Evaluation of Advanced Gravity and Magnetic Concentration of a PGM Tailings Waste for Chromite Recovery

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ABSTRACT: *This research was aimed at evaluating the efficiency of advanced gravity and magnetic separations on the recovery of chromite from the fine Platinum Group Metals (PGM) tailings consisting of particles 80% passing 75 µm with about 45% being >45 µm resulting in high chromite losses. The PGM plant tailings were subjected to X-ray fluorescence, scanning electron microscopy and particle size distribution analyses. The feed was then optimally classified with 60 mm diameter hydro-cyclone into underflow and overflow streams. The coarser underflow was further beneficiated using the spiral concentrator. The results obtained showed that the removal of fines increased the Cr_2O_3 grade for the spiral feed from 12.27% to 17.64% while spiral concentrate grade improved from 14.84% to 21.46% and recovery 69.85% to 95.53%. Magnetic separation efficiency was found to increase with particle size such that at >75 µm a concentrate with up to 17.13% grade and 61.5% recovery was achieved. The advanced Falcon concentration was also observed to be mainly particle size dependent and at <75>45 µm up to 17% grade and 60.3% recovery was achieved. The results obtained are based on particles >45 µm and the finer particles <45 µm are likely to give poorer results. The results obtained indicate that gravity and magnetic separation were reasonably efficient to pre-concentrate PGM tailings before flotation. However, the processes are mostly affected by particle size and should be preceded by size classification to improve separation efficiency.*

KEYWORDS: *Tailings; Analyses; Classified; Beneficiated; Efficiency*.

INTRODUCTION

The mining and minerals industry faces some of the most difficult sustainability challenges of any industrial sector. The natural resources used in mining are not reproducible and therefore the number of available ores can only decrease or stay the same if none is mined over time. Continued mining and liquidation of mineral assets for income have resulted in the decline of mining contribution to national income and employment decline in primary sector activities worldwide [1]. The ores are normally mined with the interest in the mineral entailed

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in them, which offers a variety of properties depending on its application. The usefulness of minerals poses a challenge to the mining industry to sustain ore supplies to the metallurgical industries. This challenge can be met by extracting almost all the available minerals of interest in the ore and extraction from other process by-products. Chromite bearing ores are mostly important in the chromium production industries. Chromium is produced in the form of ferro-chrome by various methods ranging from reduction in an electric furnace, electrolysis, thermal dissociation, thermal decomposition and it is largely used as alloying elements in steels for production of stainless and special steels [2]. In stainless steels, the chromium is chiefly responsible for improved corrosion resistance, while in special steels, it imparts properties like heat resistance, hardness, and wear resistance [3]. South Africa is one of the largest suppliers of ferro chrome to the world's stainless steel producers, hence the market for this product is growing rapidly. Some ferro-chrome producers have in recent years started to process chromite from the PGM concentrate tailings to meet the ferro-chrome industry demand. In the PGM concentration plants, chromite is one of the major gangue materials which is maximally rejected to the tailings. The chromite recovered from this tailings can serve as a source feed for ferro-chrome (FeCr) production after beneficiation to increase the chromium content [4]. This proves that chromite extraction from the tailings can offer potential upgrade for PGM beneficiation [5] therefore enhancing tertiary PGM recovery.

Re-processing of process tailings has been employed as one of the solutions for depletion of mineral resources. This re-processing also poses its own challenges since the minerals to be recovered are a by-product of another process resulting in the particle size which is already reduced according to the requirements of the initial process. The mineral industries are currently experiencing challenges with the loss of fine particles during processing. This requires a lot of study on the origin of the mineral being treated. The mineral originality is normally the guiding tool to the beneficiation process, as factors like mineralogy and particle size play a major role in beneficiation. Gravity concentration methods used for chromite beneficiation are based on differences between the specific gravities of chromite and gangue minerals. The fines (<100 μm) are however generally discarded as gangue from the gravity concentration processes. This results in a loss of fine chromite mineral to the tailings stream due to the inefficiency of gravity methods in the fine particle size range. After crushing and grinding, the gravity separation methods are used to beneficiate particles <1 mm and usually the <0.1 mm size fractions are lost as tailings in this process [6]. During the beneficiation of chromite ore, about 50% of the total feed is discarded into tailings which therefore consist of huge quantity of chromite values in the ultra-fine sizes. The beneficiation of tailings is a necessary step from the point of view of mineral conservation, utilization of scarce chromite resources and the sustainability of its supply [7] and hence this study.

METHODOLOGY

Characterization Studies

The tailing stream of a concentration plant based on Upper Group 2 (UG2) from the Western Limb of the Bushveld complex was used in this study. The sample was blended for homogeneity and subjected to particle size distribution which was performed using the laboratory Sieve Shaker (Model: SIUS 582902, Kingtest, South Africa) at 220 V and 5 A. The test was conducted by first weighing each sieve and recording the weight. The sieves were then stacked from 425 μm (topmost) to 53 μm (bottom). About 200 g sample was fed to the top screen, the stacked sieves were closed with a lid and clamped. The machine was switched on at fixed vibration with a frequency of 150 Hz for 30 minutes. After completion, individual mass on the screen was weighed and recorded. The cumulative mass % passing each screen was calculated to determine d50 and d80 of the feed. This process was repeated for validation purposes. The same procedure was followed for all the particle size distribution done on this work. The size distribution of the feed sample is shown in Fig. 4.

The chemical analysis of the feed sample, as well as size by size analysis, were conducted using the ARL Perform'X Sequential XRF (Model: ARL 9400XP, Fisher Scientific, Switzerland) with X-Ray Fluorescence and Uniquant software. 5 g of the sample was prepared as boric acid briquettes and put into the sample holder. The Mylar film on top of the holder was pierced and the plastic sample cell was put into aluminium cup on top of the copper ring. The folded-up piece of paper was put

on top of the cell and a second copper ring on top to hold it in place. When analyzing the sample, Super Q Measure and Analysis was used and IQ+ was selected as the application and archive. The sample was then placed in the load position of the XRF; the measure sample button in the measure and analysis program was then pressed. The analysis took 20 minutes to complete for each sample using super Q IQ +. During the analysis, automatic search and match was used to identify the peaks and then quantified to put the concentration of each element in percentages. The equipment uses software analyses for all elements in the periodic table between Na and U, but only elements found above the detection limits were reported. The values were normalized as no loss of ignition was done to determine the crystal water and oxidation state changes.

X-ray diffractometer (PanAnalytical Empyrean, Netherland) was used as a rapid analytical technique to identify the phases of different minerals in the feed. The process was conducted by engaging the PAN analytical X-Pert in coral and assessing the instrument status and safety. The Prefix optics and sample stages were determined on the instrument. The 5 g sample was loaded into the sample changer and flattened. The round sample holders were loaded into the magazine and the sample magazine was then placed into the sample changer. The magazine was inserted so that the two alignment holes go over the alignment pins. The numbered side of the magazine was facing away from the goniometer and towards the enclosure doors when putting in the sample changer. The appropriate optics and accessories for the prefix optics were inserted. The generator power was turned up to 45 KV and 40 MA. The instrument configuration was changed to pert data collector. The instrumented program was then set to run. Once the sample was set to run, the shutter was closed and the generator power was turned down to 40 kV and 10 MA. Then the sample was removed. Pert Data Collector was then quitted and disengaged the PAN Analytical Pert in Coral.

Beneficiation Studies

Classification

This work included the correlation of cyclone classifier and Humphrey Spiral gravity concentrator (Humphrey, Jiangxi Jinshibao Mining Machinery Manufacturing, China) as the methods of reducing valuable fine particle losses. The required amount of water was pumped into the mixing tank and then the dry mass of 10 kg was fed in 2 kg batches to make a slurry of 20% solids. After each solid batch was added, the slurry was allowed to mix for 2 minutes. After the last batch the slurry was reticulated in a mixing drum at 1500 rpm for 5 minutes to achieve homogeneity, the slurry was then pumped to the 60 mm diameter hydro-cyclone at 0.6 m^3/h. The hydro-cyclone was used as a classifier which separated the material into the underflow and overflow, the underflow was further processed using a laboratory 3 banks spiral concentrator which was connected to the hydro-cyclone. The underflow to the cyclone was continuously fed to the spiral concentrator for further beneficiation while the overflow was collected into a drum out of the system. During Spiral Separation, the spiral was fitted with slurry pumps and feed distributors as indicated in Fig. 1. Low density particles were carried with the bulk of the water towards the outside of the spiral (perimeter), while particles with the greatest density migrated towards the inside of the spiral. The sample was allowed to separate according to the density difference of material in the spiral, then separate streams of concentrate, middling and tailings were then collected into drums. Samples of the overflow, underflow and spiral product streams were collected to determine the cut point (d_{50} size) using particle size distribution as well as the grade and recovery.

Advanced Gravity Concentration

The feed sample was then fractionalized to further understand the effect of particle size on advanced gravity separation. Falcon concentrator was utilized for such purpose as shown in Fig. 2. Laboratory Falcon concentrator, model SB4-VFD with an open-topped cylindrical bowl mounted on a revolvable shaft was used to study the interaction between the motor speed and the pulp density. The parameters were varied as indicated in Table 1 and the water pressure was controlled to give the required % solids. This was done for four different size fractions (A) -45 µm, (B) +45-75 µm, (C) -75+106 µm and (D) +106-300 µm. During operation, the 200 g dry sample was continuously introduced at the bottom of the spinning bowl by means of a conduit extending downwards along the axis of rotation. Fluidization water was introduced into the bowl (concentrate cone) through

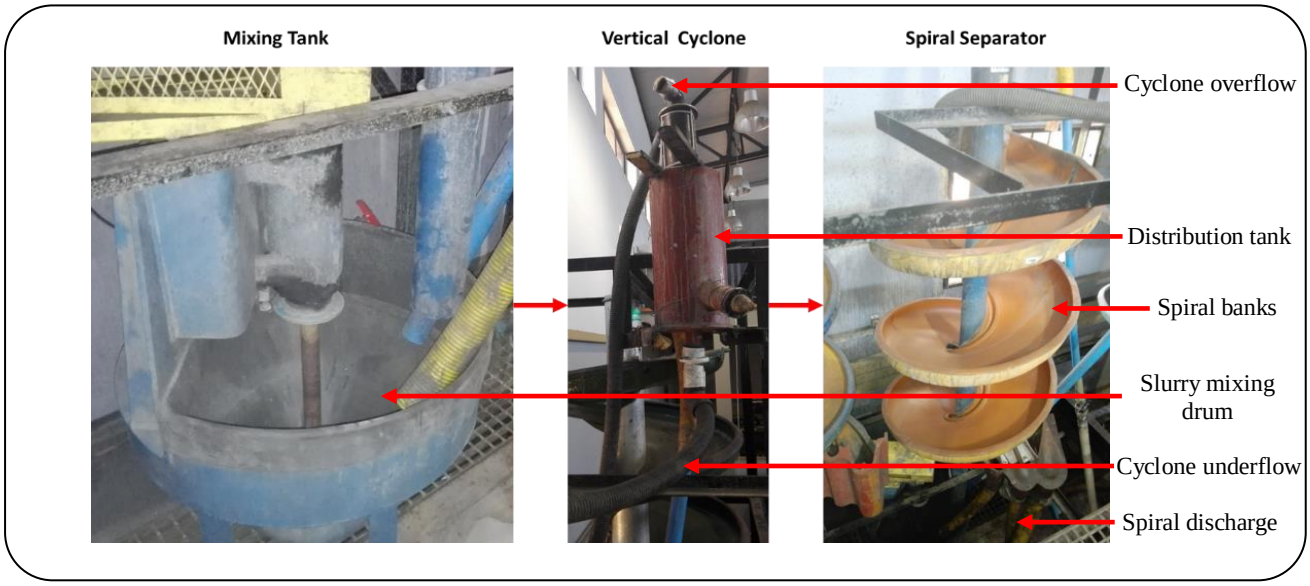

Fig. 1: Cyclone classifier and Humphrey Spiral separation setup.

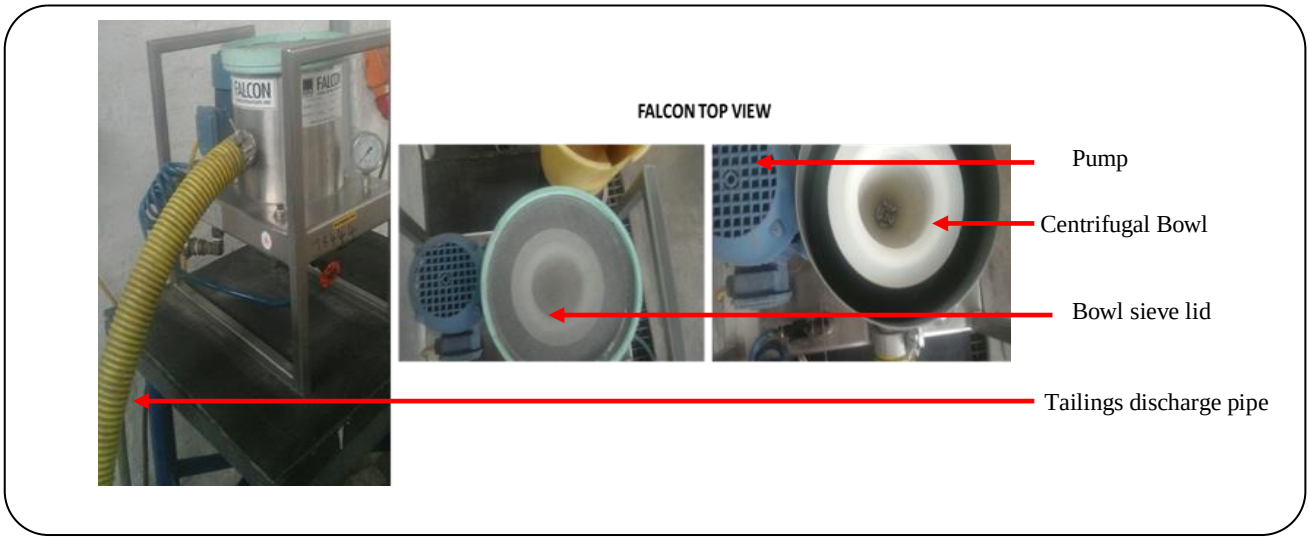

Fig. 2: Laboratory Falcon concentrator SB4-VFD.

a series of fluidization holes at the top of its wall. The slurry was then impelled to the wall of the bowl by an impeller thereby causing stratification along the inclined lower section of the bowl called the migration zone due to differential acceleration. In this zone, the enhanced gravity field generated by the spinning bowl was resolved into two force components.

The strong force component normal to the wall was the concentrating gravity force that allows the hindered settling processes and stratification of the particles in the feed according to, primarily density and secondarily particle size. The weak driving component parallel to the wall of the bowl pushes the stratified solids toward the top of the bowl. During the upward movement, heavy particles and coarse light particles continue to form a bed on the bowl surface with the heavy particles forming a layer nearest the bowl wall. During the course of the separation, tailings flowed out at the top of the cone into the tailings tube. The tailings and concentrate streams were collected, settled and dried for chemical analyses. After finishing the separation process, the tailings and concentrate were collected, settled and dried for chemical analyses.

Table 1: Experimental design for Falcon separation.

Run	1	2	3	4	5	6	7	8	9	10	11	12
Pulp Density (%)	10	10	10	10	20	20	20	20	30	30	30	30
Motor Speed (Hz)	30	40	50	60	30	40	50	60	30	40	50	60

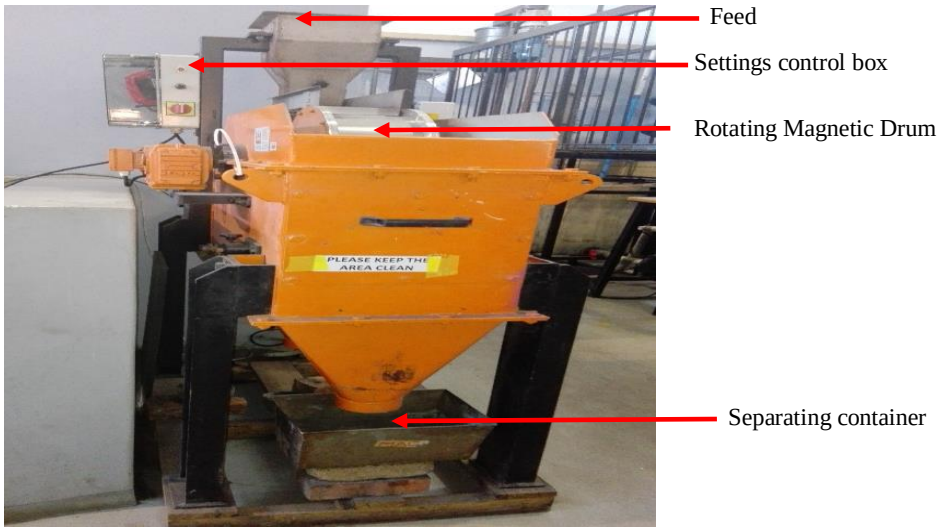

Fig. 3: Eriez High Intensity Dry Magnetic Separator.

Magnetic separation

Magnetic separation was used to maximise the beneficiation of chromite in finer particles. Eriez High Intensity Dry Magnetic separator, size 380 x 160 mm illustrated in Fig. 3, was used to separate the silica gangue (35%) in the chromite mineral sample. A sample of the chromite ore was wet sieved in different size ranges (-300+150 µm, -150+106 µm, -106+75 µm, -75+53 µm, -53+45 µm) to be beneficiated by wet high intensity magnetic separator. About 500 g of each size range was used as feed material for every test. The feed sample to the magnetic separator was 10% wet, the speed of the drum was set at 15 rpm with a vibration feeder of 8 Hz. After separation of the magnetic material (chromite mineral) with the non-magnetic (mostly silica) for every test, it was then dried in the oven at 80°C, weighed and bagged for XRF analysis. The chemical analysis of all products was conducted using XRF and Particle Size Distribution (PSD) of the products was also conducted.

RESULTS AND DISCUSSION

Characterization studies of PGM concentrate tailings

Particle size distribution

The particle size and mean distribution curve were plotted for the feed sample as shown in Fig. 4. Standard the deviation was also determined to indicate how other measurements spread out from the expected value. A low standard deviation signifies that most of the values are very close to each other and a high standard deviation means that the values are spread out. The results attained indicates that 80% of the particles are <75 µm and only 20% of the material is distributed above 75 µm. The test material can thus be classified as fine to ultra-fine material that is particularly not suitable for spiral unless finer size fractions are removed, meanwhile the size range which can be classified by spiral separator is limited to 3 mm-75 µm [8]. The as-received sample appeared to be very fine (in a flour-like form) hence wet screening was employed for Particle Size distribution (PSD) to reduce the blockage of screens by finer particles and to minimize dust formation.

Table 2: Chemical Analysis of feed sample

Oxide	SiO_2	MgO	$Al2O_3$	Fe_2O3	Cr_2O_3	CaO	Na_2O	TiO_2	Other
%	36.63	15.80	14.66	13.26	12.27	4.83	1.03	0.44	1.08

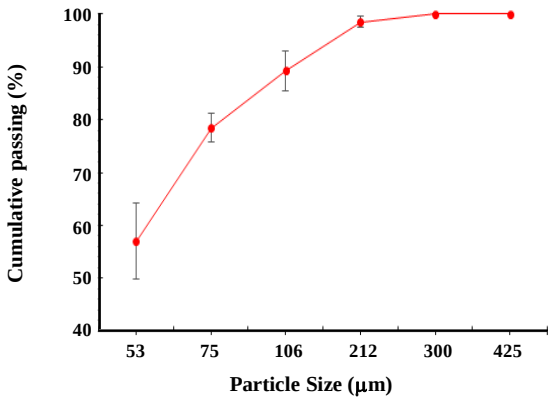

Fig. 4: PSD validation tests for the PGM tailings sample.

Chemical composition

Table 2 shows the plant tailings assay which was conducted using XRF. Although XRF gives elemental analysis the results were reported as compounds since most of the research laboratories mainly deal with variable matrices and therefore utilizes the universal standard of reporting, which is oxides. The assay values were obtained as 12.27% Cr_2O_3, 13.27% Fe_2O_3, 36.63% SiO_2 respectively and other gangue material. The Cr_2O_3 content in the tailings at 12.27% is much lower in comparison to the 44% reported for the parent chromite ore [2,9]. The lower value of the Cr_2O_3 content in the UG2 concentrator tailing might be due to the fact that some parts of the Cr_2O_3 in the primary UG2 ore have been misplaced in the PGM concentrate during flotation.SiO_2 is the main gangue mineral in this feed sample, gangue minerals have a negative impact on other processes going forward, TiO_2 as rutile above 1% and other gangue oxides like SiO_2 have an undesirable impact during ferro chrome smelting while low MgO/Al_2O_3 ratios of UG2 chromite also tend to limit achievement of high recoveries relative to some more refractory chromite [10].

It was observed as indicated in Table 3 that as the particle size fractions decrease from the coarsest 212+150 to -53+45 µm, the Cr_2O_3 content of the size fractions increase from 10.41 to 14.84% but decrease at the finest fraction of −45 µm to 11.47%. In addition to this, the silica content showed an opposite distribution to Cr_2O_3 in that the maximum was determined for the coarsest fraction and the lowest for the finest fraction. For Fe_2O_3 the maximum of 13.99% was reported at −53+45 µm size fraction. The results showed that the Cr: Fe ratios for all the size fractions were lower than 1.8. This indicates the need to improve the grade of the chromite to all size fractions. The chromite with Cr: Fe lower than 1.8 is only suitable for chemical industries. The Cr:Fe ratio plays an important role in determining the application of the material. It has been reported that only chromite with Cr:Fe>2.8 is suitable for metallurgical use, while those with Cr:Fe in the range of 2.8-1.8 are for refractory making [11].

Fig. 5 below shows the XRD results of as received sample, the picks identified moderate existence of chromite and traces of chromite in a spinel form as magnesiochromite. Maghemite also forms part of the feed sample as a ferromagnetic iron oxide, it is formed by weathering of spinels containing ferrous iron like magnetite. In the spectra, strong peaks of gangue pyroxene were identifies, this gangue mineral is a group of rock forming silicate minerals of which calcium-, magnesium-, and iron-rich varieties predominate. Pyroxene exists in igneous rock and occurs in rocks of different compositions, it is formed under conditions of regional and contact metamorphism [12].

From Fig. 6 which presents the Energy Dispersive x-ray (EDX) analysis of different size fractions, it was witnessed that the grade of Cr_2O_3 showed to be higher at a size range of <53 µm, the value was about 7.39% by weight which is in the size range where conventional gravity method fails to effectively beneficiate minerals, while lower value, that is, i.e. 3.15% by weight occurred at coarser size (>106 µm). These results thus indicate that the feed sample contains the very high content of ultra-fine chromite that needs to be recovered. The obtained results indicate that the liberation of chromite mineral was at <53µm>45µm.

Separation Studies

Fig. 7 shows the size distribution of the feed, underflow, and overflow. For the feed sample, it

Table 3: Size-by size assay of the flotation plant tailings sample.

Size (µm)	% Assay Value			Ratio
	Cr_2O_3	Fe_2O_3	SiO_2	Cr:Fe
-212 +150	10.41	11.33	39.34	0.90
-150 +106	10.48	11.24	39.29	0.91
-106 +75	13.06	12.5	36.33	1.02
-75 +53	14.79	13.59	34.84	1.06
-53+45	14.84	13.99	34.32	1.04
-45+38	11.47	13.11	37.70	0.86

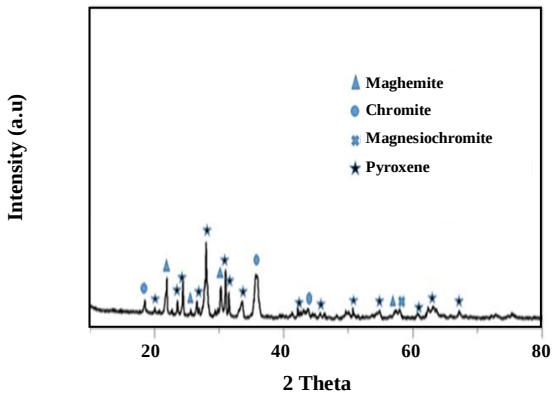

Fig. 5: XRD phase analysis of PGM tailings sample.

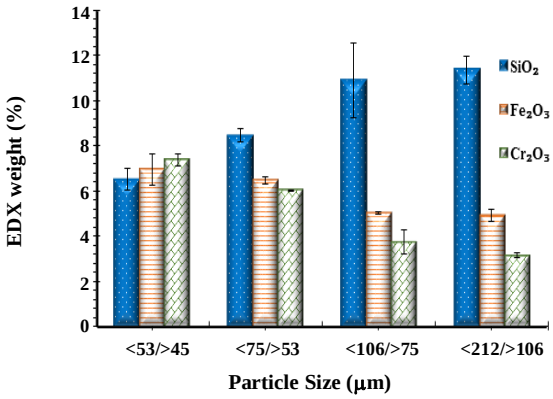

Fig. 6: EDX Analysis of PGM Concentration Plant Tailing.

was observed that it contains about the 20% (+75 µm) of coarse material with a large proportion of fines (<38 µm). It was further observed that a substantial amount, which was about 30.68% of the sample consists of <53 µm size fraction. The underflow that was subjected to the spiral for beneficiation only had 17.6% of the <53 µm particles with more than 80% reporting to the overflow. Thus, the classification step helped to separate the finer size fractions that cannot be efficiently beneficiated by the spiral and other conventional gravity separation methods.

The benefit of introducing the cyclone as the classification stage is indicated in Fig. 8. It illustrates that the beneficiation of chromite from the coarser size fraction 80% <150 µm minimized the loss of fines to the tailings stream as opposed to the feed with 80% < 75 µm. The loss of the finer particle was reduced from 70% to 35% by using a cyclone. The tailings without the cyclone showed to have finer size range indicating that some of the finer material was still retained within the stream. These results are in agreement with the work by other authors [13] who indicated that during the application of any concentration method dependent on gravity such as multi gravity separator, the particles should be thoroughly classified by hydro-cyclone and the parameters for different cut sizes for hydro-cyclone should be optimized. It is recommended that different fine particle size fractions, which could be obtained by changing the hydro-cyclone parameters should be tested using multi gravity separator for further beneficiation studies. In this work the fine particle size fractions were tested by Falcon advanced gravity separator.

Fig. 9 illustrates that the overflow stream which consists of 80% less than 53 µm particles has a grade of 10% Cr_2O_3 which will be further beneficiated by advanced gravity separation. This is the amount of Cr_2O_3 that is normally lost by the conventional gravity methods during beneficiation which needs to be beneficiated further. This is a significant loss in the ferrochrome industry in relation to the stainless steel industry demand and challenges of increasing natural ore depletion that is faced by the industry.

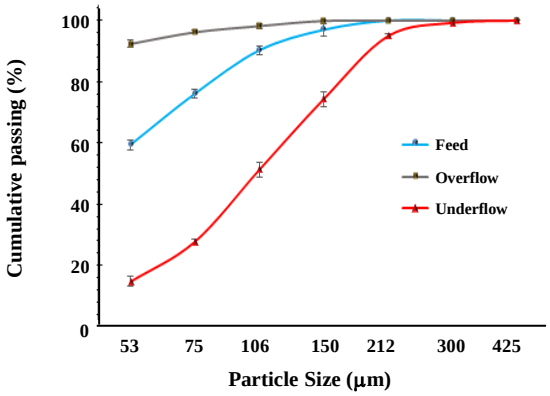

Fig. 7: Particle size distribution of Cyclone products at 0.6 m^3/h flowrate.

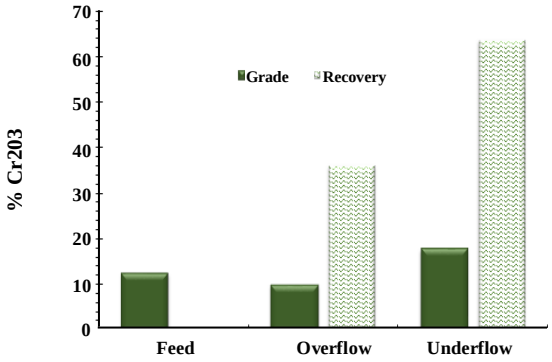

Fig. 9: Grade and recovery of Cr_2O_3 in Cyclone products.

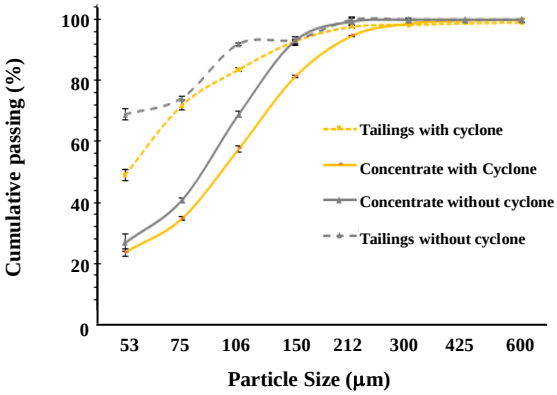

Fig. 8: Particle size distribution of Spiral products at 0.6 m^3/h flowrates.

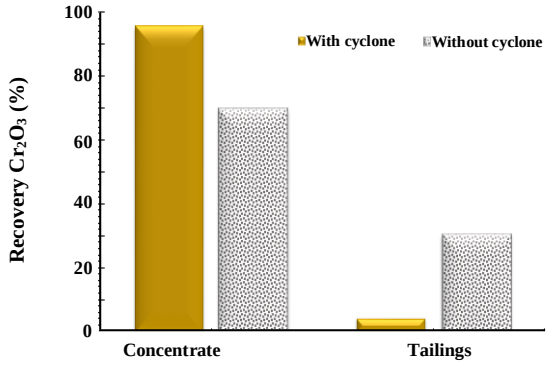

Fig. 10: Recovery of Cr_2O_3 in Spiral products at 0.6m^3/h Flowrate.

Fig. 10 indicates 5% recovery of Cr_2O_3 with classification prior to spiral separation in the tailings as opposed to the much higher 30% without classification. These results further confirmed the benefit of prior classifying of the feed according to size as this result in minimum loss of chromite in the fine particle sizes to the tailings streams. This allowed only the specific particle size range which is suitable for further gravity concentration since most mineral processing techniques fail in the ultra-fine size range. Gravity concentration techniques have especially become unacceptably inefficient at fine size fractions [8].

In Fig. 11, the grade of the concentrate was increased to 22 from 17.64% as a result of the removal of fines from the spiral feed. The fines were removed with other unwanted material that was in the feed. This gave a cleaner feed to the spiral allowing the gravity method to beneficiate at a coarser size fraction and the finer particles to be beneficiated separately. The grade was then improved by 5.64% because of the classification preceding the spiral separation.

Fig. 12 shows that the Cr_2O_3 mineral was effectively separated at the coarser size range but the process proved to be in-efficient below 106 µm. The grade improved by 5% in the magnetic product at a particle size of -106+75 µm and by 3% at -150+106 µm. Cr_2O_3 and Fe_2O_3 follow the same behaviour of grade decreasing as the particle size decrease below 75 µm. In the study conducted on the beneficiation of a low grade indigenous chromium ore using high intensity dry magnetic separator (HIDMS), the decrease in particle size resulted in the grade of Cr_2O_3 increasing to 40% but above 95% <50 mesh the grade and recovery decreased [14].

Similar behaviour of grade (decreases as the particle size decreases) between Cr_2O_3 and Fe_2O_3 was obtained

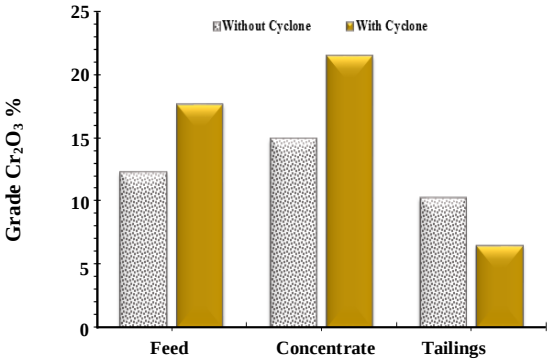

Fig. 11: Grade of Cr_2O_3 in Spiral products at 0.6 m^3/h flowrate.

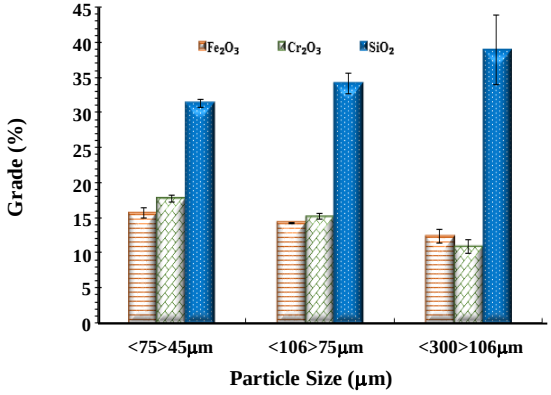

Fig. 13: Falcon concentration at 30% solids and 50 Hz.

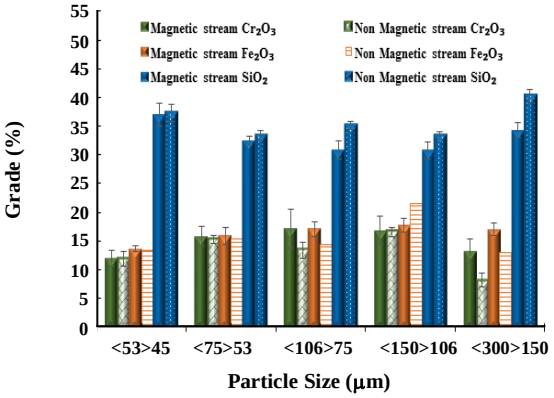

Fig. 12: Magnetic Separation at 6000 Gauss.

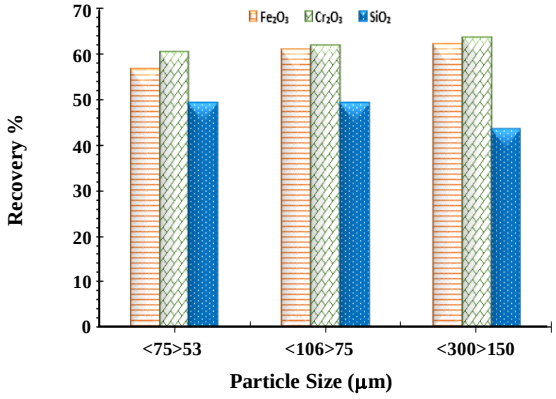

Fig. 14: Recovery of Falcon concentration at 30% solids and 50 Hz.

in previous studies where it was recommended to employ structural dissociation to separate the two [15]. Silica as the main gangue proved to be slightly removed above 75 µm. Therefore magnetic separation shows the potential to remove some of the SiO_2 gangue from the feed except at finer sizes.

Some of the chromite minerals that are removed by classification as overflow and those that still report to the tails can be further beneficiated by Falcon concentrator. Falcon Concentrators recover particles generally too fine to be recovered efficiently using conventional spirals. The preliminary tests conducted showed better efficiency at 30% solids. Fig. 13 below shows an increase in the grade of Cr_2O_3 as particle size decreases. This is in agreement with the literature [16] as they indicated that the Falcon is designed to separate and concentrate relatively fine particles, typically finer than 100 µm, according to differences in specific gravity. These results are based on particles >45 µm. The Falcon concentration results showed that at <75>45 µm up to 17% grade and 60.3% recovery was achieved. There might be a limit to the performance of the Falcon concentrator for <45 µm size fraction [8]. This suggests that the froth flotation technique will be a required process for such ultra-fine fractions.

Fig. 14 below indicates that the recovery of chromite slightly decreased with the particle size. This is in agreement with the results obtained in other studies [17] which concluded that rare earth metal recovery from the Nechalacho deposit (Avalon Rare Metals, Northwest Territories, Canada) using centrifugal gravity concentration is effective although recovery decreases with decreasing particle size. The same behaviour was found during the application of Falcon for fine coal cleaning [18]. The study also indicated that the Knelson Concentrator in this process exhibited greater selectivity for particle size

and particle specific gravity compared to the Falcon Concentrator. This resulted due to a lack of fluidizing water in the Falcon (different bowl geometry), higher centrifugal accelerations, and different distribution of mineral particles fed to the Falcon as opposed to the Knelson. In order to achieve higher grade and recovery on the PGM tailings concentrate the Knelson concentrator might be required.

CONCLUSIONS

The addition of a cyclone for complete ultra-fine particle removal showed positive contribution to the separation of ultrafine particles from the feed for further beneficiation. This allowed beneficiation of coarser size fraction material using the spiral which allows separation by density difference but not size. There is a noticeable increase in Cr: Fe ratio from 0.9 to 1.06 with classification. Removal of fines increased the Cr_2O_3 grade for spiral feed from 12.27% to 22% at the recovery of 95%. Falcon concentration proved to be efficient at fine particles whereby results showed that at <75>45 µm, up to 17% grade and 60.3% recovery of Cr_2O_3 was achieved. At <45 µm poorer results might be achieved due to the formation of slimes, while magnetic separation efficiency increased with an increase in particle size. Advanced gravity and magnetic separation were reasonably efficient to pre-concentrate PGM tailings before flotation. For sustainability of high grade chromite resources and to satisfy the continuous demand in the future needs, beneficiation of lean/sub-grade ores as well as tailings is imperative. The current focus of this research is the continuous development of processes for beneficiating fine chromite from tailing streams of other ores. This development can assist the global economy from a mineral sustainability point of view since the mining sector is facing continuous depletion of minerals. Although research is continuously conducted on fine chromite from tailing streams and other sources, this area still needs further exploration.

NOMENCLATURE

PGM	Platinum Group Metals
PSD	Particle Size Distribution
SEM-EDX	Scanning electron microscopy Energy Dispersive X-Ray
XRF	X-Ray Fluorescence
EDX	Energy Dispersive X-ray
XRD	X-ray diffraction
UG2	Upper Group 2
d50	Cumulative 50% pass particle size, µm
d80	Cumulative 80% pass particle size, µm

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