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Application of Multiple Linear Regression (MLR) Analysis on the Concentration of Chromite Plant Tailings by a Shaking Table

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***Abstract* -** In this paper, the beneficiation of the Upper Group 2 (UG-2) plant tailings was investigated to recover chromite. Multiple linear regression analysis was applied to estimate the recovery and grade of chromite. A detailed chemical and mineralogical characterization of the UG2 plant tailings was conducted using X-ray fluorescence (XRF) and Scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDS) for elemental composition and surface morphology respectively. The results showed that the major elements in the chromite plant tailings are Fe (12.96 wt%), Cr (10.97 wt%) and Si (15.64 wt%). The major mineral phases are quartz, spinel, magnesiochromite and aluminosilicates. The results attained from the Microtrac particle analyser indicated that 80% of the particles are < 95 µm and only 6% was less than 10µm. The highest recovery of Cr_2O_3 was found to be 67.27% at a grade of 21.87% chromite. Multiple linear regression equations were created based on the experimental results to forecast the recovery and grade of the chromite concentrate, and the regression coefficients between experimental and anticipated values were poor for grade and good for recovery (R2 values of 0.18 and 0.66, respectively). It was concluded that the generated MLR equations can be used to forecast the recovery of chromite from UG-2 plant tailings.

***Keywords*:** Chromite; UG2; Shaking table; Multiple linear regression

1. Introduction

Chromite is one of the most important metals in the world with a variety of uses and it is highly in demand globally. Significant deposits of chromite can be found in South Africa (accounting for 95% of chromite in the world together with Kazakhstan), Canada, Finland and Madagascar [1]. In South Africa, chromite is found within the Bushveld Igneous Complex (BIC). The BIC is remarkably large, and it is known for its mineral wealth. It is the largest layered intrusion in the world [2] and it consists of three limbs, namely the eastern limb, the northern limb and the western limb. The BIC consists of 13 chromite layers grouped into Lower Group (LG), Middle Group (MG) and Upper Group (UG), which occur in the Lower Critical Zone, between the Lower Critical Zone and the Upper Critical Zone and in the Upper Critical Zone, respectively [3]. The UG-2 is predominantly the major chromite seam in the Bushveld Complex [2]. The UG-2 contains 60–90 vol% chromite with Cr/Fe between 1.3 and 1.4 and 43.5 wt% Cr_2O_3 average.

Due to the depletion of high-grade chromite, chromite recovery from chromite tailings has become the main focus of research [4] to avoid losing valuable minerals to slimes dam. Characterization results are used to pre-determine the appropriate method for the concentration of tailings. Different authors have investigated the recovery of chromite from chromite tailings using shaking tables and spirals [4, 5]. [4] investigated the effect of the following operating parameters of the shaking table on chromite recovery from chromite tailings: feed rate (g/min), wash water (l/min), and table slope (degrees).

This study investigated the effects of the operating parameters of a Wilfley shaking table on the recovery and grade of the chromite. Multiple linear regression was then used to predict the grade and recovery of the chromite.

2. Methodology.

2.1. Materials and methods

The UG-2 tailing sample used in this project was obtained from one of the UG-2 processing plants in the Northwest Province, South Africa. The particle size distribution of the as-received sample was determined using a Microtrac Particle

Size Analyser. The chemical composition and mineralogy were determined using Rigaku ZSX Primus II X-ray fluorescence (XRF) and scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) respectively.

2.2. Design of shaking table experiments

For the purpose of recovering chromite from the chromite plant tailings, a response surface methodology using Minitab software was used. The Box-Behnken Design was selected with 4 factors, which gives a set of 27 runs for the optimization study. Feed rate, wash water rate, frequency and tilt angle are the parameters that were investigated to determine and understand their effect on the responses, i.e. grade and recovery.

Table 1: Values for four different operating variables used in the shaking table experiments

Runs	Feed rate	Wash water	Tilt angle	Frequency
1	25	300	2	50
2	40	300	2	35
3	25	300	5	35
4	25	100	5	20
5	25	300	5	35
6	10	300	2	35
7	10	500	5	35
8	10	300	8	35
9	25	500	5	50
10	25	300	8	20
11	25	300	2	20
12	40	300	5	50
13	25	100	8	35
14	25	500	2	35
15	40	100	5	35
16	25	300	5	35
17	25	500	5	20
18	10	300	5	20
19	40	500	5	35

20	25	300	8	50
21	25	100	2	35
22	10	100	5	35
23	40	300	5	20
24	25	100	5	50
25	40	300	8	35
26	10	300	5	50
27	25	500	8	35

2.3 Wilfley shaking table experiments

Buckets were prepared for sample collection and the parameters of the shaking table (flowrate, deck tilt angle and frequency) were set depending on the run according to Table 1. The feed of about 650g dry solids was poured into the feeder for the 27 runs. The feeder and the shaking table were then started. Concentrates, middlings and tailings products were collected and from the products, 50g from concentrates and tailings were riffled out for characterization using XRF. The recovery is a qualitative and quantitative parameter of the beneficiation efficiency expressed in the percentage of the total mineral or metal contained in the ore. Final concentrate recoveries in the product were calculated according to equation 1.

$$\boldsymbol{R = \frac{Cc}{Ff} * 100} \quad (1)$$

Where:

R: chromite recovery (%)
C: the total mass of concentrate (g)
c: chromite grade in concentrate (%)
F: the total mass of feed (g)
f: chromite grade in feed (%)

2.4 Application of Multiple linear regression

The experimental data was applied to multiple linear regression on the Statistical Package for Social Sciences (SPSS) software to investigate the relationship between the dependent and independent variables [1].

3. Results and discussion

3.1. Particle size distribution

The particle size distribution curve for the feed sample is shown in Fig. 1. The results indicate that 80% of the particles are < 95 µm. 6% was less than 10µm, indicating that the sample contains less slimes and is suitable for concentrating using gravity concentration.

3.2. Chemical composition of the as received sample

Elemental composition of the as received sample was determined using XRF and the results are shown in Table 1. The major elements were 12.96% Fe, 10.97% Cr and 15.64% Si. The chromite content was found to be 16.03% indicating that this is a low-grade material. Any chromite content lower than 40% is regarded as low-grade ore and needs to be beneficiated [7].

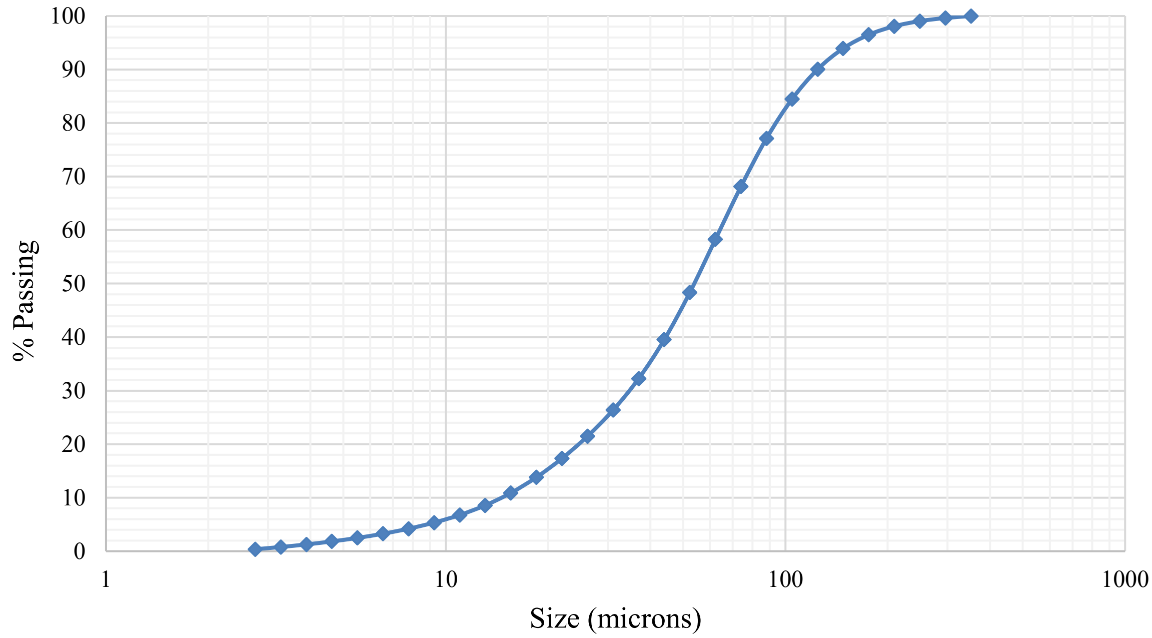


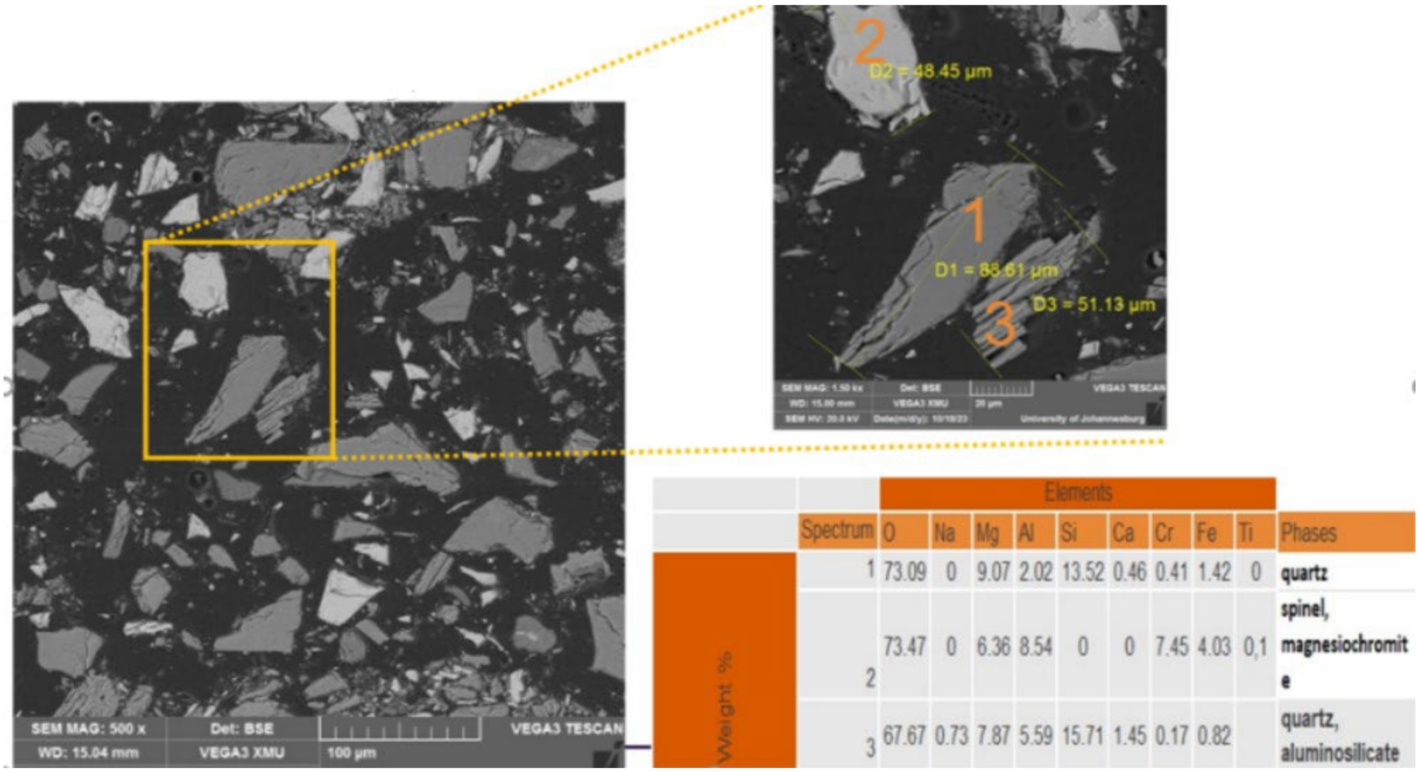
Fig.1: Particle size distribution of the chromite plant tailings sample

Table 2: Chemical composition of the as-received UG2 chromite tailings.

Element	**Fe**	**Cr**	**Si**	**Al**	**Mg**	**Ca**	**Ti**	**Na**	**Ni**	**Mn**
%Wt	12.96	10.97	15.64	8.33	4.32	4.93	0.38	0.20	0.20	016

3.3 Mineralogical composition of the as received sample

The SEM analyser was used to analyse the surface morphology of the UG-2 chromite tailings, and the results are shown in Fig. 2. The morphology shows that the mineral phases are well liberated and there is no need for further milling. Probable mineral phases found in the sample are quartz, magnesiochromite, aluminosilicates and spinels according to spectrums1, 2, and 3.



		Elements									
	Spectrum	O	Na	Mg	Al	Si	Ca	Cr	Fe	Ti	Phases
Weight %	1	73.09	0	9.07	2.02	13.52	0.46	0.41	1.42	0	quartz
	2	73.47	0	6.36	8.54	0	0	7.45	4.03	0,1	spinel, magnesiochromite
	3	67.67	0.73	7.87	5.59	15.71	1.45	0.17	0.82		quartz, aluminosilicate

Fig. 1: Micrographs of UG2 tailings showing spectrum 1, 2 and 3.

3.3. Shaking table experimental results

The shaking table experiments were conducted, and the results are shown in Table 3. Based on the results, the concentrates had a grade of less than 40%, meaning that they are below a saleable grade. For the best results of the shaking table experiments, the effects of feed rate value (X1), the wash water rate (X2), the tilt angle (X3) and frequency of the shaking table(X4) were examined. The maximum grade and recovery were found to be 26.98% and 67.27% respectively. The maximum grade was obtained after conducting run number 24 with the following operating parameters: feed rate of 25kg/hr, wash water rate of 100kg/hr, a tilt angle of 5 degrees and frequency of 50 Hz. The minimum grade of the chromite concentrate found was 10.60% at run number 12, at a feed rate of 40kg/hr, wash water rate of 300kg/hr, a tilt angle of 5 degrees and frequency of 50 Hz. The maximum recovery was found to be 67.27% at run number 1 with the following conditions: feed rate of 25kg/hr, wash water rate of 300kg/hr, a tilt angle of 2 degrees and frequency of 50 Hz. The minimum recovery was found to be 2.42% at run number 25 with the following conditions: feed rate of 40kg/hr, wash water rate of 300kg/hr, a tilt angle of 8 degrees and frequency of 35 Hz. It was obtained from these results that the frequency was determined to have a significant effect on the recovery and grade. However, the grades of the chromite in the concentrate are very low.

3.4. Multiple linear regression application

In predicting of the results, the dependent variables, which were related to the recovery (%) and the grade (% Cr_2O_3) of the chromite concentrate, were corelated with independent variables, which were X1 (the feed rate value), X2 (the wash water rate), X3 (the tilt angle, degrees) and X4 (the frequency). The most reliable regression equations that were obtained by multiple linear regression in determining the recovery and grade of concentrate as a result of the concentration of the chromite tailings with shaking table were the following equations:

$$\text{Recovery }\% = 67.15 - 0.427X1 + 0.017X2 - 7.647X3 - 0{,}124X4 \quad (1)$$

$$\text{Grade }\% = 16.529 + 0.108X_1 - 0.818X_2 + 0.75X_4 \quad (2)$$

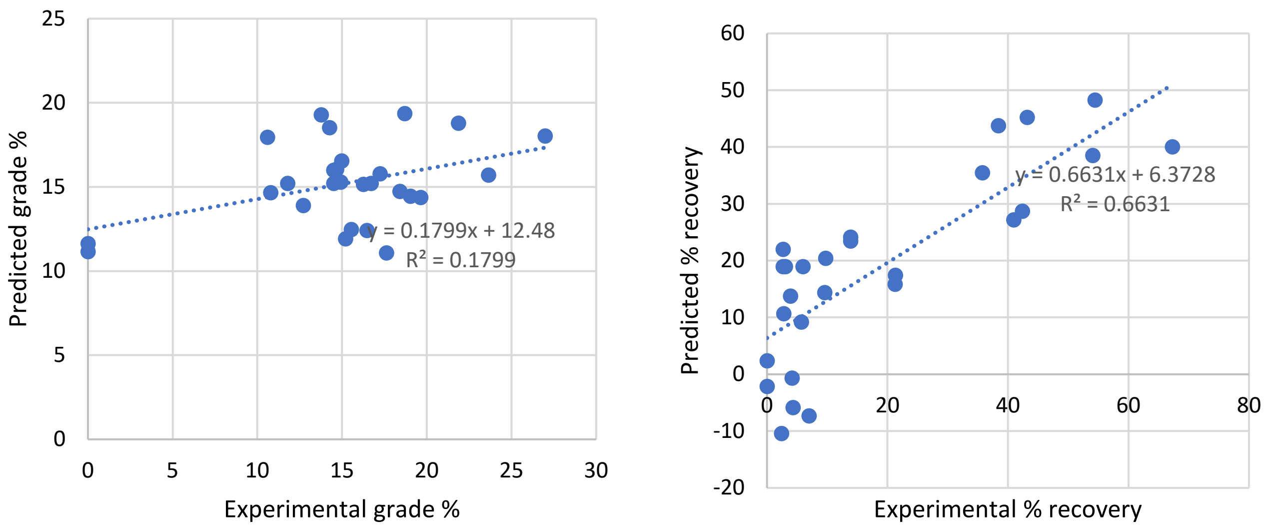
The predicted results were obtained using SPSS software, which used the grade and recovery obtained from the experiments. The predicted results are shown in Table 3 together with the number of runs and conditions. The best recovery of 67.27 % was obtained at a feed rate value of 25kg/hr, the wash water of 300kg/hr, the frequency of 50Hz and the angle of 2 degrees at a grade of 21.87% Cr_2O_3. The maximum grade of 26.89 % Cr_2O_3 was obtained at a feed rate value of 25kg/hr, the wash water of 100kg/hr, the frequency of 50Hz and the angle of 5 degrees. The best predicted results were obtained at a feed rate value of 40kg/hr, the wash water of 300kg/hr, the frequency of 35Hz and the angle of 2 degrees for recovery (35.74% vs 35. 45%)

Table 3: Number of runs with predicted results from Multiple linear regression

Test run number	**Feed rate (Kg/hr)**	**Wash water (Kg/hr**	**Tilt angle (degrees)**	**Frequency (Hz)**	**Recovery (%)**	**Grade (% wt Cr_2O_3)**	**Predicted recovery (%)**	**Predicted grade ((% wt Cr_2O_3)**
1	25	300	2	50	67.27	21.87	40.00	18.80
2	40	300	2	35	35.74	13.77	35.45	19.29
3	25	300	5	35	3.03	16.72	18.92	15.22
4	25	100	5	20	21.31	17.25	17.43	15.79
5	25	300	5	35	2.66	14.5	18.92	15.22
6	10	300	2	35	54.45	14.68	48.26	16.06
7	10	500	5	35	42.41	15.21	28.66	11.91
8	10	300	8	35	0	0	2.38	11.15
9	25	500	5	50	9.74	10.78	20.40	14.65
10	25	300	8	20	0	0	-2.17	11.64
11	25	300	2	20	38.39	14.97	43.71	16.55
12	40	300	5	50	2.77	10.6	10.65	17.96
13	25	100	8	35	6.95	19.04	-7.36	14.46
14	25	500	2	35	43.2	14.51	45.19	15.98
15	40	100	5	35	5.7	14.27	9.17	18.53
16	25	300	5	35	5.96	11.79	18.92	15.22
17	25	500	5	20	13.9	16.47	24.11	12.40

18	10	300	5	20	40.97	15.55	27.18	12.48
19	40	500	5	35	21.25	16.27	15.84	15.14
20	25	300	8	50	4.32	12.72	-5.88	13.89
21	25	100	2	35	54.07	18.69	38.52	19.37
22	10	100	5	35	2.65	14.93	21.99	15.29
23	40	300	5	20	9.6	23.64	14.36	15.71
24	25	100	5	50	3.91	26.98	13.72	18.03
25	40	300	8	35	2.42	19.65	-10.43	14.38
26	10	300	5	50	13.9	18.42	23.47	14.73
27	25	500	8	35	4.14	17.62	-0.69	11.07

The % recovery of the predicted variable is lower than that of the actual experiment. Multiple linear regression graphs were plotted to determine the relationship between the variables and for grade. The relationship was found to be weak because the R^2 is 0.18 and the relationship between variables for recovery were strong because the R^2 is 0.66.



(a) (b)

Fig. 2: Relationship between experimental and predicted values for the grade (a) and the recovery (b) of the chromite concentrate

The low grade of chromite from the concentrate shows that the separation of minerals (silica and chromite) is not efficient. This is due to the particle size of the UG-2 plant tailings. According to [2], the shaking table can only be used for particles ranging from 50 microns to 1000 microns. Based on the PSD curve of the UG-2 plant tailings, about 50% of the particles are less than 50 microns, classifying the sample as a very fine sample and this reduce the efficiency of a shaking table.

4. Conclusion

The aim of this project was to recover the chromite from chromite plant tailings and use the multiple linear regression analysis to predict the grade and recovery of the chromite. The chromite plant tailings sample was a fine low-grade material that needed no further milling. A Wilfley shaking table can be used as a preconcentration equipment for the chromite recovery. MLR can be used to predict chromite recovery whilst using a shaking table, but it cannot be used to predict the chromite grade. However, it can be concluded that the shaking table is inefficient for the sample used for this experiment due to entrainment of the particles and could not produce a saleable product. It is recommended that enhanced gravity concentration methods be used to recover the chromite from the UG-2 plant tailings for higher grades and recoveries.

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