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Gravity concentration of fines and ultrafines

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ABSTRACT

Concentration of fines by gravity methods remains one of the challenging problems to the world mineral industry. Considering the increasing losses of mineral values and the search for an economic process, it has been the major concern of the researchers and the practicing engineers to develop an efficient fine gravity separator. The development of some of the recent fine gravity separators with the application of high centrifugal forces has resulted in improvement in the separation efficiency. In the last four decades extensive studies have been carried out at National Metallurgical Laboratory (NML), Jamshedpur to develop gravity based processes for low grade ores, fines and industrial wastes involving the conventional separators to the latest equipment like multi-gravity separator for their economic exploitation. In this paper an attempt has been made to briefly present a review of the gravity concentration processes with a particular reference to the recent advances in the processing of fines. The salient results obtained from the recent studies carried out on beneficiation of lean grade finely disseminated tungsten ore, iron ore slimes and chromite slimes at NML using some fine gravity separators like Bartles-Mozley Vanner, GEC-duplex concentrator and MGS are discussed.

INTRODUCTION

Gravity concentration process which exploits the differences in densities of minerals to bring about a separation, is the oldest beneficiation method known to mankind. Although with the advent of froth flotation, the relative importance of gravity concentration has declined in twentieth century but still on an average higher tonnage of material is treated by gravity concentration than flotation. It finds diverse applications in the treatment of coal, beach sands, iron, gold, diamonds platinum, baryte, fluorspar, tin, tungsten ores etc. The gravity separation processes are comparatively cheap and environment friendly.

One of the main problems of gravity concentration processes has been its limitation in treating particles in relatively fine size range. In the fine size ranges the fluid and viscous forces become dominant relative to the gravity and this in turn affects the separation efficiency. Recently efforts have been put in to develop an efficient gravity separator for the treatment of fines, which has resulted in considerable success. The application of centrifugal forces to heavy media separation, in the D.M.S. Cyclone, Dynawhirlpool and the Triflow separator, has increased the range of sizes that can be separated down to 200 microns [1]. The recent fine gravity separators like Knelson concentrator, Kelsey jig, Bartles Mozley separator, Cross belt concentrator and Multi-Gravity separator (MGS) can treat particles further in the finer size range [2].

National Metallurgical Laboratory (NML) has got vast experience in gravity concentration of various ores and minerals using equipment ranging from conventional separators to the latest equipment like MGS. In this paper an attempt has been made to present a review of the application of gravity concentration in treating low grade ores. The paper discusses some of the salient results achieved at NML on beneficiation of tungsten ore and processing of iron and chromite ore slimes using gravity concentration techniques. The recent advances in the area of fine gravity concentration are also presented.

Principles and Mechanisms of Gravity Concentration

Principles:

Gravity separation of two minerals, with different specific gravity, is carried out by their relative movement in response to force of gravity and one or more other forces. Normally one of the forces is the resistance to motion by a viscous fluid e.g., water. So besides the specific gravity the factors like, size, shape and weight of the particles affect the relative movement and hence the separation. The ease or difficulty of separation depends upon the relative differences in these factors.

The 'Concentration Criteria' (CC) which gives an idea of the amenability of separation of two minerals, can be expressed by

$$CC = \frac{(d_H - d_F)}{(d_L - d_F)} \qquad \dots (1)$$

where d_H = sp. gr. of the heavy mineral

d_F = sp. gr. of the fluid and

d_L = sp. gr. of the light mineral

Generally when the quotient is greater than 2.5 (whether positive or negative) then gravity separation is relatively easy. With a decrease in the value of the quotient the efficiency of the separation decreases and below 1.25 generally, gravity concentration is not feasible.

As mentioned above besides the specific gravity, the motion of a particle in fluid also depends on its size. The efficiency of gravity concentration increases with an increase in particle size. The particle movement should be governed by the Newton's Law, Eq. 2[3].

$$v = \left[3\ g\ d\ \frac{(D_s - D_f)}{D_f} \right]^{1/2} \qquad \dots (2)$$

where, v = terminal velocity of the particle, D_s = density of the solid, D_f = density of the fluid, and d = diameter of the particle.

For small particle the movement is dominated mainly by surface friction and these respond poorly to commercial high capacity gravity separators. To reduce the size effect and for making the relative motion of the particles specific gravity dependent, a closely sized feed is desirable.

As expected the 'Concentration Criteria' is also affected by a decrease in particle size. Generally the concentration criteria is compared at the appropriate size with the standard curve as shown in Fig. 1. [4]

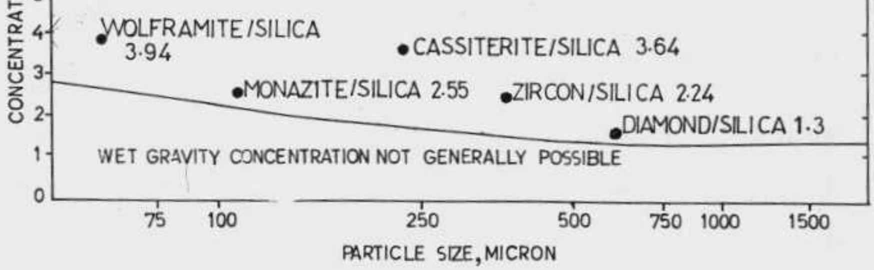

Fig. 1 : Concentration criterion at different particle sizes [4].

Mechanisms:

There is no single mechanism for the operation of a particular gravity separator. Generally a combination of two or more mechanisms is helpful in explaining the behaviour of any separator. The various mechanisms proposed are briefly described below and are schematically shown in Fig. 2.

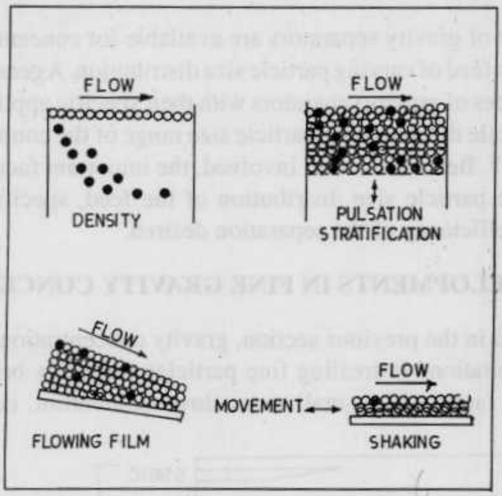

Fig. 2 : Schematic representation of various mechanisms of gravity concentration [5].

Density:

The methodology employs a fluid with the apparent density in between that of the minerals to be separated. Hence due to the difference in the buoyancy, one mineral floats while the other sinks. The most common example is the heavy medium separation.

Stratification:

In this case the minerals are stratified by an intermittent fluidization caused by the pulsation of the fluid in a vertical plane. Examples are various types of jigs used for concentration.

Flowing film:

The minerals are separated by their relative movement through a stream of slurry which is flowing down a plane by the action of gravity. Examples are sluice, Richert cone etc.

Shaking Surface

The various constituents are separated by superimposing a horizontal shear force on the flowing film. Examples are shaking tables, Bartles-Mozley separator and Cross belt concentrator.

Range of the Available Gravity Concentrators

A wide range of gravity separators are available for concentration of various types of ores with feed of varying particle size distribution. A general classification of the various types of gravity separators with their specific applications are given in Table 1 [2,6], while the operating particle size range of the common separators is shown in Fig. 3 [4]. Besides the cost involved, the important factors in equipment selection are the particle size distribution of the feed, specific duty required, throughput and efficiency of the separation desired.

RECENT DEVELOPMENTS IN FINE GRAVITY CONCENTRATION

As mentioned in the previous section, gravity concentration processes suffer from serious limitations in treating fine particles (typically below 50 microns) efficiently. The factors like small mass, low momentum, colloidal coating,

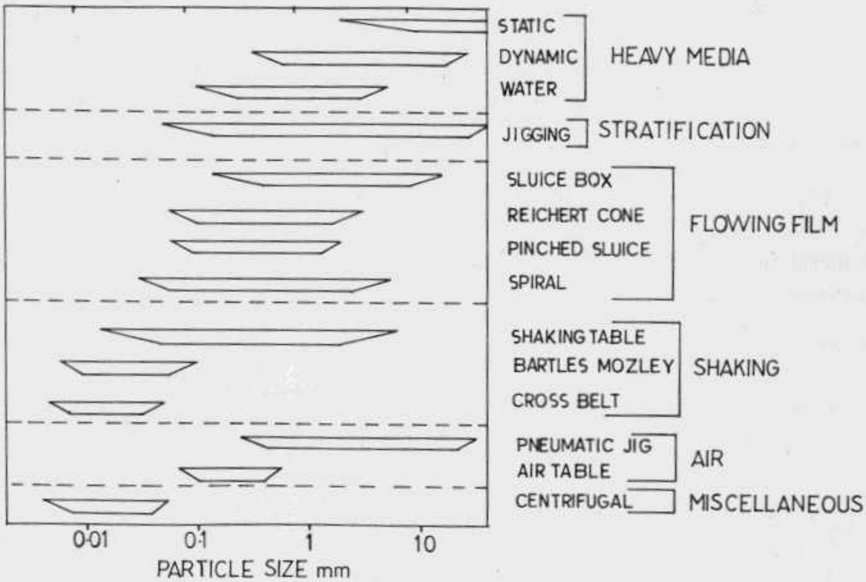

Fig. 3 : Operating particle size range of common gravity separators [4].

Table 1 : Classification & applications of gravity concentrators, modified after Kelly and Spottishwood [6]

Equipment	Applications
Stratification	
Diaphragm or Plunger Mineral jig	Roughing & cleaning of coarse casseterite, gold, scheelite
Baum jig	Mainly coal washing
Batac jig	Mainly coal washing (fine coal)
Circular jig	Extensively used on tin dredges
Pneumatic jig	Dry coal beneficiation
Shaking surface	
Shaking table	Treatment of coal, casseterite, schellite and other heavy minerals
Slimes table	Fine particle processing (cleaning)
Bartles-Mozley separator	Rougher concentrator for fine heavy minerals
Bartles-crossbelt concentrator	Fine particle processing (for cleaning rougher product)
Flowing film	
Humpreys Spirals	Beach sands, iron ores and other heavy minerals
Pinched sluice	Beach sands, phosphate ore
Reichert cone	Beach sands, coal, iron and for recovery of heavy minerals
Density	
Dense media separators	
Drum separator	Coal wahsing (6 – 300 mm)
Cone separator	Coals washing (max. 10 cm)
Trough dense media separator	coal washing (upto 30 mm)
Centrifugal dense media separators	
Cyclone	Fine coal, metallic & non-metallic
Vorsyl separator/ Dyna whirlpool	Coal, metallic and non–metallic ores
Autogenous dense media separator	Coal, lead, zinc and placer deposits of gold
Tri-Flo separator	Coal, metallic and nonmetallic ores
Miscellaneous (Recent centrifugal type separators)	
Knelson separator	Gold ore and other heavy mineral
Falcon separator	Ore fines
Multi-gravity separator	Various metallic and nonmetallic ore fines and tailings
Kelsey centrifugal jig	Tin and other ores

heteroaggregation, high surface area and increased surface energy and viscosity cause loss in selectivity of separation [7]. But considering the increasing loss of values in fines and slimes coupled with the environmental pollution problems, there has been considerable efforts to develop an efficient gravity separator for fines [2,8]. The range of available fine gravity concentrators is given in Table 2 [4]. The various early fine gravity concentrators like buddles, strakes, vanners, round tables and round frames were relied upon the principle of thin film concentration and suffer from very low capacity per unit area and the low ratio of enrichment.

Bartles Mozley Separator and bartles Cross belt Concentrator include the fine gravity separators of recent origin which have got commercial acceptance. In these units an orbital shear force is superimposed on the flowing film and these are

Table 2 : Fine gravity concentrators, modified after Burt [5]

Stationary Deck Equipment		
	......	Buddle
	......	Round table
	......	Round frame
	......	Strake
	......	Corduroy table
	......	McKelvey concentrator
	......	Denver Buckman tilting frame
Stirred Bed Devices		
	Discontinuous Shear:	
	......	Vanner
	......	Shaking table
	......	Kieve
	......	Rocking shaking vanner
	......	GEC Duplex concentrator
	Unidirectional Shear:	
	......	Endless belt concentrator
	......	Johnson barrel
	......	Hodgson separator
	......	Rotating cone separator
	Orbital Shear:	
	......	Shaken helicoid
	......	Bartles-Mozley separator
	......	Bartles cross-belt concentrator
Centrifugal Devices		
	......	Ferrara's tube
	......	Yunnan separator
	......	Knelson hydrostatic separator
	......	Falcon concentrator
	......	Multi-gravity separator

capable of recovering particles as fine as 5 microns. The bartley Mozley separator is mainly a pre-concentrator and is used for roughing and scavenging operations. The Bartles Crossbelt concentrator has been used for cleaning operations, in particular to clean the concentrate obtained from Batley Mozley separator [9]. The unit is in operation at Geevor Tin Mines, Cornwall, UK and it is reported of several installations in the chromite industry in Philippines and Europe. These units are gaining industrial importance in separation of other mineral fines also. Another flowing film type concentration equipment are the GEC Duplex concentrator and Reichert Cone concentrator. GEC Duplex concentrator is recommended for the recovery of heavies from fine sands and slimes. It finds wider application in the treatment of tungsten, tantalum, gold, chromite, platinum from fine feeds [3]. The basic element of the Reichert cone concentrator is the fibre glass cone with apex down at a slope angle 17 degree. It can treat particles ranging from 3.36 to 0.037 mm. This is a high capacity unit with low capital investment [10].

In recent times because of their simple design and less maintenance problems, water only cyclones are gaining popularity. The equipment is similar to the conventional cyclone except that it has got a large angle lower conical section. This helps in suppressing the classification and leads to separation based on the differences in the specific gravity of the suspended particles [11]. The equipment has been used for coal preparation but there exists scope for extending its application to lead-zinc, cassiterite and placer deposits of gold.

Knelson and Falcon separators are the two recent centrifugal type concentrators. The knelson separator utilises a centrifugally enhanced gravitational forces up to 60 'g' with injection of water to form fluidised bed. In Falcon separator also a centrifugal force of 300 'g' is produced but unlike Knelson separator there is no back flow of water. These separators were originally developed for the recovery of fine alluvial gold. But the application of these centrifugal separators has also been extended to cassiterite and coal. And now it is considered to treat the fine ores in general [12,14]. The Kelsey jig is another development in this area with a provision to vary the apparent gravitational field. It is basically a conventional jig, wrapped into a cylinder and rotated on a vertical axis, resulting in generation of forces 100 times gravity. This leads to a better separation efficiency even in the fine sizes. Pilot plant trials conducted in Canada have shown a consistent better results against the conventional shaking tables [15]. The first successful installation is reported at the Renison Tin Mine, Australia [16]. In the similar lines Holland-Batt studied the efficiency of rotating spirals for improved separation of fines [17].

The latest development in this area is the multi-gravity separator which uses high 'g' forces to bring about separation in finer sizes (upto 1 micron). Conceptually it can be visualised by rolling the deck of a conventional shaking table into a drum and then rotating it [18]. This apples a force of multiple 'g' on the mineral particles in the film flowing across the surface leading to improved separation efficiency particularly in the fine size ranges. The semi-continuous type equipment has shown its efficacy in treating various metallic and non-metallic ores like tin, tungsten, chromite, magnetite, zirconia, gold, coal etc. and plant tailings in the fine size ranges. The MGS has been successfully scaled upto a plant scale unit (5 t/hr) and is being evaluated for wide variety of processing applications [19,20].

Burt et. al., have evaluated the performance of different fine gravity separators for the processing of tantalum ore slimes [13]. The data shown in Fig. 4 demonstrates the superiority of MGS over other separators for tantalum ore slimes. Besides designing and developing the new fine gravity separator now there is considerable interest in studying the effect of roughness profile of the surface, viscosity of the slurry, pH, dispersants and the electrokinetic environment on the separation characteristics of fine particles [5,21].

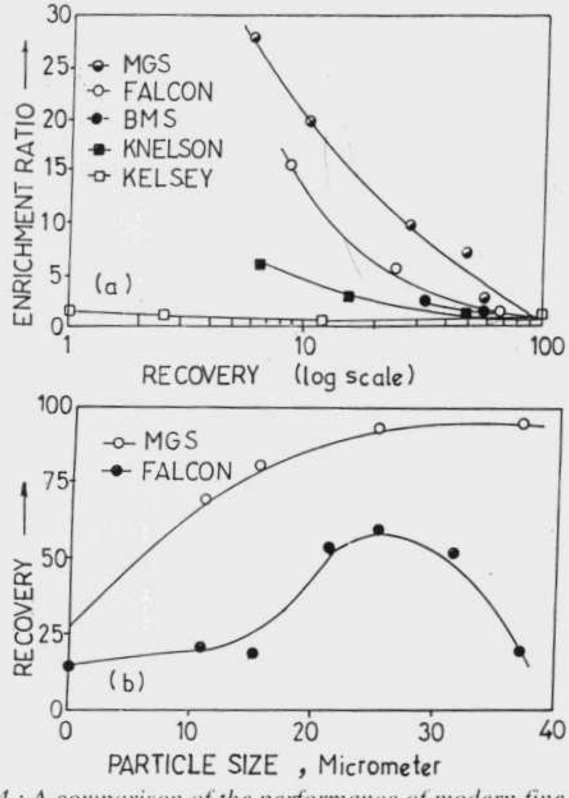

Fig. 4 : A comparison of the performance of modern fine gravity separators for beneficiation of tantalum ore slimes [13].

GRAVITY CONCENTRATION STUDIES AT NML

NML has carried out extensive gravity concentration studies for developing process flowsheets for the beneficiation of low grade metallic and nonmetallic ores and minerals from different sources. The final flow sheets are either based entirely on gravity processes or are a combination of gravity with flotation and/or magnetic separation etc. Some of the important low grade ores processed at NML utilising gravity concentration techniques include iron, blue dust, manganese, tungsten, tin, chromite, pyrite, fluorspar, kyanite, red oxide and coals etc. Some of the modern gravity separators installed at NML include Bartles-Mozley separator, Crossbelt concentrator, Diester diagonal deck concentrating table, GEC Duplex concentrator, Multi-gravity separator, Carpco spirals, Mozley HMS cyclone etc.

The salient results on the use of modern fine gravity separators for the concentration of low grade ores and fines and slimes are discussed below [22,24].

Concentration of Finely Disseminated Tungsten ore Samples Using GEC Duplex Concentrator and Bartles-Mozley Vanner

The tungsten ore is normally beneficiated by gravity concentration techniques followed by cleaning of the gravity-concentrate by magnetic separation and flotation methods [2]. But considering the leanness and the complexity of the Indian ores coupled with the stringent specifications for the concentrate, there is need of upgradation of technology. Studies on beneficiation and purification of tungsten ores was taken as a thrust area project at NML to have a thorough insight into the problem and to develop a radical methodology combining physical and chemical beneficiation routes for processing of lean grade tungsten ore from Degana in particular. It is appropriate to mention here that gravity concentration played an important role in the overall concentration of the ore and in achieving the desired quality of the concentrate [23]. Here some results on the use of GEC-Duplex Concentrator and Bartles-Mozley Vanner are presented.

Pre-concentration of lean grade finely disseminated tungsten ore:

GEC-Duplex concentrator was basically used for the pre-concentration of low grade tungsten bearing granite sample. The sample used for the investigation assayed 0.138% WO_3 with 65.74% SiO_2; 14.74% Al_2O_3, and 6.0% Fe_2O_3. The detailed petrological studies showed the presence of pyrite, pyrrhotite, magnetite, hematite and goethite, martite and ilmenite as the metallic minerals. The rock forming minerals were dominated with quartz, mica, topaz and feldspar. Tungsten was present as wolframite with fine disseminated in the gangues. The liberation of wolfracmite from the gangue minerals was expected below 150/200 mesh. The typical beneficiation results utilising GEC-Duplex concentrator for 150 mesh ground ore are shown in Table 3.

Table 3 : Results on the use of GEC duplex concentrator for lean grade tungsten ore

Products	Wt.%		Assay, % WO_3		Distn., % WO_3	
Conc. I	0.9	5.5	5.11	2.11	29.2	75.4
Conc. II	1.7		1.97		22.0	
Midd. I	2.9		1.28		24.2	
Midd. II	13.0		0.10		8.6	
Pr. Tails	81.5		0.03		16.0	
Head (Calc)	100.0		0.152		10.00	

As we can see from Table 3, the use of GEC-Duplex concentrator has resulted in approximately fifteen fold enrichment in the concentrate starting from a lean grade ore assaying 0.138% WO_3. The combined pre-concentrate assayed 2.11% WO_3 with 5.46% yield and 75.4% recovery.

Beneficiation and purification of tungsten ore pre-concentrate:

The Bartles-Mozley Vanner was used for the beneficiation and purification of tungsten ore pre-concentrates. Broadly qualitatively mineralogical composition of the pre-concentrates was similar but as expected quantitatively these differed widely. In particular wolframite and silicate minerals showed intricate interlocking which warrant for fine grinding. Further some amount of interlocking between wolframite and sulphides and silicates persisted even below 50 microns. This necessitated for the adoption of forth flotation for removal of the major portion of sulphides followed by purification of the sulphide non–float against fine grained silicates using an efficient fine gravity separator. For this purpose Bartles Mozley Vanner was chosen.

The typical results on the use of Bartles-Mozley Vanner for tungsten ore pre-concentrate ground to 200 mesh is shown in Table 4. As it is evident from the data presented in Table 4, that vanner has shown its efficacy in producing a high grade tungsten concentrate assaying 65.65% WO_3 and also satisfied the stringent specifications with respect to low silica and sulphur. The middlings resulted from this operation was suitable for treatment by chemical method.

Use of Multi-Gravity Separator for Processing of Iron and Chromite Ore Slimes

During the washing and beneficiation of iron and chromite ores substantial amount of slimes are produced. These fines and slimes are generally not amenable to beneficiation by conventional techniques and/or the available processes are not

Table 4 : Results on the use of vanner for purification of tungsten ore pre-concentrate

Products		Assay, %			Distn.
	Wt.%	WO_3	SiO_2	S	$\%WO_3$
V. Conc.	28.4	65.65	0.55	0.07	69.1
V. Tails	46.6	6.84	35.49	0.42	14.4
Sul. Float	25.0	17.31	12.62	14.25	16.5
Head (Calc)	100.0	26.16	19.85	3.78	100.00

considered economically variable. Besides the losses of mineral values these slimes cause severe environmental pollution problems [8]. Processing of such slimy material is of great importance to the mineral industries.

Recently studies on the recovery of mineral values from iron and chromite slimes have been carried out at NML using multi-gravity separator (MGS) under the sponsored research projects. The results are briefly discussed below.

Reduction of alumina in iron ore slimes:

The iron ore slimes sample used for the studies assayed 55.5% Fe with 7.45% Al_2O_3 and 4.24% SiO_2. the sample was all passing below 150 mesh. Due to the high alumina and silica content the sample as such is not considered suitable for iron making. MGS was used for processing this sample with a particular reference to reduction of alumina content.

Extensive studies were carried out under the varying conditions of process and machine design parameters. The data are graphically shown in Fig. 5 as yield versus grade plot. As we can see from Fig. 5 for ~2% Al_2O_3 the yield was ~42% with 65.9% Fe and 1.5% SiO_2. Thus the performance of MGS has proved superior over the conventional gravity separators for lowering alumina in the iron ore slimes.

Processing of chromite ore slimes:

The chromite slimes sample, all passing below 40 microns was used for this study. The sample analysed 10.52% Cr_2O_3, 29.6% Fe, 33.60% SiO_2 with 13.13% Al_2O_3. X-ray diffraction and microscopic studies indicated the presence of chromite in association with hematite, goethite, limonite and ilmeno-rutile, quartz with minor proportion of magnetite and some altered silicates.

Like the iron ore slimes the effects of various design and operating parameters were studied in detail for the concentration of above mentioned chromite slimes using MGS. The experimental results on the effects of some of the important

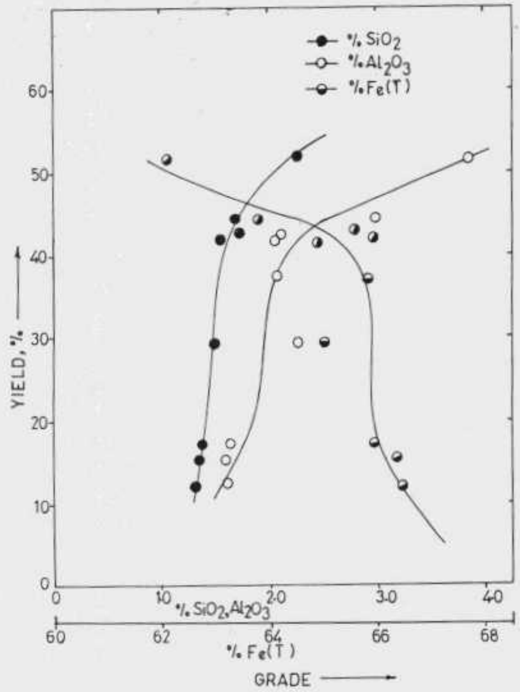

Fig. 5 : Results on concentration of iron ore slimes using MGS.

parameters are shown in Figs. 6 to 8.

Fig. 6 presents the data on the effects of wash water on the concentrate grade at drum speed of 240 and 200 rpm. As we can see from this figure an increase in wash water from 3 to 7 rpm improves the % Cr_2O_3 and decreases the % Fe in the concentrate mainly due to the improved cleaning action at higher rate of wash water addition. This action is more pronounced at low drum speed (200 rpm) as indicated by a sharp rise in concentrate grade. This may be attributed to the better rejection of the lights and middlings' to the stream of lighter particles at reduced value of 'g' at low drum speed.

Fig. 7 shows the effects of drum rotational speed on the assay of the concentrate. At a given slope angle an increase in the drum speed from 160 to 240 increases the 'g' value acting on the particles and causes increase in the weight percent of 'heavies' diluting the concentrate grade. On the other hand high slope improves the grade to some extent but at the cost of yield.

The effect of slope on the concentrate grade at varying wash water is shown in

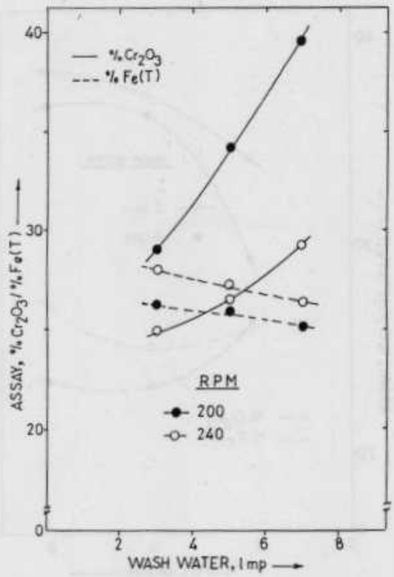

Fig. 6 : Effects of variation of wash water on chromite concentrate grade using MGS.

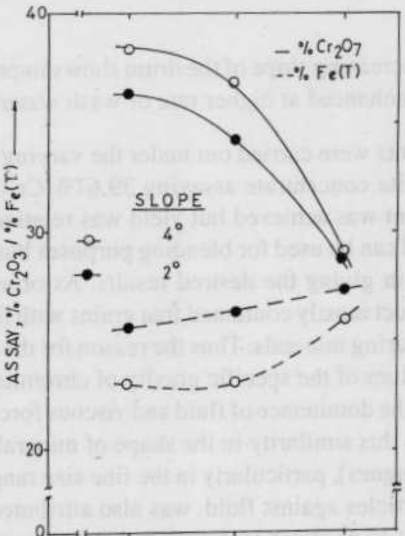

Fig. 7 : Effects of variation of drum speed on the chromite concentrate grade using MGS.

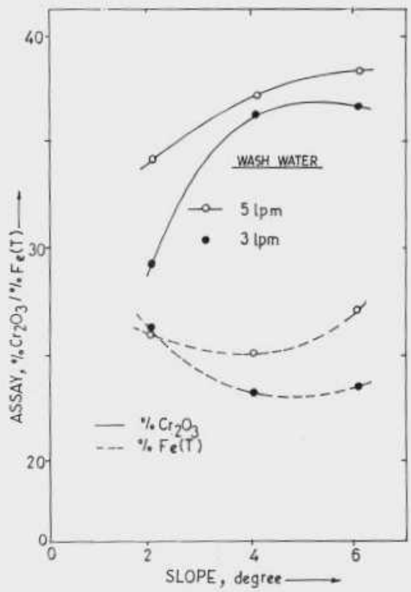

Fig. 8 : Effects of variation of drum slope angle on the chromite concentrate grade using MGS.

Fig. 8. As expected increasing slope of the drum shows improvement in the grade. The effect is further enhanced at higher rate of wash water addition.

Further experiments were carried out under the varying conditions of various parameters. A chromite concentrate assaying 39.67% Cr_2O_3 i.e., approximately four fold improvement was achieved but yield was relatively low. Although the concentrate produced can be used for blending purposes but in this case MGS has shown its limitation in giving the desired results. As observed by microscopic examination the product mostly contained free grains with few locked particles of chromite with iron bearing minerals. Thus the reason for the unsatisfactory results could be the close values of the specific gravity of chromite and the iron bearing gangue minerals and the dominance of fluid and viscous forces in the ultrafine size ranges. In addition to this similarity in the shape of mineral grains (spherical for both chromite and gangues), particularly in the fine size ranges affecting the relative movement of particles against fluid, was also attributed to the cause for unsatisfactory results. It is needless to mention that basic studies are required to clearly understand the role of various factors and to develop means to overcome the same through radical improvement in the machine design and process parameters.

CONCLUSIONS

Gravity concentration processes are the oldest beneficiation methods but its relative importance has declined in 20th century. In the recent times there has been an upsurge of interest, particularly in the development of newer fine gravity separators. Considering the increasing stress from Government agencies for pollution free technologies and the increasing cost of processing of lean grade and complex ores, the gravity methods has lot of potential. The future will depend on the development of methods for an efficient recovery of fine particles perhaps using centrifugal forces coupled with better design of machine and improved methods of comminution.

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