

# Chrome Ores on Ferrochrome Smelting

Xiaowei. Pan

**Abstract**—Chrome ores from six locations across the Bushveld Igneous Complex in South Africa are used to investigate the effects of ore types on the smelting processes, such as the consumption of fluxes, reductant; and most importantly, the consumption of electricity.

The electric energy consumption is highly related to the SiO<sub>2</sub> content of chrome ores. The lowest electric consumption of 3.31 MWh/t is required when the SiO<sub>2</sub>% of chrome ores is 6%. Considering the fact that the other contents do not change much in the selected 6 lumpy ores, an increase of SiO<sub>2</sub> will decrease the contents of Cr and Fe oxides in the ores. As a result, it requires more ore and less quartzite to feed in the furnace. With the combined effect of more ores and less quartzite, the smelting process produces more slag and requires more electric energy to heat and melt the slag.

**Keywords**—ferrochrome production, ferroalloy process optimization, chrome ore

## I. INTRODUCTION

High carbon ferrochrome (HCFerCr) is produced by carbothermic reduction of chrome ore. Electric power is generally used to supply the energy required to carry out the heating, melting and reduction reactions. The production process is energy intensive, and consumes approximately 3,300-3,800 kWh per ton of metal produced. The cost of electricity counts for about 35-40% of total production cost. Due to the shortage of power supply in South Africa, the cost of electricity has more than doubled since 2008, and a plan has been tabled to increase the electricity price by 16% every year from 2013 to 2018. South Africa, with 80% of world chrome or reserves, is one of the major producers of ferrochrome, and its production accounts for about 34% of the total production in the world.

With a sharp increase in electricity cost, all ferrochrome producers in South Africa are looking for any alternatives that can use less electricity. An investigation of the effect of various chrome ores on the electric energy consumption is, no doubt, one of the alternatives under consideration. The selected chrome lumpy ores contains mainly Cr<sub>2</sub>O<sub>3</sub>, FeO, SiO<sub>2</sub>, MgO, Al<sub>2</sub>O<sub>3</sub> and small amount of CaO. The contents of MgO, Al<sub>2</sub>O<sub>3</sub> and CaO have small changes in the selected chrome ores, particularly CaO with a range of only 1-2%. The major changes of the chrome ores appear in the contents of SiO<sub>2</sub>, Cr<sub>2</sub>O<sub>3</sub> and FeO.

Xiaowei. Pan is with the Department of Metallurgy, University of Johannesburg, PO Box 17011 Doornfontein, 2028 Johannesburg, South Africa, phone: +27 11 559 6371; fax: +27 11 559 6194 ; e-mail: xpan@uj.ac.za

Chrome ores produced in South Africa are mainly from the mines that operate in the Bushveld Igneous Complex. The Bushveld Complex contains a series of overlapping funnel shaped intrusions oriented from Doornvlei of North West Province to Steelpoort of Mpumalanga Province [1], covering an area of 180, 000 km<sup>2</sup>, see Fig. 1.

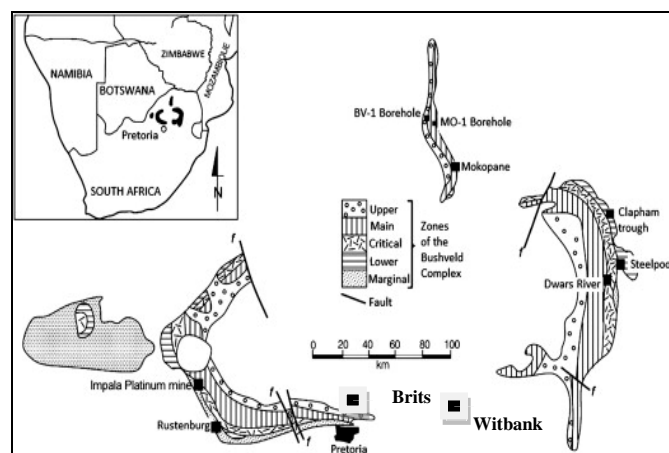


Fig. 1 Stratigraphy of Bushveld Igneous Complex in South Africa, oriented from Doornvlei of North West Province to Steelpoort of Mpumalanga Province, covering an area of 180, 000 km

Most ferrochrome producers have its own mining and smelting operations and are located near the Bushveld Complex, in Rustenburg, Brits, Witbank, Lydensberg, and Steelpoort. Those producers include Xstrata, Samancorcr, Hercul, SAS Metals, Assmang Chrome, Mogale Alloys.

## II. SOUTH AFRICA CHROME ORES

Chrome ores are selected from the following mining locations, which are located along the Bushveld Igneous Complex:

- Elandsdrift
- Millsell
- Mooinooi
- Tweefontein
- Lannex
- Steelpoort

UG2 concentrate from a PGM mine in Rustenburg is also selected. Each mine produces 3 grades of chrome ore, namely lumps, chips, and concentrates. The lumps and chips of chrome ores are used as raw material and are directly fed in submerged arc furnace, while the concentrates of chrome ore

must undergo agglomerating treatment, such as sintering or pelletizing. Due to the advantages of DC furnace process, chrome concentrates are fed in DC furnace directly without any agglomerating treatment. Considering the feature of chrome ore usage, the effect of concentrate ores on the production of ferrochrome will be conducted separately. From Table I, it is noticed that the difference in chemical composition between the lumpy ores and chip ores is limited, to such extent that it is worth to focus on lumpy ores only in the current phase of the investigation.

TABLE I  
CHEMICAL COMPOSITION OF CHROME LUMPY ORES PRODUCED IN SOUTH AFRICA (WT %)

Chrome ores	Cr2O3	MgO	FeO	SiO2	Al2O3	CaO	H2O
Elandsdrift lumps	39.59	10.49	23.51	7.9	14.24	1.13	3
Elandsdrift Chips	38.35	10.96	22.92	9.43	14.11	1.72	3
Millsell Lumpy	38.26	12.25	22.67	11.33	13.11	1.12	3
Millsell Chips	37.23	12.84	22.11	11.47	13.26	0.84	3
Mooinooi Lumps	39.51	10.65	23.45	8.32	14.49	1.08	3
Mooinooi Chips	39.61	10.77	23.54	8.16	13.86	1.04	3
Tweefontein Lumps	30	13.9	19.5	19.3	12.1	1.5	3
Tweefontein Chips	37.6	11.7	22.2	10.1	13.7	0.83	3
Lannex Lumps	40.9	10.9	23.9	5.8	14.3	0.74	3
Lannex Chips	37.5	12.2	22.6	9.5	13.4	0.9	3
Steelpoort Lumps	42.9	11.8	23.7	3.7	13.8	0.69	3
Steelpoort Chips	29.2	17.1	18.4	19.9	10.2	1.9	3

(SAF), which uses electric energy and is fed with raw materials of chrome ores, fluxes, reductant and electrode paste. The Ferrochrome Simulation is developed using the principles of mass balance and heat balance, the interface can be seen in Fig. 2. The simulation requires three inputs and generates the results of charge recipe, mass and composition for slag, metal, and off gas, with the energy consumption associated with the production process.

Ferroalloy Simulation Inputs:

- Chemical composition of chrome ores (%)
- Chemical composition of reductant (%)
  - Coke

- Anthracite
- Coal
- Chemical composition of fluxes (%)
  - Quartzite
  - Lime
  - Dolomite

Ferroalloy Simulation Outputs:

- Charge recipe (chrome ore/fluxes/reductant)
- Mass and composition of slag
- Mass and composition of metal
- Mass and composition of off gas (with or without CO combustion)
- Electric energy consumption
- Recovery rate of Cr, Fe

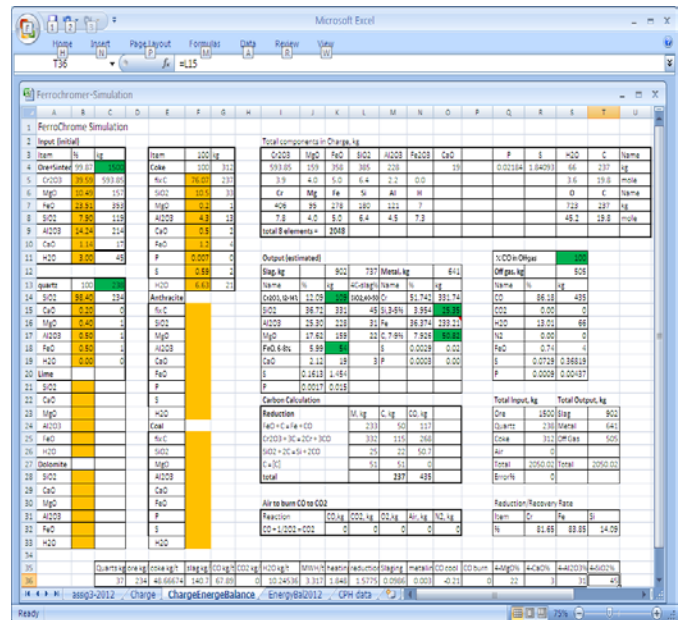


Fig. 2 Ferroalloy simulation used to calculate charge and electricity consumption of ferrochrome production in a submerged arc furnace

Lumpy chrome ores from six different locations of the Bushveld Igneous Complex are used. Quartzite is added as flux, and coke is used as reductant. The chemical composition of quartzite and coke are listed in Table II. Based on the production of ferrochrome in South Africa, the following conditions are used as major smelting parameters:

- 6% FeO in slag
- 12% Cr2O3 in slag
- 45% SiO2 in the 3-component slag of SiO2-MgO-Al2O3
- 8% carbon in metal
- 4% silicon in metal
- Slag temperature 1700 °C
- Metal temperature 1600 °C

TABLE II  
COMPOSITION OF FLUX QUARTZITE AND  
REDUCTANT COKE (WT %)

Name	Coke Nuts (Newcastle)	Delmas Quartzite (Chert lumpy)
Fixed Carbon	76.07	0
H <sub>2</sub> O	6.63	0
S	0.59	0
FeO	1.2	0.5
SiO <sub>2</sub>	10.5	98.4
CaO	0.5	0.2
MgO	0.2	0.4
Al <sub>2</sub> O <sub>3</sub>	4.3	0.5

#### IV. RESULT AND DISCUSSION

##### A. Smelting Parameters

The main parameters, used to produce high carbon ferrochrome in a submerged arc furnace, are selected and listed in Table III, including raw material consumption, energy consumption, mass of metal, slag and offgas. They are expressed in terms of kilogram per ton of produced metal (kg/t):

- Ore consumption, ore-kg/t
- Flux, quartzite consumption, quartzite-kg/t
- Reductant, coke consumption, coke-kg/t
- Electric energy consumption, MWh/t
- Metal produced, t
- Slag produced, slag-kg/t
- Offgas produced, offgas-kg/t

TABLE III  
MAJOR SMELTING PARAMETERS USED TO  
PRODUCE ONE TON OF HCF<sub>e</sub>Cr IN SAF USING  
DIFFERENT SA CHROME LUMP ORES

##### B. Composition of SA Chrome Lumpy Ores

The selected chrome lumpy ores contains mainly Cr<sub>2</sub>O<sub>3</sub>, FeO, SiO<sub>2</sub>, MgO, Al<sub>2</sub>O<sub>3</sub> and small amount of CaO. The range

ore names	ore kg/t	quartzite kg/t	coke kg/t	slag kg/t	CO kg/t	MWH/t
Steelport	2202.02	455.73	490.86	1350.10	684.61	3.33
Lannex	2265.62	413.24	488.43	1369.81	680.29	3.31
Elandsdrift	2338.73	371.27	486.67	1405.82	678.95	3.32
Mooiwooi	2339.57	372.90	487.49	1423.85	678.63	3.33
Millsell	2460.79	338.00	489.06	1563.55	679.01	3.41
Tweefontein	3196.63	164.69	483.11	2017.23	670.50	3.63

of chemical composition is 29-43% of Cr<sub>2</sub>O<sub>3</sub>, 20-24% of FeO, 4-20% of SiO<sub>2</sub>, 11-17% of MgO, 10-14% of Al<sub>2</sub>O<sub>3</sub>, 1-2% of CaO, see in Fig. 3.

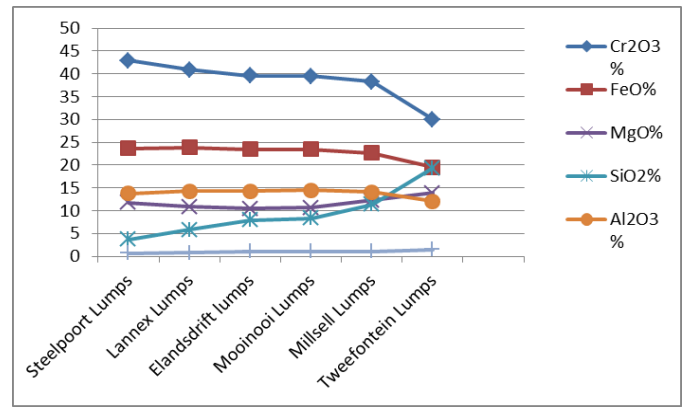


Fig. 3 Chemical Composition of Chrome Lumpy Ores of South Africa, with main contents of Cr<sub>2</sub>O<sub>3</sub>, FeO, SiO<sub>2</sub>, MgO, Al<sub>2</sub>O<sub>3</sub>, and 1-2% of CaO.

The contents of MgO, Al<sub>2</sub>O<sub>3</sub> and CaO have small changes in all selected chrome ores, particularly CaO with a range of only 1-2%. The major changes of the chrome ores appear in the contents of SiO<sub>2</sub>, Cr<sub>2</sub>O<sub>3</sub> and FeO. The content of SiO<sub>2</sub>% increases from 4% of Steelport ore to 19% of Tweefontein ore, and the contents of Cr<sub>2</sub>O<sub>3</sub>%, FeO% decreases from 43 to 38, and 24 to 23 respectively, as shown in Fig. 4. The total content of Cr<sub>2</sub>O<sub>3</sub> and FeO decreases from 67% to 50%, from Steelport ore to Tweefontein ore.

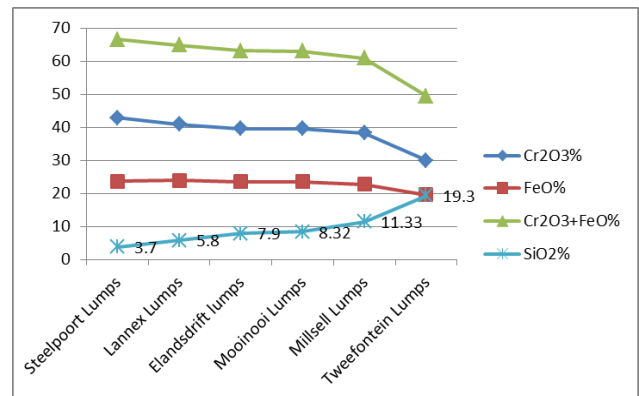


Fig. 4 Chemical composition of chrome lumpy ores, with increase of SiO<sub>2</sub>% and decrease of Cr and Fe oxides from Steelport ore to Tweefontein ore

##### C. Raw Material Consumption

The consumption of ores, flux quartzite, reductant coke, and the produced mass of slag and CO gas are shown in Fig. 5, with left axis in terms of kg per ton of metal (kg/t). The electric energy consumption is also shown the same figure with right axis in mega watt hour per ton of metal (MWh/t).

When producing one ton of high carbon ferrochrome in SAF, the Tweefontein lump ore has the highest ore consumption at 3200 kg/t, 22% and more than 30% higher than the consumption of Millsell and other ores. At the same time, the Tweefontein lump ore requires the lowest quartzite consumption at 160 kg/t. It is 205%-225% lower than the quartzite consumption comparing the ores of Millsell,

Elandsdrift, and Mooinooi, and it is 277%-251% lower when comparing the ore of Steelpoort and Lannex, see in Fig. 6.

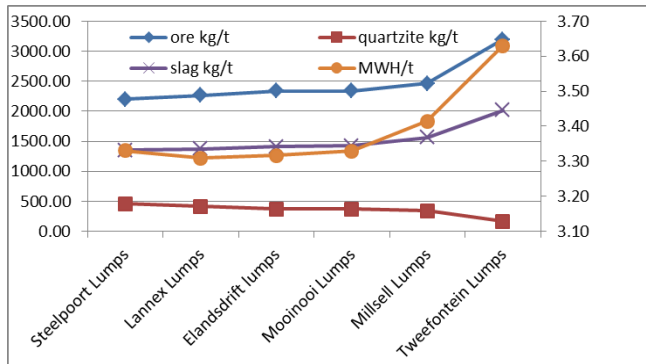


Fig. 5 Raw material consumption, when producing one ton of high carbon ferrochrome using different chrome lumpy ores of South Africa, with left axis for kg/t, and right axis for MWh/t

With the combination of high ore consumption and low quartzite consumptions when using lump ore from Tweefontein, the production process generates the most slag, about 2000 kg/t. it is 22% more than that of Millsell ore, and 29-33% more than the others.

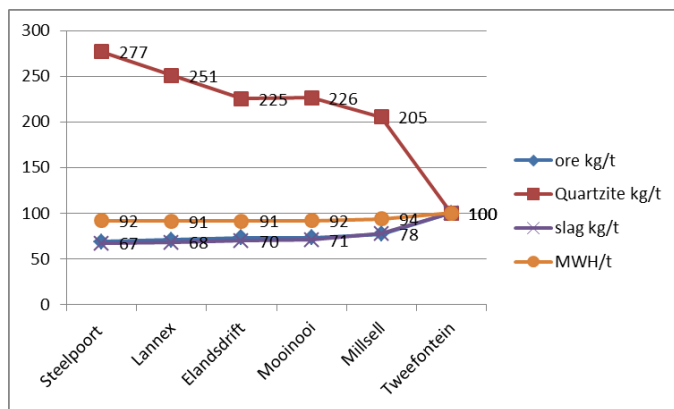


Fig. 6 Consumption of ore, quartzite, energy and production of slag when producing one ton of high carbon ferrochrome, compared with Tweefontein chrome lump ore

#### D. Electric Energy Consumption

The electric energy consumption ranges from 3.31 to 3.63 MWh per ton metal produced (MWh/t), when using the selected 6 different chrome lumpy ores. Tweefontein lumpy chrome ore requires the highest electric energy, with amount 3.63 MWh/t, as shown in Fig. 7. Millsell lumpy ore requires the second highest energy at 3.41 MWh/t, and the rest of 4 chrome ores consumes similar amount electric energy from 3.31 to 3.33 MWh/t.

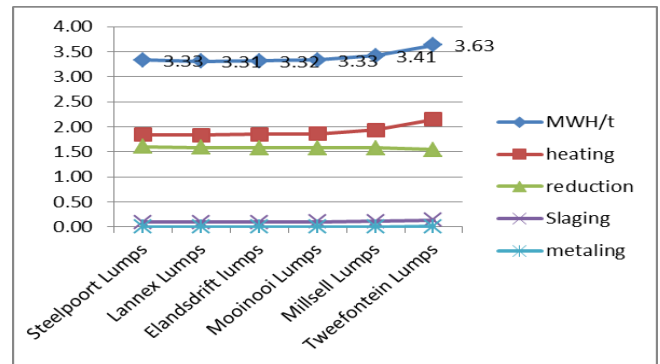


Fig. 7 Electric energy used for heating, reduction of oxides and forming of molten slag and metal, when using different chrome lumpy ores produced in South Africa

The total consumption of electric energy can be broken into 3 different categories, namely heating, reduction of oxides, forming molten slag and metal, considering the cooling of the off gas from reduction temperature 1700 °C to the roof temperature 800 °C before exiting the submerged arc furnace.

Among the three categories, heating and reduction require the most electric energy, about 97% of the total electric energy. The energy used for heating and reduction counts for 52% and 45% respectively. Only about 3% of the electric energy is used to forming molten slag and metal, see **Figure 8**.

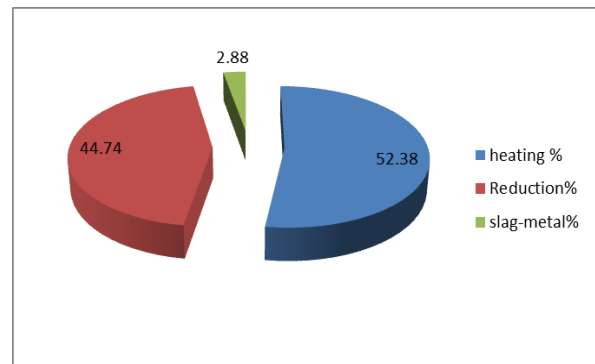


Fig. 8 Total electric energy consumption of 3.32 MWh/t, 52% used for heating, 45% for reduction of oxides and only 3% for forming of molten slag and metal

The electric energy consumption is highly related to the SiO<sub>2</sub> content of chrome ores, ranging from 4 to 20%. The lowest electric consumption of 3.31 MWh is required to produce one ton of high carbon ferrochrome, when the SiO<sub>2</sub> content of chrome ore is about 6%. When the SiO<sub>2</sub> content increases from 6% to 19%, the electric energy consumption increases from 3.31 to 3.63 MWh/t, see in Fig. 9. Furthermore, based on the limited data, it seems that the energy consumption increases from 3.31 to 3.33 MWh/t, when SiO<sub>2</sub> content decreases from 6% to 4%. The electric energy consumption with the SiO<sub>2</sub> content in the selected six chrome lumpy ores can be seen in Fig. 10.

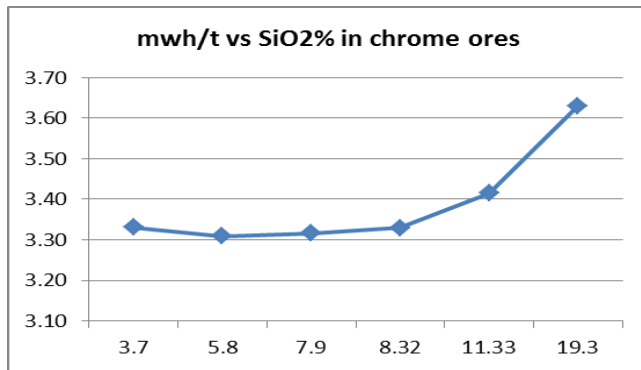


Fig. 9 Electric energy consumption with SiO<sub>2</sub> content in the SA chrome ores, the lowest energy consumption of 3.31 MWh/t when ore contains 6% of SiO<sub>2</sub>

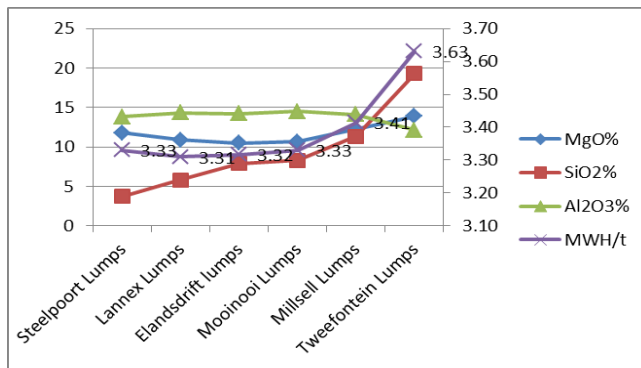


Fig. 10 Electric energy consumption versus SiO<sub>2</sub> content of chrome lumpy ores, with the lowest energy consumption required when SiO<sub>2</sub> is at 6% of Lannex chrome ore

The chemical composition of ores is one of the main factors that result in different consumption of electric energy. Less amount of quartzite is required when a chrome ore has higher SiO<sub>2</sub>, and more ore is required when the ore contains less Cr and Fe oxides. With the combination of higher SiO<sub>2</sub> and lower contents of Cr<sub>2</sub>O<sub>3</sub> and FeO, more tonnage of ore and less tonnage of quartzite are needed to feed into the submerged arc furnace. The net combined effect results in a higher slag mass, and consequently a higher electric energy is required to heat and melt the slag, see in Fig. 11. The similar results have been reported in various investigation [2-6].

Electric consumption of 3300-3400 kWh is reported [2] to produce one ton of high carbon ferrochrome using submerged arc furnace in India. The raw materials include chrome ore with 50% of Cr<sub>2</sub>O<sub>3</sub>, quartzite of 98% SiO<sub>2</sub>, and coke with 80% fixed carbon.

Another investigation reported that the electric energy consumption is highly linked to the content of Cr<sub>2</sub>O<sub>3</sub> of the Iranian chrome ores [3]. When the Cr<sub>2</sub>O<sub>3</sub> content is between 43 to 46%, the production can achieve 95% Cr recovery with the lowest consumption of electric energy. Their investigation was based on actual experiences obtained from Fayab Ferroalloy Plant over a period of three years. Other similar investigations have been conducted on the effects of chrome ores on the production of ferrochrome [4-6].

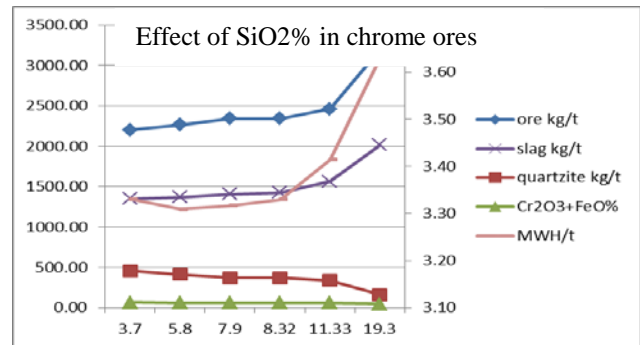


Fig. 11 Effect of SiO<sub>2</sub> in chrome lumpy ores, with a combination of more ores and less quartzite, which results in a higher slag mass, and consequently a higher electric energy required to heat and melt the slag

## V.CONCLUSION

Chrome lumpy ores are selected from 6 different locations across the Bushveld Igneous Complex, from Rustenburg on the north-west side, to Steelpoort on the South-East side of the complex.

The electric energy consumption is highly related to the SiO<sub>2</sub> content of chrome ores, ranging from 4 to 20%. The lowest electric consumption of 3.31 MWh is required to produce one ton of high carbon ferrochrome, when the SiO<sub>2</sub> of chrome ore is 6%. The required electric energy consumption increases when SiO<sub>2</sub> content increases from 6% to 19% in the ores. Furthermore the energy consumption increases, when SiO<sub>2</sub> content decreases from 6% to 4%.

The current investigation is mainly focused on the effect of ore compositions on the electric energy consumption. The effects of other factors will be carried out separately.

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