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Applicability of the Teetered Bed Separator for Beneficiating Indian Iron Ore Fines: An Experimental Study

Biswakant Pradhan[1], Ipsita Dipamitra Behera[2*], Kshetramohan Sahoo[2] and Saytabrata Mohanta[2]

[1]*State Pollution Control Board, Sambalpur - 768002, Odisha, India*

[2]*Department of Chemical Engineering, Indira Gandhi Institute of Technology, Sarang - 759146, Odisha, India; ipsitadbehera@gmail.com*

Abstract

Higher alumina and lower iron content in Indian iron ore fines is a major problem for its effective utilization in the iron-making process. India is the second largest steel producer in the world with an annual production of 200 million tons in the year 2020, whereas iron ore beneficiation of this country is highly derisory. Only 52 concentrators are required to produce 220 MTPA of iron ore. Most of the concentrator's benefits are limited to sizing and washing. In recent years, the Teetered Bed Separator (TBS) has gained significant importance and appeared as a viable option for beneficiating a variety of fine minerals. So, a systematic study has been carried out to verify the suitability of the TBS to reduce the alumina content and improve the iron grade in Indian iron ore fines. As the performance of gravity separation processes strongly depends on the feed particle size, a size-by-size beneficiation study was carried out to delineate the role of particle size on the performance of the TBS. Based on this study, the TBS is established to be a possible alternative to the other conventional equipment used for the beneficiation of iron ore fines.

Keywords: *Beneficiation, Iron Ore Fines, Partition Coefficient, Separation Efficiency, Teetered Bed Separator*

1.0 Introduction

India has a substantial amount of iron ore capital of about 31,213 million tons, of which about 34% is of magnetite and 66% of hematite type[1]. The physical and mineralogical properties of an ore play a vital role in the extraction of metal in a profitable process. High hematite content and low energy requirement for crushing are two prominent features. Indian iron ore is generally softer with high clay content with fines (-10 mm size) during the preparation of the ore. The use of these fines is restricted due to its lower quality. These fines were rejected into the tailing dam. Indian iron ore which makes it a potential economic source of iron. As per the Steel Policy 2017-18, around 450 MTPA (million tons per annum) of high-grade iron ore resources are required to meet the steel demand of 300 MTPA in 2030[2]. However, as it is of lateritic origin with goethite abundance, a huge number of fines (-10 mm size) are produced in the size reduction step. The generated fines are characterized by aluminium gangue mineral (3-6 %) in addition to low iron percentage[3]. The low iron content of these fines prevents them from being processed in blast furnaces for iron extraction and chart their path to the tailing ponds used for the waste. Further, it has been documented that, a -100 mesh fraction in the sinter feed can be used up to 40%, by micro-balling of the sinter mix before sintering. The scarcity of high-grade iron ores and environmental concern in using new mines

**Author for correspondence*

compete us to look for new alternatives. Source of iron ore Indian Bureau of Mines has come up with a regulation insisting on the usage of iron ore with more than 45% Fe content. The fines have iron content above this threshold which can be processed to extract iron. It will solve two problems in ore shot *viz.,* availability of alternative sources for iron ore and alleviation of problems relevant to storage and handling of fine waste. The idea of utilization of low-grade iron ore fines has received nationwide attention and has created renewed research interest in its upgradation by adopting suitable beneficiation techniques.

A splendid effort has been made by various researchers for the operative utilization of the iron ore fines for iron making through sintering or palletization route after suitable upgradation. Iron ore with high alumina content is susceptible to viscous slag fraction and smelting step leading to excess coke requirement, high slag volume and low-capacity utilization. To ensure smooth operation in sintering and smelting, the alumina content in the fines must be kept low. In addition to this, the alumina content should be proportionately lower than the silica content. There have been efforts through the flocculation route for the recovery of hematite and goethite from minerals of gibbsite or kaolinite which also contain alumina[4,5]. However, this process gains limited success because of the development of highly selective flocculation-dispersion reagents. Also, Sahoo *et al*., pointed out that the grade and recovery of alumina-bearing ore is low for the flotation process because of the intimate adherence of clay particles to other minerals[5]. Further, as the liberation studies point towards the liberation form of a substantial proportion of alumina, some scientists advocate for the suitability of physical beneficiation followed by selective flocculation or flotation for the removal of alumina in the iron ore[6-8]. Raghukumar *et al*., showed that the multi-gravity separation is the most promising technique for treating the Indian iron ore fines, particularly for reducing alumina stating that the concentrate product quality depends on the presence of the goethite in the product[9].

According to the database, the total hematite reserves in India have been estimated to be 22,487 million tonnes. By grades, lumps constitute about 56% followed by lumps with fines (17%), fines (16%), and the remaining 11% constitutes black Iron ore, lump low and medium grade, beneficial grade, others, unclassified, not known and lumps, fines, and blue dust unclassified grade. Hematite and magnetite are the most prominent of the iron ores found in India. The major deposits of iron ore are in Jharkhand, Orissa, Chhattisgarh, Karnataka, and Goa. About 60% of hematite ore deposits are found in the Eastern sector and about 80% of magnetite ore deposits occur in Karnataka, Andhra Pradesh, and Rajasthan. India possesses hematite resources of 14,630 million tonnes of which 7,004 million tonnes are reserves and 7,626 million tonnes are remaining resources. Major hematite resources are located mainly in Jharkhand-4036 million tonnes (28%), Orissa-4761 million tonnes (33%), Chattisgarh-2731 million tonnes (19%), Karnataka-1676 million tonnes (11%) and Goa-713 million tonnes (5%).

A critical literature review identifies the key strategy for beneficiation of the Indian iron ore in general. It has been found that the quality of ores dictates the choice of benefit technique, and a technique must be useful to handle a range of products. The beneficiation of iron ore fines by Floatex Density Separator is somewhat like the TBS[9-11]. The successful application of TBS for beneficiation of iron ore fines indicates the possibility of TBS for the upgradation of high alumina content Indian iron ore fines to match the required quality[12,13].

The TBS has been developed from the classical Hydrosizer concept and works on the principles of hindered settling of fluidized particles. The water stream pumped from the bottom maintains a bed of fine particles, which are fed from the top in a fluidized state for separating the particles according to their densities[14]. The non-uniformity in size and density of the particles facilitates their separation based on size/mass difference. The finer and lighter particles form a layer at the top of the bed whereas, the coarser and heavier particles settle in a layer at the bottom. The particles of intermediate size/mass are distributed in the bed based on the particle dynamics[15]. Other particles are distributed throughout the bed depending on their density and size[16]. Based on the distribution of particles inside the vertical cylindrical body it may be divided into six characteristic zones shown in Figure 3 *viz*., overflow collection zone (A), upper intermediate zone (B), feed zone (C), lower intermediate zone (D), thickening zone (E) and underflow collection zone (F)[17]. The overflow collection zone contains mainly water and lower-density iron ore particles. Heavy particles settle at the under-flow collection zone and contribute to its high compactness. The compactness of the bed decreases from bottom to top due to the gradual density variation of the particles. With increasing height from the bottom, the heavy material content reduces, and the compactness of the bed decreases[18]. Below the overflow zone is the upper intermediate zone where fine particle segregation occurs. The introduction of feed volume through a narrow opening creates turbulence in the feed zone, which in turn offers good axial mixing. The fluidized bed retains its identity in the lower intermediate zone. This zone is characterized by a self-generating heavy medium which is crucial for specific gravity-based separation. In recent years, teetered bed separators have found applications in a variety of mineral processing and beneficiation processes, such as coal, kaolin clay and iron ore beneficiation, mineral sands and industrial minerals processing, precious metal recovery, recycling, and waste sorting, and environmental remediation[12]. These applications demonstrate the versatility and effectiveness of teetered bed separators in various mineral processing and beneficiation industries. Numerous studies have been dedicated to exploring the potential applications of TBS. To enhance separation efficiency, various equipment enhancements have been implemented, including optimizing the feeding structure, incorporating inclined plates, and introducing pulsating water flow and bubbles[19-21]. Their ability to efficiently separate particles based on density and size makes them valuable tools for improving the quality and value of mineral and ore products while also reducing environmental impact in some cases.

In this study, the suitability of the TBS for treating high alumina content Indian iron ore fines was tested. Also, a size-by-size beneficiation study was carried out to verify the effect of particle size on the performance of the TBS. The separation performance and E_p were calculated for the evaluation of this process.

2.0 Materials and Methods

2.1 Sample Collection and Preparation

Approximately one tonne of iron ore sample was collected from five different locations of Joda iron ore mines in the Keounjhar district of Odisha, India (location: between latitude 21059' N to 220 03' N and longitude 850 25' E to 850 27' E) and a representative sample of 10 kg was prepared from it by adopting the coning and quartering method. The representative sample was screened at 1 mm and the oversize was stage crushed to 100% passing the 1 mm screen and it was blended with the undersize. This blended sample was riffle split into representative sub-samples of 100 g for chemical head analysis, 1 kg for size-by-assay analysis and for beneficiation study. The measured size distribution of the representative sub-sample used for this study is presented in Figure 1 and the size-by-size chemical assays are presented in Figure 2. It has been observed from the feed size distribution and assays analysis that 32.6% mass is below 0.075 mm size and the feed sample had a feed grade of 51.6% total Fe with 9.96% SiO_2 and 7.73% Al_2O_3. Also, it has been observed that with a decrease in particle size, the Al_2O_3 and SiO_2 content in the feed increases and the total Fe content decreases. As the particles smaller than 0.045 mm in size are lean in iron content and rich in silica and alumina content, these are not considered for this beneficiation study. Further, a linear relationship between the percentage of Fe and the percentage of Al_2O_3 in the feed was observed.

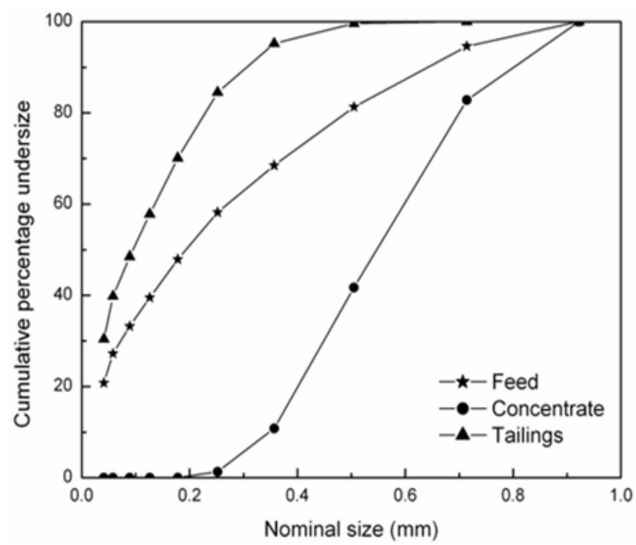

Figure 1. Size distribution of particles in the feed, concentrate and tailings streams of TBS.

2.2 Experimental Set-Up

The experimental campaign was undertaken in a Perspex vertical cylindrical TBS of 15 cm diameter and 120 cm high followed by a 15 cm high conical section as shown in Figure 3. The teeter water was supplied to the equipment through the teeter water feed pipe from a feed tank by a metering pump and its flow rate was controlled by the flow control valve. The teeter water flow rates were measured

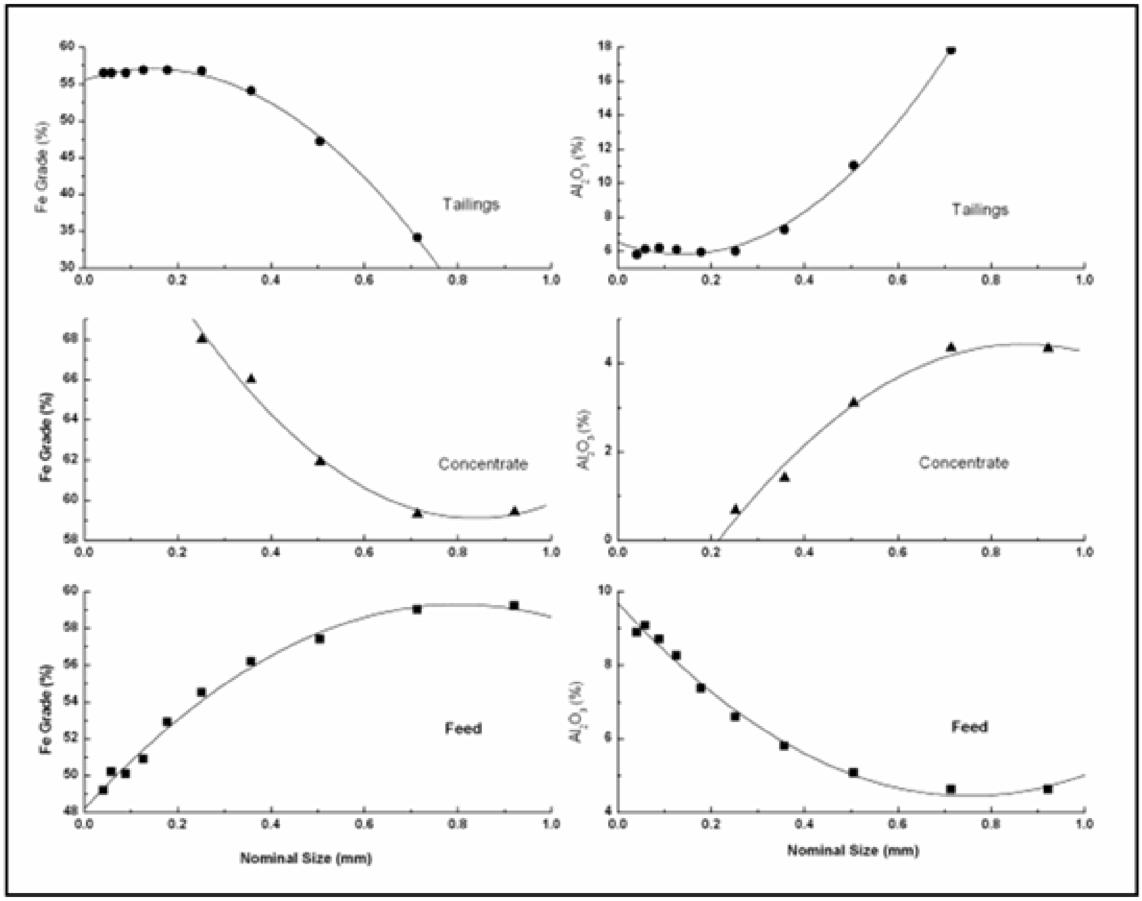

Figure 2. Size-by-size total Fe and Al_2O_3 content in feed, concentrate and tailings of TBS.

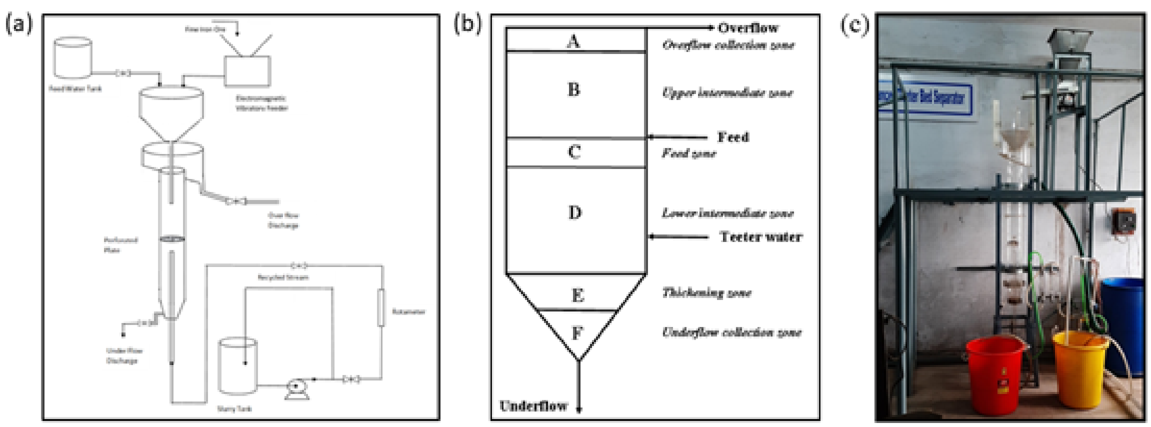

Figure 3. Schematic diagram of **(a)** Teetered bed separator **(b)** Characteristic zones in the TBS **(c)** Experimental set-up of laboratory scale TBS.

with rotameters. To prevent a direct jet onto the feed and minimize the turbulence, a dissipative structure was built onto the teeter water inlet pipe. The feed distributor is inserted inside down to 50 cm from the top. Further, provision is there to adjust the feed distributor location and teeter water feed location. An electromagnetically operated vibratory feeding system is there to maintain a constant feeding rate of fine iron ore.

2.3 Experimentation

The performance of the TBS was evaluated for treating the -1.0+0.045 mm size iron ore fines. So, the representative sub-sample of -1.0 mm size was screened at 0.045 mm to remove the particles finer than 0.045 mm. Further, to delineate the role of feed size on the performance of TBS, three different size feeds (-1.0+0.4, -0.4+0.15 and -0.15+0.075 mm) were considered and the representative sub-sample of -1.0 mm size was screened at 0.4 mm, 0.15 mm and 0.075 mm, respectively to obtain these feed size. Beneficiation studies were carried out with TBS for each size feed separately.

The teeter water was introduced into the TBS at the bottom of the lower intermediate zone and flowed in the upward direction. As the TBS filled with water, the teeter water flow rate was controlled by adjusting the flow control valve and waiting till steady state condition. On adjusting the electromagnetic vibratory feeder, a constant rate of dry feed material was fed into the TBS at the feed zone. A controlled rate of feed water was used to carry this dry feed material into to feed zone. Both the underflow (concentrate) and overflow (tailings) were collected, filtered, dried, and weighed and representative sub-samples were subjected to size-by-assay analysis. The experimental results were examined, and the performance of the TBS was evaluated in terms of separation efficiency and partition curve.

2.4 Calculation Methodology

Separation efficiency is performed here to assess the effectiveness of TBS in reducing the alumina content in the iron ore concentrate when different-sized iron ore feed is processed. For better interpretative convenience, the separation efficiency is calculated based on the recovery of non-alumina fraction (R_c^{na}) and rejection of alumina fraction (R_c^{a}) in the concentrate (Schulz, 1970). The yield (Y) of the process can be expressed in terms of concentration as

$$Y = \frac{(f-t)}{(c-t)} \times 100 \quad (1)$$

where, *f*, *t* and *c* are the percentage of alumina in feed, concentrate and tailings, respectively. The alumina rejection in tailings R_t^a is calculated as

$$R_t^a = 100 - Y\frac{c}{f} \quad (2)$$

$$R_c^a = 100 - R_t^a \quad (3)$$

The recovery of non-alumina fraction can be expressed as

$$R_c^{na} = \frac{Y(100-c)}{(100-f)} \quad (4)$$

Finally, the separation efficiency is

$$\text{SE}=R_c^{na} - R_c^a \quad (5)$$

As the higher non-alumina fraction and less alumina fraction are desired in the concentrate, the higher the value of *SE*, the better the separation process.

3.0 Results and Discussion

3.1 Performance Study for Feed Of -1.0+0.045 mm Size

The performance of TBS is tested for beneficiating the iron ore feed containing a wide size range of particles (-1.0+0.045 mm). The size distribution of particles in the feed, concentrate and tailings are shown in Figure 1 and the size-by-size assay results are shown in Figure 2. The size-by-assay analysis results of the feed show that iron is well distributed in all size classes and the silica and alumina lean towards concentrate in the finer size fraction. The Fe grade in the concentrate has improved to 60.7% with 3.83% Al_2O_3 content from the feed of 55.7% Fe grade with 6.43% Al_2O_3 content and the yield is 31.6%. It is worth noting that although significant Fe upgradation has not been observed in the concentrate a significant Al_2O_3 rejection has been achieved which is desired for the iron-making process from Indian iron ore fines. Further, the size distribution in the concentrate and tailings demonstrated that the coarser particles are passed to the most desirable concentrate. The separation efficiency as calculated by Equation (5) for -1.0+0.045 mm size fraction is 13.68.

As the forces causing the separation of particles inside the TBS are diverse and fluctuating in nature, it is difficult to represent the performance of TBS through a realistic model derived from the first principle of particle mechanics and fluid dynamics. Also, the behaviour of any particle during a hindered settling condition is strongly influenced by its size, shape, and its specific gravity. So, in

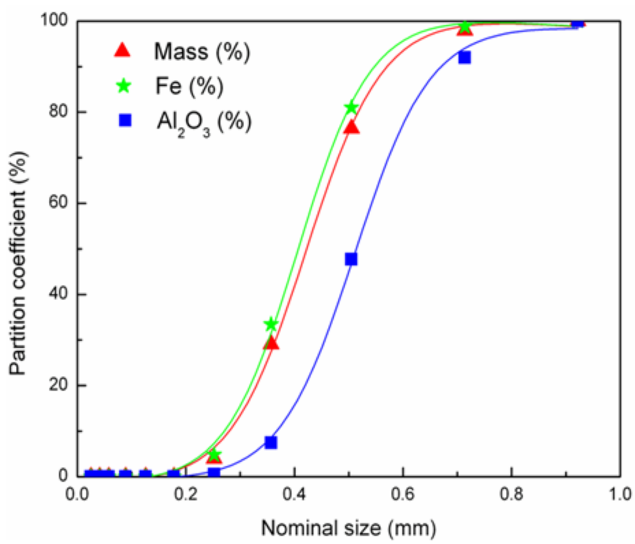

Figure 4. Partition curve for Mass, Fe and Al_2O_3 for -1.0+0.45 mm feed size.

this study, the performance of TBS has been represented by the partition curve as shown in Figure 4 by plotting the weight percent of feed in a specified size reporting to underflow. Further, for better visualization of the size-wise reporting of Fe and Al_2O_3 to the underflow, their partition coefficient is calculated and shown in Figure 4. It may be seen (Figure 4) that the cut size (d_{50}) for partitioning for mass is 0.42 mm and a sharp separation has been observed with an E_p value of 0.07. The proximity of the partition curves for mass and *Fe* points towards the good distribution of iron in all size classes, whereas the shifting of the partition curve for Al_2O_3 towards bigger particle size confirms the concentration of alumina in the finer size fraction.

3.2 Performance Study for Feed of -1.0+0.4, -0.4+0.15 and -0.15+0.075 Mm Size

Apart from other factors, the relative settling velocity of particles depends mainly on their specific gravity, size, and shape. If any of these two factors are uniform for the feed particles, their settling velocities depend on the third factor. In this investigation, as the particle size in the feed is small, their shapes are approximately uniform and spherical. Further, to make the relative settling velocities of the particle's specific gravity dependent to the maximum extent possible and minimize the size effect, three different feeds of narrow size distribution i.e., -1.0+0.4, -0.4+0.15 and -0.15+0.075 mm are considered. The TBS test conditions and the beneficiation results are summarized in Table 1. It has been observed that the Fe grade in the concentrates has increased from the feed concentration of 59.4% to 66.0%, 57.5% to 65.9% and 56.9% to 63.0% for -1.0+0.4 mm, -0.4+0.15mm and -0.15+0.075 mm feed size, respectively. Also, the Al_2O_3 content in the concentrates has decreased from the feed concentration of 4.66% to 1.4%, 5.52% to 1.43% and 6.01% to 2.78% for -1.0+0.4 mm, -0.4+0.15 mm and -0.15+0.075 mm feed size, respectively. The result is quite encouraging and points towards the satisfactory performance of TBS for Al_2O_3 rejection from Indian iron ore fines.

In this study, a significant size effect on the partitioning of mass, Fe and Al_2O_3 has been observed. To visualize this size effect, the mass partitioning is considered and the partition coefficients for mass are calculated for each feed size and shown in Figure 5. It is evident from Figure 5 that for the wider feed size distribution (i.e., -1.0+0.045 mm), the finer size particles are not separated and directly

Table 1. Test conditions and assays of the products obtained from TBS tests

Feed size (mm)	Test conditions			Weight (%)			Fe Grade (%)			Al_2O_3 Grade (%)		
	Teeter water (lph)	Solid feed rate (kg/h)	Feed water (lph)	Feed	Under flow	Over flow	Feed	Under flow	Over flow	Feed	Under flow	Over flow
-1.0+0.045	1.3	0.032	0.1	100	31.6	68.4	55.7	60.7	53.4	6.43	3.83	7.64
-1.0+0.4	0.8	0.051	0.1	100	32.0	68.0	59.4	66.0	56.3	4.66	1.40	6.19
-0.4+0.15	0.4	0.028	0.1	100	19.7	80.3	57.5	65.9	55.5	5.52	1.43	6.53
-0.15+0.075	0.35	0.011	0.1	100	23.4	76.6	56.9	63.0	55.0	6.01	2.78	6.99

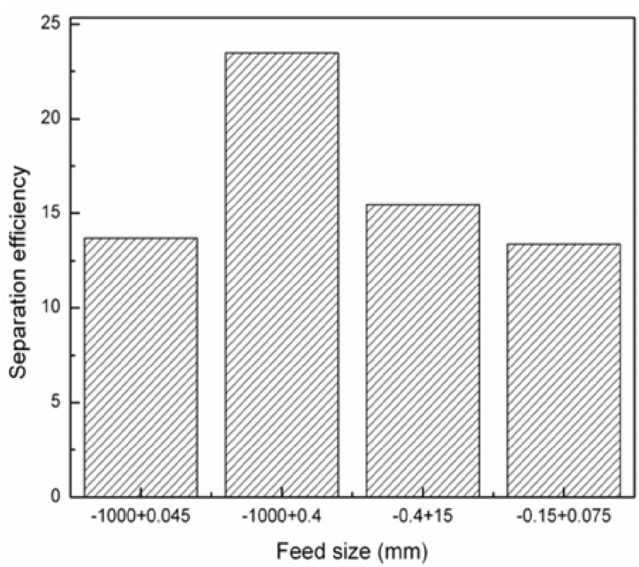

Figure 5. Partition coefficient for mass for -1.0+0.45 mm, -1.0+0.425 mm, -0.425+0.15 mm, -0.15+0.075 mm feed size.

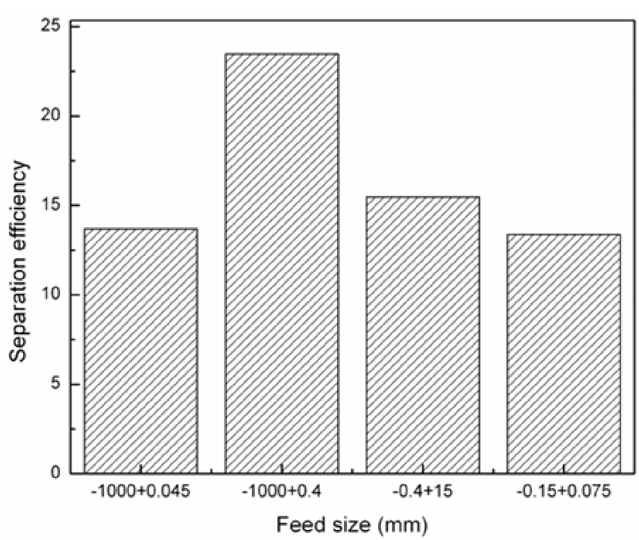

Figure 6. Separation efficiencies for different iron ore feed sizes.

reported to the overflow stream because of the higher drag force acting on them due to higher teeter water flow rate. This also confirms the lower separation efficiency for this feed size as calculated from Equation 5 and shown in Figure 6. But for the narrow feed size distribution, the particles are well separated according to their density. Further, a good separation efficiency has been observed even for the finer size feed (i.e., -0.15+0.075 mm). The calculated separation efficiencies for all the feed sizes are plotted in Figure 6 for a better comparison.

4.0 Conclusion

The suitability of TBS for treating high alumina content Indian iron ore fines is established. Its satisfactory separation performance established a high degree of confidence to be a substitute for the other conventional equipment used for iron ore fines beneficiation. Also, this separator has demonstrated an excellent level of efficiency for removing the alumina from iron ore fines. Further, the separation performance was improved by reducing the size as well as splitting the feed into different closely sized fractions and then treating these fractions separately in the TBS. The size-wise chemical analysis shows a linear relationship between the percentage of Fe and the percentage of Al_2O_3 in the feed and reveals that the Al_2O_3 and SiO_2 are concentrated on the finer size fraction. This beneficiation process would contribute to higher production and export of iron ore, benefiting the mining and steel industry in India and potentially leading to increased revenue and job creation. Effective beneficiation can reduce the amount of waste generated in the mining and beneficiation process. This can lead to cost savings for mining companies through reduced disposal costs and improved overall process efficiency. A more efficient beneficiation process can make Indian iron ore products more competitive in the global market, potentially increasing exports, and foreign exchange earnings for the country. The use of TBS can potentially reduce the environmental impact of mining and ore beneficiation. Recovering more iron ore from fines, it reduces the need for extensive mining operations and associated environmental disruption. Effective beneficiation can lead to lower tailings production, reducing the environmental impact associated with tailings disposal, including the risk of dam failures and contamination of water bodies. If the new beneficiation process is more energy-efficient, it can lead to a reduction in energy consumption, which is both cost-effective and reduces the environmental footprint, particularly if the energy source is fossil fuels. The increased recovery of iron ore from fines means that fewer natural resources need to be exploited, contributing to resource conservation and sustainability. However, additional research, field testing, and regulatory considerations may be necessary to realise these benefits fully.

5.0 Acknowledgment

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Symbols

c = % of alumina in concentration

d_{50} = Cut density

E_p = Separation performance

f = % of alumina in feed

R_c^a = Rejection of alumina fraction

R_c^{na} = Rejection of non-alumina fraction

SE = Separation efficiency

t = % of alumina in tailing

Y = Yield