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Investigation of chromite recovery possibilities from coarse and fine plant tailings

İri ve ince tesis atıklarından kromit kazanım olasılıklarının incelenmesi

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A B S T R A C T

Tailing streams of an existing chromite plant were characterized and then beneficiated in different methods. Characterization studies have been indicated that chromite grains finely disseminated on the coarse gangue particles in all size fractions (+100 µm). Increase in fineness did not show a significant effect on disseminated chromite grains during coarse tailing beneficiation studies. Neither a salable concentrate nor an acceptable recovery could not be obtained from coarse tailing. For this reason, optimization studies were focused on fine tailing sample. Removal of the gangue minerals was determined to be more efficient using gravity concentration rather than magnetic separation. The effect of parameters of shaking table were optimized using empirical models. It was determined that grade and recovery in the concentrate majorly depended on the variation of table slope. To achieve high grade (>42%) with acceptable recovery (>40%), a medium level of wash water (>4lpm) and lower level of table slope (<3 degree) is necessary. Validation of the empirical models were verified with set of tests which measured versus predicted values resulted good agreement on the y=x line.

Keywords: *Chromite, Plant in tailings, Experimental design, Shaking table, Magnetic separation*

Introduction

The low-grade chromite ores found around the world are mined and beneficiated by using several gravity concentration methods. Density-based separations are the most convenient and cost effective methods for chromite beneficiation. Effective separation of chromite from gangue minerals is very crucial in case of the complexity of ore texture along with presence of near density minerals. The amount of minerals and/or metals that remain in tailings depends mainly on the separation and extraction methods employed, the equipment efficiencies and ore texture. The design and selection of these methods is based primarily on the characteristics of ores.

Mineralogical characteristic, chemical composition and mineral liberation are also essential when considering tailings for reprocessing as a secondary source of minerals and metals of economic interest. Concentration methods for tailings reprocessing may differ those initially used for treatment of primary ores due to mineral variations (Mulenshi et al., 2019).

To avoid loss of valuable minerals to tailings, it has become increasingly attractive to upgrade the ore tails using the appropriate concentration method (gravity separation, magnetic separation and flotation) as pre-determined by the characterization results (Araujo et al., 2004). The importance of ore characterization and characterization techniques well described in the literature (Can and Çelik, 2009; Çelik and Can, 2009; Ozcan et al., 2019).

Globally, significant research effort has been focused on recovery of chromite plant tailings. Many studies have been focused on recovering chromite from the plant tailings (Goodman et al., 1985; Rao et al., 1987; Kumar et al., 2009; Murthy et al., 2011; Tripathy et al, 2011; Tripathy et al., 2013; Tripathy et al., 2017).

In the last two decades, many processes for the recovery of Turkish chromite and plant tailings have been performed and reported (Guney et al., 1991; Ucbas and Ozdag, 1994; Cicek et al., 1998; Gence, 1999; Ozkan and İpekoglu, 2001; Cicek and Cocen, 2002; Ozcan and Ergun, 2013; Altın et al., 2018; Can et al., 2019; Deniz, 2019).

The tailing generated from the Turkish chromite beneficiation plants were treated in the multi gravity separator for producing the desirable grade concentrate (Cicek et al., 1998; Cicek and Cocen, 2002; Ozkan and İpekoglu, 2001). Low-grade chromite sample from Karaburhan ore was treated with combination of wet shaking table and multi-gravity separator for obtaining marketable grade (Sonmez and Turgut, 1998). A combination of multi gravity separator and column flotation has been studied for the upgradation of the plant tailing in Turkey (Guney et al., 2001).

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These studies mostly dealt with the grade and recovery of the products, and there is lack of studies on size based classification of tailings, textural properties of the tailings and liberation characteristics of chromite in the bulk ores and the plant tailings. In the literature limited studies were performed on bulk ores and plant tailings (Gu and Wills, 1988; Das, 2015; Can et al., 2019).

Characterization of chromite plant tailings is fundamental to identify their physical, chemical and mineralogical characteristics and to develop an optimum beneficiation route and flowsheet.

Statistical design of experiments refers to the process of planning the experiment so that appropriate data will be collected and analyzed by statistical methods, resulting in valid and objective conclusions. The statistical approach to experimental design is necessary if we wish to draw meaningful conclusions from the data (Montgomery, 2017).

Factorial designs are widely used in experiments involving several factors where it is necessary to study the joint effect of the factors on a response. The most important of special cases is that of k factors, each at only two levels. These levels may be quantitative, such as two values of temperature, pressure, or time; or they may be qualitative, such as two machines, two operators, the "high" and "low" levels of a factor, or perhaps the presence and absence of a factor. A complete replicate of such a design requires 2 x 2 x . . . x 2 = 2k observations and is called a 2k factorial design (Mee, 2009; Montgomery, 2017).

Suppose that three factors, A, B, and C, each at two levels, are of interest. The design is called a 2^3 factorial design, and the eight treatment combinations can now be displayed geometrically as a cube (Taguchi, 1987). Using the "+ and -" orthogonal coding to represent the low and high levels of the factors, we may list the eight runs in the 2^3 design. There are seven degrees of freedom between the eight treatment combinations in the 2^3 design. Three degrees of freedom are associated with the main effects of A, B, and C. Four degrees of freedom are associated with interactions; one each with AB, AC, and BC and one with ABC. Many statistics software packages are available that will set up and analyze two-level factorial designs. The output from one of these computer programs, is shown in a Table. In the upper part of the table, an ANOVA for the full model is presented (Montgomery, 2017).

Box and Behnken (1960) have proposed some three level designs for fitting response surfaces. These designs are formed by combining 2k factorials with incomplete block designs. The resulting designs are usually very efficient in terms of the number of required runs, and they are either rotatable or nearly rotatable. the Box–Behnken design is a spherical design, with all points lying on a sphere of radius. Also, the Box–Behnken design does not contain any points at the vertices of the cubic region created by the upper and lower limits for each variable. This could be advantageous when the points on the corners of the cube represent factor-level combinations that are prohibitively expensive or impossible to test because of physical process constraints (Montgomery, 2017).

In the present study, detailed characterization and beneficiation of chromite plant tailing by shaking table with various deck surfaces, high intensity magnetic separation and ultra-fine desliming have been studied. The experimental program was designed after characterization of tailing samples. Two different strategy has been followed at coarse tailing and fine tailing samples. Optimization of shaking table performance was determined for the grade and recovery of Cr_2O_3 in the concentrate fraction using empirical models which were derived from the experimental data. The levels of process variables have been adjusted according to particle size distribution of samples and physical limits of laboratory equipment and facilities. The effect of most significant process variables and their interactions are analyzed using ANOVA and 3D surface plots. Also validations of the obtained empirical models were done by set of tests.

1. Sampling studies

A detailed sampling campaign was performed in a chromite concentration plant in Turkey. The simplified flowsheet of the plant and sampling points are shown in Figure 1. Chromite concentration plant have two parallel circuit. Grinding circuit of each part consist of two ball mills with a grinding size of P_{80} 960 µm. The mills are closed circuit with screens with a 600 µm opening size. Screen oversize recirculates to ball mill. Screen undersize stream is fed to cyclone and cyclone overflow rejects as fine tailing. Cyclone underflow stream is fed to spiral concentration circuit to obtain a pre-concentrate. The spiral concentration circuit consist of a rougher, a scavenger and three stage cleaner spirals. The tailing of the spiral concentration circuit is spiral tailing. Spiral concentrate fed to teetered bed separator (TBS) to obtain two narrow size fractions for final concentration stages. TBS underflow is fed to coarse tables and TBS overflow stream is fed to fine tables. The tailings of coarse and fine tables rejects as coarse table tailing and fine table tailing.

A detailed sampling campaign has been performed to obtain tailing samples from operating plant. To obtain representative samples for each stream a long period sampling has been performed. Sampling campaign was completed in a week (21 shifts). In each shift tailing samples were collected and accumulated. Prior to each sampling survey, steady state conditions were verified by examining the values of variables recorded in the control room.

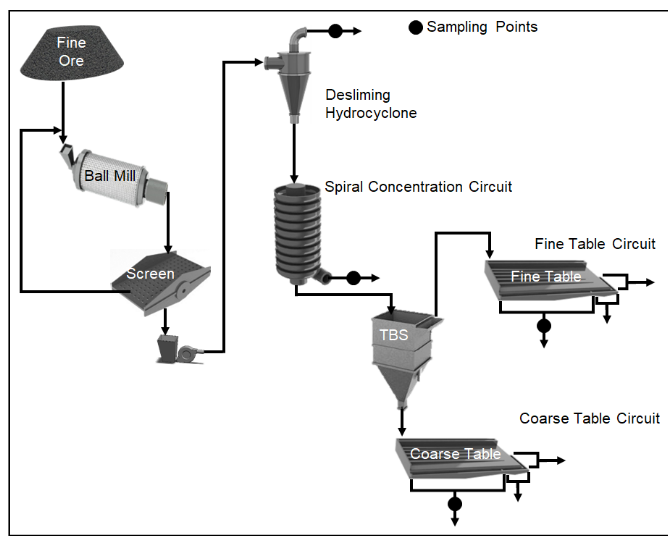

Figure 1. *Simplified flowsheet of chromite concentration plant and sampling points*

2. Characterization studies

The collected samples were characterized in detail in terms of their physical and chemical properties to identify the chromite behavior in tailing stream. The previous modal mineralogy and liberation data on run of mine ore (R.O.M) were also used. The detailed procedures of characterization studies are explained below.

2.1. Mineralogical analysis

Detailed modal mineralogical investigations and liberation analyses on R.O.M were performed and reported (Can et al., 2019). According to modal mineralogical analyses it was reported that the R.O.M ore is mainly associated with magnesium silicates (forsterite) 86.46%, oxide minerals (brucite) 5.48% and hematite and goethite 0.3% with 5.25% of chromite content. The percentages of Cr and Fe in chromite were 46.46% and 24.94%, respectively.

According to liberation analysis, chromite and forsterite as it is the major gangue mineral in the ore have a liberation degree of more than 80% in the particle size range of −200+20 µm (Can et al., 2019). The MLA listed all the locking minerals and 13.46% of this amount was resulted from forsterite mineral. (Can et al., 2019).

2.2. Particle size distribution

Particle size distributions of each sample has been determined from top size down to 20 µm by using the wet Vibratory Laboratory Sieve Shaker (RETSCH AS 200 basic). Particle size distributions of samples are shown in Figure 2.

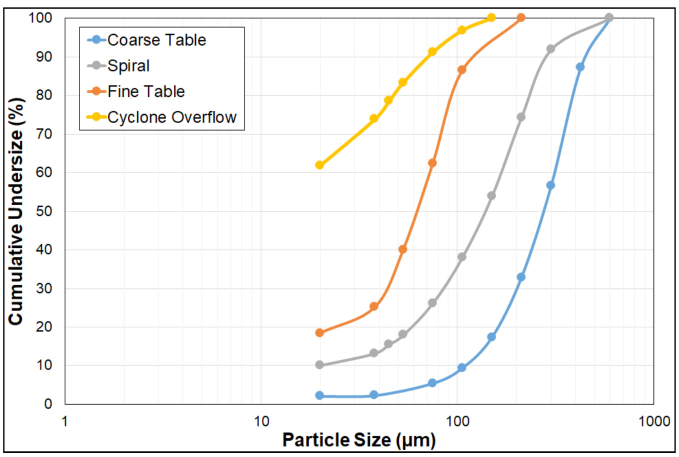

Figure 2. *Measured particle size distributions of samples*

As it can be seen in Figure 2 that coarse table tailing has the coarsest particle size distribution while cyclone overflow has the finest particle size distribution as expected. It is elucidated from the size distributions that the cyclone overflow is extremely fine in nature and substantial amount of the sample is finer than 20 µm (61.82wt%). Coarse table tailing has the lowest amount of -20 µm fraction. It can be seen in Figure 2 that fine table tailing and spiral tailing samples also have particles below 20 µm. It can be a result of lower classification efficiency of desliming cyclone uses to remove -45 µm particles in the gravity concentration circuit feed.

2.3. Image analyses of fractions

Image analysis have been performed to evaluate the textural properties of locked particles by using a Clemex Vision type optical microscope (Figure 3). During the analysis numerous images of +100 µm size fractions were taken. The relationship of the chromite and gangue minerals in the fractions were determined using the images. The general textural views of images are shown in Figure 4.

It is observed from Figure 4 that very fine disseminated chromite grains in the coarse gangue particles. The general view of particles is similar in all tailing samples. No liberated chromite particles were observed in -600+425 µm, -425+300 µm, -300+212 and -212+150 µm fractions. The number of liberated chromite in -150+106 µm fraction is negligible.

Can et al. (2019) also used to determine the liberation of the chromite mineral at coarser particle sizes by using Clemex Vision P.E 5.0 image analysis software. The ore was crushed down to 1 mm and sieved to narrow particle size fractions to facilitate the liberation analysis. The liberation degree of chromite is reported as very low, particularly in the case of coarse sizes; however, they were reported that significant liberation (>75%) can be achieved at sizes finer than 0.300 mm, which was also supported by the MLA (Can et al, 2019). The image analysis results of this study are in broad agreement with those of previous results. No locked particles were observed in the size fractions of the tailing samples. However, there are very fine and disseminated chromite grains on almost all particles.

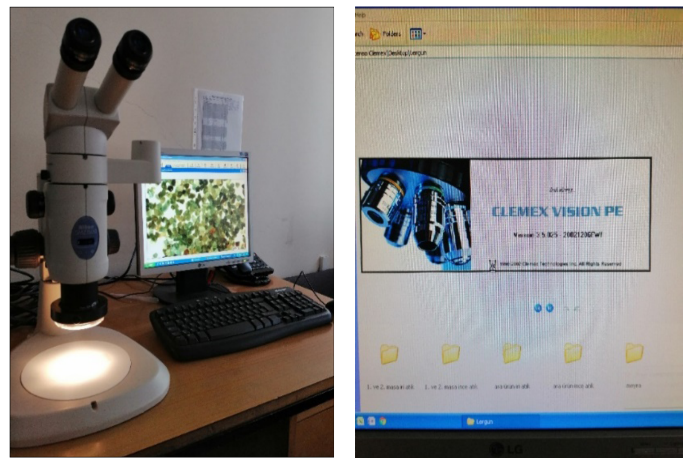

Figure 3. *General view of optical microscope and image analysis software*

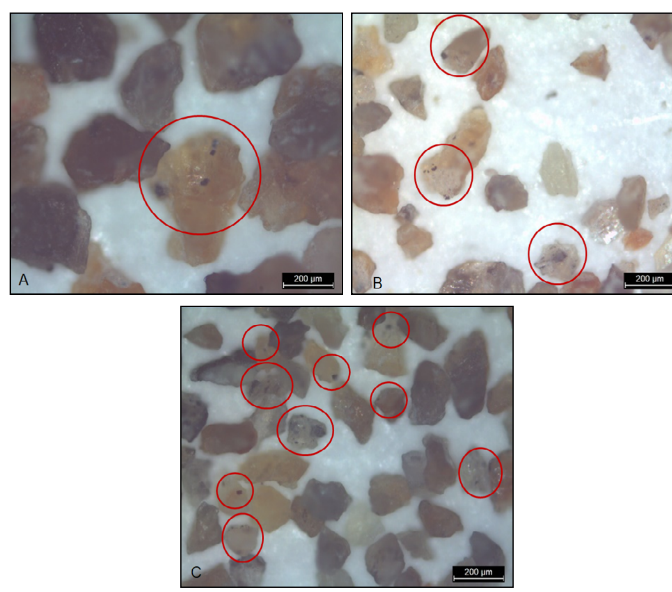

Figure 4. *General view of particles in the tailings (A spiral tailing, B coarse table tailing, C fine table tailing)*

2.4. Fractional chromite analysis

All size fractions obtained from sieve analyses were subjected to chromite analysis by using the wet titration chemical analysis method. Fractional chromite analysis results are tabulated between Table 1 and Table 4.

Table 1. *Fractional Cr_2O_3 content of cyclone overflow*

Size Fraction (μm)	Weight (%)	Cumulative Weight (%)	Grade (%)	Distribution (%)	Cumulative Distribution (%)
-150+106	3.14	100.00	3.21	3.07	100.00
-106+75	5.67	96.86	3.11	5.37	96.93
-75+53	7.86	91.19	2.98	7.13	91.56
-53+45	4.74	83.33	3.60	5.20	84.43
-45+38	4.74	78.59	3.16	4.56	79.24
-38+20	12.03	73.85	4.51	16.52	74.68
-20	61.82	61.82	3.09	58.16	58.16
Total	**100.00**		3.28	100.00	

Table 2. *Fractional Cr_2O_3 content of spiral tailing*

Size Fraction (μm)	Weight (%)	Cumulative Weight (%)	Grade (%)	Distribution (%)	Cumulative Distribution (%)
-600+300	8.15	100.00	1.92	8.05	100.00
-300+212	17.61	91.85	1.08	9.79	91.95
-212+150	20.44	74.24	1.12	11.78	82.17
-150+106	15.81	53.80	1.46	11.88	70.39
-106+75	11.84	37.99	1.10	6.71	58.51
-75+53	8.22	26.15	1.72	7.27	51.81
-53+45	2.41	17.93	6.48	8.03	44.54
-45+38	2.31	15.52	6.75	8.03	36.51
-38+20	3.13	13.21	6.22	9.99	28.48
-20	10.08	10.08	3.57	18.50	18.50
Total	100.00		1.95	100.00	

Table 3. *Fractional Cr_2O_3 content of coarse table tailing*

Size Fraction (μm)	Weight (%)	Cumulative Weight (%)	Grade (%)	Distribution (%)	Cumulative Distribution (%)
-600+425	12.79	100.00	3.26	13.48	100.00
-425+300	30.71	87.21	3.18	31.59	86.52
-300+212	23.66	56.50	3.34	25.56	54.93
-212+150	15.51	32.84	3.01	15.10	29.37
-150+106	7.93	17.33	1.52	3.90	14.27
-106+75	3.94	9.39	3.34	4.26	10.37
-75+38	3.15	5.45	4.06	4.14	6.11
-38+20	0.21	2.29	4.29	0.30	1.97
-20	2.08	2.08	2.48	1.67	1.67
Total	**100.00**		3.09	100.00	

Table 4. *Fractional Cr_2O_3 content of fine table tailing*

Size Fraction (μm)	Weight (%)	Cumulative Weight (%)	Grade (%)	Distribution (%)	Cumulative Distribution (%)
-212+106	13.48	100.00	3.83	15.65	100.00
-106+75	24.12	86.52	1.44	10.53	84.35
-75+53	22.40	62.40	1.30	8.82	73.83
-53+38	14.85	40.00	3.54	15.93	65.00
-38+20	6.71	25.15	8.99	18.28	49.07
-20	18.44	18.44	5.51	30.79	30.79
Total	**100.00**		3.30	100.00	

Fractional chemical analysis show that the chromite content of tailings varies from 1.95% to 3.30% and the fine table tailing has the highest chromite content. As it can be seen in Table 1 to Table 4 that the Cr_2O_3 content of size fractions varies from 1.08% to 8.99%. As the particle size decreases, chromite content increases up to 38 µm, and below that, it decreases significantly. Highest chromite contents can be obtained between -75+38 µm size fractions. According to previous mineralogical analyses (Can et al., 2019) and fractional chemical analyses results it can be concluded that larger amount of alumina, silica and MgO distributes below -38 µm size fraction.

-38 µm size fraction contains approximately 75% weight of chromite in cyclone overflow (Table 1). However, there is a significant decrease in chromite loss of +38 µm size fractions. According to this result, it can be established a relationship between ultrafine generation in the ball mill and chromite losses in the cyclone overflow. Grinding in any beneficiation plant is a critical unit operation to achieve the desired product size and to control the generation of the ultrafine particles. Furthermore, the current plant data reports that the amount of -38 µm material in the mill discharge is about 15%. It can be concluded from Table 1 that the generation of ultrafine particles causes high amount of ultrafine chromite losses in the cyclone overflow. In addition, bypass of some ultrafine particles to the cyclone underflow stream also adversely affects the efficiency of downstream processes.

Chromite distribution of spiral tailing can be evaluated in two different part. It is known from liberation studies that the degree of liberation of chromite is very low, particularly in the case of coarse sizes; however, liberation degree increases significantly (>75%) at sizes finer than 300 µm. Table 2 shows that chromite losses in the spiral circuit increase significantly below 100 µm. Spiral concentrators are gravity separators usually separating particle sizes between 0.1 and 2 mm in a water carrier medium (Holland-Batt, 1995; Wills and Napier-Munn, 2006). Feed size distribution is a crucial point in spiral concentration. Recovery of particles decreases sharply below 75 µm (Hearn, 2002). Size fractions below 40 µm can be described as slime fraction in spiral concentration (İzerdem, 2018). It is known that the high levels of slime adversely affect the performance of spiral concentrators (Brown, 2001; Abela, 2003; Ramsaywok et al, 2010). The previous studies showed that the slime content of the spiral concentrator feed should be reduced to around 10% to ensure good separation (Brown, 2001). However, another work indicates a negative effect even at lower slimes content (Ramsaywok et al, 2010). According to Gupta and Yan (2016), the presence of slimes adversely affects the spiral performance. More than 5% of −45 µm slimes will negatively affect the separation efficiency (Gupta and Yan, 2016). In the present study, spiral concentrator feed (cyclone underflow) contains 11.33 wt% slime fraction which is higher than the recommended values. The slime fraction increases to 15.52 wt% in the spiral tailing. The high amount of slime fraction in the spiral feed can be a reason of chromite loss in the fraction finer than 100 µm. Microscope images of the -600+300 µm fraction revealed that there are no liberated chromite particles in this size fraction. In addition, the number of chromite-bearing grains is limited. However, finely disseminated chromite grains were observed in almost all particles (Figure 4A). The results of the fractional chemical analysis and microscope images are interpreted that liberated and locked chromite particles were concentrated in spiral circuit with higher efficiency. Similar images were captured from -300+212 µm and -212+150 µm size fractions. A significant decrease of number of disseminated chromite could not be observed as the particle size decreases. According to results it can be revealed that chromite losses of +100 µm fractions in spiral tailing is in the form of very fine disseminated locked particles. The absence of liberated chromite in the spiral tailing above 100 µm fraction is interpreted as chromite loss due to material properties rather than operational conditions.

It is observed from the Table 3 that 89.63% of the chromite is distributed at coarser than 100 µm. Similarly, it is known from Figure 2 that approximately 90wt% of coarse table tailing is coarser than 100 µm, which means that the amount of finer fraction is very low in the coarse table circuit. Only 10wt% of the chromite is distributed below 100 µm. It can be revealed that with narrow size fraction and sufficient liberation, coarse table can separate finer size chromite effectively. This also shows the importance of removal of slime fraction and sort material in narrow size/density fractions in order to improve the recovery of shaking tables. It is observed from image analyses that very fine disseminated chromite grains report to tailing with coarse gangue particles. The textural behavior of these particles is similar with spiral tailing sample (Figure 4B). It is unlikely that these very fine chromite grains on the coarse gangue particles will be liberated after a regrinding operation. No liberated chromite particles were observed in -425+300 µm, and -300+212 µm fractions. The number of liberated chromite in -150+106 µm fraction is negligible. It can be considering that 90.61wt% of the coarse table tailing is coarser than 150 µm and the chromite in this size is in the form of completely very fine disseminated locked particles.

It is observed from the Table 4 that 73.83% of the chromite is distributed below 75 µm. Fractional chromite distribution of fine table tailing shows a similar trend with fractional chromite distributions of spiral tailing (Figure 4C). Therefore, the increasing chromite distribution below 75 µm can be described as adversely effect of fine and ultrafine particles on the separation efficiency of gravity concentration equipment. Chromite distribution of tailing decreases significantly in intermediate size range (-212+75 µm). It is revealed that the importance of removal of ultrafine particles, and sort material in narrow size/density fractions for coarse and fine table circuits.

3. Beneficiation studies

In this part of the study, different beneficiation methods, including regrinding, desliming, high intensity magnetic separation and shaking table have been performed for recover of chromite from tailing samples. According to detailed characterization studies the tailing samples were divided as fine and coarse samples. The fine tailing has been described as cyclone overflow, however, coarse tailings have been defined as a sum of spiral and table tailings. Suitable methods and statistical experimental programs have been developed according to size distributions and textural properties of tailing samples.

Wet shaking table tests were performed as a final concentration method on coarse and fine tailing samples separately. A sand deck surface was used to recovering coarse tailing after regrind. The slime deck surface is used for recovering fine particles in the fine tailing. Several tests were carried out by varying the process variables of the shaking table and magnetic separator.

3.1. Beneficiation studies with coarse tailing

The textural properties of locked particles and distribution of chromite in spiral and table tailings sign a difficult beneficiation situation. According to detailed characterization test results; it was revealed that chromite losses above 100 µm fractions in concentration circuit is in the form of intergrowths particles. Therefore, a size reduction of the coarse tailing below 212 µm can helps a partial liberation. Considering the liberation data, it was envisaged that an ultra-fine grinding will be required to achieve a better liberation. However, it is a crucial point that it is more energy intensive to ultra-fine grinding by using conventional grinding methods in an operating plant. In addition to this, it is well known that slime size had an extreme negative effect on separation efficiency of conventional gravity separation equipment. For these reasons 212 µm feed size has been determined both to obtain a partial liberation and minimum amount of finer size particles. The simplified flowsheet of coarse tailing beneficiation studies is shown in Figure 5.

As shown in Figure 5, spiral tailing, coarse table tailing and fine table tailing samples were blended, prescreened and crushed below 212 µm in a laboratory scale roller crusher. Then, slime size (P_{80} 17 µm) was discarded by using a laboratory scale hydrocyclone to prevent the negative effect of slimes on the final beneficiation stage. Particle size distribution of hydrocyclone products were determined by using a Sympatec laser sizer in wet mode. Then, all products were subjected to chemical analysis.

After desliming process, coarse tailing sample was beneficiated in a laboratory scale shaking table (Figure 6). In the shaking table tests, three operational parameters were considered with each factor at three levels as tabulated in Table 5. A Taguchi L8 design has been performed to determine the effect of operational parameters to achieve maximum grade and recovery.

Table 5. *Operational parameters and their levels for coarse tailing beneficiation tests*

Parameters	Low Level (L)	High Level (H)
Feed rate (g/min)	1200	1800
Wash Water Rate (l/min)	10	15
Table Slope (degrees)	4	6

3.2. Beneficiation studies with fine tailing

Evaluations on the cyclone overflow sample revealed that 74.68% of the chromite is distributed at slime size range below 38 µm. In order to recovery of fine chromite from cyclone overflow sample detailed experimental studies were performed (Figure 7). In the first stage of fine tailing beneficiation studies, the sample has been subjected to ultra-fine size classification. A 50 mm diameter laboratory scale hydrocyclone (Richard Mozley Ltd.) was used for the test work. The laboratory scale hydrocyclone has an ability to closed circuit testing with a slurry pump and a bypass line (Figure 8). Slurry feed rate to the hydrocyclone and the feed pressure was adjusted using the by-pass valve. Before performing the experiment, pre-calculated amount of test material and water were properly mixed in the slurry tank to obtain the desired feed pulp density.

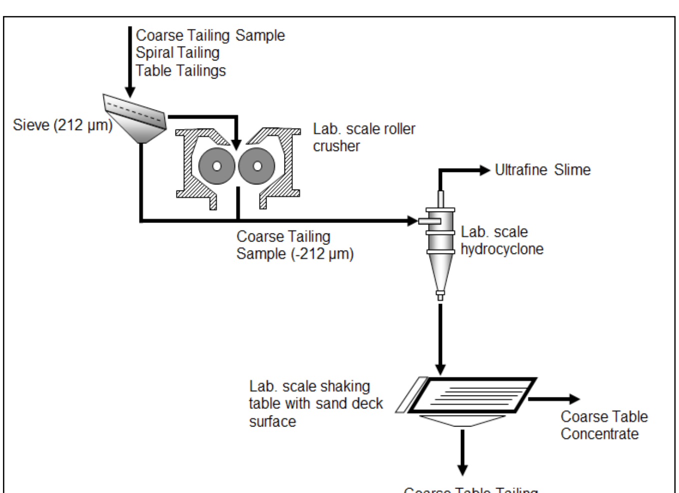

Figure 5. *Simplified flowsheet of coarse tailing sample beneficiation studies*

Figure 6. *General view of shaking table with sand surface, feeder and sampling apparatus*

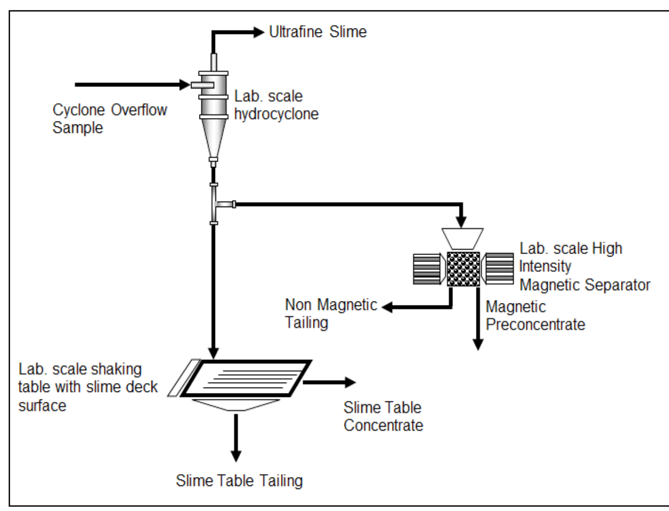

Figure 7. *Simplified flowsheet of fine tailing sample beneficiation studies*

Figure 8. *Mozley laboratory scale hydrocyclone and apex apparatus*

Solid content of the hydrocyclone feed was diluted below 10% in order to aid ultrafine separation. The circuit was allowed to perform for a five minutes to obtain a steady state condition. Then, the samples were collected using a hand cutter under steady-state condition. After collecting sample for each step particle size distribution of hydrocyclone overflow sample was determined by using a Sympatec laser sizer (Germany) having size measurement range between 1.8 μm and 500 μm in wet mode.

After obtaining optimum results, the hydrocyclone underflow material was subjected to wet high intensity magnetic separation (WHIMS) and shaking table concentration, separately. The goal of WHIMS experiments was to investigate the possibility of a pre-concentration method with acceptable recoveries. Chromite can be separated as a magnetic product from the dia/paramagnetic gangue minerals inside high intensity magnetic field (~0.8–1.4 T) (Tripathy et al., 2016).

Pre concentration tests on hydrocyclone underflow were performed on a laboratory-scale wet high-intensity magnetic separator (Carpco Research & Engineering, Inc. CC34-159, USA). The most important operational parameter that affected the performance of WHIMS, the magnetic field intensity, was varied by varying the electrical current at the different levels (0.4 to 2.0 A).

The principle of test method has been described in the literature (Carpenter, 1964; Svoboda, 1987) and the equipment is shown in Figure 9. The pulp is fed into the chamber with a ferromagnetic matrix (3 mm diameter steel balls) in-place and coil current at the desired setting. Magnetic material will be retained in the chamber after flushing with water while non-magnetic material will be washed through the chamber. The magnetic fraction can then be washed from the ferromagnetic matrix after the coil current has been turned off. After tests, both magnetic and non-magnetic fractions were collected, dried and subjected to chromite analysis.

Figure 9. *Carpco laboratory scale wet high intensity magnetic separator*

Slime table beneficiation tests have been performed on hydrocyclone underflow sample. 3-level Box-Behnken design has been performed to determine the effect of operational parameters to achieve maximum grade and recovery (Table 6).

Table 6. *Operational parameters and their levels for fine tailing beneficiation tests*

Parameters	Low Level (L)	Center Level (M)	High Level (H)
Feed rate (g/min)	750	1000	1250
Wash Water Rate (l/min)	4	6	8
Table Slope (degrees)	2	3	4

4. Results and discussion

Desliming, ultra-fine classification, shaking table tests with sand and slime surfaces and WHIMS tests have been performed to recover coarse and fine chromite particles from plant tailings. The experimental program has been developed according to physical and textural properties of tailing samples. Final shaking table concentration stages have been carried out on both samples to obtain a chromite concentrate with acceptable recovery. In order to reach this goal, the grade and recovery of chromite were studied as the response of operational parameters in final concentration stages. The models have been developed based on feed rate, wash water rate and table slope factors. Mass balance and metallurgical balance of each test has been performed.

4.1. Coarse tailing beneficiation results

The first stage of coarse tailing beneficiation was desliming. Desliming test results are tabulated in Table 7. The hydrocyclone overflow has extremely fine in size as 80% material is finer than 17 μm and has lower chromite grade. It can be observed from chromite distribution in hydrocyclone products that, chromite is present between the size ranges of 212 and 20 μm significantly. The presence of centrifugal force in the hydrocyclone seems to be aid reporting to the underflow the higher specific gravity chromite particles present in the slime. Test results clearly shows that an effective desliming before shaking table test was achieved.

Table 7. *Desliming test results of coarse tailing (optimum condition)*

Sample Name	Weight (%)	d_{80} (μm)	Cr_2O_3 (%)	Cr_2O_3 Distribution (%)
Feed	100.00	180	2.77	100.00
Hydrocyclone Underflow	87.16	185	2.98	93.72
Hydrocyclone Overflow	12.84	17	1.36	6.28

Final concentration on coarse tailing was conducted by shaking table with sand deck surface. Coarse shaking table test results are tabulated in Table 8.

It can be observed from Table 8 that, the experimental studies on coarse tailing provided a narrow range of grade with a broad range of recovery values. It can be observed from Table 8 that the coarse tailing sample was concentrated up to 32.32% Cr_2O_3 with recovery of 33.66% whereas a maximum of 50.21% Cr_2O_3 recovery is obtained with Cr_2O_3 grade of 28.00%.

The grade of concentrate varies with a minor change in these three operational parameters. However, test results clearly indicate that a high grade concentrate with an acceptable recovery cannot be obtained from coarse tailing sample even a regrinding to finer size. Detailed microscopic analyses indicated that chromite grains finely disseminated on the gangue particles in all size fractions. Results of coarse tailing beneficiation tests shows that a partial increase in fineness does not a significant effect on disseminated chromite grains and intergrowth particles. As a result, chromite loss in coarser fractions seems inevitable, and this is supported by textural analyses and concentration test results.

Table 8. *Coarse shaking table test results*

Experiment	Was Water Rate	Table Slope	Feed Rate	Weight (%)		Cr_2O_3 (%)		Recovery (%)
				Concentrate	Tail	Concentrate	Tail	
1	L	L	L	5.34	94.66	28.00	1.57	50.21
2	L	L	H	4.55	95.45	31.44	1.62	48.02
3	L	H	H	3.65	96.35	31.68	1.89	38.81
4	L	H	L	4.11	95.89	32.15	1.73	44.36
5	H	H	L	3.88	96.12	31.80	1.82	41.38
6	H	L	H	3.10	96.90	32.32	2.04	33.66
7	H	L	L	3.58	96.42	29.85	1.98	35.87
8	H	H	H	3.44	96.56	31.87	1.95	36.74
Feed	-	-	-	100.00		2.98		100.00

4.2. Fine tailing beneficiation results

Ultra fine size classification, WHIMS and shaking table with slime deck surface have been performed in order to recover chromite from fine tailing sample. The main purpose of second stage classification was to remove particles which finer than 10 µm. Then, the hydrocyclone underflow sample was subjected to WHIMS and shaking table tests to determine whether a concentrate can be obtained from the fine tailing by using gravity concentration and/or magnetic separation. The ultra-fine size classification test results under optimum condition are tabulated in Table 9. Optimum result was obtained by using smallest diameter apex (1.5 mm) and 0.8 bar feed pressure.

Table 9. *Laboratory scale ultra-fine classification test results obtained in optimum condition*

	Feed	Underflow	Overflow
Weight (%)	100.00	50.86	49.14
P_{80} (µm)	47.38	71.19	9.90
Cr_2O_3 (%)	3.28	4.59	1.93
Recovery (%)	100.00	71.07	28.93

Table 9 indicates that in case of a second stage size classification of cyclone overflow sample, approximately one half of material can be removed as ultrafine slime at a size 80% is finer than 10 µm. The chromite content of this ultrafine slime is lower than the feed. The 71.07% of the total chromite in the cyclone overflow sample can be recovered in the lab scale hydrocyclone underflow. The lab scale hydrocyclone underflow material then subjected to WHIMS and shaking table tests separately as shown in Figure 7. WHIMS test results are tabulated in Table 10.

It is obvious from Table 10 that as the electrical current intensity increases, weight of magnetic concentrate increases up to 72.25%. In contrast, the Cr_2O_3 grade of the magnetic concentrate decreases significantly with an increasing current intensity. There is a sharp decrease in the grade of the magnetic product with an increase in electrical current intensity. This can be due to the paramagnetic properties of the chromite and removal of the magnesium silicates and oxides at lower magnetic field intensities. However, at higher electrical current intensities may be the attraction of paramagnetic minerals i.e. hematite and goethite can report to the concentrate. The grade/recovery data shows that there are no possibilities to produce a high grade pre-concentrate with acceptable recovery values at fine tailing samples. Shaking table test results of fine tailing sample are tabulated in Table 11.

Table 10. *WHIMS test results*

Electrical Current (A)	Weight (%)		Chromite (%)		Recovery (%)	
	Concentrate	Tail	Concentrate	Tail	Concentrate	Tail
0.4	19.78	80.22	7.35	3.91	31.67	68.33
0.6	29.97	70.03	6.92	3.59	45.18	54.82
0.8	40.14	59.86	6.54	3.28	57.19	42.81
1.0	46.08	53.92	6.14	3.27	61.64	38.36
1.2	60.26	39.74	5.14	3.76	67.48	32.52
1.6	72.18	27.82	4.98	3.58	78.31	21.69
2.0	78.38	21.62	4.72	4.12	80.60	19.40
Feed	100.00		4.59		100.00	

Table 11. *Results of slime table beneficiation tests*

Experiment	Wash Water Rate	Table Slope	Feed Rate	Weight (%)		Cr_2O_3 (%)		Recovery (%)
				Concentrate	Tail	Concentrate	Tail	
1	L	L	M	7.21	92.79	33.77	2.32	53.04
2	H	L	M	3.02	96.98	49.96	3.18	32.85
3	L	H	M	1.49	98.51	55.87	3.81	18.16
4	H	H	M	1.65	98.35	53.42	3.77	19.26
5	L	M	L	4.30	95.70	41.34	2.94	38.77
6	H	M	L	3.26	96.74	45.91	3.20	32.63
7	L	M	H	3.22	96.78	46.94	3.18	32.92
8	H	M	H	4.76	95.24	38.08	2.92	39.46
9	M	L	L	4.85	95.15	40.59	2.76	42.89
10	M	H	L	5.98	94.02	33.21	2.77	43.29
11	M	L	H	7.75	92.25	29.21	2.52	49.34
12	M	H	H	1.67	98.33	51.89	3.79	18.88
13	M	M	M	2.01	97.99	53.17	3.59	23.31
14	M	M	M	1.98	98.02	53.29	3.60	23.02
15	M	M	M	2.03	97.97	53.00	3.59	23.40
Feed	-	-	-	100.00		4.59		100.00

It is observed from Table 11 that a salable grade (>42% Cr_2O_3) concentrate can be obtained from fine tailing sample. As the results show, the slime table can produce a higher grade concentrate than the table with the sand surface. The slime table also produces the low-grade tailing.

However, with a minor change in operational variables, the performance of the slime table changes drastically. So, an attempt was made to fit the grade/recovery relationship and predict the performance of table by using trial version of Minitab 19 statistics software. The model was developed based on operational parameters via wash water rate, table slope and feed rate. The equation of model to fit the experimental data in coded form for recovery and grade of Cr_2O_3 have been presented in Equation (1) and Equation (2) respectively. The level of confidence for analysis of experiments has been 95% (P<0.05).

$$Cr_2O_3 Grade\ (\%) = -161{,}3 + 15{,}13\, WW + 16{,}7\, TS + 0{,}2665\, FR - 0{,}069\, WW*WW - 4{,}62\, TS*TS - 0{,}000157\, FR*FR - 2{,}330\, WW*TS - 0{,}00672\, WW*FR + 0{,}03006\, TS*FR \quad (R^2 = 0.93) \qquad (1)$$

$$Cr_2O_3\, Recovery\ (\%) = 293{,}6 - 22{,}9\, WW - 25{,}6\, TS - 0{,}2815\, FR + 0{,}616\, WW*WW + 5{,}12\, TS*TS + 0{,}000164\, FR*FR + 2{,}66\, WW*TS + 0{,}00634\, WW*FR - 0{,}0309\, TS*FR \quad (R^2 = 0.92) \qquad (2)$$

Where;

WR: wash water rate (l/min),

TS: table slope (degree),

FR. Feed rate (g/min)

According to equations it can be indicated that linear effect of TS has the higher coefficient than the other parameters which can be defined as more effective on grade and recovery. These results indicate that the TS have major influence on the separation of the chromite bearing minerals to the concentrate. In addition to this, in case of the grade model terms, the double interaction of table slope (TS^2), double interaction of feed rate (FR^2), WW*TS and TS*-FR are significant as the Prob>F are lower than 0.05. In case of the recovery model terms also, FR, WW, the double interaction of feed rate (FR^2), and TS*FR are significant as the Prob>F are lower than 0.05. lack of fit values of both equations have also higher F values and lower P values. The results of analysis of variance of fitted models for grade and recovery are presented in Table 12. Analysis of variance (ANOVA) was obtained by using the trial version of Minitab 19.

All major statistics indicate that the grade and recovery models can be used for describing the operational parameters effects on the response variables. Both the models have higher value of R^2 for grade and recovery which indicates the models are well agreement with the experimental data. For models of chromite grade and recovery, the F-values for grade and recovery in slime table are 8.47 and 7.03. The high F-value and also the low P-values indicate the validity of proposed models. The models are significant as the F value is high, the Prob>F value is less than 0.05. However, in case of the grade and recovery model terms, double interaction of wash water flow rate (WW^2) and double interaction of table slope (TS^2) are not significant as the Prob>F are higher than 0.05, while double interaction of feed rate (FR^2) is important for both grade and recovery.

Table 12. *Analysis of variance (ANOVA) for Box-Behnken design of slime table tests*

GRADE Source	DF	Sum of Square	Mean Square	F-Value	P-Value
Model	9	993.73	110.415	8.47	0.015
WW	1	11.16	11.163	0.86	0.040
TS	1	208.69	208.692	16.01	0.010
FR	1	3.21	3.213	0.25	0.641
Square	3	412.81	137.603	10.55	0.013
WW*WW	1	2.12	0.285	0.02	0.888
TS*TS	1	55.51	78.824	6.05	0.057
FR*FR	1	355.18	355.182	27.24	0.003
2-Way Interaction	3	357.85	119.285	9.15	0.018
WW*TS	1	86.86	86.862	6.66	0.049
WW*FR	1	45.09	45.091	3.46	0.122
TS*FR	1	225.90	225.901	17.33	0.009
Error	5	65.19	13.038		
Lack-of-Fit	3	65.15	21.715	122.70	0.001
Pure Error	2	0.04	0.021		
Total	14	1058.92			
RECOVERY Source	DF	Sum of Square	Mean Square	F-Value	P-Value
Model	9	1705.81	189.534	7.03	0.022
WW	1	43.66	43.665	1.62	0.026
TS	1	770.87	770.870	28.60	0.030
FR	1	36.04	36.040	1.34	0.030
Square	3	463.64	154.545	5.73	0.045
WW*WW	1	6.98	22.428	0.83	0.404
TS*TS	1	69.71	96.776	3.59	0.117
FR*FR	1	386.95	386.946	14.36	0.013
2-Way Interaction	3	391.60	130.532	4.84	0.061
WW*TS	1	113.32	113.316	4.20	0.096
WW*FR	1	40.20	40.196	1.49	0.276
TS*FR	1	238.08	238.085	8.83	0.031
Error	5	134.77	26.954		
Lack-of-Fit	3	134.69	44.896	138.54	0.001
Pure Error	2	0.08	0.039		
Total	14	1840.58			

For graphical interpretation of interactions, the use of three-dimensional plots of the model is highly recommended. Variables giving quadratic and interaction terms with the largest absolute coefficients in the fitted model were chosen for the axes of response surface plots to account for curvature of the surfaces. This is useful to visualize the relationship between the response and experimental levels of each factor. The response is mapped against two experimental factors while the third is held constant at its middle value. Figure 10 explains the effect of the process parameters of slime table on concentrate grade.

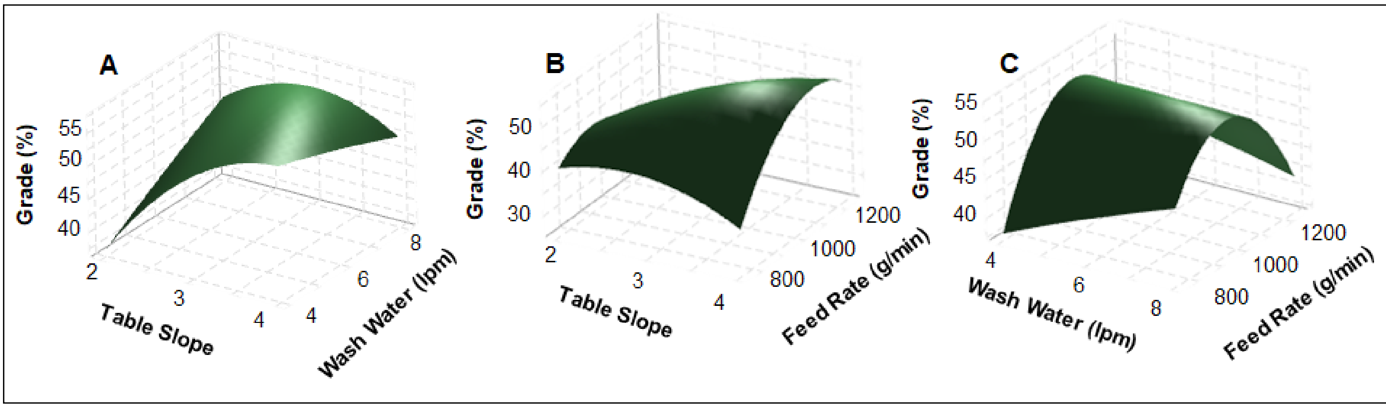

Figure 10. *The binary effects of operational parameters on concentrate chromite grade*

Figure 10(A) shows the effect of TS and WW on concentrate grade at center level (1000 g/min) of FR. It is observed that higher grade is obtained at lower level of wash water flow rate and higher level of table slope. The increase in concentrate grade can be explained by the residence time of gangue particles. Residence time of these particles in the flowing film decrease with increasing slope. In this short period of time, better transportation of the gangue particles to tailing can increase the selectivity. It is clear that table slope (TS) and the interaction between TS and WW are the significant parameters to increase chromite grade in beneficiation with shaking table on studied sample.

Figure 10(B) shows the effect of table slope and feed rate on concentrate grade at center level of wash water flow rate (6 lpm). The higher grade of the concentrate is obtained at higher level of both table slope and feed rate. It is also noted that at lower level of table slope, as the feed rate increases there is decrease in the concentrate grade but at higher deck tilt angle and vice versa. Interaction between TS and FR (P=0.009) has also significant for concentrate grade (Table 12).

Figure 10(C) shows the effect of WW and FR on concentrate grade of the slime table at center level (3°) of TS. The concentrate grade is maximum at intermediate of both feed rate and the wash water rate. It is also observed that as the wash water flow rate increases, there is an increase in concentrate grade at lower level of feed rate however, at higher level of feed rate concentrate grade decreases. As the wash water flow rate increases, the transport of the gangue minerals to the tailing fraction increases which in turn improves the grade of the concentrate at lower and intermediate feed rate values. The significant decrease of concentrate grade at the highest level of the feed rate can be described by insufficient capacity of shaking table in this condition.

Similarly, Figure 11 explains the effect of the process parameters of slime table on concentrate recovery.

Figure 11(A) shows the effect of WW and TS on chromite recovery of concentrate at center level (1000 g/min) of FR. It is observed from Figure 11(A) that higher recovery can be achieved at lower and center level of wash water rate and lower level of table slope. The table slope was varied between 2° and 4°. At lowest level of table slope, large amount of chromite and gangue particles reported to the concentration end of the table, which increased the recovery and had an adverse effect on the grade of the concentrate (Fig 10a). It is also noted that there is significant effect of the table slope compared to the wash water rate on the recovery.

Figure 11(B) shows the effect of TS and FR on concentrate recovery at center level (6 lpm) of WW. The higher recovery is observed at higher level of feed rate and lower level of the table slope. As the table slope decreases, the retention time for the segregation of particles increases and significant amount of particles can report to concentrate end of table with the aid of higher level of feed rate. It was found that interactions between TS and FR (P=0.031) has an important effect on the recovery (Table 12).

Figure 11(C) shows the effects of WW and FR on concentrate recovery at center level (3°) of TS. The recovery of the concentrate is maximum at lower level of both feed rate and wash water rate. As the wash water rate increases the transport of the fine chromite minerals to the tailing fraction increases which in turn decreases the recovery. Similarly, as the feed rate increases, the retention time for the segregation of particles decreases. The decrease of both grade and recovery at the highest level of the feed rate clearly shows that 1200 g/min is the critical capacity for the laboratory scale shaking table with slime surface.

A good indicator of fitted models evaluation is the diagram with model predicted values versus actual values. These diagrams are shown in Figure 12 for recovery and grade of chromite in slime table. These figures confirmed the goodness of fitness applying the predicted models on y=x line. These results proved the suitability of the models.

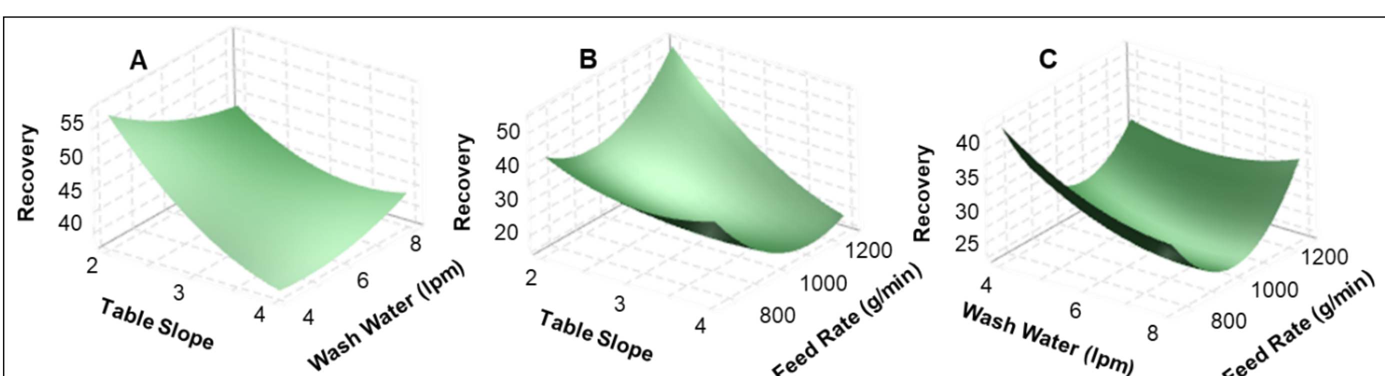

Figure 11. *The binary effects of operational parameters on concentrate chromite recovery*

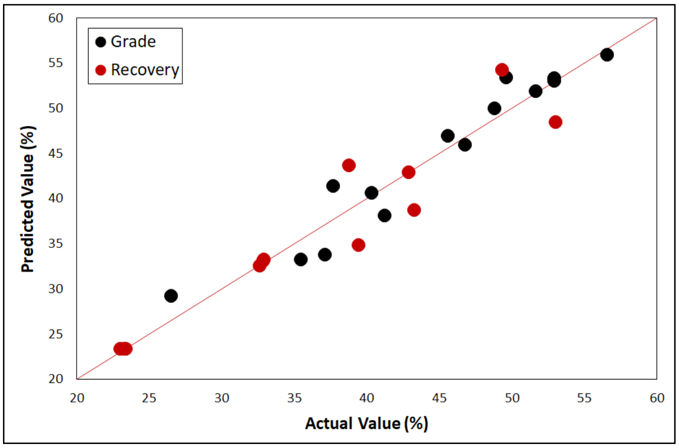

Figure 12. *The comparison of actual and predicted values on y=x line*

Conclusion

Detailed characterization and beneficiation of tailings from a chromite beneficiation plant in Turkey has been studied. At first, a detailed characterization has been performed to evaluate the feasibility of the separation process. Then, the coarse and fine size chromite tailings produced by a gravity-based beneficiation plant has been reprocessed using desliming (hydrocyclone), gravity concentration (shaking table) and magnetic separation (WHIMS) to recover the chromite.

Detailed microscopic analyses have been indicated that chromite grains finely disseminated on the gangue particles in all size fractions at coarse tailing samples. Increase in fineness did not show a significant effect on disseminated chromite grains during coarse tailing beneficiation studies. Neither a salable concentrate grade nor an acceptable recovery could not be obtained from coarse tailing. Detailed characterization and beneficiation studies revealed that, chromite loss in coarse tailings are inevitable, a partial liberation by regrinding also not beneficial to beneficiation results. During regrinding the lower acceptable size limit of conventional circuit and size reduction specific energy consumption relations were considered. Approximately 80% of the final tailing of the existing plant is produced as coarse tailing. For this reason, a novel beneficiation process followed by ultrafine grinding of coarse tailing streams should be considered both technically and economically.

In addition to this, slime by-pass to the cyclone underflow stream is a significant problem for spiral concentration circuit and shaking table circuit in the existing plant. Detailed characterization of the tailing samples revealed that chromite losses increases as the particle size decreases in coarse tailing streams. To decrease the amount of slime size, an optimization on grinding circuit can be recommended.

Evaluations on the cyclone overflow sample revealed that 74.68% of the chromite is distributed at slime size range below 38 µm. It is well known from the previous studies that approximately 30% of total chromite is lost in cyclone overflow in the existing plant. According to fractional analysis of the cyclone overflow stream an ultrafine size classification was studied to removal of very fine gangue minerals. After ultrafine size classification approximately half of the material was removed with 29% chromite losses in ultrafine tailing. These results reveals that a second stage classification before final concentration method is crucial.

Removal of the gangue minerals was found to be more efficient using gravity concentration rather than magnetic separation. The grade/recovery relations of the magnetic separation tests revealed that a high grade concentrate or pre-concentrate with acceptable recovery values cannot be obtained by using WHIMS.

The effect of process parameters on grade/recovery values were evaluated in detail by using statistical experimental designs and ANOVA method. It can be note from Table 12 that the main effects of parameters are highly significant which have very small P-values. According to grade and recovery models on the slime table the most effective parameters on Cr_2O_3 recovery and grade in shaking table were linear effect of TS. In addition to this, the double interaction of table slope (TS^2), double interaction of feed rate (FR^2), WW*TS and TS*FR are significant for grade model, however, FR, WW, the double interaction of feed rate (FR^2), and TS*FR are significant for recovery model as the Prob>F are lower than 0.05. Lack of fit values of both equations have also higher F values and lower P values. The maximum Cr_2O_3 recovery was 53.04% with grade of 33.77% Cr_2O_3, using in the table slope of 2 degrees, feed rate of 1000 g/min, and wash water flow rate of 4 lpm. The maximum Cr_2O_3 grade was 55.87% Cr_2O_3 with recovery of 18.16%, using in the table slope of 4 degrees, feed rate of 1000 g/min, and wash water flow rate of 4 lpm. In this experiment (Exp. 3) chromite grade in the slime table was enhanced but the both chromite recovery and mass recovery was very low.

According to model predictions the slime table can produce a salable grade (42% Cr_2O_3) concentrate with 43% recovery. In this condition approximately 5% of the feed material can be obtained as concentrate. These results reveal that, advance gravity techniques such as slime tabling, multi-gravity separator (MGS), Falcon concentrator, and Knelson concentrator can be used to beneficiation of chromite slimes and improve the recovery of existing plant. In addition, magnetic separation, flotation, and selective flocculation, as well as magnetic carrier separation studies can also be carried out for cyclone overflow to separate ultrafine chromite from the gangue minerals. A second stage desliming can also positive effect on desliming. Fully liberation of the minerals and density difference between chromite and forsterite, can give sufficient results on beneficiation of fine and ultra-fine chromite by the novel techniques.

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