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Chromite is an important mineral used in the metallurgy, chemistry, and refractory industries. For this reason, beneficiation of chromite tailings is very important. In this study, the possibility of beneficiation of chromite tailings in the Uckopru/Fethiye-Turkey region by Hydrocyclone and Multi Gravity Separator (MGS) combination was investigated. The two signification operational parameters of hydrocyclone, which were diameter of apex and diameter of vortex, and the three signification operational parameters of MGS, which were drum speed, tilt angle, and wash water, were varied and the results were evaluated with the Central Composite Rotatable Design. The results of beneficiation studies showed that commercial concentrate containing 48.18% Cr_2O_3 was obtainable with a 69.79% rate of recovery.

Keywords hydrocyclone; modelling; Multi Gravity Separator (MGS); optimization; waste processing

INTRODUCTION

Chromite is an important mineral used in the metallurgy, chemistry, and refractory industries. Chromite ores contain a variety of gangue minerals such as serpentine and olivine (1). The world supply and reserves of chromite or chrome ore ($FeCr_2O_4$) have been dominated mainly by South Africa and the former USSR, which made chromite a strategic material in many Western countries (2). In Turkey, the most commonly used beneficiation methods for chromite ores are the gravity methods, such as shaking table, jig, spiral, and Reichert cone. Magnetic separation is also used depending on the ore characteristics. Upper 0.5 mm chromite and finer parts are discharged as tailings. In most chromite plants, around 10–50% of total run-of-mine chromite is found to be minus 0.5 mm. The total amount of fine chromite gravity tailings in Turkey is around 3,000,000 tons with a quite high Cr_2O_3 content of about 9–20% (3). 1.2 million tons of tailings with average chromite content of 13–14% Cr_2O_3 were discharged as a result of the gravity separation method from the Uckopru Concentration Plant since 1920. The increased use of highly mechanized mining methodologies to enhance productivity has been the major cause for the generation of large quantities of chromite fines. So, not only a great deal of material is economically lost, but also coal areas encounter serious environmental issues.

A few decades ago, a new gravity based processor, the multi-gravity separator (MGS) is one of the fine particle mineral concentration machines based on gravity separation. The Multi Gravity Separator (MGS), has appeared on the market with an operating principle that seems to be very promising for processing fine particle (4). This device was developed for the selective separation of fine and ultra-fine particles mostly based on the differences in density. MGS is specifically designed for the efficient separation and upgrading of fine metals and minerals, particularly in the particle range 5 μm to 100 μm (5). The use of centrifugal forces in a MGS enhances the relative settling velocity differential between the particles differing in size and density (6,7), and the additional shearing force created by the shaking motion of the drum enhances the particle separation process (8). A detailed description of the MGS is given by Venkatraman et al. (9).

The early applications of the unit for concentrating heavy minerals like tin, tungsten, tantalum, fine coal and celestite have been reported elsewhere (4,7–25). Recently, research studies have increased on its use in fine chromite processing (3,26–28). In all of this study, the MGS performance of only -0.1 mm sized ores is analyzed. But tailings of the chrome concentrator are usually obtained under 0.5 mm. Because of this, under 0.5 mm sized materials are taken into consideration in a committed study.

In this study, clean chrome is obtained from tailings of the chrome concentrator under 0.5 mm. So, a combination of MGS and hydrocyclone is used in the enrichment of fine sized ores and this combination is modeled and optimized; it did not appear in any study. It has been predicted to play a very significant role in chromite concentration using hydrocyclone and MGS. So, the optimization of two

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operational variables of hydrocyclone (diameter of vortex, and diameter of apex) and three operational variables of MGS (drum speed, tilt angle, and wash water flow rate) have been focused on.

MATERIALS AND METHODS

Materials

The head sample was taken (ASTM D2234-72, 1972) from waste dam discharged of fines tailing refuse of Concentrator Plant Uckopru (Fethiye-Turkey). The technical feasibility to upgrade the properties of the fines refuse of the chromite plant was investigated by employing gravity methods. Samples taken from the waste dam was screening from the 0.5 mm size. Table 1 presents the Cr_2O_3% of the chromite tailing samples with respect to particle size. The minus 0.5 mm sample containing 14.79% Cr_2O_3. Table 1 show that the content of the sample increased with a decrease in particle size. Maximum Cr_2O_3 determined to −0.038 mm.

Experimental Equipments

Hydrocyclone

Mineral processes use hydrocyclone separators to perform separations on the basis of size and/or density differences between the dispersed particulate phases (29,30). Hydrocyclones consist of two main parts. There is a cylindrical part, with an inlet through which the feed enters tangentially. In this part an outlet is located vertically on top of the cylinder which extends within the cylinder and is called a vortex finder. The second main part is a conical part connected to the cylindrical section on the top and to the underflow from bottom end and is called a spigot. The centrifugation forces exerted by the vortex carry larger particles to the cyclone wall; these are discharged by an underflow orifice. Small particles are moved to the central axis of the cyclone and carried out by the overflow stream (31,32).

TABLE 1
The chemical composition of chromite tailings used in the experiments according to particle size

Particle Size μm	Weight %	Grade (Cr_2O_3) %
−500 + 425	4.77	4.75
−425 + 300	5.08	5.24
−300 + 212	4.70	4.98
−212 + 106	7.19	5.12
−106 + 75	6.59	6.38
−75 + 53	8.44	10.14
−53 + 38	9.98	12.12
−38	53.25	21.05
Total	100	14.79

Multi Gravity Separator (MGS)

The operating principle of the MGS is similar to that of a conventional shaking table, except that centrifugal forces are used to enhance the separation of fine particles. The laboratory/pilot plant scale C-900MGS consists of a slightly tapered open-ended drum measuring 600 mm long with a diameter of 500 mm that rotates in a clockwise direction and is shaken sinusoidally in an axial direction. In this system, feed slurry is distributed along the inner surface of a slightly tapered rotating drum. Light particles are carried by the flowing film to the far end of the drum, while heavy particles pinned against the wall by the centrifugal field are carried by rotating scrapers to the opposite end of the drum. A small amount of wash water is added to the heavies discharge end of the drum to wash out entrained low-density particles. Successful applications of the MGS technology include the concentration of cassiterite, chromite, wolfamite, graphite, mixed sulfides, and gold. In addition, testing of a pilot-scale MGS unit was recently completed at the Pittsburgh Energy Technology Center (PETC) for applications involving the desulfurization of fine coal. The results of this work showed that the pyritic sulfur rejection obtained by the MGS was nearly twice that was achieved using conventional fine particles processing techniques. Since the unit operates under a low centrifugal field (<25 g's) its capacity throughput is very low compared to the other enhanced gravity separators (33). The parameters affecting the efficiency of separation on the MGS are the drum speed (infinitely variable from 100 to 300 rpm), tilt angle (0° to 9°), shake amplitude (10/15/20 mm), shake frequency (4.0/4.8/5.7 cps), wash water flow rate (0 to 10 l/min) and pulp density of the feed slurry (10% to 50% by mass) (25,28).

Experimental Design

Experimental design methods and response surface methodologies are widely used for modeling process parameters, especially in chemical processes, and pharmaceutical systems. It has, however, not been widely applied to mineral processing systems. Among different RSM experimental designs, the CCRD has been widely used because it requires fewer experimental runs and provides sufficient information as compared to a factorial design. For five variables, the recommended number of tests at the center is six (34). Hence the total number of tests required for the four independent variables is $\frac{2^5}{2} + (2 \times 5) + 6 = 32$, which is at least 32 experiments less than that required for a half factorial design.

Once the desired ranges of values of the variables are defined, they are coded to lie at ±1 for the factorial points, 0 for the center points and $\pm\,\beta$ for the axial points. The codes are calculated as functions of the range of interest of each factor as shown in Table 2. Thus for the four

TABLE 2
Relationship between coded and actual values of a variable

Code	Actual value of variable
$-\beta$	x_{min}
-1	$[(x_{max}+x_{min})/2]$-$[(x_{max}$-$x_{min})/2\alpha]$
0	$[(x_{max}+x_{min})/2]$
$+1$	$[(x_{max}+x_{min})/2]+[(x_{max}$-$x_{min})/2\alpha]$
$+\beta$	x_{max}

X_{max} and x_{min} = maximum and minimum values of x respectively; $\alpha = 2^{(k-1)/4}$; k = number of variables (in this study; $\alpha = 2^{4/4} = 2$).

variables under consideration, the response model is:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} B_{ij} x_i x_j + \varepsilon \quad (1)$$

The β coefficients are obtained by the least squares methods. The coefficients, that is, the main effect (β_i) and two-factors interactions (β_{ij}) can be estimated from the experimental results by computer simulation programing applying the least squares method using "Minitab 15."

CCRD was used to design the experiments to the reason mentioned above. In order to obtain the required data, the range of values of each of six variables was defined as follows:

- For hydrocyclone, diameter of vortex of 5.0–17.0 mm, diameter of apex of 1.6–8.0 mm,
- For MGS, drum speed of 105–245 rpm, tilt angle of 0°–8°, wash water of 1–9 lpm.

Applying the relationships in Table 2, the values of the codes were calculated as shown in Table 3. These were then used to determine the actual levels of the variables for each of the 32 experiments (Table 4).

Considering the effects of main factors and also the interactions between two-factors, Eq. (1) takes the form:

$$\begin{aligned} y = {} & \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_{11} x_1^2 \\ & + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{44} x_4^2 + \beta_{55} x_5^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 \\ & + \beta_{14} x_1 x_4 + \beta_{15} x_1 x_5 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{25} x_2 x_5 \\ & + \beta_{34} x_3 x_4 + \beta_{35} x_3 x_5 + \beta_{45} x_4 x_5 \end{aligned} \quad (2)$$

where y is the predicted response, β_0 model constant; x_1, x_2, x_3, x_4, and x_4 independent variables; β_1, β_2, β_3, β_4, and β_5 are linear coefficients; β_{12}, β_{13}, β_{14}, β_{15}, β_{23}, β_{24}, β_{25}, β_{34}, β_{35}, and β_{45} are cross product coefficients, and β_{11}, β_{22}, β_{33}, β_{44}, and β_{55} are the quadratic coefficients (24–25, 35–38).

Experimental Procedure

In this study, the CCRD was chosen to find out the relationship between the response functions (chromite grade and recovery of the chromite concentrate) and two variables of the hydrocyclone (diameter of vortex, and diameter of apex) and three variables of the MGS (drum speed, tilt angle, and wash water flow rate). Whereas the other operational parameters of hydrocyclone (cyclone diameter of 44 mm, solid ratio of 10%, feed suspension of 30 L, pre-feed mixture of 5 min, and inlet pressure of 1 bar) and MGS (15 mm of shakes amplitude and 4.8 cps of shakes frequency) were kept constant. The hydrocyclone and MGS variables were adjusted at the required levels as per the CCRD. The batch hydrocyclone and MGS tests were conducted in our mineral processing laboratories using the experimental setup shown in Fig. 1.

Samples were dried at 100°C. In each test, 3000 g of the dry chromite ore was used. The dried samples were added to water (10% solid ratio) and were stirred for 5 min by a propeller agitator. The suspension was passed through 500 μm sieve and then, sieved suspension was fed hydrocyclone. The suspension was stirred with a peristaltic pump

TABLE 3
Five independent variables of hydrocyclone and MGS and their levels for CCRD

		Coded variable level				
Variable	Symbol	Lowest $-\beta$	Low -1	Center 0	High $+1$	Highest $+\beta$
Diameter of apex, (*a*), mm	x_1	1.6	3.2	4.8	6.4	8.0
Diameter of vortex (*v*), mm	x_2	5.0	8.0	11	14	17
Drum speed (*d*), rpm	x_3	105	140	175	210	245
Tilt angle (*t*), °	x_4	0	2	4	6	8
Wash water (*w*), lpm	x_5	1	3	5	7	9

TABLE 4
Coded and actual levels of five variables of hydrocyclone and MGS

Run	Coded level of variables					Actual level of variables				
	x_1	x_2	x_3	x_4	x_5	a	v	d	t	w
1	+1	+1	+1	+1	+1	6.4	14	210	6	7
2	+1	+1	+1	−1	−1	6.4	14	210	2	3
3	+1	+1	−1	+1	−1	6.4	14	140	6	3
4	+1	+1	−1	−1	+1	6.4	14	140	2	7
5	+1	−1	+1	+1	−1	6.4	8	210	6	3
6	+1	−1	+1	−1	+1	6.4	8	210	2	7
7	+1	−1	−1	+1	+1	6.4	8	140	6	7
8	+1	−1	−1	−1	−1	6.4	8	140	2	3
9	−1	+1	+1	+1	−1	3.2	14	210	6	3
10	−1	+1	+1	−1	+1	3.2	14	210	2	7
11	−1	+1	−1	+1	+1	3.2	14	140	6	7
12	−1	+1	−1	−1	−1	3.2	14	140	2	3
13	−1	−1	+1	+1	+1	3.2	8	210	6	7
14	−1	−1	+1	−1	−1	3.2	8	210	2	3
15	−1	−1	−1	+1	−1	3.2	8	140	6	3
16	−1	−1	−1	−1	+1	3.2	8	140	2	7
17	0	0	0	0	0	4.8	11	175	4	5
18	0	0	0	0	0	4.8	11	175	4	5
19	0	0	0	0	0	4.8	11	175	4	5
20	0	0	0	0	0	4.8	11	175	4	5
21	0	0	0	0	0	4.8	11	175	4	5
22	0	0	0	0	0	4.8	11	175	4	5
23	$-\beta$	0	0	0	0	1.6	11	175	4	5
24	$+\beta$	0	0	0	0	8.0	11	175	4	5
25	0	$-\beta$	0	0	0	4.8	5	175	4	5
26	0	$+\beta$	0	0	0	4.8	17	175	4	5
27	0	0	$-\beta$	0	0	4.8	11	105	4	5
28	0	0	$+\beta$	0	0	4.8	11	245	4	5
29	0	0	0	$-\beta$	0	4.8	11	175	0	5
30	0	0	0	$+\beta$	0	4.8	11	175	8	5
31	0	0	0	0	$-\beta$	4.8	11	175	4	1
32	0	0	0	0	$+\beta$	4.8	11	175	4	9

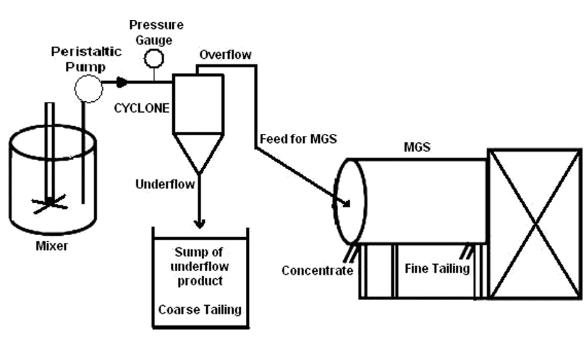

FIG. 1. Hydrocyclone and MGS combination experimental setup.

and by-pass valve for 5 minutes to achieve homogeneity. Later, material was fed to hydrocyclone by closing the by-pass valve, and two discrete overflow and underflow products were obtained. The overflow fed directly to MGS. The diameter of the apex, the diameter of the vortex, the drum speed, the tilt angle, and the wash water flow rate were changed during these tests as per the levels in the design matrix in Table 4, while the other parameters of hydrocyclone and MGS were kept constant.

Samples from the chromite concentrate, coarse tailing streams, and fine tailing streams were collected at steady-state conditions. The samples were filtered, dried, weighed, and analyzed for grade and recovery. For each sample 0.5 g was analyzed by titrimetric method (39).

RESULTS AND DISCUSSION

Model Development

From the experimental results in Table 5 and Eq. (2), the second-order response functions representing chromite concentrate grade and recovery could be expressed as a function of the two operating parameters of hydrocyclone and three operating parameters of MGS, namely the diameter of apex (a), diameter of vortex (v), drum speed (d), tilt angle (t), and wash waster (w).

TABLE 5
Observed and predicted values of grade and recovery of chromite concentration

Run	Grade, Cr_2O_3% Observe	Grade, Cr_2O_3% Predicted (R^2 90.05)	Recovery, Cr_2O_3% Observe	Recovery, Cr_2O_3% Predicted (R^2 95.62)
1	40.12	41.60	71.92	71.10
2	48.18	44.80	69.79	71.51
3	39.22	40.91	73.89	72.79
4	38.86	39.29	74.65	74.47
5	38.15	38.30	76.65	76.56
6	32.21	32.13	80.94	80.69
7	37.17	36.90	74.92	75.40
8	38.63	37.30	76.21	76.93
9	33.15	32.86	79.84	79.87
10	42.86	41.93	71.12	71.80
11	40.41	41.86	73.21	71.92
12	38.15	38.30	76.65	76.56
13	38.15	38.30	76.65	76.56
14	36.36	35.41	77.69	78.33
15	45.96	44.90	67.88	68.43
16	43.87	44.70	70.02	69.81
17	38.06	37.02	75.86	76.50
18	40.24	40.47	73.09	73.19
19	38.33	38.26	77.03	76.83
20	38.15	38.30	76.65	76.56
21	33.76	35.23	78.78	77.91
22	35.01	36.10	77.28	76.49
23	36.15	36.46	76.98	76.70
24	45.17	45.62	69.11	68.98
25	34.14	34.30	78.52	78.54
26	35.98	33.64	77.44	79.29
27	42.44	41.71	69.00	69.41
28	36.85	36.23	75.84	75.93
29	35.35	37.84	79.12	77.97
30	38.15	38.30	76.65	76.56
31	38.96	39.10	75.35	75.27
32	38.15	38.30	76.65	76.56

The equation relating the hydrocyclone and MGS variables and the concentrate chrome grade was as follows:

$$y = 51.18 + 0.17a + 0.65v - 1.737d10^{-1} + 1.44t - 1.05w - 2.32a^2 10^{-2} - 4.83v^2 10^{-2} + 2.66d^2 10^{-4} - 3.45t^2 10^{-2} + 0.189w^2 + 2.37av10^{-2} + 1.16ad10^{-3} + 1.95at10^{-3} - 1.91aw10^{-2} + 5.71vd10^{-4} - 1.88vt10^{-3} + 2.94vw10^{-2} - 5.0dt10^{-4} - 9.64dw10^{-4} - 6.56vw10^{-3} \quad (3)$$

The equation relating the hydrocyclone variables, MGS variables, and the concentrate chrome recovery was as follows:

$$y = 35.51 + 2.97a + 1.2v + 3.11d10^{-1} - 2.51t + 1.16w - 6.52a^2 10^{-2} - 2.48v^2 10^{-2} - 6.27d^2 10^{-4} - 5.93t^2 10^{-2} - 1.136w^2 10^{-1} - 1.126av10^{-1} - 5.5ad10^{-3} + 5.25at10^{-2} - 1.08aw10^{-1} - 4.1vd10^{-4} + 4.76vt10^{-2} - 3.72vw10^{-2} + 4.795dt10^{-3} - 1.51dw10^{-3} + 9.02tw10^{-2} \quad (4)$$

The actual and predicted values of both the concentrate grade and recovery obtained using model Eqs. (3) and (4) were presented in Figs. 2 and 3, respectively. The respective correlation coefficient (R^2) values of 90.05 and 95.62 establish the validity of the proposed equations within the range of the variables studied.

Effect of MGS Variables and Diameter of Apex on Concentrate Grade and Recovery

For better understanding of the results, the predicted models were described in dimensional (3D) response

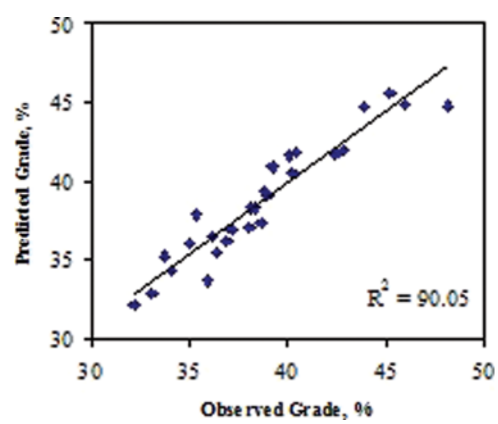

FIG. 2. Relation between experimental and predicted grade of the chromite concentrations using Eq. (4). (Color figure available online)

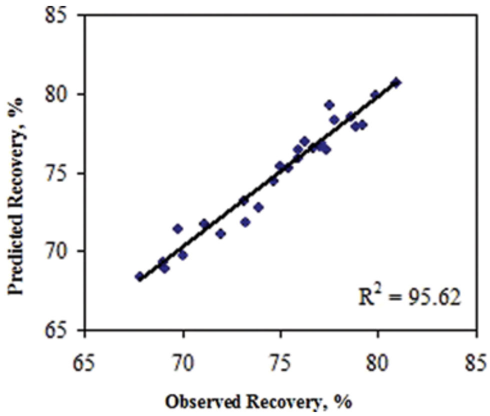

FIG. 3. Relation between experimental and predicted recovery of the chromite concentrations using Eq. (5). (Color figure available online)

surface plots which show the effect of process variables of MGS, and the diameter of the apex of hydrocyclone on concentrate chrome grade and recovery were depicted in Figs. 4(a-f). The figures were shown the 3D response surface plots relationship between variables of MGS, diameter of apex of hydrocyclone and chrome content of the concentrate or chrome recovery of the concentrate at center level of other three variables.

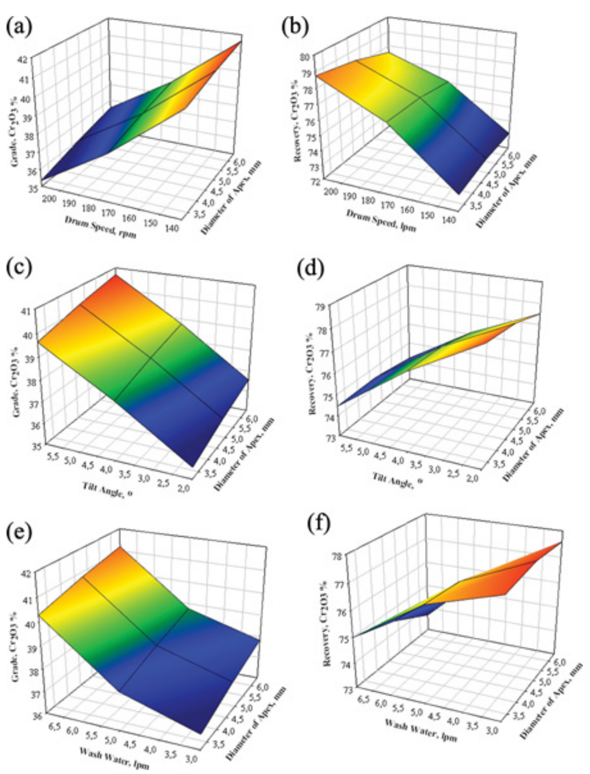

FIG. 4. Response surface plots showing the effect of drum speed (a-b), the effect of tilt angle (c-d), the effect of wash water (e-f), with diameter of apex of hydrocyclone on the grade and recovery of chromite concentrate. (Color figure available online)

In Figs. 4 (a-e), the chrome content of the concentrate was shown which is effected by the diameter of the apex. The chrome content of the concentrate was changed between 1–2% by variation of the diameter of the apex. The chrome content of the concentrate was on the decrease when the diameter of apex was decreased in three figures. Because of this, heavy and coarse products were obtained from underflow of hydrocyclone. So, coarse and heavy products tend to vortex-out, that is, the overflow when the diameter of apex shrank. For this reason, products were polluted which inputs to MGS; however, chrome content was on the decrease. The obtained final concentrate began to lower because the feed chrome content of MGS occurred to lower. In Fig. 4 (b, d, and f), the recovery of the concentrate was shown which was affected by the diameter of the apex. Recovery of the concentrate was not affected too much by variation of the diameter of the apex and the effecting is between 1–2%. In Fig. 4 (a-b), when the drum speed was decreased, the chrome content of the concentrate is on the increase but recovery of concentrate decreased. When drum speed is increased, centrifugal force is on the increase and ores are caused to increase which is close to chrome destiny that comes from the concentrate. So, it decreases the chrome content of the concentrate but the recovery of the concentrate is on the increase. Lower velocity should be opted for higher chrome content of the concentrate. Also, higher velocity should be opted for higher recovery.

In Fig. 4 (c-d), when the tilt angle was decreased, the chrome content of the concentrate was on the decrease but the recovery of the concentrate was on the increase. This effect may be explained by the fact that with an increase in tilt angle, the downward flow velocity of the wash water increases. As a result, the residence time of the particles inside the drum decreases, which eventually decreases the separation time between the heavies and lights inside the drum. Because of this, when wash water was increased, the chrome content of the concentrate was on the increase but the recovery of the concentrate was on the decrease. Higher tilt angle should be opted for higher chrome content of the concentrate and lower tilt angle should be opted for higher recovery.

In Figs. 4 (e-f), when the wash water was decreased, the chrome content of the concentrate was on the decrease but the recovery of the concentrate was on the increase; a similar state is seen with the tilt angle. This effect may be explained by the fact that with an increase in wash water, the wash water flow velocity increases. As a result, more feed material gets transported toward the tailing out, which ultimately increases the chrome grade of the concentrate and decreases the chrome recovery of the concentrate. Higher wash water should be opted for higher chrome

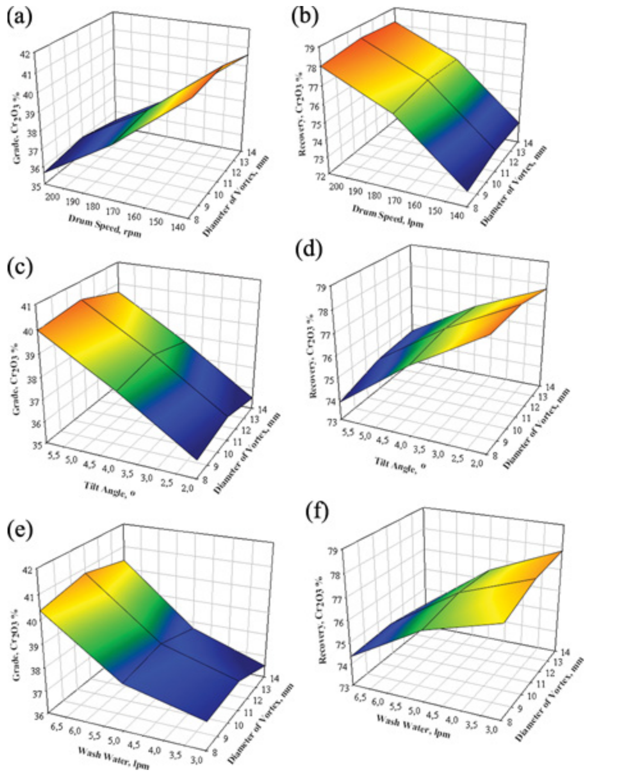

FIG. 5. Response surface plots showing the effect of drum speed (a-b), the effect of tilt angle (c-d), the effect of wash water (e-f), with diameter of vortex of hydrocyclone on the grade and recovery of chromite concentrate. (Color figure available online)

content of concentrate and lower wash water should be opted for higher recovery of concentrate.

Effect of MGS Variables and Diameter of Vortex on Concentrate Grade and Recovery

Figures 5 (a-f) show the 3D response surface plots relationship between a variable of MGS, the diameter of the vortex of hydrocyclone, and chrome content of the concentrate or chrome recovery of the concentrate at center level of other three variables.

In Figs. 5 (a, c, and e), the diameter of the vortex is shown clearly which is affected by the chrome content of the concentrate. As is seen, the diameter of the vortex is not affected too much but small variation occurs. In Figs. 5 (b, d, and f), the diameter of the vortex is shown which is affected by the recovery of the concentrate. Recovery of the concentrate is changed between 0-1% by variation of the diameter of the vortex. Fine and light products are obtained from overflow of hydrocyclone. Because of this, when the diameter of the vortex is decreased, fine and light product leans towards underflow, that is to say, apex-out. Accordingly, chrome content is on the decrease which escapes from the underflow of hydrocyclone and the recovery of the final product is decreased.

In the figures, when the drum speed, the tilt angle, and wash water were examined, which is affected by the chrome content and the recovery of concentrate. The results are shown to be the same which is obtained by the diameter of apex. Chrome content and recovery of materials are changed which is fed on MGS by variation of the diameter of the vortex. So, the chrome content and the recovery of the final products are observed which is obtained from MGS.

Optimization of Variables of Hydrocyclone and MGS on Response

One of the main aims of this study was to maximize the chrome grade and recoveries of chrome concentrates in the process and find the optimum operation conditions from the mathematical models developed. Optimization of the operational variables of the hydrocyclone and MGS for maximum grade and recovery of the chrome concentrates could be obtained using quadratic programing of the mathematical software package Minitab 15 (40).

Using quadratic programing, to get a maximum grade (%) and recovery (%), the operation variables of the hydrocyclone and MGS were calculated (Table 6).

CONCLUDING REMARKS

In this study, a three-level and Central Composite Rotatable Design with a response surface methodology

TABLE 6
Optimization of variables of hydrocyclone and MGS on response

	Variables of hydrocyclone and MGS					Maximum predicted values obtained with variable of hydrocyclone and MGS	
Optimization	Diameter of Apex, (mm)	Diameter of Vortex, (mm)	Drum speed (rpm)	Tilt Angle (°)	Wash water (lpm)	Chrome Grade (%)	Chrome Concentrate Recovery (%)
Maximum Grade	4.8	11	140	6	7	45.76	69.24
Maximum Recovery	3.2	14	210	2	3	31.35	81.38

was employed for modeling and optimizing five operations parameters of a combination of a hydrocyclone and MGS to produce chromites concentrate.

The predicted values match the experimental values reasonably well, with R^2 of 0.9005 for grade and R^2 of 0.9562 for the recovery of chromite concentrates. As a result of the experimental studies, the grade of chromite increased substantially through hydrocyclone and MGS combination beneficiation. The highest increase of grade was achieved on Test 2 with an increase of 225% (48.18% Cr_2O_3 to 14.79% Cr_2O_3). The highest recovery process is obtained on Test 6 with 80.94%.

Taking advantage of the quadratic programming, a diameter of the apex of 4.8 mm, diameter of the vortex of 11 mm, drum speed of 140 rpm, tilt angle of 6°, and wash water of 7 lpm have been determined as optimum levels to achieve the maximum grade of 45.76% for chromite concentrate. In the same way, a diameter of apex of 3.2 mm, diameter of vortex of 14 mm, drum speed of 210 rpm, tilt angle of 2°, and wash water of 3 lpm have been determined as optimum levels to achieve the recovery of 81.38% for chromite concentrate. This study demonstrates that the CCRD and response surface methodology can be successfully used for modeling the same operating parameters of hydrocyclone and MGS combination for Chromite Concentrator Plant of Uckopru and CCRD was an economical way of obtaining the maximum amount of information in a short period of time and with the fewest number of experiments. The hydrocyclone and MGS combination tests were carried out to verify the accuracy of these practical values obtained from optimization and it was shown that theoretical values were close to practical ones. In the results of the study, this method was determined that the beneficiation method of chromites by hydrocyclone and MGS combination in laboratory scale will perform successfully with 70–80% recovery. Moreover, the results of this method may be used for attempts in industrial scale. The usage of Uckopru concentrate tailinigs in raw state was limited because of their low chromite grade. But, these properties were enhanced to the desired values for industry after beneficiation. Thus, chromites having low grade for industry were beneficiated by hydrocyclone and MGS combination and these enhanced chromites can be sold.

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