CHAPTER-8

MAGNETIC SEPARATION - PRINCIPLES AND APPLICATION IN BENEFICIATION OF IRON ORES

A. Das and S. Roy

INTRODUCTION

Magnetic Separation is one of the physical concentration processes that utilizes the differences in magnetic properties of various minerals present in the ore body. The magnetic fraction may be valuable or gangue depending upon its end use in a particular process and so also the non-magnetic fraction, e.g., separation of magnetite (magnetic) from quartz (non-magnetic), separation of tin bearing mineral cassiterite (non-magnetic) from magnetite (magnetic) impurity etc.

BACKGROUND THEORY OF MAGNETIC SEPARATION

The force acting between two magnetic poles (may be attractive or repulsive) can be accounted for by the following equation

$$P = \frac{km_1m_2}{r^2}$$

Where m_1 & m_2 denote the pole strength and r denotes the distance between two poles and k is the constant of proportionality. k can be expressed as $\mu=1/k$, where μ is the permeability of the medium.

Let us consider a north pole having magnetic strength m_2 of a magnet situated in proximity of a magnet of pole strength as shown in the following figure

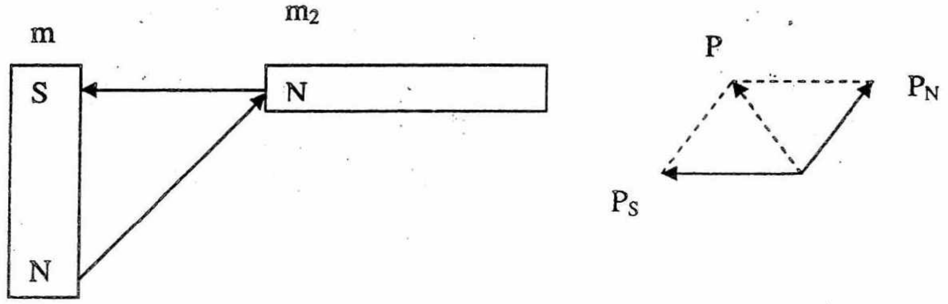

Fig. 8.1. Force vectors in a magnetic field

Force exerted by south and north poles on foreign north pole can be expressed by following equation

$$P_S = \frac{kmm_2}{r_S^2}$$

$$P_N = \frac{kmm_2}{r_N^2}$$

Resultant force acting on the foreign pole will be the sum of these two force vectors

$$P = P_N + P_S$$

$$P = kmm_2\left(\frac{1}{r_N^2} + \frac{1}{r_S^2}\right)$$

From this resultant force field intensity (H) can be defined as

$$H = \frac{P}{m_2} = km\left(\frac{1}{r_N^2} + \frac{1}{r_S^2}\right)$$

The field intensity in the interior of a solenoid of n turns and l length and with a current of i amperes can be expressed as

$$H = \frac{ni}{l}$$

The unit of field intensity is Oersteds (Oe) which can be expressed as

$$1\,Oe = \frac{1000}{4\pi} A/m$$

The magnetic force in a magnetic field is generally conceived and represented by magnetic force lines. For a magnet they are envisaged as running from the south pole to the north pole. In its field magnet always exert some force on the body placed there. That force may be attractive or repulsive depending on the properties of the placed body. When a body is placed in a magnetic field, the magnetic line may be concentrated inside the body and the body is pushed towards the higher field intensity or the force line may be expel from the placed body and as a result the body pushed towards the lower field intensity. Depending on this material may be categorized in to two major groups namely paramagnetic material (as in the first case) and diamagnetic material (second case). There are some material which shows special kind of paramagnetism called ferromagnetic material. They have very strong attractive force in the magnetic field. These behaviors of material in magnetic field are utilized in magnetic separation. It is observed that the diamagnetic force is too weak and in practical purpose it can not be utilized for separation. Paramagnetic force is strong enough and is used industrially for magnetic separation.

In a magnetic field the foreign material is endowed with magnetic permeability which can be defined as

$$\mu = \frac{B}{H}$$

Where B is flux density or magnetic induction. Here the medium is air or water but air is weakly paramagnetic and water is weakly diamagnetic. For further correction of induction constant (permeability) of vacuum is defined as

$$\mu_0 = \frac{4\pi}{10^7}\frac{Vs}{Am}$$

Therefore flux density can be expressed as

$$B = \mu_0 \mu H$$

The unit of flux density is gauss which is

1 gauss = 10^{-4} Vs/m^2

One gauss of flux density is belongs to one oersted of filed intensity.

When a paramagnetic material is placed in a magnetic field, the body temporarily turned into a magnet of pole strength m' by the lines of force that it concentrate itself. The magnetic moment (M) of the of the paramagnetic body so placed is

$$M' = m'L$$

Where L is the length of the body placed. The magnetization is defined as magnetic moment per unit volume as

$$I = \frac{M'}{v} = \frac{Lm'}{SL} = \frac{m'}{S}$$

Where v is the volume of the body and S is the cross sectional area. The ratio of magnetization and field intensity is called the magnetic susceptibility (x) and can be expressed as

$$x = \frac{I}{H}$$

Table 8.1. Magnetic susceptibilities of common minerals

Mineral	Specific susceptibility (10^{-8} m^3/kg)	Mineral	Specific susceptibility (10^{-8} m^3/kg)
Calcite	-0.3 to -1.4	Pyrrhotite	10 to 30,000
Quartz, Feldspar, Magnesite	-0.5 to -0.6	Hematite	10 to 760
Kaolinite	-2	Ilmenite	46 to 80,000
Halite, Gypsum, Anhydride	-0.5 to -2.0	Magnetite	20,000 to110,000
Serpentinite	120 to 2900	Dolomite	-1 to -41
Illite, Montmorillonite	5 to 13	Sandstones, Shales, Limestone	0 to 1200
Biotite	5 to 52	Serpentine	110 to 630
Goethite	26 to 280	Clay	10 to 15
Chalchopyrite	0.6 to 10	Coal	1.9
Pyrite	1 to 100		

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The susceptibility per unit mass is called specific susceptibility. The relation between magnetic susceptibility and permeability can be expressed as

$$\mu = 1 + 4\pi x$$

For paramagnetic material $I>0$, $x>0$ and $\mu>1$ where as for diamagnetic material $I<0$, $x<0$ and $\mu<0$. Here point to be noted that the value of μ and x are no material constant in minerals, it is greatly influenced by mechanical impurities adhering to the grain and even more so by alien substance dissolved in the lattice.

When a magnetizable body is placed in a magnetic field of intensity H an effective field H' is generated which cane expressed as

$$H' = H - H_B$$

Where H_B is the countervailing field, the body's won field, act against external magnetizing field, is function of magnetization and its shape property.

$$H_B = CI$$

C is one for very thin disc, and zero for very long rod. For general ore particles it varies from 0.15 to 0.25

Any change in field intensity causes the change in permeability and hence flux density. If field intensity is increased the flux density also increases.

When a particle placed in to a homogeneous magnetic field, the particle is exposed to a pure torque. But introduction of inhomogenity induce a translating force (tractive force) on the particle. In a inhomogeneous field the field intensity varies in space. The mechanical force acting on the particle in the inhomogeneous field is

$$F_m = \mu_0 \left(\frac{x}{1+Cx} - x_m \right) vH \,\mathrm{grad}\, H$$

Where x_m is the volume susceptibility of the medium. This relation hold good where the H and grad H constant within the particle (for very small particles).

SEPARATION PRINCIPLE

When a magnetisable particle is placed in a non- homogeneous magnetic field, it is acted upon by the magnetic force (F_m) given by the above equation. Magnetic force is thus proportional to the product of the external magnetic field and the field gradient and has the direction of the gradient. In a homogeneous magnetic field the force on a particle is zero.

In a magnetic separator several competing forces are acting on the particles. These are, among others, the force of gravity, the inertial force, the hydrodynamic drag, and surface and inter-particle forces. This situation is shown schematically in Fig. 8.2. The force of gravity can be written as

$$F_g = \rho V g$$

where, ρ is the density of the particle. The hydrodynamic drag force is written as

$$F_d = 6\pi\eta d_p v_p$$

where, η is the fluid viscosity, d_p is the particle size and v_p is the particle velocity relative to the fluid.

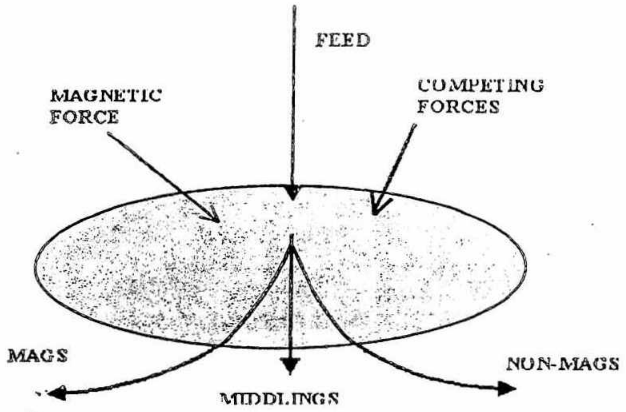

Fig. 8.2. Schematic diagram of magnetic separation

Magnetic particles will be separated from nonmagnetic (or more magnetic particles from less magnetic particles), if the following conditions are met:

$$F_m^{mag} > \sum F_c^{mag} \quad \text{and} \quad F_m^{nomag} > \sum F_c^{nonmag}$$

where F_C is a competing force while F^{mag} and F^{nonmag} are forces acting on magnetic and non-magnetic particles, respectively.

In order to achieve high recovery of magnetic particles, the magnetic separating force must thus be greater than the sum of the competing forces, as shown in the above equation. If, however, magnetic force is much greater than the competing force, selectivity of separation will be poor, as no distinction will be made between various magnetisable particles. The selectivity of the process will be critically deter- mined by the relative values of the magnetic and competing forces. And these are affected by a correct choice of a separator itself and its operating conditions.

Although the conditions of efficient separation are clearly defined, a complication arises because the relative significance of the forces is determined mainly by the particle size. It can be seen from the above Equations that while $F_m \propto d_p^3$ or d_p^2, the competing forces have the following dependence on particles size: $F_d \propto d_p^1$ and $F_g \propto d_p^3$. In dry magnetic separation where F_d is usually negligible, the particle size, as a rule, does not affect the efficiency of separation significantly because of the same particle size dependence of the magnetic force and of the force of gravity. On the other hand, in wet separation where the hydrodynamic drag can be important, selectivity of the separation will be influenced by particle size distribution. With decreasing particle size the relative importance of the hydrodynamic drag increases in comparison to the magnetic force.

The non-selective nature of the magnetic force is illustrated in Table 2. It can be seen that the same magnetic force is exerted on a coarse, weakly magnetic particle as on a small, considerably more strongly magnetic particle. Both particles will appear in the same product of separation unless the competing forces affect particles of different sizes in a different manner.

Table 8.2. The effect of particle size on separability (with arbitrary units)

Particle Size	Magnetic Susceptibility	Magnetic Force
10	1	1000
1	1000	1000

FUNDAMENTALS OF INDUSTRIAL MAGNETIC CONCENTRATION

Concentration is achieved by simultaneously applying to all particles in an ore a magnetic force that acts on magnetic particles and a second force or combination of forces which acts in a different direction and affects both magnetic and non-magnetic particles. The most commonly applied nonmagnetic forces are gravitational, centrifugal and fluid drag. Other forces that usually enter in an incidental manner are frictional, electrostatic, Van Der Waals, and capillary. A magnetic separator is generally classified as low intensity if its maximum field intensity is less than about 2000 gauss ($H = 1.6 \times 10^5$ A/m, $B = 0.20$ T). Low intensity magnetic separators (LIMS) are used to treat ferromagnetic and highly paramagnetic minerals such as iron and magnetite. High intensity magnetic separators (HIMS) generally have field strengths of 10 to 20 kilogauss. These separators are used to treat weakly magnetic minerals, such as hematite.

Magnetic separators are commonly classified into two broad groups, namely, wet and dry based on their usage. A more definitive classification within these two basic groups is made based on the relative magnetic field strength of the individual units, i.e. wet low intensity magnetic separators, wet high intensity magnetic separators etc. Table 8.3 shows the basic groupings of the most commonly used magnetic separators.

Table 8.3. Basic Groupings of Common Magnetic Separators

Wet magnetic separators		Dry magnetic separators	
Low:	Drum separators Bowl traps	Low:	Magnetic pulleys Suspended magnets

Magnetizing coils and blocks Demagnetizing coils High: WHIMS, HGMS, Magnetic drums	Magnetic drums-radial pole types Magnetic drums-axial pole types Plate magnets Grate magnets High: Induced roll magnetic separators Cross belt magnetic separators Ring type magnetic separators

COMMON TYPES OF MAGNETIC SEPARATORS USED FOR CONCENTRATION

Ore Cobbing Magnetic Pulleys

Ore cobbing or concentrating magnetic pulleys utilize more poles across the pulley width so as to develop as uniform field depth as possible and a sufficient area of collecting magnetic poles to carry the large amount of magnetic material commonly encountered in such applications. Generally, ferromagnetic minerals are used for concentration.

Magnetic Drums

Magnetic drums with axial pole design are used to concentrate ferromagnetic minerals. Feed materials up to 1-inch diameter can be treated. The drum speed can be varied between 20-45 rpm in low intensity whereas it is up to 200 rpm for high intensity separators.

Induced Roll Magnetic Separator

It develops high intensity magnetic fields and is capable of removing particles that do not respond to the low intensity magnetic separator. This is widely used to treat beach sands, wolframite, tin ores, glass sands and phosphate rocks.

Cross-belt High Intensity Magnetic Separators

A cross belt runs across the face of the electromagnetic pole, and the sharp magnetized points of this upper pole attract the weakly magnetic material. The cross belt transports it to a suitable discharge point. Selective mineral concentration of weakly magnetic minerals can be performed by using this instrument.

Ring Type Magnetic Separators

The basic construction is similar to the cross belt but a magnetized steel ring is substituted for the cross belt.

Low Intensity Wet Drum Magnetic Separators

This is used to concentrate ferromagnetic particles such as iron of abrasion, magnetite and some pyrrhotites. The feed size is limited to 1/8 inch or even finer. Two well known usage are the concentration of magnetic taconite ores and the recovery of magnetite media in heavy media separation plants.

Wet High Intensity Magnetic Separators (WHIMS)

WHIMS are used for the separation of weakly magnetic materials such as (1) hematite and geothite in the beneficiation of iron ores, (2) iron oxides and ferrosilicates from quartz and clays used in manufacturing glass, ceramics and glazes (3) ilmenite, wolframite and chromite from gangue during concentration, and (4) ferro-oxides and ferrotitanium oxides from cassiterite, zircon and rutile concentrate. A background field intensity of from 15,000 to 20,000 gauss could be achieved in this type of separators. Slurry feed is introduced into the magnetic matrix, which is contained in a stainless steel ring moving at controlled speed between the poles of the powerful stationary electromagnets. Exceptional performance on even weakly magnetic materials, high magnetic field intensity, middling splitter setting, etc. are the key feature of WHIMS.

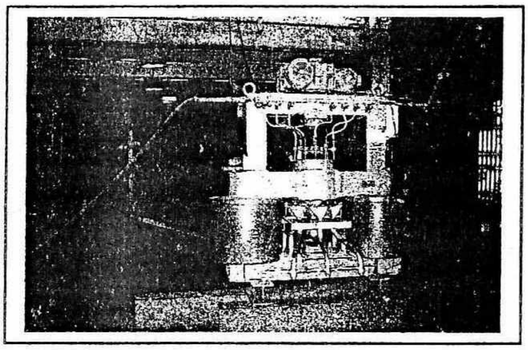

Fig. 8.3. The Wet High Intensity Magnetic Separator

High Gradient Magnetic Separators (HGMS)

High intensity separators generally use a field strength of about 20,000 gauss. Use of a matrix of shaped iron pieces which produce high field gradients to act as collection sites for paramagnetic particles. The commonly used matrix to form the high gradient sites is balls, rods, grooved plates, expanded metal and fibers. High gradient magnetic separators use uniform field of a solenoid. The core is filled with a matrix of secondary poles such as ball bearings or wire wool to obtain the high gradient.

Super Conducting Separators

Small laboratory super conducting solenoids with fields up to about 60 kilogauss are commonly available and are used for the production of large volumes of relatively permanent magnetic field. Negligible power loss is an important advantage.

MAGNETIC SEPARATION OF HEMATITE AND LIMONITE FINES AS HYDROPHOBIC FLOCS FROM IRON ORES – A CASE STUDY

Two typical weakly magnetic iron ores in China, namely East Anshan (EA) hematite ore and Tiekeng (TK) limonite ore were crushed to -2 mm size. The EA iron ore was characterized by poor iron (30.5% Fe) and rich silica content, and the TK iron ore was assayed to contain 38.11% Fe. The main mineral compositions of the ore samples are given in Table 4.

Table 4
Main mineral compositions of the EA and TK iron ore samples

	Hematite	Limonite	Magnetite	Quartz	Chlorite	Calcite
EA hematite ore	38.0	2.1	0.4	55.5	3.1	
TK limonite ore	0.7	67.5		11.1	16.8	3.6

Sodium silicate and sodium hydroxide were used as a dispersant and pH regulating agent, respectively. Sodium oleate was used as the surfactant to selectively render iron minerals hydrophobic.

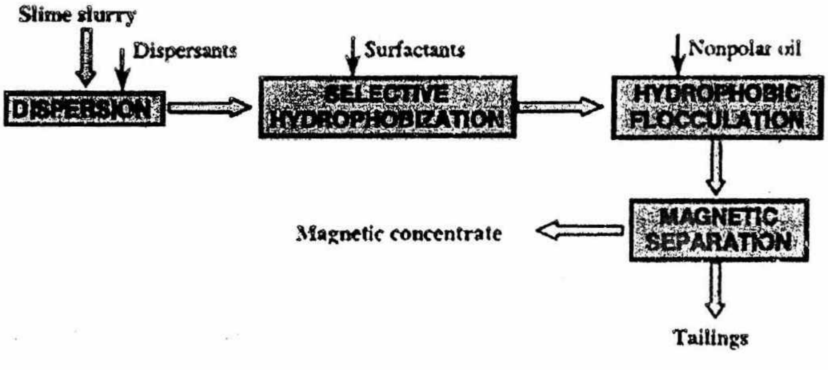

Fig. 4. Schematic representation of the Floc Magnetic Separation (FMS) process.

The iron ore samples were first finely ground by using a wet ball mill in the presence of sodium silicate of 0.9 kg/ton for the EA iron ore and 1.0 kg/ton for the TK iron ore, respectively. Not only particle size reduction, but also slurry dispersion were achieved in this step. The size distributions of the products are shown in Fig. 8.5.

The ground ore slurries were diluted to a given solid concentration, and transferred to a mixing tank of 14 cm inner diameter with four 1 cm width baffles. The stirring shaft was equipped with a cross-shape impellor of 7 cm diameter and 1 cm height. The slurry was first adjusted for pH using sodium hydroxide solution, and then strongly conditioned at 1200 rev/min for a given time while sodium oleate or kerosene emulsion was added, leading to the formation of hydrophobic flocs of iron minerals. After the conditioning, the slurry was fed to a laboratory Jones magnetic separator in 500 ml/min flow rate and 15% solid concentration. The separation box of the separator was equipped with four grooved plates of 6 cm height and 0.8 cm width. The field intensity could be adjusted through 0.5–1.4 T. 200 ml washing water in 200 ml/min flow rate was used as soon as the slurry feeding was terminated. From this operation, one concentrate (magnetic product) and one tailing (non-magnetic product) were produced. In addition, conventional magnetic separation was also performed on the fine iron ores for a comparison, which was carried out at the same test conditions as the FMS process, including pH, dispersion, field-intensity and washing water, etc. except for hydrophobic flocculation processing.

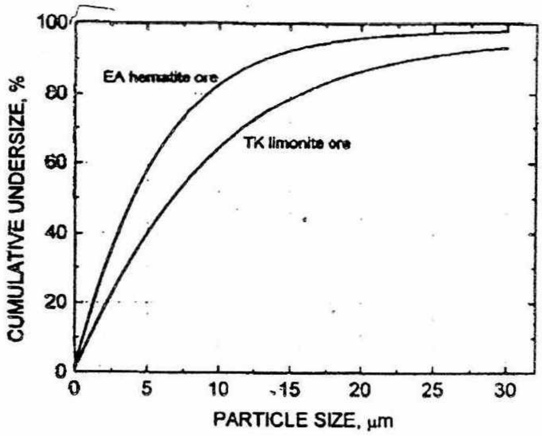

Fig 5. Size distribution of the ground EA and TK iron ores.

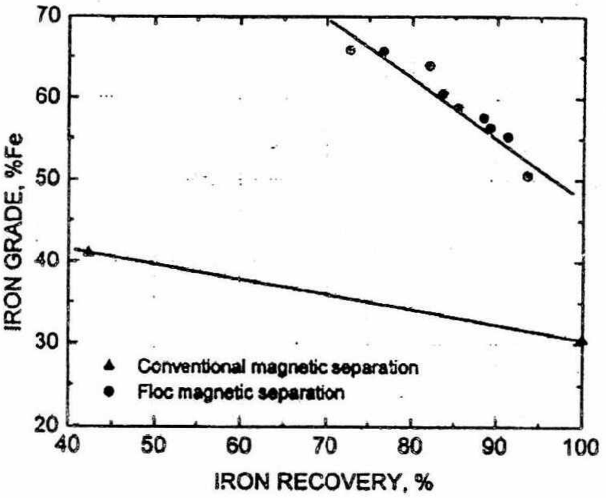

Fig. 6. Iron grade vs. recovery from the concentrates obtained by the FMS process and conventional magnetic separation applied to the fine EA iron ore.

Strong hydrophobic flocculation of hematite fines in aqueous suspensions could be induced by sodium oleate upon its adsorption on the particles under a strong slurry conditioning. This flocculation could be enhanced by adding a small amount of non-polar oil. Such flocs are just in the operating particle size range of middle intensity magnetic separators. Accordingly, the FMS process in which the hydrophobic flocculation of hematite fines was induced by sodium oleate and kerosene was tested on the fine EA iron ore at 1.0 T field intensity. Fig. 8.6 shows the beneficiation results in the form of Fe grade vs. recovery of the concentrates, compared with those obtained by the conventional magnetic separation. As it is expected, the conventional magnetic separation achieved a very poor separation efficiency for the fine iron ore, produced a concentrate assaying 41% Fe with 43% recovery. Obviously, most of the iron loss was due to the weak magnetic force on hematite fines, resulting in that the fines past straight through the separation box of the magnetic separator and thus were collected as tailings. However, by applying hydrophobic flocculation to the hematite fines, the separation efficiency was considerably increased, leaving the iron grade vs. recovery line of the FMS process much above that of the conventional magnetic separation. By one pass through the separator, a concentrate assaying 56% Fe was produced with 88% recovery, and was upgraded to be 66% Fe with the recovery of 75% by one more pass.

MAGNETIC SEPARATION OF INDIAN IRON ORES – SOME CASE STUDIES

Most of the studies so far in India were carried out on recovery of enriched fines from slimes using Wet High Intensity Magnetic Separators (WHIMS). Since Indian iron ore slimes are highly aluminous, the slimy/clayey particles give a coating on ore particles, making the separation quite difficult. Techno-economic efficacy of WHIMS on slimes is not established very conclusively as recovery of concentrates is low (around 45%) due to repeated desliming of clayey matter. WHIMS is very effective on high silica ores as most of the silica gets liberated at finer sizes while the alumina is present in very finely disseminated form and does not liberated even at 9/10 micron size.

Studies at RDCIS, Ranchi indicated that Barsua slime having 70% below 200 mesh and analysing 48% Fe & 14% Al_2O_3 could be upgraded to a concentrate having >63% Fe and 3.2% Al_2O_3 by the application of Wet High Intensity Magnetic Separator (WHIMS).

Similarly slime from Kiriburu was enriched to >66% Fe.

KHD Humboldt Wedag carried out studies on recovery of values from Barsua slime by High Intensity Magnetic Separator (WHIMS). Since the first successful application of large WHIMS of Jones Type in Brazil in 1972, these kind of magnetic separators have been installed to an increasing extent for the production of fine grained sinter feed and/or pellet feed from feebly magnetic iron ore fines and superfines.

The sample under investigation had 80% -325# size and analysed Fe - 48.3%, SiO_2 - 10.1% and Al_2O_3 - 12.6%. The objective was to produce concentrate having Fe more than 63% and <5% Al_2O_3. Findings of WHIMS on Barsua Slime is given in Table 8.5. The study indicated that a two stage WHIMS with double pass of magnetics is necessary to produce a concentrate of +66% Fe with <3% Al_2O_3.

Studies by NMDC indicated that beneficiated fines obtained by hydrocycloning and dewatered Slow Speed Spiral classifier meets the grade specification for mixing with normal classifier sand for sinter making. However, in order to produce DRI pellet grade concentrate from slime, wet high intensity magnetic separation was found to be essential. Exhaustive beneficiation studies were carried out at NMDC's R&D Centre on WHIMS test on iron ore slimes from Bailadila and Donimalai mines of NMDC. Test results conclusively proved that by the process of WHIMS the fine ore concentrate of +66% Fe can be produced. Some results are shown in Table 8.6.

Use of High Gradient Magnetic Separators (HGMS) is gaining wider industrial application for beneficiation of hematite ore superfines/slimes. Particularly a recent development of use of permanent ceramic magnets in the form of Ferrous Wheel Separator (FWS) is quite cost effective in recovering iron values from superfine tailings of beneficiation plants. Large capacity plants are under operation in Mexico and Argentina using FWS. Capital cost as well as power consumption is quite low in FWS. In India one such plant is under installation at Goa. RDCIS got samples of Dalli and Bolani mines tested on lab. scale model of FWS at Eriez lab. of USA. The results are given below in Table 7

Table 8.5: Results of WHIMS on Barsua Slime Sample

Stage	Intensity te	Gap mm	Product	Wt(%)	Fe(%)	SiO_2(%)	Al_2O_3(%)
One	0.95	1.8	Conc.	45.8	62.9	3.20	3.51
			Mid	5.8	39.0	14.00	19.38
			Tail	48.4	38.2	15.60	17.22
	1.02	2.5	Conc	45.0	61.2	3.90	4.43
			Mid	6.6	39.9	14.48	16.58
			Tail	48.4	38.9	17.24	18.07
	1.08	1.8	Conc	48.0	64.5	2.20	2.75
			Mid	52.0	34.6	18.30	19.77
			Feed	100.0	49.4	9.48	12.07
Two	1.15	2.5	Conc.	37.6	66.3	1.28	2.38
			Mid 1	4.3	47.0	11.40	12.63
			Tail 1	58.3	38.8	14.60	18.25
	1.08	1.8	Conc	36.0	66.1	1.26	1.71
			Mid 1	3.8	39.2	15.26	17.08
			Tail 1	60.2	36.4	15.90	20.50
			Feed	100.0	47.3	10.61	13.61

Table 8.6: Results of WHIMS Test

Test No.	Products	Wt(%)	Fe(%)
1	Magnetic Conc.	57.8	67.30
	Non-magnetic Tailings	42.2	56.08
	Feed	100.0	62.57
2	Magnetic Conc.	65.4	66.40
	Non-magnetic Tailings	34.6	55.04
	Feed	100.0	62.47
3	Magnetic Conc.	66.2	66.00
	Non-magnetic Tailings	33.8	55.65
	Feed	100.0	62.50

Table 8.7: Results of HGMS on Slime samples from Bolani and Dalli (Yield and Grade of Magnetic Concentrate)

Sample : Bolani Slime				
Magnetic Field	Yield	Fe(%)	SiO_2(%)	Al_2O_3(%)
1000	20.4	67.65	0.96	0.7
1500	33.3	67.33	1.02	0.81
2200	63.3	66.53	1.16	1.17
2500	62.0	66.00	1.52	1.32
Feed Assay	100.0	57.5	5.8	6.7
Sample : Dalli Slime				
1200	54.2	67.86	1.13	0.84
1700	67.3	66.73	1.21	1.17
2200	74.5	66.04	1.27	1.38
Feed Assay	100.0	52.5	8.70	9.50

Test results obtained on Bailadila iron ore slimes with SALA HGMS unit indicated that a concentrate assaying 67% Fe could be produced from a feed of 60% Fe at an overall recovery of 78-88% depending upon the field strength (3 to 4.4 kilo gauss).