INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

OPEN ACCESS

Received: 03.09.2020

Accepted: 29.09.2020

Published: 22.10.2020

Editor: Dr. Natarajan Gajendran

Citation: Nanda SK, Pani S, Beura D (2020) Recovery of Iron values through conventional beneficiation techniques from Banded Hematite Jasper of Eastern India with special reference to mineralogical and chemical characterization. Indian Journal of Science and Technology 13(38): 3960-3969. https://doi.org/10.17485/IJST/v13i38.681

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Recovery of Iron values through conventional beneficiation techniques from Banded Hematite Jasper of Eastern India with special reference to mineralogical and chemical characterization

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Abstract

Background/Objectives: Due to soaring demand and rapid depletion of high-grade iron ores, lean grade iron ores of India like BHJ and BHQ needs to be utilized through suitable beneficiation techniques. **Methods:** Banded Hematite Jasper (BHJ) sample of Bonai-Keonjhar belt (BK belt), Odisha, India assayed 35.3 % Fe, 47.1% SiO_2 and 0.96% Al_2O_3 was investigated in respect of mineralogy, liberation characteristics and chemistry to finding out its optimum beneficiation potential. In the present investigation, efforts have been made to characterize the BHJ sample with reference to its beneficiation response. The sample was subjected to various beneficiation operations like Jigging followed by hydrocyclone, two-stage tabling and magnetic Separation. **Findings:** Mineralogical studies indicate that quartz and hematite are the major mineral phases, whereas goethite, martitized magnetite and clay (kaolinite) are present in very minor amounts. The liberation characteristic indicates that the average band thickness of Iron bearing mineral is of 1680 microns and 80% of the iron bearing minerals are liberated at -105 microns size. The two stage tabling of jig concentrate with desliming gives better outcome as compared with direct tabling of jig concentrate. An iron ore concentrate assayed 64.5% Fe, 5.6% SiO_2 and 0.80% Al_2O_3 with wt% recovery of 23.2% can be obtained from two stage tabling. Another concentrate from magnetic separation of table middling and hydrocyclone assayed 63.2% Fe, 7.2% SiO_2 and 0.7% Al_2O_3 with wt% recovery of 12.4% can be obtained. **Novelty/ Application:** Here a conventional beneficiation flow sheet is developed with a finding that, in order to beneficiate ore like banded hematite jasper (BHJ), an integral characterization approach is very much essential. Both of the concentrates obtained through the flow sheet assayed 64% Fe, 6.2% SiO_2 and 0.7% Al_2O_3 with a wt% recovery of 35.6% can be utilized as a feed stock for pellet making in iron ore industries.

Keywords: Banded Hematite Jasper (BHJ); mineral beneficiation; wet high intensity magnetic separator (WHIMS); jigging; Bonai-Keonjhar belt

1 Introduction

Iron and Steel are the most important products of the modern world and of strategic importance to any developing industrial nation like India. India is endowed with a vast resource of iron ore which is the basic raw material for the iron and steel industry. As per National Steel Policy of India (2017)[1] the steel production target will be 300 MTPA by 2025[2]. The targeted steel production will require 324 MTPA of processed ore and 505 MTPA of raw iron ore. The current iron ore production of India is 170 MTPA mostly of which are high grade in nature. Due to the rapid depletion of high-grade iron ores and exponential demand for steel, it has put pressure on iron resources of India in respect of grade and reserve. To overcome the demand, low-grade iron ore resources like Banded Hematite Quartzite (BHQ) and Banded Hematite Jasper (BHJ) need to be utilized for a sustainable future. Generally, low-grade Indian iron ores are rich in aluminous gangue minerals which is unsuitable for steel making[3]. The Banded Hematite Quartzite (BHQ) and Banded Hematite Jasper (BHJ) have an advantage over other low-grade iron ores due to very low alumina content. Banded iron formations (BHJ and BHQ) are abundantly available in Odisha, Karnataka and Chhattisgarh states of India and remain unutilized due to high silica content and lack of beneficiation techniques.

1.1 General geology of study area

The Bonai-Keonjhar belt (BK belt) which is popularly known as Horse-Shoe belt[4] of Keonjhar district of Odisha has two limbs. The eastern limb extends from Gua (22°13'N; 85°23'E) in Jharkhand in the north up to Chelliatoka (21°44'N; 85°09'E) in the south, and the west limb runs eastward up to Malangtoli (21°48'N; 85°19'E) wherefrom it turns northward to Noamundi (22°09'N; 85°29'E). The country rock is least metamorphosed sedimentary formation consisting of Banded Iron Formations (BIFs) of iron ore group[5]. Banded Hematite Jasper (BHJ), Banded Hematite Quartzite (BHQ), Banded Hematite Shale (BHS), Banded Hematite Jasper Shale (BHJS) and Ferruginous Shale (FS) are the major litho units noticed in the BK belt[6,7]. BHJ and BHQ are characterized by their alternate layers of iron oxide in the form of hematite and silica in the form of quartz/chert/jasper[8]. The strike direction of the BK belt is NNE-SSW and dipping westerly with local contortions and folding.

Mineral characterization plays an important role in the development of beneficiation flowsheet. The current study focuses on the detailed characterization and beneficiation studies of Eastern India BHJ samples from the BK belt. The study area comes under part of the Survey of India's topo sheet no. 73G/5 and 73F/8.

Many researchers from time to time investigated on different aspects Mineral characterization and beneficiation aspects of Banded iron formations (BIFs) and associated iron ores of India[9–13] . However, very few of the researchers[9,12–14] were made an integral approach for the development of beneficiation strategy with reference to mineral characterization. Previous researchers used the costly beneficiation methods like reduction roasting[12,15] enhance gravity separation[9] and froth flotation methods for beneficiation of BHQ and BHJ iron ore. The developed technology by the researchers is far from conventional beneficiation techniques and requires huge capital and operating resources. Here in this paper, an essential approach was made to develop a conventional beneficiation process flow sheet with reference to the mineralogical and chemical characteristics of the ore.

2 Materials & Methods

The scope of the study includes the collection of the representative BHJ sample from the eastern part of India; characterize it through chemical as well mineralogical techniques, and finally beneficiate it with an aim to recover maximum usable iron values by employing various beneficiation techniques. Representative Banded Hematite Jasper (BHJ) samples weighing around 300 kilograms were collected from different outcrops of the Bonai-Keonjhar belt in Eastern India.

2.1 Collection of samples and characterization study

2.1.1 Chemical

The sample was crushed and ground by using a laboratory scale jaw crusher and roll crusher. The ground sample of size 74 micron was analyzed chemically for different radicals viz. Fe(T), SiO_2, Al_2O_3 and LOI respectively. The radicals viz. Fe(T), SiO_2, Al_2O_3 were analyzed by using X-Ray Fluorescence (XRF) instrumental technique and Loss on Ignition (LOI) was determined separately by conventional pyrometallurgical weight difference technique.

2.1.2 Mineralogical

The mineralogical characterization study was carried out by employing an optical microscope (model: Leica DM-750P) supported by X-ray diffraction studies. The sample was ground to different sizes starting from 1680 micron to 63 microns for mineralogical and liberation study. Several thin sections, polished sections, and thin polished sections were prepared from representative samples for microscopic studies under both transmitted and reflected light. The modal distributions of minerals were carried out by using the grain counting method.

A representative portion of the sample was crushed to below 75 microns size to obtain a homogeneous sample for X-ray diffraction study. X-ray diffraction study was conducted by using the PanAnalytical X-pert PRO X-ray diffractometer. A nickel filter was used in the path of the X-ray beam to monochromatised the Cu-Kα radiation (1.5418 angstroms) by absorbing extra radiations of X-ray. The accelerating voltage was maintained at 40 kV and the tube current 30 mA. The X-ray scanning on the sample was carried out from 5° 2θ to 70° 2θ with a constant scanning speed approximately 1° 2θ / minute. The characteristic X-ray data for the mineral phases present in the sample were obtained in the form of peaks with relative intensities, angle of the peaks in 2θ with their respective 'd' values in Angstrom units. The X-ray data obtained on the sample was interpreted by using diagnostic patterns of standard minerals in JCPDS (1974) [16] diffraction file.

2.2 Beneficiation study

A beneficiation process route is developed for the optimum utilization of Banded Hematite Jasper. The beneficiation studies were conducted by adopting different techniques like jigging, classification/desliming and gravity separation followed by magnetic separation. For each stage of operation, several experiments were conducted for the optimization of parameters. After completion of each experiment, samples were dried, weighed, and analyzed chemically as well as mineralogically (as and when required).

2.2.1 Sample preparation, size analysis and screening

After getting the actual band thickness and liberation characteristics, the collected sample was crushed to -1680 micron size in a laboratory scale jaw and roll crusher. Representative batches of -1680 microns sized samples were drawn and the beneficiation experiments were performed. A representative batch of sample was subjected to dry sieving through different BSS (British standard sieves) standard sieves from 1680 microns to 63 microns size. The sieve fractions were weighed and analyzed for its chemical constituents. From the chemical analysis data, the distribution patterns of valuable iron along with silica gangue at different size fractions were determined.

After size analysis, a representative batch of the sample was screened through 210 microns screen. The top size i.e. -1680+210 micron was subjected to jigging and the -210 micron fraction was kept aside for further studies.

2.2.2 Jigging of top size screened fraction (-1680+210 micron)

The top size i.e. -1680+210 micron was subjected to jigging through a laboratory-scale Denver jig at 9/16 mm stroke length and a wash water rate of 4ltr/min. The jig concentrate and jig tails were collected after attaining the steady-state of the jig. It was observed that the top sized fraction (-1680+210 microns) was enriched around 7 units from the original iron content in the form of jig concentrate. The jig tailing contains less iron value, therefore it is rejected. The iron content in the jig concentrate is far from the useable grade. The jig concentrate was ground to 210 microns size to get adequate liberation, and subjected to further processing.

2.2.3 Tabling of Jig concentrate ground to -210 microns size and bottom size fraction (-210 microns) from screening

The ground jig concentrates along with the -210 micron screened fraction, subjected to tabling by two routes. The first route is the ground jig concentrate was mixed with the -210 microns subjected to tabling by a laboratory-scale diester table directly without desliming. The second route is the former mixture subjected to desliming followed by tabling in a laboratory scale diester table. The desliming process was carried out by a 2 inches mozley hydrocyclone to cut and oversize of 90% passing 63 microns. The best results were observed in the desliming followed by the tabling process. The table concentrate product was met the stipulated specification for useable iron ore. The table tailing contains less iron values and is rejected.

2.2.4 Magnetic separation table middling product and slime fraction

The middling fraction of the tabling process as well as slime products from the hydrocyclone contains a higher iron value. To recover the iron values, the products were ground to 105 microns size and subjected to two-stage magnetic separation through WHIMS (Wet High-Intensity Magnetic Separation) at two magnetic intensities (1 and 1.5 tesla). The magnetic fraction was mixed with table concentrate and meets the stipulated specification for useable iron ore. The middling product from the magnetic separation process is kept as a subgrade product. The non-mag product contains less iron value was discarded.

3 Results & Discussion

3.1 Chemical and physical characteristic of original sample

From the chemical analysis data it was observed that the sample assayed 35.3% Fe, 47.1% SiO_2, 0.96% Al_2O_3 with other elements like K_2O, Na_2O, and TiO_2 are present in very minor amounts (Table 1). Likewise, the other BIFS, BHJ ore is banded with alternating layers of hematite and jasper, and the band thickness of iron varies from 500 microns to 2500 microns in size. The average band thickness of the iron layer in the study sample is around 1680 micron. Therefore the sample was crushed to -1680 micron size to liberate iron-bearing layer from silica-rich layers.

Table 1.

Radicals	Fe(T)	SiO_2	Al_2O_3	Na_2O	K_2O	CaO	MgO	TiO_2	LOI
Assay (%)	35.3	47.1	0.96	0.09	0.08	0.05	0.08	0.07	1.1

3.2 Mineralogical Characteristics

Microscopic studies reveal that the sample consists predominantly of hematite and quartz with very minor to traces of clay, goethite/limonite, and magnetite/martitized magnetite. Hematite occurs as very thin to thick bands with alternating layers of jasper (Figure 1 A & B). The band thickness of hematite and jasper varies from place to place. Hematite grains carry finely disseminated inclusion of quartz (Figure 1C & D). The degree of inclusion also varies from grain to grain. Textural study reveals complex intergrowth/ intergrown patterns exhibit between hematite and quartz. At places, hematite shows intimately intergrowth/interlocked with silicate gangue (Figure 1D). The grain size of hematite varies from a minimum of 50 μm to a maximum of 1300 μm. At places, hematite is transformed to specularite and these are found in association with martitised magnetite. Some remnants of unaltered magnetite are noticed within the groundmass of hematite (Figure 1C). Quartz is very fine to medium-grained in size and occurs as micro-crystalline to crypto-crystalline aggregates (Figure 1E). The grain size of quartz varies from < 10 μm to a maximum of 380 μm. Some of the quartz occurs as minute inclusion within the bands of iron oxide (hematite) and vice-versa (Figure 1D & E). The majority of the places, quartz grains are intricately associated or interlocked with hematite grains and vice versa which creates difficulty in liberation.

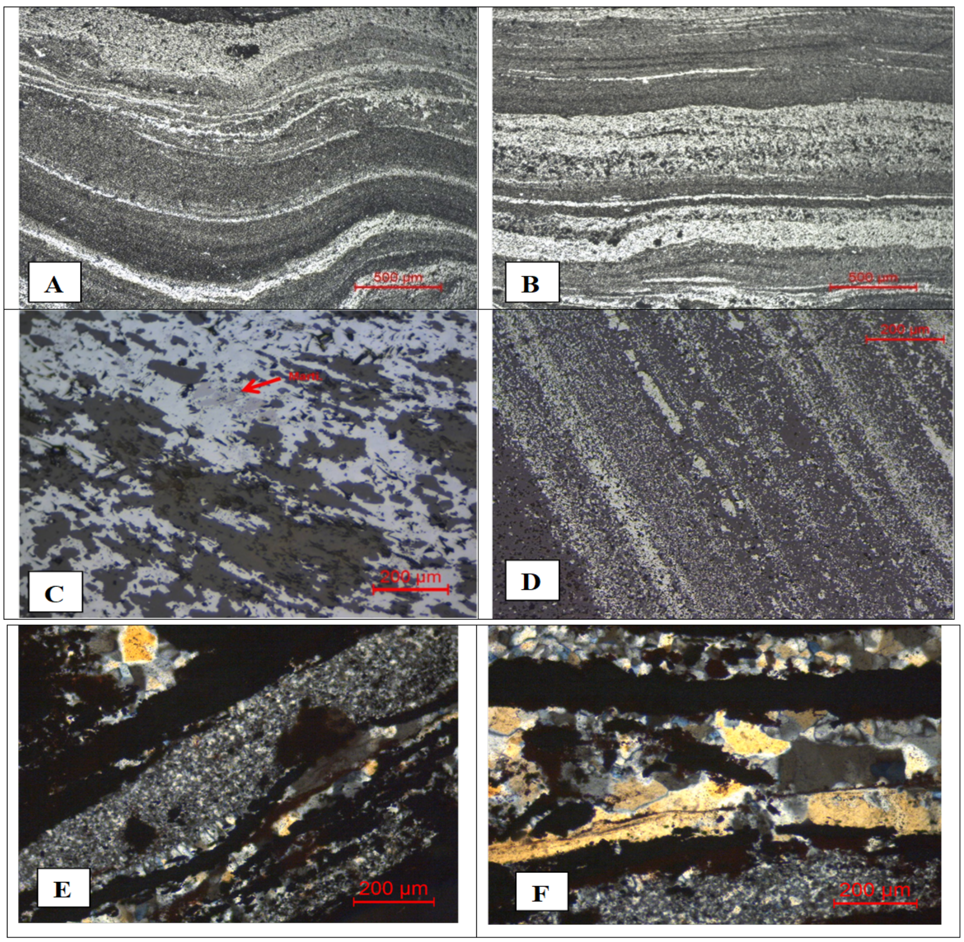

Fig 1. Photomicrographs of BHJ samples A, B, C, D under reflected light microscope and E, F under transmitted light microscope showing different textures

A. Prominent alternate layers of hematite and jasper/quartz showing micro folding

B. Finely laminated BHJ where iron-rich bands are inter-laminated with dark gray silica layers

C. Hematite (white grey) and jasper (dark grey) grains are intricately associated with each other, which exhibit complex interlocking patterns between hematite and jasper. Unaltered remnant patches of magnetite/martitized magnetite (pinkish brown) occur within the groundmass of hematite.

D. Sporadically distribution of hematite within the bands of jasper and vice-versa

E. Quartz grains carry finely disseminated inclusions of opaque (hematite).

F. The hematite band (opaque) transversed into the quartz band and showing a complex interlocking pattern between quartz and hematite

3.2.1 XRD Studies and Modal Analysis

From the XRD study, it reveals that the quartz and hematite are the major mineral phases in the sample (Figure 2). The modal distribution of minerals shows that the sample contains (Figure 2). Though the presence of clay (kaolinite) and goethite are identified by an optical microscope but can't be detected by the X-ray diffraction pattern. It is due to their presence in lower concentration levels and poor crystallinity of the phases.

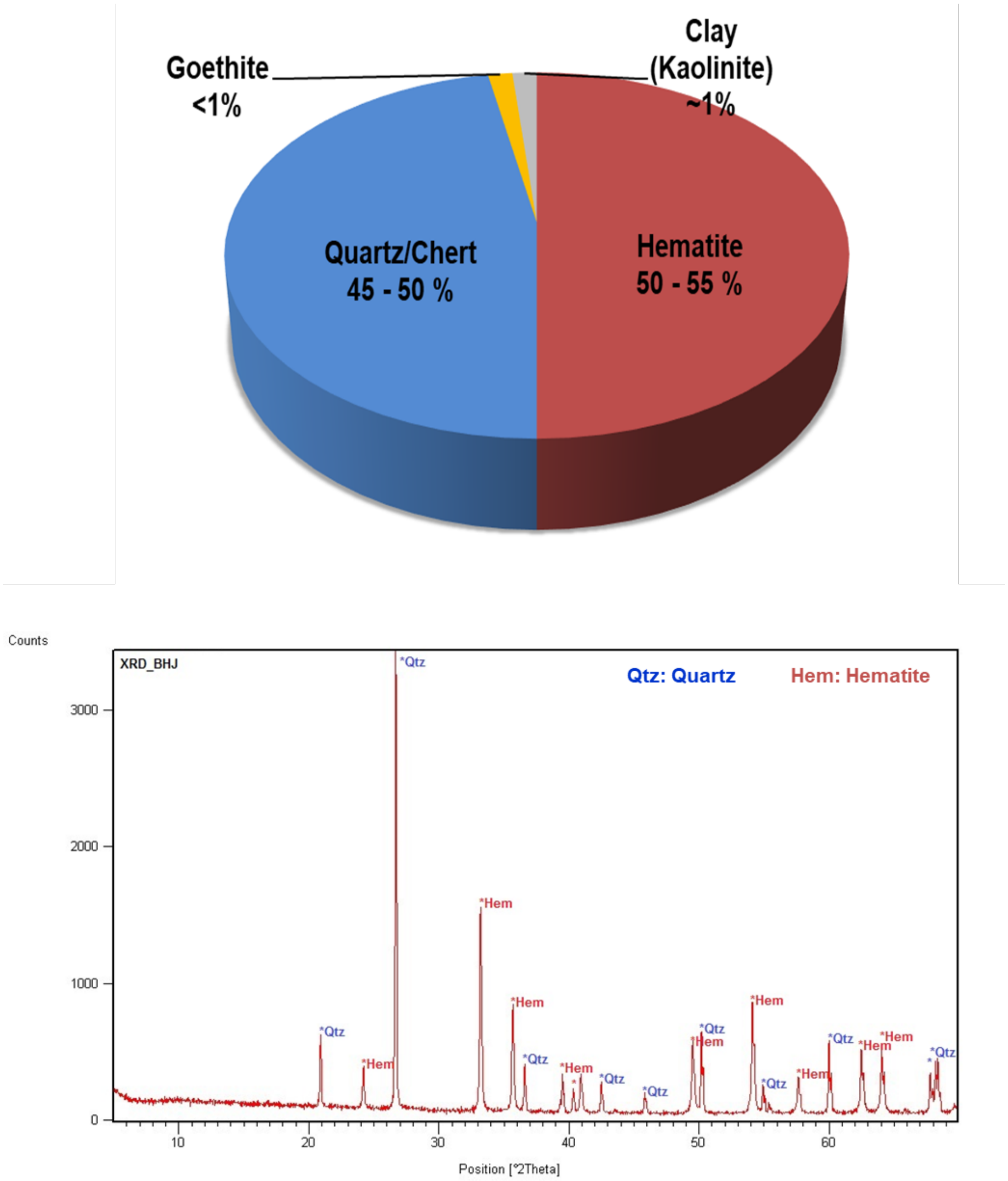

Fig 2. Modal distribution of minerals and X-Ray diffraction graph showing different mineral phases present in the feed sample.

3.2.2 Size analysis & liberation characteristic

The liberation study indicates that only 35% of the hematite grains are liberated at -1680 micron fraction (Figure 3) and the rest are interlocked with gangue minerals (quartz). However, the maximum liberation is attained at -75 to 63 microns size (Figure 3). The study also shows that about 80% of the Fe distributed in relatively coarser size i.e. -150 microns size (Figure 3).

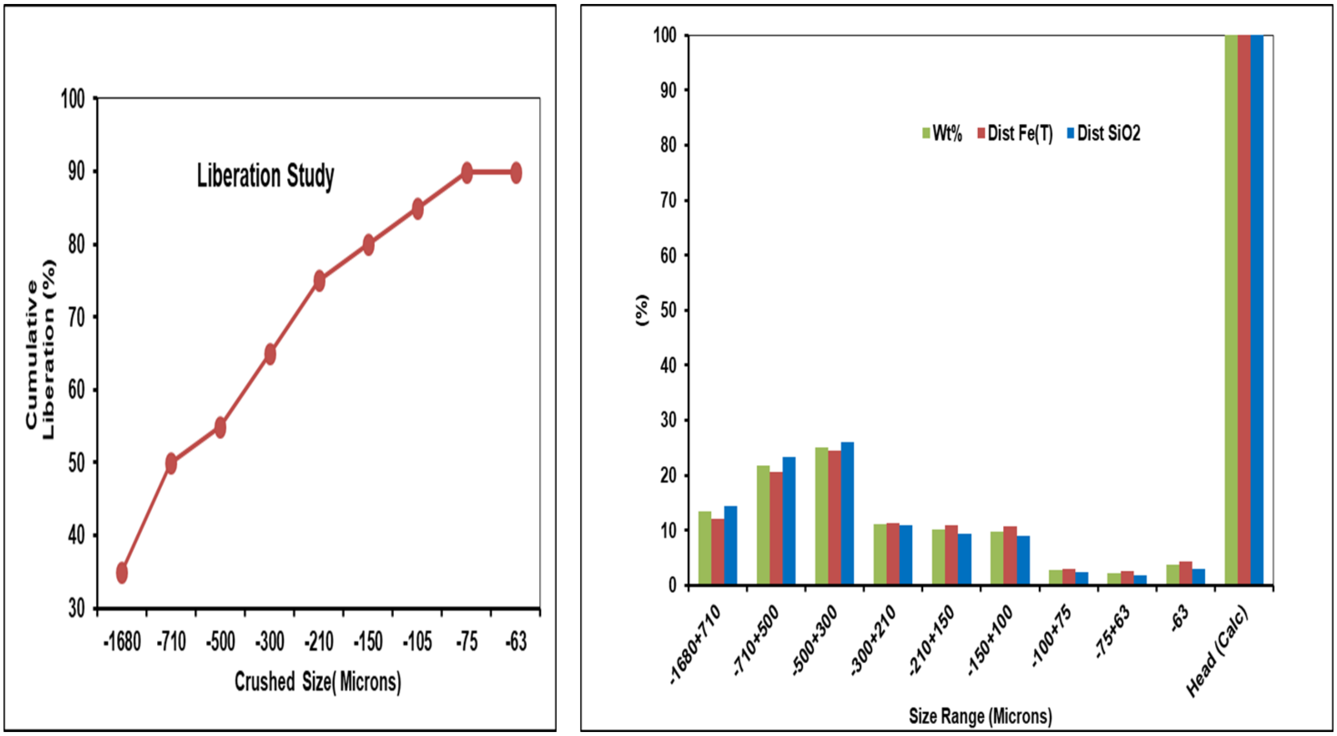

Fig 3. Liberation study and size analysis of feed sample all crushed to -1680 micron

3.3 Results of beneficiation study

The sample was first crushed to all -1680 micron and screen through 210 microns. The -1680 +210 microns size assayed 33.8% Fe, 48.9% SiO_2, 0.96% Al_2O_3 with a weight of 71.4% and the -210 microns sized fraction 38.6% Fe, 42.3% SiO_2, 0.94% Al_2O_3 with a wt % of 28.6. The Fe content is high in finer fraction than coarser fraction because of the difference in hardness of iron and silicate gangue minerals.

3.3.1 Results of jigging

The jig concentrates assaying 42.8% Fe, 36.4% SiO_2 and 0.8% Al_2O_3 with a wt % of 52.9. The iron value in jig concentrate is not up to the desired limit and the silica content is also high. The mineralogical findings of jig concentrate indicate that the quartz grains are reported in this fraction is due to inadequate liberation and complex interlocking pattern exhibit between hematite and quartz. The jig concentrate was ground to 210 microns size to liberate the hematite grains. The grounded sample was mixed with the rest 210 microns fraction and subjected to tabling. The jig tailing assayed 8.2 % Fe, 84.7% $SiO_{2,}$ and 1.5 % Al_2O_3 with a yield of 18.5%. The Jig tail fraction is treated as a reject due to high silica content with very minimum iron values.

3.3.2 Results of tabling

The tabling test was carried out in two ways viz. desliming followed by tabling and tabling without desliming. In the desliming route, the overflow and underflow of hydrocyclone assayed 40.2% Fe, 39.4% SiO_2, 1.1% Al_2O_3 & 41.8 % Fe, 38.2% SiO_2, 0.6% Al_2O_3 with wt % of 16.1 and 65.4 respectively. It was observed that there is a very minor change in iron concentration in slimes and coarse fractions. This is because the hydro cyclone feed consists of the jig concentrate ground to a particle size of 210 microns. Here the hydrocyclone operates in the principles of size classification and gravity separation. In the case of size classification, due to the difference in hardness of silicate gangue (quartz) and valuable mineral (hematite), the valuable minerals are more enriched in slime than that of coarse fraction. But when gravity separation comes into the picture the iron-bearing minerals are heavier than that of silica, therefore coarser iron reported to underflow and finer iron reported to overflow making equal distribution of iron values in underflow (coarser) and overflow (slimes).

The result of tabling is given in Figure 4. It was noticed that the table concentrates on desliming route assayed 64.5% Fe, 5.6% SiO_2, 0.6% Al_2O_3 with an overall wt % of 23.2. Whereas the table concentrate from other route assayed 62% Fe, 9.2% SiO_2, 0.5% $Al_2O_3$with overall wt %

of 23.4. It was observed that tabling with desliming is more effective than that of tabling without desliming (Figure 4). This is because of uneven particle size as well as mineral distribution in case of direct tabling operation. Whereas in the case of desliming followed by tabling route the particle size and minerals are more evenly distributed resulting in more efficient operation with higher assay and wt% recovery. Therefore, desliming followed by tabling route is selected for beneficiation. The desliming route also generated a middling product. The middling product assayed 54.6% Fe, 19.6% SiO_2, 0.8% Al_2O_3 with an overall wt % of 15.6. The tailing product from the desliming route assayed 13.8% Fe, 78.1% SiO_2, 0.9% Al_2O_3 with overall wt % of 26.6 is rejected due to high silica and very low iron value.

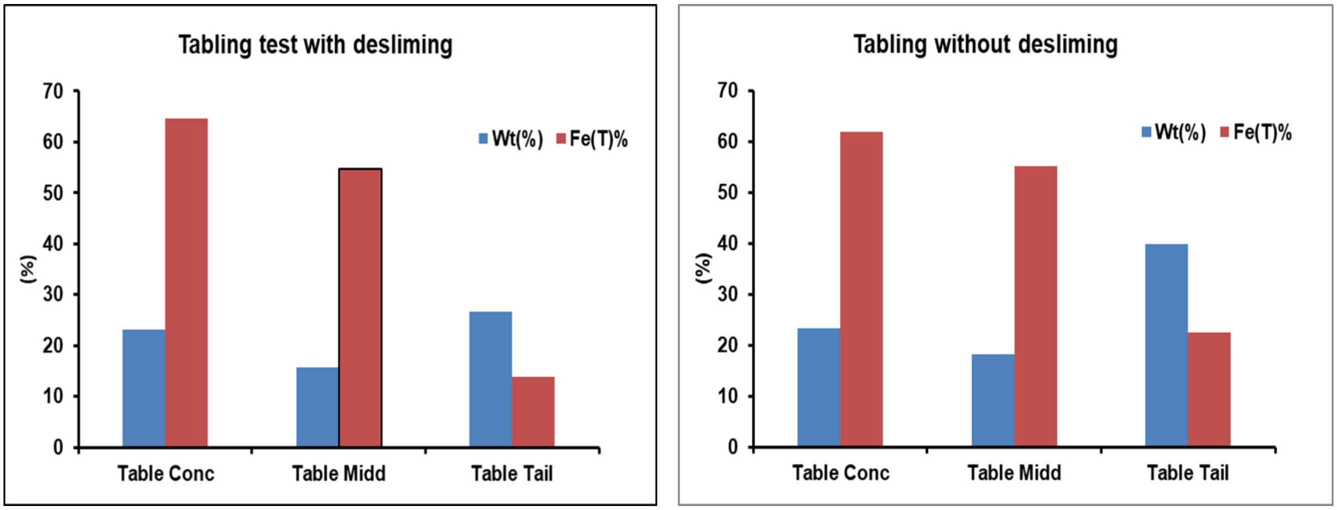

Fig 4. Results of tabling study

Mineralogical study of the middling product indicates that several hematite grains are intricately interlocked with quartz grains. The middling product was ground to 105 microns size to liberate the interlocked grains. The ground sample cannot be further processed for gravity separation due to size limitations. It was mixed with hydrocyclone overflow (slimes) and subjected to magnetic separation.

3.3.3 Results of Magnetic Separation (WHIMS)

The composite material hydrocyclone overflow (slimes) and table middling assayed 47.5% Fe, 29.7% SiO_2, 1.0% Al_2O_3 was subjected to Magnetic separation (two stages) at different intensities. Though the top size of the sample is 105 microns, however, more than 60% of the grains in the sample are below 63 microns. Hence, the ground sample was subjected to magnetic separation (two stages) at different intensities. The final magnetic product at 1 tesla intensity assayed 63.2% Fe, 7.2% SiO_2, and 0.7% Al_2O_3 with an yield of 12.4%. The magnetic product at 1.5 tesla intensity assayed 50.9% Fe, 24.9% SiO_2, and 0.8% Al_2O_3 with a wt % of 11.7 is treated as a sub-grade product. Mineralogical analysis of sub-grade products reveals that finely disseminated inclusions of hematite are found within the quartz grains. Therefore, it is very difficult to enhance the grade of sub-grade products further. However, mineralogical analysis of the final magnetic product reveals that the product contains predominantly of hematite with very minor amounts of quartz. Quartz grains are mainly reported due to inclusions of hematite. The nonmagnetic product assayed 16.1% Fe, 73.8% SiO_2, and 1.1% Al_2O_3 with wt % of 7.6 can be rejected due to lower iron and high silica content.

3.3.4 Final developed process flowsheet with mineral characterization

The final developed flow sheet with material balance along with Fe grade is given in Figure 5. The table concentrates and magnetic concentrates are mixed and make a composite concentrate. The rejects of jigging, tabling and magnetic separation mixed and made a composite reject. The results are given in Table 2

Table 2.

Product	**Wt(%)**	**Fe(T)%**	**SiO_2 (%)**	**Al_2O_3 (%)**
Composite Conc	35.6	64.0	6.2	0.7
Composite Subgrade	11.7	50.9	24.9	0.8
Composite Reject	52.7	12.2	79.8	1.1
Head (Calc)	100	35.2	47.2	0.9

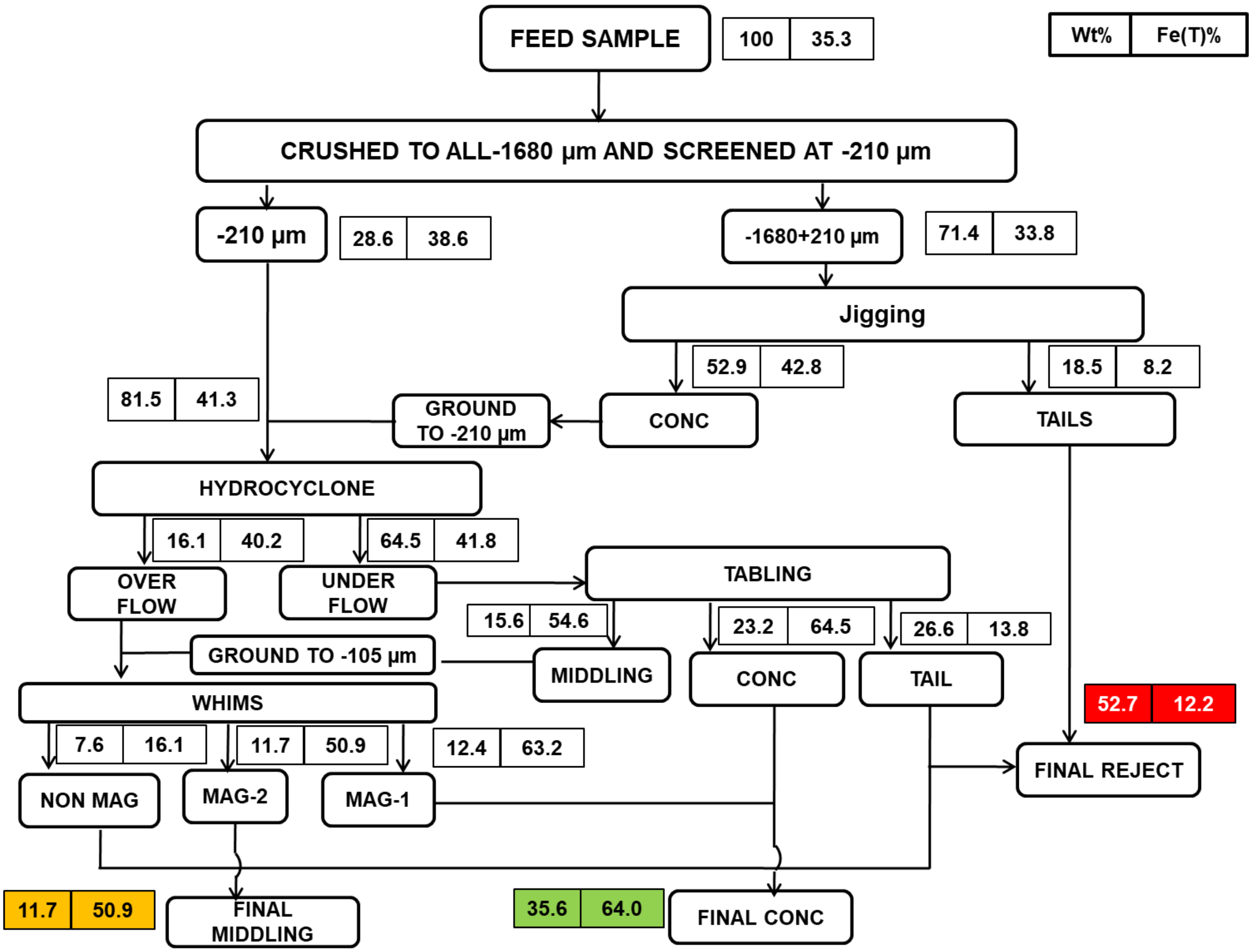

Fig 5. Final developed flowsheet

It was observed that the products generated during the process are enriched in iron values, which can be evident from mineral characterization (Figure 6). From the mineralogical point of view, it was observed that the final product consists predominantly of hematite with minor amounts of quartz. The quartz grains are reported in the final product due to the complex interlocking pattern of hematite and quartz. However, some of the free quartz grains are reported due to size limitations in gravity separations (below 10 microns size). The final product can be utilized in pellet making for low alumina iron ore pellet. The sub-grade product contains major amounts of hematite with subordinate amounts of quartz with a size range of 20 to 30 micron. In this product, the majority of the quartz grains are interlocked with hematite and carry minute inclusions (<10 to 20 microns) of hematite. Due to extremely fine sized, further up-gradation is not possible by the conventional beneficiation route. The product may utilize as a blending material for high-grade alumina rich iron ore to maintain alumina silica ratio. The final reject predominantly consists of quartz with minor amounts of hematite. This product is considered as reject and can be used in other applications like sand in building material and other construction works.

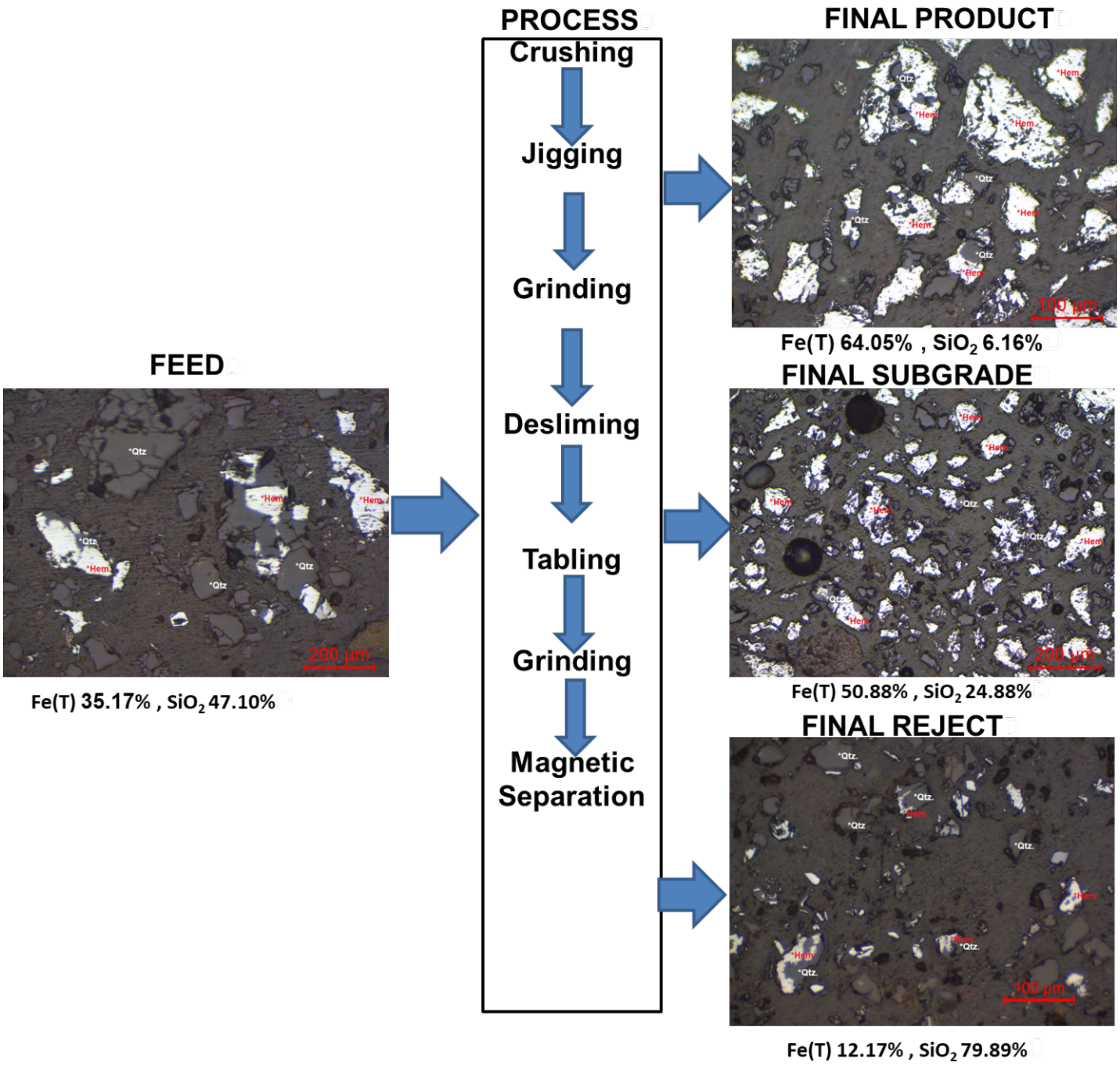

Fig 6. Schematic mineral characterization of feed and different beneficiated products

4 Conclusion

Beneficiation of Banded iron ore is a mammoth task, but here it was observed that utilizing mineralogical characterization the total number of beneficiation operations can be significantly reduced. Therefore, mineralogical characterization plays an important role in deciding the selection of cutting-edge mineral beneficiation flowsheet. It can be observed that a composite concentrate comprising of table heavies and magnetic product assayed 64.0% Fe, 6.2% SiO_2, and 0.7% Al_2O_3 with a yield of 35.6% can be recovered from Banded Hematite Jasper. The concentrated product may find its application in iron industries for pellet making. The final reject assayed 12.2% Fe, 79.8% SiO_2, and 1.1% Al_2O_3 wt % of 52.7 may be rejected due to the low iron content and high silica values. The secondary magnetic product assayed 50.9% Fe, 24.9% SiO_2, and 0.8% Al_2O_3 with wt % of 11.7% may be kept aside and treated as a sub-grade product.

Acknowledgment

The authors would like to extend their sincere thanks to Controller General, Indian Bureau of Mines (IBM), Nagpur for kind permission for Ph.D. research work, and all the officers, technical staffs of Mineral Processing Division, IBM for their cooperation. The authors are thankful to faculty members of Dept. of Geology Utkal University Bhubaneswar for their support and appreciation. The authors also thankfully acknowledge the warm hospitality and technical supports provided by the mining industries, M/s Tata Steel, M/s Essel Mining, M/s Rungta Mines and M/s Sarda Mines Private Limited.

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