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Development of Carbon Composite Iron Ore Production and Improvement in Blast Furnace Reduction Efficiency

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Abstract

High efficiency of a blast furnace is an important element contributing to reduction of the production cost of iron ore and CO_2-saving. To this end, the close arrangement of iron ore and carbonaceous materials is effective for high efficiency of production cost reduction. Therefore, the carbon composite iron ore, Reactive Coke Agglomerate (RCA), has been developed. An off-line test of RCA strength was carried out before using RCA for a commercial blast furnace and the production condition of RCA was determined by this off-line test. Based on the above experimental results, 21 000 t RCA was produced by a commercial plant and long-term plant trials have been conducted at the Oita Works No. 2 Blast Furnace with a maximum use of 54 kg/tHM. These trials have shown that the carbon consumption can be decreased. The method of RCA production on a commercial scale was also investigated. To achieve a high productivity of supplying RCA to large blast furnaces, a rapid curing process of RCA using steam was investigated. We obtained a rapid treatment method of RCA with primary curing, stream curing, and drying. RCA involving the steam curing process has been implemented in Oita Works and it has helped to maintain stable operation of two large blast furnaces under a low RAR.

1. Introduction

The steel industry in Japan faces an increase in the pig iron production cost due to the recent rise in iron ore and coal prices and decrease in high-quality resources. Such changes also demand that the industry use raw materials with low reducibility and difficulty in use effectively. Under such circumstances, the steel industry in Japan needs to refine the resource strategy based on current situations related to raw materials and develop new raw fuel usage technologies that contribute to production cost reduction. To reduce the pig iron production cost, it is important to enhance the reduction efficiency of blast furnaces and decrease the amount of carbonaceous materials to be used to produce pig iron.

To decrease the usage amount of carbonaceous materials in blast furnaces, researchers have been actively working to lower the reduction equilibrium temperature through the utilization of high-reactive carbonaceous materials.[1)]

The means to increase the reactivity of coke[2–5)], reduction, and gasification rate using carbon composite iron ore in which ore and carbonaceous materials have been closely arranged have been studied.[6–9)]

Regarding the utilization of carbon composite iron ore in commercial blast furnaces, in particular, previous studies have reported that the utilization has improved the reduction reaction efficiency of commercial blast furnaces.[10–12)] One method of producing such carbon composite iron ore is unfired agglomeration where cement is used as a binder for agglomeration.[13, 14)]

In the past, tests were performed in which a large amount of cement bonded carbon composite iron ore was used in blast furnaces.[15)] However, changes in the carbon consumption and other blast furnace specifications and appropriate carbon composite iron ore production conditions were not clear. Accordingly, to increase the reaction rate and efficiency in blast furnaces, Nippon Steel Corporation

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started developing cement bonded carbon composite iron ore that could improve blast furnace operation specifications and performed production tests and tests using a commercial blast furnace at Oita Works, succeeding in improving the efficiency of the blast furnace and reducing the carbon consumption.

After verifying the effects of cement bonded carbon composite iron ore in a commercial blast furnace, Nippon Steel started developing technologies for producing such composite iron ore using a commercial apparatus toward practical use. An issue with the production of cement bonded carbon composite iron ore on a commercial scale is the time required to cure cement. As the required output of carbon composite iron ore increases, the issue becomes more serious. Agglomerates for which cement is used as a binder take a few weeks to exert their strength by cement hardening and various curing methods are used.[13, 14, 16–20] In particular, yard curing, which is the simplest curing method, requires a vast yard for curing. To use cement bonded carbon composite iron ore in large blast furnaces, a technique to cure cement bonded carbon composite iron ore rapidly in as short a period of time as possible is required because high output within a limited space of the plant is necessary. We focused on a rapid curing technique with steam and conducted an experiment using a small-scale thermostat oven, continuous steam curing test using a fixed bed, and steam curing test using a commercial apparatus.

2. Experimental Procedures

2.1 Study of gasification and reduction reaction of carbon composite iron ore

To improve the reduction efficiency of blast furnaces and reduce the usage ratio of carbonaceous materials, it is necessary to lower the reduction equilibrium point temperature of the blast furnaces to improve the efficiency of reduction of iron oxides itself by reduction gas. In addition, to lower the reduction equilibrium point temperature, the gasification temperature of carbonaceous materials needs to be lowered by using high-reactive carbonaceous materials. However, if the reduction gas produced at low temperatures is not efficiently used to reduce iron oxides, that may contribute to the increase in the use amount of carbonaceous materials instead. Therefore, iron oxides need to be efficiently reduced by reduction gas to decrease the usage ratio of carbonaceous materials.

Regarding this point, because iron oxides and carbonaceous materials have been closely arranged in carbon composite iron ore, reduction gas produced through carbonaceous material gasification can reduce the neighboring iron oxides immediately. In addition, when carbon composite iron ore is produced without sintering, the reactivity of residing carbonaceous materials is high, so the reduction equilibrium point temperature could be lowered further. However, the ratio of iron oxides to the carbon amount contained in carbon composite iron ore may affect the reduction behavior and strength of agglomerates. Therefore, off-line tests were performed to determine the production conditions from the perspective of composition.

In the production tests, the main raw material of carbon composite iron ore was dust generated in the works. This carbon composite iron ore was assumed to be used in a blast furnace, so the dust with small contents of impurities (e.g., Na, K, and Zn) that would possibly affect the blast furnace adversely was selected.

To produce the carbon composite iron ore, a pan pelletizer was used for granulation. To maintain the strength of the cement bonded pellets, the content of the cement was determined as 10% of the total weight. We called this agglomerate RCA (Reactive Coke Agglomerate).

The ratio of the carbonaceous materials to be mixed was changed to produce five different types of carbon composite pellets. **Table 1** lists the compositions. RCA1 and RCA2 were cement bonded carbon composite iron ore produced using a commercial apparatus at a dust treatment plant. RCA3 and RCA4 were pellets produced off-line. The carbon composite iron ore cured for 14 days to harden the cement was subjected to a reduction test.

For the reduction test, a tester for reduction testing at a load that could perform a reaction test by applying a load to a sample charged in the crucible was used. As the sample, 100 g of carbon composite iron ore was charged into the crucible. The particle diameter was 10 to 15 mm. This carbon composite iron ore was inserted between 200 g of sinter layers with a thickness of 10 to 15 mm. The temperature was increased to 1 100°C for temperature-programmed reduction at a load of 1 kgf/cm^2. As the temperature conditions, data on the temperature inside a commercial blast furnace that had been measured by inserting a thermometer into the furnace vertically was used.

Table 1 Chemical compositions of sinter and pellet used in reduction tests

		Sinter	Fired pellet	Carbon composite iron ore			
				RCA1	RCA2	RCA3	RCA4
Manufactured in [*1]		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
Actual C/Fe[*2]	–			0.55	1.16	2.29	3.26
Stoichiometrical C/Fe[*3]	–			0.77	0.46	0.80	0.79

[*1] P: Plant, L: Laboratory

[*2] Actual C/Fe based on RCA component

[*3] Repuired carbon content of iron per 1 mol to reduce the iron oxide in RCA

Table 2 Chemical compositions and basic properties of RCA

T.C	T.Fe	M.Fe	FeO	CaO	SiO_2	Al_2O_3	MgO	P	S	Na_2O	K_2O	ZnO	Combined water	Moisture	Mean size	Crushing strength (average)	Crushing strength (minimum)
mass%	mass%	mass%	mass%	mass%	mass%	mass%	mass%	mass%	mass%	mass%	mass%	mass%	mass%	mass%	mm	N	N
21.3	36.6	0.3	2.6	11.4	7.6	2.6	0.9	0.08	0.38	0.05	0.12	0.03	2.1	9.7	13.6	1 125	982

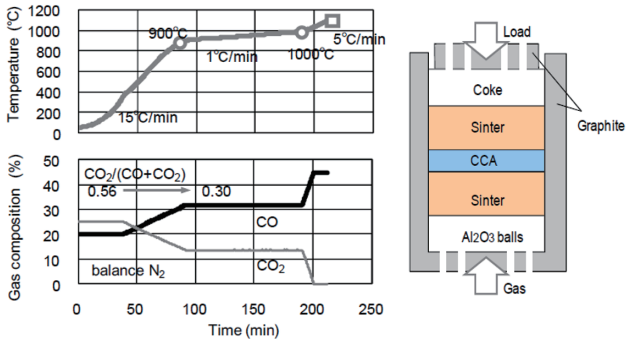

Fig. 1 Tests procedure of reduction test under load

Figure 1 shows the temperature and gas pattern.

2.2 Study of cold strength

In blast furnace operation, preventing raw materials from powdering is an important task to secure the permeability. The main effective means to prevent raw materials from powdering are enhancing the cold and hot strength. In our study, the cold strength of RCA was studied.

The main factors that affect the cold strength of RCA are the content of cement, curing period, and ratio of carbonaceous materials. In our test, the content of cement and curing conditions were fixed and only the ratio of carbonaceous materials (carbon content) was changed to produce different types of carbon composite iron ore to study their cold strength. The cement content was 10 mass% for all of them and RCA was cured for 14 days after the production, before the strength test. In the strength test, one particle of carbon composite iron ore pellet was placed on a flat stand and the load was measured while the pellet was compressed. The peak load until the pellet crashed was evaluated as the crushing strength (JIS M 8718).

2.3 Test of production of carbon composite iron ore using a commercial blast furnace

The RCA was used in a commercial blast furnace for testing. To evaluate changes in the reduction efficiency of the blast furnace precisely, the usage ratio of the carbon in the carbonaceous materials was determined as carbon consumption and evaluated. In this test, commercial apparatuses were used throughout the processes from the production of the ore to the blast furnace for verification. More detailed production techniques and decrease in the carbon consumption in the blast furnace were evaluated.

A commercial pan pelletizer with a diameter of 5 m was used to produce 21 000 tons of RCA and RCA was subjected to a test using a commercial blast furnace. RCA was used in the test as products which cured for at least two weeks after the production. In addition, because the RCA was produced in winter, the curing of the cement might be delayed. Therefore, when the RCA was used in the blast furnace, increase of the slag volume by approximately 0.54 kg/t hot metal (HM) (when 54 kg/tHM of RCAs were used) was tolerated and the cement content was increased by 1 mass% to 11 mass% from that in the off-line tests. **Table 2** lists the compositions and physical properties of the produced RCA. The content of carbon in RCA affects the ratio of carbonaceous materials to be used in the blast furnace, so the components were measured on a daily basis during the RCA production and the mixture ratio between the raw materials was finely adjusted to bring the composition closer to the target.

The produced RCA was used at Oita Blast Furnace No. 2 with a furnace capacity of 5 775 m^3 for 80 days. The reduction efficiency (carbon consumption) in the blast furnace was calculated from the top gas components of the blast furnace, hot metal temperature, and other conditions. In addition, the maximum usable amount of RCA may be varied depending on the contents of carbonaceous materials and cement, and blast furnace operation conditions. Therefore, the maximum use amount in the blast furnace was determined as 54 kg/tHM in this test considering the influence of the water content in the RCA and ratio of the cement that would eventually turn to slag. Furthermore, the use amount was gradually increased to study the relation between the use amount and reduction efficiency quantitatively.

Regarding the material balance of the blast furnace, the amounts of coke and pellets to be charged were adjusted such that each of the total input iron and the total input carbon derived from the carbonaceous materials would be the same before and after the use of RCA. In addition, when the furnace heat balance needed to be adjusted due to changes in the reduction efficiency, it was managed by changing the amount of pulverized coal injection or coke charge. Regarding the charging location of RCA, the charging condition was determined so that RCA was charged into the peripheral portion from the middle of the furnace where the reduction of iron ore is most liable to be delayed.

2.4 Rapid curing test of cement bonded carbon composite iron ore

In addition to the test of the cement bonded carbon composite iron ore using the commercial blast furnace in Section 2.3, a more specific production test was performed considering commercial production of such ore. As described previously, a major task toward the production in the commercial level is shortening the curing period. As a solution, we focused on steam curing as a rapid curing method and conducted a small-scale thermostat oven test, continuous curing test using a fixed bed, and production test using a commercial apparatus.

First, to study the influence of retention time and temperature in rapid curing of RCA, a thermostat oven test was performed where granulated products of the same type were batch processed in each manufacturing process. **Figure 2** illustrates the test procedures. The crushing strength of RCA before and after the curing was measured in accordance with JIS M 8718. For the total 12 pellets, the minimum and maximum values were excluded and the mean value of the remaining pellets was calculated. High-early-strength Portland cement (HPC, JIS R 5210) was mixed into the raw materials by 10 mass% and a small-scale granulator was used to produce RCA. The

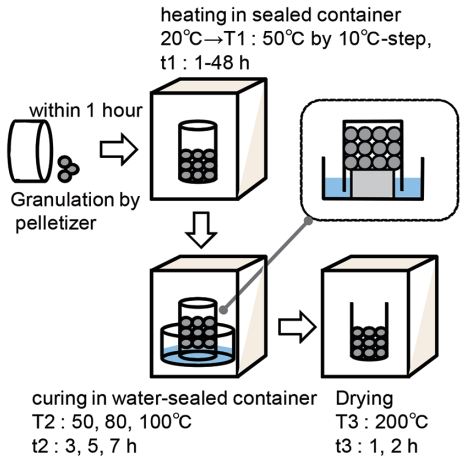

Fig. 2 Batch test procedure of rapid curing of RCA

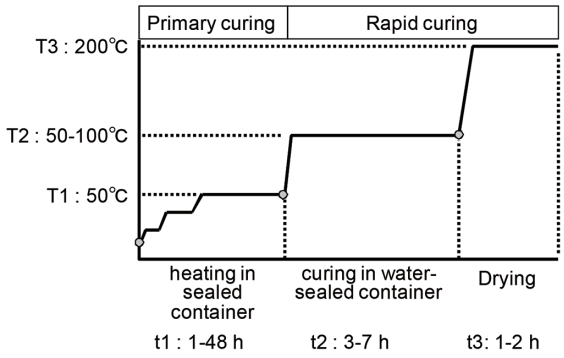

Fig. 3 Conditions and parameters of rapid curing test in small-scale batch

total carbon (T.C) of the RCA was 30.4 mass%, the T.Fe was 30.4 mass%, and the mean particle size was 13.0 mm (11 to 15 mm). Fifty particles (approximately 150 g) were used for each type of ore.

The basic curing pattern (conditions) consisted of the primary curing, high-temperature curing, and drying. The time and temperature in each phase were changed (**Fig. 3**). A preliminary test revealed that the leaving time from after the granulation to curing start would affect the strength of the cured products significantly, so the leaving time in all the tests was within one hour.

Secondly, a continuous curing test using a fixed bed was performed. **Figure 4** shows a schematic diagram of the apparatus. The apparatus consists of a curing chamber, blower (with a maximum capacity of 0.4 N m^3/min), hot air generator (maximum performance of 250°C), and boiler. The inner diameter of the curing chamber is 13 cm and the furnace capacity is 3 300 cm^3. It can cure up to 1.5 kg of ore. The curing chamber and steam pipes were heated to approximately 80 to 100°C with heaters to prevent dew condensation. For the primary curing, a thermostat oven was used, as is the case with the small-scale thermostat oven test, to heat the sealed container to 50°C. After that, the test samples were moved to the curing chamber

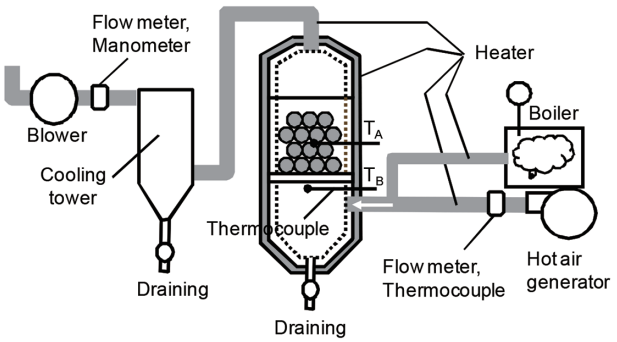

Fig. 4 Schematic diagram of continuous rapid curing test

and subjected to steam curing and drying. The steam supply from the boiler was adjusted such that the atmosphere in the curing chamber was in the saturated aqueous vapor state even at high temperatures. The drying time was determined as two hours considering that it was a charge layer. Then, the samples were cooled with cool air. The gas flow rate was constant at 0.08 Nm^3/min (superficial velocity of 0.10 Nm/s) throughout the test.

Table 3 lists the chemical components of the RCA subjected to the continuous curing test using the fixed bed. The mean particle size of the RCA granulated by the small-scale granulator was 12.4 mm (11.2 to 15.3 mm), the wet weight was 1.2 kg, the water content was 12.4%, and the wet charge bulk density was 1.48 g/cm^3.

Finally, an RCA rapid curing test was performed using a commercial apparatus. Five tons of RCA produced using a commercial apparatus with a diameter of 16 mm were stacked on a perforated metal, completely covered with a sheet, and subjected to primary curing for a predetermined time. After that, steam was supplied from the nozzle installed on the bottom of the perforated metal for a predetermined time. Some were cured in the sun and the others were forcibly dried.

3. Results

3.1 Study results of gasification and reduction reaction of the carbon composite iron ore

Figure 5 shows the reduction test results of the carbon composite iron ore. The reduction degree of the carbon composite iron ore is significantly high as compared to the fired pellet. As the content of the carbon in the carbon composite iron ore is higher, the reduction of the iron oxides in the agglomerates is accelerated and when the content is 10 mass% or more, the reduction degree reaches 90% or more. In this test, the temperature and gas conditions were equal for all types. Therefore, the improvement may be thanks to the acceleration effect by the close arrangement of the iron oxides and carbonaceous materials in the carbon composite iron ore. In addition, gasification of the carbonaceous materials in the carbon composite iron ore regenerated the reduction gas to enhance the reduction degree of the sintered ore in the upper layer. This effect was also higher when the carbon content was higher.

Meanwhile, the metal formation in carbon composite iron ore and the reaction rate of the carbonaceous materials are closely relat-

Table 3 Chemical compositions of RCA used in continuous rapid curing test

(mass%)

T.Fe	M.Fe	FeO	CaO	SiO_2	Al_2O_3	MgO	CW	T.C	Na_2O+K_2O	P	S	ZnO
33.99	0.35	1.80	12.22	7.37	2.81	0.83	2.59	20.70	0.108	0.067	0.338	0.021

ed to the strength of the pellets in the lower section of a blast furnace, that is to say, closely related to powdering behavior in the lower section of the furnace. This is an important factor from the perspective of carbon composite iron ore production. Therefore, the consumption rate of the carbon contained in the carbon composite iron ore was calculated using Equation (1) and it was evaluated along with the residual carbon rate. **Figure 6** shows the evaluation results. The carbon in the carbon composite iron ore was consumed to almost 100% up to 20 mass%; however, the carbon remained when the content was higher than 20 mass%.

$$\text{Carbon consumption} = \left(1 - \frac{C_A/T.Fe_A}{C_B/T.Fe_B}\right) \cdot 100 \qquad (1)$$

The reduction was terminated after the temperature reached 1 100°C in the reduction test and the gas was changed to nitrogen at the normal temperature to cool the samples. Then, the reduced samples were taken out and their microstructures were observed. **Figure 7** shows the microscope images. Many metals are observed on RCA2 to RCA4 with a high carbon content and coarse residual carbon in approximately 200 μm was observed on RCA4 with the highest carbon content for which carbon remained after the reaction. From these results, when the content of carbon in carbon composite iron ore is 20 mass% or higher, the decrease in the strength after reduction due to residual carbon is of concern.

3.2 Cold strength evaluation results

Figure 8 shows the relationship between the carbon content and

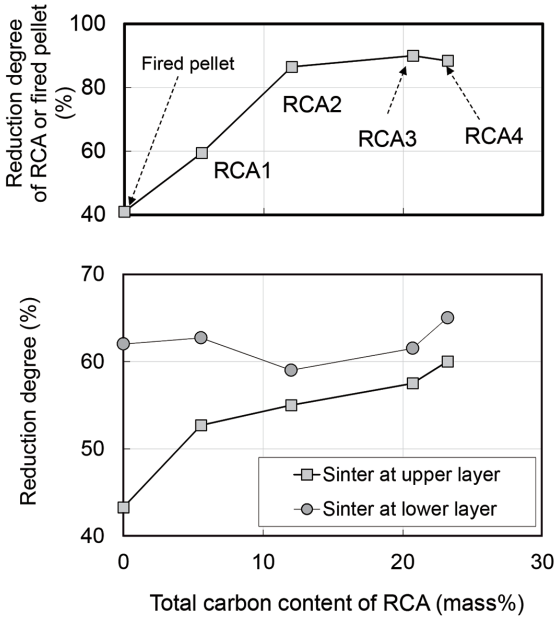

Fig. 5 Influence of carbon content of RCA on reduction degree of materials at 1 100°C

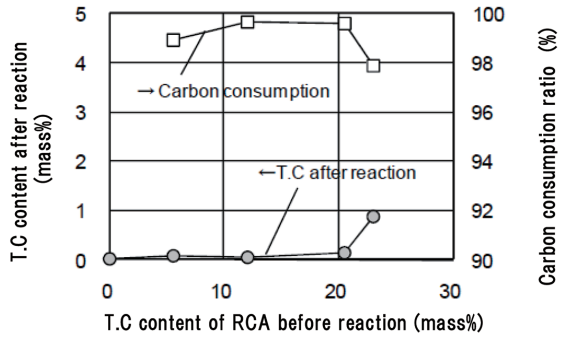

Fig. 6 Influence of carbon content of RCA on residual carbon after reaction at 1100°C

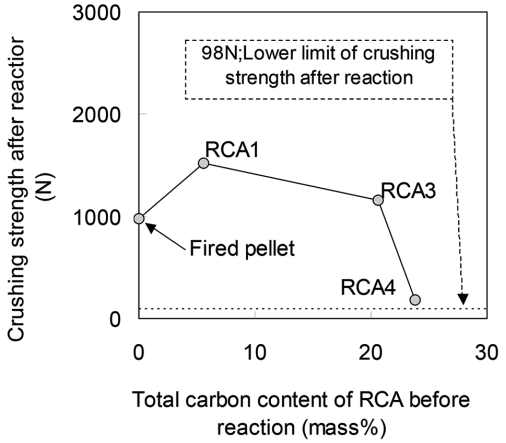

Fig. 8 Relationship between total carbon in RCA before reaction and crushing strength after reaction

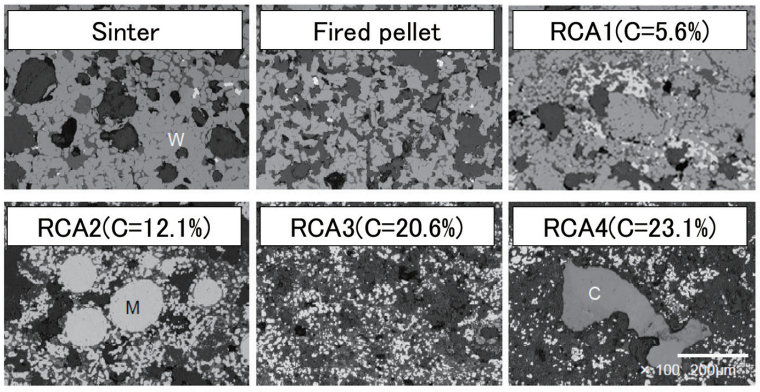

Fig. 7 Microstructure of carbon composite agglomerate after reduction at temperature up to 1 100°C, together with sinter and fired pellet
White: metal (M), Pale grey: Wüstite (W), Dark grey: Residual carbon materials (C), Black: Pores.

cold strength. The higher the content of the carbon in the carbon composite iron ore, the lower the strength of the carbon composite iron ore. This may be because the collected coke powder used as a carbon source in the agglomerates is hydrophobic, so its affinity with cement is weak and thereby, as the content increases, the strength of the agglomerates decreases.

Based on the aforementioned results, the effect of accelerating the reduction of iron oxides charged into blast furnaces is higher as the content of the carbon in the agglomerates is higher; however, it was judged that it would be desirable to set the content of carbon in agglomerates to less than 20 mass% from the perspective of the cold strength and strength after reaction. Therefore, the composition was adjusted such that the carbon content in RCA produced using a commercial apparatus would be 20 mass%.

3.3 Test results using a commercial blast furnace

Based on the aforementioned results, 21 000 tons of the RCA produced using the commercial pan pelletizer were used at Oita Blast Furnace No. 2. **Figure 9** shows the operational results when the RCA was used. To maintain the pig iron production at a constant rate throughout the test, the blast volume and oxygen enrichment amount were adjusted. In addition, to maintain the heat balance of the blast furnace and flame temperature constant, blast temperature and moisture were adjusted.

The test results show that the gas usage ratio at the blast top increased from the start of the RCA use and the solution loss carbon decreased. As a result, the carbon consumption of the blast furnace was able to be decreased. The carbon consumption for the blast furnace was calculated as corrected carbon consumption by correcting

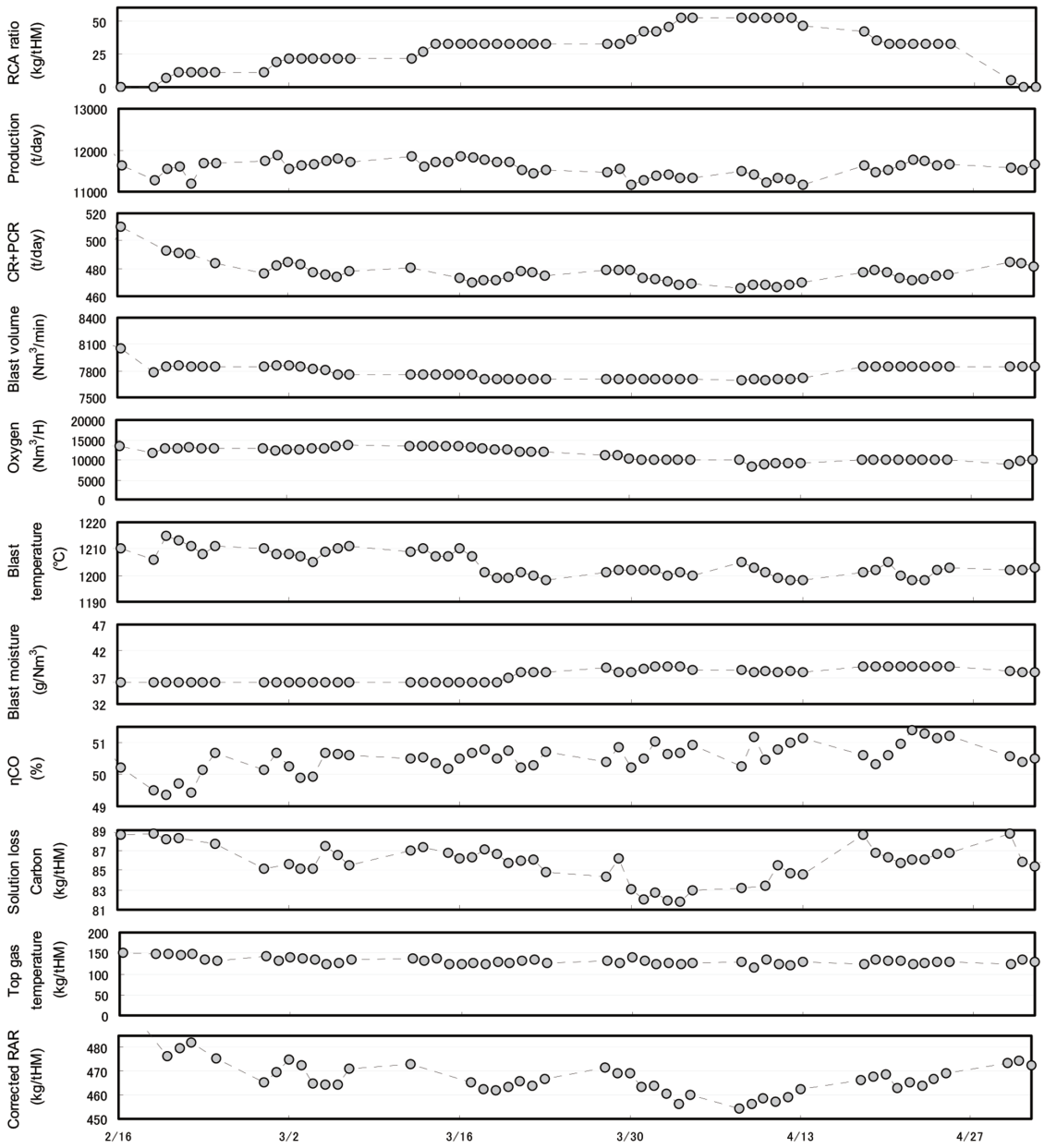

Fig. 9 Operational results of plant trial test of RCA at Oita No. 2 BF

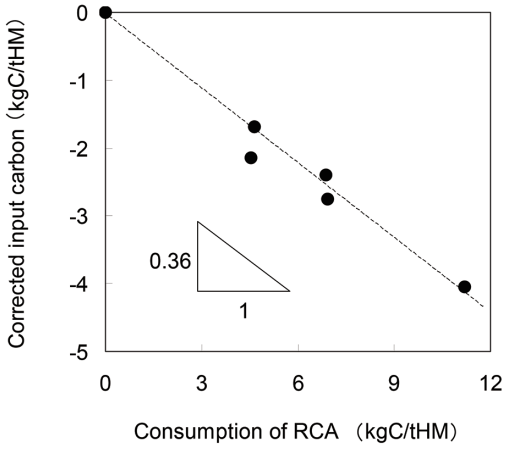

Fig. 10 Relationship between consumption of RCA and corrected input carbon

the hot metal and slag temperature, heat loss at the furnace body, blast temperature, blast moisture, amounts of the carbon content in top gas, and contents of the carbon in hot metal and pulverized coal, by material and heat balance calculation based on a list model.

Figure 10 shows the relation between the consumption of RCA and corrected carbon consumption for the blast furnace. It was calculated that the reduction rate of carbon consumption at the blast furnace attributable to the use of RCA is 0.36 kgC/tHM per 1 kg/tHM of carbon derived from RCA. These results show that cement bonded carbon composite iron ore is a technique that contributes to reducing the ratio of carbonaceous materials used in blast furnaces and pig iron production cost, so Nippon Steel started the study toward the commercial production. As conditions to produce cement bonded carbon composite iron ore by commercial equipment, a study to determine curing conditions was first conducted. The following section describes the results.

3.4 Production test results of cement bonded carbon composite iron ore

To determine the curing conditions of cement bonded carbon composite iron ore, a small-scale thermostat oven was used to study the influence of curing time and temperature. When the primary curing temperature (T1) was 18°C, the strength was 52 daN/p and it was 144 daN/p at 50°C, so the influence of the temperature was large. T1 is an important parameter in rapid curing. When commercially produced RCA is stacked in yards, their temperature increases to approximately 50°C without heating due to the latent heat of steam, heat from the cement hydration reaction, and frictional heat during granulation. Therefore, T1 in this test was maintained constant at 50°C.

After primary curing under base conditions (primary curing time (t1) = 48 hours and T1 = 50°C), the RCA was cured in the sun for 12 days. The strength was 144 daN/p. The lower limit of the strength for the use in commercial blast furnaces is 100 daN/p from experience.

Figure 11 shows the influence of t1 in curing at 50°C on the crushing strength of the RCA. The longer t1 is, the higher the crushing strength. The effects are particularly large from 1 to 12 hours. When t1 was one hour, even when the following high-temperature curing time was extended, the strength did not sufficiently increase.

Figure 12 shows the influence of the high-temperature curing (t2) and curing temperature (T2) on the crushing strength. The longer t2 was, the higher the crushing strength. However, when the primary curing time (t1) was sufficiently long for 12 hours or more, the influence of t2 was relatively small. Meanwhile, the influence of T2 varied depending on the primary curing time (t1). In the case of long-time curing of 20 hours or more, low-temperature curing at 50°C was optimum. Meanwhile, high-temperature curing at approximately 80°C was required to increase the strength when the primary curing time was 24 hours or less. This trend was also seen in the steam curing of cement, so that may be caused by changes in the form of cement hydrate reactants. The influence of the drying time (t3) was small and one hour of drying was sufficient.

From these results, the shortest curing time in which the crushing strength reaches 120 daN/p was 18 hours including drying of

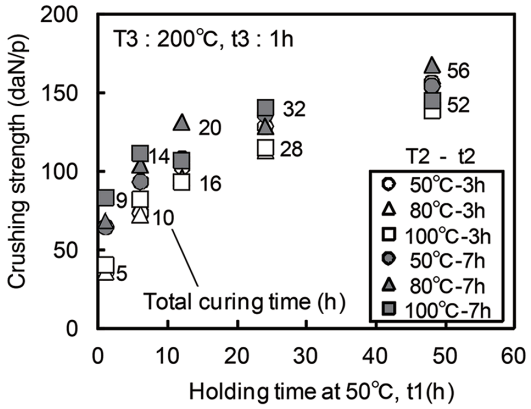

Fig. 11 Influence of holding time at 50°C in the primary curing on crushing strength of RCA

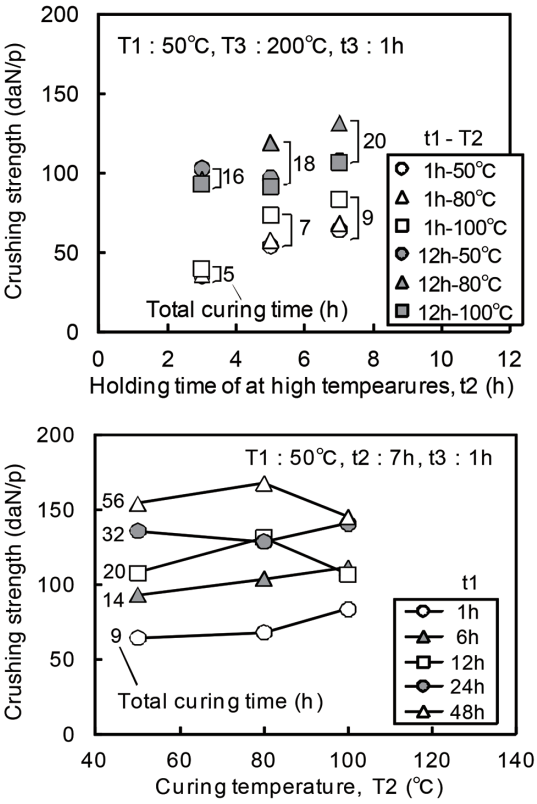

Fig. 12 Influences of holding time at high temperatures t2 (A) and curing temperature T2 (B) on crushing strength

one hour. The conditions were t1 = 12 hours, T2 = 80°C, and t2 = 5 hours.

Based on the acquired knowledge above, a continuous curing test was performed. **Figure 13** shows the curing test results. T_A and T_B in the figure are temperatures of the thermocouples shown in Fig. 4. The crushing strength increased to 67 daN/p prior to the drying and further increased to 105 daN/p thanks to the drying. The crushing strength of green pellets in the same type cured in the sun was 122 daN/p.

Finally, based on the knowledge above, a large-scale curing test was performed using RCA (HPC: 10 mass%) produced at a pilot plant. The crushing strength of the product RCA subjected to this test was 108 daN/p after curing in the sun for two weeks without drying.

Table 4 lists the test conditions and results. The basic processes consisted of primary curing, steam curing, and drying. The influence of the primary curing time (t1) (runs 1 to 3), steam curing temperature (T2) (runs 4 and 5), and steam curing time (t2) (runs 6 to 8) was studied. To evaluate the influence of the drying, a small amount of the RCA after the steam curing was sampled and dried with a drier.

The influence of the primary curing time (t1) was large and when primary curing was omitted, the crushing strength of the product did not increase sufficiently even after the steam curing and drying. Meanwhile, when the primary curing time was 24 hours, the strength was the highest. The strength was higher when the steam curing temperature was low at 60°C. In addition, the shorter the steam curing time (t2), the lower the strength. From these results, the optimum rapid curing conditions to achieve the strength equal to that of the product cured in the sun are t1 = 24 hours, T2 = 60°C, and t2 = 12 hours. In this test, it was difficult to make the temperature and steam conditions uniform under the sheets during the primary curing and steam curing. This may differentiate the results even under the same conditions (□ and ◇ in Table 4) from the aforementioned off-line continuous curing test results.

Furthermore, to decrease the number of manufacturing processes, the possibility of shortening the necessary curing period by omitting drying (steam curing only) was studied. RCA was subjected to primary curing for 48 hours and then cured in the sun for 12 days (normal curing) and other RCA was subjected to primary curing and then steam curing for 12 hours and cured in the sun. The strength increase (curing behavior) was compared between them. **Figure 14** shows the changes in the curing behavior of the RCA by the steam curing. The RCA took 14 days until its strength reached 100 daN/p in the normal curing in the sun while it was shortened only to five days thanks to the steam curing. In addition, combining the drying increased the strength to as high as 169 daN/p.

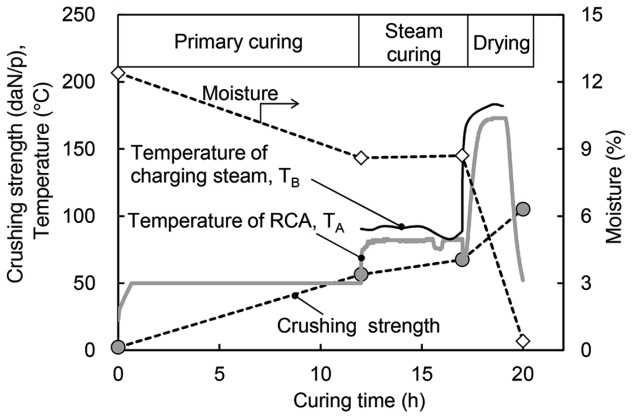

Fig. 13 Results of continuous curing test

Table 4 Results of plant rapid curing test of RCA in Oita Works

Run No.	T1 °C	t1 h	T2 °C	t2 h	Crushing strength after drying daN/p
1	38–58	0	80	12	19.9
2		12			133.6
3 □		24			165.0
4 □		24	80	12	110.7
5 ◇			60		158.0
6 ◇		24	60	12	133.8
7				8	90.6
8				4	79.4

4. Practical Use of Carbon Composite Iron Ore

Based on the results of the production of the carbon composite iron ore using the commercial apparatus, curing test, and test using the commercial blast furnace, RCA equipment was introduced into Oita Works in November 2011. **Figure 15** illustrates the RCA production flow. Raw materials roughly crushed are mixed with cement and they are granulated in the pelletizer. The green pellets are subjected to primary curing with steam and then they are moved to the yard for secondary curing.

Figure 16 shows the changes in the operation of Oita Blast Furnace No. 1 before and after the RCA use. The output of RCA is ap-

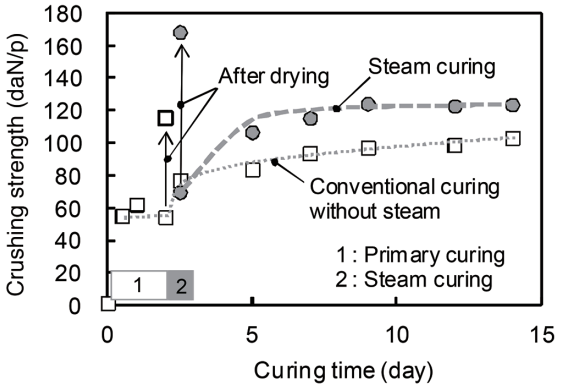

Fig. 14 Curing behavior of RCA after stream curing for 12 hours

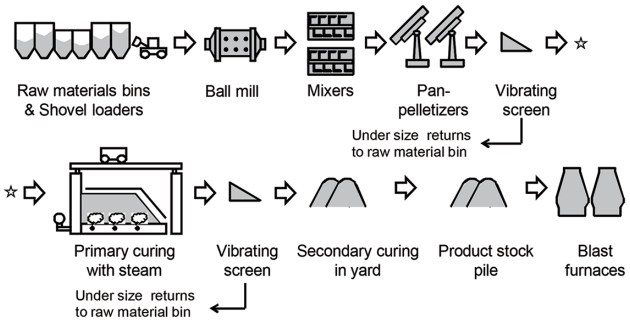

Fig. 15 Production flow sheet of RCA implemented in Oita Works

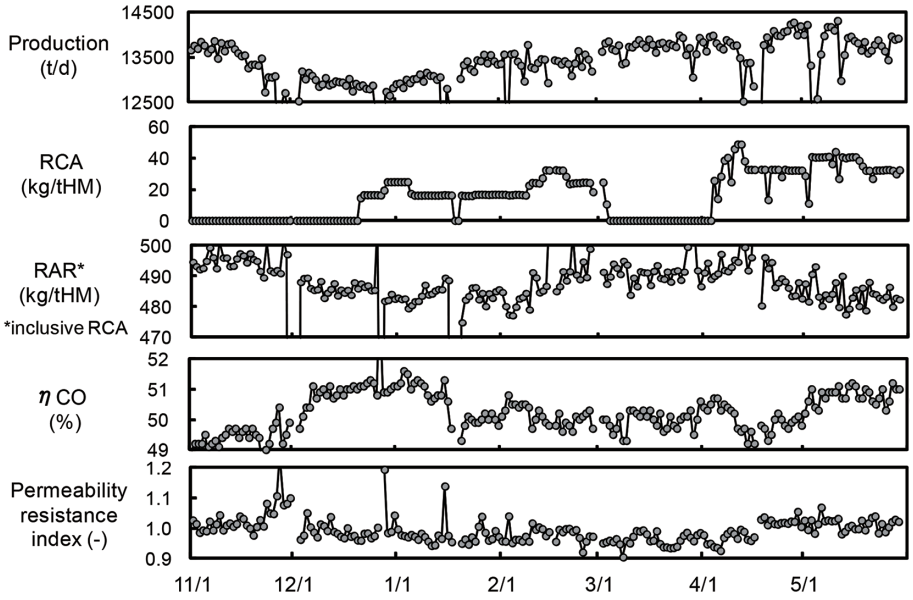

Fig. 16 Operational data of RCA use in Oita No. 1 Blast Furnace

Table 5 Operational change of Oita No. 1 Blast Furnace between before and after RCA use

		Without RCA	With RCA	Difference
Production	t/d	13 554	13 815	+261
Reducing agent rate*		490.2	487.6	−2.6
Coke rate	kg/tHM	338.7	324.7	−14.0
PCR	kg/tHM	151.5	162.8	+11.3
Ore composition				
Sinter	%	82.8	76.5	−6.3
Pellet	%	1.7	4.9	+3.2
RCA	%	0	2.1	+2.1
Hot metal temperature	°C	1 530	1 537	+7
Horizontal shaft probe data				
Temperature	°C	687	672	−15
$CO_2/(CO+CO_2)\cdot 100$	%	37.1	38.8	1.7

* RAR includes carbon in RCA.

proximately 900 t/day and the use amount is 40 kg/tHM at maximum in two large-scale blast furnaces (furnace capacity of 5 775 m^3). **Table 5** lists the changes in the main specifications before and after the RCA use. When the RCA use in the blast furnaces was evaluated, the amounts of the ore and reduction materials were adjusted such that the iron input would be equal and the hot metal temperature would be equal regarding the carbon input. Utilizing RCA could reduce the ratio of the reduction materials almost equal to the level of the acquired knowledge. The sonde data at the center of the shaft (15.225 m above the tuyeres) shows that the RCA use increases the gas reduction efficiency when the temperature level is equal. The coupling reaction (proximity effect of carbon) may have improved the reduction efficiency at the shaft.

In addition, rapid steam curing was also introduced and the strength of 100 daN/p can be achieved by curing for four days, which has contributed to stabilizing the RCA distribution and quality.

5. Conclusion

Nippon Steel developed cement bonded carbon composite iron ore that would decrease the carbon consumption at blast furnaces by higher speed and efficiency of the reaction in the blast furnaces thanks to close arrangement of the carbon and iron oxides in the ore. The knowledge acquired through the off-line basic test and integrated test of production using the commercial pan pelletizer and utilization of the produced product in the commercial blast furnace is shown below.

(1) The optimum ratio of the carbon in carbon composite iron ore is 20 mass% from the perspective of rapid iron oxide reduction, residual carbon after reaction, cold strength, and strength after reaction.

(2) 21 000 tons of RCA were produced at Oita Works. A long-time use test in which the RCA up to 54 kg/tHM was used in Oita Blast Furnace No. 2 was performed. As a result, the reduction equilibrium point temperature decreased, the gas use rate increased, and the carbon consumption decreased by 0.36 kgC/tHM per 1 kgC/tHM of carbon contained in the RCA.

(3) In the curing processes consisting of primary curing, high-temperature curing, and drying, the shortest RCA curing conditions by which the strength equal to that of normal curing for 14 days can be obtained are primary curing for 12 hours and steam curing for 5 hours at 80°C. The period could be shortened to 18 hours including drying. The test using the commercial apparatus has shown that the curing period can be shortened to 12.5 days with drying and to 9 days even without drying.

(4) The RCA production equipment including the steam curing process was introduced into Oita Works and the regular use of RCA in the blast furnaces commenced. They have contributed to low RAR operation of the two large-scale blast furnaces.

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