

# Beneficiation of Low Grade Chromite Ore and Its Characterization for the Formation of Magnesia-Chromite Refractory by Economically Viable Process

Amit Kumar Bhandary, Prithviraj Gupta, Siddhartha Mukherjee, Mahua Ghosh Chaudhuri, Rajib Dey

**Abstract**—Chromite ores are primarily used for extraction of chromium, which is an expensive metal. For low grade chromite ores (containing less than 40% Cr<sub>2</sub>O<sub>3</sub>), the chromium extraction is not usually economically viable. India possesses huge quantities of low grade chromite reserves. This deposit can be utilized after proper physical beneficiation. Magnetic separation techniques may be useful after reduction for the beneficiation of low grade chromite ore. The sample collected from the sukinda mines is characterized by XRD which shows predominant phases like maghemite, chromite, silica, magnesia and alumina. The raw ore is crushed and ground to below 75 micrometer size. The microstructure of the ore shows that the chromite grains surrounded by a silicate matrix and porosity observed the exposed side of the chromite ore. However, this ore may be utilized in refractory applications. Chromite ores contain Cr<sub>2</sub>O<sub>3</sub>, FeO, Al<sub>2</sub>O<sub>3</sub> and other oxides like Fe-Cr, Mg-Cr have a high tendency to form spinel compounds, which usually show high refractoriness. Initially, the low grade chromite ore (containing 34.8% Cr<sub>2</sub>O<sub>3</sub>) was reduced at 1200 °C for 80 minutes with 30% coke fines by weight, before being subjected to magnetic separation. The reduction by coke leads to conversion of higher state of iron oxides converted to lower state of iron oxides. The pre-reduced samples are then characterized by XRD. The magnetically inert mass was then reacted with 20% MgO by weight at 1450 °C for 2 hours. The resultant product was then tested for various refractoriness parameters like apparent porosity, slag resistance etc. The results were satisfactory, indicating that the resultant spinel compounds are suitable for refractory applications for elevated temperature processes.

**Keyword**—Apparent porosity, beneficiation, low grade chromite, refractory, spinel compounds, slag resistance.

## I. INTRODUCTION

MAG-CHROME refractories are widely used in non-ferrous metallurgical reactors, such as copper, lead and zinc refining, because of their excellent slag corrosion resistance properties under smelting conditions. The mag-chrome bricks are still used in steelmaking ladles, in argon-oxygen decarburises (AODs) and in tap-hole plugging. Cement and lime kilns are the second largest user of these refractories. Mag-chrome bricks are used in high temperature furnaces in the glass industry too. [1]

The most common compositions of commercial chromium bricks are: 100% chromite, 75% chromite and 25% magnesite,

Amit Kumar Bhandary\*, Prithviraj Gupta, Siddhartha Mukherjee, and Rajib Dey are with the Department of Metallurgical and Material Engineering, Jadavpur University, Kolkata-700032, India (\*Corresponding author; phone: +918972813900; e-mail: amitkumarbhandary@gmail.com).

Mahua Ghosh Chaudhuri is with the School of Materials Science and Nanotechnology, Jadavpur University, Kolkata-700032, India.

60% chromite and 40% magnesite, and 25% chromite and 75% magnesite. Chromite is used as a refractory due to its high melting point of 2180 °C. It shows moderate thermal expansion, the stability of its crystalline form at high temperatures and its neutral chemical behaviour. Chromite has a linear expansion of about 1.3% at 1400 °C, which is approximately 50% of that of magnesia (MgO). Therefore, when added to magnesia refractories, chromite will improve the thermal shock resistance of the refractory. Chromite has exceptionally good resistance to pyrometallurgical slags. Slags that are acidic and contain high levels of iron—in other words, are silica-rich fayalite (2FeO·SiO<sub>2</sub>)—rapidly attack and deeply penetrate alumino-silicate refractories. The resistance of chromite against fayalitic slags – which are common in many non-ferrous metallic smelting processes – is exceptional. High Cr<sub>2</sub>O<sub>3</sub> contents give rise to low wettability by fayalitic slags and a high Chromite-spinel content gives rise to low slag solubility. Magnesia imparts greater refractoriness, volume stability, and resistance to spalling [2]-[4].

Magnesia reacts with the relatively non-refractory magnesium silicates, present as gangues in chrome ores, to form forsterite and excess MgO grains leads to chrome spinel formation. This gives an extra heat-resistant product with improved load-bearing capacity. [5]

Chromite ore is the only commercial source of chromium in the metallurgical industries. It occurs as a chromium spinel, a complex mineral containing chromium, iron, aluminium and magnesium in changeable proportions depending upon the deposit. The chemical composition of chromite is FeO.Cr<sub>2</sub>O<sub>3</sub> or FeCr<sub>2</sub>O<sub>4</sub>. Chromite stoichiometrically contains 68% Cr<sub>2</sub>O<sub>3</sub> and 32% FeO with Cr:Fe ratio of about 1.8:1. The Cr<sub>2</sub>O<sub>3</sub> content is, however, diluted significantly due to the presence of gangue materials. Chromium may be replaced by aluminium and iron replaced by magnesium. [6]

Chromite can be classified on the basis of their Cr/Fe ratio. The highest-grade chromites are those having Cr/Fe ratio of more than 2 (usually approximately 2.8) and those containing a minimum of 46 to 48% Cr<sub>2</sub>O<sub>3</sub>. Chemical and refractory-grade chromites typically have Cr/Fe ratios ranging from 1.4 to 2.0. Chemical-grade (high-iron) chromite contain large amounts of iron, which often results in Cr/Fe ratios from 1.5 to 2.1, although the total amount of chromium ranges from 40-46% Cr<sub>2</sub>O<sub>3</sub>. Refractory-grade chromite contains relatively large quantities of Al<sub>2</sub>O<sub>3</sub> (> 20%) and have (Cr<sub>2</sub>O<sub>3</sub>+Al<sub>2</sub>O<sub>3</sub>) levels of more than 60% [6]. Low grade chromite ores are those having less than 40% Cr<sub>2</sub>O<sub>3</sub>.

South Africa and Zimbabwe have the major share of the chromite ore reserve of the world, followed by Kazakhstan, Turkey, Finland and India. The world-wide demand for primary chromium is expected to increase at an annual growth rate of 3.4%. Although world reserves of high-grade ores can meet this demand, these ores are found positioned at great distances from highly industrialized areas. Accordingly, huge availability of lower-grade Chromite ores, its demands increases annually as the higher-grade ores become scarce. In 2013, 26.3 million tons of Chromite was mined in the world. The largest producers were South Africa (41%), Kazakhstan (19%), India (14%), Finland (4%) and Brazil (2%) [2].

Due to gradual depletion of rich chromite ores, the need for utilizing the lower-grade ores available has assumed greater importance. Beneficiation usually begins with crushing and grinding the run of mine ore (ROM) followed by enrichment of the liberated ore by various techniques. But physical methods cannot be used to separate the Chromites from fines generated during mining, intergrowths with other materials. Upgrading to yield higher Cr/Fe ratios requires pyrometallurgical and hydrometallurgical treatment. [3]

In India, 5 MT of Chromite overburden/low grade chromite ore (< 40% Cr<sub>2</sub>O<sub>3</sub>) is generated each year in addition to the 140 MT that has already been accumulated over the several years of mining. The scenario is similar in all countries with Chromite reserves and involved in Chromite mining. Extraction of Chromium value from this huge low-grade ore poses a big challenge. Utilization of this ore in production of ferrochrome and Chromite-based refractory has attracted attention of researchers worldwide [7]-[9].

The main objectives of the present work are

- To beneficiate low grade chromite ore for the improvement of Cr/Fe ratio.
- To synthesize Chrome-mag refractory by reacting beneficiated ore with magnesia.
- To characterize the refractory by carrying out different standard tests
- To assess the suitability of the refractory for use in steel plants or other high temperature metallurgical/chemical industrial applications.

## II. MATERIALS AND METHODS

### A. Raw Materials Used

- Chromite Ore:** Low grade chromite ore samples were collected from the eastern, southern and western parts of Greenstone-granite terrain of East Indian Shield which is bounded by 21° to 25° N latitude and 85° to 88° E longitude including parts of the states of Bihar, Jharkhand, U.P., Odisha and West Bnegal with the help of Tata Steel Limited. Balasore Alloys Ltd. Balgopalpur, Balasore, Orissa, India.
- Coke Dust:** Coke fines were collected from the Coke Oven plant of Vizag Steel Plant, India.
- Molasses:** Molasses are obtained from Tata steel plant, Jamshedpur, Jharkhand, India.

- Bentonite:** Bentonite is collected from JSW Steel, toranagallu, Bellary, Karnataka, India.

### B. Experimental Setup

The chromite ore were crushed and ground to particle size of 75 microns or finer with the help of BBS standard sieves. The Fine particles (below 75 μm) chromite overburden have been characterized by XRD, SEM and XRF analysis.

#### 1. Formation of Chromite-Coke Briquettes

In the present research work, low grade chromite ore fines were homogeneously mixed with calculated weight percentage of coke fine (below 75 μm particle size) and molasses, bentonite, water as binders. After homogeneous mixing, 12.5% of that mixture was taken in a cylindrical die. The die along with the sample was placed in a hand operated hydraulic press. A pressure of 350 Kgf was applied to the die and it was kept at rest for one minute. Then, the sample was taken out in the form of cylindrical nuggets. The nuggets had an average diameter of 2.5 cm and an average height of 1 cm. Flow chart of briquettes making was shown in Fig. 1.

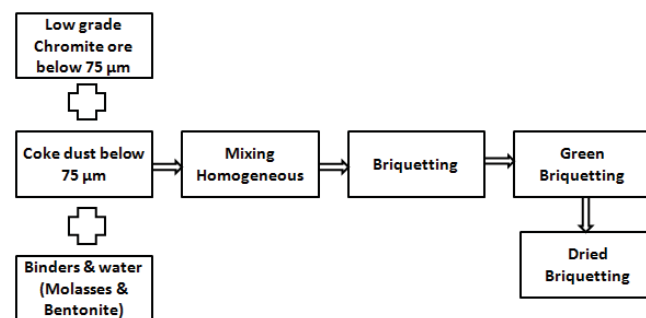


Fig. 1 Flow chart for briquettes formation

Beneficiation of the chromite ore would be done by reduction. The process involves preparation of briquettes containing chromite ore and coke fines. The briquettes would be treated in a reducing furnace at four different temperatures, each for four different time intervals. During the reduction, the higher oxidation state iron oxides are expected to reduce to lower oxidation state iron oxides that show magnetic properties. So, magnetic separation would be done after the reduction to separate the magnetic iron oxides. After reduction, the magnetic separation process was carried out with the help of a magnetic disc of strength 0.02 Tesla. The reduction process was carried out in electrically heated PID controlled tube furnace. The product of the reduced and magnetically separated samples would be characterized by SEM-EDX analysis. A firing process was carried out at 1450 °C, for 2 hours in Raising Hearth Furnace. Then, the furnace temperature was allowed to drop to room temperature before the sample being taken out to ensure a slow rate of cooling of the sample. Two sets of experiments were carried out; one without MgO addition and the other with MgO addition. The resultant product was then tested for refractoriness parameters like Apparent Porosity, Slag Resistance. For the apparent porosity and slag resistance test refractories (with MgO and

without MgO) were sintered at 1500 °C under 50 MPa pressure. Finally, the synthesized refractories were characterized by XRD and SEM-EDX analyses.

### III. RESULTS AND DISCUSSIONS

#### A. Characterization of Materials

Chromite ore was characterized by wavelength dispersive x-ray fluorescence (WDXRF; MagiX 2424, PAN analytica, SuperQ) and the result is shown in Table I. It was observed

that chromite ore contains mainly 34.82% of Cr<sub>2</sub>O<sub>3</sub> with 23.12% of Fe<sub>2</sub>O<sub>3</sub>, 13.02% of MgO and 12.31% of Al<sub>2</sub>O<sub>3</sub>.

Phase analysis was performed by X-ray diffractometers (XRD; Rigaku Ultima III) using Cu K<sub>α</sub> which is shown in Fig. 2. X-ray scene is done with the range of angle from 20° to 80° with a constant speed of 2°/min. The d-values were compared with PDF database (PCPDF-WIN software, JCPDS-International). The major phase were observed in the sample are Chromite (Fe,Mg)<sup>2+</sup>(Cr,Al,Fe)<sup>3+</sup>2O<sub>4</sub>, Clinochlore ((Mg,Fe<sup>++</sup>)5Al(Si<sub>3</sub>Al)O<sub>10</sub>(OH)<sub>8</sub>), Hematite (Fe<sub>2</sub>O<sub>3</sub>) and aluminium silicate.

TABLE I  
 WDXRF ANALYSIS OF CHROMITE ORE

Cr <sub>2</sub> O <sub>3</sub>	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	CaO	Na <sub>2</sub> O	TiO <sub>2</sub>	LOI	Total
34.82	13.02	12.31	9.96	23.12	0.26	0.27	0.06	0.28	5.9	100

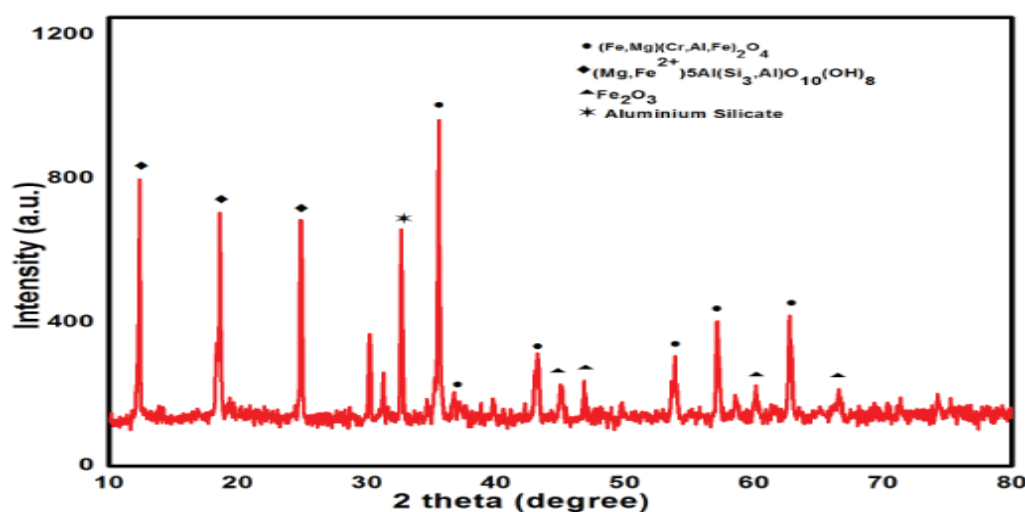


Fig. 2 XRD analysis of Chromite Ore

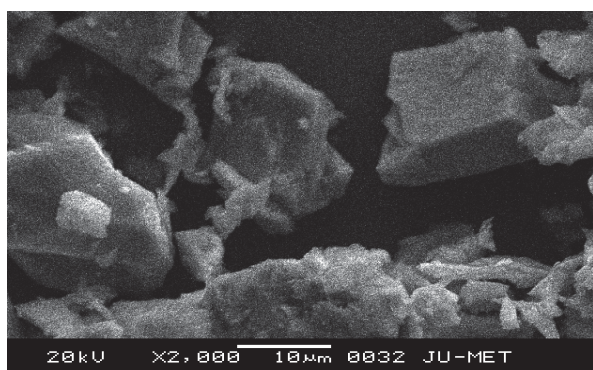


Fig. 3 SEM image of ore sample at 500X

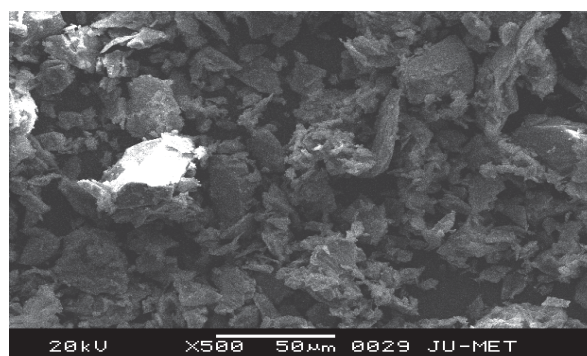


Fig. 4 SEM image of ore sample at 2000X

The surface morphology of chromite ore has been observed using a scanning electron microscope (SEM, JEOL JSM-8360) and the SEM images are shown in Figs. 3 and 4 with different resolutions. Dissimilarities in shapes and sizes are observed from the images.

Sample of the chromite ore fines was analyzed by EDX. The EDX result showed that chromium oxide was the compound present in maximum percentage along with magnesium oxide, iron oxide and aluminium oxide (Table II).

TABLE II  
 EDX RESULTS FOR THE CHROMITE ORE SAMPLE

Element	Weight%	Atomic%
O K	42.41	60.89
Mg K	16.77	15.85
Al K	4.57	3.89
Si K	9.68	7.91
Cr K	17.41	7.69
Fe K	9.16	3.77
Total	100.00	

TABLE III  
PROXIMATE ANALYSIS OF COKE DUST

Coke Dust	Fixed carbon (%)	Volatile matter (%)	Moisture (%)	Ash (%)
Composition	79.46	4.01	0.53	16

### B. Reductant

Coke fines were procured from the Coke Oven plant of Vizag Steel Plant, and its proximate analysis showed a carbon

content of 79.46%. [10] The composition of coke fine was analysed and presented in Table III.

Thermal analysis (TG/DTA; Perkin Elmer) of coke dust was done under nitrogen atmosphere from room temperature to 1000K and is shown in Fig. 5. From the curve weight loss around 79-80% was observed after 737 °C.

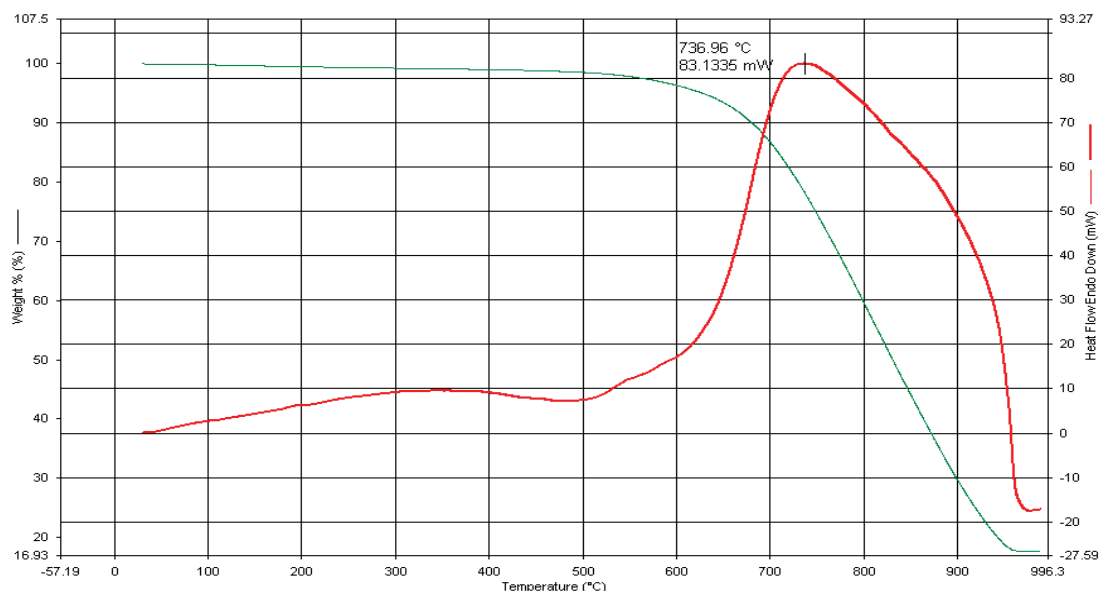
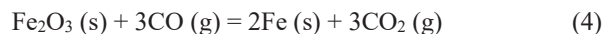
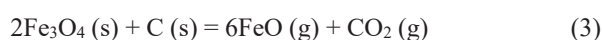
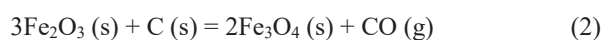
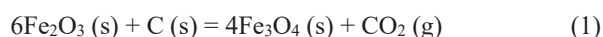


Fig. 5 TG/DTA analysis of Coke dust

### C. Reduction and Magnetic Separation for Beneficiation of Low Grade Chromite Ore

The raw chromite ore contains a lot of Fe<sub>2</sub>O<sub>3</sub> (23.1%) which has a low melting point and should negatively affect the refractoriness of the ore. So, it is essential to lower of this Fe<sub>2</sub>O<sub>3</sub> in order to increase Cr/Fe ratio, or at least reduce the detrimental effect. Cr<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, MgO and Al<sub>2</sub>O<sub>3</sub> are mainly the oxides that make up the raw material (low grade chromite ore). Ellingham diagram suggests that none of these oxides other than Fe<sub>2</sub>O<sub>3</sub> will be chemically affected in the reduction temperature range of 1100 °C to 1250 °C. [11] Hence, the reduction process is expected to improve the melting point and refractoriness of the chromite ore. The entire chromite ore is treated with coke fines at elevated temperatures (1100, 1150, 1200 and 1250 °C) so that some Fe<sub>2</sub>O<sub>3</sub> can be reduced to magnetic components like Fe<sub>3</sub>O<sub>4</sub>, FeO and Fe and is subsequently separated by magnetic separation. The probable reaction which occurred for the formation of magnetic part during reduction of chromite ore briquettes is given by (1)-(5) [12]:



Reduction fraction with respect to weight loss calculated by following manner: After the elimination of moisture, the initial weights of the nuggets were measured as W<sub>initial</sub>. After the reduction process, the nugget weights were measured as W<sub>final</sub>. Fractional decrease in mass after reduction = (W<sub>initial</sub> - W<sub>final</sub>) / W<sub>initial</sub>. Experimental results for reduction are presented in Table IV and variation in fractional decrease in mass of sample after reduction with time is shown in Fig 6.

TABLE IV  
FRACTIONAL DECREASE IN SAMPLE MASS AFTER REDUCTION

Time (min)	Temperature (°C)			
	1100	1150	1200	1250
40	0.0910	0.1020	0.1136	0.1263
80	0.1239	0.1298	0.1479	0.1507
120	0.1407	0.1439	0.1492	0.1513
160	0.1506	0.1505	0.1502	0.1505

From Fig. 6, it is evident that the mass of the sample decreases with time due to reduction of chromite ore by coke. The results show that the increase in extent of reduction beyond 1200 °C is marginal and it increases very slowly beyond 80 min. Result of the fractional separation of magnetic materials is shown in Table V and Fig. 7.

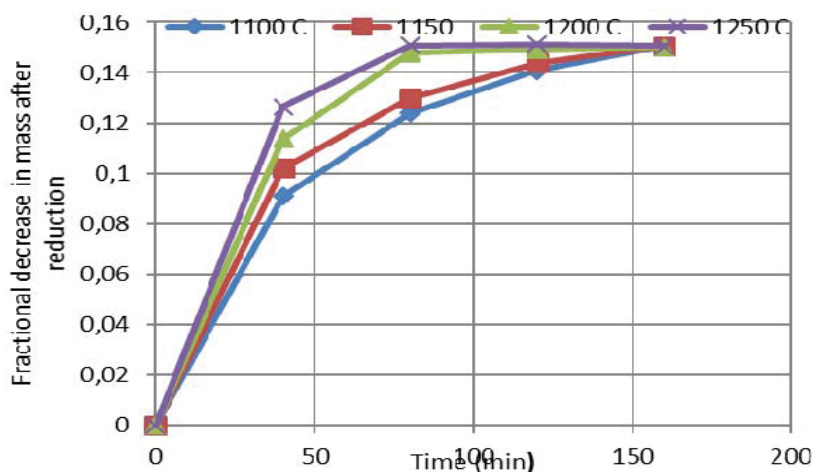


Fig. 6 Variation in Fractional Decrease in Mass of Sample after Reduction with Time

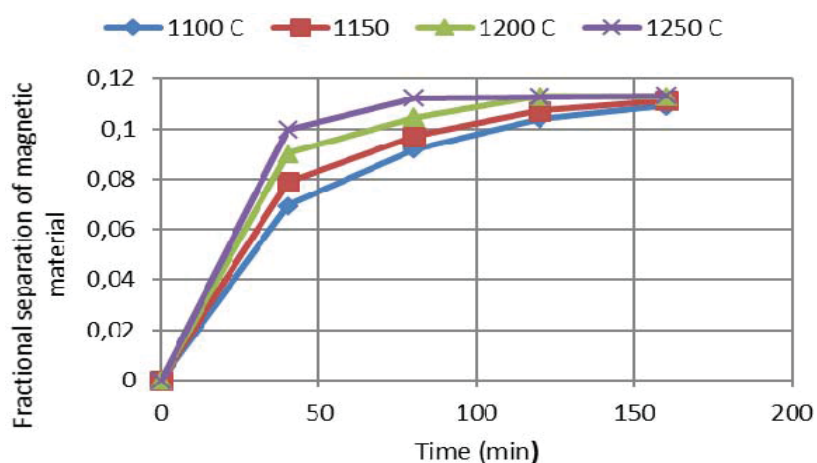


Fig. 7 Variation in Fractional Separation of Magnetic Materials in Chromite Ore with Time

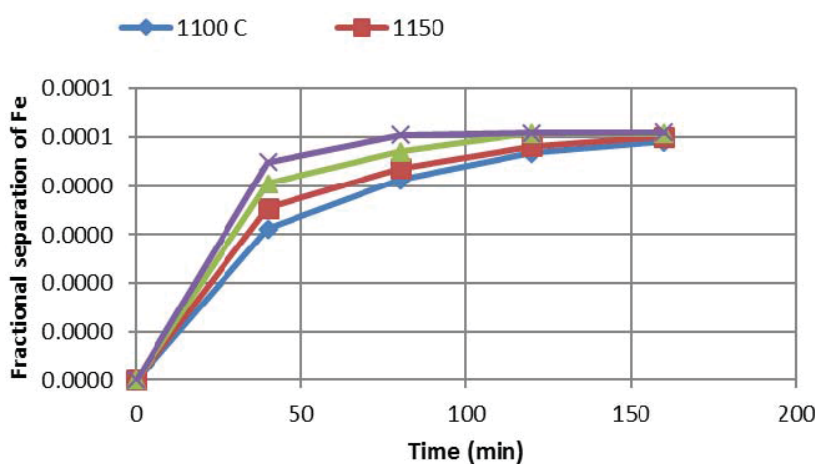


Fig. 8 Variation in Fractional Separation of Fe from Chromite Ore with Time

Stoichiometric calculations were made to calculate the amount of Fe present initially in low grade chromite ore, assuming that Fe is present as  $Fe_2O_3$ . Also, assuming that it was  $Fe_3O_4$  only that was magnetically eliminated, stoichiometric amount of Fe separated was calculated. Fractional separation of Fe is presented in Table VI and Fig 8.

Raw chromite ore contains 23.12% of  $Fe_2O_3$ . After magnetic separation 50% of Fe is separated at 1200 °C after 80 min reduction time. Hence, a reduction temperature of 1200 °C and reduction time 80 min may be chosen to be optimum reduction conditions.

TABLE V  
 FRACTIONAL SEPARATION OF MAGNETIC MATERIALS

Time (min)	Temperature (°C)	1100	1150	1200	1250
40		0.0694	0.0788	0.0901	0.0997
80		0.0918	0.0971	0.1045	0.1123
120		0.1041	0.1072	0.1129	0.1129
160		0.1091	0.1113	0.1127	0.1133

TABLE VI  
 FRACTIONAL SEPARATION OF FE

Time (min)	Temperature (°C)	1100	1150	1200	1250
0		0	0	0	0
40		0.3122	0.3546	0.4054	0.4486
80		0.4130	0.4366	0.4699	0.5050
120		0.4683	0.4821	0.5079	0.5077
160		0.4907	0.5007	0.5068	0.5096

#### D. SEM-EDX Image after Reduction of Chromite Ore

The SEM images of partially reduced samples followed by magnetic separation are presented in Figs. 9-11 which have clearly indicated that the granular grains of the sample decreased significantly with the extent of reduction at 1200 °C.

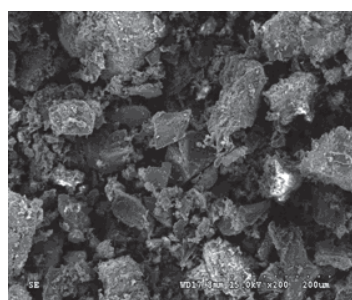


Fig. 9 After 40 min - 200X

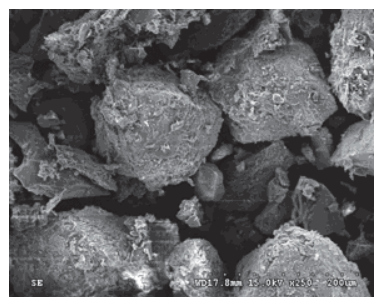


Fig. 10 After 80 min - 200X

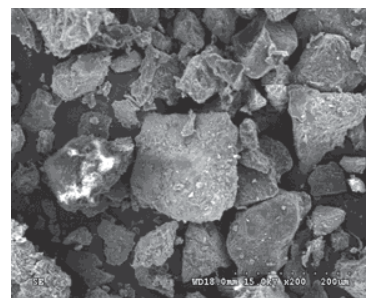


Fig. 11 After 120 min - 200X

#### E. Characterization of Mag-Chrome Refractory

The beneficiated chromite ore and MgO (composition; 99.1% MgO, 0.8% CaO and 0.1% Na<sub>2</sub>O) was charged in Raising Hearth Furnace at 1450 °C for 2 hours for the preparation of mag-chrome. Another similar experiment was carried out without the MgO. The mag chrome containing refractory was characterized by XRD, SEM and EDX analysis. The XRD analysis of both refractories show (Fig. 12) peaks of magnesium chromium oxide but in case of refractory with MgO the intensity of peaks is high. A significant intensity peak of MgO is also observed in case of mag-chrome prepared by chromite ore with MgO.

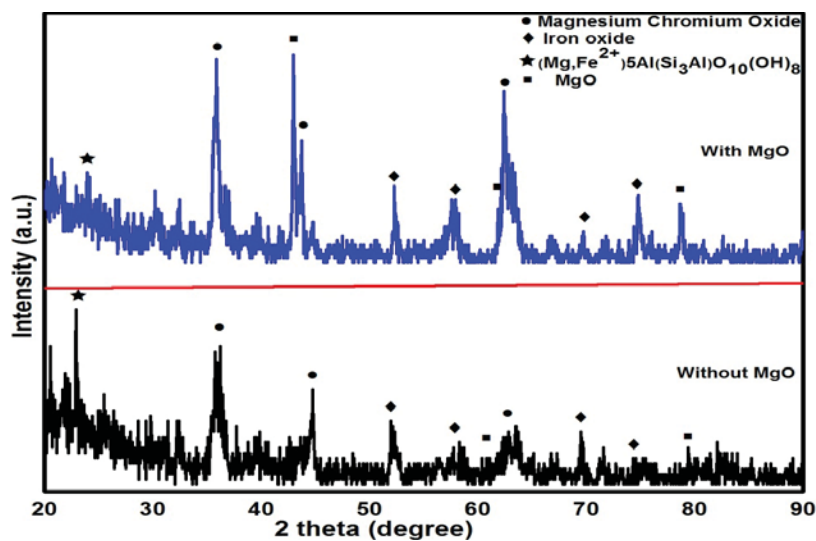


Fig. 12 XRD Analysis of Mag-Chrome Refractory with and without Additional MgO

The SEM image in Fig. 13 suggests that there was proper fusing of MgO in beneficiated chromite ore. Proper fusing of MgO is essential for good refractoriness. [13]

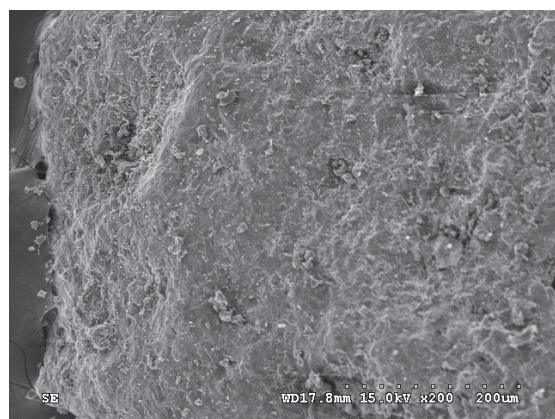


Fig. 13 SEM Image of Mag-Chrome Refractory with Additional MgO

TABLE VII  
EDX RESULT OF MAG--CHROME REFRACTORY WITH ADDITIONAL MgO

Element Line	Weight %	Weight % Error	Atom %	Atom % Error
C K	0.18	+/- 0.07	0.34	+/- 0.14
O K	35.16	+/- 0.36	50.86	+/- 0.53
Mg K	31.41	+/- 0.29	29.91	+/- 0.27
Al K	0.65	+/- 0.11	0.56	+/- 0.10
Si K	14.13	+/- 0.18	11.64	+/- 0.15
Si L	---	---	---	---
Ca K	0.59	+/- 0.10	0.34	+/- 0.06
Ca L	---	---	---	---
Cr K	5.10	+/- 0.47	2.27	+/- 0.21
Cr L	---	---	---	---
Mn K	0.01	+/- 0.39	0.01	+/- 0.16
Mn L	---	---	---	---
Fe K	5.41	+/- 0.71	2.24	+/- 0.29
Fe L	---	---	---	---
Zr L	6.40	+/- 0.53	1.62	+/- 0.13
Zr M	---	---	---	---
Pd L	0.96	+/- 0.27	0.21	+/- 0.06
Pd M	---	---	---	---
Total	100.00		100.00	

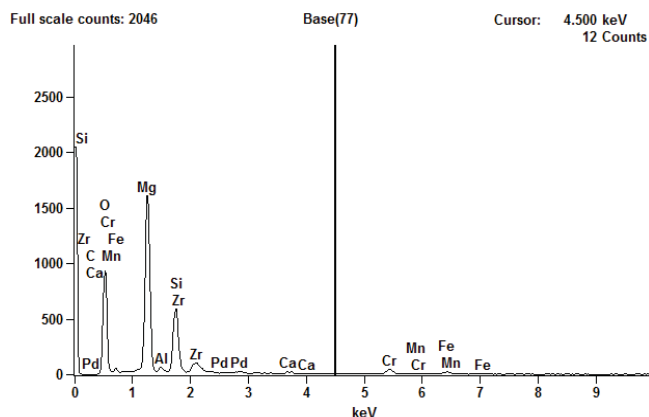


Fig. 14 EDX analysis of mag-chrome refractory with additional MgO

The high amount of Mg shown by the EDX results (Table VII & Fig. 14) suggests proper synthesis of an effective refractory. The low content of Fe shown by the EDX results indicates successful beneficiation of the chromite ore.

A direct bonding between MgO crystals and chromite grains is developed during firing which is exhibited by the XRD analysis. By fusing the chromite and magnesia, the chromite spinel is completely stabilised and is completely dispersed as small spinel crystals throughout the magnesia.

#### F. Apparent Porosity Results

The beneficiate chromite ore and MgO having composition; 99.1% MgO, 0.8% CaO and 0.1% Na<sub>2</sub>O refractory product was charged in Raising Hearth Furnace at 1450 °C for 2 hours for the preparation of mag-chrome. The refractory product was sintered at 1500 °C under 50 MPa pressure and calculate apparent porosity. Initial mass of the refractory was measured as W<sub>A</sub>. Then, it was suspended in water its mass was measured as W<sub>B</sub>. Then, the refractory was immersed in water for 2 hours, so that air in the pores is replaced by water. Its weight is then taken and recorded as W<sub>C</sub>. Apparent porosity (%) = [(W<sub>C</sub>-W<sub>A</sub>)/(W<sub>C</sub>-W<sub>B</sub>)\*100. Hence, the apparent porosity for refractory formed without additional MgO was calculated to be 17.84%, whereas the apparent porosity for the refractory formed with additional MgO was calculated to be 14.09%. Results are shown in Tables VIII and IX.

TABLE VIII  
APPARENT POROSITY TEST RESULTS FOR REFRACTORY FORMED WITHOUT ADDITIONAL MGO

W <sub>A</sub> (grams)	W <sub>B</sub> (grams)	W <sub>C</sub> (grams)	Apparent Porosity (%)
38.17	30.57	39.82	17.84

TABLE IX  
APPARENT POROSITY TEST RESULTS FOR REFRACTORY FORMED WITH ADDITIONAL MGO

W <sub>A</sub> (grams)	W <sub>B</sub> (grams)	W <sub>C</sub> (grams)	Apparent Porosity (%)
36.42	29.33	37.58	14.09

Apparent porosity denotes the fraction of total volume occupied by open pores in a solid. More the volume of open pores, more the solid will be susceptible to corrosion or slag attack. [14] In this test, it was found that the refractory formed by the addition of external MgO has lesser porosity than the refractory formed without addition of external MgO. Hence, it is expected to be more resistant to corrosion and slag attack, and is thus likely to serve better in high temperature applications.

#### G. Slag Resistance Test Results

The refractories were sintered at 1500 °C under 50 MPa pressure. The initial weight was taken. Then, it was immersed in liquid slag bath at 1600 °C. The composition of the slag is given in Table X. The slag had a basicity of 2.7.

TABLE X  
COMPOSITION OF SLAG USED IN SLAG RESISTANCE TEST

Constituent	CaO	SiO <sub>2</sub>	FeO	MgO	Al <sub>2</sub> O <sub>3</sub>	MnO	P <sub>2</sub> O <sub>5</sub>	Metallic Fe	Total
Composition (weight percent)	49.22	18.15	18.92	5.18	2.28	3.96	0.63	1.66	100

TABLE XI  
SLAG RESISTANCE TEST RESULTS FOR REFRACTORY PREPARED WITHOUT ADDITIONAL MgO

Time (min)	Initial weight (g)	Final weight (g)	Loss in weight (g)	Loss in weight (%)
30	40.73	31.70	9.03	22.17
60	40.73	23.11	17.62	43.26
90	40.73	16.15	24.58	60.35

TABLE XII  
SLAG RESISTANCE TEST RESULTS FOR REFRACTORY PREPARED WITH ADDITIONAL MgO

Time (min)	Initial weight (g)	Final weight (g)	Loss in weight (g)	Loss in weight (%)
30	42.71	37.87	4.84	11.33
60	42.71	34.09	8.62	20.18
90	42.71	30.48	12.23	28.63

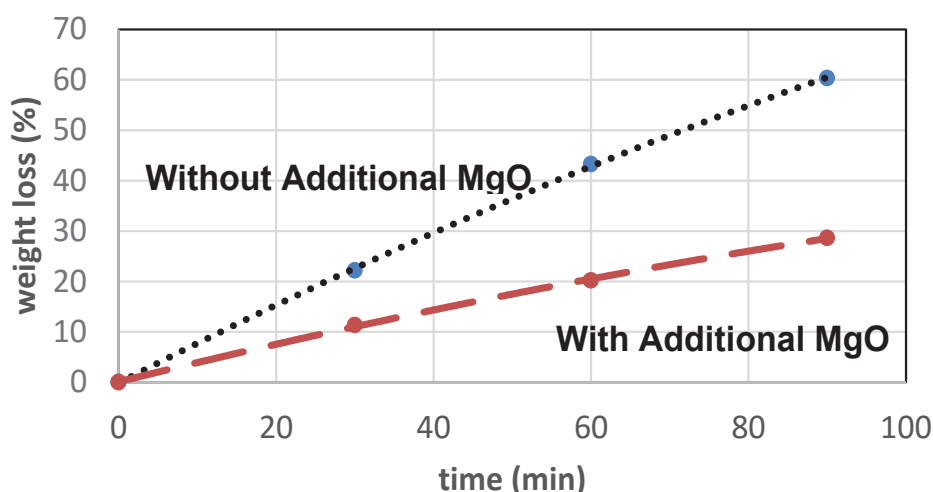


Fig. 15 Weight Loss Comparison for Mag-Chrome Refractories – Slag Resistance Test

From Tables XI, XII, Fig. 15 has been plotted which shows the comparison of the two refractories, in terms of weight loss vs. time variation, as observed in the slag resistance test. The line on top and with a greater slope corresponds to that of the refractory prepared without the addition of external MgO. It is clearly evident that refractory prepared with the addition of external MgO suffers lesser erosion due to enhanced spinel formation and is thus more suited to high temperature applications [15]

During firing, Fe<sub>2</sub>O<sub>3</sub> diffuses at high temperature into MgO forming magnesio-ferrite, a refractory spinel. Magnesia added to chrome ores tends to replace FeO in the spinel structure. It also combines with the Fe<sub>2</sub>O<sub>3</sub> in a stable solid solution. The Chromite is “stabilised”, thereby reducing the risk of undergoing subsequent redox reactions. Magnesia combines with the relatively non-refractory magnesium silicates, present as impurities in chrome ores, to form forsterite in the bonding mass surrounding the grains of chrome spinel. This gives a more heat-resistant product with better load-bearing capacity. [16], [17]

#### IV. CONCLUSIONS

Following conclusions have been drawn from the above investigations:

1. A technique has been established to beneficiate low-grade chromite ore by reduction and magnetic separation

process. The higher oxidation state iron oxides were found to be reduced to lower oxidation state iron oxides (Fe<sub>3</sub>O<sub>4</sub>) that show magnetic properties. These magnetic oxides were separated magnetically leading to high Cr/Fe ratio.

2. The effect of time and reduction temperature was studied on the degree of reduction. It was observed that the reduction is very fast initially and the rate decreased with time. By 150 min, the reduction almost ceases. The rate of reduction increased with temperature. However, beyond 1200 °C, the enhancement rate is marginal.
3. Mag chrome containing refractory was successfully been made from low grade chromite ore. Presence of fused magnesium-chrome oxide was confirmed by XRD analysis for both refractories, prepared with and without the external addition of MgO while firing. However, refractory prepared with the additional MgO exhibited higher intensity peaks of mag-chrome oxides, indicating its presence in greater amount.
4. Apparent porosity and slag resistance tests showed that the synthesized refractory possessed satisfactory properties, even though the refractory prepared with additional MgO while firing showed better results than the one prepared without additional MgO.



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