

# PHYSICAL BENEFICIATION OF LOW-GRADE CHROMITE SAND USING A SHAKING TABLE AND DAVIS TUBE

## BENEFISIASI FISIK PADA PASIR KROMIT KADAR RENDAH MENGGUNAKAN MEJA GOYANG DAN DAVIS TUBE

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### ABSTRACT

The rapid growth of the global steel industry has significantly intensified the demand for the metallurgical-grade chromite ore required for ferrochrome production. This surge has led to a depletion of high-grade chromite reserves, necessitating the utilization of low- and medium-grade chromite to support a stable raw material supply for ferrochrome. This research was conducted to determine the characteristics of the ore and to analyze the effects of physical beneficiation processes using shaking table and Davis tube in enhancing the chromium (Cr) grade and the Cr : Fe ratio of low-grade chromite sand from Morowali, Central Sulawesi. The characterization process was conducted using XRF, XRD, and SEM-EDS. Experimental parameters for the shaking table included variations in table inclination and water flow rate, while magnetic separation was analyzed across various electric current intensities. The optimal shaking table test results were achieved at an inclination of 7.5° with a water flow rate of 18 liters/minute. In contrast, the optimal test using the Davis tube was obtained at an electric current of 0.4 amperes (660 gauss). This integrated process successfully increased Cr grade from 8.5% to 20.77% (corresponding to Cr<sub>2</sub>O<sub>3</sub> 30.36%) and improved the Cr : Fe ratio from 0.97 to 1.62, achieving a recovery rate of 94.93%.

Keywords: chromite sand, Davis tube, ferrochrome, and shaking table.

### ABSTRAK

Permintaan bijih kromit untuk produksi ferokrom terus meningkat seiring dengan pesatnya pertumbuhan industri baja global. Kenaikan ini menyebabkan pasokan bijih kromit kadar tinggi menurun, sehingga diperlukan pemanfaatan kromit kadar rendah dan sedang untuk mendukung kestabilan pasokan bahan baku ferokrom. Penelitian ini dilakukan untuk mengetahui karakteristik bijih kromit dan menganalisis pengaruh proses benefisiasi fisik menggunakan meja goyang (shaking table) dan tabung Davis (Davis tube) terhadap peningkatan kadar Cr dan rasio Cr : Fe pasir kromit kadar rendah asal Morowali, Sulawesi Tengah. Proses karakterisasi dilakukan dengan menggunakan XRF, XRD, dan SEM-EDS. Proses meja goyang menggunakan parameter pengujian berupa kemiringan meja dan laju aliran air, sedangkan proses pemisahan magnetik diujikan pada berbagai kuat arus listrik. Melalui pengujian meja goyang diperoleh hasil optimal pada kemiringan 7,5° dengan laju aliran air 18 liter/menit. Sebaliknya, pada

*pengujian menggunakan tabung Davis diperoleh hasil optimal pada kuat arus listrik 0,4 ampere (660 gauss). Kombinasi kedua proses ini berhasil meningkatkan kadar Cr dari 8,5% menjadi 20,77% ( $Cr_2O_3$  30,36%) dan rasio Cr : Fe dari 0,97 menjadi 1,62 dengan tingkat recovery 94,93%.*

*Kata kunci: pasir kromit, tabung Davis, ferrokrom, dan meja goyang.*

## INTRODUCTION

Chromite is a complex mineral containing Cr, Fe, Al, and Mg in proportions that can vary depending on the deposit (Bhandary *et al.*, 2016). In Indonesia, particularly in Morowali Regency, there are chromite resources which occur as chromite-bearing sands and classified as secondary chromite, manifesting as coastal alluvial black sand deposits (Puspita, 2021). About 90% of mined chromite ore is processed to obtain chromium. This chromium metal will later be processed into ferrochrome through metallurgical processes (Murthy, Tripathy and Kumar, 2011).

The demand for metallurgical-grade chromite ore for the production of ferrochrome, a material for stainless steel, is increasing along with the rapid growth of the steel industry (Tripathy, Singh and Ramamurthy, 2012). This surge has led to a limited supply of high-grade chromite ore. Therefore, it is necessary to utilize low and medium-grade chromite to continue supporting the supply of raw materials for ferrochrome (Al-Tigani, Mohamed and Seifelnasr, 2019). To enhance the value of chromite, particularly the low-grade ores, physical beneficiation processes can be employed (Murthy and Tripathy, 2020).

The physical beneficiation process of chromite ore is typically divided into two main parts. The first part involves comminution (reducing the grain size or liberating the ore) if the ore is still in the form of chunks or rocks that do not yet meet the size requirement. The second part is upgrading or concentrating the ore (Bhandary *et al.*, 2016). In the concentration process of chromite sand, gravity concentration and magnetic concentration techniques are commonly used (Murthy, Tripathy and Kumar, 2011). Shaking tables represent the widely utilized gravity concentration equipment for processing low-grade chromite ores. In this process, magnetic concentration is typically integrated to reduce Fe content or ferromagnetic impurities, thereby optimizing the Cr : Fe ratio in the concentrate.

Research conducted by Motasim *et al.* (2019) used Heavy Media Separation (HMS) and Low Intensity Magnetic Separator (LIMS) in processing low-grade chromite ore from Sudan. Additionally, the research by Bhandary *et al.* (2016) discussed the beneficiation of low-grade chromite ore for the formation of magnesia-chromite refractories. There has been limited research on the physical beneficiation of low-grade chromite sand samples with  $Cr_2O_3$  content of less than 15% and a Cr : Fe ratio of less than 1. Furthermore, the integration of shaking table with Davis tube as a magnetic separator remains sparsely documented in existing literature.

Therefore, the development of physical beneficiation processes utilizing these two methods is essential to enhance the technical feasibility of upgrading chromite sand, especially for low-grade local chromite sand. This study was conducted to increase the chromium content and the chromium to iron ratio (Cr : Fe) in low-grade chromite sand sourced from Morowali, Central Sulawesi, and to yield a chromite concentrate suitable as raw material for ferrochrome production (46-48%  $Cr_2O_3$  and a Cr : Fe ratio greater than 2) (Bhandary *et al.*, 2016).

## METHOD

### Materials

The as-received low-grade chromite ore utilized in this research originates from Morowali, Central Sulawesi, Indonesia. The particle distribution of chromite sand is shown in Table 1.

The chemical composition of the ore was analyzed using XRF testing, as presented in Table 2. The XRD analysis shown in Figure 1 revealed the presence of minerals such as chromite, magnesioferrite, magnetite, enstatite, quartz, diopside, lizardite, cordierite, calcite, and dolomite, along with their respective densities as shown in Table 3.

Table 1. Distribution of particles of each size fraction of chromite sand

Particle Size		Weight (%)
Mesh	Micron ( $\mu\text{m}$ )	
+ 10	+ 1680	0
- 10 + 20	- 1680 + 841	0.32
- 20 + 40	- 841 + 420	4.91
- 40 + 60	- 420 + 250	70.22
- 60 + 80	- 250 + 177	2.91
- 80 + 100	- 177 + 149	0.83
- 100 + 120	- 149 + 125	20.21
- 120	- 125	0.26
Loses		0.33
Total		100

The ore was further analyzed using SEM-EDS, with the results presented in Figure 2. The analysis identifies several impurities such as Fe, Si, Ca, Al, and Mg. These impurities are not all chemically bonded with Cr, as indicated. This result suggests that the

chromium grade can be effectively enhanced through physical beneficiation methods.

Table 3. The density of the minerals composing the ore

Minerals Name	Density ( $\text{gr}/\text{cm}^3$ )
Chromite	4.5 – 4.8
Magnesioferrite	4.51
Magnetite	5.2
Enstatite	3.1
Quartz	2.65
Diopside	3.26
Lizardite	2.5 – 2.7
Cordierite	2.6
Calsite	2.71
Dolomite	2.8

sources: Camerucci, Urretavizcaya and Cavalieri (2003); Davila, Risbud and Shackelford (2008); Macke *et al.* (2010); Hakim *et al.* (2017); Ma *et al.* (2019); Dzvinamurungu *et al.* (2020); Masoud *et al.* (2020); Pagona *et al.* (2022)

Table 2. XRF test result of ore in initial condition (as-received)

Elements/Compounds	Cr ( $\text{Cr}_2\text{O}_3$ )	Fe	MgO	$\text{Al}_2\text{O}_3$	$\text{SiO}_2$	CaO	Cr : Fe Ratio
Grade (%)	8.5 (12.42)	8.77	11.33	6.04	12.02	7.73	0.97

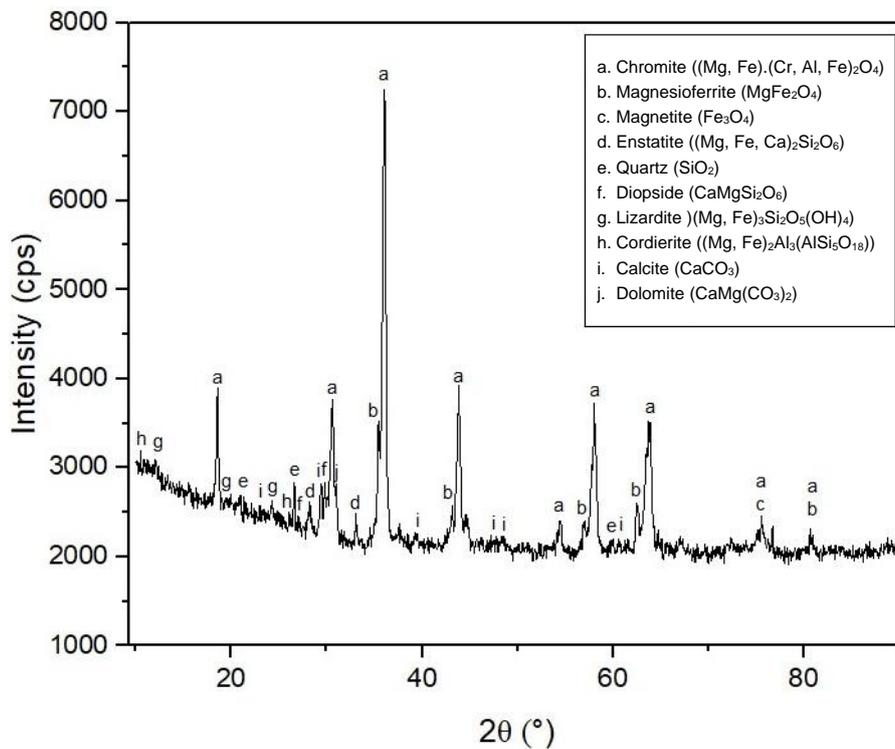


Figure 1. XRD test result of ore in initial condition (as-received).

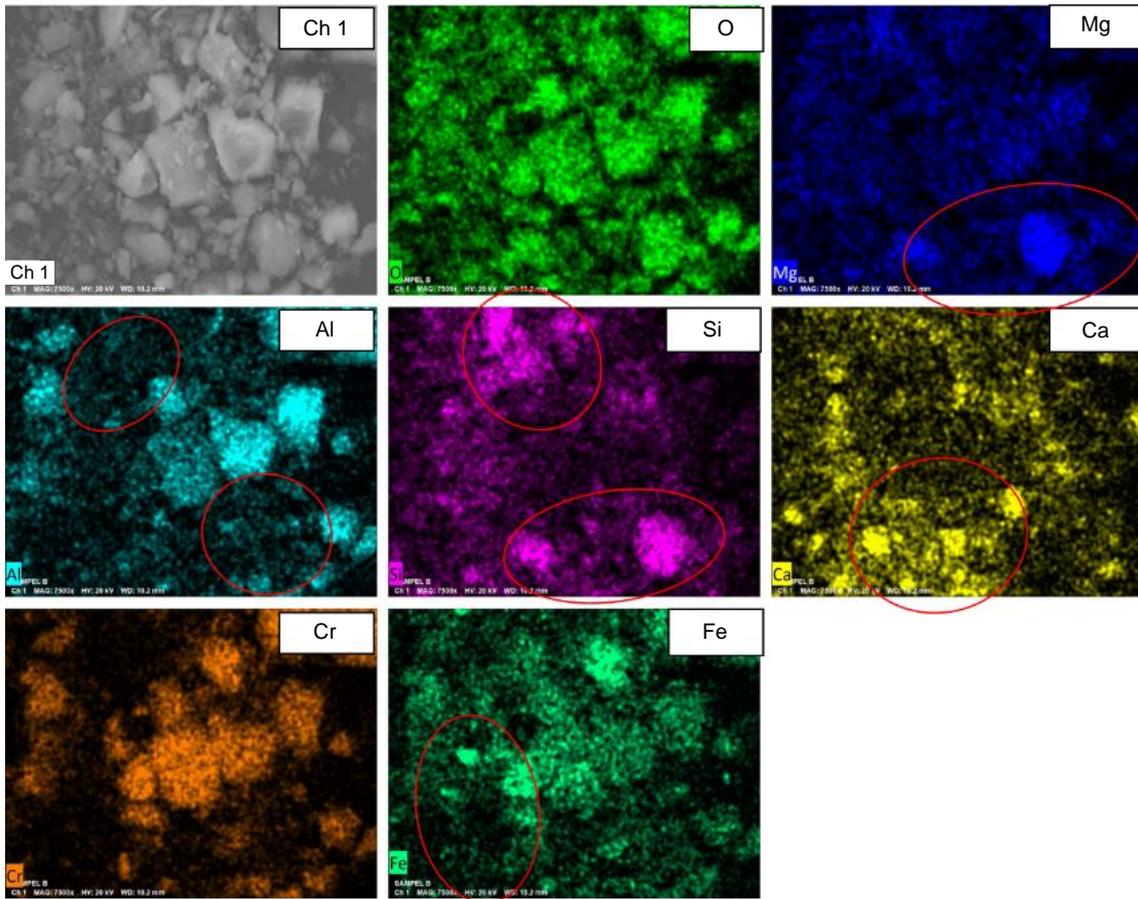


Figure 2. SEM EDS results of the initial condition ore (as-received) magnification 7500X.

### Gravity Concentration and Magnetic Concentration Process

The gravity concentration process was executed using a shaking table with experimental variables including table slope and water flow rate. This table has several holes. The initial holes collect the tailings, comprising material with low specific gravity. Meanwhile, the distant holes collect the concentrate, which consists of material with higher specific gravity. The intermediate region between these two fractions collects the middling, which have medium specific gravity. This is illustrated in Figure 3.

The experiment involved table inclination variations of 2.5°, 5°, 7.5°, and 10°. Upon determining the optimal inclination, subsequent tabling processes were conducted at water flow rates variations of 14 liters/minute, 18 liters/minute, and 22 liters/minute. Each experiment run for approximately 10 minutes, after which the

resulting concentrate, middling, and tailing fractions were collected.

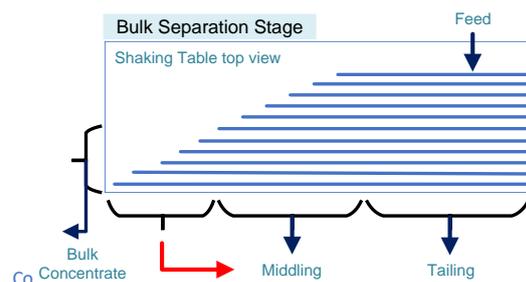


Figure 3. Schematic diagram of a shaking table.

The feed rate for each experiment (10 minutes) was 1 kg/minute of chromite sand.

After tabling, the samples were dried at temperature approximately 120°C for approximately 240 minutes. XRF, XRD, and SEM-EDS analyses were then performed to evaluate the optimal results.

The most optimal concentrate obtained from the shaking table process, referred to as Concentrate 1, was subjected to a magnetic separation process, with each experiment using 50 grams sample. The most optimal concentrate obtained from the magnetic separation process is referred to as Concentrate 2. The subsequent process utilized a Davis tube model EDT serial 22G 1162 C with varying electric current as presented in Table 4. The conversion of Ampere to Gauss in Table 4 were obtained from a measuring instrument of a Gauss meter.

Table 4. Conversion of amperes to gauss

Ampere	Gauss
1.4	1940
0.8	1230
0.4	660
0.3	510
0.2	370
0.1	210

After magnetic separation, both the concentrate and tailing samples from each variation were dried at temperature approximately 120°C for approximately 240 minutes. Subsequently, the samples were reanalyzed using XRF. The most optimal samples, both concentrate and tailing, were further analyzed using XRD and SEM-EDS.

**Characterization**

During the concentration process, XRF testing was performed to determine the elements grade changes after the shaking table and Davis tube processes. XRD analysis was conducted to observe changes in the intensity of each mineral present in the sample, while SEM-EDS analysis was employed to examine the morphological composition of the material, elemental distribution, and the mineral distribution map of the ore before and after the concentration process.

**RESULTS AND DISCUSSION**

**The Effect of Table Inclination on the Shaking Table Process**

Figure 4 shows the effect of table inclination towards Cr grade, Fe grade, oxide impurity grade, Cr : Fe ratio, weight, and recovery. This process utilized a constant water flow

rate of 18 liters/minute. Table inclination influences the amount of concentrate and impurities produced, as well as the quality of the grades in the concentrate, middling, and tailing (Oediyani *et al.*, 2018). The highest Cr grade in the concentrate was achieved at 2.5° inclination, reaching 22.54%, as shown in Figure 4(a).

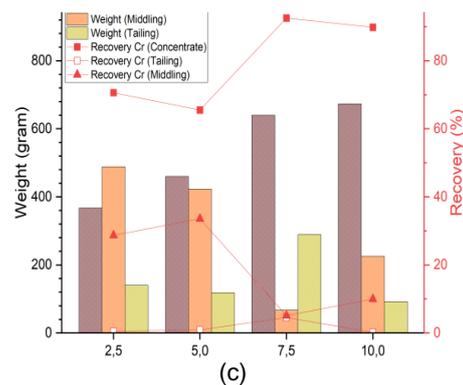
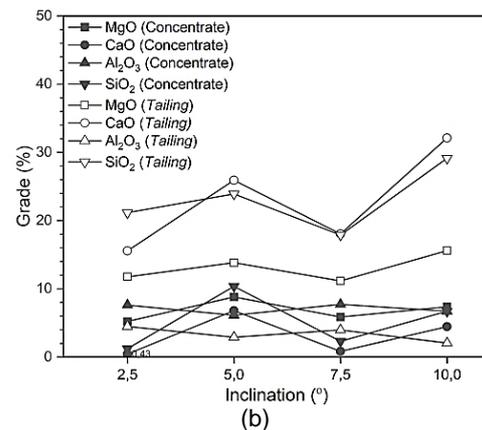
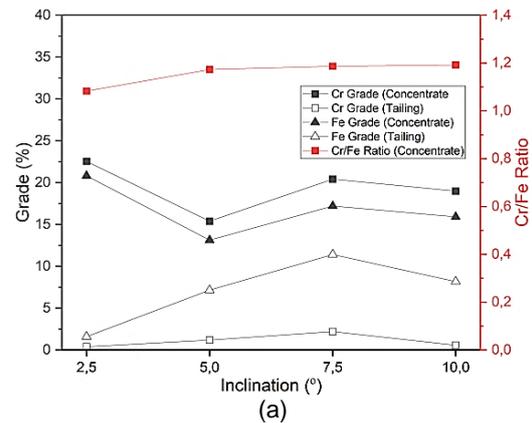


Figure 4. Graph of table inclination angle against: (a) concentrate and tailing grades of Cr, Fe, and Cr : Fe ratio (concentrate), (b) oxide impurities in concentrate and tailing, (c) weight and percentage of Cr recovery (concentrate, middling, and tailing)

The Fe content in the concentrate and the Cr content at each inclination are not significantly different because the Fe formed in the magnesioferrite (4.51 g/cm<sup>3</sup>) and magnetite (5.2 g/cm<sup>3</sup>) minerals are not optimally separated through the tabling process. This phenomenon is attributed to the marginal density differentials between these minerals with chromite (4.5–4.8 g/cm<sup>3</sup>), and some Fe remains directly bonded with Cr. Rietveld quantitative phase analysis for as-received material at each inclination showed in Table 5.

The Cr : Fe ratio demonstrates a positive correlation with the table inclination. Higher Cr content and lower Fe content result in a higher Cr : Fe ratio. The highest Cr : Fe ratio was achieved at inclinations of 7.5° and 10°, both at ratio of 1.19.

As illustrated in Figure 4(b), the concentrations of oxide impurities most notably SiO<sub>2</sub> and CaO, exhibit a significant reduction in the concentrate relative to the tailings, whereas MgO and Al<sub>2</sub>O<sub>3</sub> are not significantly separated from the concentrate. This is because some Mg and Al are included in heavy minerals bonded with Fe in various mineral phases such as chromite, magnesioferrite, and cordierite, as indicated by the XRD results in Figure 1. The graph shows that oxide impurities in the concentrate at each slope range from 0.43% to 10.35%. These results demonstrate that the tabling process achieves a high separation efficiency in rejecting oxide impurities such as SiO<sub>2</sub> and CaO from the concentrate.

Based on the Cr and Fe levels in the concentrate, the Cr and Fe recovery values are formulated as follows:

$$R = \frac{K.k}{F.f} \times 100\%$$

- R : recovery
- K : weight of concentrate produced (kg)
- F : weight of feed (kg)
- k : mineral or metal content in the concentrate produced (%)
- f : mineral or metal content in the feed (%)

As indicated in Figure 4(c), the 7.5° inclination yielded the highest Cr concentrate recovery at 92.54%. Concentrate recovery can be increased by reprocessing the middling fraction during the tabling process, resulting in higher concentrate weight and recovery (Tripathy, Murthy and Singh, 2013). The weight of the concentrate exhibits a proportional increase relative to the inclination angle, with the highest yield achieved at a 10° inclination, with the total amount of 673.36 grams. The highest middling weight was 488 grams at an inclination of 2.5°. This weight followed a declining trend as the inclination increased, but a notable deviation was observed at an inclination of 10°, where the weight increased. This behavior indicates that an inclination of 7.5° represents the optimal operating condition for phase separation, thereby minimizing the middling weight compared to the middling weight tested at other inclinations.

Based on Figure 4, the optimal table inclination is 7.5°, resulting in a Cr (Cr<sub>2</sub>O<sub>3</sub>) concentrate grade of 20.40% (29.82%). This grade is close to the highest Cr concentrate grade at a 2.5° inclination. The Cr:Fe ratio achieved at a 7.5° inclination also yields the highest value of 1.19 with a recovery rate of 92.54% and a substantial concentrate weight of 640 grams. Therefore, 7.5° is considered

Table 5. Rietveld XRD of as-it-is and concentrate at each inclination at a flow rate of 18 liters/minute

Minerals Name	As-it-is	Inclination at a flow rate of 18 liters/minute			
		2.5°	5°	7.5°	10°
Chromite	36.6%	82.5%	42.1%	43.3%	57.8%
Magnesioferrite	15.0%	12%	17.5%	23.5%	8.5%
Magnetite	29.5%	5.5%	6.2%	32.9%	1.7%
Enstatite	8.7%		34.3%		22.22%
Quartz	0.9%				6.4%
Diopside	1%			0.2%	3.4%
Lizardite	1.3%				
Corderite	1.3%				
Calcite	3.2%				
Dolomite	2.4%				

the most optimal inclination. The concentrates at each inclination and the most optimal results (concentrate, middling, and tailing) were subjected to XRD analysis, as shown in Figure 5 and Figure 6.

The XRD analysis results in Figure 5 reveal that the concentrate at 10° inclinations contains the highest impurities, as indicated by the mineral peaks on the graph. This phenomenon is attributed to the large number

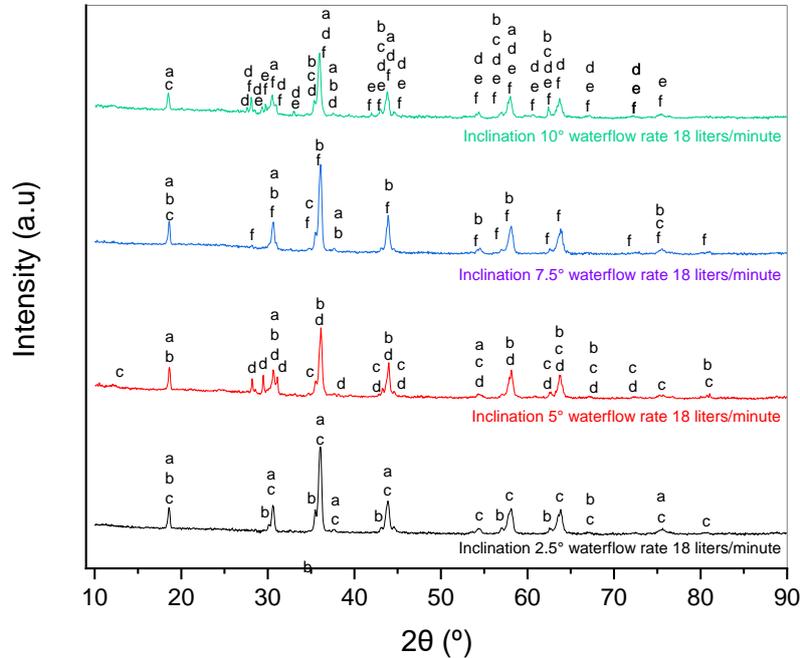


Figure 5. The XRD graph of concentrate at each inclination at a flow rate of 18 liters/minute a-chromite ((Mg, Fe).(Cr, Al, Fe)<sub>2</sub>O<sub>4</sub>); b-magnesioferrite (MgFe<sub>2</sub>O<sub>4</sub>); c-magnetite (Fe<sub>3</sub>O<sub>4</sub>); d-enstatite ((Mg, Fe, Ca)<sub>2</sub>Si<sub>2</sub>O<sub>6</sub>); e-quartz (SiO<sub>2</sub>); f-diopside (CaMgSi<sub>2</sub>O<sub>6</sub>)

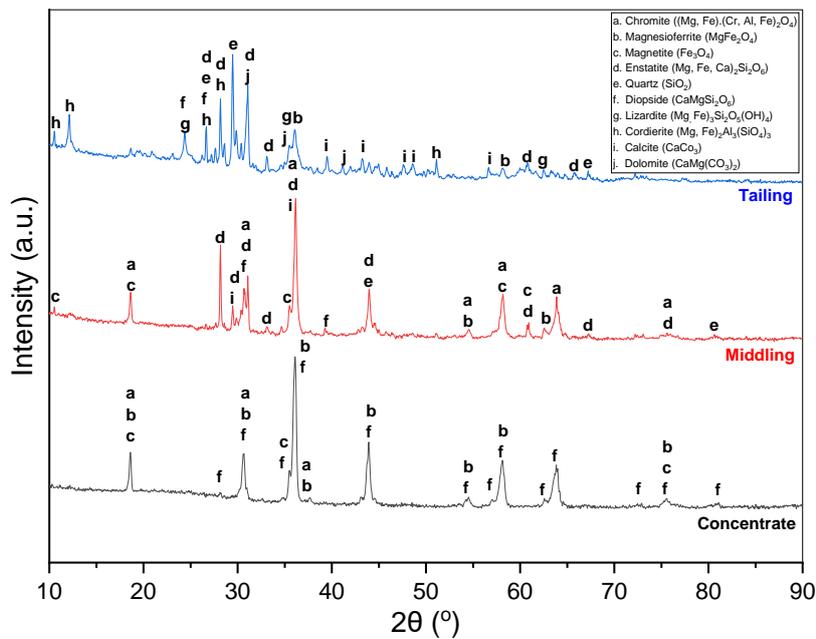


Figure 6. The XRD graph at 7.5° inclination with a flow rate of 18 liters/minute

of impurities that chemically bond to Cr or Fe, resulting in a high density and then carried out into the concentrate, as confirmed by SEM results in Figure 2. The minerals contained in the concentrate at each inclination remain largely consistent with the as-received ore. However, some mineral peaks, such as lizardite, cordierite, calcite, and dolomite, are no longer detected after the tabling process. The graph shows that chromite still dominates the peaks. This confirms the fact that the tabling process effectively increases the Cr grade by separating light impurities present in chromite sand.

XRD analysis was also performed on the optimized sample produced at a 7.5° table inclination (Figure 6). The diffraction pattern for the 7.5° inclination concentrate reveals only a few mineral phases, such as chromite, magnesioferrite, magnetite, and diopside, whereas the middling and tailing graphs show more impurities, including enstatite, quartz, diopside, lizardite, cordierite, calcite, and dolomite. While the middling graph still detects some peaks identified as chromite, they are entirely absent from the tailing graph. Based on the results shown in Figure 6, it is confirmed that the tabling process at a 7.5° inclination achieves high effectiveness in separating impurities with lower densities than chromite ore.

**The Effect of Water Flow Rate on the Shaking Table Process**

In this variation, using the optimized 7.5° table inclination sample, the effects of water flow rate on the shaking table process are presented in Figure 7. As shown in Figure 7(a), the highest Cr concentrate grade of 20.40% was achieved with a flow rate of 18 liters/minute. The Fe concentrate grade showed a similar trend with the highest Fe concentrate grade of 16.35% also achieved with a flow rate of 18 liters/minute. Notably, the Cr grade in the tailings was found to be very low, while the Cr:Fe ratio demonstrated a linear increase with flow rate, reaching a maximum of 1.25 at a flow rate of 22 liters/minute. These results confirm the effectiveness of the tabling process in increasing the Cr grade and the Cr : Fe ratio in the concentrate. However, the Fe content in the concentrate at each flow rate was still relatively high, indicating a requirement for a subsequent process to separate Cr from Fe impurities that are not directly bonded, which

can be achieved through magnetic concentration.

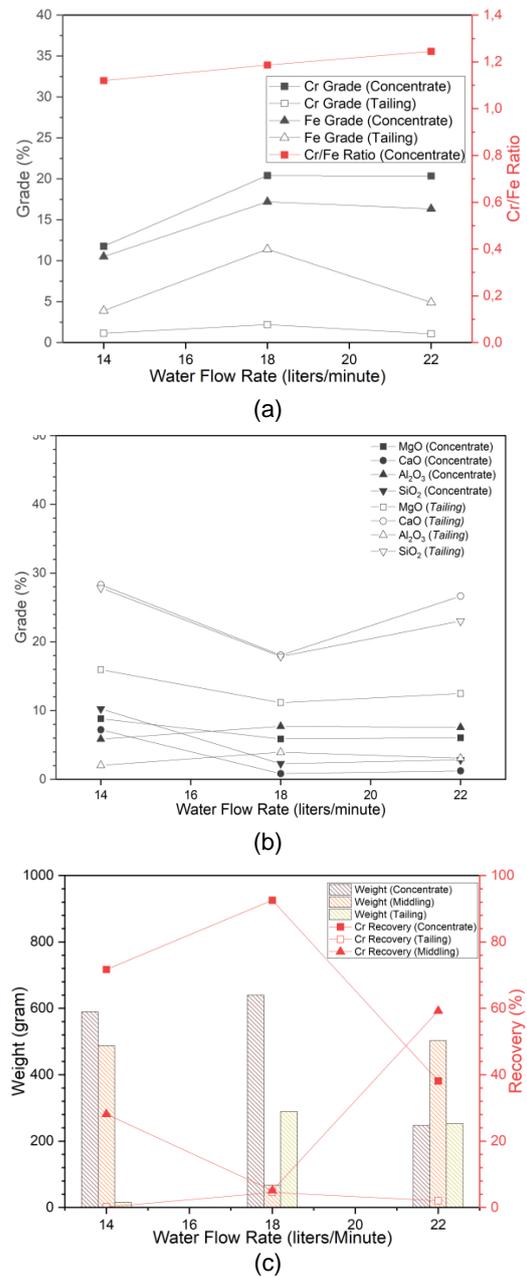


Figure 7. Graph of the effect of water flow rate at table inclination of 7.5° on: (a) Concentrate and tailing grades of Cr, Fe, and Cr : Fe ratio (concentrate), (b) Oxide impurities in concentrate and tailing, (c) Weight and recovery of concentrate, middling, and tailing

Figure 7(b) shows a graph of oxide impurity levels in the concentrate and tailing, exhibiting a trend consistent to the graph of oxide impurities levels at different

inclinations. The oxide impurities in the concentrate for each water flow rate ranged from 1.24% to 10.30%, while in the tailing, they ranged from 2.05% to 28.30%. These results confirm that oxide impurities, particularly  $\text{SiO}_2$  and  $\text{CaO}$ , can also be effectively separated from the concentrate at varying water flow rates. Furthermore, Figure 7(c) shows that a flow rate of 18 liters per minute produces the highest Cr concentrate recovery at 92.54%. The more Cr that enters the concentrate, the higher the recovery. At 18 liters per minute, less Cr is diverted to the middlings during the tabling process and flows more into the concentrate zone, resulting in the lowest middling recovery and the highest concentrate recovery. This optimization is reflected in the highest concentrate weight achieved with 640 grams at 18 liters per minute.

The water flow rate of 18 liters per minute was identified as the optimized operating parameter for the tabling process, as it maximizes both Cr content and concentrate recovery compared to other flow rates.

Although the Cr : Fe ratio is lower than at 22 liters per minute, the 18 liters per minute flow rate produces significantly higher concentrate weights, making it the optimal choice for tabling. XRD tests were conducted on the most optimal water flow results (concentrate, middling, and tailings) with the result shown in Figure 6. Furthermore, the XRD results for the concentrate at each flow rate are depicted in Figure 8.

The optimized concentrate was then subjected to SEM EDS analysis, as shown in Figure 9. The results reveal that Si and Ca have been significantly reduced compared to the as-received ore in Figure 2, which is attributed to they were having lower densities than chromite, allowing them to be effectively separated through the tabling process. However, besides Si and Ca, many other impurities, particularly heavy impurities like Fe, have not yet been separated from the chromite. Therefore, to achieve more optimal impurity separation, a magnetic separation process based on magnetic properties was implemented.

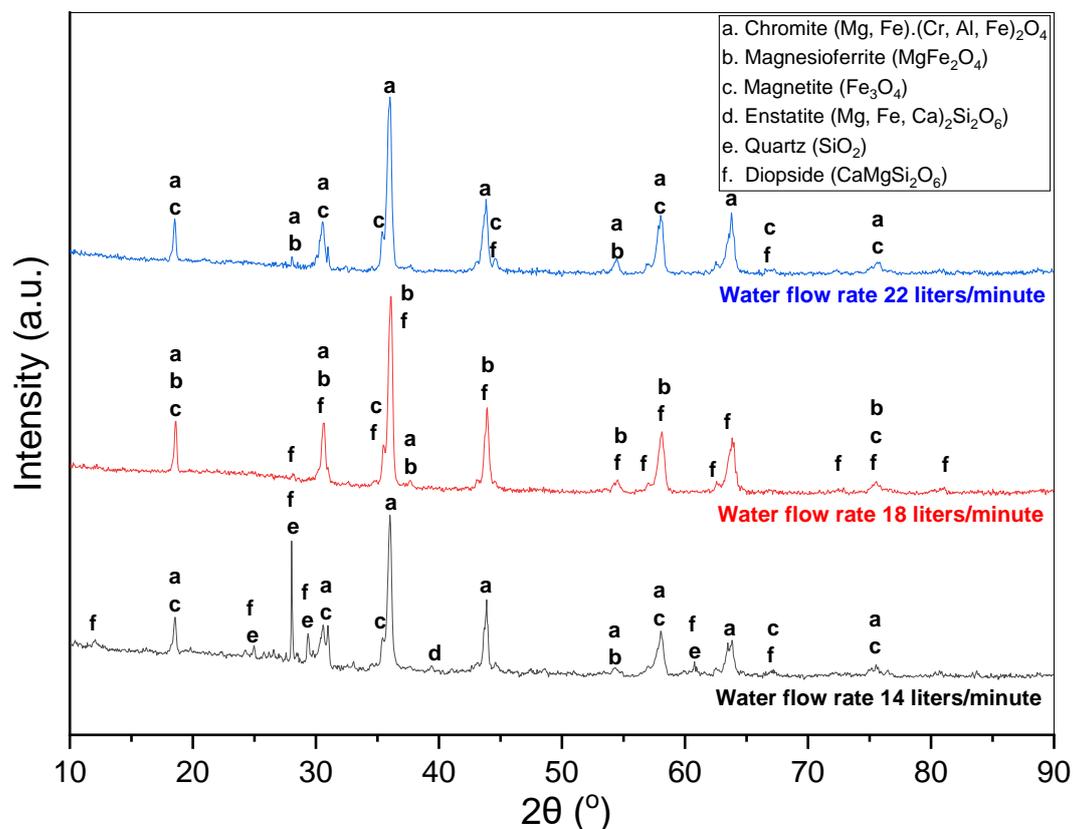


Figure 8. Graph of concentrate for each water flow rate at 7.5 degrees inclination

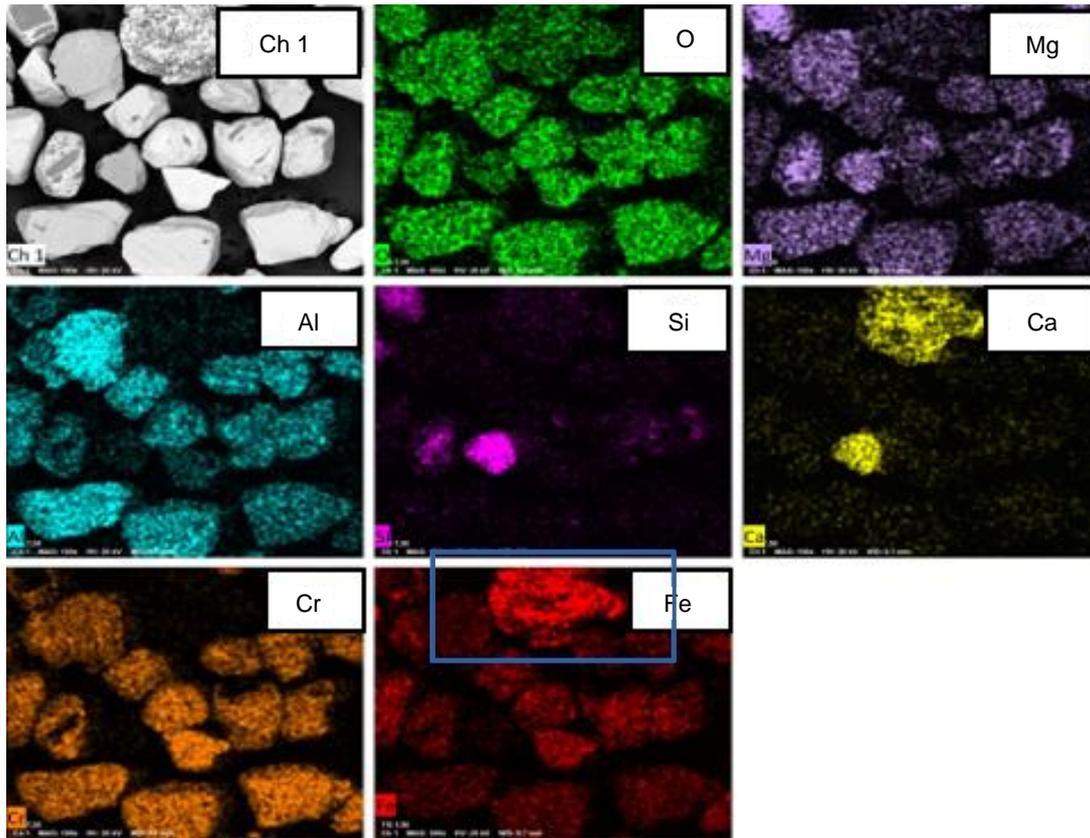


Figure 9. SEM EDS test results of concentrate after going through the shaking table process

### Magnetic Concentration Process Using Davis Tube

Following the tabling process, the optimized concentrate produced at a 7.5 degrees inclination and an 18 liters/minute flow rate was subjected to proceed to the magnetic separation process using a Davis tube. This secondary process aims to separate heavy impurities such as Fe, Al, and Mg that persisted through the tabling process. The optimal magnetic field strength was varied to determine the threshold required to enhance the Cr : Fe ratio in the chromite concentrate. In this configuration, the non-magnetic fractions are referred to as concentrate, while magnetic fractions are referred to as tailings. This distinction arises because Cr exhibits paramagnetic properties while Fe exhibits ferromagnetic properties (Gu and Wills, 1988).

The experimental variable used in the magnetic separation process was the strength of the electric current, starting from 0.1 ampere, 0.2 ampere, 0.3 ampere, 0.4 ampere, 0.8 ampere, to 1.4 ampere. The Cr and Fe content in the concentrate and tailings

from the magnetic separation process were analyzed using XRF, and the results are shown in Figure 10. According to the graph in Figure 10(a), the highest Cr : Fe ratio is obtained at 0.4 ampere (660 gauss) with a ratio of 1.62 and Cr content of 20.77%. However, an inverse relationship was observed between magnetic intensity and the weight of the concentrate, as depicted in Figure 10(b). The highest concentrate weight (49.95 grams) was achieved at a magnetic intensity of 0.1 ampere (210 gauss). This phenomenon is attributed to the fact that the low magnetic intensity allowed paramagnetic materials such as chromite to pass more easily the magnetic field and move towards the concentrate zone. Conversely, higher magnetic intensities facilitate paramagnetic materials such as chromite to be attracted more easily to the magnet and mixed into the tailings. The highest tailings weight (5.04 grams) is achieved at a magnetic intensity of 1.4 ampere (1940 gauss), while a magnetic intensity of 0.8 ampere (1230 gauss) yields a recovery of 95.49% and a concentrate weight of 45.06 grams.

Based on Figure 10, the optimal magnetic field strength in this magnetic separation process is 0.4 ampere (660 gauss). At this point, the highest Cr : Fe ratio of 1.62 was achieved, with a Cr concentrate content of 20.77% and a high weight of 45.65 grams. The 660 gauss (0.4 ampere) magnetic field also yields a recovery rate close to the highest at 94.93%. The most optimized results were then subjected to XRD analysis, the results of which can be seen in Figure 11.

The XRD analysis results for the optimized products at a magnetic field strength of 660 gauss are presented in Figure 11. The graph shows that while there are still some peaks of chromite in the tailing, their intensity is lower compared to the concentrate. The concentrate graph also indicates the presence of some impurities that have not been separated, such as magnesioferrite, magnetite, and diopside. This incomplete separation is likely attribute to these impurities still being chemically bound with Cr, as observed in the SEM EDS results in Figure 12.

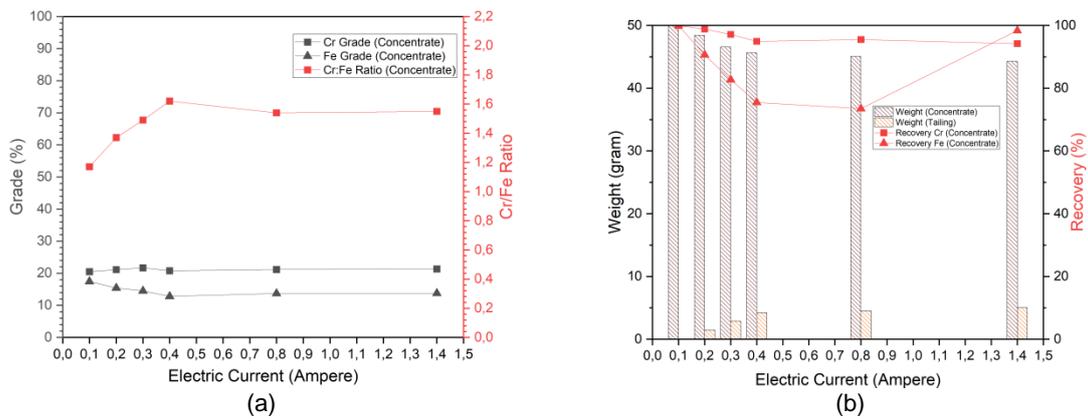


Figure 10. Graph of electric current strength against: (a) Cr, Fe content, and Cr : Fe ratio of concentrate, (b) concentrate weight, tailing weight, and concentrate recovery

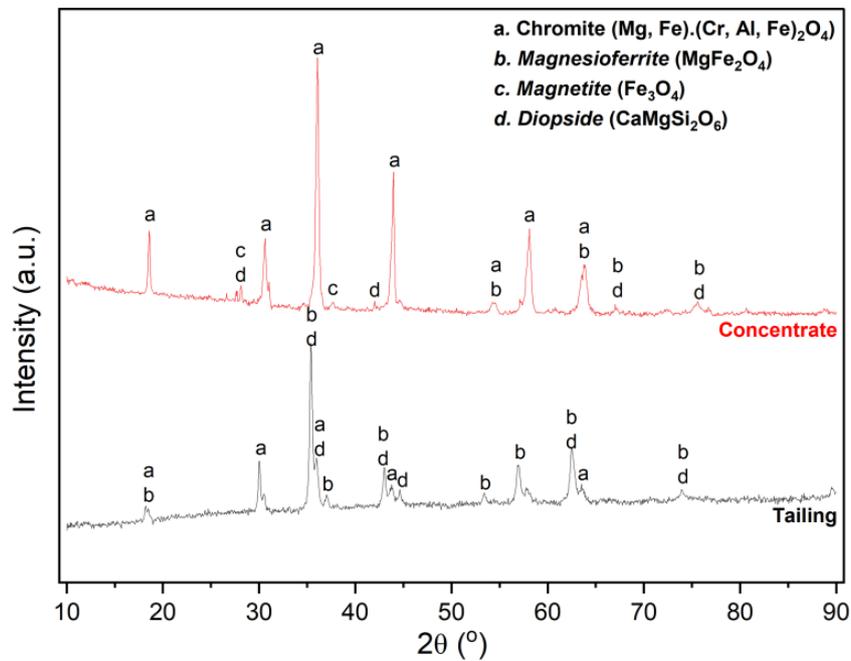


Figure 11. XRD graph of magnetic separation results at magnetic field strength of 660 gauss

The SEM EDS analysis in Figure 12 reveals the morphology of the concentrate after passing through the tabling and magnetic separation processes. The image shows several Fe elements still directly bound with Cr and Mg. XRD results confirm that Fe chemically bonds with chromite minerals ((Mg, Fe).(Cr, Al, Fe)<sub>2</sub>O<sub>4</sub>) and magnesioferrite (MgFe<sub>2</sub>O<sub>4</sub>), indicating the need for further separation processes such as thermal beneficiation to separate Cr from these interlinked impurities.

**Results of Combined Gravity Concentration and Magnetic Concentration**

The cumulative performance of the physical beneficiation process of low-grade chromite sand using a combination of shaking table and Davis tube is presented in Figure 13. The ore represents initial untreated chromite sand, concentrate 1 is the result of gravity concentration using a shaking table, and concentrate 2 is the result of gravity

concentration followed by magnetic concentration using a Davis tube.

Figure 13 shows that, there is an increase in Cr content up to 20.4% with Fe content at 17.19%, a recovery of 92.54%, and a Cr : Fe ratio of 1.19 after the gravity concentration process using the shaking table. The Cr:Fe ratio further increases to 1.62 after the magnetic concentration process using the Davis tube, with Cr content reaching 20.77% and Fe content at 12.8%, along with a recovery of 94.93%.

Based on the results summarized in Figure 13, it can be concluded that the shaking table process is effective in increasing the Cr content by separating impurity minerals based on measurable density differences. Magnetic separation further enhances the Cr : Fe ratio by separating Fe that is not chemically bound to Cr. Through the combination of these processes, the Cr content can be increased up to 20.77% with a total Cr recovery of 94.93% and a Cr : Fe ratio of 1.62.

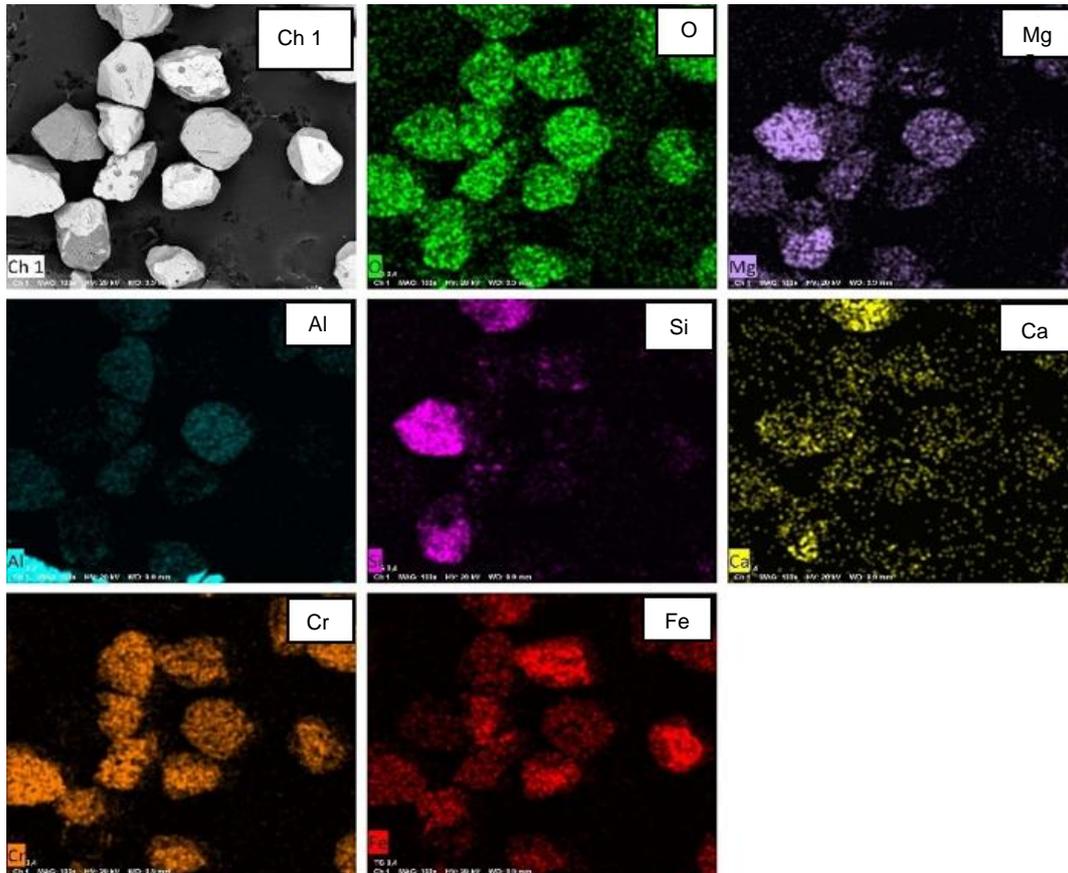


Figure 12. SEM EDS test of concentrate from magnetic separation process

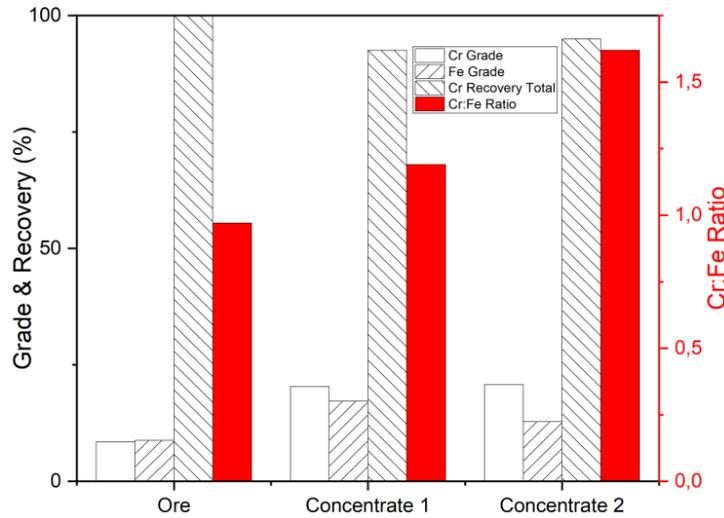


Figure 13. Concentrate resulting from combined concentration

Table 6. XRF test results of chromite sand after combined concentration processes

Elements/Compounds	Cr (Cr <sub>2</sub> O <sub>3</sub> )	Fe	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	CaO	Cr:Fe Ratio
Grade (%)	20.77 (30.36)	12.8	6.26	8.63	3.36	1.77	1.62

The Cr<sub>2</sub>O<sub>3</sub> content and Cr : Fe ratio summarized in Table 6 remain below the criteria required for raw material in ferrochrome production, despite physical beneficiation (shaking table and magnetic separation) significantly upgrades the chromite sand. This is due to impurity elements that are still present and chemically bound to chromite, as shown in Table 6 and Figure 13. Consequently, further processes such as thermal beneficiation are required to separate these interconnected impurities, thereby significantly increasing the Cr<sub>2</sub>O<sub>3</sub> content and Cr : Fe ratio in the chromite sand to meet the criteria as raw material for ferrochrome production.

## CONCLUSION AND SUGGESTION

The chromite sand from Morowali, Central Sulawesi, is classified as low-grade chromite sand with a Cr content of 8.5%, Cr<sub>2</sub>O<sub>3</sub> 12.42%, and a Cr : Fe ratio of 0.97. This chromite sand contains minerals such as chromite ((Mg,Fe).(Cr,Al,Fe)<sub>2</sub>O<sub>4</sub>), magnesioferrite (MgFe<sub>2</sub>O<sub>4</sub>), magnetite (Fe<sub>3</sub>O<sub>4</sub>), enstatite ((Mg,Fe,Ca)<sub>2</sub>Si<sub>2</sub>O<sub>6</sub>), quartz (SiO<sub>2</sub>), diopside (CaMgSi<sub>2</sub>O<sub>6</sub>), lizardite ((Mg,Fe)<sub>3</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>), cordierite ((Mg,

Fe)<sub>2</sub>Al<sub>3</sub>(AlSi<sub>5</sub>O<sub>18</sub>), calcite (CaCO<sub>3</sub>), and dolomite (CaMg(CO<sub>3</sub>)<sub>2</sub>).

Physical beneficiation utilizing a shaking table at a 7.5° inclination and a water flow rate of 18 liters/minute effectively separates impurities which have lower density than chromite, such as Si, Ca, and Mg found in minerals like enstatite, quartz, diopside, lizardite, cordierite, calcite, and dolomite. This process increased the Cr content from 8.5% to 20.4%, with a Cr : Fe ratio of 1.19 and a recovery of 92.54%.

The magnetic concentration method utilizing a Davis tube significantly enhances the Cr : Fe ratio by reducing Fe impurities present in magnesioferrite minerals. The optimal electrical current strength is 0.4 amperes (660 gauss). Under these parameters, the Cr : Fe ratio of this chromite sand was successfully increased to 1.62 with a Cr content of 20.77% (Cr<sub>2</sub>O<sub>3</sub> 30.36%).

Despite these improvements, the final results remain below the criteria required for ferrochrome raw material, indicating the necessity of further beneficiation processes (such as thermal beneficiation).

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## REFERENCES

- Al-Tigani, M.M.H., Mohamed, A.A. and Seifelnasr, A.A.S. (2019) 'Beneficiation of disseminated low-grade Sudanese chromite ore in Gedarif State at Umm Saqata-Qala Elnahal', *Journal of Environmental Analytical Chemistry*, 6(4), p. 1000261.
- Bhandary, A.K., Gupta, P., Mukherjee, S., Chaudhuri, M.G. and Dey, R. (2016) 'Beneficiation of low grade chromite ore and its characterization for the formation of magnesia-chromite refractory by economically viable process', *International Journal of Chemical and Molecular Engineering*, 10(8), pp. 1096–1104. Available at: <https://doi.org/https://doi.org/10.5281/zenodo.1126131>.
- Camerucci, M.A., Urretavizcaya, G. and Cavalieri, A.L. (2003) 'Sintering of cordierite based materials', *Ceramics International*, 29(2), pp. 159–168. Available at: [https://doi.org/10.1016/S0272-8842\(02\)00100-1](https://doi.org/10.1016/S0272-8842(02)00100-1).
- Davila, L.P., Risbud, S.H. and Shackelford, J.F. (2008) 'Quartz and silicas', in J.F. Shackelford and R.H. Doremus (eds) *Ceramic and Glass Materials*. Boston, MA: Springer US, pp. 71–86. Available at: [https://doi.org/10.1007/978-0-387-73362-3\\_5](https://doi.org/10.1007/978-0-387-73362-3_5).
- Dzvinamurungu, T., Rose, D.H., Viljoen, K.S. and Mulaba-Bafubiandi, A.F. (2020) 'A process mineralogical evaluation of chromite at the nkomati nickel mine, Uitkomst Complex, South Africa', *Minerals*, 10(8), p. 709. Available at: <https://doi.org/10.3390/min10080709>.
- Gu, F. and Wills, B.A. (1988) 'Chromite-mineralogy and processing', *Minerals Engineering*, 1(3), pp. 235–240. Available at: [https://doi.org/10.1016/0892-6875\(88\)90045-3](https://doi.org/10.1016/0892-6875(88)90045-3).
- Hakim, S.S., Olsson, M.H.M., Sørensen, H.O., Bovet, N., Bohr, J., Feidenhans'l, R. and Stipp, S.L.S. (2017) 'Interactions of the calcite {10.4} surface with organic compounds: Structure and behaviour at mineral – organic interfaces', *Scientific Reports*, 7(1), p. 7592. Available at: <https://doi.org/10.1038/s41598-017-06977-4>.
- Ma, J., Querci, L., Hattendorf, B., Saar, M.O. and Kong, X.-Z. (2019) 'Toward a spatiotemporal understanding of dolomite dissolution in sandstone by CO<sub>2</sub>-enriched brine circulation', *Environmental Science & Technology*, 53(21), pp. 12458–12466. Available at: <https://doi.org/10.1021/acs.est.9b04441>.
- Macke, R.J., Consolmagno, G.J., Britt, D.T. and Hutson, M.L. (2010) 'Enstatite chondrite density, magnetic susceptibility, and porosity', *Meteoritics & Planetary Science*, 45(9), pp. 1513–1526. Available at: <https://doi.org/10.1111/j.1945-5100.2010.01129.x>.
- Masoud, M.A., El-Khayatt, A.M., Kansouh, W.A., Sakr, K., Shahien, M.G. and Zayed, A.M. (2020) 'Insights into the effect of the mineralogical composition of serpentine aggregates on the radiation attenuation properties of their concretes', *Construction and Building Materials*, 263, p. 120141. Available at: <https://doi.org/10.1016/j.conbuildmat.2020.120141>.
- Murthy, Y.R. and Tripathy, S.K. (2020) 'Process optimization of a chrome ore gravity concentration plant for sustainable development', *Journal of the Southern African Institute of Mining and Metallurgy*, 120(4). Available at: <https://doi.org/10.17159/2411-9717/990/2020>.
- Murthy, Y.R., Tripathy, S.K. and Kumar, C.R. (2011) 'Chrome ore beneficiation challenges & opportunities – A review', *Minerals Engineering*, 24(5), pp. 375–380. Available at: <https://doi.org/10.1016/j.mineng.2010.12.001>.
- Oediyani, S., M., I.A., N., M.V. and Juniarsih, A. (2018) 'Beneficiation of Kulon Progo iron sand by using tabling and magnetic separation methods', in M.I.P. Hidayat

- (ed.) *Proceedings of the 3rd International Conference on Materials and Metallurgical Engineering and Technology (Icommet 2017): Advancing Innovation in Materials Science, Technology and Applications for Sustainable Future*. Surabaya: AIP Conference Proceedings, p. 020024. Available at: <https://doi.org/10.1063/1.5030246>.
- Pagona, E., Kalaitzidou, K., Zaspalis, V., Zouboulis, A. and Mitrakas, M. (2022) 'Effects of MgO and Fe<sub>2</sub>O<sub>3</sub> addition for upgrading the refractory characteristics of magnesite ore mining waste/by-products', *Clean Technologies*, 4(4), pp. 1103–1126. Available at: <https://doi.org/10.3390/cleantechnol4040067>.
- Puspita, R. (2021) 'Kontrol geologi dan potensi kromit pada P.T. X Daerah Wosu, Kab. Morowali, Prov. Sulawesi Tengah', *Jurnal Sains dan Teknologi Tadulako*, 7(2), pp. 75–88. Available at: <https://doi.org/10.22487/jstt.v7i2.372>.
- Tripathy, S.K., Murthy, Y.R. and Singh, V. (2013) 'Characterisation and separation studies of Indian chromite beneficiation plant tailing', *International Journal of Mineral Processing*, 122, pp. 47–53. Available at: <https://doi.org/10.1016/j.minpro.2013.04.008>.
- Tripathy, S.K., Singh, V. and Ramamurthy, Y. (2012) 'Improvement in Cr:Fe ratio of Indian chromite ore for ferro chrome production', *International Journal of Mining Engineering and Mineral Processing* [Preprint], (3). Available at: <https://doi.org/10.5923/j.mining.20120103.01>.

