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Optimisation of Process Variables for Recovery of Iron Values from Sub Grade Iron Ore by using Enhanced Gravity Separation

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***Abstract* – Studies Were Carried Out Attempts Were Made To Beneficiate Sub Grade Iron Ore (Sgio) From Bacheli Complex Of Bailadila Mines Of Nmdc Limited In Chhattisgarh, India By Using A Multi Gravity Separator. The 'As Received' Sample Assayed 40.8% Fe, 40.9% Sio_2. Mineralogical Studies Indicated That The Main Ore Mineral Is Hematite And Main Gangue Mineral Is Quartz. Mineral Liberation Study Indicated That The Liberation Of The Ore Mineral Takes Place Around 100 To 150 Microns. Therefore The 'As Received' Sample Was Stage Crushed And Ground To Less Than 150 Microns.**

Experiments were carried out by varying the process variables viz. drum rotational speed, drum inclination and wash water flow rate. Other variables like shake amplitude and shake speed, feed percent solids and feed rate were kept constant. It was found that the single unit operation of beneficiation using multi gravity separator was not able to produce a concentrate suitable for pellet feed (< 62% Fe) economically. Optimisation of parameters were done to maximise the recovery with 55% Fe. It was possible to produce an optimum concentrate with a yield of 55% by weight with a grade of 55% Fe and 12-16% SiO_2 and a recovery of around 75% Fe values.

Key Words: Sub Grade Iron Ore, Enhanced Gravity Concentration, Multi Gravity Separator, Mineral Liberation Studies And Optimisation.

1.0 . INTRODUCTION

The ability of traditional gravity separators to treat fine particles has been limited by the lack of particle inertia relative to the surface drag forces. However, particle inertia can be enhanced by the application of a centrifugal field in the enhanced gravity separation. The enhanced gravity separators are based on application of centrifugal force to enhance the particle settling behaviour. The new genre of enhanced gravity separators overcome the problems associated with the surface-based separation processes as well as conventional gravity processes. As a general rule, the separation efficiency decreases when the particle size becomes finer. Therefore an enhanced gravity method utilizes centrifugal force to accentuate the density separation. This is widely refer to as 'G' force, which significantly increase the terminal velocity of particles and decreases the dependence of terminal velocity on the particle size. Even though these enhanced gravity separators are in use since 1980's, they were not widely used in commercial scale. In order to beneficiate minerals economically, enhanced gravity concentrators are being used widely.

Falcon concentrator, Knelson concentrator, Kelsey jig and Multi gravity separator are mostly used enhanced gravity separators. Multi-Gravity Separator (MGS) is enhanced gravity separation equipment for the separation ultra-fine minerals. The MGS is a continuous thin film separation device used mainly for beneficiating ores with fine particle distribution using an enhanced Gravitational field. It separates the particles based on the combined effect of centrifugal acceleration and forces acting on a conventional shaking table. The MGS is suitable for the treatment of fines and ultra fines with a maximum particle size of approximately 500 microns (0.5mm) and lower limit of approximately 1 micron.

As the iron ore grades are depleting, low grade and sub grade iron ores are to be exploited in future. The liberation size of these low grade and sub grade iron ores is around 100 microns. Hence, particles with smaller size are to be recovered with maximum possible efficiency. As the size of the particle decreases the conventional gravity methods may fail to recover iron values. Multi gravity separator is proved to be one of the best enhanced gravity method.

Extensive work has been carried out by numerous researchers for beneficiation of ores and tailings by adopting different beneficiation techniques exploiting the difference of physical properties [1, 2]. Descriptions of Enhanced gravity separation, developments and devices are available in literature [3]. Bhaskar et al. used multi gravity separator for rejection of graphite in lead concentrate [4]. The minimum particle size that can be effectively processed depends on the settling force applied. Several researchers studied beneficiation of chromite ore and its tailings using multi gravity separator [5, 6, 7]. Majumder et al. discussed modeling of enhanced gravity separators [8] elsewhere. A team of researchers beneficiated chromite tailings by using MGS [9, 10, 11]. Plant trails with the multi gravity separator for the reduction of Graphite was done by Patil and team [12]. Traore and his team discussed how MGS evolved as fine particle processing gravity device [13]. Optimisation of various parameters by using response surface methodology was studied by Raissi [14]. Subrata Roy used multi gravity separator for improving the recovery of fine iron ore particles [15]. MGS was used to reject graphite from lead concentrate by Yerriswamy et al. [16]. There are no evidences of usage of MGS for beneficiation/ separation of iron values from sub grade iron ore in the literature. It was also observed that much literature is not available on use of multi gravity separator for beneficiation or recovery of iron particles.

The objective of this study aim to applicability and optimisation of enhanced gravity separation for the recovery of ultra-fine iron particles from the sub grade iron ore available at Bailadila region, India. Further it was aimed to understand the

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effect of process variables such as drum rotational speed, drum inclination and wash water flow rate on performance of MGS for recovering iron values. A lab scale MGS was used for conducting the tests.

2.0 THE METHOD AND MATERIAL.

2.1 The Machine

The lab scale MGS consists basically a slightly tapered open-ended drum measuring 600 mm with a diameter of 500 mm which rotates in clockwise direction and is shaken sinusoidal in an axial direction. The drum is made up of steel and coated with a polyurethane/steel lining inside. The lining is tapered, thereby providing an angle of about 1° to the inside of the drum. A scraper assembly is fitted inside the drum which rotates in the same direction drum but at a slightly higher speed. Feed slurry is introduced continuously midway onto the internal surface of the drum via a perforate ring. Wash water is added via a similar ring positioned near the open end of the drum. The drum rotates in the speed range of 100 to 300 rpm. A set of scrapers, mounted within the drum on a separate concentric shaft rotating in the same direction as the drum but at a higher speed, pushes the settled material to the outer, narrower end of the drum. A sinusoidal shake is imposed to the drum in the axial direction through a separate drive and eccentric arrangement.

The feed is introduced into the machine via accelerating rings which help to distribute the material uniformly on the drum in side surface. Wash water is provided via another similar ring. The parameters affecting the efficiency of separation on MGS are the drum rotational speed (100 to 300 RPM), wash water (0 to 10 liter per minute), inclination (0° to 9°), shake amplitude (10/15/20 mm), shake frequency (4.0/4.8/5.7 cycles per second) and pulp density of the feed slurry (10% to 50% by weight)

2.1.1 Principles of Operation

Feed is introduced into the drum surface in slurry form (25-50% by weight) via an accelerator ring which allows uniform distribution of solids and also reduces the velocity. The heavy particles (larger or more dense) settle quickly to the drum surface under enhanced gravity field and are slowly scrapped "up" the drum surface to the outer end and get discharged as concentrate. Due to the shake of the drum and the continuous washing of the settled material, the fines tend to remain in suspension and get discharged in the reverse end.

2.1.2 Experimental Procedure

A 10 litre stainless steel cylindrical vessel was used to feed slurry. The vessel was equipped with a turbine impeller agitator to mix the sample with water. 3000 cc of water was poured in the vessel and 1000 grams of the dry sample was added for each MGS test. The water and the sample were agitated at a low agitation rate by the impeller to prepare homogeneous slurry in the vessel. Feeding was carried out by a peristaltic pump at a flow rate of 2.5 l/min. 20 litre containers were used to collect concentrate and tailings separately under the tailing discharge pipe and concentrate discharge pipe. The test products, concentrate and tailings were separately collected, dried, weighed and prepared for chemical analysis as per standard methods.

2.2 The Material

The SGIO sample was collected from Deposit 5, Bacheli complex, Bailadila, Chhattisgarh, India. The 'as received' sample is an admixture of lumps, fines and friable ore. The size of the 'as received' sample varied from 0-150. The +30 mm, -30+1 mm and -1mm size fractions contributes to around 35%, 31% and 34% respectively. The lumps (+10 mm) show alternate bands of hematite and quartzite. The detailed size analysis of 'as received' sample and ground sample were shown in Figure 1.

The 'as received' sample was subjected to characterization studies in order to investigate its amenability for up-gradation and develop beneficiation strategies after through mixing and homogenization. The characterisation studies involves chemistry of 'as received' sample, size fractional chemical analysis, mineralogy and mineral liberation studies. It was found that, the main ore minerals were Hematite and Goethite, where as the gangue minerals were Quartz and Ferruginous clay. As a whole the ore minerals are about 46% where as the gangue minerals are 54% by their area of distribution. Among the ore minerals, hematite is chief ore type contributing about 40% where as goethite is about 6% as calculated by their area of distribution. The 'as received' sample is a low to medium grade ore type consisting about 40% quartz, 9% jasper and around 5% ferruginous clay as gangue minerals. Among the lumps, physically, hematite contributes approximately 40% whereas quartz contributes approximately 50% and jasper covers around 10% of the total area. Mineral liberation studies indicate that the liberation of ore mineral takes place around 100 to 150 microns.

2.2.1 Chemistry of the 'as received' sample

A representative sub sample was subjected for chemical analysis after stage crushing and grinding 200 mesh (to 75 microns) followed by sampling at each stage. The 'as received' sample was found to be 40.8 % Fe and 40.90% SiO_2. The Chemistry of the head sample was presented in Table 1. Chemical analysis of samples was done by using wet classical methods and ICP. It was evident that the sample has low iron content with remarkably high silica. More over the alumina content of the sample is very low which is desirable for the Iron making.

Table 1 Chemical analysis of 'as received' SGIO Sample from Bacheli

Constituent		Fe	FeO	SiO_2	Al_2O_3	LOI	P	S	TiO2	CaO	MgO	MnO
Assay %		40.80	2.70	40.90	0.24	0.22	0.05	<0.01	0.091	0.119	0.110	0.045

2.2.2 Screen – Assay – Analysis of 'stage crushed and ground' product

The 'as received' sample was stage crushed and ground to -0.15 mm (liberation size). The stage crushed and ground sample was subjected for size analysis (wet) up to 37 microns. The products obtained were dried, weighed and prepared for chemical analysis individually. The size fractional chemical analysis of stage crushed and ground sample is presented in Table 2. Size analysis of 'as received' sample and stage crushed and ground sample (-0.15 mm) are presented in Figure 1. It can be noticed that 80% of ground product (P_{80}) is around 100 micron size.

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Table 2 Characterisation of stage crushed and ground sample to 0.150 mm

Product Size	Wt%	%Fe	$\%SiO_2$
+152 microns	Nil	---	---
-152 +104 microns	12.75	36.50	48.20
-104 +75 microns	11.22	36.00	48.00
-75 +66 microns	7.77	37.70	45.20
-66 +44 microns	19.10	40.50	42.20
-44 +37 microns	6.21	41.50	38.48
-37 microns	42.95	43.00	36.00
Head (Calculated)	100.00	40.40	40.96
Head (Actual)		40.80	40.90

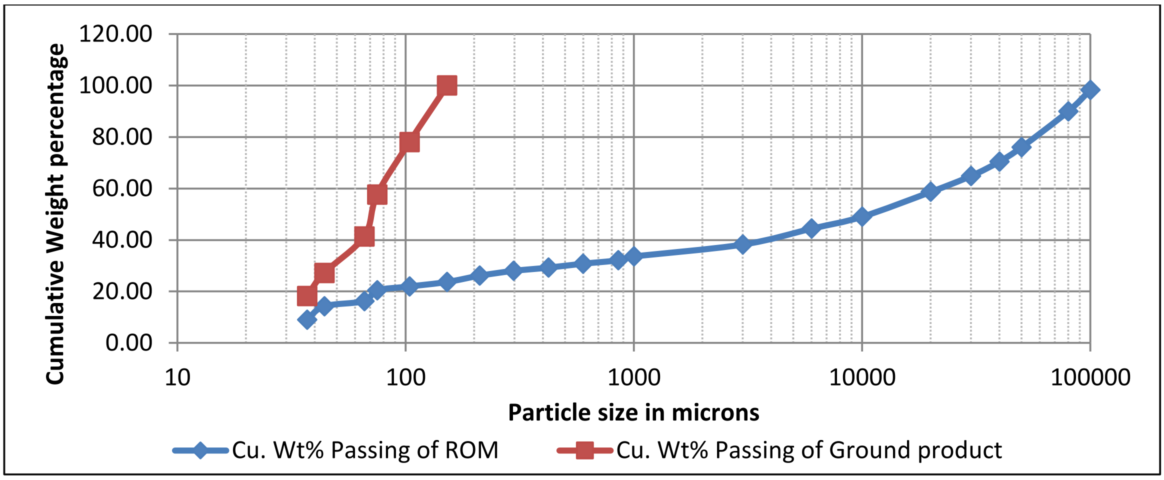

Figure 1 Size analysis of 'as received' sample and stage crushed and ground sample

3.0 TESTING AND TEST RESULTS

The sample ground to -150 microns (0.15mm) was subjected for testing at different parameters by using Multi Gravity Separator. A total of 48 tests were carried out to find out the separation behaviour of SGIO using MGS. Experimental condition like slope (angle of inclination) of the drum, wash water flow rate (Litre Per Minute – LPM) and drum rotational speed (Revolutions Per Minute - RPM) were varied, where as other parameters like percent solids (33% by weight), shake speed (4.8 cycles per second- mid range), amplitude (15 mm mid range) were kept constant for all experiments. The experiments were carried out at a drum inclination of 3°, 4° and 5°, wash water flow rate of 2, 4, 6 and 8 LPM drum rotational speed of 175,200, 225 and 250 RPM. The test results aree presented in Table 5, Table 6 and Table 7.

Table 3 Concentrate grade, yield and percent recovery of iron values at 3° drum inclination

RPM	Wash Water 2 LPM			Wash Water 4 LPM			Wash Water 6 LPM			Wash Water 8 LPM		
	Yield	Grade	Recovery	Yield	Grade	Recovery	Yield	Grade	Recovery	Yield	Grade	Recovery
175	38.5	57.8	54.5	32.5	62.0	49.4	26.5	62.6	40.7	20.0	64.0	31.4
200	52.0	52.0	66.3	41.1	53.0	53.4	38.3	54.0	50.7	36.0	55.8	49.2
225	70.7	48.2	83.5	60.0	50.0	73.5	59.9	50.5	74.1	55.0	55.0	74.1
250	83.1	46.4	94.5	77.1	48.0	90.7	69.1	49.7	84.2	65.0	51.0	81.3

Table 4 Concentrate grade, yield and percent recovery of iron values at 4º drum inclination

RPM	Wash Water 2 LPM			Wash Water 4 LPM			Wash Water 6 LPM			Wash Water 8 LPM		
	Yield	Grade	Recovery	Yield	Grade	Recovery	Yield	Grade	Recovery	Yield	Grade	Recovery
175	31.0	58.0	44.1	28.9	59.6	49.4	18.9	60.6	28.1	17.8	62.2	27.1
200	54.2	55.4	73.6	40.0	56.4	53.4	36.8	56.8	51.2	34.0	58.0	48.3
225	66.0	50.6	81.9	58.0	51.0	73.5	54.2	55.0	73.1	52.0	52.2	66.5
250	80.5	45.0	88.8	75.7	47.2	90.7	72.3	48.2	85.4	62.4	47.9	73.3

Table 5 Concentrate grade, yield and percent recovery of iron values at 5º drum inclination

RPM	Wash Water 2 LPM			Wash Water 4 LPM			Wash Water 6 LPM			Wash Water 8 LPM		
	Yield	Grade	Recovery	Yield	Grade	Recovery	Yield	Grade	Recovery	Yield	Grade	Recovery
175	26.8	57.0	37.4	26.5	58.0	37.7	18.0	58.8	25.9	14.5	61.0	21.7
200	59.7	53.0	77.6	35.9	54.0	47.5	36.0	56.0	49.4	33.0	56.7	45.9
225	74.2	48.2	87.7	55.1	49.0	66.2	53.2	49.6	64.7	50.0	51.5	63.1
250	76.0	45.2	84.2	74.2	47.2	85.8	71.7	48.8	85.8	59.8	50.0	73.3

4.0 DISCUSSION

It could be observed that maximum grade of 64.00% Fe with 20.00% yield was achieved (3ºangle of inclination, 175 RPM rotational speed and 8 LPM wash water flow rate) at higher levels of wash water flow rate, intermediate levels of drum rotational speed and drum angle of inclination. This can be attributed as at higher wash water flow rate helped to prevent entrapment of low density particles (gangue minerals). Similarly the maximum yield of concentrate of 83.1% by weight was achieved with 46.4% Fe (drum angle of inclination 3º, drum rotational speed 250 RPM and wash water flow rate 2 LPM) at lower levels of drum angle of inclination, higher level of drum speed and low level of wash water flow rate. This indicates that, as the drum rotation increases, the gravitational force acted upon the particle increases which assist in particle size recovery as well as density of the fraction reporting to concentrate fraction increases. Effect of process variables on the performance of the MGS is discussed below.

4.1 Effect of Drum Rotational Speed

The drum revolution generate centrifugal force on particles which not only allow the heavier iron ore particles to reach the compact solids bed, but also allow some portion of lighter minerals (quartz) to penetrate the heavies bed. The effect of drum rotation on recovery and grade at different RPM was studied while keeping other variables constant. Figure 2 to 4 depicts the effect of drum rotational speed on concentrate grade, yield and recovery of iron values. It was found that the Fe recovery in concentrate fraction increases with increase in drum rotation whereas the grade decreases. This can be explained as increased drum revolutions generate higher centrifugal forces on particles which not only allow the heavier coarse locked iron particles reach the compact solids bed, but also allows some portion of lighter silica minerals thus decreasing the overall grade and increasing the recovery.

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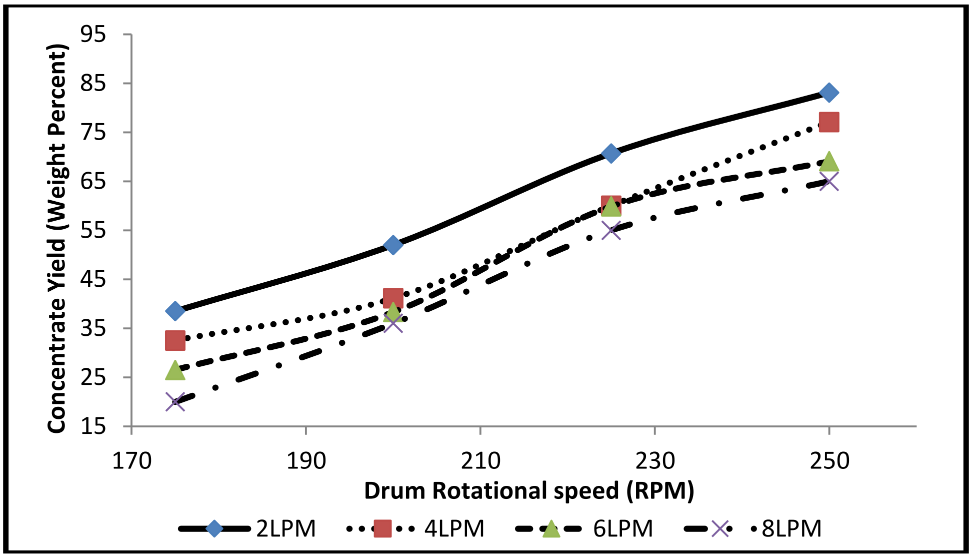

Figure 2 Effect of drum rotational speed on concentrate yield

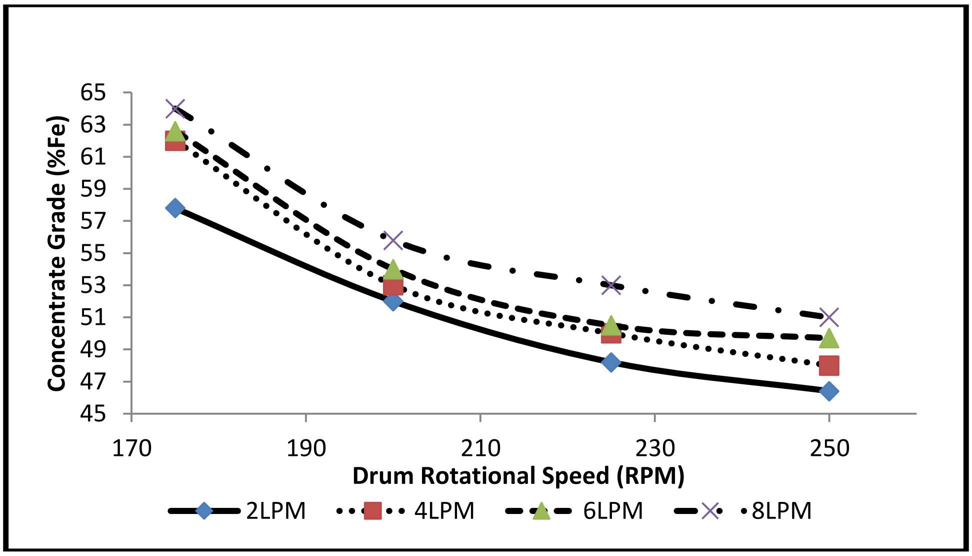

Figure 3 Effect of drum rotational speed on concentrate grade

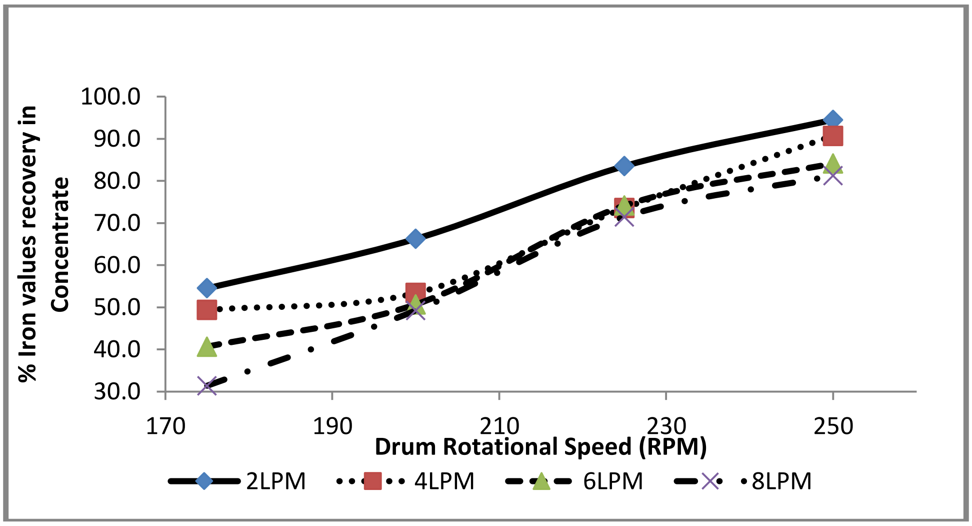

Figure 4 Effect of drum rotational speed on percent recovery of iron values in concentrate

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4.2 Effect of Wash Water

An increase in wash water from 2 to 8 litre/min has increased the concentrate grade (%Fe) in all combinations of other variables. For example, an increase in wash water from 2 to 8 litre per minute, keeping drum inclination and drum rotation constant at 4^o and 225 rev/min respectively there is an increase in iron grade from 50.0% to 52.8%. The similar observation is made in all other combinations of variables. Figure 5 to 7 depicts the effect of wash water on grade, yield and recovery of iron values. It can be observed that an increase in wash water decreases the recovery of iron values irrespective of drum speed and angle of slope. It may be due to the fact that increase in volume of water increases the forward flow of water which carries the fine iron particles to the tailing stream causing the reduction in recovery.

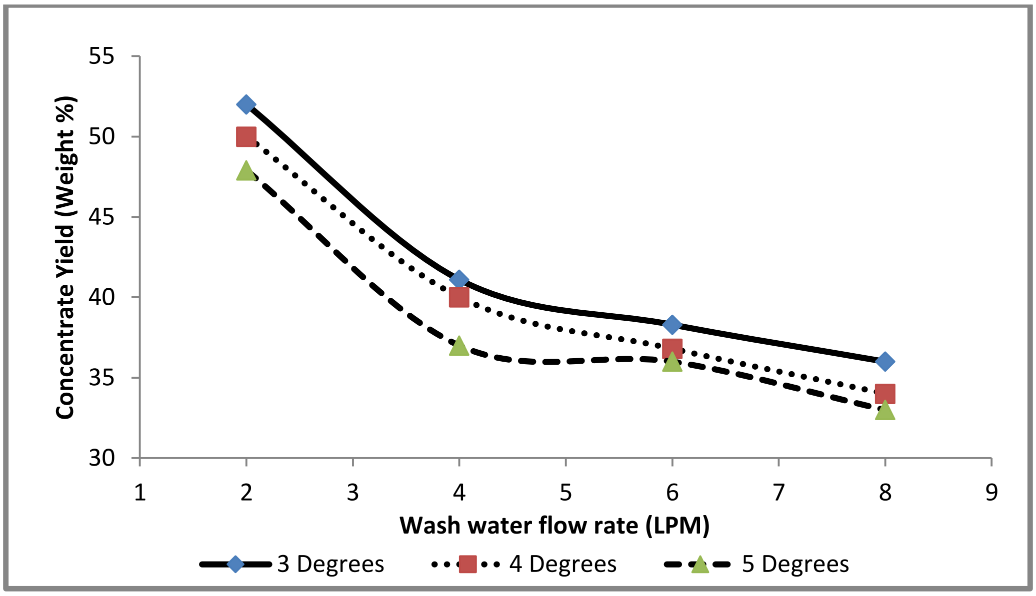

Figure 5 Effect of wash water flow rate on concentrate yield

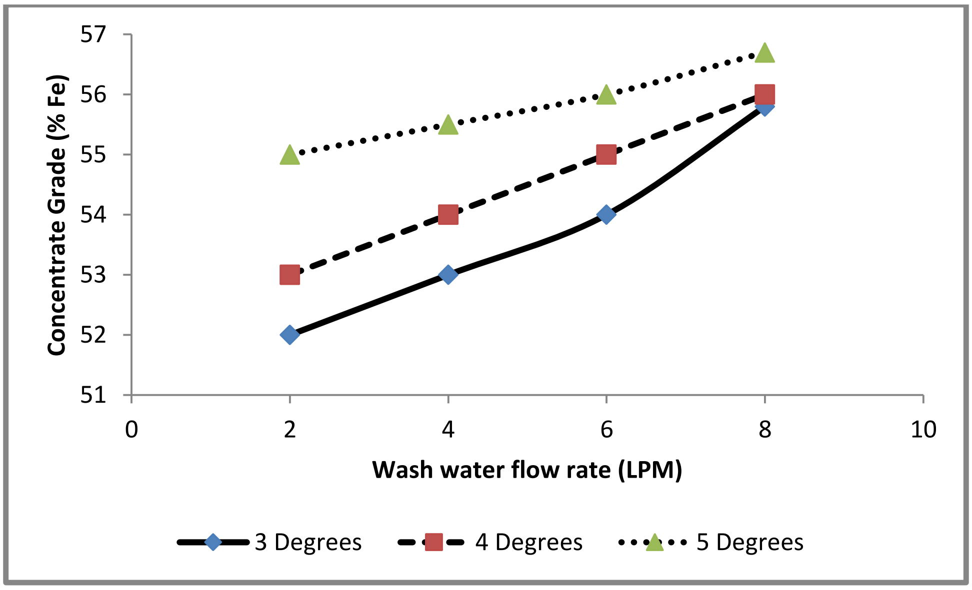

Figure 6 Effect of wash water flow rate on concentrate grade

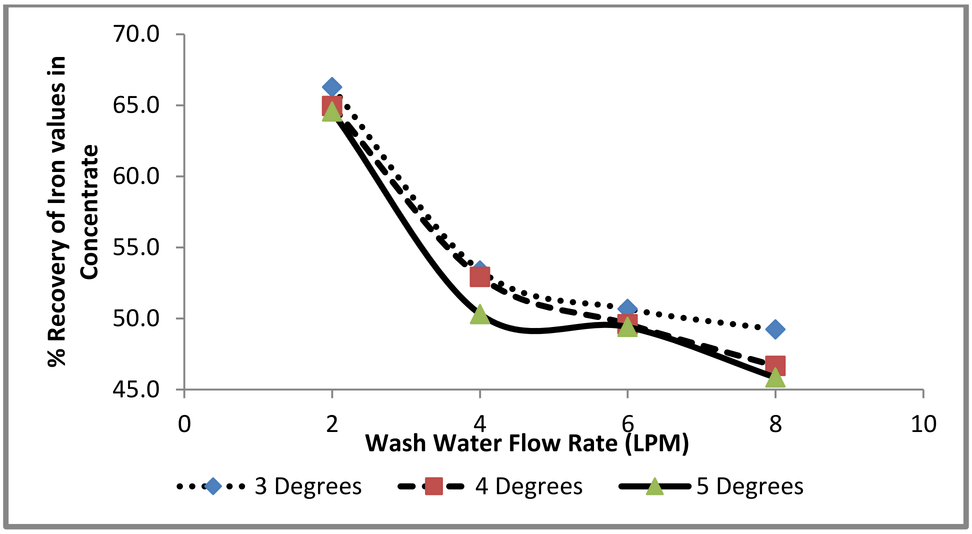

Figure 7 Effect of wash water flow rate on recovery of iron values in concentrate

4.3 Effect of Drum Inclination

MGS test result showing effect of drum inclination on concentrate grade, yield and percent recovery of iron values were presented in Figure 8, 9 and 10. An increase in drum inclination from lower level to higher level, results in increase concentrate grade. An increase of drum inclination from 3º to 5º keeping wash water and drum rotation constant at 2 litre/min and 225 rev/min respectively, resulted in 48.2% to 51.0% Fe. Similar trend was observed in all other combinations of variables. It can be shown from the Figure 8 to 10 that the recovery is decreased by increasing the drum angle at all levels of drum speed and wash water, which may be due to more mobility of particles in the bed at higher slope.

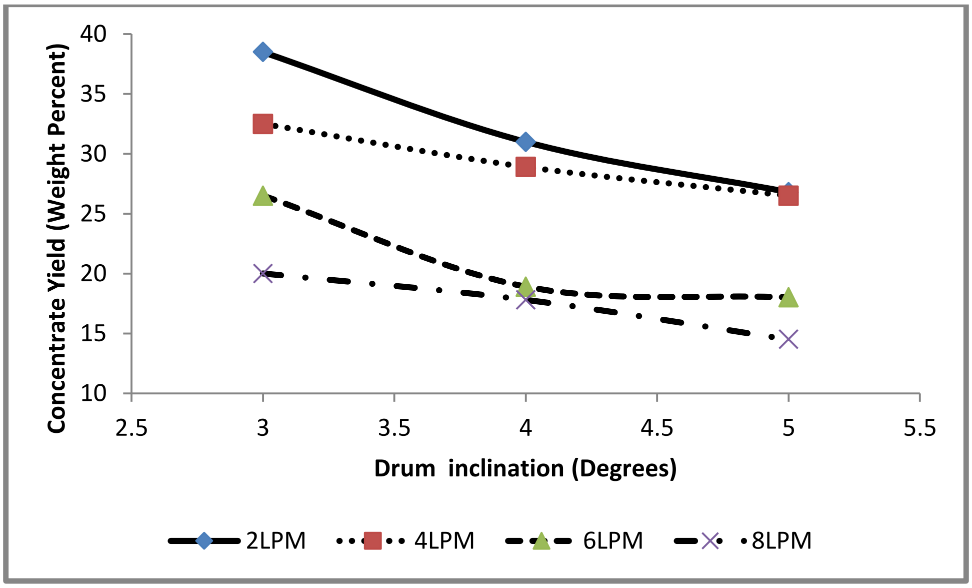

Figure 8 Effect of drum inclination on concentrate yield

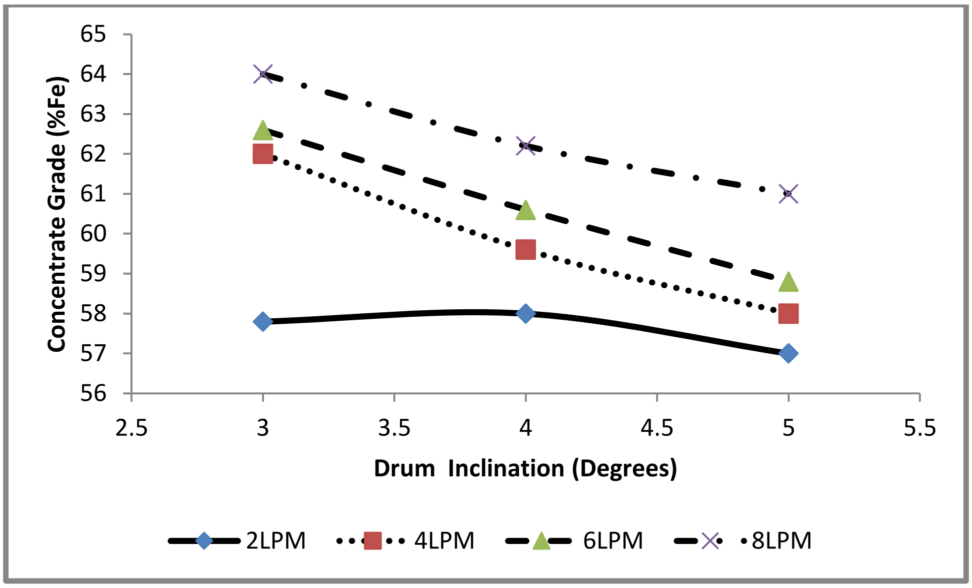

Figure 9 Effect of drum inclination on concentrate grade

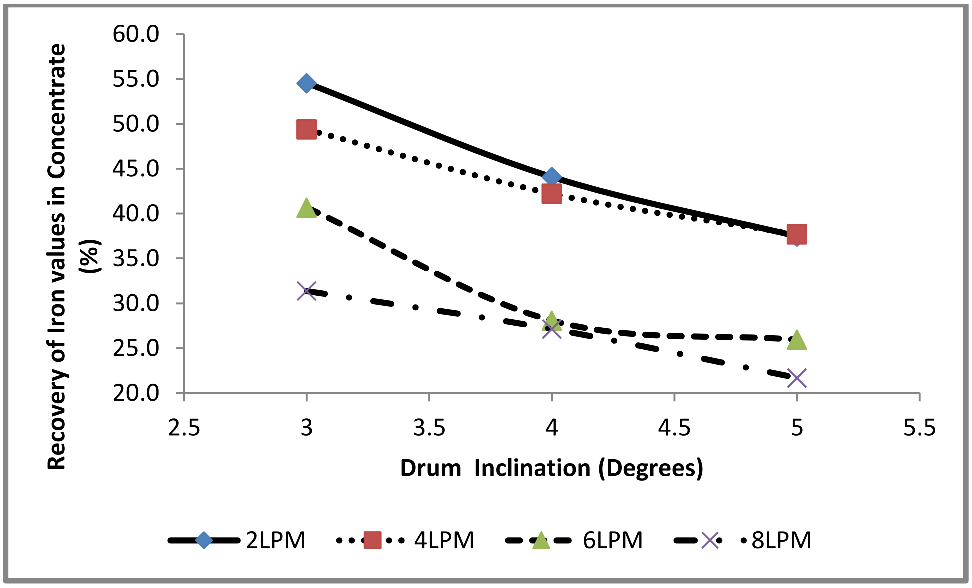

Figure 10 Effect of drum inclination on recovery of iron values in concentrate

4.4 Optimisation studies

Grade and yield are always inversely proportional to each other in any mineral processing operation. It can be observed from the test results MGS cannot produce a marketable product of 65% Fe in a single unit operation economically. It may be possible to produce pellet grade concentrate of around 65% Fe from MGS Concentrate at optimised parameters. To produce an economically viable Blast Furnace grade or Direct Reduction (DR) grade product (pellet feed), and yield should be optimised.

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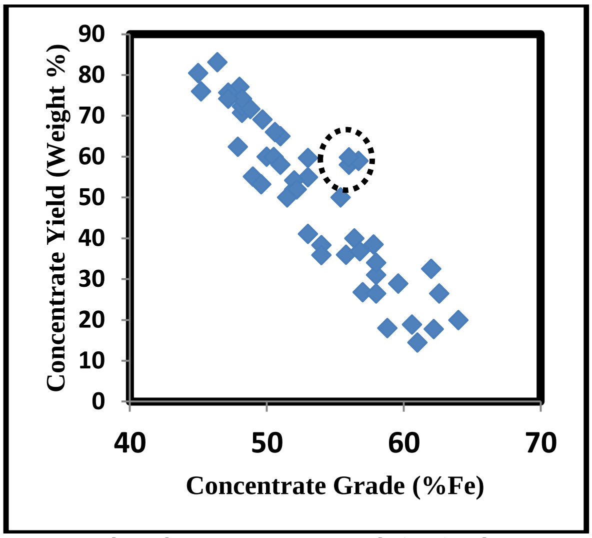

Figure 11 Relation between concentrate grade (%Fe) and concentrate yield (Weight %)

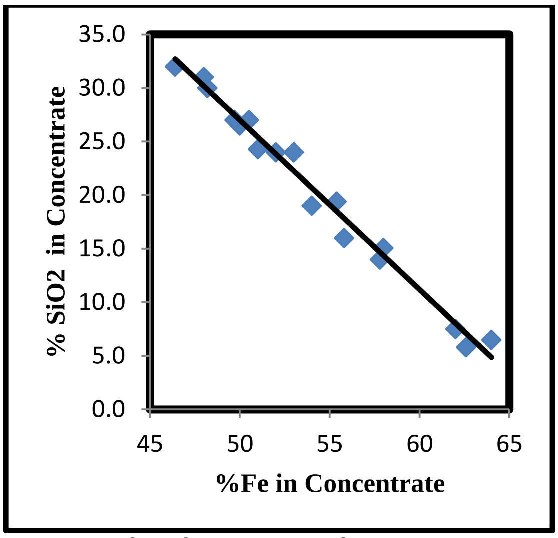

Figure 12 Relation between % Fe and %SiO_2 in concentrate

Relation between MGS concentrate grade (%Fe) and yield (weight %) is shown in Figure 11 which resembles theory. The grade and recovery values of selected portion of the Figure 11 was fixed for optimisation based on the Fe grade of feed sample. The marked test conditions produces a concentrate of around 56% Fe with an yield of around 60% by weight, recovering around 75% Fe values.

In the feed sample SiO_2 (Quartz) is the main gangue mineral. The relation between %Fe and % SiO_2 in the concentrate fraction is shown in the Figure 12. The figure demonstrates that, as there is an increase in Fe content in the concentrate fraction, the silica content decreases.

5.0 CONCLUSION

1. The 'as received' sub grade iron ore sample assayed 40.80% Fe, 40.90% SiO_2, 0.24% Al_2O_3 and 0.20% LOI.
2. The 'as received' sample can be termed as Sub Grade Iron Ore sample.
3. As a whole the ore minerals are about 46% where as the gangue minerals are 54% by their area of distribution. Among the ore minerals, hematite is chief ore type contributing about 40% where as goethite is about 6% as calculated by their area of distribution.
4. The 'as received sample' consisting about 40% quartz, 9% jasper and around 5% ferruginous clay as gangue minerals
5. Mineral liberation studies indicates that the liberation of ore and gabgue particles takes place at around 100-150 microns.
6. It is possible to produce an optimum concentrate yield of 53 – 55% with 53-56% Fe and 12-16% SiO_2, a recovery of 66-75% Fe values.
7. The optimised parameters for producing a concentrate of around 56% Fe, 50% Yield with a recovery of around 65% Fe values are given below:
   - i.) Angle of Inclination 3°; Drum rotational speed 225 RPM; wash water 8 LPM
   - ii.) Angle of Inclination 4°; Drum rotational speed 200 RPM; wash water 2 LPM
   - iii.) Angle of Inclination 4°; Drum rotational speed 225 RPM; wash water 6 LPM

6.0 ACKNOLEDGMENTS

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