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DECREASE IN THE CARBON CONSUMPTION OF A COMMERCIAL BLAST FURNACE BY USING CARBON COMPOSITE IRON ORE[1]

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Abstract

Increasing coke gasification rate lowers the temperature of the thermal reserve zone, resulting in a decrease of carbon consumption and a reduction of the reducing agent rate of blast furnaces. To achieve this increase, the enhancement of coke reactivity itself or the close arrangement of iron ore and carbonaceous materials has been investigated in Japan. Against this, RCA, "Reactive Coke Agglomerate," having a high carbon content, has been developed, and it was found that the agglomerate mixed-in sinter layer had two functions: one having high reducibility itself and the other enhancing the reduction of the surrounding sinter. As a result of the two functions, a significant decrease of the temperature of the thermal reserve zone and an increase of gas utilization by using the agglomerate mixed-in sinter layer in a BIS test was achieved. As for the strength after reaction, disintegration was fairly small in comparison with that of the sinter both in the laboratory scale test and in a basket test using a plant's vertical probe. Long-term plant trials have been conducted at the Oita Works No. 2 Blast Furnace with a maximum use of 54 kg/tHM. It was found that RCA could lower the temperature of the thermal reserve zone and carbon consumption in a commercial blast furnace. Carbon consumption was decreased along the relationship of 0.36 kgC/tHM per 1kgC/tHM of input carbon from RCA.

Key words: Blast furnace; Reduction; Agglomeration; Carbon composite.

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1 INTRODUCTION

Recently, in order to drastically lower the carbon consumption rate of blast furnaces, efforts have been made toward "lowering the reduction equilibrium temperature," which is one of the constraints regarding reduction efficiency inside such a furnace.(1) As a means for a solution, including for coke reactivity enhancement,(2-5) a method was found for faster reduction and gasification reaction (coupling mechanism) by closely arranging iron ore and carbonaceous materials, and this mechanism was extensively studied.(6-9)
Many of the results of these studies suggest that the use of carbon composite iron ore in blast furnaces will improve the efficiency of reduction reaction, and thus proves also, as it is reported, the result of its use in a commercially operated blast furnace.(10-12) As one of the manufacturing methods of such carbon composite ore, there is a method of manufacturing non-fired carbon composite iron ore using cement as a binder.(13-14) In the past, tests were carried out blending a large quantity of non-fired carbon composite iron ore,(15) but such tests are without any clear information on the changes of various blast furnace data, such as the carbon consumption rate and on the manufacturing conditions of optimal carbon composite ore, which is why, aiming to realize faster reaction/higher efficiency inside a blast furnace, we worked on the development of non-fired carbon composite iron ore that enables the improvement of various operation data from blast furnaces – along with why we conducted manufacturing tests and using tests in the blast furnaces at Oita Works. This report thus summarizes the results of fundamental studies and evaluation result of manufacturing the non-fired carbon composite iron ore and of use in a commercially operated blast furnace.

2 EXPERIMENTAL METHOD

2.1 Investigation of Reduction Behavior

In order to raise the use efficiency of carbon in a blast furnace, it is necessary to bring down the reduction equilibrium temperature in the blast furnace and to improve a reduction efficiency of iron oxide by reducing gas. It is also important to ensure low-carbon consumption operation in order to reduce as quickly as possible the charged iron oxide, as when iron oxide reduction is delayed and when the amount of direct reduction increases at the lower part of the blast furnace, there will be no choice but to increase the use of carbon to deal with the lowered molten iron temperature etc. Where this concerns non-fired carbon composite iron ore, the iron oxide inherent within is reduced rapidly if iron oxide and carbonaceous materials are arranged closely together. Furthermore, as this ore has been agglomerated using fine carbonaceous materials and used in a non-fired state in the blast furnace, the reactivity of the contained carbon is high, and it can be expected that the temperature at the reduction equilibrium point will drop. However, it is anticipated that the reduction efficiency changes depending on the amount of iron oxide and carbon contained in the carbon composite iron ore, and we first conducted an offline test for determining manufacturing conditions.
For the manufacturing of carbon composite iron ore, there are many options concerning iron oxide and carbonaceous materials, but we used here raw materials consisting mainly of dust found at the worksite itself. However, we selected this as the material for mixing dust containing few impurities such as Na, K and Zn, because the

material is intended to be used in a blast furnace. As a method of manufacturing carbon composite iron ore, we adopted the pan-pelletizer method, and to maintain pellet strength, we added cement in the amount of 10% of the total weight.

We manufactured five types of pellets containing different amounts of carbon, as given in Table 1, and we compared them in terms of their reduction properties. CCA1 and CCA2 are non-fired carbon composite iron ores manufactured in a commercially operated dust treatment plant,6 and CCA3 and CCA4 are green pellets manufactured offline. Regarding the carbon composite iron ore, for cement to harden, we used a type that cures in 14 days.

For the reduction test, we used 100 g of a pellet whose diameter was 10-15mm, sandwiching it between 200 g of sintered ore of same diameter, and raised the temperature up to 1,100˚C, reducing it under the loading condition of 1 kg f/ cm2. As the temperature pattern, we adopted the result of measurements conducted with a thermometer inserted beforehand into the blast furnace (Figure 1).

Table 1. Chemical composition of sinter and pellet used in reduction tests

		Sinter	Fired Pellet	Carbon composite agglomerate			
				CCA 1	CCA 2	CCA 3	CCA 4
Manufactured in *		P	P	P	P	L	L
T.Fe	mass%	58.0	67.1	47.0	48.4	32.8	33.0
M.Fe	mass%	-	-	1.67	20.73	0.20	0.32
FeO	mass%	8.88	0.69	8.70	7.30	1.40	1.68
CaO	mass%	8.65	2.57	10.24	11.59	12.86	12.28
SiO_2	mass%	5.19	2.45	6.34	5.00	7.87	7.44
Al_2O_3	mass%	1.83	0.66	2.63	1.55	3.13	2.91
MgO	mass%	1.55	0.04	1.70	1.40	1.19	1.27
T.C	mass%	Trace	Trace	5.6	12.1	20.6	23.1

* P ; Plant, L; Laboratory

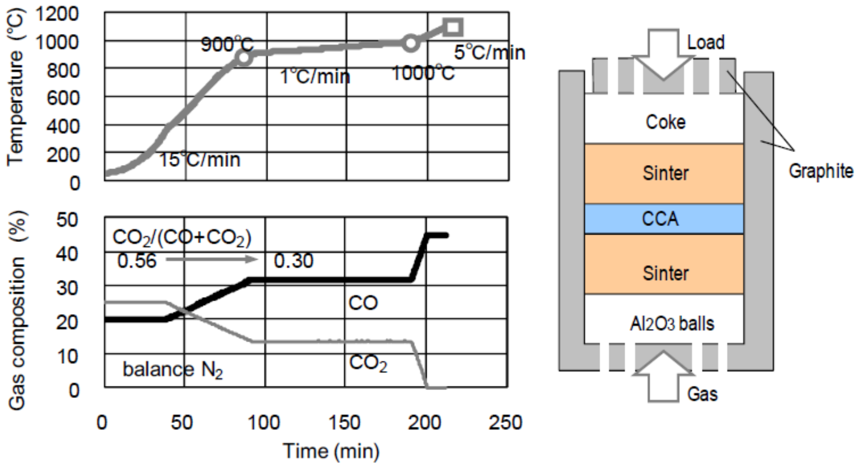

Figure 1. Tests Procedure of reduction test under load.

2.2 Investigation of Cold Strength

The cold strength of non-fired carbon composite iron ore is one of the important physical properties when determining manufacturing conditions from the viewpoint of preventing the ore from becoming finely crushed at the time of its transportation and subsequent charging into the blast furnace. As a major influencing factor contributing to the cold strength of carbon composite iron ore, when the cement addition rate is held constant, is a percentage of carbon in the carbon composite iron ore, and therefore, we investigated offline the changes of cold strength by manufacturing carbon composite iron ore of different carbon content percentages. For these tests, we used 10% of cement addition for all, and we measured the crushing strength (JIS M8718) of the carbon composite iron ore after 14 days of curing after its manufacture.

2.3 Experimentation in a commercially operated furnace

For verifying the merits of carbon composite iron ore in commercially operated facilities, we manufactured 21,000 t of non-fired carbon composite iron ore (RCA: Reactive Coke Agglomerate; hereinafter abbreviated as “RCA”) in a commercially operated plant, and conducted tests using it in the No. 2 Blast Furnace of Oita Works. A total of 21,000 t of RCA was manufactured by a pen-pelletizer of 5 m in diameter and was cured for more than two weeks after the manufacture. As it was manufactured during winter, taking into consideration the risk of delayed cement hardening, the amount of cement was increased by 1% to 11%, which is higher than the percentage applied for the offline tests. The composition and physical properties of the manufactured RCA are shown in Table 2. While manufacturing RCA, its components are measured every day, and by adjusting the ratio of each mixed raw material, adjustments were made so that the contained carbon ratio was maintained at 20%. Regarding the cold strength of RCA with 11% of cement-mixing, It is judged that RCA was strong enough for use in the blast furnace.

The RCA thus manufactured was used for testing for 80 days in the No. 2 BF of Oita Works (furnace volume of 5775 m3). Taking into consideration the combined water/moisture of RCA and the effect of a certain percentage of mixed cement that will result in slag at the end, the maximum volume of its use in the blast furnace was set at 54 kg/t HM. RCA was increased stepwise the volume of use and studied quantitatively the relationship between the volume of use and reduction efficiency. While increasing the volume of RCA used, we maintained constant the amount of total carbon (T. C.) and total Fe (T. Fe) for charging, by adjusting the charging volume of cokes and pellets; and where it concerned the heat adjustment required due to the changes of reduction efficiency, it was managed by changing the amount of pulverized coal injection or of the coke charge. Regarding the charging location of RCA, the charging condition was determined so that RCA is charged to the inner perimeter of the furnace where the reduction of iron ore in the blast furnace is most liable to be delayed.

Table 2. Chemical composition and basic properties of RCA

T.C	T.Fe	M.Fe	FeO	CaO	SiO_2	Al_2O_3
%	%	%	%	%	%	%
21.3	36.6	0.3	2.6	11.4	7.6	2.6

MgO	P	S	Na_2O	K_2O	ZnO	Combined water
%	%	%	%	%	%	%
0.9	0.08	0.38	0.05	0.12	0.03	2.1

Moisture	Mean Size	Crushing strength (average)	Crushing strength (minimum)
%	mm	kg/P	kg/P
9.7	13.6	114.8	100.2

During the RCA use experiment, we inserted a vertical probe inside the blast furnace and learned the temperature distribution and reduction performance therein. The vertical probe was inserted vertically into the furnace from the location of the blast furnace perimeter (500 mm from the wall at the furnace throat), and the temperature distribution in the direction of the BF height was measured. Furthermore, A basket with the RCA sample and sinter was attached at the tip of the vertical probe and inserted into the blast furnace down to the zone of 900–950˚C and then taken out to analyze the sample after reduction.

2.4 Experiment in the Blast Furnace Inner Reduction Simulator

Concurrently with the experiment of using RCA in a commercially operated furnace, using a blast furnace inner reaction simulator,1 we conducted tests where RCA is used in an amount as high as 10% (160 kg/ tHM), in order to evaluate the drop of temperature at the reduction equilibrium point, along with the changes in carbon consumption. In this experiment, two conditions were applied, of which the base condition was to use only coke and sinter, and the other was to mix carbon composite iron ore in the amount of 10 mass% of sinter in the sinter layer. Meanwhile, with regard to the iron oxide and carbonaceous materials charged from the carbon composite iron ore, the amount of sinter and coke to be charged was adjusted so that the total Fe (T. Fe) and input carbon (T. C) stayed constant. As for charging conditions, carbon composite iron ore was placed between the sinter and coke, and the conditions of the gas/charging materials were set, with a carbon consumption rate (RAR: Reducing Agent Rate) at 496 kg/ tHM and a coke ratio (CR) at the equivalent of 336 kg/ tHM.

2.5 Observation of the behavior of Micro-Particles During the Drying Process

In order to check the behavior of micro-particles in suspension during the drying process, observation was made using a transmission digital microscope. A pattern diagram of the tests is shown in Fig. 1. A suspension of 1 mass % jet-milled pulverized iron ore C was prepared and 50 μL of it was dropped onto a glass plate and spread thinly to 5 mm. By heating this suspension using a halogen lamp, the behavior of micro-particles in the drying process was observed using a transmission digital microscope. In order to check the influence of APD on the behavior of micro-particles, an observational comparison of two levels was made, one where APD was not added to the suspension, and the other to which was added 5 mass % APD.

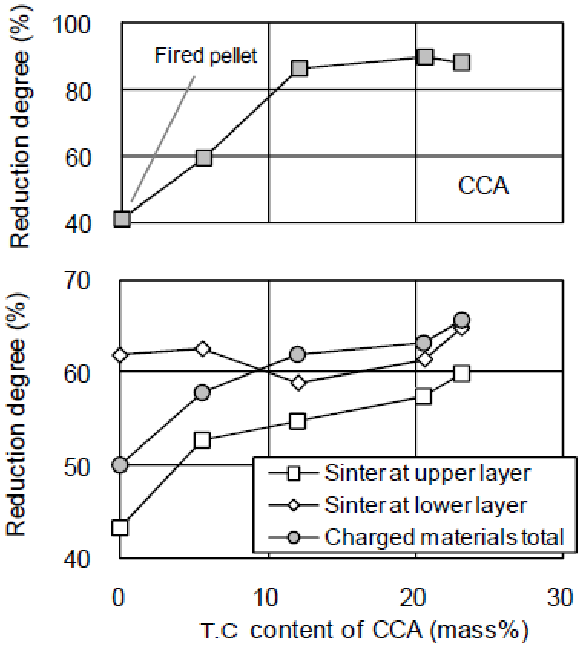

Figure 2. Influence of carbon content of CCA on reduction degree of materials at 1100°C.

3 RESULTS

3.1 Result of Offline Reduction Tests

Figure 2 shows the result of reduction tests conducted using carbon composite iron ore manufactured under individual conditions. The carbon composite iron ore itself showed a striking improvement of reduction degree at all levels, compared with fired pellets. It also shows that the higher the carbon content of carbon composite iron ore, the faster the reduction of iron oxide in the carbon composite iron ore, and that, where the content percentage is higher than 10%, a reduction degree higher than 90% was recorded. Furthermore, the use of carbon composite iron ore regenerates reduction gas, which then improves the reduction degree of sinter in the upper layer, and the higher the carbon content, the stronger its influence.

We also looked at the results from the viewpoint of the reaction of carbon in the carbon composite iron ore. We calculated the carbon consumption rate in the carbon composite iron ore by formula (1), and showed the results in Figure 3 together with the residual carbon. The carbon in the carbon composite iron ore was consumed 100% until it reached 20%, but thereafter, residual carbon was seen to exist. Based on the above and from the viewpoint of the use efficiency of the carbon in the carbon composite iron ore, it was judged that 20% carbon in the agglomerate was desirable.

$$\text{Carbon consumption} = \left(1 - \frac{C_A/\text{T.Fe}_A}{C_B/\text{T.Fe}_B}\right) \bullet 100 \quad \cdots(1)$$

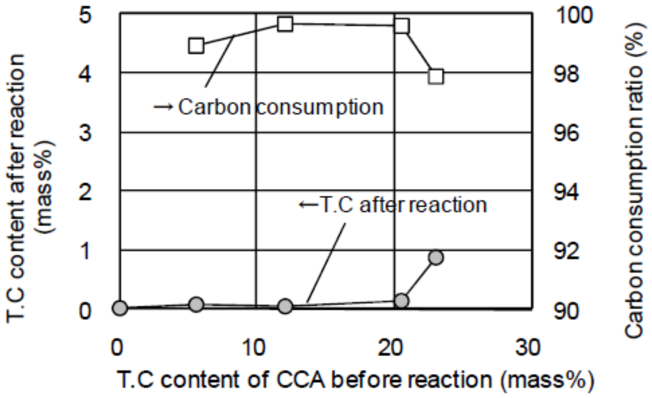

Figure 3. Influence of carbon content of CCA on residual carbon after reaction at 1100°C.

3.2 Microstructure After Reduction

During the reduction tests, after heating to 1100˚C, the sample was cooled down with N2, and the reduced sample was taken out to observe its microstructure (Figure 4). The carbon composite iron ores after reduction have all retained their own shape, and with regard to CCA2, CCA3, and CCA4, a lot of metal was observed. However, CCA4 had the highest carbon content and therefore residual carbon after reaction, and coarse residual carbon as large as 200μm was observed. The higher the carbon content in carbon composite iron ore means a lower content of oxide iron. Therefore, the higher the carbon content in carbon composite iron ore, the larger the distance between oxide iron particles, obstructing the metal-to-metal bonding, resulting in no formation of metal bridges, where, thereby, it was assumed that the strength after reaction became weakened.

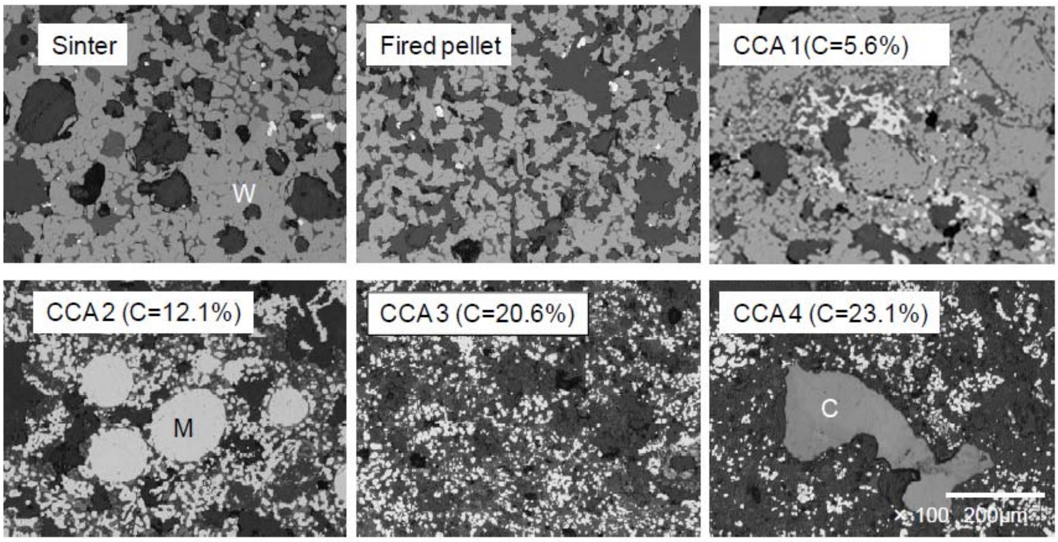

Figure 4. Microstructure of carbon composite agglomerate after reduction at temperature up to 1100°C, together with sinter and fired pellet. White: metal(M), pale grey: Wustite(W), dark grey: Residual carbon materials(C), Black: Pores.

3.3 Cold Strength

Figure 5 shows the relationship between cold strength and carbon content. The higher we raised the carbon content in the carbon composite iron ore, the weaker the strength of the carbon composite iron ore. This is thought to be attributable to the fact that the collected coke dust used as a carbon source in CCA is hydrophobic, and therefore, weak in bonding force with cement, and the strength of agglomerate weakens as the ratio of addition increases.

Based on the above, it was judged that 20% of carbon in the agglomerate enables the effective use of carbon in carbon composite iron ore, and in order to maintain the strength after reaction and the cold strength at the highest level, CCA was manufactured aiming to achieve C = 20% for using in the experiment in a commercially operated blast furnace. And we selected the name of this agglomerate as RCA (Reactive Coke agglomerate).

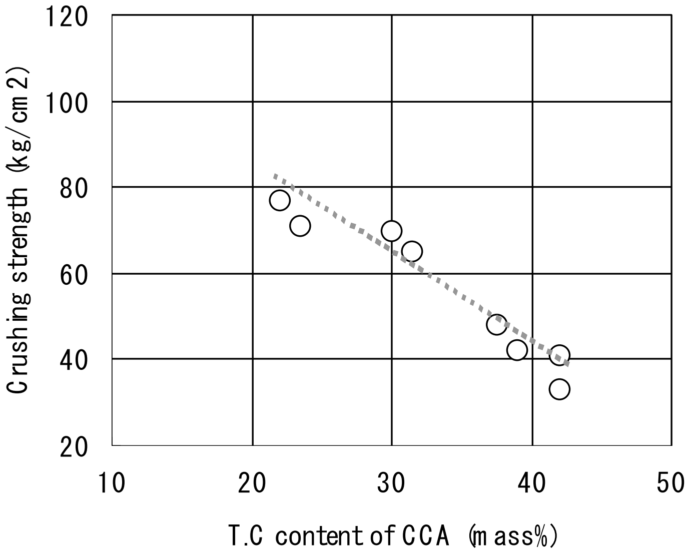

Figure 5. Relationship between Cold strength after curingand Carbon content in cement-bonded pellet.

3.4 Result of the Experiment Using RCA in a Blast Furnace

Figure 6 shows the transition of the operational results of Oita No. 2 Blast Furnace while using RCA. Ever since the start of RCA use, the utilization ratio of the top gas improved and the amount of solution loss carbon decreased. As a result, the carbon consumption rate in the blast furnace could be lowered. Regarding the carbon consumption rate used in the blast furnace, a corrected carbon consumption rate was calculated taking into consideration thermal indices, such as the temperature of molten slag and heat loss, and showed in Figure 7 the relationship between the amount of RCA used and the corrected input carbon at the blast furnace. As a result, it was calculated that the margin of the reduction of carbon consumption at the blast furnace attributable to the use of non-fired carbon composite iron ore (RCA) is 0.36 kg C/tHM per 1 kg/tHM of carbon derived from RCA.

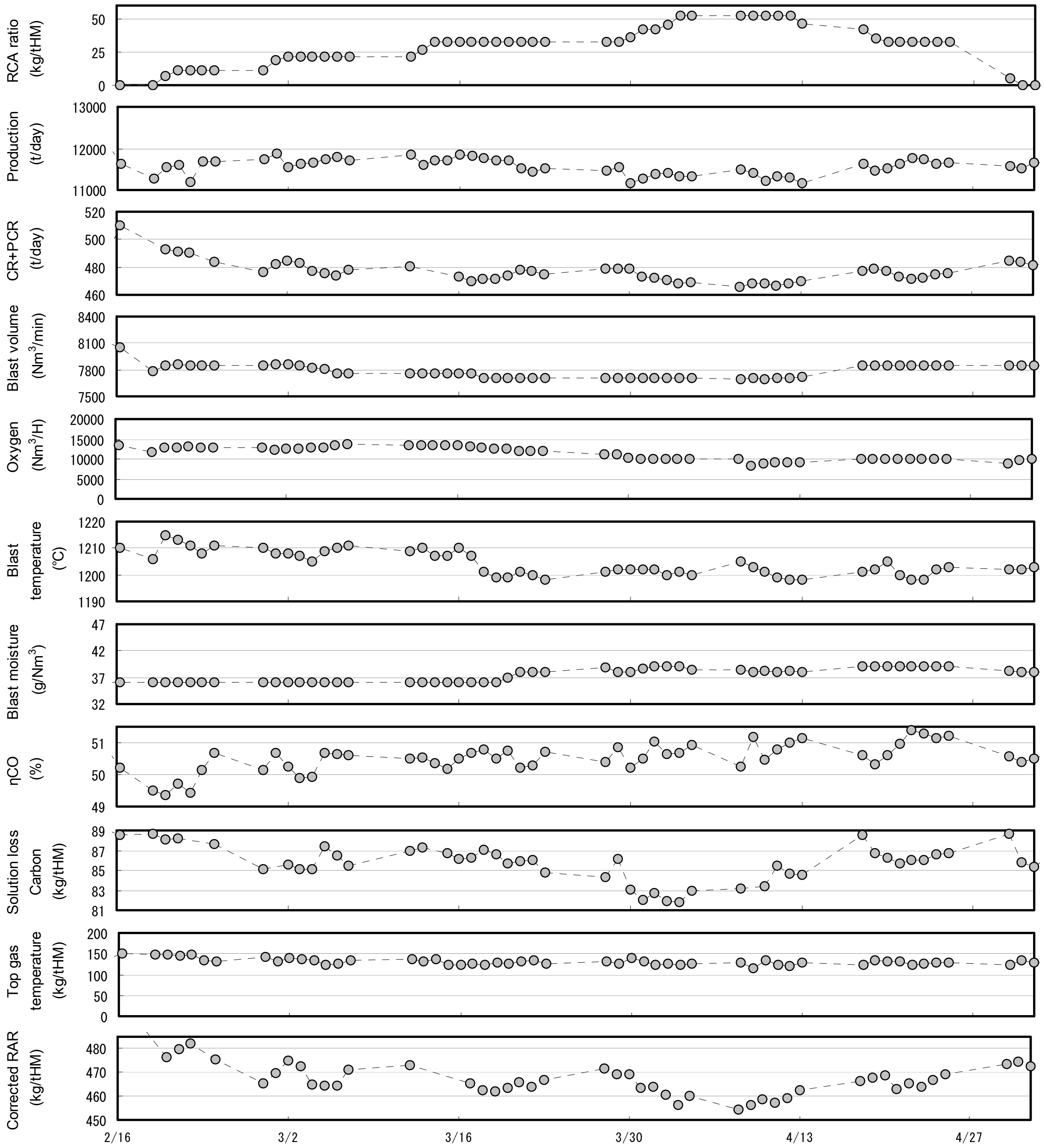

Figure 6. Operational results of plant trial test of RCA at Oita No.2 BF

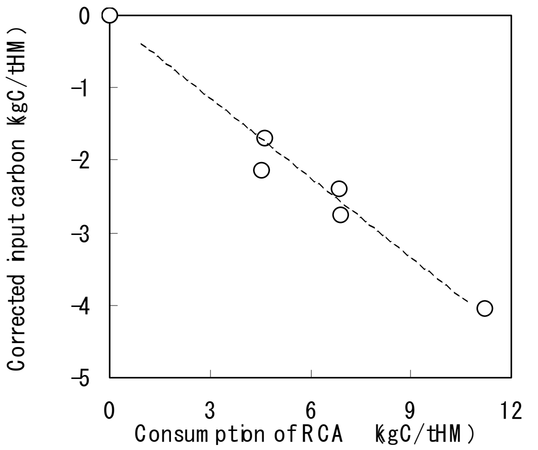

Figure 7. Relationship between consumption of RCA and corrected input carbon.

4 DISCUSSION

The reduction tests with carbon composite iron ore up to 10% (equivalent to 175 kg/ tHM) was conducted by using Blast Furnace Inner Reaction Simulator1 and this result was compared and evaluated with those from tests conducted using a commercially operated blast furnace. After the tests, RCA samples was taken out and carbon consumption at each temperature and reduction degree was measured. Furthermore, during the experiment conducted using the commercially operated No. 2 Blast Furnace of Oita Works, a basket with RCA was attached and inserted into the blast furnace. Then, the RCA sample in the basket taken out was analyzed after the reduction was affected under temperatures up to 950˚C. Figure 8 shows the relationship between the carbon consumption and the reduction degree of the RCA samples from these two kinds of tests. As a result, both the blast furnace experiment and the simulator tests showed almost the same reduction behavior of RCA, and it could be verified through the commercial furnace experiment that RCA is reduced earlier than sinter.
Figure 9 shows the distribution of temperatures in the blast furnace measured by the vertical probe. The temperature at the reduction equilibrium point at the time of using 54 kg/tHM of RCA dropped about 65˚C compared with the temperature at the time of no RCA, and it is now known that the use of carbon composite iron ore enables one to control the temperature at the reduction equilibrium point. Based on this result, it was calculated that the expected reduction of carbon consumption in a blast furnace by every 1˚C of the temperature lowered at the reduction equilibrium point is 0.064 kg C/˚C.

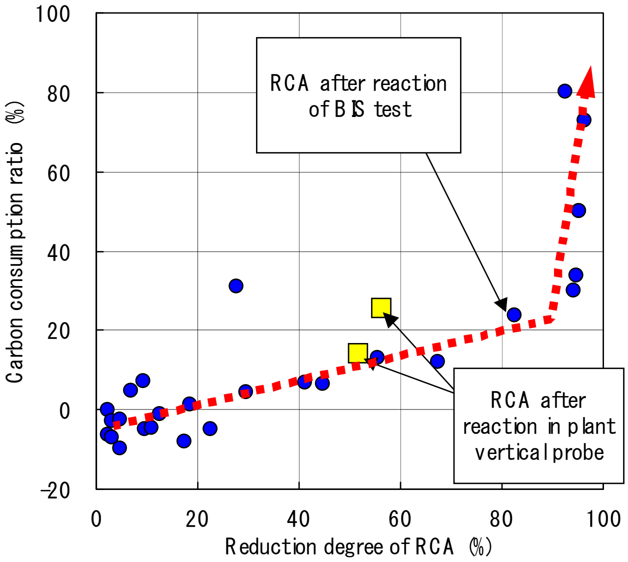

Figure 8. Relationship between reduction degree and carbon consumption of RCA (Results of BIS test and vertical probe of Oita No.2 BF).

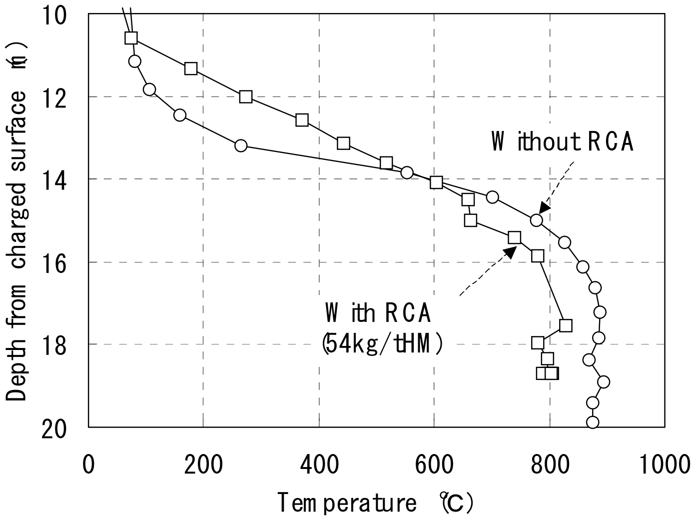

Figure 9. Distribution of temperature in blast furnace measured by using vertical probe of Oita No.2 BF.

Table 3. Result of reduction indices of BIS test with using 10 mass% CCA

		Without CCA	With CCA 10%	diff.
Temperature of thermal reserve zone	℃	1011	954	▲ 57
Shaft efficiency (900℃ base)	%	96.8	100.2	3.3
Indirect reduction degree	%	70.3	75.4	5.0
Solution loss carbon	kg/tHM	86.3	71.8	▲ 14.5
ηCO of top gas	%	54.6	55.2	0.6

We made a further detailed study of the relationship between the reduction behavior of carbon composite iron ore and the record of the blast furnace carbon consumption reduction. Table 3 shows the result obtained from the Blast Furnace Inner Reaction Simulator tests for the case where 10% carbon composite iron ore was used. In these tests, the amount of charged carbon derived from carbon composite iron ore was 40.5 kg C/tHM, and it was calculated that the expected reduction of carbon consumption at the blast furnace per 1 kg C/tHM of carbon derived from carbon composite iron ore is 0.23 kg C/tHM. It was also calculated based on the result of the commercial furnace experiment that the expected reduction of carbon consumption in a blast furnace by every 1˚C of temperature lowered at the reduction equilibrium is 0.167 kg C/˚C, and compared with the result of the simulator, the blast furnace experiment showed that the reduction record of carbon consumption in response to the range of temperature drop at the reduction equilibrium point is at a poor level. This is considered attributable to the fact that, with the simulator, RCA was charged evenly everywhere, but, with the furnace experiment, RCA was charged heavily around the blast furnace perimeter, the place where the vertical probe was inserted, and where the reduction is most liable to be delayed, which means that the temperature was measured at a location where more RCA was accumulated.

It is reported that among past tests that used non-fired carbon composite iron ore (T. C. = 5%) there were cases where the shaft portion temperature was low due to the dehydration endothermic reaction of combined water, delaying reduction.15 The simulator test this time uses carbon composite iron ore at as much as 10%, and therefore, the temperature at the shaft portion dropped by 20–30˚C, similar to the past known information, resulting in the delay of iron ore reduction. The low temperature of this shaft portion is considered one of the reasons that account for the low-level performance of RCA use in the case of the simulator (0.23 kg C/tHM) compared with the case of a commercial furnace (0.36 kg C/tHM).

5 CONCLUSION

Non-fired carbon composite iron ore is promising for reducing the consumption of carbon used in blast furnaces, thanks to fast reduction caused by closely arranging carbon and oxide iron, and we used this idea in a commercially operated blast furnace and verified its positive effect.

- Where it concerns carbon composite iron ore, if its carbon content is high, it not only does it quickly reduce the oxide iron inherent within, but it also prompts the reduction of surrounding sinter, and we learned that such positive effects are attributable to the high carbon content in the carbon composite iron ore. Based on this knowledge and from the viewpoint of residual carbon after reaction, cold strength, and strength after reaction, it is considered that 20% carbon in the non-fired carbon composite iron ore is desirable.
- We manufactured at Oita Works 21000 t of non-fired carbon composite iron ore (RCA) and conducted a long-term experiment at No. 2 Blast Furnace, using it at the maximum amount of use of 54 kg/tHM. As a result, it was confirmed that the temperature was lowered at the reduction equilibrium point and that the gas utilization ratio was higher, reducing the carbon consumption, in which the effect was calculated as 0.36 kg C/tHM per 1 kg C/tHM of input carbon derived from RCA.

REFERENCES

1 M. Naito, A. Okamoto, K. Yamaguchi, T. Yamaguchi and Y. Inoue : Tetsu-to-Hagané, 87(2001), 357.
2 S. Nomura, H. Ayukawa, H. Kitaguchi, T. Tahara, S. Matsuzaki, M. Naito, S. Koizumi, Y. Ogata, T. Nakayama and T. Abe: ISIJ Int., 45 (2005), 316.
3 T. Yamamoto, T. Sato, H. Fujimoto, T. Anyashiki, K. Fukada, M. Sato, K. Takeda, T. Ariyama :Tetsu-to-Hagené, 97 (2011), 501.
4 K. Higuchi, S. Nomura, K. Kunitomo, H. Yokoyama and M. Naito: ISIJ Int., 51 (2011), 1308.
5 K. Sunahara, T. Natsui, K. Shizawa and Y. Ujisawa: ISIJ Int., 51 (2011), 1322.
6 M. Nakano, M. Naito, K. Higuchi and K. Morimoto: ISIJ Int., 44 (2004), 2079.
7 Y. Kashiwaya, M. Kanbe and K. Ishii: ISIJ Int, 46 (2006), 1610.
8 M. Shimizu: ISIJ Int, 51 (2011), 1203.
9 M. Kawanari, A. Matumoto, R. Ashida and K. Miura: ISIJ Int, 51 (2011), 1227.
10 T.de Bruin, L. Sundqvist: Proc. ICSTI/ Ironmaking Conf ISS,Warrendale., (1998), 1263.
11 A. Kasai, H. Toyota, K. Nozawa and S. Kitayama: ISIJ Int, 51 (2011), 1333.
12 S. H. Son and Y. J. Kim : Proc. 6th ECIC, VDEh, Dusseldolf(2011), session17,DVD-ROM.
13 T. Inazumi, H. Furutaku, T. Kuwabara and K. Esaki : Conservation & Recycling, 6(1983), 167.
14 S. Kabuto, K. Nishikawa, H. Yoshida, S. Matsunaga, M. Kobayashi, K. Oka: CAMP-ISIJ,10(1997), 14.
15 S. Takagi, H. Maeda, A. Yumura, K. Takatani, T. Ohsawa, Y. Fujiwara and K. Mio: Tetsu-to-Hagané, 72 (1986), S886.