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Investigation of chromite ore beneficiation possibilities with different gravity concentrators

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Abstract

The rapid development of industry increases the demand and importance of chromium. In this study, beneficiation possibilities of the representative chromite ore taken from the Tokat Province with a laboratory type jig, spiral concentrator, shaking table and multi gravity separator (MGS) were investigated. Appropriate particle size fractions were fed into each beneficiation device. Experimental studies were shown as a flow chart. The shaking table gave the best results for chromite beneficiation and a concentrate of 47.02% Cr_2O_3 grade and 94.29% recovery were obtained by using a -0.3+0.106 mm particle size fraction. It was observed that concentrates with saleable grade could be obtained as a result of the beneficiation of chromite ore with a spiral concentrator. The tailings obtained from the jig, spiral concentrator and shaking table were blended and scavenger experiments were carried out with an MGS to recover the remaining chromite in the tailings. 93.55% of the chromite in this blended sample was recovered with a grade of 34.96% Cr_2O_3. Hence, MGS seems to be the promising equipment for the beneficiation of tailings.

Keywords:

chromite; jig; spiral concentrator; shaking table; MGS

1. Introduction

The ores produced from mines contain unwanted minerals called gangue. In order to separate these gangue minerals and make valuable minerals usable in industry, valuable minerals should be enriched by various methods by utilizing differences in physical or chemical properties. With the application of the enrichment methods, it is possible to reduce the costs of transportation and smelting operations (**Malekabadi, 2022**).

The main usage areas of chromium, which is an important metal, are metallurgy, refractory and the chemical industry. The aim of the use of chromium in the iron, steel and non-ferrous alloy sector is to increase the resistance against oxidation and corrosion, as well as to give hardenability to metal (**USGS, 2023**). There is no alternative metal to chromium in the production of stainless steel. Therefore, it is necessary for both the military defense industry and the production of stainless steel (**Aratoğlu, 2017**).

Chromite is the most important commercial mineral in which chromium is produced economically. Chromite mineral ($FeCr_2O_4$), which is mineralogically in the spinel group, crystallizes in the cubic system (**Er, 2011**). The metallurgical grade chromite used in the production of alloy steel contains 48% Cr_2O_3. The chemical grade chromite ore with a Cr_2O_3 content of over 44% can be used in the production of sodium dichromate. Refractory grade chromite has a low (30-40%) Cr_2O_3 content (**Gu and Wills, 1988**). There are two groups of chromite deposits, namely stratiform and podiform ores. Most of the world's resources are found in the Bushveld complex (South Africa) and the Great Dyke (Zimbabwe) as stratiform-type chromite deposits. There are important podiform deposits in Russia, Kazakhstan, Turkey, Albania, the Philippines, Cuba, New Caledonia and India (**Misra, 2000; Revuelta, 2018**). Turkey is one of the important chromite producing countries in the world (**Özkan and İpekoğlu, 2001**). In 2021, approximately seven million tons of chromite ore were produced in Turkey (**Mapeg, 2023**). Turkey is also among the countries producing ferrochrome (**Çiçek et al., 1998**).

Chromite ores, when they are first mined, do not have the properties desired by the industry. Therefore, enrichment processes are required to bring these ores to the desired properties. The degree of liberation of the chromite and the properties of the ore and gangue minerals are effective when choosing the beneficiation methods to be applied to the chrome ores. One or several methods can be used together in beneficiation. Gravity methods (jigs, spirals, shaking tables, multi gravity methods, etc.), which are applied by separating valuable mineral and gangue minerals in a fluid medium (usually water) by utilizing the difference between their densities, are frequently used in the enrichment of chromite today (**Er,**

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Table 1: Particle size distribution of the sample

Particle size (mm)	Weight (%)	Cumulative passing (%)	Density (g/cm^3)
-3.35+2	25.85	100.00	3.29
-2+1	24.75	74.15	3.45
-1+0.5	19.91	49.40	3.59
-0.5+0.3	13.53	29.49	3.48
-0.3+0.106	8.03	15.96	3.35
-0.106	7.93	7.93	3.02
Total	100.00		

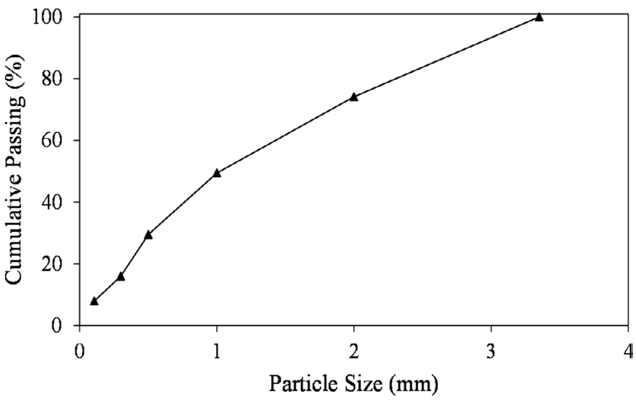

Figure 1: Plot of cumulative passing of the sample

Table 2: XRF results of the sample

Content (%)			
Al_2O_3	2.47	Cr_2O_3	35.46
CaO	5.66	SiO_2	16.77
MgO	27.20	MnO	0.18
Fe_2O_3	9.01	TiO_2	0.07

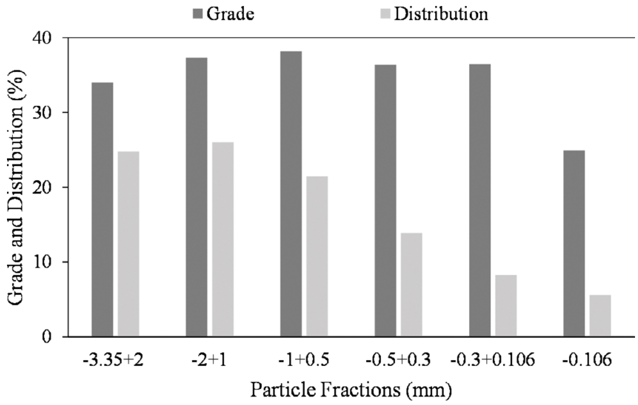

Figure 2: Cr_2O_3 grade and Cr_2O_3 distribution depending on particle fractions

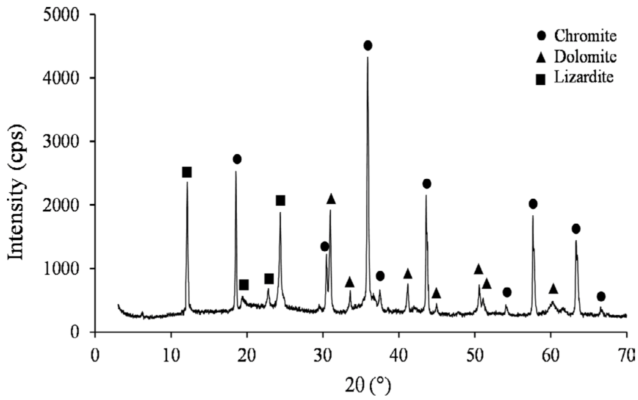

Figure 3: XRD results of the sample

2011). While high grade chromite ores can be sold without any beneficiation processes, low grade chromite ores should be enriched with the appropriate methods (**Deniz, 1992; Aydın, 2001; Er, 2011; Öztürk and Temel, 2014; Öztürk and Temel, 2016; Aratoğlu, 2017; Tabazık and Öztürk, 2019**).

Chromite ore, especially metallurgical grade, is produced by selective mining and then the lump ore is used directly in a smelting plant (**Deniz, 2019**). Gravity methods are the most suitable and inexpensive processes for chromite beneficiation (**Özcan, 2022**). If the liberation particle size of the ore is coarse, heavy media or jigs can be used. Shaking tables, spirals and multi gravity separators can be preferred for finer particles (**Gu and Wills, 1988; Kıdıman, 2009; Er, 2011; Bozkurt, 2017**). The advantages of gravity methods compared to other beneficiation methods can be summarized as lower operating costs, lower energy requirements, simplicity, no need for expensive reagents and less impact on the environment (**Gupta and Yan, 2016; Deniz, 2019**).

According to this study, it will be possible to see which gravity beneficiation methods can produce efficient results with laboratory experiments before proceeding to the chromite beneficiation plant stage. In addition, by re-enriching the tailings generated as a result of the beneficiation, chromite losses will be prevented and its environmental impact will be reduced. In this study, gravity-based beneficiation experiments were carried out using chromite ore obtained from the Tokat Province. In the experiments a jig, spiral concentrator, shaking table and multi-gravity separator (MGS) were used. The results were evaluated and a beneficiation flow chart was presented.

2. Material and methods

2.1. Material

In this study, 30 kg of representative chromite ore taken from the Tokat Province was brought to Konya Technical University Mining Engineering Department laboratories for experimental studies and sample preparation processes were carried out. Crushing was done using a jaw crusher. Afterwards, sieving was performed and fractions of -3.35+2 mm, -2+1 mm, -1+0.5 mm, -0.5+0.3 mm, -0.3+0.106 mm and -0.106 mm were obtained. The particle size distribution and cumulative passing of the sample are given in **Table 1** and **Figure 1**,

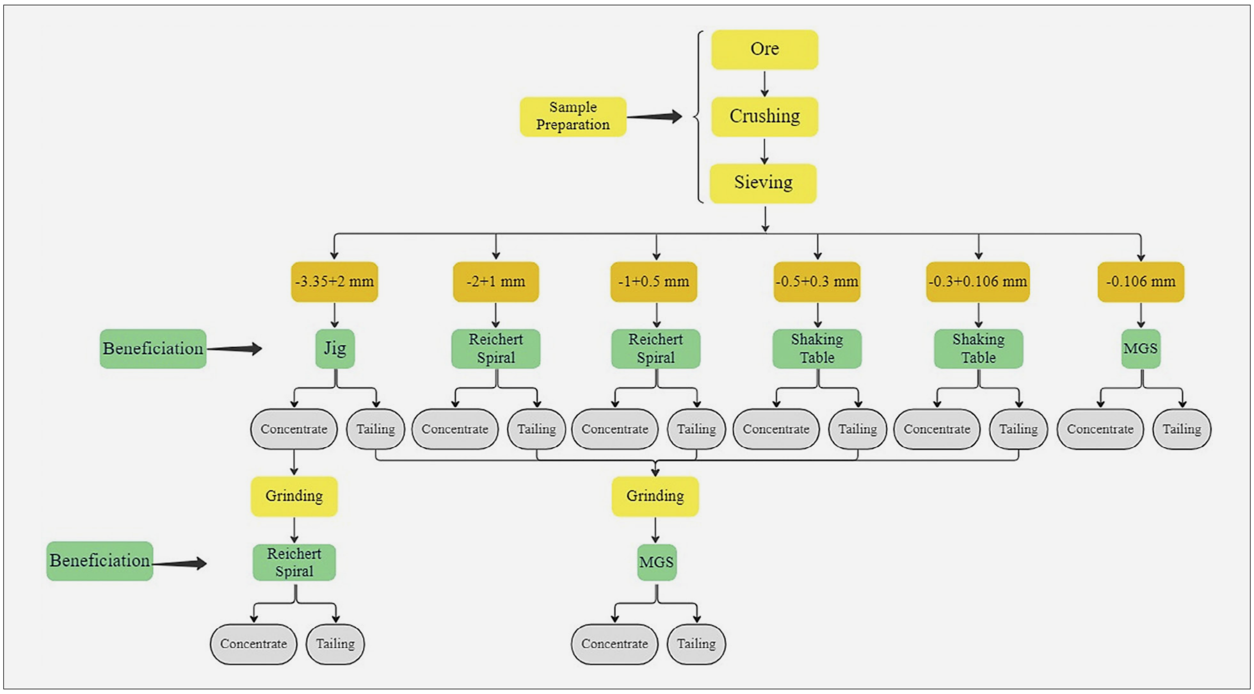

Figure 4: Flow chart followed in experimental studies

respectively. The d_{80} value of the sample was determined as 2.30 mm. The density of the sample was determined as 3.36 g/cm^3 and the density distribution of particle size fractions was also given in **Table 1**.

It was determined by XRF analysis that the sample contained 35.46% Cr_2O_3 (see **Table 2**). In **Figure 2**, the Cr_2O_3 grades and Cr_2O_3 distribution of the sample according to the fractions are given. 72.28% of the chromite in the ore was distributed in fractions coarser than 0.5 mm. As seen in **Figure 1** and **Figure 2**, the amount and Cr_2O_3 distribution of fine-sized fraction (below 106 mm) in the sample was low. This can be considered as an advantage in beneficiation of the sample with gravity methods. It was determined by XRD analysis that the sample contained chromite, dolomite and lizardite minerals (see **Figure 3**).

2.2. Method

The appropriate particle size feeding was made to the gravity equipment for the efficient beneficiation. In the experiments, a Denver jig, Reichert spiral, Wilfley type shaking table and C900 type multi gravity separator (MGS) were preferred for beneficiation of the chromite ore. The fraction of -3.35+2 mm was used in the experiment performed with the jig. The solid ratio was applied as 20% and the fractions of -2+1 mm and -1+0.5 mm were used in the spiral concentrator experiments. In the experiments performed with the shaking table, the solid ratio was applied as 20% and the fractions of -0.5+0.3 mm and -0.3+0.106 mm were used. The fraction of -0.106 mm, 20% of solid rate, 6 L/min of feed rate, 2 L/min of washing water, 160 rpm of drum rotation speed and 1.5° of slope were used in MGS experiments.

In order to achieve better liberation and increase the beneficiation efficiency, the particle size of the concentrate obtained from the jig was reduced to -0.6 mm. This concentrate was re-beneficiated with a spiral concentrator at 20% solid ratio. The particle size of the tailings obtained from the experiments using jig, spiral concentrator and shaking table was reduced to -0.106 mm. In order to recover the chromite remaining in the tailings, experiments were carried out with an MGS (in the same conditions as the MGS experiments). The grades and recoveries were determined for feed samples, concentrates and tailings by XRF analysis. The flow chart showing the experimental studies is given in **Figure 4**.

3. Results and discussions

Gravity concentration methods separate mineral particles of several specific gravity by relative motions based on their reaction to the gravity force and other forces. The movement of a particle in a liquid depends on both its specific gravity and size. Coarse particles will be more affected than small particles. Since the effectiveness of the gravity concentration increases with particle size, it is desirable that the particles should be adequately coarse. In the application of gravity beneficiation, in order to reduce the effect of particle size and make the relative movement of the particle dependent on its specific gravity, the feed should be in a narrow size range of particles. The application of gravity beneficiation to coarse minerals where liberation could be achieved provides important advantages for subsequent processes (**Wills, 1988**). When using gravity concentrators, it is generally desired that the feed is in different size ranges. Effective gravity concentrators, such as jigs and shaking tables, are widely used in many plants where chromite ores are beneficiated in the world (**Malekabadi, 2022**). In this study, the feed was sieved and separated into fractions in a narrow size range of particles, and beneficiated with the appropriate concentrators.

3.1. Beneficiation experiment performed with a jig

Beneficiation with a jig takes place via vertical expansion and contraction of the bed, which consists of coarse mineral particles by the pulse of fluid. Jigging is characterized by the separation of dense and light minerals into separate layers. In jigging, the ore should be liberated in coarse sizes and should be classified into a narrow size range of particles (**Gupta and Yan, 2016**). Chromite ore in the fraction of -3.35+2 mm was used in the beneficiation experiment performed with laboratory scale jig, and the results are given in **Table 3**. As a result of the experiment, a concentrate with a Cr_2O_3 grade of 38.35% was obtained with a recovery of 92.04%. Although a high recovery was obtained, it was thought that the concentrate should be re-enriched because the concentrate grade did not increase much compared to the feed.

Table 3: Results of jig beneficiation experiment (%)

Products	Weight	Cr_2O_3	Recovery
Concentrate	81.64	38.35	92.04
Tailing	18.36	14.75	7.96
Feed	100.00	34.02	100.00

Agacayak et al. (2007) investigated the beneficiation possibilities of chromite ore. In the experiments, -3.35+2 mm and -2+1 mm particle sizes were used for jigging. The concentrates of 48.75% and 50.68% Cr_2O_3 grades were obtained with 76.52% and 87.58% recoveries by using -3.35+2 mm and -2+1 mm fractions, respectively.

3.2. Beneficiation experiments performed with a spiral concentrator

This concentrator is actually a simple sluice with a spiral shape and the pulp flowing on it makes a circular movement. The pulp fed to the spiral spreads on the surface under the influence of the outward centrifugal force and the downward gravity force. While heavier particles sink on the spiral surface, lighter particles are liable to remain suspended. The Humphrey spiral, developed by Humphrey in 1943, was used commercially for the first time in the beneficiation of chromite (**Goodman et al., 1985; Acarkan and Önal, 2014**). Spiral concentrators were first produced and used for the beneficiation of minerals such as zircon, rutile, chromite and ilmenite in the mineral sand industry. These concentrators present simplicity, efficiency, ease of use, low maintenance, low operating cost and low capital cost (**Gupta and Yan, 2016; Malekabadi, 2022**). The fractions of -2+1 mm and -1+0.5 mm were used in the experiments performed with the laboratory scale spiral concentrator and the results are given in **Table 4**. In the experiment, using the fraction of -1+0.5 mm, it was seen that both the Cr_2O_3 grade and the recovery were higher.

Table 4: Results of spiral concentrator beneficiation experiments (%)

Particle size	Products	Weight	Cr_2O_3	Recovery
-2+1 mm	Concentrate	41.63	39.31	43.87
	Tailing	58.37	35.87	56.13
	Feed	100.00	37.30	100.00
-1+0.5 mm	Concentrate	60.61	45.10	71.56
	Tailing	39.39	27.58	28.44
	Feed	100.00	38.20	100.00

Gül et al. (1995) investigated the beneficiation possibilities of low-grade chromite. In the experiments in which a Reichert spiral was used, a concentrate of 48.38% Cr_2O_3 grade was obtained with 54.5% recovery by using a -1 mm fraction containing 4.71% Cr_2O_3. **Bilici (2018)** obtained the highest Cr_2O_3 grade (14.90%) and recovery (81.30%) at -600 µm particle size fraction in beneficiation experiments carried out using a spiral concentrator of plant tailings.

3.3. Beneficiation experiments performed with a shaking table

Shaking tables are widely used in the mineral preparation industry, especially in the beneficiation of chromite ores. They apply a horizontal movement to the pulp to cause effective separation of heavy and light particles. The table moves forward-backward in the direction of its long axis and the backward movement is faster. The surface of the table is inclined and covered with riffles in order to create hindered settling conditions (**Gupta and Yan, 2016**). Shaking tables can be used efficiently in gravity concentration with a particle size of -1+0.1 mm (**Can et al., 2019**). In the study, a laboratory scale shaking table was used with a particle size of -0.5+0.3 mm and -0.3+0.106 mm and the results are given in **Table 5**. According to **Wills and Finch (2016)**, if the feed consists of a wide size range of particles, then the recovery will remain low as a result of the enrichment. The feed used in this study with the shaking table is both in the size that can be beneficiated with the shaking table and in the narrow size range. From the examination of **Table 5**, it was seen that a concentrate was obtained with a high grade and recovery from the beneficiation of both fractions with the shaking table. The similarity of these results showed that both fractions were well beneficiated by the shaking table and the obtained concentrates were close to metallurgical chromite grade.

Deniz (1992) obtained a concentrate of 48.22% Cr_2O_3 grade with 75.26% recovery by using a -0.425+0.3 mm

Table 5: Results of shaking table beneficiation experiments (%)

Particle size	Products	Weight	Cr_2O_3	Recovery
-0.5+0.3 mm	Concentrate	72.33	46.43	92.31
	Tailing	27.67	10.11	7.69
	Feed	100.00	36.38	100.00
-0.3+0.106 mm	Concentrate	73.11	47.02	94.29
	Tailing	26.89	7.74	5.71
	Feed	100.00	36.46	100.00

fraction in shaking table experiments with a sample containing 30.81% Cr_2O_3. **Aydın (2001)** investigated the beneficiation of concentrator plant tailings with a shaking table and obtained a concentrate of 34.08% Cr_2O_3 grade with 90% recovery. **Turgut (1995)** obtained a concentrate of 50.64% Cr_2O_3 grade with 75.31% recovery by using a -0.425+0.210 mm fraction in beneficiation of 22.54% Cr_2O_3 grade chromite with a shaking table.

3.4. Beneficiation experiment performed with an MGS

An MGS, which is a gravity concentrator manufactured for the beneficiation of fine and very fine mineral particles and used in the industry, can be described as a shaking table transformed into a drum. The scrapers inside the drum spin at a slightly higher velocity than the drum and in the same direction as the drum. The feed made to the MGS as a pulp is given to the inner surface of the drum. Washing water is added near the open end of the drum. The drum has a slope of 0-9 degrees (**Chan et al., 1991; Çiçek et al., 1998**). A much greater force than normal gravity is applied to the particles in the flowing film, thus increasing the separation of fines (**Gupta and Yan, 2016**). In consequence of high centrifugal forces and shearing effect, heavy particles pass through the sludge film, making a semi-solid layer on the wall of the drum. The heavy particles are moved to the open end of the drum, where they are collected as a concentrate, by means of scrapers. On the other hand, the light minerals are conveyed by the flow of washing water to the back of the drum, where they are discharged as waste (**Chan et al., 1991; Deniz, 2019**). In this study, a C900 type laboratory scale MGS device, drum speed of 100-300 rpm in a clockwise direction, with a capacity of 150 kg/h and sinusoidal motion in axial direction, was used. **Aslan and Canbazoğlu (1995)** stated that particle size is very important in beneficiation with an MGS. It has also been reported that the separation is good in fine particles, and the sensitivity of separation is reduced in coarse particles. Chromite ore in a -0.106 mm fraction was used in the beneficiation experiment performed with the MGS and the results are given in **Table 6**. Due to the low grade of the fraction fed to the MGS compared to other fractions, a relatively low-grade concentrate was obtained with acceptable recovery.

Table 6: Results of the MGS beneficiation experiment (%)

Products	Weight	Cr_2O_3	Recovery
Concentrate	62.07	34.21	85.14
Tailing	37.93	9.77	14.86
Feed	100.00	24.94	100.00

Deniz (2019) obtained a concentrate of 41.72% Cr_2O_3 grade with 81.34% recovery in the experiments with an MGS using 23.84% Cr_2O_3 grade chromite tailings. **Özkan and İpekoğlu (2001)** obtained a concentrate of 47% Cr_2O_3 grade with 72% recovery as a result of the experiments carried out with an MGS using a sample with 25.20% Cr_2O_3 grade**. Eskibalci et al. (2002)** obtained a concentrate of 47% Cr_2O_3 grade with 64.42% recovery as a result of beneficiation of the 18.74% Cr_2O_3 grade concentrator plant tailings with an MGS. **Özgen (2012)** obtained a concentrate of 48.18% Cr_2O_3 grade with 69.79% recovery with an MGS using chromite tailings.

3.5. Re-enrichment and scavenger experiments

The concentrate obtained from the jig was ground to a -0.6 mm particle size for better liberation and beneficiated again with a spiral concentrator. In this way, it was aimed to obtain a higher-grade concentrate and the results are given in **Table 7**. As can be seen in **Table 7**, a slight increase was observed in the grade of the concentrate obtained as a result of re-enrichment of the concentrate obtained from the jig with a spiral. It was concluded that the tailings obtained from the spiral concentrator could be considered as a middling.

Table 7: Re-enrichment of the concentrate obtained from the jig with spiral concentrator (%)

Products	Weight	Cr_2O_3	Recovery
Concentrate	55.77	42.36	61.60
Middling	44.23	33.29	38.40
Feed	100.00	38.35	100.00

As shown in the flow chart in **Figure 4**, tailings obtained from the jig, spiral concentrator and shaking table were combined considering their amounts and a homogeneous mixture was obtained. This material was ground to a particle size of -0.106 mm for better liberation and scavenger experiment was carried out with an MGS to recover the chromite in the tailings. The obtained results are given in **Table 8**. As can be seen in **Table 8**, it was seen that a concentrate with high recovery and a tailing

Table 8: Scavenger experiment with an MGS (%)

Products	Weight	Cr_2O_3	Recovery
Concentrate	66.07	34.96	93.55
Tailing	33.93	4.69	6.45
Feed	100.00	24.69	100.00

with very low Cr_2O_3 grade were obtained from the scavenger experiments performed with the MGS.

4. Conclusions

In this study, beneficiation experiments were carried out using chromite ore taken from the Tokat Province. Different gravity concentration methods including a jig, spiral concentrator, shaking table and multi gravity separator were performed for the beneficiation of chromite ore. The results obtained from the experiments were as follows:

- In the experiment, carried out with a jig using the fraction of -3.35+2 mm, a concentrate of 38.35% Cr_2O_3 grade was obtained with a recovery of 92.04%.
- In the spiral concentrator experiments, a concentrate with a grade of 39.31% Cr_2O_3 was obtained with a recovery of 43.87% using the -2+1 mm fraction, while a concentrate of 45.10% Cr_2O_3 grade was obtained with a recovery of 71.56% using the -1+0.5 mm fraction.
- In the shaking table experiments, a concentrate of 46.43% Cr_2O_3 grade was obtained with a recovery of 92.31% using the -0.5+0.3 mm fraction, while a concentrate with a grade of 47.02% Cr_2O_3 was obtained with a recovery of 94.29% using the -0.3+0.106 mm fraction.
- Chromite concentrates at a grade close to metallurgical grade chromite was obtained with the shaking table and spiral concentrator experiments.
- In the experiment, carried out with the MGS using the fraction of -0.106 mm, a concentrate with a grade of 34.21% Cr_2O_3 was obtained with a recovery of 85.14%.
- The concentrate obtained from the jig was re-enriched with a spiral concentrator and a concentrate of 42.36% Cr_2O_3 grade was obtained with a recovery of 61.60%.
- The mixture obtained from the tailings of the jig, spiral concentrator and shaking table was ground to -0.106 mm and a scavenger experiment was carried out with an MGS. A concentrate with a grade of 34.96% Cr_2O_3 was obtained with a recovery of 93.55%.

When all the experimental results were examined, it was seen that the best results were obtained with the shaking table, taking into account the chromite grade and recovery. In addition, according to a flow chart that can be recommended for industrial application, firstly the ore should be comminuted. Then the ore should be enriched with a shaking table after the classification process. In order to recover the chromite in the obtained tailing, scavenger enrichment can be done with an MGS. Thus, it can be stated that the final tailing to be obtained from an MGS will have a very low Cr_2O_3 grade.

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SAŽETAK

Istraživanje mogućnosti oplemenjivanja kromitne rude s različitim gravitacijskim koncentratorima

Brzi razvoj industrije povećava potražnju i važnost kroma. U ovoj studiji istražene su mogućnosti oplemenjivanja kromitne rude iz provincije Tokat s laboratorijskim tipom plakalice, spiralnim koncentratorom (žlijebom), koncentracijskim stolom i više gravitacijskim separatorom (MGS -*Multi gravity separator)*. Kao ulazni materijal svakog uređaja za oplemenjivanje korištene su frakcije odgovarajuće veličine čestica. Eksperimentalne studije prikazane su dijagramom toka. Najbolji rezultati postignuti su oplemenjivanjem kromitne rude na koncentracijskom stolu, pri čemu je preradom materijala granulacije -0.3+0.106 mm ostvarena kvaliteta koncentrata od 47,02% Cr_2O_3 uz iskorištenje od 94,29%. Rezultati ispitivanja također pokazuju da se oplemenjivanjem kromitne rude u spiralnom žlijebu može proizvesti koncentrat kvalitete koja omogućuje njegovu prodaju. Jalovina dobivena oplemenjivanjem u plakalici, spiralnom koncentratoru i na koncentracijskom stolu pomiješana je i zatim su s tom jalovinskom smjesom provedeni testovi u MGS-u kako bi se iz nje izdvojio preostali kromit. Iz tog miješanog uzorka izdvojeno je 93,55% kromita s udjelom Cr_2O_3 od 34,96%. Stoga se čini da je MGS obećavajuća oprema za oplemenjivanje jalovine.

Ključne riječi:
Kromit; plakalica; spiralni koncentrator; koncentracijski stol; MGS

Author's contribution

Ali Aras (1) (Assistant Professor, Konya Technical University Mining Engineering Department) conducted all experimental work, evaluated the results and wrote the draft of the manuscript. **Hasan Ali Taner (2)** (Researcher, Konya Technical University Mining Engineering Department) gathered samples, prepared the presentation of the results and reviewed the draft manuscript. The entire work was written collaboratively by both of the authors.