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Recovery of Chromite from Processing Plant Tailing by Vertical Ring and Pulsating High-Gradient Magnetic Separation

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Abstract
Magnetic separation has been used widely since 1955 for processing a variety of minerals from iron ore in steel production to desulphurization of coal. The accumulation of fines and tailing during mineral processing operations and the increasing global demand for quality products motivated the use of the semi-continuous pilot wet high gradient magnetic separator. In this study the possibility of recover the chromites from the tailings of the chromite enrichment plant, by vertical ring and pulsating high gradient wet magnetic separator (VPHGMS) was investigated. Magnetic separation and concentration experiments were studied on pilot scale laboratory with 1-5 tons tailing materials. Tailings were fed first to hydrocyclone then the bottom fluid of the cyclone was fed to magnetic separator. Pre concentrate, obtained by magnetic separator, was beneficiated by shaking tables as a final enrichment step. On the experimental studies different currents (100-400 amperages) were studied to find out the effect of these parameters on the Cr_2O_3 grades and on the recovery yield. Therefore the parameters were evaluated in collaboration with particle size distributions, grades and the quantity of feeding and concentrate. According to experiments 300 amperage was determined as an optimific value. With reference to results 47% Cr_2O_3 concentrates were produced from approximately 3.40 % Cr_2O_3 tailings. Also the efficiency of chromite beneficiation for magnetic and shaking table tests was changed between 40-70 %.

Keywords: Chromites, tailing, recycling, magnetic separation, high-gradient, pulsating, vertical-ring

1.Introduction

Chromium has a wide usage area especially in chemical, refractory, metallurgical and casting industries but the main consumer of chromiums; metallurgy industry with very high share of mined chromite ore in the World around 90% and 80% of these metallurgical converted ferrochromites are using in stainless steel industry (Murthy et al., 2011). The main cause which makes chromium a unique metal is his feature that aid steel industry to produce stainless materials. Despite chromium was discovered first by French chemist Lois Nicholas Vauquelin in Siberia, the importance of this metal was realized by Harry Brearley in 1913 during the preparations of First World War due to same feature of this metal. Harry Brearley was realized during his investigation on samples for moulding artillery tube; all samples except few of them were rusted after that he was analyzed these stainless specimens and find out these steels contain 14% of chromium. This discovery paves the way of usage the chromium in producing of fork, knife and spoon (Das et al., 2012). Also chromium became important in every divisions of human life, especially in military defense industry, and the usage of this metal increases swiftly.

With the decreases of reserves of chromite ore which is the main available source of chromium, the importance of minimizing the losts during processing stages, beneficiation of low grade chromite ores and recovery from tailings become unavoidable. For these kinds of purposes many researchers were studied on magnetic separation possibility of chromite by wet high intensity magnetic separators (WHIMS), dry high-intensity rare-earth drum (RED) separators and dry high-intensity rare-earth roll (RER) separators to find out alternative methods to improve classical methods using for chromite enrichment commonly based on gravity separation such as shaking table, jig, spiral and Reichert cone (Agacayak et. al, 2004; Dobbins et al., 2007; Aslan and Kaya, 2009; Tripaty et. al, 2012; Das, 2015).

According to Livingston (1997) first observation of magnetism go long way back to as early as 550 BC; Euripides stone called the magnet does not simply attract the iron rings, it also impart to the rings a force enabling them to do the same thing as the stone itself which is realized by Socrates. However the practical significance of magnetism and magnetic separation was recognized only as late as middle of the 19th century and since end of the 19th century possibility of magnetic and less magnetic materials was proved (Svoboda and Fujita, 2003). Moreover the development of magnetic separators especially high gradient magnetic separators was declared by some researchers as a most important fact for mineral processing from technical and economical point of view (Silva and Luz, 2013). Nevertheless recent years with appreciable progress to understand the fundamentals of magnetism and development of permanent magnetic materials extend the usage of magnetic separation from coarse to colloidal and from strongly magnetic to diamagnetic materials (Svoboda and Fujita, 2003).

As well as all stages of mineral processing, the magnetic separation technology depends on many factors according to own rights such as particle size, specific assemblage of minerals, grade and corresponding magnetic susceptibility (Dobbins et al., 2007). Additionally WHIMS technology which was studied by researchers to beneficiate chromite ore is traditionally has demonstrated inefficiencies with finer feeds under 100μm (Dobbins et. all, 2007; Dobbins et. all, 2009). After first introducing of Slon Vertical-Ring and Pulsating High Gradient Magnetic Separator (VPHGMS) in 1988, many researchers were studied over fine iron ore minerals and obtained promising results (Dahe, 1993; Dahe, 2000; Zeng and Dahe, 2003; Dahe, 2003; Dobbins et al., 2007; Hearn and Dobbins, 2007; Dobbins et al., 2009; Chen et al., 2009; Umadevi et al., 2012; Chen et al., 2013; Silva and Luz, 2013).

In this study chromite processing plant tailings containing; chromite, olivine and serpentine were beneficiated by VPHGMS and followed by shaking tables. Due to close density of olivine and chromite ores, olivine was removed by VPHGMS as a non-magnetic part and then chromite was cleaned by shaking table from serpentine. During two phased enrichment processes imposed on firstly magnetic susceptibility then density differences of minerals (Table 1). According to the theoretical background vertical pulsating high gradient type magnetic separator was chosen as a magnetic separator due to particle size distribution of tailings which is under 500 µm with Cr_2O_3 grade accumulation under 200 µm. In this study from 200 to 400 amperages with constant ring velocity (4 rpm) and pulsation rate (304 rpm) were suited as working parameters. especially for magnetic separation step encouraging results were obtained on all particle sizes and as distinct from other magnetic separation methods high beneficiation rates and efficiencies for fine particles were also obtained.

Table 1. Magnetic susceptibilities of olivine, chromite and serpentine (Hunt et al.,1995).

Mineral	**Magnetic susceptibility, k (µSI)**	**Density (gr/cm^3)**
Olivine	1,600	4.32
Chromite	3,000-120,000	4.80
Serpentine	3,100-75,000	2.78

2.Slon Vertical Ring Pulsating Magnetic Separator

Magnetic separators were classified by many researchers depending on their different properties but most common and basic classification among these is classifying magnetic separators according to their magnetic field strengths and working with or without water such as low intensity, medium intensity, high intensity and dry or wet magnetic separators.

In this study, types of magnetic separators will not explore but at this point a briefly literature information of the evaluation stages of magnetic separation, particularly in terms of matrix usage could be necessary to better understanding of VPHGMS. The idea Frantz (Frantz, 1937) was told, inspired Jones (1960) to use matrix in magnetic separators and this was a tremendous change on high magnetic field separators and also extended the applicability of magnetic separators dramatically.(Svoboda and Fujita, 2003). Following this; vertical magnetic separator (VMS), developed in Czech Republic, solve the matrix blockage problem of high gradient magnetic separators via vertical rotating ring and reverse flush and finally 'Slon' vertical pulsating high gradient magnetic separator was introduced which is expose slurry within matrix by pulsation (Svoboda and Fujita, 2003). Slon vertical ring and pulsation high-gradient magnetic separator (VPHGMS) was developed in 1988 at Ganzhou Non-Ferrous Metallurgy Research Institute and following that the design was improved by designers to increase the reliability and beneficiation efficiency. VPHGMS was applied firstly in China on production or pilot-plant scales at many companies and promoted the progress of technology at these companies, mines and plants (Dahe, 1993). This novelty on magnetic separation technology excites attention of many researchers and companies. Also scientific and industrial works on VPHGMS was increased rapidly particularly for iron ores (Dahe, 1993; Dahe, 2000; Zeng and Dahe, 2003; Dahe, 2003; Dobbins et al., 2007; Hearn and Dobbins, 2007; Dobbins et al., 2009; Chen et al., 2009; Umadevi et al., 2012; Chen et al., 2013; Silva and Luz, 2013).

2.1.Advantages of VPHGMS

Magnetic separation is under control of competing forces which are acting on the particles and magnetic force. Competing forces mainly consist from gravity force, the inertial force, the hydrodynamic force and surface and inter-particle forces (Svoboda and Fujita, 2003). Particle collection capacity, matrix plugging and particle trapping issues which are interplay each other basically cause unbalance between competing forces and magnetic force in VHIMS.

In magnetic separation on VHIMS, the balance between hydrodynamic drag forces and magnetic attraction forces tend to the drag forces. To overcome capacity problems on WHIMS, increasing the magnetic force is an option to attract weakly magnetic particles but it induces a decrease on effective range, so more points of collection are required to collect fine particles effectively. However, even more grooved plates are using to obtain more collection points it's not possible to overcome the opposing physical forces within magnetic zone for particles around 100 µm (Hearn and Dobbins, 2007). Additionally depending on the particle size distribution hydrodynamic drag force became more important, for instance; same magnetic force effect on 10 times smaller particle and coarse particle which is the smaller particle has 1000 times more magnetic susceptibility then coarse particle (Svoboda and Fujita, 2003). On the other hand matrixes with more collection points are magnetizing and collecting multiple particles at each high-gradient location and also trapping the non-magnetic particles. When coarse particles held the non-magnetic fine particles and non-magnetic particles cannot flow to the non-magnetic launder, as a result of this, reduction in grade and recovery is become unavoidable (Dobbins, 2006).

Innovative features of VPHGMS which are distinguish this technology from other magnetic separators especially from VHIMS can be summarized under 3 titles which are vertical carousel, straightforward rod matrix system and pulsation mechanism. Although these features have a synergy effect on separation efficiency and each of them provides advantages to solve problems on magnetic separation.

Vertical Carousel

The vertical carousel which is opposed to traditional Jones-type WHIMS, allows magnetic flush which is opposed direction of the feed, to remove strongly magnetic and/or coarse particles without passing through the full depth of the matrix volume. Magnetic flushing also reduces any residual grip on the magnetic particles successfully in a location with low stray magnetic field (Dobbins et al., 2009). Hereby, removing a coarse particle by magnetic flush under favor of vertical carousel allows bettering treatment of fine particles and increasing the effective capacity of separator.

Pulsation

Agitating the slurry and keeping particles in a loose state in the separation zone by pulsation assist the performance of the separation minimizing entrapment. Pulsation mechanism creates more usable surface are for magnetic collection through the maximizing particle accumulation on all sides of rod matrix (Dobbins et al., 2009) (Figure 1).

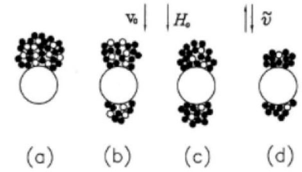

Figure 1. Particle build-up on a single wire in PHGMS: (a) no pulsation; (b) pulsation is weak; (c) pulsation is fair; (d) pulsation is strong (Dahe et al. 1998).

Matrix

Filamentary matrix of VPHGMS constructed of rods which are oriented perpendicular and in equidistant pattern to obtain optimum magnetic force. This pattern minimizing the risk of particle entrapment when compared to randomly positioned filaments (wool) or expanded metal sheets (Dobbins et al., 2009).

2.2.Design and Working Principles of Slon VPHGMS

VPHGMS enables to beneficiate fine weakly magnetic particles through the combined magnetic force field, pulsation in separation zone, gravity and vertical rotating ring which allows flushing magnetic fractions opposite to the feed direction. VPHGMS is a unique magnetic separator with less matrix blockage problems and more flexible and adaptable working conditions when compared to other high-gradient magnetic separators (Figure 2). VPHGMS has a separating zone filled with flowing water, which is adjustable according to purpose and requisite of work, to transmit the pulsation energy to the separation zone. The slurry is feeding into the matrix through feeding box and magnetic particles are attracting onto matrix surface while non-magnetic particles pass through the matrix and go out from tailings output. Particles are effecting combined action of pulsation, gravity, hydrodynamic drag and magnetic force during the process. Particles are threatening in a loose state in the matrix under pulsation mechanism which is assisting capturing magnetic particles more easily by matrix while non-magnetic particles are dragging out through the matrix. Also entrapment of particles is preventing by pulsation too. VPHGMS became a higher performance machine especially for fine weakly magnetic minerals by these innovative features particularly pulsation mechanism compared to other HGMS (Dahe, 1993, Chen et. all, 2013).

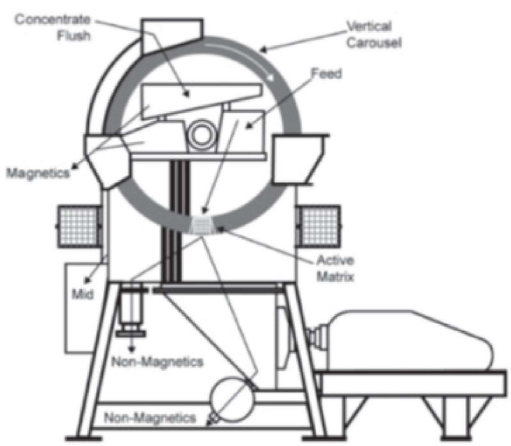

Figure 2. Schematic view of VPGHMS (Url 1).

3.Materials And Methods

3.1. Materials

In this study, Şetat Mining located in Orhaneli-Bursa concentration plant's tailings were used. At this plant chromite enrichment process is based on shaking tables as a gravity separation method but loss of the plant is very high in terms of feed grade which changes between 4.5 to 6 % Cr_2O_3. Also grade of tailing change approximately between 2.60 to 5 % Cr_2O_3 depending on mainly to the feeding grade and efficiency of shaking tables and other factors such as particle size distribution, classifiers efficiency and especially olivine content of ore which is the unique problem of this facility. Excessive amount of olivine presence (around 25-30 %) as a gangue mineral in the ore decrease shaking tables efficiencies regardless to particle size due to close density of olivine (3.2-4.5 gr/cm3) and chromite (4.5-5.09 gr/cm3). On the other hand losses of Cr_2O_3 dramatically increase on fine particles due to more similar acts of olivine and chromite minerals on shaking table (Table 2).

Table 2. Plants tailings representative grade depend on particle size

Particle Size (Micron)	Weight (gr)	Weight (%)	Cumulative Undersize (%)	Cr_2O_3 Grade (%)	Cr_2O_3 Distribution (%)
500	21.86	11.1	100	3.37	13.03
-500+355	24.72	12.64	88.82	2.66	11.63
-355+250	24.88	12.72	76.1	1.72	7.57
-250+180	25.85	13.22	63.46	1.79	8.19
-180+125	25.91	13.25	50.25	1.75	8.02
-125+90	19.55	10.00	37.00	2.29	7.92
-90+36	40.82	20.7	27.00	4.40	31.78
-36	11.99	6.13	6.13	5.57	11.82
Total	195.58	0.00	0.00	2.89	100.00

3.2 Method

In this study VPHGMS which is the best option for fine particles among magnetic separators was used to remove olivine from tailings and following that shaking table was used to remove serpentine. Tailings were fed to VPHGMS with % 25 solid rate and 0,4 Mpa was chosen as a water pressure. Since the tailings were fed from tailing storage area, grades of feeding were not constant and changed between 3-5 % Cr_2O_3. On the contrary, pulsating stroke (20 mm), wire diameter of rod matrix (1.8 mm) were chosen constant. Effect of pulsation and ring were not fully investigated but only some observations were obtained which were leads to choose constant parameters during studies on effect of amperages. The features of VPHGMS used in this study which was rented from Aksa Magnet were given Table 3.

Table 3. Technical features of Aksa Magnet YMS-10 VPHGMS

Ring Dia. (mm)	Ring Width (mm	Ring Speed (rpm)	Feed Size (mm)	Feed Solid (%)	Capacity (t/h)	Magnetic Induction (T)	Pulsating Stroke (mm)	Pulsating Freq. (r/min)	Water Pres. (Mpa)
1000	300	2-4	-1,2	10-40	4-7	1.2	20	0-300	0.2-0.4

In this study amperages from 200 to 400 were investigated with constant pulsation frequency 304 (r/min) and ring 4 (rpm). In other words, magnetic (background) fields which are approximately 0.23, 0.28, 0.32 and 0.46 Tesla generated by Aksa Magnet YMS-10 were studied on VPHGMS for working condition of 200, 250, 300, 400 amperages respectively (Figure 3).

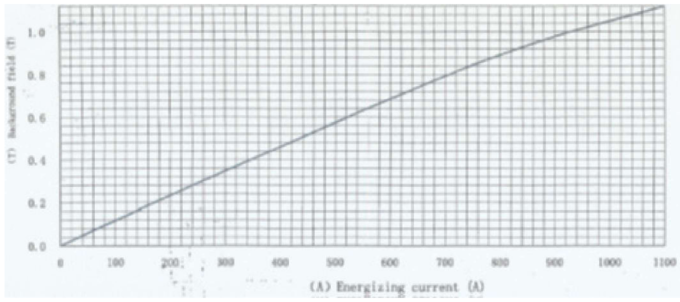

Figure 3. Relation between background field and amperages of VPHGMS

Concentrates of VPHGMS were feed directly to the shaking table to remove serpentine content and produced final concentrate (Figure 4). Shaking table working conditions were kept constant and magnetic concentrate were fed with approximately 15-20 % solid rate (Table 4).

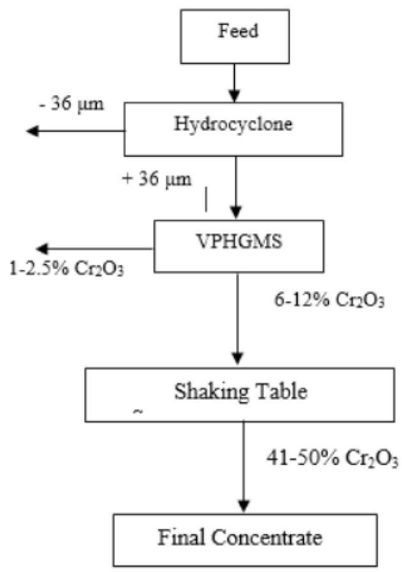

Figure 4. Experimental beneficiating flowsheet of plants tailings

Table 4. Shaking table working conditions

Shaking Table Properties	
Amplitude (mm)	2.20
Frequency (Stroke)	280
Transverse inclination (°)	4
Longidutional inclination (°)	-0.2
Solid Rate %	15-20
Feeding Speed, kg/min	12.5

4. Result And Discussion

The presence of olivine mineral as a gangue in ore deposit effects negatively the gravity separation process and consider a feeding grade led to relatively high value of chromite loss during the concentration stage. In this industrial scale study, Cr_2O_3 content of tailings accumulated mostly in fine sizes were first tried to beneficiate by only shaking table and the process was failed as expected. Because of the close density of olivine and chromite especially under 355 mm, grade of shaking table concentrate decrease dramatically and marketable concentrate couldn't produced by shaking table. By this primer test which was a demonstration of impossibility that producing a marketable concentrate, grade of Cr_2O_3 could increase maximum to 29.13% Cr_2O_3 (Table 5).

For this reason tailings of processing plant were fed first to hydrocylone to get rid of very fine particles (under 36 micron) and then the underflow of hydrocyclone was fed to VPHGMS to remove olivine minerals as a non-magnetic part. Depending on the feeding rate and amperages, relatively high pre-concentrates were produced by VPHGMS which are vary approximately from 6 to 12% Cr_2O_3. Also satisfactory beneficiation in fine particles were obtained which increase linearly while particle size decrease especially from 250 to 36 micron and distribution of Cr_2O_3 was accumulated under 250 micron (around 67%) (Table 6).

From this pre-concentrate marketable Cr_2O_3 concentrates were produced by shaking table under favor of removing olivine minerals via VPHGMS. In this study, from 6.31 to 12.12 % Cr_2O_3 grades with 55 to 88% recovery rates pre concentrates were obtained by VPHGMS depending on the feeding rates and amperages. It's obvious that with an increase of amperages recovery of VPHGMS increase while grade of pre concentrate decrease. The reason of low recovery while operating 200 amperages is insufficient magnetic field (around 0,23 T) to catch chromite particles due to relatively low magnetic susceptibility of chromite. On the other hand high recovery rates but low grades were obtained when operating on 400 amperages (around 0.46 T) due to catching even unliberated particles by magnetic separator. As a result of this marketable final concentrates couldn't produce by shaking table when relatively low grade VPHGMS concentrates were fed to shaking table (Table 7).

Table 5. Shaking table representative concentrate grades depends on particle size which fed from tailing

Particle Size (Micron)	Weight (gr)	Weight (%)	Cumulative Undersize (%)	Cr_2O_3 Grade (%)	Cr_2O_3 Distribution (%)
500	11.81	6.46	-	45.69	10.12
-500+355	19.11	10.45	93.54	48.24	17.29
-355+250	22.52	12.31	83.09	37.85	15.98
-250+180	38.93	21.29	70.78	22.85	16.68
-180+125	54.83	29.98	49.49	19.91	20.47
-125+90	24.39	13.34	19.51	25.71	11.76
-90+36	11.18	6.11	6.18	36.59	7.67
-36	0.12	0.07	0.07	14.59	0.03
Total	182.89	100	-	29.16	100.00

Table 6. VPHGMS concentrate (pre-concentrate) grades depends on particle size distribution

Particle Size (Micron)	Weight (gr)	Weight (%)	Cumulative Undersize (%)	Cr_2O_3 Grade (%)	Cr_2O_3 Distribution (%)
500	46.34	24.66	-	3.91	11.35
-500+355	20.75	11.04	75.34	5.35	6.95
-355+250	18.52	9.86	64.29	3.26	3.78
-250+180	18.75	9.98	54.43	8.03	9.43
-180+125	22.53	11.99	44.45	10.29	14.52
-125+90	18.10	9.63	32.46	13.25	15.02
-90+36	33.69	17.93	22.30	14.49	30.57
-36	9.20	4.90	4.90	14.59	8.41
Total	169.88	100.00	-	8.50	100.00

Table 7. Experiment parameters and analyzes of VPHGMS and shaking table

Magnetic Field (A)	Tailings Grade (%)	Feed Amount (kg)	VPHGMS Conc. Grade (%)	VPHGMS Tailings Grade (%)	VPHGMS Tailings Amount (kg)	Shaking Table Conc. Grade (%)	Shaking Table Conc. Amount (kg)	VGHGMS Recov. (%)	Shaking Table Recov. (%)	Overall Recov. (%)
200	3.4	2998	10.01	2.49	2433	50.16	37.5	55	33	18
250	4.00	4690	12.12	2.30	3551	42.35	95	74	29	21
300	3.4	3295	11.95	1.90	2520	47.08	78.5	83	40	33
300	3.65	3114	10.4	1.93	2296	47.57	77	75	43	32
300	3.65	3114	10.4	1.93	2296	47.57	77	75	43	32
300	4.15	780	6.72	1.55	388	44.36	19.4	81	33	27
300	3.60	780	6.31	1.46	436	42.36	19	77	37	29
400	3.02	3441	6.65	1.01	2073	41.70	86.5	88	40	35
400	3.65	2606	6.63	1.32	1462	42.36	60	80	34	27

Analyzes of shaking table concentrates (final concentrate) reveal that beneficiation of fine particles by gravity process also increase as expected when olivine minerals removed by VPHGMS (Table 8). Also 300 A was found as optimum amperage among studied amperages according to relation between grade and recovery (Figure 5).

Table 8. Shaking table representative concentrate fed from VPHGMS

Particle Size (Micron)	Weight (gr)	Weight (%)	Cumulative Undersize (%)	Cr_2O_3 Grade (%)	Cr_2O_3 Distribution (%)
500	46.34	24.66	-	3.91	11.35
-500+355	20.75	11.04	75.34	5.35	6.95
-355+250	18.52	9.86	64.29	3.26	3.78
-250+180	18.75	9.98	54.43	8.03	9.43
-180+125	22.53	11.99	44.45	10.29	14.52
-125+90	18.10	9.63	32.46	13.25	15.02
-90+36	33.69	17.93	22.30	14.49	30.57
-36	9.20	4.90	4.90	14.59	8.41
Total	169.88	100.00	-	8.50	100.00

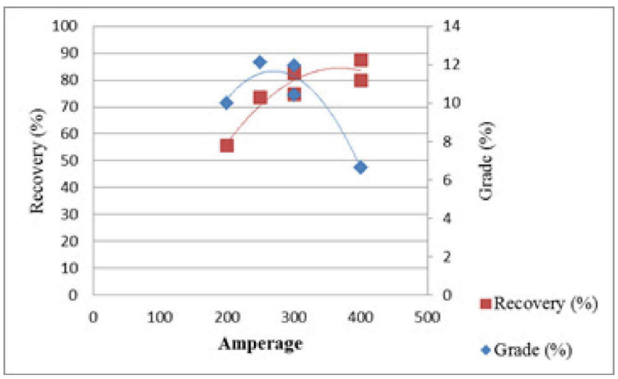

Figure 5. Effect of amperage on recovery and grade

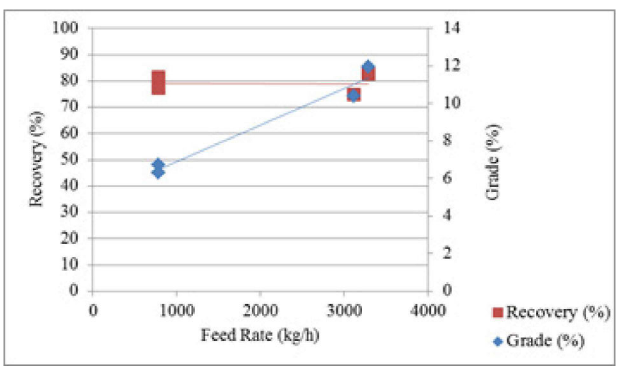

Figure 6. Effect of feed rate on recovery and grade

Beside these effect of feeding rate was investigated for 300 A. Results indicate that when feeding rate is less than 1000 kg/h, grade of the VPHGMS decrease dramatically. On the other hand feeding rate has no important effect on recovery among studied values. Even it could say the optimum feeding rate is a 3000 kg/h for this study, the need to comprehensive further studies to determination of optimum feeding rate is obvious (Figure 6).

5.Conclusions

Magnetic separation technologies have been used in recovery and concentration of different minerals including chromite minerals. Fine particle chromite ores and tailings of plants processed via high intensity magnetic separators by many researchers and VPHGMS were used to beneficiate especially iron ores but VPHGMS usage for enrichment of chromite ores and recovery of chromite tailings is limited.

In this industrial scale study, chromite tailings of typical chromite processing plant which have 2.60 to 5% Cr_2O_3 content were recovered by VPHGMS and pre concentrates were produced with relatively high grades (6-12% Cr_2O_3). Following that these pre concentrates cleaned substantially from olivine minerals were fed to shaking table and marketable chromite concentrates were obtained. Some important results of this study were specified below;

- In this study, pre concentrates have approximately 6-12% Cr_2O_3 content with 55-80% recovery of magnetic separation part were produced as pre concentrates from plants tailings with 2.6-5% Cr_2O_3. After that from these pre-concentrates bendable or direct sealable final concentrates have 41.70-50.16% Cr_2O_3 content with 29-43% recovery value were produced by shaking table.
- It’s obvious that marketable chromite ore can produced from plants tailings with two steps which are VPHGMS and following that shaking table with approximately 30% overall recovery and 47% Cr_2O_3 content.
- When the recovery of Cr_2O_3 from tailings and grade of pre concentrate produced by VPHGMS were evaluated together in constant pulsation frequency 300 A (0.32 T) was found as an optimum amperage to beneficiate this chromite tailings.
- Results about feeding rate experiments show that under limits of VPHGMS feeding rates produced pre concentrates’ grades are very low which cannot beneficiate in shaking table stage while recovery rate is very high. The main reason of this result is presence of too many free places on matrix of separator which cause to catch almost all particles even if they are unliberated particles with small chromite pieces.
- Further studies are needed to determine exact optimum working conditions of VPHGMS for using on chromite. Effect of pulsation, magnetic field strength, feeding rate and grade, water pressure and wire diameters of rod matrix have to investigate detailed to find out combined effect of vertical pulsating high gradient magnetic separator working parameters on chromite beneficiation.

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