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Quantitative mineralogical characterization of chrome ore beneficiation plant tailing and its beneficiated products

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Abstract: Mineralogical characterization and liberation of valuable minerals are primary concerns in mineral processing industries. The present investigation focuses on quantitative mineralogy, elemental deportment, and locking–liberation characteristics of the beneficiation of tailings from a chrome ore beneficiation plant in the Sukinda region, Odisha; methods used for the study of the beneficiated tailings are QEMSCAN®, X-ray diffraction (XRD), and mineral chemistry by a scanning electron microscope equipped with an energy-dispersive spectrometer (SEM-EDS). The tailing sample was fine grained (69.48wt% below 45 μ m size), containing 20.25wt% Cr₂O₃ and 39.19wt% Fe₂O₃, with a Cr:Fe mass ratio of 0.51. Mineralogical investigations using QEMSCAN studies revealed that chromite, goethite, and gibbsite are the dominant mineral phases with minor amounts of hematite, kaolinite, and quartz. The sample contained 34.22wt% chromite, and chromite liberation is more than 80% for grains smaller than 250 μ m in size. Based on these results, it was predicted that liberated chromite and high-grade middling chromite particles could be separated from the gangue by various concentration techniques. The tailing sample was beneficiated by hydrocyclone, tabling, wet high-intensity magnetic separation (WHIMS), and flotation in order to recover the chromite. A chromite concentrate with 45.29wt% Cr₂O₃ and a Cr:Fe mass ratio of 1.85 can be produced from these low-grade chromite ore beneficiation plant rejects.

Keywords: tailings; mineralogy; chromites; beneficiation

1. Introduction

Chromite is the main source of chromium metal and an important raw material for the production of stainless steel, ferrochrome alloys, refractories, and chemicals. About 90% of mined chromite ore is converted into different grades of ferrochrome by the metallurgical industry. The stainless steel industry consumes about 80% of the ferrochrome. The important criteria for classifying the chromite ores into different industrial grades, such as metallurgical (low- and high-carbon ferrochrome, silico-ferrochrome, and charge chrome), refractory, and chemical, are the Cr₂O₃ content, Cr:Fe mass ratio, and friable/massive nature of the ore. The total chromite deposits in the world and the beneficiation practices have been described by various authors [1–2]. The estimated reserve of chromite ores in India is approximately 1.87×10^8 t, and India is the third largest producer of chromite.

mite ores with approximately 3.5×10^{6} – 4.0×10^{6} t/a. The bulk of the reserves (about 98%) is located in the Sukinda valley (21°00'-21°04'N, 85°40'-86°00'E), Odisha, India. The production of chromite ores from the Sukinda valley comprises of predominantly powdery and friable ore types, and during mining, considerable quantities of low-grade ores (Cr₂O₃: <40wt%) are also handled. The low-grade ores are beneficiated in chrome ore beneficiation plants in order to obtain high-grade concentrates (Cr₂O₃: >45wt%). During beneficiation, approximately 50wt% of the total feed is discarded as tailings which contain significant amounts of chromite. Several studies have been focused on recovering chromite from the plant tailings [3-4]. These studies mostly dealt with the grade and recovery of the products, and there is lack of studies on quantitative mineralogy and liberation characteristics of chromite in the bulk ores and the beneficiated products. In this study, the mineralogical and chemical characteristics of the tailings of a chrome-ore beneficiation

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plant of Sukinda and the beneficiated products obtained by laboratory experiments are quantitatively described.

2. Materials and methods

The tailing sample was collected from a typical chrome ore beneficiation plant of Sukinda, Odisha, India. The schematic flow sheet adopted for the beneficiation of chromite tailings in laboratory setting is given in Fig. 1. The feed sample and the beneficiated products were subjected to particle-size analysis by wet sieving up to 45 µm size. Each size fraction was split to obtain a representative aliquot and poured in a 30-mm mold containing a mixture of low-viscosity epoxy and hardener. Graphite powder was added in order to disperse the particles, create random orientation, and minimize density-induced particle segregation or settling. After hardening, the sample blocks were ground, polished, and carbon-coated. The blocks were loaded into the chamber of the QEMSCAN® 4300 unit, and the mineralogical data analysis of the samples was performed using iDiscover software (version 4.2).

The X-ray diffraction (XRD) analysis of the powdered sample was performed using PANalytical XPert Pro X-ray diffractometer equipped with a Mo target, operating at 40 kV and 30 mA in the 2θ scan range of 5°–40°. Energy-dispersive analyses of mineral phases were obtained using a scanning electron microscope (SEM) (M/s. Zeiss; EVO 50) fitted with a SDD energy-dispersive spectrometer (EDS) (M/s. Bruker Gmbh). Representative samples were obtained from each beneficiated stream and finely powdered in an agate mortar. Pellets were prepared by applying pressure (294 kN for 20 s) with a boric acid layer at the top of the sample. The exposed flat surface of the powdered sample

was irradiated using an X-ray fluorescence unit (M/s. PANalytical, model- Magix PRO PW 2440 XRF). The instrument was pre-calibrated with appropriate ore standards.



Fig. 1. Schematic diagram showing the beneficiation flow sheet for the chrome ore beneficiation plant tailings with the sample identifications used for QEMSCAN analyses.

3. Results and discussion

3.1. Bulk sample

(1) Size analysis and chemical analysis. The particle-size distribution of the tailing sample is given in Table 1. The results show that the sample is dominantly fine grained (69.47wt% is below 45 μ m). The chemical analyses of the size fractions of the plant tailings are given in Table 2. The analysis results indicated that as the particle size decreases, Cr₂O₃ content increases from 13.28wt% to 28.56wt% at 250 + 125 μ m size and further decreases steadily to 17.66wt% below 45 μ m size. The Cr₂O₃ and Cr/Fe mass ratio in the bulk sample are 20.25wt% and 0.51, respectively, and Cr₂O₃ is strongly distributed (12.27wt%) below 45 μ m size.

wt%

Sing / um	Samples										
Size / µiii	Ch-1	Ch-2	Ch-3	Ch-4	Ch-5	Ch-6	Ch-7				
350 + 250	3.82	—	—	_	_	_	_				
250 + 125	9.74	17.42	—	25.97	7.85	_	21.05				
125 + 63	9.53	17.35	—	28.66	17.07	_	21.40				
63 + 45	7.44	12.66	_	16.97	10.88	_	17.35				
<45	69.47	52.57	100	28.40	64.21	100	40.21				
Total	100	100	100	100	100	100	100				

 Table 1.
 Particle size analysis of plant tailing and beneficiated products. Sample details as in Fig. 1

(2) Mineralogy. The mineralogical, textural, and chemical characteristics of chromite ores of Sukinda have been published by numerous authors [5–6]. The chromite grains in the tailing sample vary widely in shape and size from euhedral, subhedral, and splintery to irregular grains. The chromite grains are occasionally intensely fractured exhibiting cataclastic texture (Fig. 2(a)). Angular and elongated grains of chromite are due to the release of chromite grains from the coarse fractured grains and grinding in the beneficiation plant.

Contont	Sizes of tailing (Ch-1) / µm						Ch-1 Beneficiated samples					
Content	350 + 250	250 + 125	125 + 63	63 + 45	<45	Bulk	Ch-2	Ch-3	Ch-4	Ch-5	Ch-6	Ch-7
Cr_2O_3 / wt%	13.28	28.56	27.88	22.43	17.66	20.25	24.64	9.14	48.05	18.05	45.81	16.57
$Fe_2O_3 / wt\%$	43.96	30.86	29.46	33.75	42.09	39.19	34.78	49.58	24.16	38.10	23.40	48.71
Al_2O_3 / wt%	17.44	14.87	16.45	18.65	19.42	19.24	18.76	20.59	12.60	22.31	17.31	14.23
SiO_2 / wt%	10.60	11.35	12.16	8.70	5.20	6.80	6.65	7.06	3.58	7.56	1.06	9.78
Cr / wt%	9.09	19.54	19.08	15.35	12.08	13.86	16.86	6.25	32.88	12.35	31.35	11.54
Fe/wt%	30.77	21.6	20.62	22.23	29.46	27.43	24.34	34.71	16.91	26.67	16.38	34.10
Cr/Fe mass ratio	0.30	0.90	0.93	0.69	0.41	0.51	0.69	0.18	1.94	0.46	1.91	0.35
Cr ₂ O ₃ distribution / %	0.51	2.78	2.66	1.67	12.27	_	_			_	_	_

Table 2. Chemical analyses (oxide), element, and element ratio of size fractions of plant tailing and the bulk beneficiated samples, and Cr₂O₃ distribution in different size fractions. Sample details as in Fig. 1.

Goethite is the major constituent of the tailing samples. Goethite is of two types: vitreous and ochreous (limonite). Vitreous goethite is gray to dark gray in color, occurs in large masses, and possesses colloform bands and nodules (Figs. 2(b)-2(f)). Ochreous goethite (limonite) is highly friable, clayey, constituted of ultrafine crystallites, and dark to brownish dark in color. Hematite occurs as irregular masses; colloform bands, streaks, lines, and laths are intimately associated with goethite, gibbsite, and kaolinite (Figs. 2(g)-2(j)). Gibbsite grains are coarse- and fine-grained and sometimes stained by iron oxyhydroxides. The dominant textural types are replacement and open-space filling types. The secondary minerals formed during weathering cycles-goethite, hematite, gibbsite, and kaolinite-occur as fracture and cavity filling within the chromite grains (Figs. 2(h)-2(j)). The replacement texture is prominent, in which the vitreous goethite replaces chromite in varying degrees (Figs. 2(b) and 2(e)). The nodular goethite is often mantled by ochreous goethite and colloform-banded goethite (Figs. 2(c) and 2(d)). Quartz is fine- as well as coarse-grained.

The X-ray diffractogram of the tailing sample is shown in Fig. 3. The minerals identified from the characteristic X-ray peaks are chromite, hematite, goethite, gibbsite, and quartz.

Semi-quantitative chemical analysis results of different mineral phases are given in Table 3. It was observed that goethite contains significant amounts of chromium (Cr₂O₃: 8.07%–19.38%), aluminum (Al₂O₃: 5.25%–11.32%), and minor contributions of silicon (SiO₂: <0.73%) and titanium (TiO₂: <1.77%) elements. Goethite (FeO·OH) is formed during the chemical weathering of chromiferous ultrabasic rocks, and can incorporate variable amounts of other elements, such as Al, Cr, Mn, P, Si, Ni, V, Zn, and Co, in the crystal structure [7]. The elemental spectra of vitreous goethite and ochreous goethite are given in Figs. 4(a) and 4(b), respectively. In the spectra, moderately strong peaks of Cr and distinct peaks of Al, Si, and Ti are observed. Hematite, gibbsite, and kaolinite comprise less than 2.07%, 0.50%, and 1.53% Cr₂O₃, respectively. The elemental spectra of these minerals are depicted in Figs. 4(c), 4(d), and 4(e). Hematite shows small peaks of Cr, Ti, Al, and Si, while kaolinite has small Fe and Cr peaks. The chrome spinel contains 61.80% Cr₂O₃ and 14.44% FeO. The elemental spectrum of the chrome spinel is given in Fig. 4(f) which depicts strong Cr, distinct Fe, Mg, and Al, and weak Ti spectral features. The previous studies have reported that the composition of chrome spinel of Sukinda varies widely according to the chemical composition (Fe⁺²,Mg)(Cr,Al,Fe⁺³) with trace amounts of Ti and Mn [6].

(3) Quantitative mineralogy by QEMSCAN. The modal analysis results of different size fractions and calculated amounts in the bulk sample are given in Table 4. The sample contained 34.22wt% chromite, 32.93wt% goethite, 16.25wt% gibbsite, 6.88wt% hematite, 3.89wt% kaolinite, and 4.47wt% quartz. Liberation spectra of chromite in particle category grouped as 0%-30% (reject), 30%-60% (low-grade middlings), 60%–90% (high-grade middlings), and 90%–100% (liberated) chromite in each size fraction and total sample are given in Table 5. The data revealed high percentages of chromite liberation (80.1%-84.4%) in coarse sizes while the fine-size fraction (<45 µm) has slightly less-liberated chromite (78.3%). The total sample had 80.1wt% and 14.0wt% liberated and high-grade middling chromite particles, respectively (Table 5). Apart from the mineral distribution and chromite liberation spectrum in each size fraction, QEM-SCAN results were also used to investigate the occurrence of chromite phase and its association with the gangue phases.



Fig. 2. (a) Chromite grains showing cataclastic texture. Gibbsite occurs as fracture and cavity filing. BSE image. 1—Scan point of gibbsite. (b) Inclusions of chromite within nodular vitreous goethite depicting replacement texture. Reflected light. 2—Scan point of vitreous goethite; 3—Scan point of chromite. (c) Nodular goethite is mantled by ochreous goethite. BSE image. 4—Scan point of vitreous goethite; 5—Scan point of ochreous goethite. (d) Nodular goethite is mantled by ochreous goethite, which is partially rimmed by colloform-banded vitreous goethite. BSE image. 6—Scan point of vitreous goethite; 7—Scan point of ochreous goethite. (e) Chromite (C) is partly replaced by massive vitreous goethite (Go). Note laths of hematite (white) within goethite. Reflected light. (f) Liberated colloform-banded vitreous goethite. Reflected light. (g) Intimate intergrowths between gibbsite and hematite. BSE image. 8—Scan point of gibbsite (Gi). Another and splintery chromite grains (C) within a mass consisting of gibbsite (Gi), kaolinite, and hematite. BSE image. 10—Scan point of kaolinite. (i) Coarse to very fine chromite grains within a mass of kaolinite, ochreous goethite, and gibbsite. The left-hand side grain shows intergrowth between hematite and gibbsite. 12—Scan point of ochreous goethite; 13—Scan point of hematite.

Locking–liberation (Table 6) data of chromite indicated that 27.3wt% of chromite is liberated and it is mainly locked with goethite (chromite–goethite binary: 16.2wt%). The mass balance of chromite in terms of particle category in

10% increments of chromite (by area) of the bulk sample indicated that 10.6wt% of the chromite is in the rejected particle category (0%–30% chromite) and free gangue minerals (0% chromite) constitute 52.1% (Table 7).



Fig. 3. X-ray diffractogram of chrome ore beneficiation plant tailings. Gi—Gibbsite, G—Goethite, C—Chromite, Q—Quartz, and H—Hematite.

Minerals	Chromite	Vitreous goethite	Vitreous goethite	Vitreous goethite	Ochreous goethite	Ochreous goethite	
Points	3	2	4	6	5	7	
Cr ₂ O ₃	61.80	14.15	10.51	19.38	12.22	8.07	
Al_2O_3	10.00	5.71	11.32	8.33	10.02	10.77	
Fe ₂ O ₃	14.44	67.36	68.65	64.35	67.88	70.10	
MgO	13.01	n.d.	n.d.	n.d.	n.d.	n.d.	
TiO ₂	0.20	0.29	0.68	0.83	0.98	0.72	
SiO ₂	n.d.	0.36	0.54	n.d.	0.36	n.d.	
Total	99.45	87.87	91.7	92.89	91.46	89.66	
Minerals	Ochreous goethite	Hematite	Hematite	Gibbsite	Gibbsite	Kaolinite	Kaolinite
Points	12	8	13	1	9	10	11
Cr ₂ O ₃	14.84	1.78	2.07	0.50	n.d.	0.66	1.53
Al_2O_3	5.25	1.36	1.29	67.61	66.61	41.15	41.56
Fe ₂ O ₃	69.43	94.87	95.31	0.53	0.84	2.53	2.04
TiO ₂	1.77	1.13	1.38	n.d.	n.d.	n.d.	n.d.
SiO_2	0.73	0.54	0.32	n.d.	n.d.	41.29	39.76
Total	92.02	99.68	100.37	68.64	67.45	85.63	84.89

 Table 3. EDS analysis results of different minerals

Note: n.d.-not detected; Fe as FeO in chromite.

Chromium and iron elemental deportments to different mineral phases were analyzed. It was found that 9.41wt% Cr metal is reported from goethite which is due to its complex mineral chemistry. It was also found that deportment of Cr from hematite, gibbsite, and kaolinite is 0.51wt%, 0.46wt%, and 0.07wt%, respectively. Iron deportment is mainly from goethite (64.89wt%) followed by hematite (18.8wt%), chromite (14.33wt%), and kaolinite (1.98wt%).

From the above detailed characterization studies, it is

observed that in the tailing sample: (a) Cr_2O_3 is strongly distributed below 45 µm particle size, (b) goethite and gibbsite are the major gangue minerals, (c) Cr metal is predominantly locked in chromite and in small amounts in goethite, and (d) liberated + high-grade middling chromite particle content is high (94.1wt%). Based on the mineralogical findings, a flow sheet was developed to beneficiate the tailings (Fig. 1) and details of the mineralogy and chemistry of the beneficiated products are given in the following sections.

wt%



Fig. 4. (a) Elemental spectra of vitreous goethite. Scan point 2 of Fig. 2(b). (b) Elemental spectra of ochreous goethite. Scan point 5 of Fig. 2(c). (c) Elemental spectra of hematite. Scan point 8 of Fig. 2(g). (d) Elemental spectra of gibbsite. Scan point 1 of Fig. 2(a). (e) Elemental spectra of kaolinite. Scan point 11 of Fig. 2(i). (f) Elemental spectra of chromite. Scan point 3 of Fig. 2(b).

Table 4.	Modal analysis of bulk (Ch-1), HC-UF (Ch-2), and HC-OF (Ch-3) sampl	les
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,	w	ť	9	1
	vv	ι	/	1

						Si	ze / µm						
Mineral	350 + 250	250	+ 125	125	+ 63	63	+ 45		<45		(Combined	1
	Ch-1	Ch-1	Ch-2	Ch-1	Ch-2	Ch-1	Ch-2	Ch-1	Ch-2	Ch-3	Ch-1	Ch-2	Ch-3
Chromite	1.01	5.13	7.05	4.91	7.41	3.01	5.83	20.16	20.44	11.53	34.22	40.74	11.53
Hematite	0.34	0.68	1.38	0.58	1.15	0.75	0.98	4.52	4.33	2.50	6.88	7.85	2.50
Goethite	1.44	1.88	3.39	1.62	2.85	1.49	2.03	26.50	19.86	49.63	32.93	28.13	49.63
Gibbsite	0.54	0.87	2.67	1.13	3.23	1.38	2.56	12.33	4.60	27.22	16.25	13.06	27.22
Kaolinite	0.23	0.32	0.79	0.29	0.65	0.33	0.41	2.72	1.99	4.44	3.89	3.84	4.44
Quartz	0.23	0.82	2.08	0.95	2.01	0.42	0.78	2.06	0.71	2.08	4.47	5.58	2.08
Others	0.03	0.04	0.06	0.05	0.05	0.07	0.07	1.19	0.63	2.60	1.37	0.82	2.60
Total	3.82	9.75	17.42	9.52	17.35	7.44	12.66	69.48	52.55	100	100	100	100

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Size / um	Comm1a	Particle grade / %								
Size / µm	Sample	0–30	30-60	60–90	90–100	Total				
250	Ch-1	16.09	19.28	22.84	41.79	100				
	Ch-1	2.6	6.2	11.1	80.1	100				
	Ch-2	6.3	6.9	7.4	79.4	100				
+125	Ch-4	1.0	1.5	5.2	92.3	100				
	Ch-5	47.7	31.9	9.3	11.1	100				
	Ch-7	12.1	10.0	12.4	65.6	100				
	Ch-1	1.7	3.1	11.2	84.1	100				
	Ch-2	3.1	3.1	7.8	86.1	100				
+63	Ch-4	0.6	2.2	3.6	93.8	100				
	Ch-5	30.1	20.0	20.0	29.9	100				
	Ch-7	7.7	6.2	14.7	71.4	100				
	Ch-1	2.4	1.3	12.0	84.4	100				
	Ch-2	1.6	1.8	3.0	93.6	100				
+45	Ch-4	0.8	2.0	5.9	91.3	100				
	Ch-5	7.6	7.4	35.7	49.3	100				
	Ch-7	2.5	3.5	9.3	84.7	100				
	Ch-1	2.3	3.4	16.0	78.3	100				
	Ch-2	3.8	7.9	18.3	70.0	100				
	Ch-3	15.6	7.1	33.6	43.7	100				
<45	Ch-4	0.4	0.9	6.2	92.6	100				
	Ch-5	1.7	2.6	12.9	82.8	100				
	Ch-6	0.5	0.9	4.2	94.4	100				
	Ch-7	1.0	3.0	16.8	79.2	100				
	Ch-1	2.3	3.6	14.0	80.1	100				
	Ch-2	3.8	5.9	12.1	78.2	100				
	Ch-3	15.6	7.1	33.6	43.7	100				
Total	Ch-4	0.7	1.6	5.1	92.6	100				
	Ch-5	4.5	4.4	16.9	74.2	100				
	Ch-6	0.5	0.9	4.2	94.4	100				
	Ch-7	4.5	5.0	12.8	77.8	100				

Table 5.Liberation data of chromite in particle categories of each size fraction (particle categories: 0%–30%, rejects; 30%–60%,
low-grade middlings; 60%–90%, high-grade middlings; 90%–100%, liberated grains)wt%

3.2. Beneficiated samples

3.2.1. Hydrocyclone underflow and hydrocyclone overflow samples

(1) Size analysis and quantitative mineralogy by QEM-SCAN. The size analyses (wt%) of the hydrocyclone underflow (HC-UF) and hydrocyclone overflow (HC-OF) samples are given in Table 1. The results indicated that the HC-UF sample was coarse-grained (52.57% is below 45 μ m) compared to the HC-OF sample containing fine particles (100wt% of the sample is below 45 μ m). The modal analyses of the HC-UF and HC-OF samples are given in Table 4. The modal data indicated that the HC-OF sample was highly depleted in chromite content (11.53wt%) and enriched in goethite (49.63wt%) and gibbsite (27.22wt%) compared to respective mineral contents of the HC-UF sample (Table 4). Quartz content is higher in the HC-UF sample (5.58wt%) compared to the HC-OF sample (2.08wt%).

Liberation data of chromite in the HC-UF and HC-OF samples are given in Table 5. The chromite liberation is moderately high (78.2wt%) in the HC-UF sample compared to low chromite liberation in the HC-OF sample (43.7wt%). Locking–liberation data (Table 6) indicated that the HC-UF

Table 6. Locking and liberation characteristics of the minerals in different samples. Sample details as in Fig. 1 wt%

					-	-	-	-
No.	Locking + Liberation	Ch-1	Ch-2	Ch-3	Ch-4	Ch-5	Ch-6	Ch-7
1	Liberated chromite	27.3	30.5	5.2	71.6	18.4	62.7	15.3
2	Liberated goethite	4.0	6.1	4.6	3.8	10.2	6.2	14.0
3	Liberated gibbsite	6.4	7.6	15.9	1.0	4.7	6.3	2.9
4	Liberated quartz	2.7	5.2	0.7	0.9	5.6	0.3	7.2
5	Liberated kaolinite	1.3	0.8	1.9	0.1	0.8	0.2	1.2
6	Liberated others	0.2	0.2	0.2	0.1	0.1	0.0	0.3
7	Chromite + Goethite	16.2	13.7	24.4	8.0	9.4	5.9	12.5
8	Chromite + Gibbsite	4.4	5.2	3.6	1.2	4.1	2.7	2.9
9	Goethite + Hematite	12.1	11.3	3.2	8.2	19.3	8.1	18.0
10	Goethite + Gibbsite	11.9	6.2	29.4	1.3	6.4	4.2	6.8
11	Goethite + Kaolinite	2.5	2.9	1.2	0.9	5.0	0.6	7.1
12	Quartz + Kaolinite	0.5	0.5	0.2	0.2	1.0	0.3	1.2
13	Chromite + Gibbsite + Goethite	1.2	1.9	2.3	0.3	0.9	0.2	1.3
14	Chromite + Gibbsite + Kaolinite	0.8	1.2	0.4	0.3	1.3	0.3	1.1
15	Chromite + Goethite + Kaolinite	0.5	0.4	0.3	0.1	0.3	0.2	0.3
16	Hematite + Goethite + Gibbsite	1.9	1.5	1.3	0.5	2.7	0.7	1.3
17	Kaolinite + Gibbsite + Goethite	0.9	0.5	0.2	0.2	1.3	0.2	1.1
18	Exposed grains	5.5	4.3	5.0	1.3	8.2	0.9	5.5
Total		100	100	100	100	100	100	100

Table 7.Sample distribution of chromite in 10% increment (by area) from no chromite (0% chromite) to chromite with an areapercent more than 90% (liberated chromite) in the bulk and the beneficiated products. Sample details as in Fig. 1wt%

P				···· P · · · · · · · · ·	~····P··· ······	····		ĩ
Chromite	Ch-1	Ch-2	Ch-3	Ch-4	Ch-5	Ch-6	Ch-7	
90%-100% chromite	27.3	30.7	4.9	71.7	18.4	62.7	15.2	
80%-90% chromite	4.1	3.4	1.2	2.5	2.4	2.0	1.8	
70%-80% chromite	2.0	1.6	2.1	1.3	0.9	0.6	0.9	
60%–70% chromite	1.3	1.7	0.9	0.9	0.6	0.5	0.7	
50%–60% chromite	0.7	1.2	0.6	0.9	0.6	0.2	0.6	
40%–50% chromite	1.0	1.7	0.4	0.9	0.6	0.2	0.6	
30%–40% chromite	0.9	1.5	0.4	0.5	0.7	0.7	0.7	
20%-30% chromite	1.2	2.0	0.5	1.0	1.1	0.4	1.2	
10%–20% chromite	1.4	2.7	3.6	0.7	1.5	0.5	1.4	
0%-10% chromite	8.0	5.6	23.5	2.4	7.1	1.8	4.5	
0% chromite	52.1	47.9	61.9	17.4	66.1	30.4	72.4	
Total	100	100	100	100	100	100	100	

sample contained 30.5wt% liberated chromite while the HC-OF sample had 5.2wt% liberated chromite particles. In both of the beneficiated streams, chromite is predominantly locked with goethite. The chromite distribution with 10% increments (area%) in particles in the HC-OF sample showed that chromite grains are mostly locked (27.6wt%) in 0%–30% chromite; the HC-UF sample has 10.3wt% chro-

mite in the 0%–30% particle category (Table 7). The free gangue contents in the HC-OF and HC-UF samples are 61.9wt% and 47.9wt%, respectively.

(2) Chemical analysis. Chemical analysis results of the HC-UF and HC-OF samples are given in Table 2. Hydrocyclone underflow and overflow samples contained 24.64wt% and 9.14wt% Cr₂O₃ and 34.78wt% and 49.58wt% Fe₂O₃, respectively. The analysis results corroborated the mineralogical data regarding preferential concentration of chromite grains in the HC-UF samples.

The HC-UF stream was subjected to separation by a Wilfley shaking tabling experiment (Fig. 1). The HC-OF sample which yielded 9.14wt% Cr₂O₃ and 11.53wt% chromite was discarded as reject tailings.

3.2.2. Samples from shaking table

(1) Size analysis and quantitative mineralogy by QEM-SCAN. The particle size analyses of the table concentrate and middling + tailing are given in Table 1. The concentrate is significantly coarse-grained (28.40wt% is <45 μ m) compared to the middling + tailing product having 64.21wt% fine particles (<45 μ m). The mineral quantities of the tabling products are given in Table 8. The concentrated stream contained large amounts of chromite (76.70%) and small amounts of goethite (13.08%), gibbsite (2.48%), hematite (5.28%), kaolinite (1.01%), and quartz (1.04%). In contrast, the middling + tailing sample contained smaller amounts of chromite (24.87%) and large amounts of hematite (8.58%), goethite (35.91%), gibbsite (17.40%), and quartz (6.90%).

Chromite liberation data in different particle grades of each size fraction and in the total sample are given in Table 5. The data revealed that the chromite liberation was very high (>91.3wt%) in all the size fractions and in the bulk concentrated products. In the middling + tailing product, the chromite liberation is very poor (<49.3wt%) for particle sizes larger than 45 μ m and is 74.2wt% in the total sample. Locking–liberation characteristics indicated that the concentrate had 71.6wt% liberated chromite and chromite–goethite binary mixture constituted 8.0wt%. The middling + tailing sample contained 18.4wt% liberated chromite (Table 6). For the middling + tailing stream sample, mass balance data with respect to chromite in different particle categories indicated that the reject particle category (0%–30% chromite) contains 9.7wt% chromite (Table 7).

(2) Chemical analysis. Chemical analysis (wt%) results indicated that the chromite concentrate had 48.05% Cr_2O_3 , 24.16% Fe_2O_3 , 12.6% Al_2O_3 , 3.58% SiO_2 , and a Cr:Fe mass ratio of 1.94. The middling + tailing sample has low Cr_2O_3 (18.05%) and high Fe_2O_3 (38.10%), Al_2O_3 (22.31%), and SiO_2 (7.56%) (Table 2).

Table 8. Modal analysis results of chrome ore tabling concentrate (Ch-4) and middlings + tailings (Ch-5) in different sizes wt%

					Size	/ µm				
Mineral	12	125		125 + 63		+ 45	<45		Total	
	Ch-4	Ch-5	Ch-4	Ch-5	Ch-4	Ch-5	Ch-4	Ch-5	Ch-4	Ch-5
Chromite	22.02	0.46	22.06	1.05	12.05	1.68	20.57	21.68	76.70	24.87
Hematite	0.62	0.52	1.65	1.74	1.14	1.37	1.87	4.94	5.28	8.58
Goethite	3.07	3.11	3.01	6.15	2.40	3.50	4.60	23.15	13.08	35.91
Gibbsite	0.06	1.44	0.86	3.45	0.90	2.03	0.67	10.49	2.48	17.40
Kaolinite	0.09	0.51	0.40	1.44	0.21	0.68	0.31	2.41	1.01	5.04
Quartz	0.08	1.77	0.57	3.09	0.22	0.75	0.16	1.29	1.04	6.90
Others	0.05	0.04	0.11	0.15	0.05	0.87	0.22	0.25	0.42	1.31
Total	26.00	7.85	28.66	17.07	16.97	10.88	28.40	64.21	100	100

The tabling experiment was effective in concentrating mostly coarse and subordinate amounts of fine chromite grains in the concentrated stream. The chromite grains are predominantly fine-grained in the middling + tailing sample. The middling + tailing stream of the tabling experiment contained significant quantities of materials (about 58wt% with respect to feed) with substantial amounts of Cr_2O_3 content (18.05wt%) and free chromite grains (18.4wt%). The product was subjected to wet high-intensity magnetic separation (WHIMS) in order to separate paramagnetic minerals (chromite, goethite, and hematite) from nonmagnetic minerals (gibbsite, kaolinite, and quartz). It was observed that the magnetic stream was enriched to 24.50wt%

 Cr_2O_3 and nonmagnetic products comprised 12.30wt% Cr_2O_3 with yield of around 28wt% materials (with respect to feed). However, this enrichment of Cr_2O_3 content in the magnetic products is not suitable for chrome ore-based industries. In the flow sheet, the magnetic products (about 30wt% with respect to feed) were processed by flotation techniques for further upgrade.

3.2.3. Samples from flotation column

(1) Size analysis and quantitative mineralogy by QEM-SCAN. The particle size data revealed that the tailing sample was coarse grained (40.21wt% is <45 µm) compared to the concentrated sample (100wt% below 45 µm size) (Table 1). Modal mineralogical data obtained by QEMSCAN

analysis for flotation products are given in Table 9. Chromite contents in concentrate and tailings are 66.62% and 19.61%, respectively. The tailing sample is highly enriched in goethite (42.84%), kaolinite (6.39%), and quartz (8.98%) compared to the respective contents in the concentrates. The chromite liberation spectrum (Table 5) indicated that the concentrate and tailing products contained 94.4wt% and 77.8wt% liberated chromite grains (90%–100% particle category), respectively. Locking–liberation characteristics indicated that the concentrate and tailing contained 62.7wt% and 15.3wt% liberated chromite, respectively (Table 6). For the tailing sample, chromite grains also occur significantly in 0%–30% chromite (7.1%) and 30%–60% chromite (1.9%) particle categories (Table 7). The flotation experiment yielded 7wt% and 23wt% (with respect to feed) concentrate and tailing products, respectively.

				Size / µm			
Mineral	125	125+63	63 + 45	<	<45		otal
	Ch-7	Ch-7	Ch-7	Ch-6	Ch-7	Ch-6	Ch-7
Chromite	3.32	4.15	3.55	66.62	8.59	66.62	19.61
Hematite	0.78	2.09	1.26	6.02	5.97	6.02	10.10
Goethite	8.88	8.14	7.32	17.00	18.50	17.00	42.84
Gibbsite	3.62	2.46	1.68	8.57	2.43	8.57	10.19
Kaolinite	1.07	1.48	1.32	0.88	2.52	0.88	6.39
Quartz	3.17	2.84	1.92	0.53	1.05	0.53	8.98
Others	0.21	0.24	0.30	0.39	1.15	0.39	1.90
Total	21.05	21.40	17.35	100	40.21	100	100

Table 9. Modal analysis results of chrome ore flotation concentrate (Ch-6) and tailing (Ch-7) in different sizeswt%

(2) Chemical analysis. The chromite flotation concentrate was analyzed and shown to contain 45.81wt% Cr₂O₃, 23.40wt% Fe₂O₃, 17.31wt% Al₂O₃, and 1.06wt% SiO₂. Compared to the concentrate, the tailing sample is depleted in Cr₂O₃ (16.57wt%) and enriched in Fe₂O₃ (48.71wt%) and SiO₂ (9.78wt%) values (Table 2).

4. Conclusions

(1) Physical, chemical, and mineralogical characteristics of tailings from a chrome ore beneficiation plant in Sukinda were studied with the goal of recovering chromite from the tailings. The tailing was fine grained (\sim 70wt% <45 µm), contained 34.22wt% chromite, 32.93wt% goethite, 16.25wt% gibbsite, and small amounts of hematite, kaolinite, and quartz. Chromium is predominantly contributed as chromite and liberation studies by QEMSCAN® indicated 27.3wt% liberated chromite particles in the bulk sample.

(2) The beneficiation flow sheet comprised hydrocyclone, followed by tabling, WHIMS, and flotation experiments. Hydrocyclone experiments removed about 27wt% of the very fine-grained particles (<45 μ m) as overflow with low Cr₂O₃ (9.14wt%) and chromite contents (11.53wt%). Tabling experiments of the HC-UF were effective in concentrating predominantly coarse and small amounts of fine lib-

erated chromite grains in the concentrated stream which contained 76.70wt% chromite and 48.05wt% Cr_2O_3 and a Cr:Fe mass ratio of 1.94 and yield of ~15wt%. The middling + tailing stream containing 24.87wt% chromite and 18.05wt% Cr_2O_3 was subjected to a WHIMS experiment which yielded magnetic (24.50wt% Cr_2O_3 , 30wt% yield) and nonmagnetic (12.30wt% Cr_2O_3 , 28wt% yield) products. The magnetic stream was beneficiated by flotation and the concentrate and tailing products contained 66.62wt% and 19.61wt% chromite, respectively. The beneficiation studies of the plant tailing resulted as the following. (i) Concentrate: yield, 22%; Cr_2O_3 grade, 45.29wt%. (ii) Tailing/reject: yield, 78%; Cr_2O_3 grade, 12.70wt%.

(3) The beneficiation studies revealed loss of chromite mineral in the different tailings/rejects: HC-OF, WHIMS nonmagnetic, and flotation tailing. The chromite loss in the HC-OF is explained by the facts that the chromite grains are very fine ($<20 \mu$ m) coupled with poor liberation characteristics of chromite particles (43.7wt%). Significant chromite loss occurred in flotation tailings having 16.57wt% Cr₂O₃ and 19.61wt% chromite with moderately high chromite liberation (77.8wt%). The improvement in the recovery of chromite from WHIMS nonmagnetic products and flotation tailings is achievable by regrinding and recycling the products into the respective feed streams. It has also been sug-

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gested that incorporation of a slime table and multigravity separator in the beneficiation circuit can enhance the recovery of chromite mineral [2,4].

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References

- A. Güney, G. Önal, and T. Atmaca, New aspect of chromite gravity tailings re-processing, *Miner. Eng.*, 14(2001), No. 11, p. 1527.
- [2] Y.R. Murthy, S.K. Tripathy, and C.R. Kumar, Chrome ore

beneficiation challenges & opportunities: a review, *Miner*. *Eng.*, 24(2011), p. 375.

- [3] R.B. Rao, P.S.R. Reddy, S. Prakash, and M.I. Ansari, Recovery of chromite values from chrome ore beneficiation plant tailings, *Trans. Indian Inst. Met.*, 40(1987), p. 203.
- [4] S.K. Tripathy, Y. Rama Murthy, and V. Singh, Characterisation and separation studies of Indian chromite beneficiation plant tailing, *Int. J. Miner. Process.*, 122(2013), p. 47.
- [5] K.L. Chakraborty and T.L. Chakraborty, Geological features and origin of the chromite deposits of Sukinda Valley, Orissa, India, *Miner. Deposita*, 19(1984), No. 4, p. 256.
- [6] A.K. Sen, P.K. Sharma, D. Mohanty, and T.K. Ghosh, Composition of Cr-spinel: an ore genetic indicator of Kathpal chromite deposit, Sukinda ultramafic complex, Orissa, India, *Curr. Sci.*, 88(2005), No. 10, p. 1547.
- [7] J. Garnier, C. Quantin, E. Guimarães, and T. Becquer, Can chromite weathering be a source of Cr in soils? *Mineral. Mag.*, 72(2008), No. 1, p. 49.