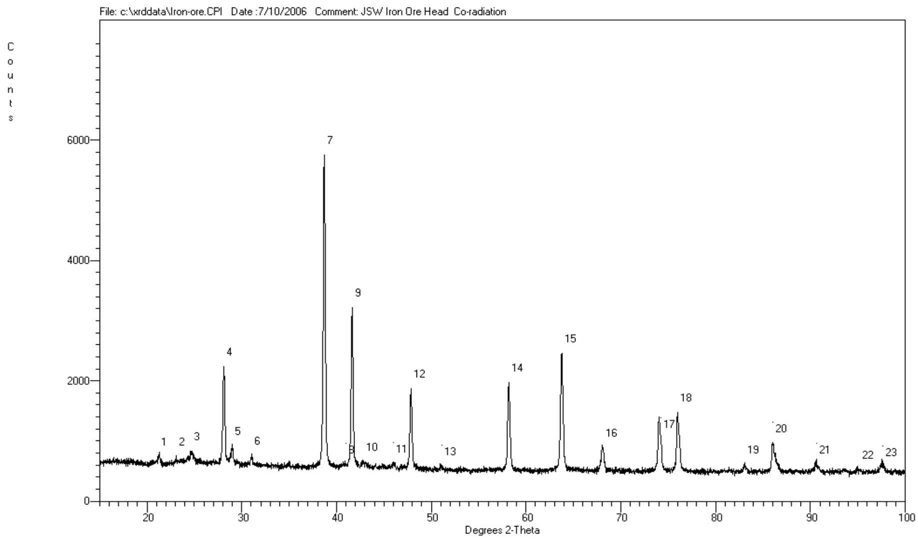

Figure 2. *XRD pattern of screw classifier*

Table 2. *Phase identification of the XRD peaks*

No	Angle	Counts	Dspace	Rel I	Phases identified
1	21.18	742	4.867	13	Goethite
2	23.12	749	4.464	13	Kaolinite
3	24.70	830	4.182	14	Goethite / Kaolinite
4	28.12	2240	3.682	39	Hematite
5	28.96	921	3.577	16	Goethite / Kaolinite
6	31.10	758	3.337	13	Goethite / Quartz / Kaolinite
7	38.7205	5756	2.698	100	Hematite / Goethite
8	40.96	621	2.557	11	Goethite / Kaolinite
9	41.6432	3222	2.516	56	Hematite / Goethite
10	42.84	661	2.449	11	Goethite / Quartz / Kaolinite
11	46.00	633	2.289	11	Hematite / Goethite / Quartz / Kaolinite
12	47.88	1875	2.204	33	Hematite / Goethite / Kaolinite
13	51.14	591	2.072	10	Hematite / Goethite / Kaolinite
14	58.20	1978	1.839	34	Hematite / Goethite / Quartz / Kaolinite
15	63.78	2457	1.693	43	Hematite / Goethite / Quartz / Kaolinite
16	68.10	889	1.598	15	Hematite / Goethite / Quartz / Kaolinite
17	74.22	1045	1.483	18	Hematite / Goethite /
18	75.96	1478	1.454	26	Hematite / Goethite / Quartz
19	83.08	610	1.349	11	Hematite
20	86.06	971	1.311	17	Hematite
21	90.68	620	1.258	11	Hematite / Quartz
22	95.16	527	1.212	9	Hematite / Quartz
23	97.66	576	1.188	10	Hematite / Quartz

2.2. EPMA Studies

It was observed that minute inclusions of gibbsite (Fig. 3), in the range of 10 to 50 microns, occur within the iron oxide minerals. They are very intricately and intimately present along with the iron oxide minerals, the liberation of which is very difficult. Quantitative EPMA analysis of iron ore minerals along with their associated phases indicated that alumina is present in more or less all the phases. The highest amount is observed in the limonite as solid solution within the structure / lattice of the iron oxide phases.

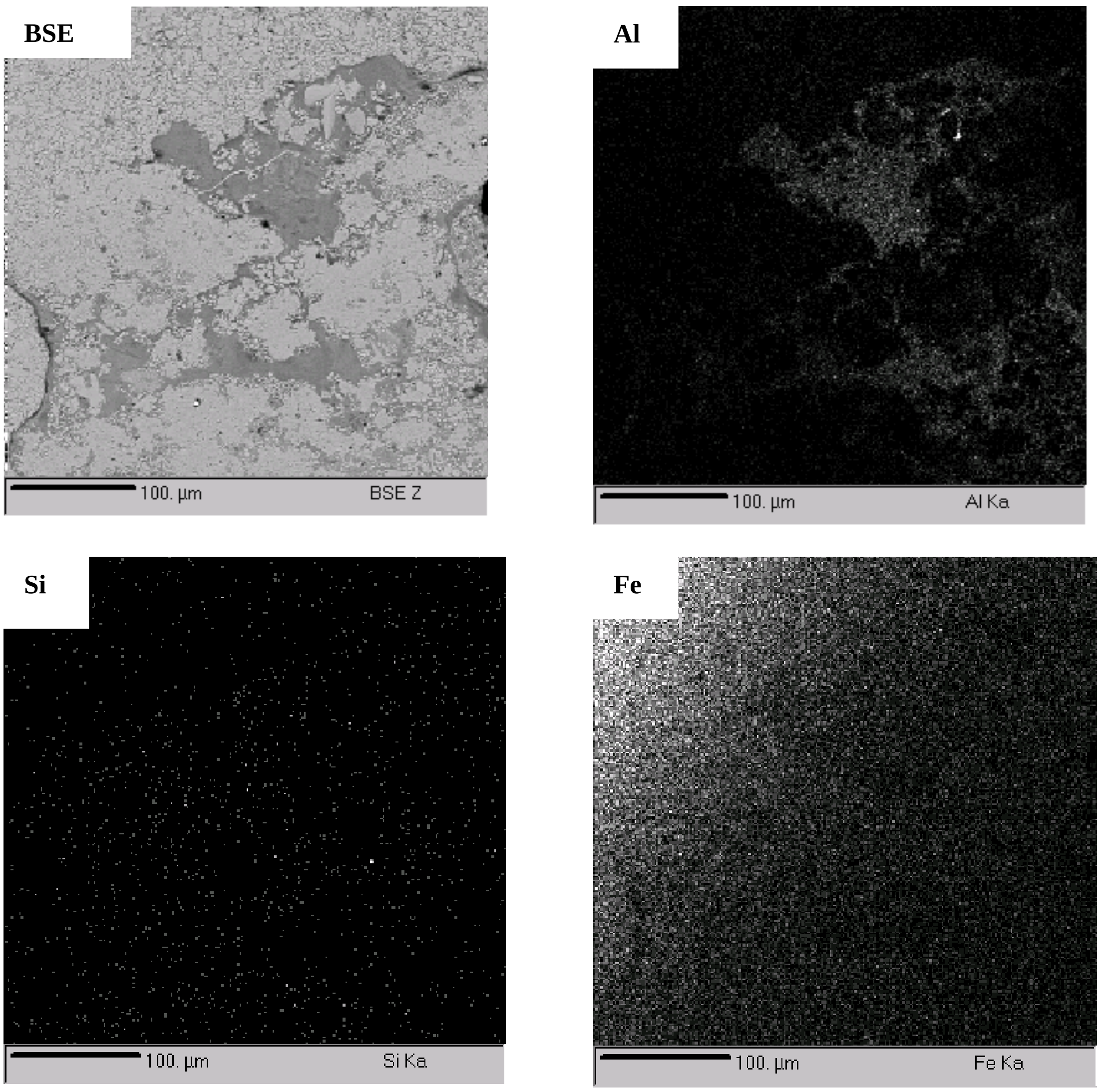

Figure 3. *Electron microscopic mapping studies of an iron ore sample showing presence of gibbsite phase along with other iron ore minerals*

It is well known that iron oxide and alumina have identical crystal structures as well as the surface chemical properties and this is likely to have a bearing on the efficiency of any separating process. Analysis number 15 is apatite, 16 is clay and 17 is gibbsite phase (Table 3).

Table 3. *EPMA analysis of the various iron oxides along with other associated phases*

	Al_2O_3	SiO_2	P_2O_5	Fe_2O_3	Total
	Hematite				
1	0.39	0.00	0.00	94.97	95.36
2	0.48	1.16	0.06	95.12	96.82
3	1.34	0.70	0.10	91.35	93.48
4	1.07	1.06	0.04	92.51	94.68
5	0.68	0.00	0.01	95.21	95.90
	Goethite				
6	4.67	0.00	0.10	76.01	80.78
7	3.98	0.00	0.11	76.91	81.01
8	2.23	0.00	0.60	85.55	88.38
9	2.70	1.80	0.09	82.82	87.42
	Limonite				
10	2.68	1.07	0.05	60.99	64.79
11	7.59	0.00	0.26	70.68	78.53
12	6.18	0.68	0.14	71.32	78.31
13	1.10	0.36	0.00	68.95	70.41
14	8.48	0.17	0.14	57.72	66.52
	Other Phases				
15	0.00	1.01	44.5	0.01	45.51
16	18.52	69.07	0.00	0.02	87.62
17	59.39	1.45	0.02	0.08	60.94

2.3. Particle Size Analysis

A representative sample was drawn from the dried screw classifier overflow. Its specific gravity was found to be 4.3058 and d_{80} = 40.5µm. The detailed particle size analysis and distribution is presented in Table 4. It can be observed that more than 80% of the material by weight and Fe, SiO_2, Al_2O_3 and LOI are distributed in below 45µm size range making recovery of iron values by physical separation methods difficult and inefficient at industrial scale operations. All physical separation processes are known to be sensitive to particle size, mineralogy, liberation and feed grade.

Table 4. *Particle Size Analysis of screw classifier overflow*

Size (µm)	Wt.% retained	Assay,%				Distribution,%			
		Fe	SiO_2	Al_2O_3	LOI	Fe	SiO_2	Al_2O_3	LOI
+150	0.38	38.60	21.85	6.68	---	0.24	1.23	0.72	---
-150+125	0.32	48.81	18.27	6.68	---	0.26	0.86	0.60	---
-125+106	0.63	51.94	14.50	5.61	5.20	0.55	1.35	1.00	1.04
-106+90	1.57	56.97	10.01	4.33	3.83	1.49	2.32	1.91	1.91
-90+75	2.11	60.43	6.96	3.42	2.83	2.12	2.17	2.03	1.90
-75+63	2.99	62.44	5.75	2.23	2.40	3.10	2.54	1.88	2.28
-63+53	5.97	63.78	4.16	2.72	2.10	6.33	3.67	4.57	3.98
-53+45	5.02	61.32	5.62	2.85	3.21	5.12	4.17	4.03	5.11
-45	81.01	59.98	6.82	3.65	3.26	80.79	81.69	83.26	83.78
Head (by cal.)		60.14	6.76	3.55	3.15				
Head (by assay)		60.43	6.88	3.26	3.03				

2.4. Heavy Media Separation (HMS) Tests

Similarly a representative sample was subjected to wet sieving cum washing studies in auto sieve shaker and the individual sieve fractions were subjected to heavy medium separation using tetra bromoethane to elicit information on liberation characteristics of the sample and the results are presented in Table 5.

Table 5. *Heavy Media Separation of screw classifier overflows sieve fractions*

Size (µm)	Wt.%			Assay, %				Distribution, %			
				Fe	SiO_2	Al_2O_3	LOI	Fe	SiO_2	Al_2O_3	LOI
+75	3.48	Sink	2.54 (73.04)	64.67	2.68	1.99	2.45	2.73 (90.1)	1.08 (14.9)	1.38 (33.5)	1.94 (24.7)
		Float	0.94 (26.96)	19.21	41.26	10.69	20.22	0.30 (9.9)	6.18 (85.1)	2.75 (66.5)	5.91 (75.3)
+45	9.05	Sink	7.57 (83.68)	66.91	1.56	1.10	1.34	8.42 (88.7)	1.88 (27.3)	2.27 (40.2)	3.15 (48.5)
		Float	1.48 (16.32)	43.67	21.25	8.38	7.27	1.07 (11.3)	5.01 (72.7)	3.39 (59.8)	3.35 (51.5)
+25	12.99	Sink	10.49 (80.72)	66.24	2.45	1.02	1.48	11.54 (82.6)	4.09 (55.6)	2.92 (47.6)	4.83 (69.9)
		Float	2.50 (19.28)	58.71	8.22	4.71	2.68	2.44 (17.4)	3.27 (44.4)	3.22 (52.4)	2.08 (30.1)
-25	74.48	Sink	71.59 (96.12)	60.99	5.96	2.75	3.21	72.52 (98.7)	67.92 (86.5)	53.81 (64.0)	70.46 (90.8)
		Float	2.89 (3.88)	20.53	22.97	38.32	8.11	0.98 (1.3)	10.57 (13.5)	30.26 (36.0)	8.28 (9.2)
100.00		Head (Cal.)		60.21	6.28	3.66	3.22				
		Head (assay)		60.43	6.88	3.26	3.03				

Note: Figures in parentheses indicate the percentage contribution of each entity (Sink & Float) in the respective size fraction

2.5. Flotation tests

Separation processes based on the surface-chemical differences between iron and silica and alumina containing minerals, for example, froth flotation and selective dispersion – flocculation are also promising but have not been investigated adequately for processing Indian iron ores, especially from industrial application point of view [4].

Exploratory laboratory scale reverse flotation (collecting gangue into froth) tests were conducted in a D12 Denver Flotation Cell at randomly fixed and constant process parameters to assess the response of screw classifier overflow to separation. Sodium hydroxide was used as pH regulator, causticised starch was used as depressant for iron bearing minerals and a cationic collector, 'Sokem 524C' supplied by M/s Somu Organo-Chem Pvt. Ltd., Bengaluru, India was used as a collector for silica and alumina bearing minerals. The experimental conditions maintained in one of the tests and the results obtained were shown in Table 6.

Table 6. *Flotation Tests using 'Sokem 524C' (*pH: 9.5; Starch: 1.0 kg/ton; Cell rpm: 1250; Conditioning time: 5 mins.; Flotation time: 15 mins.; Conditioning at 50% solids & Flotation at 40% solids by wt.)

Sl. No.	Sokem 524C (kg/t)	Product	Wt. %	Assay, %			Distribution, %		
				Fe	SiO_2	Al_2O_3	Fe	SiO_2	Al_2O_3
1	0. 20	Tailings	20.64	52.82	11.15	7.67	18.16	36.35	38.76
		Conc.	79.36	61.90	5.08	3.15	81.84	63.65	61.24
		Head (Calc.) Head (Assay)		60.02 60.43	6.33 6.88	4.08 3.26	100.0	100.0	100.0
2	0.30	Tailings	33.87	53.30	10.95	7.37	30.08	58.58	61.11
		Conc.	66.13	63.46	3.97	2.40	69.92	41.42	38.89
		Head (Calc.) Head (Assay)		60.02 60.43	6.33 6.88	4.08 3.26	100.0	100.0	100.0
3	0.40	Tailings	44.29	54.45	10.35	6.72	40.18	72.37	72.85
		Conc.	55.71	64.45	3.14	1.99	59.82	27.63	27.15
		Head (Calc.) Head (Assay)		60.02 60.43	6.33 6.88	4.08 3.26	100.0	100.0	100.0

It could be observed that there is a gradual reduction of alumina and silica in the concentrate as the dosage of the collector was increased with improvement in the grade of the concentrate. At 0.40 kg/t of the collector, concentrate of 55.71% by weight and 59.82% Fe recovery could be achieved with a grade of 64.45% Fe, 3.14% SiO_2 and 1.99% Al_2O_3 from a feed assaying 60.43% Fe, 6.88% SiO_2 and 3.26% Al_2O_3. These results are superior to those obtained for classification of screw classifier overflow by cyclone (underflow) in the beneficiation plant. The distribution of Fe, SiO_2 and Al_2O_3 in tailings and concentrate as the collector dosage increased show that the liberation characteristics of the material favor fairly good separation by flotation. There exists scope for further improvement in recovery when the process parameters (dosages of starch and Sokem 524C, pH and pulp density etc.) are optimized.

The presence of alumina in the form of kaolinite in predominant form appears to have favoured its separation from iron bearing minerals. Further reduction of alumina in concentrate is limited by the fact that alumina in the form of gibbsite is in solid solution form within the crystal lattice of iron oxide minerals as indicated by EPMA studies. This was reflected in the results of flotation tests as well. Any further reduction in alumina levels below 1.99% in the concentrate will be at the cost of recovery of iron values. The reduction of quartz is also significant. The results obtained were well within the acceptable levels of alumina in the concentrate (≤ 2.50%) for pellet making.

3. Conclusions

The ultrafine iron ore sample / slimes from an operating washing plant was characterized in terms of XRD and EPMA for identification of valuable and gangue minerals present in it. XRD studies indicated the presence of hematite and goethite as the iron bearing minerals and quartz and kaolinite as the gangue minerals. EPMA studies show the presence of gibbsite as the only alumina bearing phase and apatite as phosphorous bearing mineral. Intricate association of alumina and iron oxide phases was observed below 25 microns particle size range. This was found to impose limitation in reducing alumina below 2.0% in the concentrate. It was further corroborated from HMS tests that, theoretically, 20.6% by weight of the feed could be obtained as a concentrate assaying 66.29% Fe, 2.15% SiO_2 and 1.17% Al_2O_3 from the feed analyzing 60.43% Fe, 6.88% SiO_2 and 3.23% Al_2O_3 which formed the lower bench mark for recovery of iron values by any technique. Further increase in concentrate recovery should accrue from moderately liberated iron bearing particles. Considering the limitations in particles size (d_{80}: 40.5µm), intricate association of iron and alumina bearing minerals at lower particle size range and the liberation of iron values from gangue (from HMS studies), it was evident that flotation could be the best possible industrial process that could recover iron values economically. Exploratory flotation tests revealed that a concentrate of 55.71% by weight and 59.82% Fe recovery could be obtained with a grade of 64.45% Fe, 3.14% SiO_2 and 1.99% Al_2O_3 from the above mentioned feed. These results are encouraging and superior to those obtained from classification of screw classifier overflow by cyclones (underflow) (concentrate of 45.9% by weight and 48.65% Fe recovery with a grade of 63.43% Fe, 4.43% SiO_2 and 2.23% Al_2O_3) in the beneficiation plant as is being practiced now.

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