Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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To cite this Article Roy, S. , Das, A. and Mohanty, M. K.(2007) 'Feasibility of Producing Pellet Grade Concentrate by Beneficiation of Iron Ore Slime in India', Separation Science and Technology, 42: 14, 3271 — 3287
To link to this Article: DOI: 10.1080/01496390701514824
URL: http://dx.doi.org/10.1080/01496390701514824

Separation Science and Technology, 42: 3271–3287, 2007

ISSN 0149-6395 print/1520-5754 online
DOI: 10.1080/01496390701514824

Feasibility of Producing Pellet Grade Concentrate by Beneficiation of Iron Ore Slime in India

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Abstract: Beneficiation of low grade iron ore slime from Chitradurga, India was studied with a view to produce pellet grade fines. The slime sample had a feed grade of 49.86% total Fe, 7.93% Al_2O_3, and 10.19% SiO_2. Kaolinite and quartz was found to be the main gangue minerals and they formed porous and friable oxide and hydroxide of iron. Over 54% of the materials in the slime were less than 20 micron and this size fraction contained higher percentage of gangue minerals. Liberation of free gangue minerals was observed to be substantial in all size classes. Beneficiation studies indicated that excellent rejection of silica and alumina could be obtained through physical separation. The low grade slime could be enriched to 66.36% Fe with 1.75% silica, and 1.44% alumina.

Keywords: Iron ore slime, characterization, beneficiation, pellet grade, flowsheet development

INTRODUCTION

Iron ore industries are demanding increasingly high grade raw materials to improve quality and reduce cost of production. However, the ore being a

Received 7 January 2007, Accepted 24 April 2007
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non-renewable natural resource, the reserve of good quality ore is ever dwindling. Marginal to sub-marginal grade iron ore must be utilized to meet the present and future requirements and avoid environment related problems. In case of iron ore there is increasing realization that more needs to be done to conserve high grade mineral resource by judiciously utilizing it. It is also imperative to develop viable technology for the beneficiation of hitherto unutilized low grade and ultrafine materials (slimes). Washing plant and pilot plant data indicate that slime generation is about 30–35% of the ore mined. Presently, due to the difficult nature of the fines and slimes and the lack of availability of efficient technology to process them, a large amount of these remain unused. They are generally lost in the dumps that cause environmental hazard (1). If pellets are produced directly from such fines they become extremely high in alumina. It has now been clearly established both by laboratory studies and plant trials that alumina has an adverse effect on pellet properties, typically measured by Reduction Degradation Index (RDI) and Reducibility Index (RI). A drop in alumina content would improve these properties which in turn would reduce the coke rate and increase productivity in blast furnace.

High alumina also increases the slag viscosity in blast furnace operation, increases the metal loss in slag, increases the thermal requirement, and makes the blast furnace operation more problematic. Steel industries are looking for means to reduce the alumina in the burden. The use of pellets in the burden has increased manifold over the last few years in blast furnace operation worldwide. It is reported that world production of pellets increased from 160 MT in 1980 to 300 MT in 2003 (2). However, use of pellets in blast furnace iron making has not been practiced in India so far. It is envisaged that there would be a heavy demand of pellets for blast furnace operation in the next few years in India. In view of this, it is worthwhile to develop suitable indigenous technology/process for beneficiating low grade fines and slimes to produce pellet grade material. Research in this regard would not only meet the future demands but also solve, at least partially, the problems associated with storage of such vast amounts of fines in the form of slimes.

Several researchers have worked on the improvement of the quality of slime by selecting proper beneficiation techniques (3–8). However, it is still not a very common practice to implement rigorous mineral characterization studies, both qualitative and quantitative, prior to beneficiation of iron ore fines. Such studies are, indeed, very important in mineral processing for understanding the nature of the fines and finally, for the design and optimization of beneficiation flowsheet. The little research work that has been done in this respect (9–11) has limited scope as it dealt with either relatively high grade slimes (total Fe $>$ 52%) or detailed characterization was not carried out. Efforts were made to fill the existing gap in the present work. Mineralogical characterization results were correlated with the processing of low grade slime with a view to develop a viable beneficiation strategy using the conventional beneficiation techniques. In the present work, efforts were also made to develop a technology that utilizes at least part of the available slime, in order to reduce the severity of the environment-related problems if not solve them completely.

CHARACTERIZATION

Bulk Ore Sample

The iron ore sample studied in the present work was obtained from Chitradurga, India and it belongs to Dharwarian banded iron ore formation. Optical microscopy was used for mineralogical and microstructural characterization studies that allowed the identification of mineral phases, nature of iron bearing minerals and gangue minerals and their occurrences.

Hematite occurs as major iron bearing mineral phase in the bulk ore samples. Fine to medium grained microplaty crystals of hematite are intricately associated with each other leaving very fine inter-granular micro pores, as shown in the micrographs in Figs. 1A and 1B. These microplaty hematite crystals are called specularite. Most of the samples show a high degree of porosity with a substantial amount of clay. Apart from hematite, the other major iron bearing phase is goethite. It occurs as colloform bands

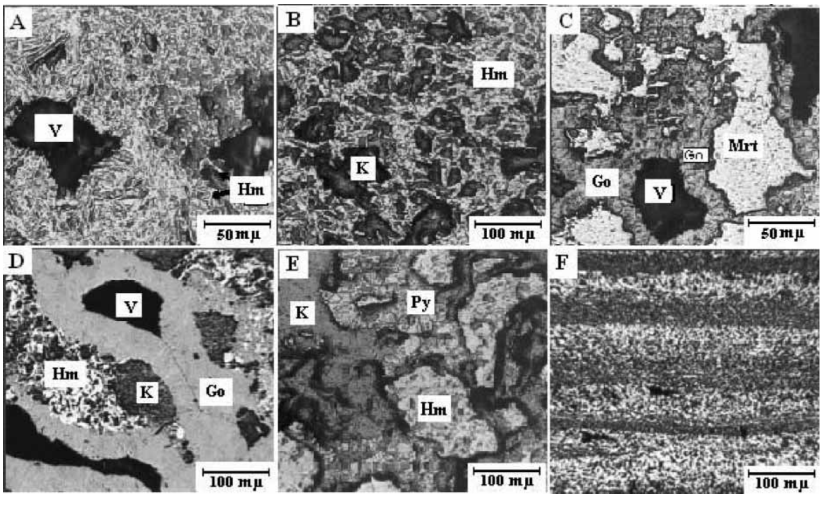

Figure 1. Microphotographs of iron ore sample under stereo-microscope, (A) Microplaty specularite, (B) Specularites with kaolinite precipitated in void spaces/cavities, (C) Martite (Mt) and inconspicuously developed microplaty hematite around which goethite (Go) is deposited in the voids, (D) Goethite and kaolinite along the weaker rock zone and voids, (E) Pyrolusite and kaolinite precipitated in void spaces/cavities, and (F) Laminated iron ore with iron and silicate band (Hm-hematite, Go-goethite, Mrt-martite, K-kaolinite, V-void/cavity, Py-pyrolusite).

and vein filling within the voids (Figs. 1C and D). The cavities developed mostly along the weaker planes in between the mineral bands. This may have resulted due to the leaching out of pre-existing minerals. In many cases these cavities are also subsequently filled by clay material (Figs. 1B, D and E) or secondary goethite. The banding nature of the iron ore is visible in some samples that show high degree of interlocking as shown in Fig. 1F. Some of the samples are martitized and the presence of martite could be observed as shown in Fig. 1C. Few relict magnetite is observed in the ore samples. Some of the ore samples are characteristically manganeferous. Manganese minerals such as pyrolusite, braunite, and hausmanite have been observed. Pyrolusite occurs as cavity filling deposit as can be seen in Fig. 1E. However, the overall presence of manganese minerals in the bulk sample is low.

The presence of hematite, goethite, magnetite, kaolinite, and quartz is also supported by X-ray diffraction data as shown in Fig. 2. XRD analysis of the clay material shows that it is mainly composed of kaolinite, as evident from Fig. 2C. Some of the ore fragments have undergone weathering, producing ochreous goethite, and kaolinite. Therefore, this can be termed as lateritic ore. It is generally soft and friable and leads to slime generation during handling.

The chemical analysis of the bulk iron ore sample, presented in Table 1, shows that it contains 57.16% Fe, 5.6% silica, and 4.05% alumina with 1.38% manganese.

Slime Sample

Characterization of the iron ore slime consisted of various methods, including size analysis, chemical analysis, density measurement, XRD study, scanning electron microscopy with EDS, microscopic analysis, and image analysis. These steps are described in detail in the following sections along with the observations.

Size Analysis

Particle size measurements of the iron ore slime were done using Shimadzu SA-CP3 particle size analyzer. In order to collect samples in each size range, sieving of iron ore slime sample was carried out using the Vibratory Laboratory Sieve Shaker "Analysette3". For the separation of −50 micron particles micro-precision sieves were used. Graphical representation of the size analysis data of the slime sample is shown in Fig. 3. It is seen from the size measurement that the slime is extremely fine in nature. Substantial amount of the slime is below 20 μm (54.46% by weight). D_{80} of the distribution is about 60 micron.

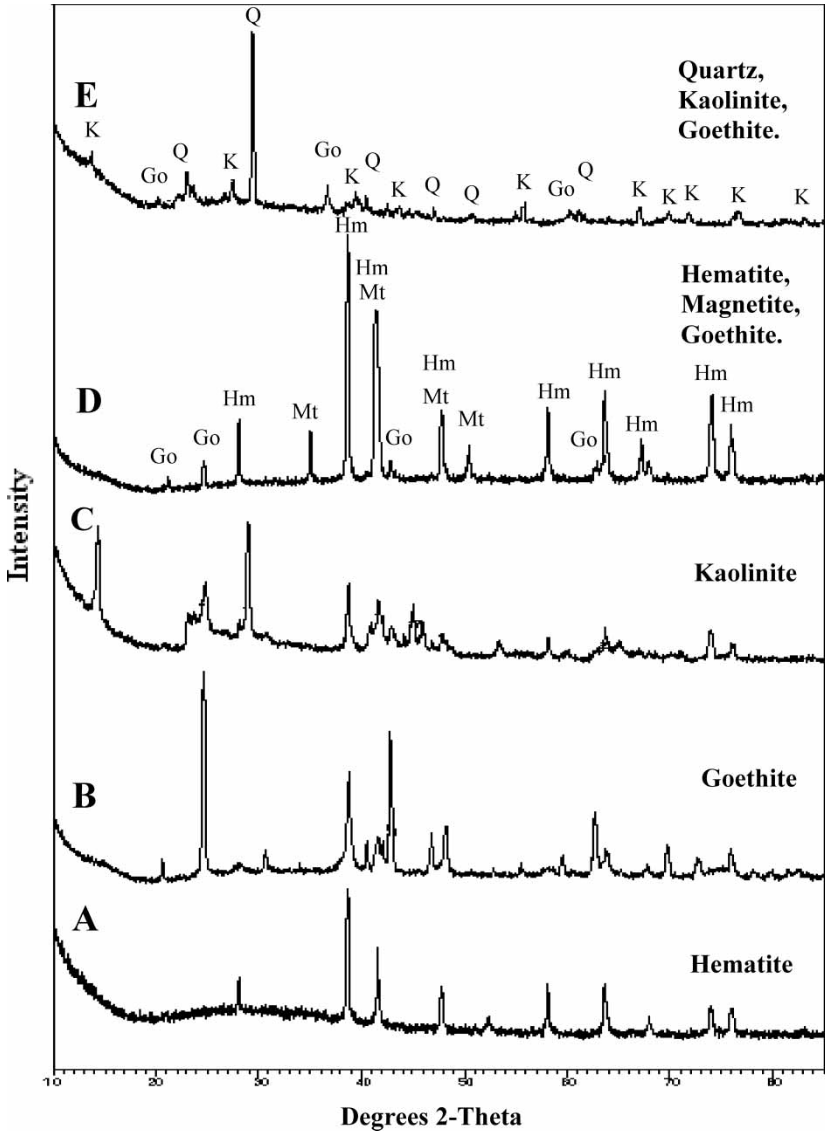

Figure 2. XRD pattern of iron ore samples with identified phases (A) Hematite, (B) Goethite, (C) Kaolinite, (D) Hematite, Magnetite, Goethite, and (E) Quartz, Kaolinite, Goethite. (Hm-hematite, Mt-Magnetite, Go-goethite, K-kaolinite, and Q-quartz).

Chemical Analysis and Density Measurement

From the chemical compositions of various size fractions, listed in Table 2, it can be calculated that the +20 micron fraction contains about 54.6% Fe

Table 1. Chemical analysis of iron ore bulk sample

Radicals	wt%
Fe	57.16
SiO_2	5.60
Al_2O_3	4.05
Mn	1.38
CaO	0.17
MgO	0.15
P	0.075
S	0.01
LOI	7.51

vis-à-vis 45.9% in the −20 micron fraction. More amounts of alumina and silica are concentrated in the finer size fractions. The specific gravity of various size fractions of the iron ore slime measured using a picnometer is also listed in Table 2.

XRD Study

X-ray diffraction study was taken up with a view to identify mineral phases in the slime sample. In the diffractogram, shown in Fig. 4, it can be seen that hematite is the major iron bearing phase and goethite is the other iron bearing mineral phase. Kaolinite and quartz occur as the major gangue phases.

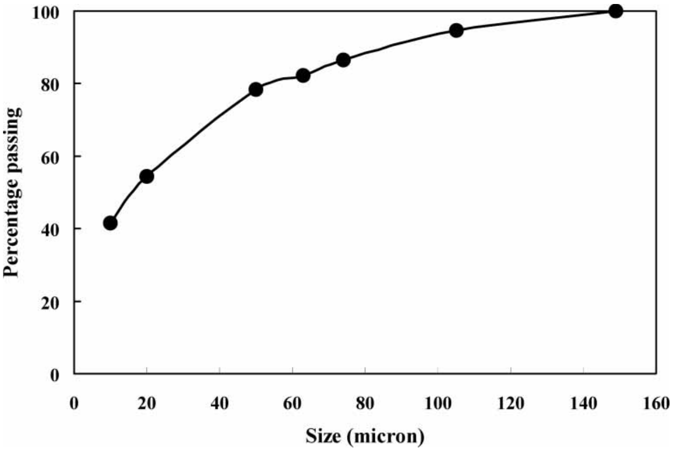

Figure 3. Graphical representation of size distribution.

Table 2. Chemical analysis of iron ore slime in different size fractions

Size in μm	Weight (%)	Fe (%)	Al_2O_3 (%)	SiO_2	Specific gravity
−150 + 50	21.54	56.28	4.43	7.26	3.37
−50 + 20	24.0	53.03	6.12	8.57	3.56
−20	54.46	45.91	10.11	12.07	3.33
Composite	100.0	49.86	7.93	10.19	3.47

SEM Study

Micro-morphological and mineralogical characterization studies were carried out using scanning electron microscopy with attached EDS micro-analyser (SEM/EDS). This study allowed the identification of mineralogy, micromorphology of the individual particles, and elemental composition of the slimes. The results of this investigation were compiled in the form of photomicrographs and microanalysis tables. SEM analysis with EDS has been done with the slime head sample and individual mineral particles. The analysis results, shown in Fig. 5A, indicate that the slime head sample contains variable quantities of gangue along with iron (Fe). Iron bearing particles contain variable quantities of Si and Al along with some Mn, as shown in Fig. 5B. Among the gangue minerals, kaolinite is most abundant and it occurs as limonitic kaolinite having elements Si, Al, and Fe, as shown in Fig. 5C. This Kaolinite is the main source of alumina in the slime.

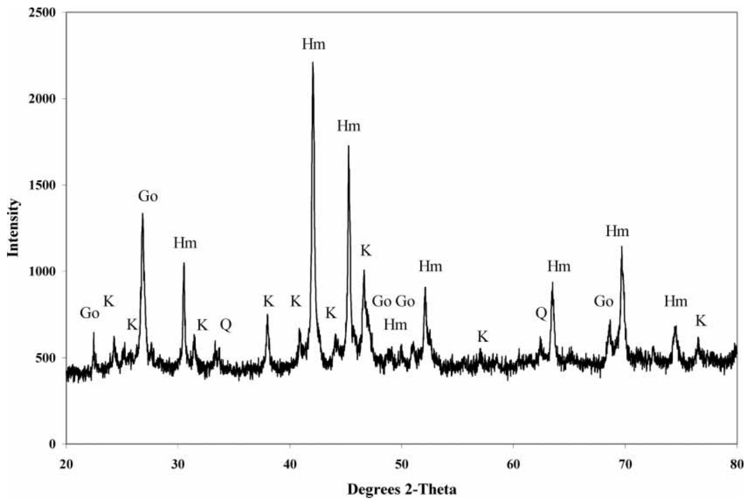

Figure 4. XRD pattern of iron ore slime with identified phases (Hm-hematite, Go-goethite, K-kaolinite, and Q-quartz).

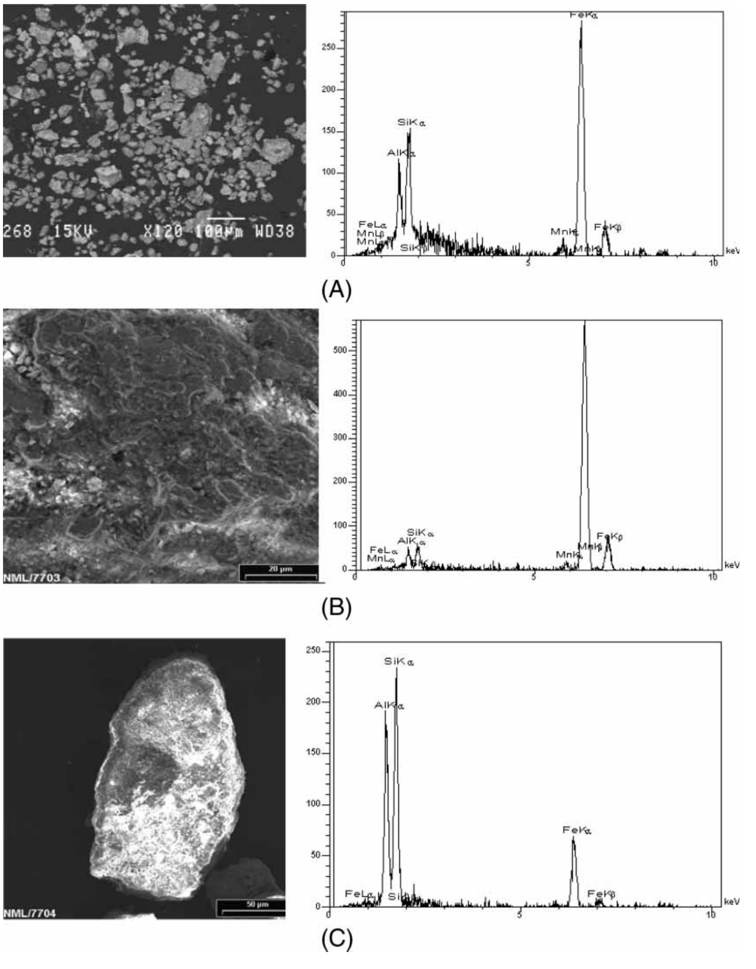

Figure 5. SEM photomicrograph with EDS (A) composite slime sample, (B) hematite particle, (C) ferruginous kaolinite.

Image Analysis and Microscopic Studies

Image analysis and microscopic examination of different size fractions were taken up to identify mineral phases and to estimate their volumetric distribution. These studies were done by collecting representative sample from each size fraction. The size fraction finer than 10 μm was not utilized due to the associated difficulty in mounting. Several sets (30–35 nos.) of images for each size class were processed to distinguish phases and were carefully analyzed by image analyzer (CLEMEX PE 3.5 MEIJI). Good resolution was utilized so that phase distinction is possible among different mineral phases. Inspection of images revealed that iron oxide is the most abundant phase. Occurrence of hematite and goethite is identified with white and light grey features, respectively, as shown in Fig. 6. Due to their dull grey and black features, respectively, quartz and kaolinite gangue mineral phases can easily be distinguished from all iron bearing phases. Volumetric distribution of different phases in each size fraction was estimated using the Grey Threshold technique and summarized in Table 3.

It can be seen from Table 3 that iron bearing phases are more concentrated in coarser sizes whereas, quartz and kaolinite are more concentrated in finer size fractions. Chemical analysis data corroborate such observations.

Liberation study was carried out through stereo-microscope by point counting method. The volumetric percentages of mixed phase (iron + gangue) particles and the free minerals liberated in each size fraction were estimated. Liberation analysis shows that in coarser fractions, interlocking between hematite and clay is significant as shown in Figure 7. Predictably, the percentage of clay-hematite interlocking decreases with decreasing particle size. The percentage of free hematite increases from 89% at 150 × 75 micron size to 92.5% at the finest particle size of −20 micron as given in Table 4. Over the same size range, the percentage of liberated clay mineral increases from 73.9% to 92.7%. Unlike other minerals, quartz is found to be nearly fully liberated even at the coarsest particle size of 150 × 75 micron. The degree of

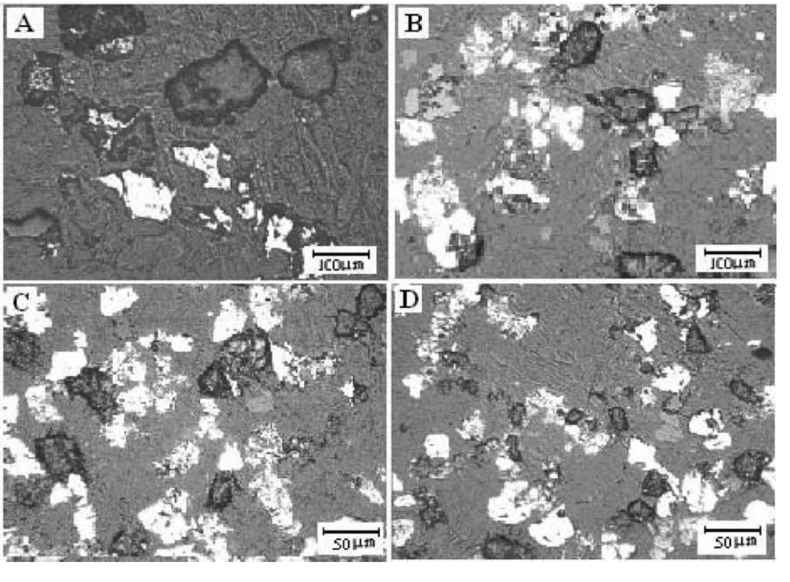

Figure 6. Photomicrographs of different size fractions of iron ore slime (A) $-50+75$ μm, (B) $-75+50$ μm, (C) $-50+20$ μm, and (D) $-20+10$ μm.

Table 3. Volumetric distribution of phases in different size fractions of iron ore slime

	Volume percent in different size fractions (μm)			
Mineral phase	−150 + 75	−75 + 50	−50 + 20	−20 + 10
Hematite + Goethite	73.48	71.16	69.45	62.39
Quartz	14.25	15.51	16.49	20.73
Kaolinite	12.27	13.33	14.00	16.88
Total composite	100.0	100.0	100.0	100.0

liberation for quartz mineral improved to near perfect level (100%) at the finest particle size (−20 micron). It may be noted that greater than 90% liberation is observed for all minerals in the slime sample finer than 20 micron (Figure 7).

BENEFICIATION STUDIES

It is evident from the detailed characterization of the iron ore slime that most of the alumina and silica are concentrated in the size fraction less than 20 μm size. Therefore, it is apparent that a desliming operation to remove this ultrafine fraction would improve the grade. The overall flowsheet was

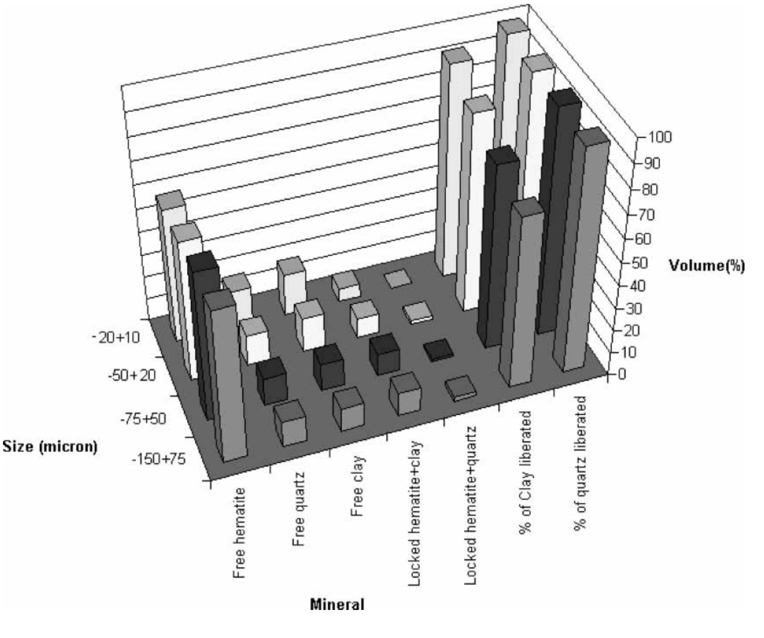

Figure 7. Liberation pattern of iron ore slime.

Table 4. Liberation analysis of different size fractions in the slime

	Volume percent in different size fractions (μm)			
Mineral phase	−150 + 75	−75 + 50	− 50 + 20	− 20 + 10
Free hematite	66.13	64.93	60.91	58.76
Free quartz	11.23	11.97	13.76	16.62
Free clay	10.34	11.83	15.03	18.43
Locked hematite + clay	10.43	10.05	8.65	05.85
Locked hematite + quartz	1.87	1.22	1.65	0.34
% of clay liberated	73.91	79.69	86.12	92.65
% of quartz liberated	96.00	97.52	97.66	99.59
% of hematite liberated	88.99	89.24	88.97	92.65

conceived with a view to exploit the differences in specific gravity, magnetic susceptibility, and surface properties between the valuable and gangue minerals. The goal was to achieve pellet grade concentrate (greater than 65% Fe and less than 3% combined alumina and silica) at a reasonably high yield. The selected flowsheet is shown in Fig. 8. The results of beneficiation studies are discussed in the following sections.

Removal of Ultrafines

The iron ore slime is first treated in a 5.08 cm diameter classifying cyclone to remove the ultrafines. A number of tests are conducted by varying spigot and vortex finder diameters, pulp density and inlet pressure. After each test, both underflow and overflow fractions are collected, dried, weighed and analysed for grade. The best results obtained in desliming operation are listed in Table 5. The Fe grade improved to over 55% from 49.8% in the feed with a yield in excess of 60% in the underflow. The alumina is also brought down to 5.5% from 7.93% in the feed stream. Recovery of total Fe in the underflow is found to be 67.95%.

Gravity Separation using Wilfley Table

To study the efficacy of flowing film concentration of slimes, the cyclone underflow is subjected to concentration in Wilfley Table. The results obtained from the best test are reported in Table 6. It may be seen that about 42% solids (w. r. t. orig.) is recovered in the concentrate product. The alumina rejection is substantial and the concentrate grade improved to 61.14% Fe

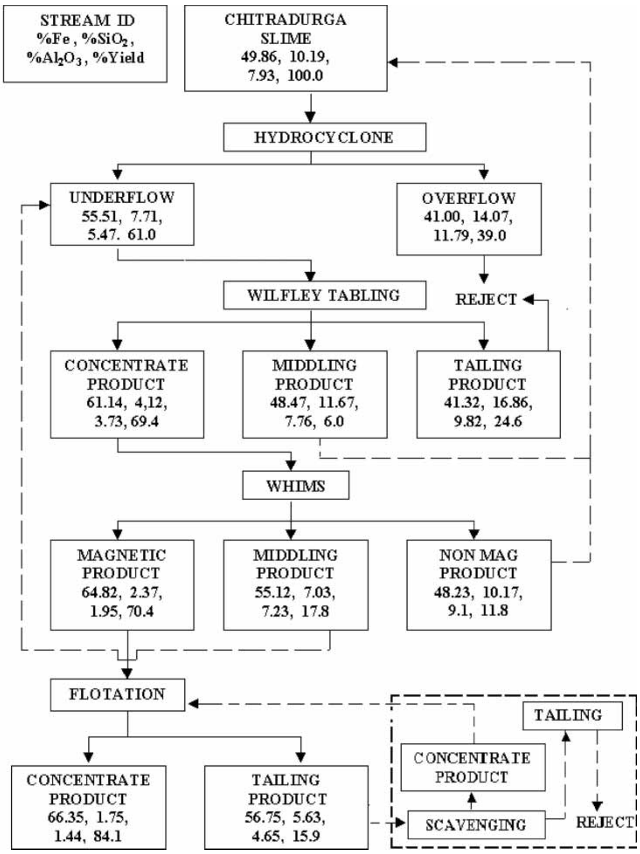

Figure 8. Complete flowsheet for beneficiation of Chitradurga iron ore slime.

from 55.5% in the Tabling feed. Fe recovery is 76.44% in this step (51.99% w. r. t. orig.). Further concentration is carried out in a wet magnetic separator.

Concentration using Wet High Intensity Magnetic Separator

The Tabling concentrate is treated in Wet High Intensity Magnetic Separator (WHIMS). The test results obtained under most favourable operating conditions are shown in Table 7. It may be seen that Fe content is enriched to 64.82% with overall yield of 30%. The alumina and silica content of this concentrate are 1.95% and 2.37%, respectively. In this unit operation 74.64% of the total Fe is recovered in the concentrate (38.74% w. r. t. orig.).

The concentrate grade is still not good enough to be acceptable as feed material for pelletisation where more than 65% Fe and a combined silica

Table 5. Classification test results with 10% solids, 15 mm vortex finder, 69 kPa inlet pressure, and 6.5 mm spigot

Product	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)
Underflow	55.51	7.71	5.47	61.00
Overflow	41.00	14.07	11.79	39.00
Feed	49.83	10.19	7.93	100

and alumina content of around 3% are desirable. Therefore, further concentration is attempted using froth flotation process.

Concentration by Froth Flotation

Flotation is carried out using the Galigher flotation cell with MIBC as frother, Sodium Oleate as collector and sodium silicate as depressant. As indicated in Table 8, substantial removal of silica and alumina is obtained in the froth flotation process. It may be seen that the Fe content is raised to 66.36% from the flotation feed of 64.82% with concomitant lowering of alumina and silica values to 1.44% and 1.75%, respectively. Total Fe recovery in this step is 86.0%. The overall yield is about 25% while the overall Fe recovery is 33.41%.

The SEM study with EDS also shows that final concentrate does not contain much of the free gangue minerals, as indicated in Fig. 9. Excellent alumina and silica rejection is obtained in this flowsheet. It may be calculated from the data that overall alumina and silica rejection in the final concentrate is 95.69% and 95.46%, respectively.

DISCUSSION

Iron ore sample obtained from Chitradurga, India is part of banded iron ore formation. Some banded structures exist in the ore samples. Most of the

Table 6. Wilfley table test results of hydrocyclone U/F with 10% solids, 0.25 inch inclination, 280 rpm speed, and 3 lpm wash water

Product	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)	Yield (%) (w. r. t. orig.)
Concentrate	61.14	4.12	3.73	69.4	42.4
Middling	48.47	11.67	7.76	6.0	3.7
Tailings	41.32	16.86	9.82	24.6	15.0
Feed	55.51	7.71	5.47	100	61.0

Table 7. WHIMS test results of Wilfley table concentrate with 10% solids, 1 amp. current, and 20 lpm wash water

Product	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)	Yield (%) (w. r. t. orig.)
Magnetic	64.82	2.37	1.95	70.4	29.8
Middling	55.12	7.03	7.23	17.8	7.5
Non-magnetic	48.23	10.17	9.1	11.8	5.0
Feed	61.14	4.12	3.73	100	42.4

iron ore samples are mainly composed of hematite and goethite along with some relict magnetite.

Hematite in the ore sample mainly occurs as specularite with inter-granular micro-pore spaces. Goethite is abundant and occurs as colloform product in cavities along the weaker bedding planes. Such inter-granular pore spaces and voids along the weaker bedding planes are very fragile making the hematite and goethite very friable during mining and processing. These friable particles break down and account for the iron content of the slime. However, the ore samples, having relict magnetite and martite, are very massive and do not participate in the formation of the slime. Most of the bulk ore samples contained numerous cavities. These cavities are mainly filled with clay in the form of kaolinite. Kaolinite, being friable, easily crumbles into ultrafine size during mining and processing operations leading to its greater concentration in the slime.

Hematite and goethite in the ore sample are closely associated with clay forming complex interlocking. Such interlocking characteristic persists in the slime leading to substantial percentage of interlocked clay-hematite/clay-goethite. However, in the finer size fractions of slime this percentage is very low paving the way for their easy removal by desliming classification. Some interlocking has been observed in the coarser size fraction indicating that a minimum percentage of gangue would be there in the beneficiation

Table 8. Flotation test of WHIMS concentrate at a pH of 5.5, 10% solids, 3 min. conditioning time, 2.5 kg/t collector (sodium oleate), 1.5 kg/t depressant (sodium silicate), 0.2 kg/t frother (MIBC)

Product	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)	Yield (%) (w. r. t. orig.)
Concentrate	66.36	1.75	1.44	84.0	25.1
Tailings	56.75	5.63	4.65	16.0	4.7
Feed (WHIMS concentrate)	64.82	2.37	1.95	100	29.8

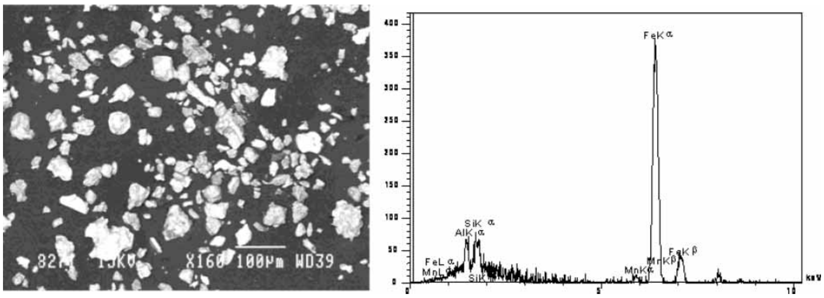

Figure 9. SEM photomicrograph with EDS of flotation concentrate.

concentrate. They may also occur as middling product during the beneficiation operations.

The manganese minerals such as pyrolusite, braunite and hausmanite occur in association with hematite and goethite. Due to their high density and close association with iron bearing minerals they are not separated during processing and remain in the final concentrate. However, their concentrations are very low.

One of the problems with slime is that they are usually very fine with substantial fraction in the −20 micron range. In the present case this figure is 55%. Processing of such fine particles is always difficult. This is reflected in the fact that although a pellet grade concentrate could be obtained the yield is a mere 25%. However, in continuous operation, recirculation of some of the intermediate streams as shown by dotted lines in Fig. 8 would significantly increase the yield. The middling stream of the tabling operation may be combined with the fresh feed stream as they have similar grade. The middling stream of WHIMS has similar grade to that of hydrocyclone underflow and they may be combined. Also, the flotation tailings may be treated in a scavenging operation, the concentrate of which may be combined with the rougher feed. Thus, it would be possible to obtain an overall yield in excess of 40% in continuous operation.

A simple analysis of the aforementioned flowsheet indicates that the low mass yield of the final concentrate is caused primarily due to the heavy loss of solids at the classifying cyclone. Nearly 39% of the total feed reports to the cyclone overflow stream, which is directly rejected, in spite of its Fe content of 41%, due to the known difficulties of treating ultrafine solid particles using conventional separation processes. However, as indicated previously in Table 4, a near complete liberation of all minerals occurs below a particle size of 20 micron. Taking advantage of the near complete liberation and considering the significant differences in specific gravity (nearly 6.0 for hematite versus 2.7 for gangue mineral), the authors believe that, the use of a simpler flowsheet may be possible. Such a flowsheet would consist of advanced technologies, including enhanced gravity concentrator or compound spiral, and flotation columns. These may help significantly improve the mass yield achievable from the beneficiation of Indian iron ore slimes while satisfying the specified grade requirement for pellet feed. This may be a topic of future research.

The present study evidently shows the feasibility of beneficiating iron ore slimes to produce pellet grade concentrate by rejecting the alumina and silica. It offers a technology that can utilize at least a part of the available slimes that is currently unused, generate a valuable product and thereby reduce the environment related problems if not solve them completely. As stated above, the application of advanced technologies will substantially enhance the benefits of the technology.

CONCLUSIONS AND RECOMMENDATION

The bulk ore is found to be of very low grade containing porous and friable oxide and hydroxide of iron along with kaolinite and quartz. The nature and texture of the ore is believed to be mainly responsible for the formation of slime during mining, processing, and handling of ores. The occurrence of kaolinite along the cavities and weaker mineral plane renders the ore highly fragile and causes high alumina content in the slime.

The present study established that excellent rejection of silica and alumina from iron ore slime is achievable using the conventional physical separation processes. It may be concluded that beneficiation of considerably low grade iron ore slime to produce pellet grade concentrate is a feasible proposition. In the present study, an iron ore slime with feed grade 49.86% Fe, 7.93% Al_2O_3, 10.19% Si_2O_3 is enriched to 66.36% Fe with consequent lowering of alumina and silica to 1.44% and 1.75%, respectively at 25% yield. The process flowsheet utilized included a classifying cyclone, shaking table, wet high intensity magnetic separator, and conventional froth flotation cell. In continuous operation it may be possible to achieve an overall yield in excess of 40% by retreating some of the process streams. Such a beneficiation scheme would not only meet the increasing demand of pellet grade concentrate, but also partially solve the burning issues of storage problem of enormous amount of iron ore slimes that are generated during mining and processing of iron ore.

The authors believe that adoption of some advanced technologies, such as enhanced gravity concentrators, compound spirals and flotation columns may help significantly improve the overall process yield to above 50%. A future study is being planned to prove this hypothesis.

ACKNOWLEDGMENT

Financial assistance in the form of a CSIR fellowship to one of the authors is gratefully acknowledged. The authors also acknowledge the advice and support of Prof. S.P. Mehrotra, Director, NML towards the completion of this work.

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