Influence of CDQ-coke produced from low quality coal blend on blast furnace operation

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1. Introduction

In recent years in Japan, CDQ(Coke Dry Quenching) plants have prevailed. About 70% coke is dry quenched using 3 CDQ equipments at Mizushima Works. The benefits of CDQ are not only sensible heat recovery of hot coke but also the improvement of coke strength. There have been several discussions on the mechanism of the improvement in coke strength and blast furnace(BF) operating results.[1,2] But there is not any reports on the influence of CDQ coke produced from low quality coal blending non or slightly caking coal. It is assumed that the reason is not only for the risk of BF operation but also the difficulty of the precise estimation of non or slightly caking coal quality. Furthermore it seems that the drum strength DI^{30}_{15} is insufficient to estimate CDQ coke because cracks in coke are stabilized in CDQ. These problems are discussed and the BF operating results with low quality coal blended CDQ coke are described in this paper.

2. Comparison of coke strength between wet and CDQ coke

The comparison of the coke strength is shown in Fig. 1. CDQ coke strength is generally larger than wet coke strength. As for the crushing strength, DI^{30}_{15}, the difference between CDQ and wet coke becomes smaller after coke transportation process, however, the difference becomes slightly larger for the abrasion strength, TI^{400}_{6}. The relationship between CDQ coke strength and wet coke strength for DI^{30}_{15} and TI^{400}_{6} is shown in Fig. 2. The lower DI^{30}_{15}, the larger the influence of strength improvement, though TI^{400}_{6} is not affected by the strength level.

It is considered that DI^{30}_{15} of CDQ coke apparently becomes high because cracks in coke are split descending in CDQ chamber. The difference between wet and CDQ coke DI^{30}_{15} at BF coke bins is narrower because wet coke also is stabilized after coke transportation process. Furthermore, the influence would be small if DI were high at wharfs.

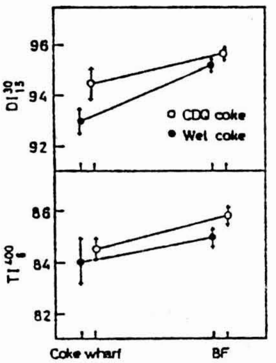

Fig. 1 Comparison of coke strength between coke wharf and BF bunker

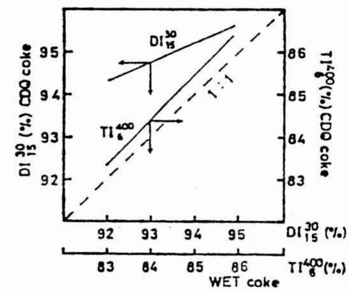

Fig. 2 Comparison of coke strength between CDQ and WET coke

The size of CDQ coke at wharfs is fine compared to wet coke, however, the distribution at BF coke bins is similar for both coke as shown in Fig. 3. It proves the above-mensioned description.

To examine the fine structure defect in coke matrix, the tensile strength was calculated by the compressive strength test using 10 mm disk samples. The results of the tensile strength distribution are shown in Fig. 4. It can be considered that the gradual quenching in CDQ chamber decreases fine structure defects in coke matrix and the abrasion strength, TI^{400}_{6}, consequently improves.

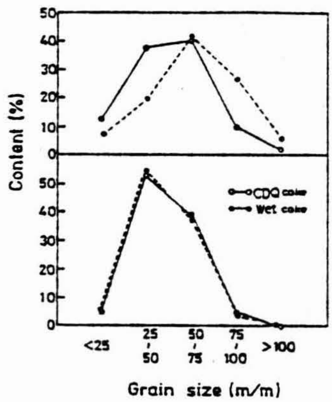

Fig. 3 Comparison of coke grain size distribution between CDQ and WET coke

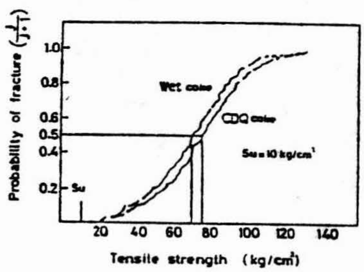

Fig. 4 Distribution of tensile strength

As shown in Fig. 5, the reactivity and the strength after reaction are generally improved for CDQ coke.

We tried degrading the coal blend quality and controlled TI_{6}^{400} of CDQ coke.

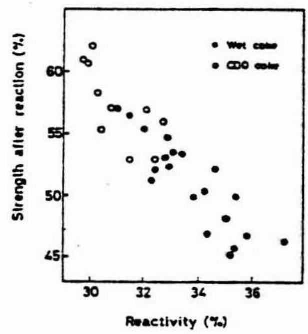

Fig. 5 Relation of strength after reaction to reactivity

3. Production of low TI_{6}^{400} CDQ coke

3.1 Estimation of non or slightly caking coal

The maximum fluidity measured by Gieseler plastometer(MF:log ddpm) is prevailed as the estimation of coal caking property. As shown in Fig. 6, tensile strength of semi-coke(σ_T) is well correlated with MF calculation of coal blend. It is considered that Gieseler plastometer is an excellent apparatus for the daily blending control. Semi-coke was measured by the apparatus shown in Fig. 7. The sample was prepared in blending 70% test coal and 30% Hongei anthracite coal(ash 8.4%, VM 5.2%), and the disk specimen(5mm thickness) of semi-coke was measured by indirect tensile test.

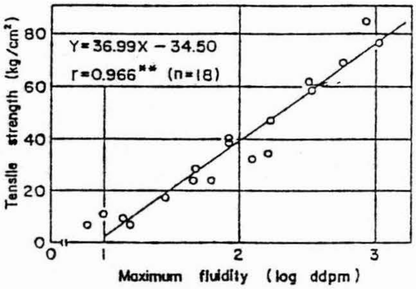

Fig. 6 Relation between tensile strength of semi-coke and MF

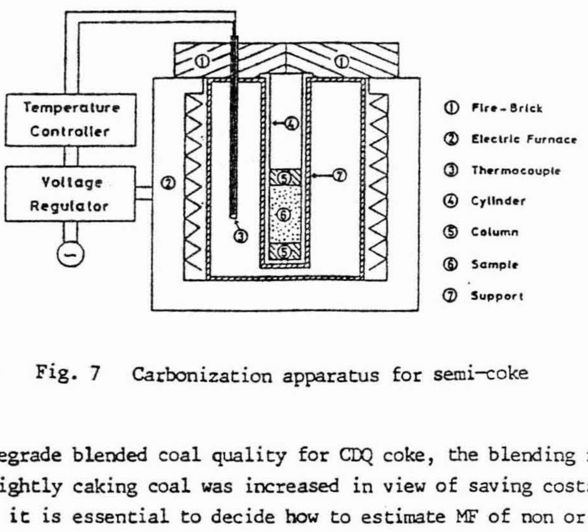

Fig. 7 Carbonization apparatus for semi-coke

To degrade blended coal quality for CDQ coke, the blending ratio of non or slightly caking coal was increased in view of saving costs. Therefore it is essential to decide how to estimate MF of non or slightly caking coal. Some kinds of coal cannot be measured by Gieseler plastometer because of non-caking, and the precision is insufficient for slightly caking coal. To solve the problems, MF is indirectly estimated by the above-mentioned semi-coke tensile strength test for these coals, which means that a part of standard coal(MF=2.3-2.5) is replaced by non or slightly caking coal and the semi-coke disk specimen is measured. An example of the results is shown in Fig. 8. As the blending ratio of non or slightly caking coal increases, σ_T decreases linearly. The following equation for estimating MF is obtained from Fig. 6 and Fig. 8.

$$MF = (\sigma_{T_0} + 34.50 - 100k)/36.99 \quad \text{①}$$

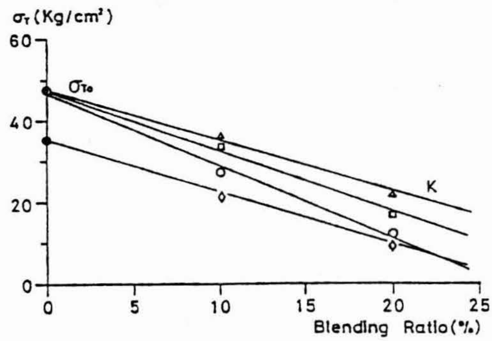

Fig. 8 Relation between tensile strength of semi-coke and non or slightly caking coal ratio

Tab. 1 Properties of non or slightly caking coal

Coal	Origin	Ash %	V M %	T S %	C S N	M F	$\bar{R}o$	T R	ϕ
Peko	Austral.	8.6	38.5	0.67	3.5	1.78	0.65	0.68	0.73
Hoskisson	Austral.	9.0	36.1	0.52	4.0	0.95	0.62	0.64	0.69
C & A	Austral.	9.4	35.1	0.45	3.0	-0.80	0.66	0.72	0.74
Wambo	Austral.	10.2	35.5	0.44	4.0	0.73	0.70	0.85	0.70
Optimum	S.Africa	10.6	34.0	0.60	1.5	-1.21	0.67	0.60	0.68
Petroleum coke	U.S.A	0.4	10.1	1.56	1.0	-1.20			0.96

Calculated MF by equation ① and other properties of non or slightly caking coal in this blending operation are shown in Tab. 1.
The parameter ϕ in Tab. 1 indicates the factor determining thermal stress generated in semi-coke, which is theoretically calculated by shrinkage coefficient, Young's modulus and Poisson's ratio of semi-coke. Practically ϕ -value is estimated by the mean maximum reflectance of vitrinite in oil($\bar{R}o$) and contents of total reactives(TR) as shown in Fig. 9.

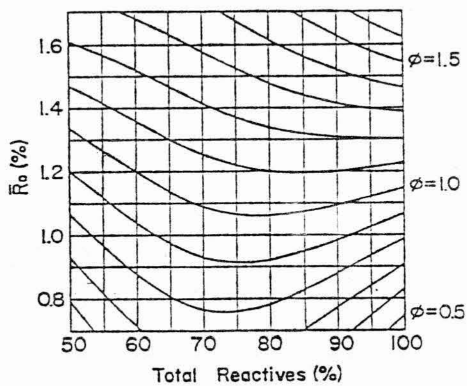

Fig. 9 ($\bar{R}o$, TR) function

3.2 CDQ coke production

At Mizushima Works, 15 to 20 kinds of coal are blended by the yard blending method. CDQ coke was produced by seven groups of blended coal ranging of non or slightly caking coal ratio from 14% to 30%. The amount of each group is 56,000 ton coal/BED × 2 BED. The target of TI_6^{400} was designed to decrease from 84.5% to 83.0% by using the TI prediction diagram in Fig. 10.

Coal and coke quality results are shown in Tab. 2 and Fig. 11. Coke strength TI_6^{400} gradually decreased with the quality degradation of blended coal as expected, however, there was not any significant deterioration in DI_{15}^{30} because of the stabilization effect in CDQ chamber.

Thus in case of CDQ coke strength, it is considered that coal blending design paying attention to TI_6^{400} is important.

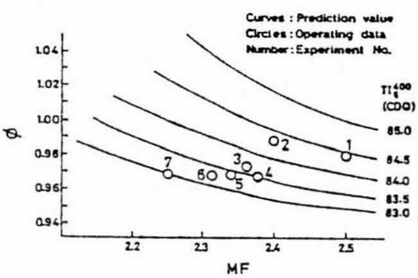

Fig. 10 Relation between TI_6^{400}, MF and φ

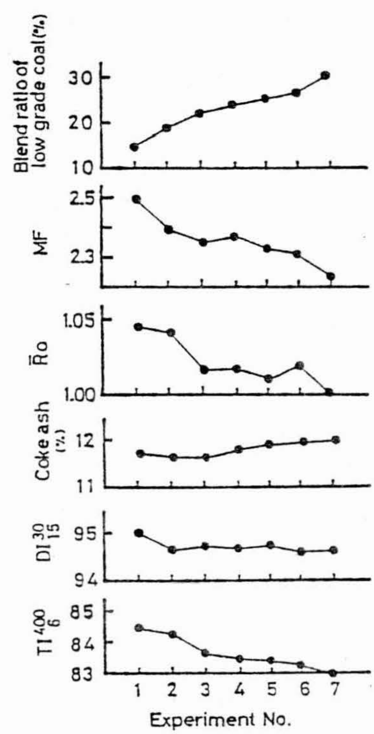

Fig. 11 Transition of coal blend quality and coke quality (No.3-6CO at Mizushima works)

Tab. 2 Coal blend quality and coke strength

No.	Coal blend quality			Coke strength	
	φ	MF	R̄o	TI_6^{400}	DI_{15}^{30}
1	0.991	2.497	1.044	84.46	95.01
2	0.986	2.398	1.040	84.31	94.68
3	0.985	2.362	1.015	83.64	94.75
4	0.968	2.375	1.017	83.50	94.68
5	0.963	2.338	1.010	83.42	94.75
6	0.974	2.312	1.019	83.24	94.60
7	0.969	2.250	1.000	83.00	94.66

4. Blast furnace operating results

Operating results of No.4BF at Mizushima Works during the experimental operation period in which TI$^{400}_{6}$ of CDQ coke was degraded are shown in Fig. 12. Productivity was as low as 1.8 t/d/m^3 , and coke rate was as high as 510 kg/t in order to supply gas enough for gas demand at the Works. CDQ coke mixing rate was about 80% in average, and changed in the range of 55% to 100%. TI$^{400}_{6}$ decreased from 84.5% to 83.0%.

In ordinary operation, the lower limit standards of wet and CDQ coke are 83.0% and 83.2% respectively, and the average of TI$^{400}_{6}$ of each blending bed is controlled as 83.6% and 83.7%, considering the variation of TI . Therefore, TI$^{400}_{6}$ at the 7th period was 0.7% below the ordinary level. Low TI$^{400}_{6}$ wet coke often triggered fluctuations of BF operation like instable burden descent and variation of pressure drop in many cases. The fluctuations were, however, acceptable and during the experimental operation periods from 2nd through 7th there were not much difference in the lower stack permeability, silicon content in hot metal, and standard deviation of silicon, except that the slip index increased a little. In other words, the results of experimental operation proved that it would be possible to decrease the TI$^{400}_{6}$ standard by 0.5% if most of coke charged in a BF was CDQ.

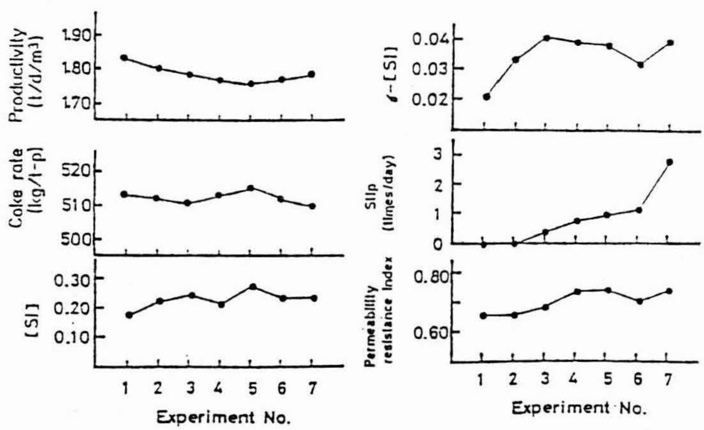

Fig. 12 Operating results of Mizusima No. 4BF

5. Discussion

It is absolutely necessary to consider the difference between CDQ and wet coke properties when the influence of low grade CDQ coke on BF operation is discussed. The difference in hot and cold physical properties were described in the last section. In this section specific phenomena observed at high CDQ mixing rate was discussed and the reason why the stability of BF operation was performed with low TI_{6}^{400} coke was also considered. Three typical phenomena observed are as follows:

(1) Increase in furnace temperature at upper stack.

(2) Decrease in lower stack permeability.

(3) Decrease in fluctuation of BF operation

5.1 Increase in furnace temperature at upper stack

Change in the temperature of CDQ coke is shown in Fig. 13, compared with that of wet coke. The temperature of CDQ coke is about 250°C at CDQ outlet and about 150°C at BF coke bin outlet through the crusher, screens and belt conveyors. Whereas the temperature of wet coke is about 30°C at BF coke bin outlet, the difference in temperature between CDQ and wet coke is about 120°C. As for the contained water, those of CDQ and wet coke are about 0% and 5% respectively. Therefore the top gas temperature increases with CDQ coke mixing rate as shown in Fig. 14. The increase in top gas temperature due to CDQ coke addition is smaller than the value which is calculated on the bases of heat balance, taking

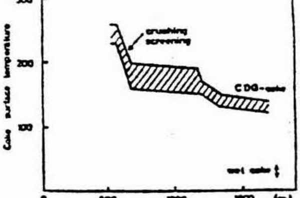

Fig. 13 Comparison between CDQ and WET coke temperature

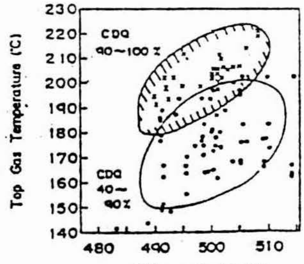

Fig. 14 Relation between coke rate and top gas temperature

account of sensible heat of coke and latent heat of water vaporization etc. That is to say, the heat corresponding to the difference in sensible and latent heat between CDQ and wet coke would not be consumed all as top gas latent heat. So, a part of the heat contributes to raise the temperature in a BF. Fig. 15 shows the temperature measured at an upper shaft probe. It is installed at 4.5m below stock level and can measure gas temperature and components at 6 points from the centre to the wall. The average values of temperatures at 6 points are shown in Fig. 15. The more the CDQ coke mixing rate, the higher the furnace temperature raising speed as shown in the figure. At upper shaft, it is well known that sinter is degraded at the temperature ranging from 400°C to 600°C with heat up and reduction. Reduction degradation is discussed quantitatively by using both a sinter reduction degradation model[3] and one-dimensional blast furnace model.[4,5] The decrease in the particle size by reduction degradation is calculated and the influence of the decrease in particle size on BF operation is quantitatively discussed from the standpoint of the fluidization index which is defined by equation ②.

Fluidization index = Pressure drop / burden bulk density ②

The large fluidization index means that the packed structure of burden is instable and the burden is easy to be fluidized. Two typical results of simulation are shown in Figs. 16 and 17. In case of Fig. 17 which shows the simulation result of higher temperature raising speed in a BF, the temperature region ranging from 400°C to 600°C is as short as 0.6m. In case of lower temperature raising speed, as shown in Fig. 17, however, the same temperature region is as long as 1.1m. As a result, the particle result after reduction degradation is 6.6mm in the former case, while 5.9mm in the latter case. Compared with the maximum fluidization index, the former has a smaller value. In these case, Reduction Degradation Index(RDI) of sinter is assumed as 30%. So the differences between both would be larger if RDI of sinter was assumed to be higher.

The reduction degree at 8m below stock level is 18% in the former case, while 12% in the latter case.

Therefore an increase in temperature raising speed contributes to the stable BF operation for both permeability and reducibility. In other words, an increase in the CDQ mixing rate effects on the improvement of permeability and reducibility at upper shaft.

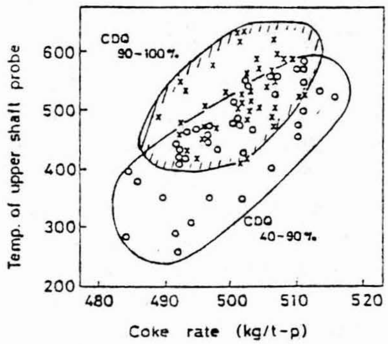

Fig. 15 relation between temperature of upper shaft probe and coke rate

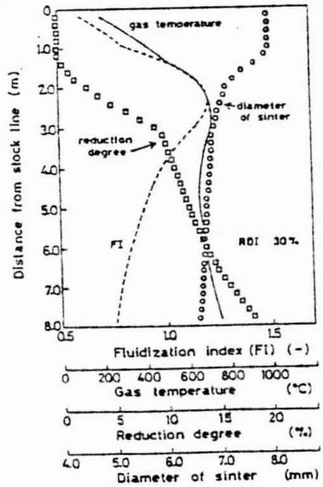

Fig. 16 Results of model simulation in case of high temperature raising speed

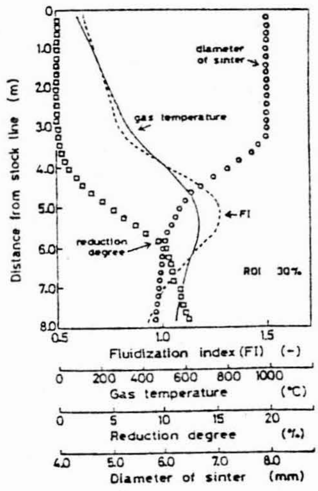

Fig. 17 Results of model simulation in case of low temperature raising speed

5.2 Decrease in permeability at lower stack

It is well known that instable burden descent(Fig. 18) and pressure variation(Fig. 19) occur when coke strength deteriorates. It is proved by coke sampling at tuyeres(Fig. 20) and mathematical model simulation[6] that the phenomena is caused by the degradation of coke at lower shaft. During the experimental operation, however, there was not significant fluctuation of BF operation though TI_6^{400} decreased under high CDQ mixing rate. In Fig. 21, the relation between TI_6^{400} and permeability resistance at lower shaft is illustrated. It is clear that permeability resistance is negatively corelated with TI_6^{400} while the influence of TI_6^{400} on permeability resistance is small at high CDQ coke mixing rate. Fig. 22

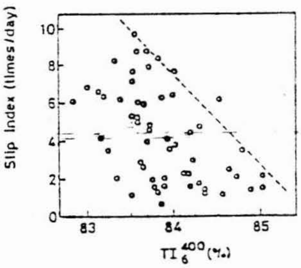

Fig. 18 Relation between slip index and TI_6^{400} of coke

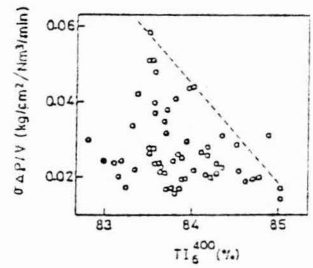

Fig. 19 Relation between variation of pressure drop and TI_6^{400} of coke

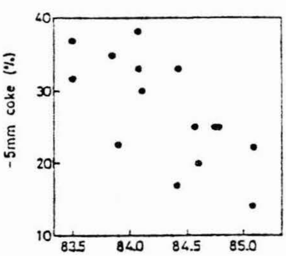

Fig. 20 Relation between fine coke at tuyere and TI_6^{400}

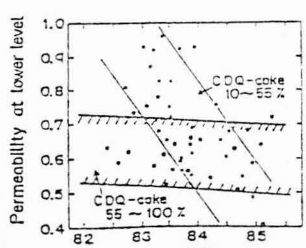

Fig. 21 Relation between permeability at lower level and TI_6^{400}

shown the relation between solution loss carbon and TI_6^{400}. Correlation between them is not clear, however, solution loss carbon is low at high CDQ coke mixing rate. To summerize these analysis, CDQ coke which is excellent in hot reactivity and strength after reaction results in less degradation at lower shaft than the same TI wet coke.

5.3 Decrease in fluctuation of BF operation

Fig. 23 -25 shown the effect of CDQ coke on standard deviation of pressure drop, gas efficiency, and silicon content in hot metal. These figures reveal that the more CDQ coke mixing rate, the more stable BF operation. It is because the permeability and the reducibility are improved at lower and upper shaft by mixing more CDQ coke mentioned in 5-1 and 2. Thus stable BF operation can be kept in spite of the decrease in TI_6^{400} for CDQ coke by 0.5% blending low quality cheap coal.

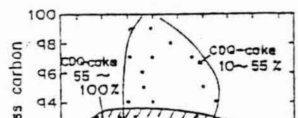

Fig. 22 Relation between solution loss carbon and TI_6^{400}

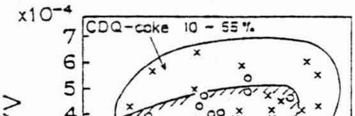

Fig. 23 Relation between $\sigma\,\Delta P/V$ and coke rate

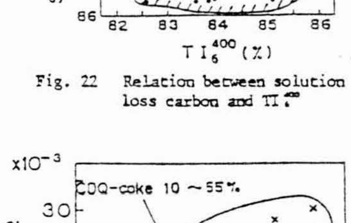

Fig. 24 Relation between σ CO/CO

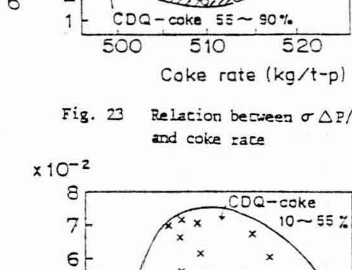

Fig. 25 Relation between σ[Si] and coke rate

6. Conclusion

Influence of CDQ coke produced from low quality coal blend on the blast furnace was investigated at KSC's Mizushima Works. As a result, it would be possible to decrease the TI_{6}^{400} standard by 0.5% if most of coke charged in a blast furnace was CDQ and productivity required was as low as 1.8 $t/d/m^3$. The reason are as follows:

1) An increase in the CDQ-coke mixing rate effects on the improvement of permeability and reducibility at the upper shaft.

2) CDQ-coke, which is excellent in hot reactivity and strength after reaction, results in less degradation at lower shaft than the same TI_{6}^{400} wet coke.

Based on these observations, the cost of coal has been reduced by the increase in the blending rate of low quality coal.

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