

# Improvement in Blast Furnace Reaction Efficiency through the Use of Highly Reactive Calcium Rich Coke

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A method to produce coke in 'lump' form with high strength and reactivity through the addition of a catalyst was investigated in order to improve blast furnace reaction efficiency. The addition of Ca compounds to coal before carbonization was found to considerably increase the reactivity of the coke at a low temperature range in the thermal reserve zone of a blast furnace. Furthermore it was proved that strong, highly reactive 'lump' form coke could be produced by adding a Ca-rich non-caking coal and adjusting the coal blend composition. Based on this fundamental study, the Ca-rich coke was successfully produced in coke ovens on a commercial scale, both at Kimitsu and Muroran works. The use of the Ca-rich coke in the Muroran No. 2 blast furnace was found to cause a decrease in the reducing agent rate by 10 kg/t-p. This technology, producing coke of high reactivity and strength through catalyst addition, is promising as a means of improving the reaction efficiency of a blast furnace.

KEY WORDS: coke reactivity; catalyst; ironmaking; reaction efficiency; blast furnace; thermal reserve zone.

## 1. Introduction

Any improvement in the blast furnace reaction efficiency during the blast furnace ironmaking process is very significant, since it has the potential to allow a decrease in the reducing agent rate (the amount (in kg) of reducing agents such as coke and coal needed to produce 1 000 kg of pig iron) as well as CO<sub>2</sub> emissions. Naito *et al.*<sup>1)</sup> proposed a technology which drastically improves reaction efficiency in the blast furnace by decreasing the temperature of the thermal reserve zone through the use of highly reactive coke. Here the reactivity of coke refers to the reaction rate of coke with CO<sub>2</sub>(C+CO<sub>2</sub>=2CO).<sup>2)</sup> It was reported that the use of highly reactive 'nut' coke in a commercial scale blast furnace improved the reaction efficiency<sup>3)</sup> and decreased the temperature of the thermal reserve zone.<sup>4)</sup> It is therefore expected that increased reactivity in normal or 'lump' form coke, representing the majority of the coke used in a blast furnace, will improve its efficiency to a greater extent. However, no practical methods have yet been devised to produce the 'lump' form of coke with high reactivity and strength. The focus here, therefore, is on the potential production method for 'lump' coke demonstrating such qualities in a commercial coke oven.

The reactivity of 'lump' coke is considered to depend on its chemical reactivity and pore diffusion<sup>5)</sup> respectively, as shown in Fig. 1. The chemical reactivity of coke depends

on its individual carbon structure and the catalytic effect of the internal mineral components. In order to decrease the temperature of the thermal reserve zone, it is important to increase the coke reactivity at a low temperature range, namely the chemical reactivity of the coke. The carbon structure depends on factors such as the coke oven temperature and the types of coals used. It is understood that a decrease in the oven temperature leads to a corresponding decrease in the degree of graphitization (crystallite size,  $L_c$ ), which in turn, leads to a high level of chemical reactivity.<sup>6)</sup> It is also known that the types of coke texture vary according to the types of coals used and that the optically isotropic coke texture is more reactive than the anisotropic texture.<sup>6)</sup> However, in terms of the operation of a coke oven for the production of blast furnace coke on a commercial scale, considerably increasing the chemical reactivity of coke through adjustment of these factors alone is difficult. Therefore, we tried to increase the coke chemical reactivity by instead making use of the catalytic effect.<sup>7)</sup>

The questions to be answered when implementing this method are 1) how the catalyst is added to the coke and 2) what kinds of compounds are suitable as a catalyst. There are considered to be two basic methods of adding the catalyst to the coke. The first method is 'post-addition of catalyst to coke', as shown in Fig. 2, where the catalyst and/or catalyst solution is sprayed onto the coke after the coke is pushed out of a coke oven chamber. The second method is

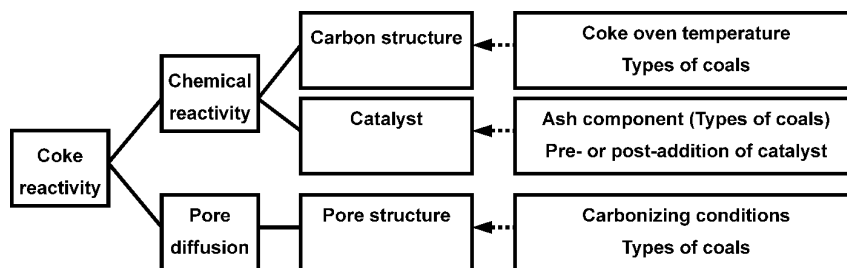


Fig. 1. The factors determining coke reactivity.

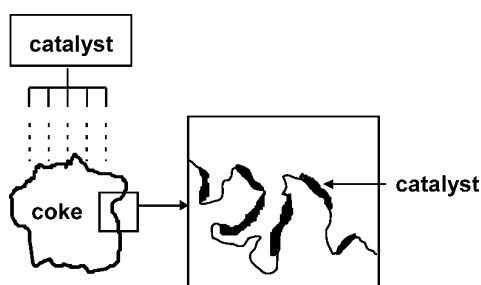


Fig. 2. 'Post-addition of catalyst to coke' method.

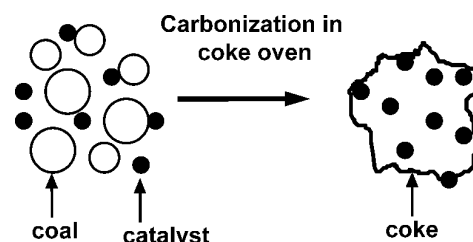


Fig. 3. 'Pre-addition of catalyst to coke' method.

'pre-addition of catalyst to coke', as shown in Fig. 3, where that catalyst is mixed with coal before the mixture is carbonized in a coke oven chamber. Adjustment of the ash components through coal selection is also part of the latter method. The internal distribution of catalyst in the coke differs in both methods; the former involving the catalyst mainly on the surface of the coke while in the latter, it exists almost homogeneously in the coke. In this report, the latter method of 'pre-addition of catalyst to coke' was investigated. The former method is now being studied and it will be interesting to compare the highly reactive cokes produced in both methods because the homogeneity of catalyst in the coke may affect the reaction behavior of the coke.

Although it is known that alkali metal, alkaline earth metal and transition metal have high catalytic activity during the C-CO<sub>2</sub> reaction,<sup>8)</sup> there are relatively few quantitative data concerning the reactivity of blast furnace coke containing these catalysts in the atmosphere of the thermal reserve zone in a blast furnace. Moreover, no practical methods have been proposed to produce a 'lump' form of coke with high reactivity and strength in a commercial coke oven.

Alkali metal is undesirable as a catalyst because its presence in coke generates the development of scaffolding on the blast furnace wall. Fe (iron), which is one of the typical transition metals, is also undesirable when considering the 'pre-addition of catalyst to coke' method, since FeO may react with SiO<sub>2</sub>, namely the main component of the coke oven wall brick, during carbonization, producing a low melting compound, fayalite (2FeO·SiO<sub>2</sub>) and damaging the wall brick. Therefore, we tested the alkaline earth metal (mainly Ca and Mg) compounds as catalysts, since large quantities are used as raw materials in the ironmaking process with the blast furnace and they are also included in coal.

First, various kinds of alkaline earth metal compounds were added to the coke using the 'pre-addition of catalyst to

coke' method and the chemical reactivity of the coke was then studied. Consequently, the high rate of catalytic activity of the Ca became apparent. We then proceeded to investigate a potential means of producing coke with high reactivity and strength by adding Ca-rich coal to charged coals in laboratory and commercial scale tests. Finally, Ca-rich coke was produced in the commercial scale coke oven at the Muroran works from June to September of 2002 and all the coke was used in the Muroran No. 2 blast furnace.

## 2. Basic Study Concerning the Production Method of Coke with High Reactivity and Strength

### 2.1. Experimental

#### 2.1.1. Sample Used

Six types of coals (Table 1, coals A-F) were used in the test. Coals A and B are caking coals, usually used for making blast furnace coke. Coal C is of low rank (vitrinite average reflectance ≤ 0.8) and low fluidity (log(maximum fluidity/ddpm) ≤ 2.5) coals. Here, this type of coal is described as a low rank and slightly caking coal, abbreviated as "SCC". Coals D, E and F are non-caking coals which show no fluidity. Coal F contains a large amount of Ca (Ca-rich coal). In addition, in order to investigate the effect of the alkaline earth metal addition on the coke reactivity, five compounds (SrCO<sub>3</sub>, CaCO<sub>3</sub>, MgCO<sub>3</sub>, CaO and MgO) were used.

#### 2.1.2. Carbonization Test

##### (1) Addition of Alkaline Earth Metal Compound

In order to study the effect of the alkaline earth metal compound addition on the coke chemical reactivity, the coal/alkaline earth metal compound mixtures were carbonized in an electrically heated test coke oven.<sup>9)</sup> Coals B and C were crushed to 80% < 3 mm and a blended coal was then prepared by mixing coals B and C (coal B 70%, coal C 30%). The moisture content was 4%. After various kinds of alkaline earth metal compound were added to the blended coal at an addition rate of 2.5 to 7.5 mass%, the sample was charged in a steel box (420 mm wide, 600 mm long and 400 mm high) at a bulk density of 830 dry-kg/m<sup>3</sup>. The box

Table 1. Characterization data for the coals used.

Coal	Proximate (mass % db)		Total dilatation (vol.%)	Maximum fluidity (log MF/ddpm)	Reflectance (av.)(%)	Major ash component (%)							
	VM	Ash				P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO
A	20.7	9.8	99	2.56	1.42	0.74	1.12	0.83	59.99	26.66	4.20	1.42	0.59
B	23.8	8.8	103	2.93	1.28	0.45	1.07	0.75	56.40	31.48	3.70	0.87	0.59
C	35.7	9.1	32	2.08	0.79	0.41	1.14	0.51	62.98	23.83	4.99	1.52	0.76
D	43.2	4.7	0	—	0.63	0.38	2.22	0.52	55.72	22.43	9.66	2.85	1.66
E	48.6	1.7	0	—	0.44	0.31	0.77	0.39	39.38	19.72	18.04	6.56	1.69
F	37.4	5.3	0	—	0.61	0.08	0.13	1.47	21.23	9.18	6.07	45.99	1.34

Table 2. The blending composition of the coals.

Coal	Test								
	1	2	3	4	5	6	7	8	9
A				20	20	20	20	20	20
B	70	90	80	50	50	50	50	50	50
C	30			30	25	20	15	20	20
D								10	
E									10
F		10	20		5	10	15		

was then placed in an electrically heated test oven and carbonized for 18.5 h under heating conditions equivalent to the flue temperature of 1 250°C in an actual coke oven.

(2) Addition of Ca-rich Coal

In order to study the effect of adding Ca-rich coal to charged coals on the coke reactivity and strength, coals were crushed to 85% <3 mm and blended as shown in Table 2, with a moisture content of 3%. The blended coals were then charged in a steel box at a bulk density of 850 dry-kg/m<sup>3</sup>. In tests 1, 2 and 3, the blending ratio of coal F was 0, 10 and 20% respectively and the changes in the coke reactivity by blending coal F were examined. In Tests 4 to 7 meanwhile, the effect of substituting coal F for coal C on coke reactivity and strength was studied, where the blending ratio of coal C was decreased from 30 to 15% while that of coal F was increased from 0 to 15%. In Tests 8 and 9, the effect of substituting coals D and E for coal F on coke reactivity and strength was studied, where coals D and E were used instead of coal F in Test 6.

2.1.3. Coke Quality Measurement

(1) Coke Strength

After the coke was quenched with nitrogen, the coke sample was stabilized by the drop shatter test apparatus,<sup>10)</sup> where the sample was dropped from the position of 2 m high, three times. The JIS drum index of coke (DI<sup>150</sup>, a percentage of coke mass retained on sieves with 15 mm apertures to the original mass of the coke sample after 150 revolutions in the JIS drum tester)<sup>10)</sup> was measured.

(2) Coke Reactivity

The JIS coke reactivity index (JIS R<sub>c</sub>I),<sup>10)</sup> which stands for the chemical reaction rate of coke with CO<sub>2</sub> at a low temperature range, was measured as a means of evaluating the chemical reactivity of coke. In this method, 10 g of 0.85–1.7 mm coke breeze is reacted with CO<sub>2</sub> at 950°C and JIS R<sub>c</sub>I is calculated by CO/(CO+2CO<sub>2</sub>)×100, where CO(%) is the concentration of CO at the outlet of the reactor and CO<sub>2</sub>(%)=100–CO(%).

Moreover, the CRI (Coke Reactivity Index: the percentage of weight loss to the original coke mass after reaction

under CO<sub>2</sub> at 1 100°C for 2 h) and CSR (Coke Strength after Reaction: percentage of coke mass retained on a sieve with 9.5 mm apertures to the mass of reacted coke sample after 600 revolutions in the I-type drum tester)<sup>11)</sup> were measured. CRI represents the reactivity of lump coke at a relatively high temperature and is therefore influenced by the pore structure as well as the chemical reactivity of coke.

In addition to the two industrial methods described above, the reactivity of coke was measured using TGA (thermogravimetric analysis). The instrument used was a Shimadzu TG-50. Samples were crushed to between 150 and 300 μm. About 5 mg of the sample was inserted into the sample cell of the TGA and heated from room temperature to the desired reaction temperature in a nitrogen atmosphere, at a heating rate of 10°C min<sup>-1</sup>. The temperature was then maintained and the gas was changed to a reaction gas, while the reaction rate was obtained through weight loss of up to 10%. The reaction temperatures were 1 000 to 1 150°C and the reaction gas composition was CO<sub>2</sub>/CO=100/0, 50/50 and 20/80. The gas flow rate was 50 cm<sup>3</sup> min<sup>-1</sup>. This experiment was conducted for the cokes of Tests 1 and 6 respectively.

Furthermore, a cylindrical coke sample (of diameter 10 mm, length 15 mm) cut out of a lump coke was examined using the TGA. The sample was heated from room temperature to 1 150°C in a CO<sub>2</sub>/CO=50/50 atmosphere at a heating rate of 10°C min<sup>-1</sup> and the weight loss was recorded as a function of temperature. This experiment was conducted for the cokes of Tests 1 and 3 respectively.

(3) Coke Porosity

The coke samples of Tests 1, 2 and 3 were crushed to between 0.84 and 1.68 mm and the coke porosity was then measured using a mercury porosimeter (FISONS, POROSIMETER2000).

(4) Ca Distribution

The distribution of Ca in coke and coal was analyzed using the EPMA technique. The cross-section of the coke samples (Tests 1 and 3) and the lumps of coals B and F were analyzed.

2.2. Results and Discussion

2.2.1. Effect of Alkaline Earth Metal Compound Addition on Coke Reactivity

Figure 4 shows the relationship between the addition rate of the alkaline earth metal and the JIS coke reactivity index. Here the addition rate of the alkaline earth metal is described as the mole of the added alkaline earth metal per unit mole of carbon in coke. It is clear that the catalytic effects of the alkaline earth metal is in the order of Sr>Ca>

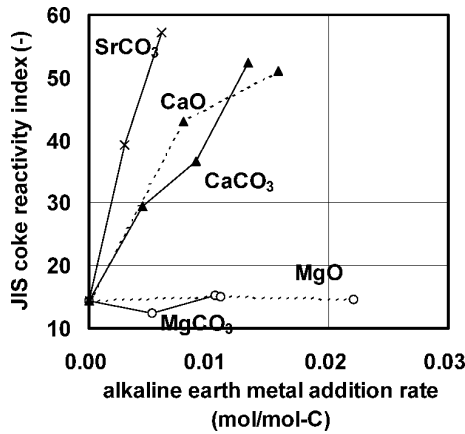


Fig. 4. The relationship between the addition rate of the alkaline earth metal and the JIS coke reactivity index.

Table 3. Effect of Ca-rich coal addition on coke quality.

	Coal F (%)	DI <sup>150</sup> <sub>15</sub>	CRI	CSR	JIS R <sub>pl</sub>
Test 1	0	84.5	23.3	66.8	6.6
Test 2	10	84.0	24.8	68.0	39.0
Test 3	20	81.8	33.2	58.6	41.8

Mg and that the addition of MgCO<sub>3</sub> or MgO showed no catalytic effects. Coal contains little Sr and there are no reasonably priced Sr compounds that can be used in large quantities in the steel industry. On the other hand, large amounts of CaCO<sub>3</sub> and CaO are already used in the iron-making process as raw materials and also there are some coals rich in Ca. Therefore, Ca is considered to be promising as a catalyst for enhancing the reactivity of blast furnace coke.

2.2.2. Effect of Ca-rich Coal Addition on Coke Quality

(1) JIS Coke Reactivity Index and CRI

Table 3 shows the results of Tests 1 to 3. It is clear that the JIS coke reactivity index increases considerably with the addition of coal F (Ca-rich coal).

Figure 5 shows the relationship between the blending ratio of non-caking coals (D, E and F) and the JIS coke reactivity index. The JIS coke reactivity index increases with increasing the blending ratio of coal F (Ca-rich coal), but tends to level off as the blending ratio increases. An increase in the blending ratio of coals D does not, meanwhile, increase the JIS coke reactivity index, although the catalytic effect of Ca in coal F is considered to do so. The reason why the JIS coke reactivity index for the blended coal containing coal E is higher than that for the blended coal containing coal D is considered to be because the rank of coal E is lower than that of coal D, which might lead to the formation of a more reactive coke texture.

Figure 6 shows that CRI increases with increasing the blending ratios of coals D, E and F. When maintaining a blending ratio of 10%, the CRI for the blended coals containing coals E and F exceeds that of the blended coal containing coal D. It is interesting that despite the far larger JIS coke reactivity index for the blended coal containing coal F than that for the blended coal containing coal E, the CRI for both blended coals are close. This is considered to be because the CRI is greatly influenced by the pore structure in the coke and the blending of coal E with the lower coal rank

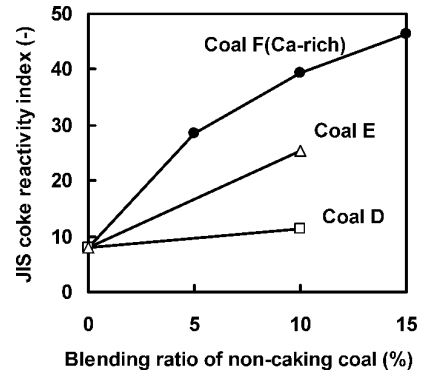


Fig. 5. The relationship between the blending ratio of non-caking coals and the JIS coke reactivity index.

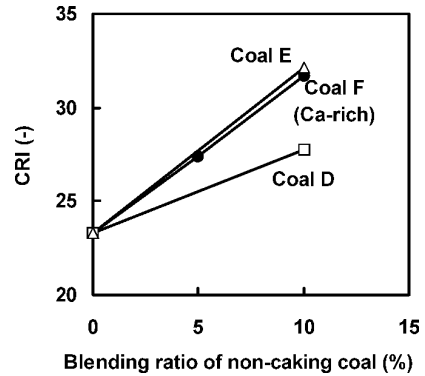


Fig. 6. The relationship between the blending ratio of non-caking coals and CRI.

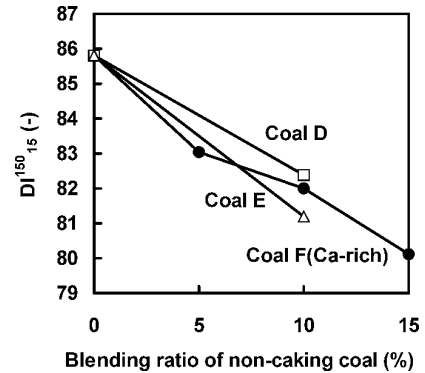


Fig. 7. The relationship between the blending ratio of non-caking coals and DI<sup>150</sup><sub>15</sub>.

leads to the formation of more porous coke structure.

(2) Coke Strength (DI<sup>150</sup><sub>15</sub> and CSR)

Figure 7 shows that the DI<sup>150</sup><sub>15</sub> decreases with increasing the blending ratio of coals D, E and F. Figure 8 shows that CSR decreases with increasing the blending ratio of coals D, E and F. When maintaining a blending ratio of 10%, the CSR for the blended coals containing coals E and F is lower than that for the blended coal containing coal D.

(3) Coke Reactivity Measured with TGA

Figures 9–11 show the relationship between the reaction temperature and rate, measured with TGA. The JIS coke reactivity index for the base coke (Test 1, produced from the blended coal without coal F (Ca-rich coal)) and the Ca-rich

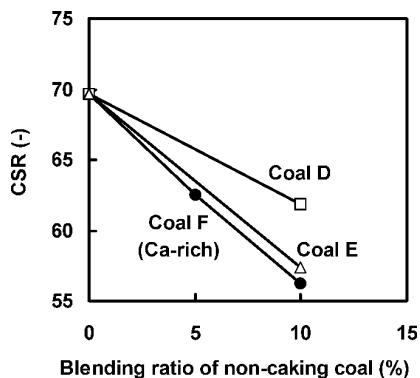


Fig. 8. The relationship between the blending ratio of non-caking coals and CSR.

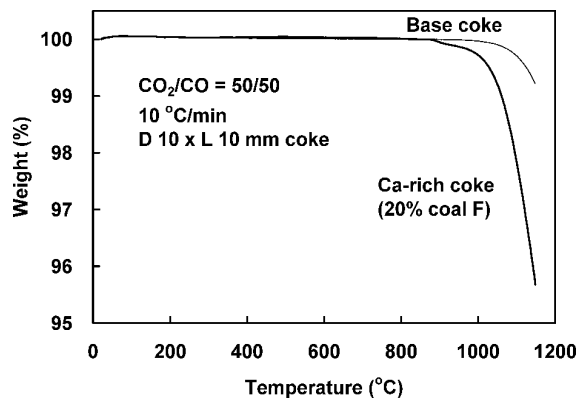


Fig. 12. The weight loss of a cylindrical coke sample in  $CO_2/CO=50/50$ .

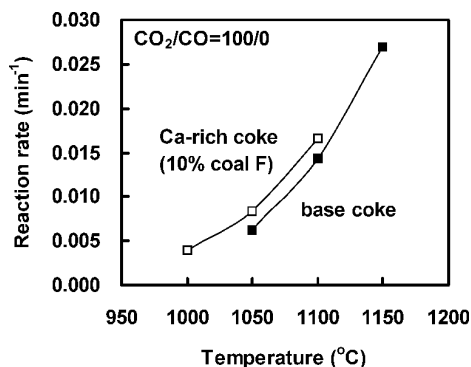


Fig. 9. The relationship between reaction temperature and rate ( $CO_2/CO=100/0$ ).

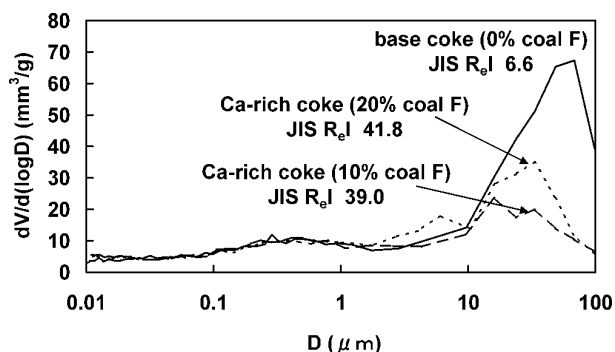


Fig. 13. The distribution of porosity measured by the mercury porosimeter.

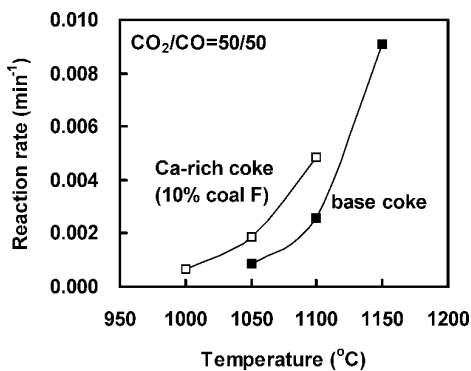


Fig. 10. The relationship between reaction temperature and rate ( $CO_2/CO=50/50$ ).

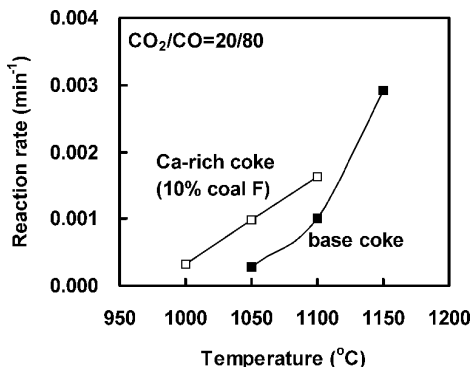


Fig. 11. The relationship between reaction temperature and rate ( $CO_2/CO=20/80$ ).

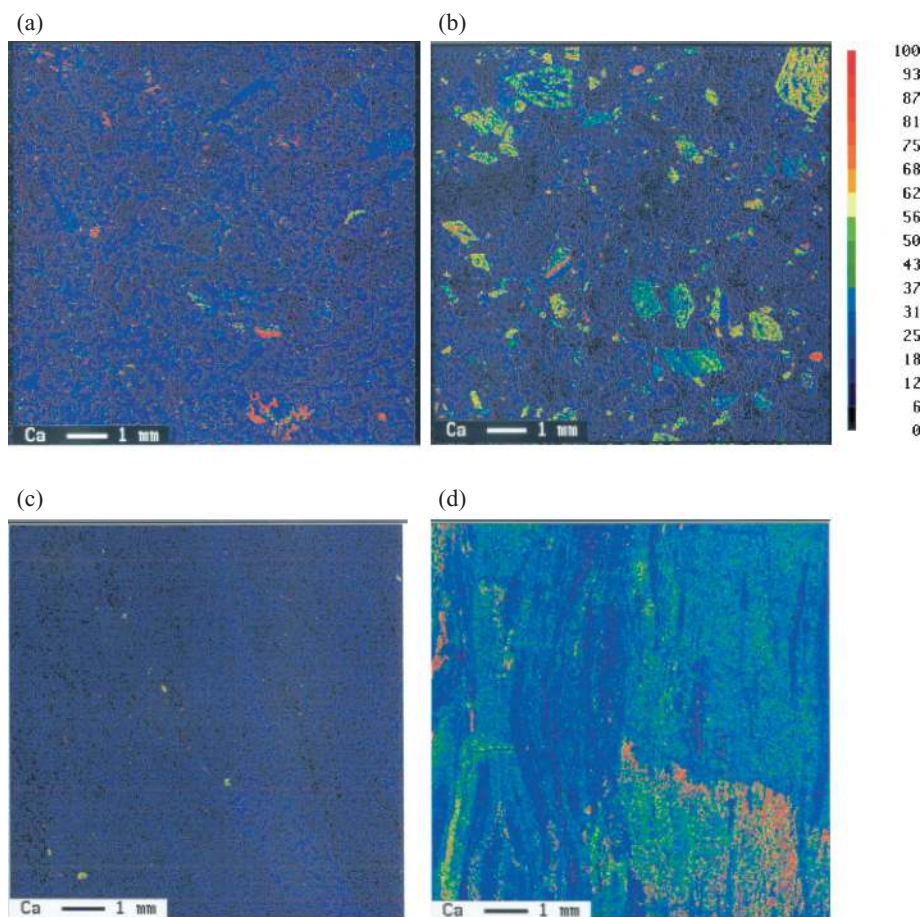
coke (Test 6, produced from the blended coal containing 10% of coal F) are 6.6 and 39.4 respectively. It is clear that the reaction rate of the Ca-rich coke (10% coal F) is higher than that of the base coke for any test temperature and any test atmosphere. In addition, in an atmosphere of  $CO_2/CO=20/80$  and  $50/50$ , closely resembling that of the thermal reserve zone in a blast furnace, the reaction rate of the Ca-rich coke (10% coal F) is more than double that of the base coke. The difference in the reaction rate between the base and Ca-rich coke (10% coal F) is remarkable in an atmosphere of relatively high CO concentration. The Ca-rich coke produced by blending coal F is considered to be suitable for decreasing the temperature of the thermal reserve zone in a blast furnace.

Figure 12 shows the weight loss of the base coke (Test 1) and the Ca-rich coke (Test 3, produced from the blended coal containing 20% of coal F). It is clear that the Ca-rich coke starts to lose weight at a lower temperature than that at which the base coke does likewise.

#### (4) Porosity

Figure 13 shows the distribution of porosity measured using the mercury porosimeter for the base coke (Test 1) and the cokes produced from blended coals containing 10% of coal F (Test 2) or 20% of coal F (Test 3). It is clear that the pore volume for the Ca-rich coke (10 or 20% coal F) does not exceed that of the base coke, suggesting that the high JIS coke reactivity index of the Ca-rich coke produced from blended coals containing coal F could not be attributed to the porosity.





**Fig. 14.** (a) The distribution of Ca for the base coke (Test 1). (b) The distribution of Ca for the Ca-rich coke (Test 3, 20% coal F). (c) The distribution of Ca for a lump of coals B. (d) The distribution of Ca for a lump of coal F (Ca-rich coal).

### (5) Ca Distribution

**Figures 14(a)** and **14(b)** show the distribution of Ca as determined using EPMA for the base coke (Test 1) and the Ca-rich coke (Test 3, produced from blended coal containing 20% of coal F). A large number of particles of size around 1 mm and containing condensed Ca are observed in the Ca-rich coke and these are considered to be derived from coal F particles.

**Figures 14(c)** and **14(d)** show the distribution of Ca in a lump of coals B and F respectively. The fine dispersion of Ca in coal F and the existence of a Ca-rich 'band' is clear. The reason for the high JIS coke reactivity index of the coke produced from the blended coal containing coal F may be attributed to the finely dispersed level of Ca in coal F. Further work is necessary concerning the difference in the mode of occurrence of Ca between the coke produced from blending coal containing coal F (Ca-rich coal) and the coke produced by adding Ca compounds such as  $\text{CaCO}_3$  and CaO to coal.

## 3. Production of Ca-rich Coke in a Commercial Scale Coke Oven

### 3.1. Investigation into the Coal Blend

When producing Ca-rich coke by blending a Ca-rich non-caking coal in a commercial scale coke oven, the blending ratio of the SCC, low rank and slightly caking

coals, should be reduced, in order to maintain the strength of coke above a certain level. On the other hand, any decrease in the blending ratio of the SCC may result in a corresponding decrease in coke reactivity. Consequently, it is important to investigate the possibility of producing the coke with a reactivity higher than that of normal coke and with virtually equivalent strength. Four kinds of blended coals were prepared as shown in **Table 4**. The coals were crushed to  $-3\text{ mm}$  78% and the moisture of the coal was 4%. The coals were then charged in a steel box at a bulk density of  $800\text{ dry-kg/m}^3$  before being carbonized in the test oven. The results (**Table 4**) show that the coke produced in Test 12 shows a higher JIS coke reactivity index than the base coke (Test 10) and that the  $\text{DI}_{15}^{150}$  and CSR of Test 12 coke is close to or higher than that of the base coke. Therefore, the potential to produce coke of high reactivity and strength by blending Ca-rich coal and adjusting the blend composition has been proved.

### 3.2. Production Test of Ca-rich Coke in a Commercial Scale Coke Oven at Kimitsu Works

Based on the previous fundamental studies, production tests of Ca-rich coke were conducted in a commercial scale coke oven (Nippon Steel Chemical Co.) at the Kimitsu works, by blending 5–7% of coal F (Ca-rich coal). The blending ratio of SCC was 19–29% as compared to 44% for normal coke production. As shown in **Table 5**, a coke of high reactivity and strength was then successfully produced

**Table 4.** The coal blending composition, coal properties and coke quality in producing the Ca-rich coke in a test coke oven.

		Test			
		10	11	12	13
Coal blend	coal F (Ca-rich) (%)	0.0	7.5	7.5	5.0
	SCC ratio (%) (incl. coal F)	30	16	11	24
Coal property	VM (mass % db)	27.2	25.5	25.0	26.5
	Ash (mass % db)	9.2	9.0	9.0	9.1
	Total dilatation (vol.%) (calc.)	90	100	105	94
	Maximum fluidity (log MF/ddpm) (calc.)	2.46	2.38	2.42	2.39
Coke quality	DI <sup>150</sup> <sub>15</sub> (-)	86.2	85.3	86.0	85.0
	CSR (-)	51.0	48.1	53.7	42.6
	JIS R <sub>c</sub> I (-)	17.0	33.9	37.3	31.2

**Table 5.** The coal blending composition, coal properties and coke quality in producing the Ca-rich coke in a commercial scale coke oven.

		Kimitsu		Muroran	
		base	Ca-rich	base	Ca-rich
Coal blend	coal F (Ca-rich) (%)	0	5-7	0	8
	SCC ratio (%) (incl. coal F)	44	19-29	42	45
Coal property	VM (mass % db)	28.5	26.1-27.3	27.6	28.7
	Ash (mass % db)	9.0	8.6-8.7	9.2	8.9
	Total dilatation (vol.%) (calc.)	56	69-76	49	81
	Maximum fluidity (log MF/ddpm) (calc.)	2.18	2.12-2.15	1.74	2.30
Coke quality	DI <sup>150</sup> <sub>15</sub> (-)	85.5	85.6-86.2	85.0	84.9
	CSR (-)	55.0	54.7-63.0	61.7	60.6
	JIS R <sub>c</sub> I (-)	15.8	33.3-39.4	15.1	45.9

in a commercial scale coke oven.

#### 4. Muroran No. 2 BF Operation with Ca-rich Highly Reactive Coke

##### 4.1. Long-term Production Test of Ca-rich Coke in a Commercial Scale Coke Oven at Muroran Works

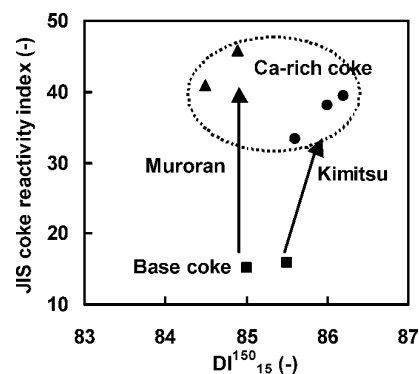
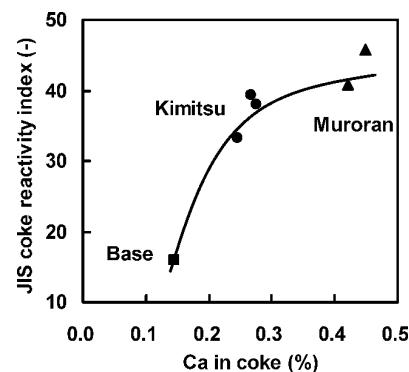
The next step involved producing Ca-rich coke in the commercial scale coke oven (Hokkai Iron & Coke Corp.) at the Muroran works from June to September of 2002 with all the cokes being used in the Muroran No.2 blast furnace. The typical coal blend during this period is shown in Table 5. Here, the blending ratio of SCC in Ca-rich coke production was found to be the same as that used in normal coke production. However, caking coals with high total dilatation were chosen, meaning the average total dilatation of the blended coal was higher than that for base coke production. During the production of Ca-rich coke, the blending ratios of coal F and SCC were 8% and 45% respectively. As shown in Table 5, a coke of high reactivity and strength was produced for a consecutive period exceeding two months.

**Figure 15** shows the relationship between the DI<sup>150</sup><sub>15</sub> and JIS coke reactivity index in terms of coke produced on a commercial scale. Blending Ca-rich coal and adjusting the coal blend composition results in the production of highly reactive coke which maintains its strength, DI<sup>150</sup><sub>15</sub>.

**Figure 16** shows the relationship between the Ca content in coke and the JIS coke reactivity index. The reactivity increases with increasing Ca content in the coke.

##### 4.2. The Evaluation of Ca-rich Highly Reactive Coke Using the Adiabatic Blast Furnace Simulator

Before the Ca-rich coke was tested in a commercial scale blast furnace, the effect of the Ca-rich coke on the reduction behavior of sinter was studied using the adiabatic blast


**Fig. 15.** The relationship between DI<sup>150</sup><sub>15</sub> and the JIS coke reactivity index.

**Fig. 16.** The relationship between Ca content in coke and the JIS coke reactivity index.

furnace simulator.<sup>1,12)</sup> Normal coke (JIS R<sub>c</sub>I=15.8) and Ca-rich highly reactive coke (produced from blended coals including 5% of coal F; JIS R<sub>c</sub>I=33.8) produced in a commercial scale coke oven at Kimitsu works, and sinter (**Table 6**) produced at the Kimitsu works were used in this test.

Table 6. The chemical composition of the sinter used.

Sinter (mass %)				
T.Fe	FeO	CaO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>
57.36	6.08	10.11	5.18	1.86

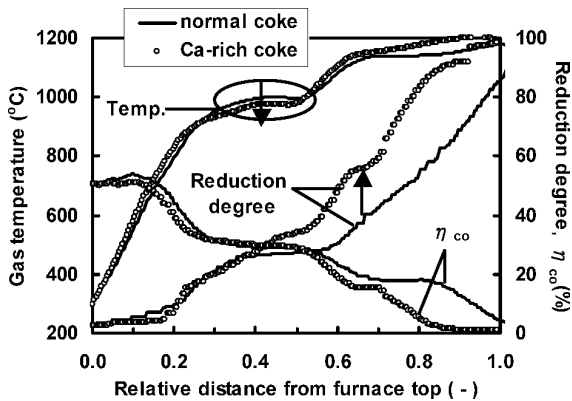


Fig. 17. Effect of Ca-rich coke on the temperature and sinter reduction behavior in the adiabatic blast furnace simulator.

The experimental conditions were as follows: RAR (reducing agent rate); 495.8 kg/t-p (PCR=160 kg/t-p), Bosh gas; 1 328 Nm<sup>3</sup>/t-p, CO; 37.5%, H<sub>2</sub>; 8.0%, N<sub>2</sub>; 54.5%.

As shown in Fig. 17, although the same sinter was used in the experiments, the Ca-rich highly reactive coke decreased the temperature of the thermal reserve zone and increased the reduction degree of the sinter. Based on these results, we decided to use Ca-rich coke in a commercial scale blast furnace.

### 4.3. Muroran No. 2 BF Operation with Ca-rich Highly Reactive Coke

As stated previously, Ca-rich coke was produced in the commercial scale coke oven at the Muroran works from June to September of 2002 and all the cokes were used in the Muroran No. 2 blast furnace (Hokkai Iron & Coke Corp.). During this period, the productivity of pig iron was between 1.89 and 2.08 (ton/d/m<sup>3</sup>) and the PCR (pulverized coal injection ratio) was between 146 and 154 (kg-coal/ton-pig iron). The coke strength was maintained at the desired value and no remarkable changes in the gas permeability in the blast furnace were observed. As shown in Fig. 18, the RAR decreases with increasing the blending ratio of Ca-rich coal. Figure 19 shows the relationship between the Ca-rich coal blending ratio and the RAR. Due to the changes in the chemical composition of the sinter during the test period, the test data were plotted depending on the level of sinter FeO and Al<sub>2</sub>O<sub>3</sub>. This analysis also shows that RAR decreases with increasing the blending ratio of Ca-rich coal.

## 5. Conclusions

A method to produce ‘lump’ coke of high reactivity and strength was investigated in order to improve blast furnace reaction efficiency. The following findings were obtained.

(1) The addition of Ca compounds to coal prior to carbonization considerably increases the reactivity of the resultant coke at a low temperature range, in the thermal reserve zone of a blast furnace.

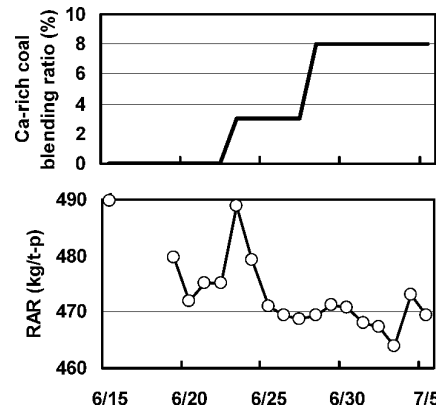


Fig. 18. Changes in RAR and Ca-rich coal blending ratio.

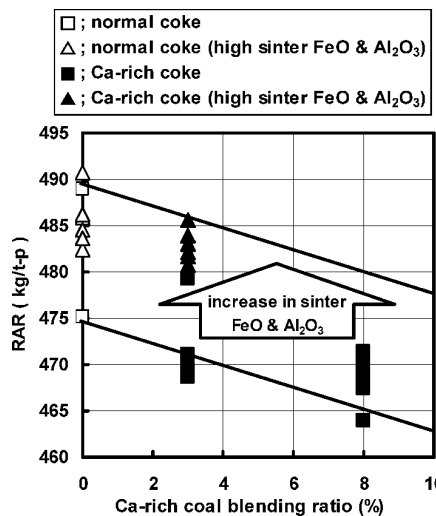


Fig. 19. Effect of Ca-rich coal blending ratio on RAR.

(2) A strong, highly reactive ‘lump’ form of coke can be produced by adding a Ca-rich non-caking coal and adjusting the coal blend composition. The Ca-rich coke was successfully produced in the commercial scale coke ovens both at Kimitsu and Muroran works.

(3) A laboratory scale experiment showed that the Ca-rich coke caused the temperature of the thermal reserve zone in a blast furnace to decrease. By using the Ca-rich coke in the Muroran No. 2 blast furnace, the reducing agent rate decreased by 10 kg/t-p.

This technology, producing coke of high reactivity and strength through catalyst addition, is promising as a means of improving the reaction efficiency of a blast furnace. In order to successfully commercialize this technology, we will continue to further study catalyst substances other than Ca-rich coal and alternative methods of adding the catalyst to the coke, such as the ‘post-addition of catalyst to coke’ method.

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