

# Laboratory Investigations of the Electrical Resistivity of Cokes and Smelting Charge for Optimizing Operation in Large Ferrochrome Furnaces

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**Abstract** - The main consumer of ferrochrome is stainless steel production. Stainless steel must maintain a reasonable price against other competitive materials. Therefore, the ferrochrome price must be low enough and profitable for the producers of stainless steel.

The investment and operational costs of ferrochrome production are greatly dependent on the availability of the process and the production rate. Thus the furnace size and production rate in submerged electric arc furnaces will be greatly increased in the near future.

The ferrochrome production per furnace, *e.g.* at Outokumpu's Tornio Works, increased from 30 000 t/a to 165 000 t/a in about 35 years. The same trend will continue globally but now much more quickly. The Outokumpu ferrochrome process at Tornio Works uses sintered chromite pellets and upgraded lumpy ore as a chromite source. Metallurgical coke is used as a reductant.

Reliable smelting in a large furnace demands the correct charge composition and well-known characteristics of the charge components. The quality and electrical conductivity of cokes (normally used) has the most important role for the electrical conductivity of the smelting charge.

The results of the measured electrical conductivity of different cokes and the smelting charge with many controlling factors are presented here. These measurements were performed over the years for our own purposes at the laboratory of Outokumpu Research Oy (ORC), in Pori, Finland.

## INTRODUCTION

The electrical resistance of the ferrochrome smelting charge is a very important factor because it makes a significant contribution to the overall resistance in a submerged electric arc furnace.

The main factors controlling the resistance of the smelting charge are the quality and amount of reductant. The smelting charge also consists of lumpy ore, sintered pellets and fluxes.

Large furnaces *e.g.* with large electrode diameters and with longer electrodes, longer bush bars and cables, are associated with a higher reactance compared to

small furnaces. Therefore especially large furnaces must be operated at as high furnace resistance as possible, *i.e.* with a high charge resistance for achieving the optimum power.

Therefore, a better knowledge of the influence of the charge composition on its resistance is important for the successful operation and design of a furnace.

The quality of cokes were analysed and the influence of the different factors on the resistance of the charge was measured at ORC.

The test results give the basis for the selection of reductant and show the significance of the various factors affecting the resistance of the charge mainly in solid state.

### CHARACTERISTICS OF COKES

The quality of cokes depends on the quality of coal and used coking process. The characterization of cokes was done according to the international standards and our scrutiny laboratory methods.

The selected cokes for investigation were as follows:

- Metallurgical coke, used at the Tornio Works
- Char coke (SA)
- Gas coke (SA)

#### Chemical analysis of cokes

The chemical analysis of cokes is presented in Table I.

**Table I:** Chemical analysis of cokes (all numbers in %)

Coke	$C_{fix}$	$S$	$P$	Ash	Vol. <sup>1</sup>	$F$	$Cl$	$Zn$
Metallurgical Coke	87.9	0.32	0.031	10.2	1.6	0.007	0.022	0.004
Char Coke (SA)	70.4	0.59	0.020	19.9	9.1	0.004	< 0.01	0.004
Gas Coke (SA)	73.2	0.49	0.019	19.4	6.9	0.005	< 0.01	0.003

	$SiO_2$	$Al_2O_3$	$Fe_2O_3$	$CaO$	$MgO$	$Na_2O$	$K_2O$
Metallurgical Coke	5.4	3.1	0.61	0.23	0.10	0.08	0.11
Char Coke (SA)	10.0	6.1	0.60	0.85	0.14	0.02	0.12
Gas Coke (SA)	9.6	6.2	0.54	0.70	0.25	0.04	0.09

<sup>1</sup> volatile

Metallurgical coke, char coke, and gas coke contained 87.9%, 70.4%, and 73.2%  $C_{fix}$ , respectively. Thus the difference in the  $C_{fix}$  content of different cokes was very great, which has a major influence on the amount of coke in the smelting charge.

The ash and volatile contents of char and gas cokes were much higher than that of the metallurgical coke. The zinc, chlorine and fluorine content of the cokes

were low. The phosphorus content of the metallurgical coke was a little higher than that of the other cokes. The difference in the  $C_{fix}$  content of cokes should be taken into consideration when the amount of harmful components is calculated in the charge.

### Grain size of cokes

The screen analysis of cokes is presented in Table II and graphically in Figure 1.

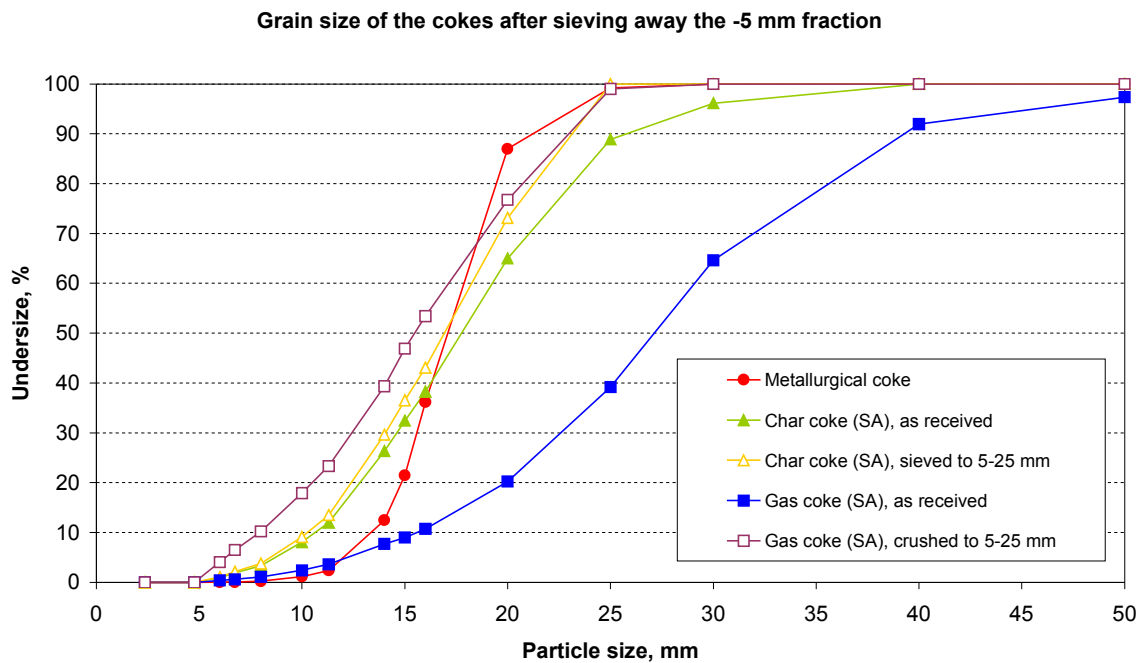
**Table II:** Screen analysis of cokes

Coke sample	Undersize %							
	40mm	30mm	25 mm	20mm	16mm	14mm	10mm	6.7mm
Metallurgical coke <sup>1</sup>	100.0	100.0	99.2	87.0	36.2	12.5	1.2	0.1
Char coke, original	100.0	96.1	88.9	65.0	38.3	26.4	8.1	1.9
Char coke, 5-25 mm <sup>2</sup>	100.0	100.0	100.0	73.1	43.1	29.6	9.1	2.2
Gas coke, original	92.0	64.6	39.2	20.3	10.8	7.7	2.4	0.6
Gas coke, 5-25 mm <sup>3</sup>	100.0	100.0	99.0	76.7	53.4	39.4	17.9	6.5

<sup>1</sup> used at the Tornio Works

<sup>2</sup> screened to 5 – 25 mm

<sup>3</sup> crushed and screened to 5 – 25 mm



**Figure 1:** Screen analysis of cokes

The grain size of the coke samples differed greatly from each other. The grain size of the metallurgical coke was mainly between 10 – 25 mm (98%). The grain size of + 5 mm was used in many tests and the average size of + 5 mm was about 17 mm.

Char coke contained about 80% between 10 – 25 mm and about 11% over 25 mm. The grain size of over 5 mm or 5 – 25 mm was used in many tests. The average grain size of over 5 mm was about 18 mm and that of 5 – 25 mm was about 17 mm. The fraction of 5 – 25 mm was prepared by sieving.

The grain size of gas coke was large and it contained about 60% over fraction of 25 mm. In several tests, a grain size of over 5 mm or 5 – 25 mm was used. The average size of over 5 mm was 27 mm and that of fraction 5 – 25 mm was 15.5 mm. The latter fraction was prepared by crushing and screening.

## Strength of cokes

### Compression strength

The cold compressive strength of cokes was tested with the original cokes using 10 x 10 x 10 mm cubes. The cokes have the layered structure and therefore the strength was measured both perpendicularly and longitudinally to the layers. The strength was calculated in kg per cm<sup>2</sup>.

The results are presented in Table III.

**Table III:** Cold compressive strength of cokes

<i>Coke sample / direction of compression</i>	<i>Metallurgical Coke</i>	<i>Char Coke (SA)</i>	<i>Gas Coke (SA)</i>
	<i>kg/cm<sup>2</sup></i>	<i>kg/cm<sup>2</sup></i>	<i>kg/cm<sup>2</sup></i>
Perpendicularly	225	280	239
Longitudinally	184	288	128
Average	204	284	183

The compression strength in the perpendicular direction to the layers was high enough in all cokes. The compression strength in the longitudinal direction to the layers was weakest in the case of gas coke and highest in the case of char coke.

### Abrasion resistance

The abrasion resistance of cokes was measured in a rotary drum, 900 mm in diameter and 460 mm in length, which was equipped with a lifter. The tests were performed with the original grain size, over 5 mm, and with the reduced grain size, 5 – 25 mm. Thus only one test with the metallurgical coke was performed. The amount of coke was 22.5 kg, the drum rotated 26.7 rpm and the rotating time was 7.5 minutes. The whole sample was screened after the test with sieves of 5.0 mm and 0.59 mm. Whole screen analysis of the feed and tumbled coke was done.

The d<sub>50%</sub> (mean size) was calculated for the original and tumbled samples. The stability of the mean size was calculated, the ratio of the mean size of the original/mean size of the tumbled samples.

**Table IV:** Abrasion resistance of cokes

<i>Specific tests</i>	<i>Metallurgical coke</i>	<i>Char coke (SA)</i>	<i>Char coke (SA)</i>	<i>Gas coke (SA)</i>	<i>Gas coke (SA)</i>
	<i>as received</i>	<i>as received</i>	<i>5-25 mm</i>	<i>as received</i>	<i>5-25 mm</i>
M <sub>10</sub> (i.e. -10 mm), % <sup>1</sup>	4.5	21.6	23.1	17.6	27.1
Tumbled coke, -5 mm, %	3.4	7.2	6.7	11.6	8.3
Tumbled coke, -0.59 mm, %	3.1	3.7	3.4	6.6	4.0
d <sub>50%</sub> before Tumbler test, mm <sup>2</sup>	17.09	17.75	16.92	27.12	15.48
d <sub>50%</sub> after Tumbler test, mm <sup>2</sup>	16.47	15.16	14.33	22.18	14.24
Tumbler stability for the mean size, %	96.4	85.4	84.7	81.8	92.0

<sup>1</sup> Micum index, % below 10 mm

<sup>2</sup> d<sub>50 %</sub> = mean grain size below 50 %

The Tumbler strength of the metallurgical coke was the best and that of the original gas coke (as received) was worst. The crushing and screening of gas coke to the grain size of 5 - 25 mm resulted in much better results compared to the original grain size. The char coke was only screened and thus the difference in the Tumbler values was very small.

The Tumbler stability for the mean size was good and high with the metallurgical coke but low with the char coke in both cases. The crushing and screening of the gas coke improved the stability value compared with the original case.

### Relative density, bulk density and porosity of cokes

#### True relative density of coke

The coke sample was crushed below 75 µm and dried for 1 hour at 105°C. The determination was carried out in pycnometer bottles, in ethanol.

#### The apparent relative density of coke

This was measured according to ASTM D 167-93. The coke sample is immersed in water for 15 minutes to fill all large pores with water. The apparent relative density was calculated according to the following formula:

Apparent relative density:

$$\frac{A}{B + (C - A)} \quad [1]$$

A = mass of dry coke

B = mass of water displaced by wet coke

C = mass of wet coke

### Bulk density of coke

A mass of coke of 2.7 litres was weighed (loose bulk density). The bulk density was measured in coarse and fine grain size.

### Porosity of coke (ASTM D 167-93)

The porosity is calculated from the apparent and true gravities of the coke as follows:

$$\text{Total Porosity} = 100 - \frac{100 \times (\text{apparent specific gravity})}{\text{true specific gravity}} \quad [2]$$

$$\text{Apparent Porosity} = \frac{W_i - W}{W} \% \quad [3]$$

where  $W$  = weight of dry coke,  $W_i$  = weight of wet coke.

The results are presented in Table V.

**Table V:** Specific gravities, bulk densities and porosities of cokes

<i>Measurement</i>	<i>Metallurgical Coke</i>	<i>Char Coke (SA)</i>	<i>Gas Coke (SA)</i>
Apparent relative density, g/cm <sup>3</sup> <sup>1</sup>	0.939	0.970	0.998
True relative density, ethanol, g/cm <sup>3</sup>	1.971	1.873	1.830
Bulk density, size 5.0-25.0 mm, g/cm <sup>3</sup>	0.497	0.577	0.573
Bulk density, size 2.36-5.0 mm, g/cm <sup>3</sup>	0.483	0.541	0.594
Open porosity, %	13.8	14.0	15.7
Total porosity, 'ethanol', %	52.4	48.2	45.5

<sup>1</sup> ASTM D 167 - 93

The specific gravities of the cokes were quite similar. The bulk density of cokes was higher in the fine grain size compared to the coarse grain size. The bulk densities of char and gas cokes were higher than that of the metallurgical coke.

The total porosity of the metallurgical coke was larger than that of the other grades.

### Reactivity of cokes

The reactivity of cokes was determined with the thermo-balance method. The test parameters were as follows:

Coke amount: 0.775 g

Grain size: 1.00-2.36 mm

Heating rate: 10°C/min to 1050°C

Retention time: at least 60 min at 1050°C

Gas: 99.9% Ar during heating and 99.7% CO<sub>2</sub> during retention time, 100 ml/min

Heating crucible: Diameter 15.5 mm

The balance records the weight loss of a sample as coke reacts with CO<sub>2</sub> according to the reaction:  $C + CO_2 \rightarrow CO$ . The reactivity was calculated from the weights at 8 min and at 33 min. The reactivity was expressed as a production rate of CO (cm<sup>3</sup>) per unit weight of coke (g) and per unit time (sec).

The results are presented in Table VI.

**Table VI:** Reactivity of cokes

Coke	Reactivity
	$cm^3 CO / (sec \cdot g_{coke})$
Metallurgical coke	0.087
Char coke (SA)	0.464
Gas coke (SA)	0.531

The reactivity of cokes depends on the degree of coking, the rheological characteristics of coal and the composition of coke ash. These factors have an affect on the isotropic and anisotropic characteristics of cokes. The higher the proportion of anisotropic area, the lower is the reactivity of coke.

The crystallite sizes of cokes were determined according to the standard ASTM D 5187-91/46, which is based on X-ray diffraction measurement and a special calculation method. The crystallite size has a great effect on the reactivity of coke.

The reactivity of the cokes differed greatly. The reactivity of the metallurgical coke was much lower than that of the char and gas cokes. The crystallite size of the metallurgical coke was far larger than that of the char and gas cokes, which explained its low reactivity compared to the other cokes.

## **SPECIFIC ELECTRICAL CONDUCTIVITY OF COKES AND SMELTING CHARGE**

### **Measuring system**

The specific electrical conductivity of cokes and the smelting charge was measured using the following method as a function of temperature. The schematic arrangement of the measuring system is described in Figure 2.

The equipment consisted of a graphite crucible with an internal diameter of 170 mm. The crucible was filled with the material to be measured to 120 mm in height. The surface of the material as well as the outer surface of the graphite crucible was flushed with nitrogen gas to protect them against oxidation by air. The electrical resistance of the crucible itself was measured before each test.

The batch was heated at 800°C/h from 25°C to 1600°C and the electrical resistance was measured at intervals of 100°C (intervals of 50°C at temperatures between 1300 - 1600°C). After the measurements the batch was cooled in the crucible in nitrogen gas.

Electrical conductivity was calculated according to the following formula:

$$G = \frac{1}{(R - R_0)} \quad [4]$$

G = electrical conductivity (Siemens)

R = measured electrical resistance, ( $\Omega$ )

R<sub>0</sub> = electrical resistance of the equipment, ( $\Omega$ )

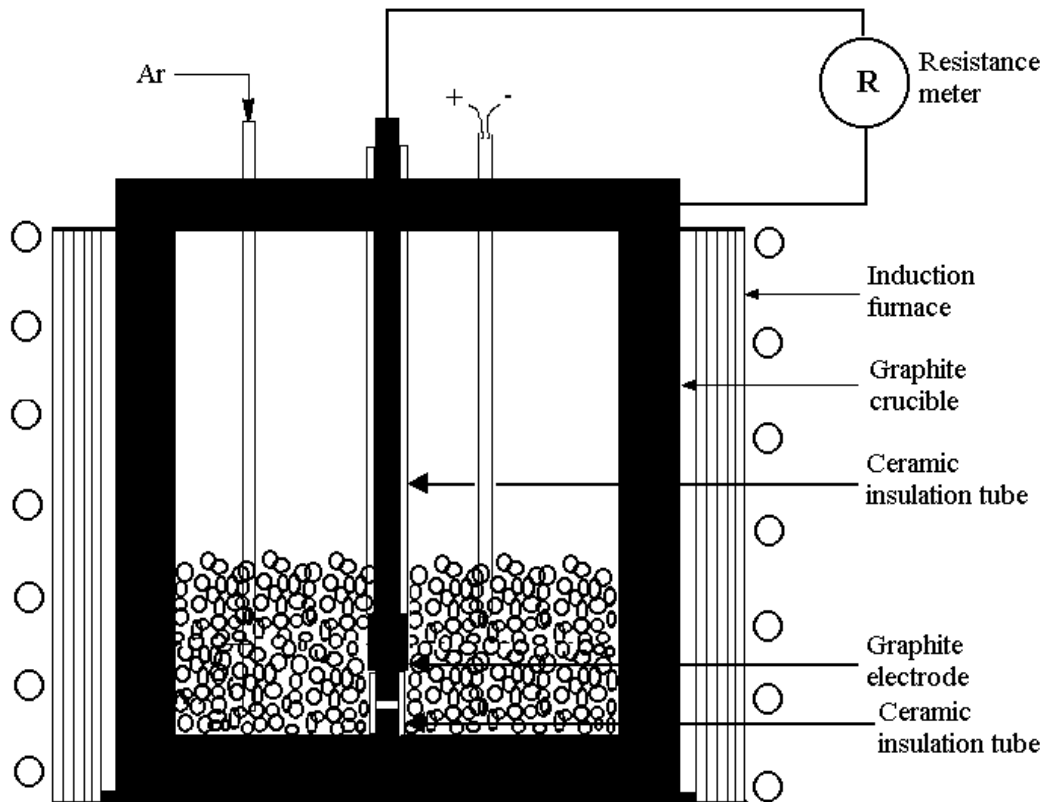


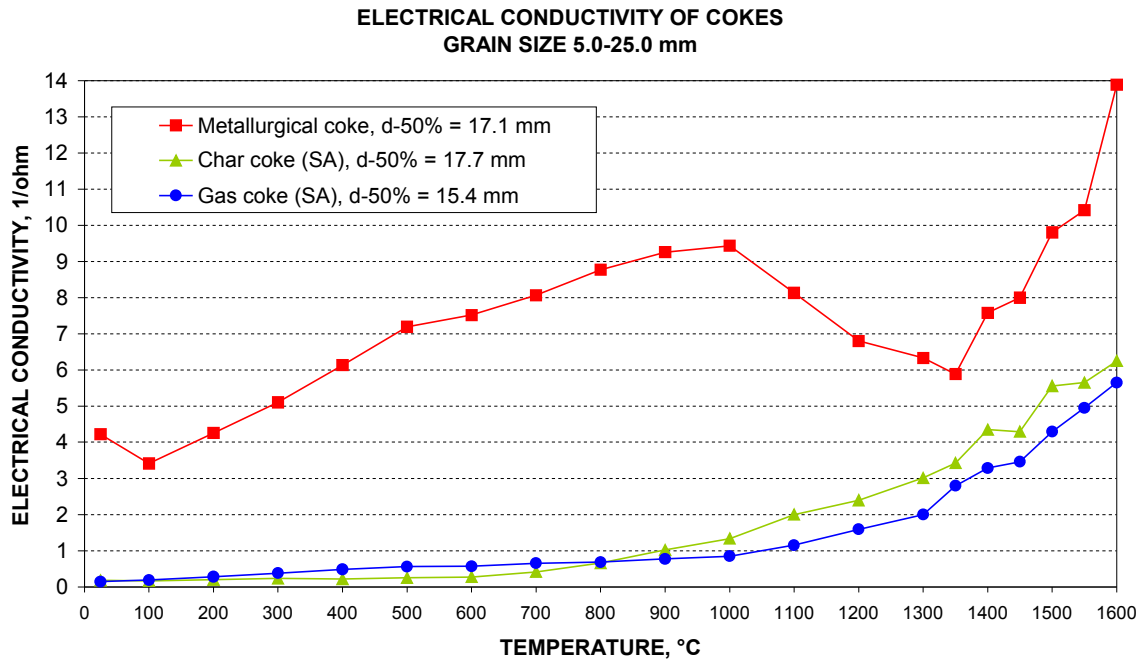
Figure 2: Arrangement for measuring of electrical resistance (maximum particle size, 25 - 30mm)

### Electrical conductivity of cokes

The electrical conductivity of cokes and their mixture (50% / 50%) was measured in two different grain sizes: 5.0 - 25 mm, and 2.36 - 5.0 mm.

The results are presented in Figures 3 - 5.



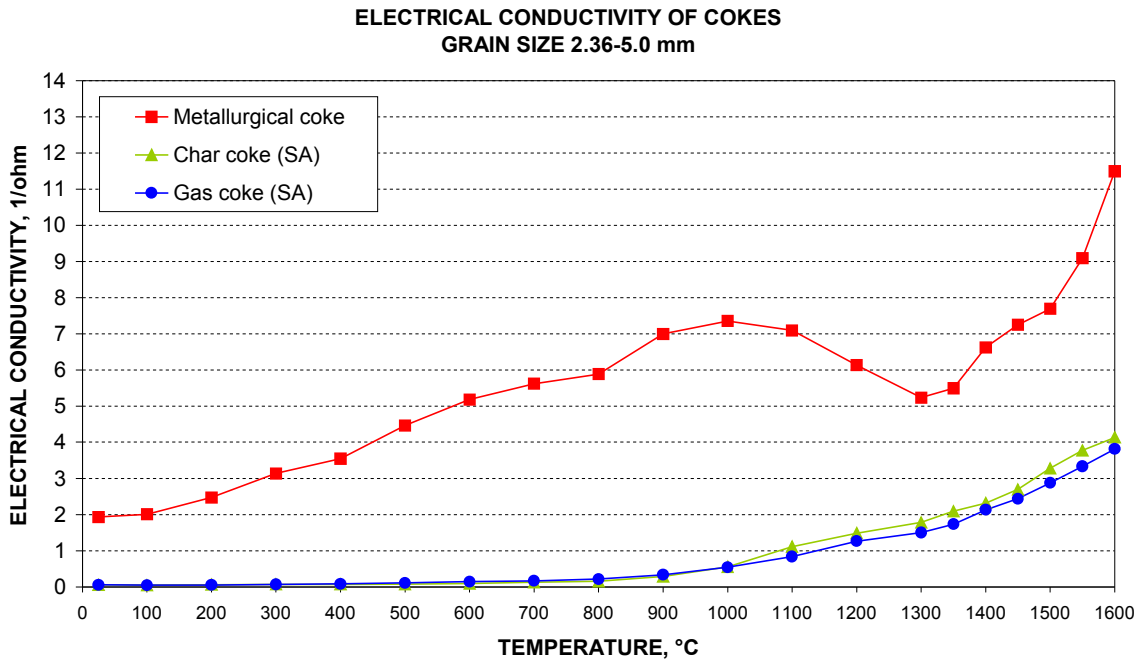


**Figure 3:** Electrical conductivity of cokes. Grain size: 5 – 25mm

The electrical conductivity,  $1/\Omega$ , of metallurgical coke was within the typical range of cokes measured earlier at ORC. This coke is used successfully in the ferrochrome smelting furnace. The electrical conductivity of the metallurgical coke increased almost linearly at the lower temperature to 1000°C and then decreased to 1350°C and again started to increase.

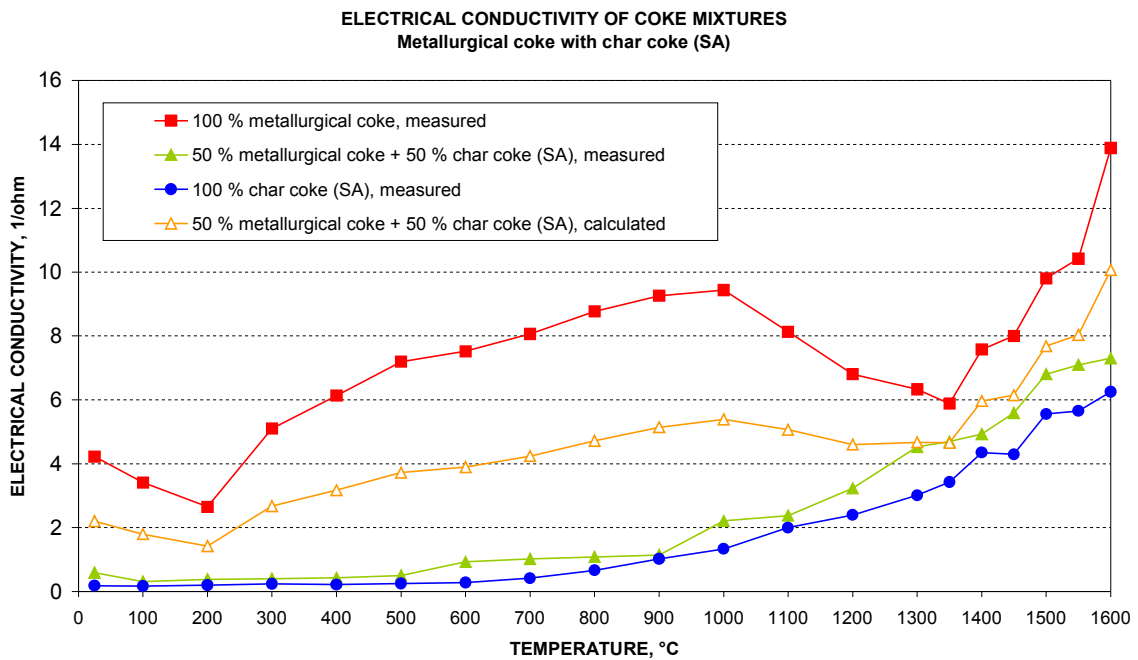
The electrical conductivity of char and gas cokes was much lower than that of metallurgical coke.

The electrical conductivity of char and gas cokes increased very regularly along with the temperature. The maximum value, of about  $6.1/\Omega$ , was achieved at 1600°C in both cases but the corresponding value of metallurgical coke was about  $14.1/\Omega$ .



**Figure 4:** Electrical conductivity of cokes. Grain size: 2.36 - 5.0 mm

The electrical conductivity of cokes was much lower in smaller grain size compared to the larger grain size in the previous figure. The difference in the conductivity of metallurgical coke and char both gas cokes remained.



**Figure 5:** Electrical conductivity of cokes and the mixture of metallurgical coke and char cokes. Grain size; 5 - 25 mm. (mixture: 50 %metallurgical coke and 50 %char coke). Measured and calculated values.

The use of char coke in the mixture of metallurgical coke and char coke strongly decreased the electrical conductivity of the mixture compared to the

metallurgical coke. The measured electrical conductivity of the mixture gave the real values compared to the directly calculated values.

It can be assumed that even a small addition of char coke decreases the electrical conductivity of the coke mixture.

### Electrical conductivity of the smelting charge

#### Test materials

Test materials were as follows:

- Process sintered pellets, Outokumpu, Tornio plant
- Sintered pellets from the batch sintering tests (concentrate from SA)
- Lumpy ore, Outokumpu, Kemi
- Quartzite, Finnish grade
- Calcite, Finnish grade
- Metallurgical coke
- Char coke

The chemical analyses of the test materials are presented in Tables VII - IX. The chemical analyses and other specific figures of the sintered pellets and lumpy ore are presented in Tables VII and VIII.

**Table VII:** Chemical analyses of sintered pellets and lumpy ore

<i>Chromite</i>	$Cr_2O_3$	$Fe_{tot}$	$Fe^{2+}$	$C_{tot}$	$S_{tot}$	<i>L.O.I.</i>	$Fe^{2+}/Fe_{tot}$	$Cr/Fe$
Tornio, process pellets	42.2	20.6	7.0	0.45	0.03	1.7	0.342	1.40
Batch sintered pellets <sup>1</sup>	41.7	21.7	4.6	0.11	0.01	0.4	0.214	1.31
Kemi lumpy ore	30.2	10.9	9.3	0.75	0.02	5.1	0.855	1.89

	$SiO_2$	$Al_2O_3$	$MgO$	$CaO$
Tornio, process pellets	3.7	12.6	9.5	0.5
Batch sintered pellets <sup>1</sup>	2.6	14.7	9.0	0.2
Kemi lumpy ore	18.0	10.7	18.6	1.5

<sup>1</sup> produced in the batch sintering test in the pilot scale at ORC (South African chromite)

The process pellets and upgraded Kemi lumpy ore are used in the ferrochrome process at the Tornio works.

The size of pellets was 8 – 16 mm and that of lumpy ore was 10 – 25 mm.

**Table VIII:** Specific characteristics of the sintered pellets

<i>Specific values</i>	<i>Tornio, process pellets</i>	<i>Batch pellets (SA)</i>
Compressive strength, kg/pellet	186	230
Modified Tumbler, % - 0.59 mm	8.7	7.6
Hot loading temperature °C, T -5% <sup>1</sup>	1433	1423
Total porosity, %	27.1	27.3

<sup>1</sup> compression of 5% from pellet height under load of 0.2 N/mm<sup>2</sup> per cross section area of pellet

**Table IX:** Chemical analyses of calcite and quartzite

<i>Material</i>	<i>CaO</i>	<i>MgO</i>	<i>SiO<sub>2</sub></i>	<i>Al<sub>2</sub>O<sub>3</sub></i>	<i>C<sub>tot</sub></i>	<i>S<sub>tot</sub></i>	<i>L.O.I.</i>
	%	%	%	%	%	%	%
Calcite	54.7	0.67	0.35	0.05	11.6	0.01	43.5
Quartz	n.a.	n.a.	98.0	1.10	n.a.	n.a.	n.a.

The quartzite and calcite were in size of 10 – 20 mm.

**Table X:** Chemical analyses of cokes and coke mixture

<i>Cokes</i>	<i>C<sub>fix</sub></i>	<i>S</i>	<i>P</i>	<i>Ash</i>	<i>Vol.</i>	<i>SiO<sub>2</sub></i>	<i>Al<sub>2</sub>O<sub>3</sub></i>	<i>Fe<sub>2</sub>O<sub>3</sub></i>	<i>CaO</i>	<i>MgO</i>
	%	%	%	%	%	%	%	%	%	%
Metallurgical coke	87.9	0.32	0.031	10.2	1.6	5.4	3.1	0.61	0.23	0.10
Char coke (SA)	70.4	0.59	0.020	19.9	9.1	10.0	6.1	0.60	0.85	0.14
Mixture (1:1), calculated	79.2	0.46	0.025	15.1	5.4	7.7	4.6	0.61	0.54	0.12

Cokes were 5 – 25 mm, 2.38 – 5.0 mm and 10 – 14 mm in size.

### Test procedure

The smelting charge was calculated according to the following simplifications:

- The basic charge contains pellets, coke (metallurgical and char coke) and quartzite
- Si in ferrochrome: 3% (base case) or 6% (effect of coke amount)
- Slag basicity: with or without calcite
- Ratio of slag/ metal: normal
- Lumpy ore: 0% or 30% of total chromite amount
- Slag melting point; 1700°C but higher without quartzite
- Recovery of chromium and iron to ferrochrome were 87% and 92% respectively when the silicon content was 3%; the corresponding values were 89% and 94% when the silicon content was 6%.

The charge components were weighed and mixed together with the target volume of 2.7 litres. The charge was poured into the graphite crucible and the crucible was closed with a graphite lid. The crucible was tapped against the table a few times until the electrical resistance of the charge was almost constant.

The surface of the material as well as the outer surface of the crucible was flushed with nitrogen gas to protect them against air oxidation.

The charge was heated to 1600°C in 120 minutes. The electrical resistance of the charge was measured at intervals of 100°C to 1300°C and then at intervals of 50°C to 1600°C. The crucible was cooled in nitrogen gas.

### Effect of coke quality

The charge consisted of sintered South African pellets from the pilot plant tests or Tornio pellets, metallurgical coke and char coke both quartzite. The melting point of slag was assumed to be 1700°C and the silicon content in ferrochrome 3%.

The electrical conductivity of two qualities of sintered pellets as a reference is presented in Figure 6.

The results of the effect of the different cokes are presented in Figures 7 - 9.

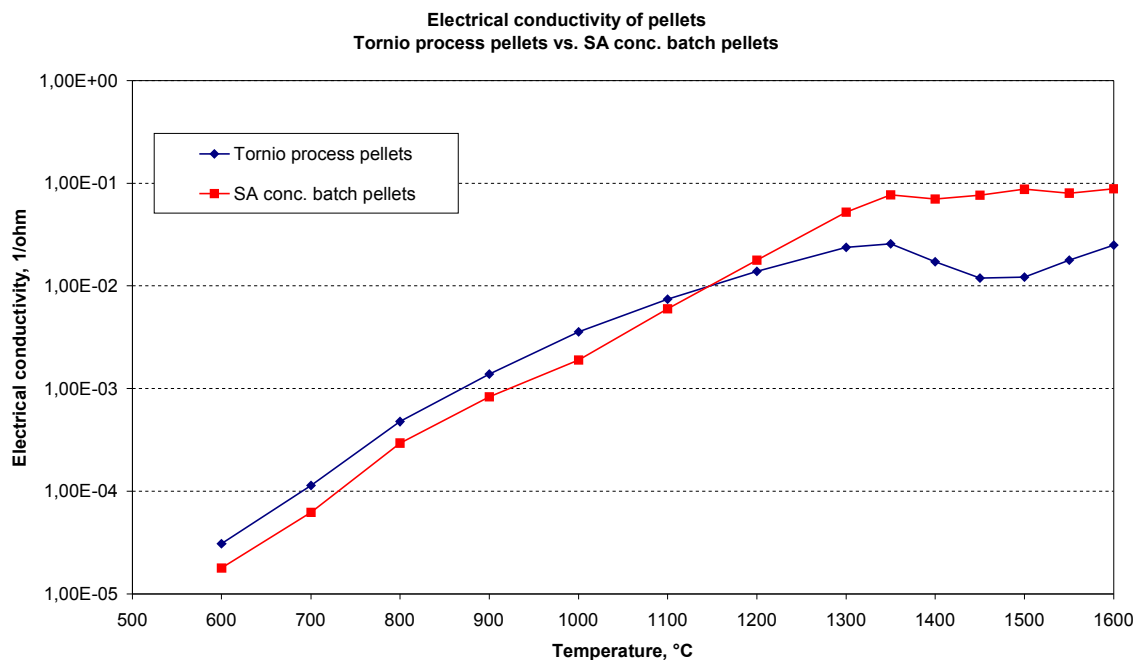
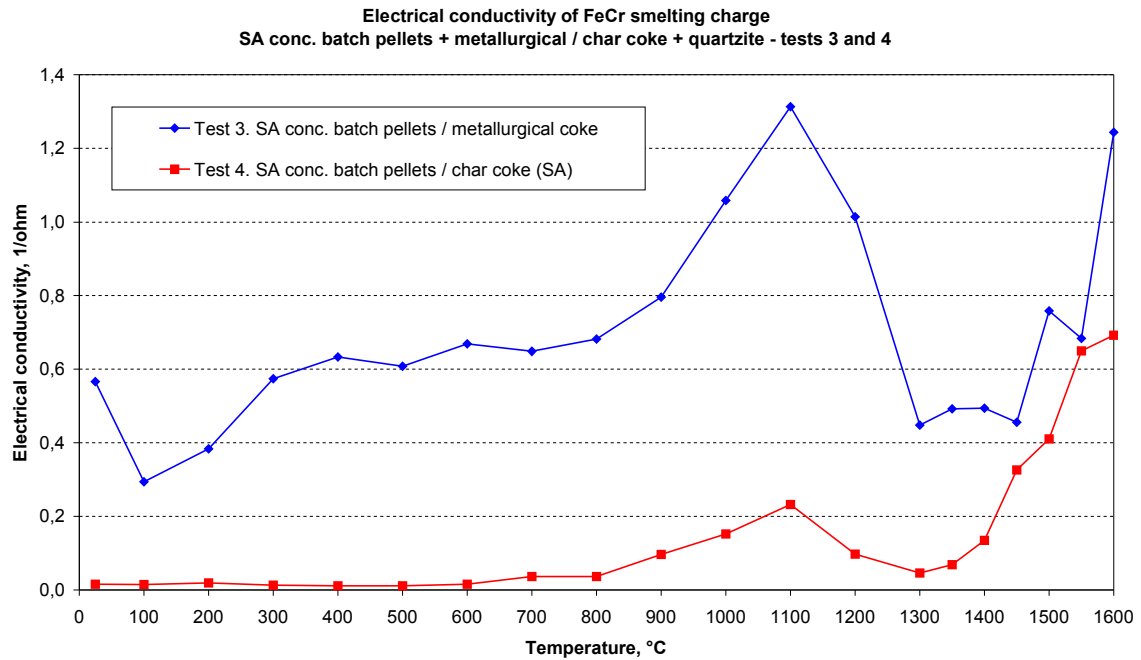


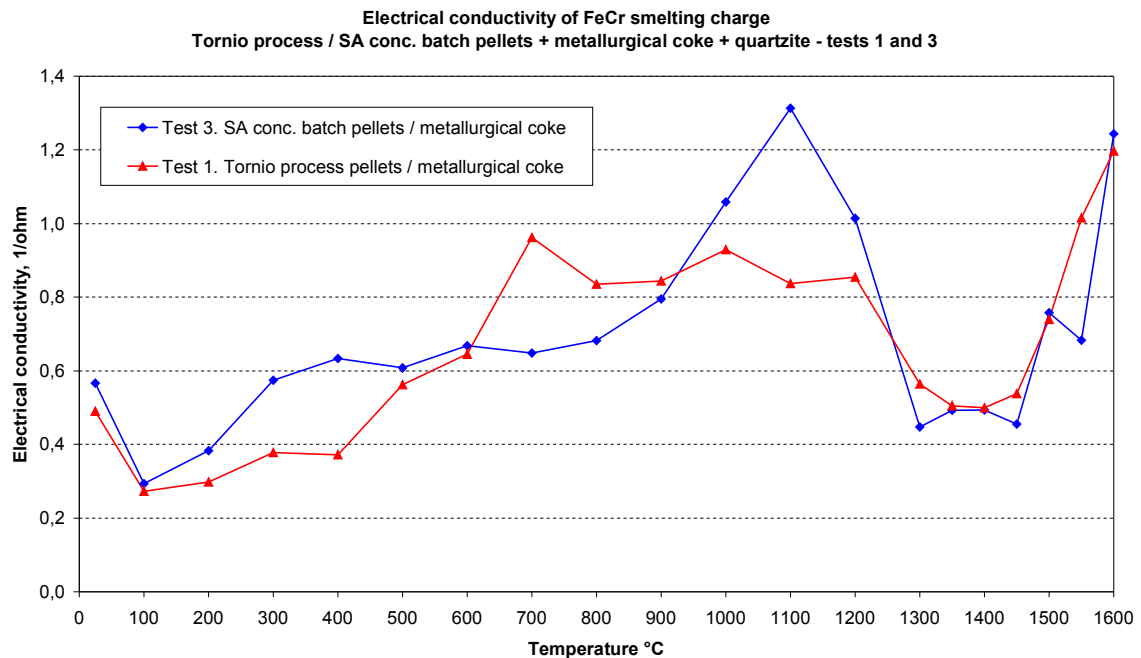
Figure 6: Electrical conductivity of the Tornio sintered pellets and the batch sintered pellets

The electrical conductivity of the two qualities of the sintered pellets was quite similar to each other. The conductivity values of the pellets were significantly lower than those of the cokes.



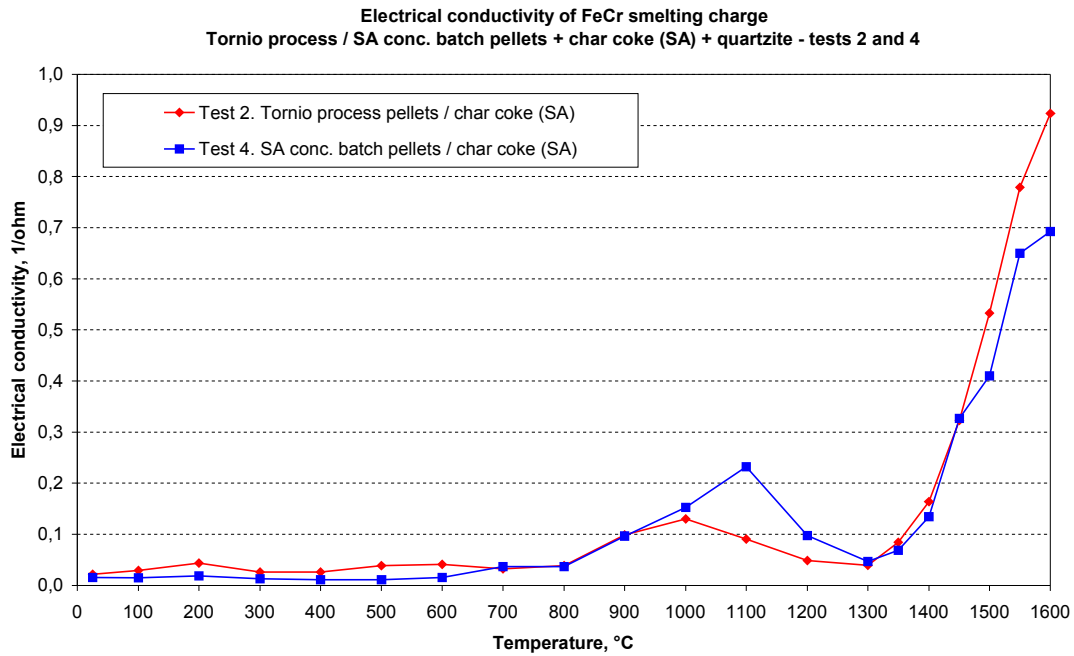
**Figure 7:** Effect of coke quality on the electrical conductivity of the smelting charge. Batch sintered pellets and quartzite

The electrical conductivity of the charge was much lower when char coke was used compared to the values achieved with metallurgical coke. The difference was quite clear. The peak reached with the metallurgical coke was at about 1100°C. Then the conductivity decreased due to the transitions of the structure in both pellets and coke.



**Figure 8:** Electrical conductivity of the smelting charge. Metallurgical coke. Tornio and batch pellets

The electrical conductivity of the smelting charge with the different sintered pellets was quite similar when the same metallurgical coke was used.

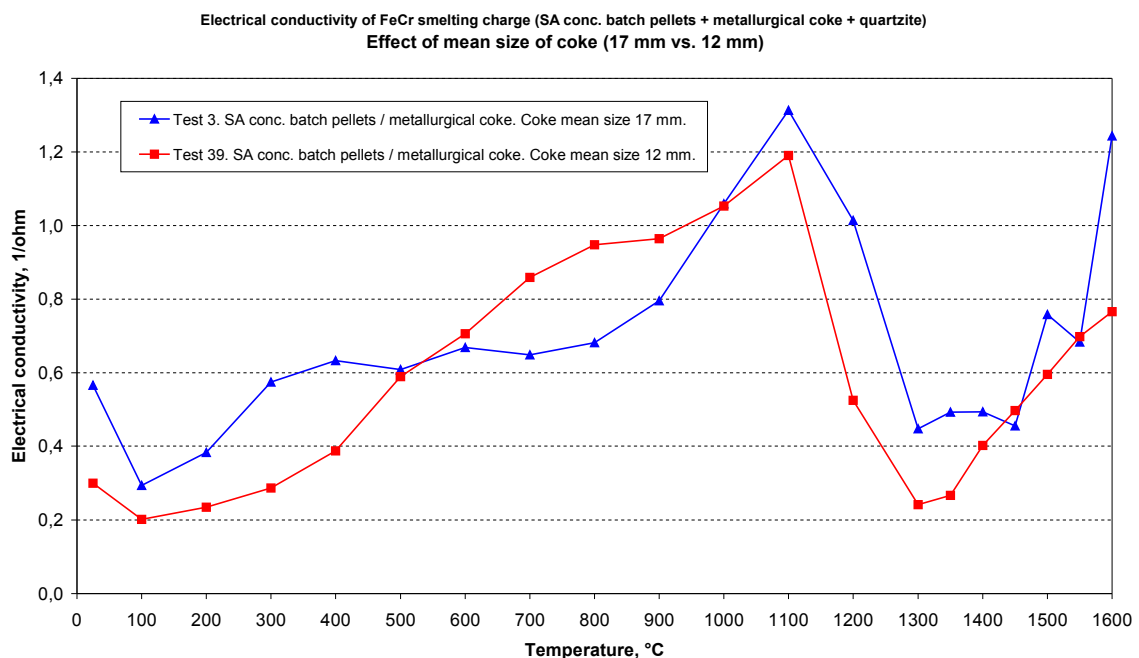


**Figure 9:** Electrical conductivity of the smelting charge. Char coke. Tornio and batch pellets.

The electrical conductivity of the smelting charge with the different sintered pellets was quite similar to each other when the same char coke was used. The electrical conductivity values of these measurements were much lower than those with the metallurgical coke. Thus the effect of char coke on the electrical conductivity of the smelting charge was significant.

### Effect of coke size

The results of the effect of the coke sizes are presented in Figure 10.



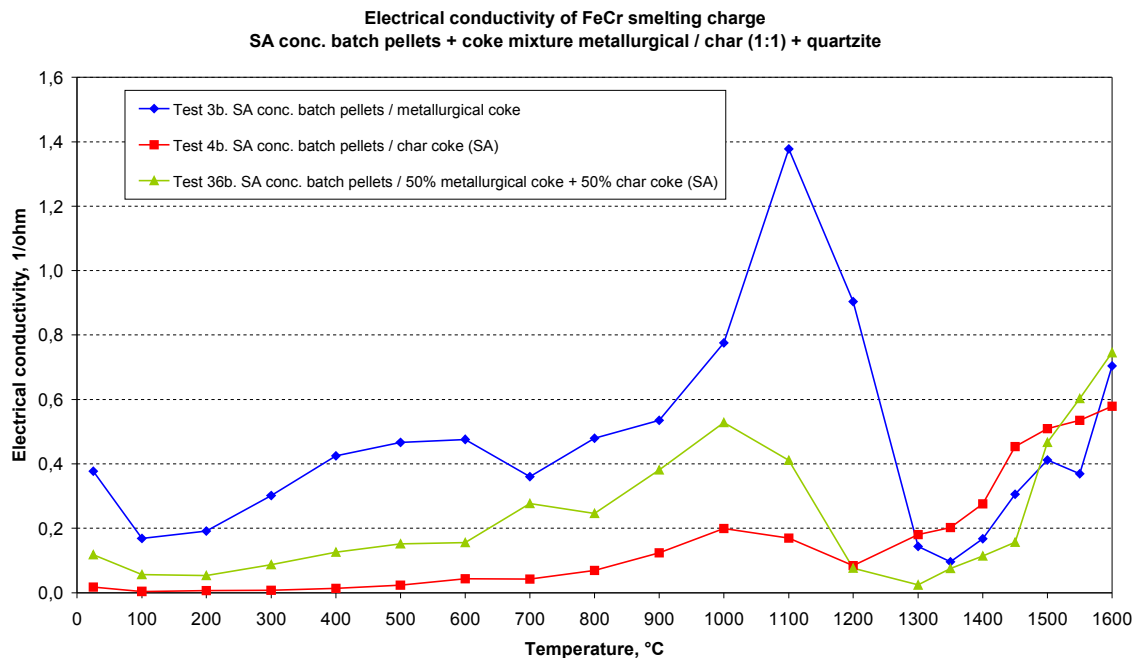
**Figure 10:** Effect of coke size, 10 – 14 mm and 5 – 25 mm. Metallurgical coke. Batch sintered pellets

The electrical conductivity of the smelting charge was little less conductive with a coke size of 10 – 14 mm than with the normally used size of 5 – 25 mm.

The conductivity was also measured with a coke size of 2.38 – 5.0 but the conductivity values were significantly higher. Thus a small coke size must be avoided in the smelting charge.

### Effect of coke mixture

The measured conductivity values of the smelting charge with cokes and their mixture are presented in Figure 11.



**Figure 11:** Cokes and mixture of metallurgical coke and char coke (1:1).  
Batch sintered pellets

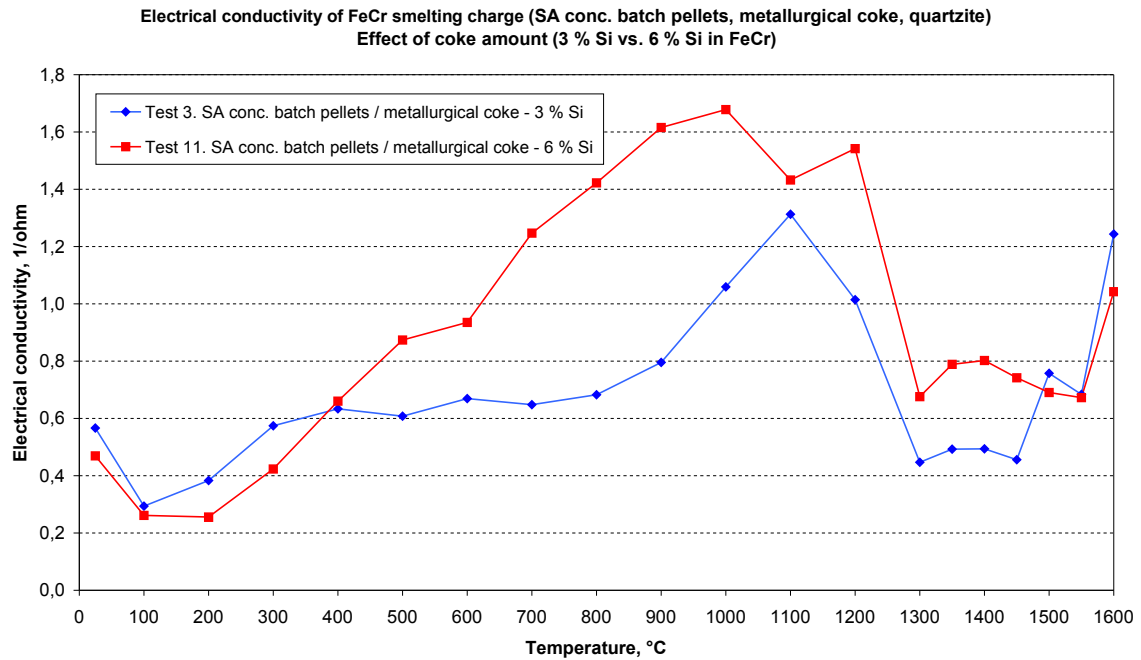
The electrical conductivity of the smelting charge with the mixture of metallurgical and char coke closely followed the values with the char coke up to 600°C. The conductivity values of the mixture followed the values of the char coke very closely over 1200°C. All conductivity values were quite close to each other when the temperature was over 1300°C.

### Effect of coke amount, silicon content of ferrochrome 3 or 6%

The silicon content in ferrochrome was increased from 3 to 6% by keeping the melting point of slag at 1700°C, *i.e.* increasing an amount of quartzite. The amount of coke increased in the case of metallurgical coke from 38.7 volume % to 40.2 volume %, which was small.

The conductivity values are presented in Figure 12.





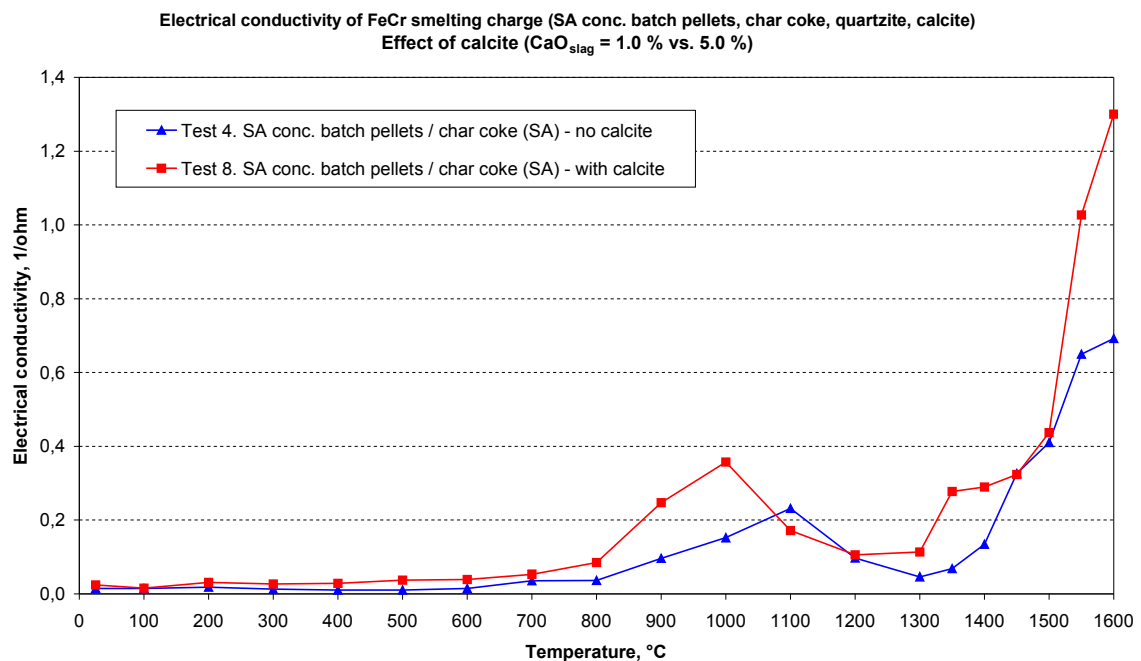
**Figure 12:** Effect of silicon content in ferrochrome. Batch pellets. Metallurgical coke.

The increase in the silicon content of ferrochrome increased the electrical conductivity of the smelting charge especially from 400°C to 1000°C. After that temperature the conductivity values differed less from each other.

### Effect of calcite

The effect of the amount of calcite on the electrical conductivity of the smelting charge was investigated. The CaO content of slag is 1.0% without calcite and 5% with calcite.

The results of the measurements are presented in Figure 13.



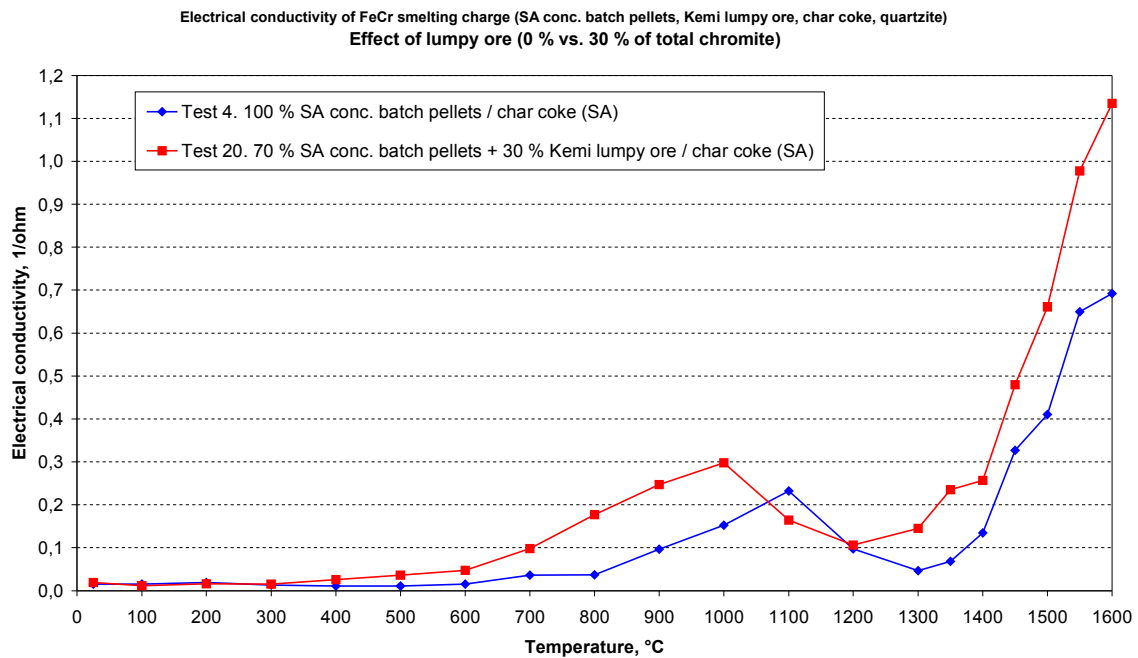
**Figure 13:** Effect of calcite. Batch sintered pellets. Char coke.

The volumetric proportion of calcite (CaO) was small and its effect on the electrical conductivity of the smelting charge was insignificant. The electrical conductivity with calcite increased the values only above 1500°C.

### Effect of lumpy ore

The measurements were performed with and without lumpy ore. The amount of lumpy ore was 30 % of total chromite (pellets + lumpy ore).

The results are presented in Figure 14.



**Figure 14:** Effect of lumpy ore. Batch sintered pellets. Kemi upgraded ore, Char coke.

The electrical conductivity of the smelting charge with lumpy ore increased slightly from 600°C to about 1000°C, compared to the charge without lumpy ore. The conductivity values increased slightly again above 1300°C where lumpy ore started to soften and to melt partially.

Agglomerates were observed in the batch after the tests with lumpy ore. This meant, that the melting of lumpy ore occurred in these conditions, which increased the electrical conductivity of the charge.

## KEY RESULTS

The cokes differed from each other physically quite a lot. The metallurgical coke looked dense, but the char and gas cokes were considerably layered in structure. The grain size of the char coke was large. The metallurgical coke had a melted structure and high porosity. The gas coke contained small pores and the structure was layered. The char coke was between the two former groups.

- The metallurgical coke contained about 88%  $C_{fix}$ , 10% ash, and 1.6% volatiles. The char type cokes contained 70 – 73%  $C_{fix}$ , 19 – 20% ash and 7 – 9% volatiles.
- The average compressive strength of all cokes was high enough, but the longitudinal strength of the gas coke was low.
- The comparison of the Tumbler value of minus 0.59 mm gave the following order of superiority: metallurgical coke, char coke, gas coke.
- The lowest reactivity was obtained with the metallurgical coke and the highest reactivity with gas coke. The reactivity was also high with char coke.
- The electrical conductivity was measured in the grain size of 5.0 – 25 mm (normally used) and in the reduced grain size of 2.38 – 5.0 mm.

The key results concerning the electrical conductivity of cokes were as follows:

- The electrical conductivity of the metallurgical coke was at the normal level and used a reference.
- The electrical conductivity of char and gas cokes were fairly similar to each other but much lower than that of the metallurgical coke.
- The electrical conductivity of cokes was much lower in the smaller grain size compared to the larger grain size.
- The use of char coke in the mixture of metallurgical coke and char coke (1:1) strongly decreased the electrical conductivity of the mixture compared to the metallurgical coke.

The key results concerning the electrical conductivity of the smelting charge were as follows:

- The electrical conductivity of the two grades of the sintered pellets was quite similar to each other. The conductivity values of the pellets were significantly lower than those of the cokes.
- The electrical conductivity of the smelting charge was much lower when the char coke was used compared to the values achieved with the metallurgical coke. The difference was quite clear.
- The electrical conductivity of the smelting charge with the different sintered pellets was quite similar to each other when the same metallurgical coke was used.
- The electrical conductivity of the smelting charge was a little less conductive with a coke size of 10 – 14 mm than with the normally used size of 5 – 25 mm. The conductivity was also measured with a coke size of 2.38 – 5.0 mm but the conductivity values were significantly higher. Thus a small coke size must be avoided in the smelting charge.
- The electrical conductivity of the smelting charge with the mixture of metallurgical and char coke (1:1) coke closely followed the values with the char coke to 600°C. The conductivity values of the mixture followed the values of the char coke very closely above 1200°C.
- The increase in the silicon content of ferrochrome, from 3 to 6%, increased the electrical conductivity of the smelting charge, especially from 400°C to

1000°C. After that temperature the conductivity values differed from each other only a little.

- The CaO content in slag was increased from 1 to 5% with calcite, but its volumetric proportion was small and its effect on the electrical conductivity of the smelting charge was insignificant. The electrical conductivity with calcite increased the values only above 1500°C.
- The electrical conductivity of the smelting charge with lumpy ore (pellets 70% + lumpy ore) increased slightly from 600°C to about 1000°C compared to the charge without lumpy ore. The conductivity values increased slightly again above 1300°C where the lumpy ore started to soften and to melt partially.

## **CONCLUSIONS**

The use of char and gas cokes should be seriously considered for substitution of the metallurgical coke in ferrochrome smelting, to increase the electrical resistance of the furnace and achieve higher production.

Changes in the composition of the smelting charge have a smaller effect on the conductivity of the smelting charge when char or gas cokes are used than in the case of metallurgical coke.