A Novel Measurement Method for Coal Thermoplasticity: Permeation Distance

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A novel measurement method for coal thermoplasticity was developed, where permeation distance of thermally plastic coal into glass beads layer placed on the coal sample was measured. The characteristic of this method is simulating the condition in a coke oven, especially void structure around the plastic layer by using glass beads and coking pressure by applying a load. In a standard condition, the coal sample is heated to 550°C, and coal sample softens and permeates into the glass beads layer, then the permeation distance is measured after cooling the sample. The maximum permeation distance measured is roughly correlated with Gieseler fluidity, however large deviation is observed especially for high fluidity coals. Moreover, the deterioration of coke strength is observed in case that long permeation distance coal is used in a coal blend for cokemaking. This new measurement method clearly shows the difference in coking property of high fluidity coal as well as solving the problems in Gieseler plastometer method for evaluating high fluidity coals. By employing the permeation distance method, contribution to the production of high strength coke and effective usage of caking coal will be expected.

KEY WORDS: cokemaking; coal thermoplasticity; caking property; coking property; blending technique; coke strength; permeation distance.

1. Introduction

Caking properties are the essential parameters in coal blending techniques for cokemaking because those properties strongly influence the coke qualities.^{1–3)} In particular, Gieseler plastometer method and dilatometer test standardized by JIS M8801 have long been used for measuring the caking properties and finally controlling coke strength.^{4–6)} For example, Miyazu *et al.* shows that Gieseler maximum fluidity (MF) of coal blend should be more than 200 ddpm to make high strength coke.⁴⁾ However, the effect of excessive MF on coke strength has not been clarified because high fluidity coal is thought to act as a binder in a coal blend to produce high strength coke while high fluidity coal produces highly-porous structure which leads fragile coke in case that the coal alone is carbonized. Nomura *et al.* shows that high strength coke needs a certain level of product of bulk density and “specific dilatation volume” which is defined as the volume of expanded coal per unit mass and measured by dilatometer test.⁶⁾ Although high total dilatation (TD) coal is thought to have the ability to fill the initial gaps between packed coal particles and to enhance the coke strength, it is reported that large particles of high TD coal produces connected pores which acts as defects.⁷⁾ As just described, it has been pointed out that those conventional caking properties sometimes have not correlated with coke

strength.

The problems of the conventional caking properties are described below. One of the problems of Gieseler plastometer method is changing shear rate in coal sample during measurement. Viscosity of high fluidity coal is underestimated because thermally plastic coal behaves as pseudo-plastic flow.^{8,9)} In addition, reliability of MF value in high fluidity coal is questioned because the phenomenon, in which the vicinity of the inner wall of a crucible becomes empty (Weissenberg effect), occurs and a stirring rod runs idle as shown in **Fig. 1**.⁸⁾ On the other hand, a problem of dilatometer test is considered that the measurement conditions, such as constraints of samples, gas and/or thermally

Fig. 1. Weissenberg effect observed in transparent Gieseler retort.⁸⁾

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Fig. 2. Conceptual diagram of coal thermoplasticity in coke oven.

plastic sample paths *etc.*, are not properly set with the objective of simulating the circumstances in a coke oven although those conditions drastically influence the dilatation behavior of coal sample.^{10,11)} In fact, the TD of commercial coal blend is quite bigger than the actual coal dilatation in coke oven.

The current status described above prompts us to develop a new measurement method of coal thermoplasticity. Our intention is to simulate the conditions around thermally plastic coal in a coke oven as shown in Fig. 2. Namely, it was considered that permeation of thermally plastic coal into void around itself and the coking pressure should be simulated. For that purpose, the measurement method of coal thermoplasticity, which includes placing glass beads layer to assume void structure on the coal sample, and applying pressure to the beads and coal sample to simulate the coking pressure during heating, was devised. In this paper, the detailed method of permeation distance measurement and its effect on coke qualities will be described.

2. Fundamental Investigations of Coal Permeation

2.1. Experiments

The characterization data of sample coal brands for measuring the permeation distance are shown in Table 1. In the table, the numbers after sample name mean the difference of lot. Measurements of Gieseler maximum fluidity (MF), total dilatation (TD), mean maximum reflectance of vitrinite ($\bar{R}_o$), and proximate analysis of coal samples were conducted according to JIS M8801, M8816, and M8812 respectively.

An apparatus for measuring the permeation distance is illustrated in Fig. 3. The apparatus basically consists of an electric furnace for heating the coal sample, a CCD camera (Keyence: XG-H500C), an image processing apparatus (Keyence: XG-7700) and a computer for measuring the permeation distance.

The experimental procedures are described below. 2.5 g of coal sample, which was crushed and sieved so that the particle diameter was not more than 2 mm, was charged to

the quartz crucible having the size of 20 mm in diameter and 100 mm in height. Then a weight (200 g) was dropped from above the sample five times with a fall distance of 20 mm to pack the sample, so that the thickness of the sample layer was around 10 mm. Glass beads (Material: soda glass, Specific weight: 2.5) were arranged on the packed layer so as to achieve a thickness of over 50 mm. On the glass beads layer, a quartz filter with a diameter of 19 mm and a thickness of 5 mm was arranged, and a quartz rod was placed on the filter. A weight was placed on the quartz rod so that the pressure was applied onto the glass beads and coal layers. The crucible was placed in the midst of electric furnace and was heated to 550°C at a heating rate of 3°C/min under nitrogen. Upon heating, the thermally plastic coal permeated into the glass beads layer as shown in Fig. 4.

The standard experimental conditions for simulating the void structure and coking pressure are set as below. The glass beads size were set to 2.0 mm in consideration of mean diameter of general commercial coal blend. The weight was set to 1.6 kg so that the pressure levels were 50 kPa according to the maximum wall pressure of coal blend whose volatile matter was 25 wt% d.a.f.¹²⁾

For understanding the fundamental permeation behavior, the effect of the experimental conditions of glass beads size and pressure of weight on the measurement value was examined for CoalA2. The levels of glass beads size were set to 0.4, 1.0 and 2.0 mm. The levels of pressure of weight were set to 25 and 50 kPa.

The permeation distance was measured in real time by image analysis technique with the image processing apparatus. The detailed analysis procedures are described below. Upon heating, the images of sample coal permeating into the glass beads layer were taken by the CCD camera via an observation window equipped on the electric furnace every 2 seconds. Those images were transferred to the image processing apparatus and computer. The coordinates of the boundary face between filter and glass beads layer (Boundary1), glass beads layer and permeating coal layer

Table 1. Coal properties and measurement results.

Coal brand	$\bar{R}_o$ (%)	TI (%)	Ash (wt% d.b.)	VM (wt% d.b.)	logMF (log/ddpm)	TD (%)	Maximum permeation distance (mm)
CoalA1	0.89	20.9	7.5	34.4	3.21	169	20.4
CoalA2	0.90	14.9	7.3	34.5	3.71	179	22.6
CoalB1	0.67	17.1	5.2	44.1	3.64	78	10.3
CoalB2	0.65	15.5	5.4	44.0	3.57	99	12.2
CoalC1	1.32	39.1	6.9	19.8	0.78	25	1.5
CoalC2	1.31	45.6	7.2	20.4	1.26	20	2.5
CoalC3	1.37	44.3	7.2	19.3	1.04	20	0.9
CoalD1	1.52	19.9	7.3	19.9	1.32	57	3.5
CoalE1	0.72	14.3	9.5	40.1	4.09	145	14.9
CoalE2	0.74	17.4	9.5	40.3	4.07	123	16.8
CoalF1	0.80	14.5	7.7	36.9	3.17	171	20.8
CoalG1	0.71	8.0	0.4	43.6	4.78	210	32.4
CoalH1	0.86	19.9	9.5	34.3	3.19	95	10.3
CoalI1	0.65	23.0	10.7	36.6	1.46	0	3.3
CoalJ1	0.78	14.6	9.0	36.6	2.10	48	7.6
CoalK1	0.84	8.7	6.0	36.4	3.50	246	29.0
CoalL1	0.88	16.0	8.3	36.1	4.04	159	23.5
CoalM1	0.89	17.3	7.3	36.1	4.08	171	15.3
CoalN1	0.90	29.3	8.2	31.1	3.48	153	11.5
CoalO1	0.94	25.6	9.8	30.2	3.52	142	10.6
CoalP1	0.96	34.9	9.5	28.0	2.67	19	7.5
CoalP2	0.93	30.2	8.8	28.9	2.76	51	8.5
CoalQ1	1.00	33.9	8.8	27.7	2.48	62	8.4
CoalQ2	1.00	34.9	8.4	27.8	2.61	50	6.3
CoalQ3	1.01	32.9	8.2	28.1	2.33	43	8.7
CoalR1	1.00	35.3	9.6	25.8	1.71	0	2.5
CoalR2	1.00	39.7	10.2	26.1	1.34	0	1.8
CoalS1	1.00	33.3	10.4	27.7	2.20	36	4.8
CoalT1	1.03	36.4	9.4	28.1	2.96	114	12.1
CoalU1	1.11	31.1	8.8	24.5	3.04	163	9.7
CoalV1	1.14	35.0	9.2	24.2	1.77	38	4.9
CoalW1	1.38	29.4	10.9	20.9	2.49	120	8.7
CoalX1	1.50	28.1	10.3	19.1	1.32	54	5.4
CoalY1	1.54	37.0	8.3	16.6	0.00	0	1.2
CoalZ1	1.60	20.1	9.2	17.6	0.70	33	3.0

(Boundary2) and bottom of coal layer and crucible (Boundary3) were measured by detecting the difference of brightness among the layers, filter and crucible. The difference of brightness was comparatively obvious. The coordinate of the boundary face between bottom of glass beads layer and not permeating coal layer (Boundary4) was calculated from the distance between Boundary1 and 3, and the length of glass beads layer on the assumption that the length was constant because the effect of thermal expansion was much smaller than the permeation distance. Then the permeation distance was calculated based on those coordinate values as shown in Fig. 4.

The maximum permeation distance was also estimated as below. The semicoke among the glass beads packed layer after the thermally plastic state became solidified and adhered to the glass beads. Those beads adhered to the semicoke were not able to be recovered from the crucible after cooling. On the other hand, the beads that had not adhered to the semicoke were able to be recovered. In addition, after the permeation distance reached maximum, the amount of adhered glass beads remained constant as will hereinafter be described in detail. Hence, the maximum permeation distance was derived from the beads weight and a relationship had been obtained beforehand between the packing height and the weight of the glass beads packed layer as shown in Eq. (1) below;

$$D = H(G - M) \dots\dots\dots (1),$$

Fig. 3. Schematic diagram of measurement apparatus. **Fig. 4.** Schematic illustration of coal permeation.

where D is the maximum permeation distance (mm), H is the height of the packed layer per 1 g of the glass beads packed into this experimental crucible (mm/g), G is the weight of the initially packed glass beads (g) and M is the weight of the beads that had not adhered together with the semicoke (g).

2.2. Results and Discussions

2.2.1. Permeation Behavior of Coal

Figure 5 shows the profiles of the permeation distance, fluidity of Gieseler plastometer method and piston displacement of dilatometer test for CoalA1 as an example of the results. The permeation behavior was observed within around the temperature range between IST (Initial softening temperature) and MFT (Maximum fluidity temperature) or T_2 and T_3 . **Figure 6** shows the comparison of profiles of the permeation distance among coal brands. The permeation profiles were different from coal to coal. In addition, the permeation distance became constant after reaching maximum although the sample coal remained in thermally plastic state. If the permeation behavior is dominated only by viscosity, the permeation distance must change during the thermally plastic state. The results therefore indicate that the permeation behavior is dominated not only by viscosity but also by other factors.

Fig. 5. Comparison of profiles between permeation distance and conventional thermoplasticity based on JIS M8801 (CoalA1).

Fig. 6. Comparison of profiles of permeation distance among coal brands.

Figure 7 shows the relationship between the maximum permeation distance measured from the method by glass beads weight and by image analysis technique. Both measurement methods were reasonable for measuring the permeation distance because there was a good relationship between both measured values. More precisely, the noise of measured value because of the tar adhesion to observation window was sometimes observed in case of the method by image analysis technique. Therefore the measured values calculated by the amount of glass beads are shown as the maximum permeation distance throughout this report if not otherwise specified.

2.2.2. Effect of Experimental Conditions on Permeation Distance

The relationships between the maximum permeation distance and experimental conditions are shown in **Fig. 8**. The maximum permeation distance was increased and saturated with increasing the diameter. On the other hand, the maximum permeation distance shows an almost constant value against the weight change.

For verifying these results and clarifying the dominant factors of the permeation behavior, a fluidics approach was attempted. It is well known that the pressure drop in packed bed layer can be represented by Darcy's law as shown in Eq. (2);

Fig. 7. Comparison between the maximum permeation distance measured from the method by glass beads weight and by image analysis technique.

Fig. 8. Relationships between experimental conditions and maximum permeation distance (CoalA2).

$$\frac{\Delta P}{L} = \frac{1}{K} \mu u \quad \dots\dots\dots (2),$$

where ΔP is a pressure loss in the packed layer (Pa), L is a height of the layer (m), K is a permeability coefficient (m^2), μ is a viscosity of the material (Pa s), and u is a flow rate (m/s). Although permeation phenomenon is not exactly the same as the pressure drop in packed bed represented by Eq. (2), the following approximation was tried. It is assumed that ΔP is a coking pressure as a driving force of the permeation, L is permeation distance, K is determined by void structure of glass beads layer, μ is a viscosity of the thermally plastic coal, u equals L/t where t is the time period of permeation. Then the Eq. (2) can be expressed as Eq. (3).

$$L = \sqrt{\frac{\Delta P K t}{\mu}} \quad \dots\dots\dots (3)$$

According to the Eq. (3), it is estimated that L is proportional to the square root of the ΔP and K . K of glass beads layer is calculated by Kozeny-Carman equation,¹³⁾

$$\frac{1}{K} = k_c S_v^2 \frac{(1-\varepsilon)^2}{\varepsilon^3} \quad \dots\dots\dots (4),$$

where k_c is a Kozeny constant ($=5.0$, in general), S_v is a specific surface area of the packed layer (m^{-1}), ε is a void ratio of the layer ($-$), respectively. When the packed bed consist of spherical material, S_v equals $6/d$ where d is a diameter of the material (m). According to the Eq. (4), the relationship between permeability coefficient of glass beads layer and glass beads diameter was derived as shown in Fig. 9. In this calculation, the measured void ratio of glass beads layer having each diameter was assigned to ε ($=0.361, 0.364, 0.387$ when the diameters are 0.4, 1.0, 2.0 mm, respectively). Thus, it is considered that the permeation constant is varied with change of the diameter, and that affects the maximum permeation distance as shown in Fig. 8. It is suggested that the permeation behavior under the actual cokemaking conditions could be controlled by changing coal size and permeability coefficient of the void structure of coal packed bed. On the other hand, it is indicated that the main driving force of the permeation behavior should not be the pressure of weight judging from the result in Fig. 8. It is considered that the most probable main driving force is expansion pressure of coal sample. As the evidence of above consideration,

Fig. 9. Relationship between permeability coefficient of glass beads layer and glass beads diameter.

the temperature range of the expansion pressure is between IST and MFT and nearly corresponds with the one of the permeation.¹⁴⁾ One of the dominant factors of expansion pressure is internal gas pressure. The internal gas pressure is varied with change of coal size.^{15,16)} Therefore the expansion pressure should be varied with change of coal size. In addition, if the expansion pressure is the main driving force of permeation behavior, it is also suggested that the permeation distance could be controlled by changing coal size.

2.2.3. Relationship between Permeation Distance and Conventional Coal Thermoplasticity

In the standard conditions, the measured maximum permeation distance of each coal brand is also shown in Table 1. Figure 10 shows a relationship between the maximum permeation distance and logMF of each coal. The maximum permeation distance showed a certain extent of correlation with logMF, however some large deviations were observed in high fluidity coal (over around 3.0). Deviations were also observed in the relationship between the maximum permeation distance and TD as shown in Fig. 11. These results show that the maximum permeation distance is a unique parameter for representing coal thermoplasticity especially for high fluidity coal which the conventional methods cannot correctly evaluate.

Fig. 10. Comparison between maximum permeation distance and Gieseler maximum fluidity (MF).

Fig. 11. Comparison between maximum permeation distance and total dilatation (TD).

3. Investigations of Relationship between Permeation Distance and Coke Quality

3.1. Experiments

The difference in the maximum permeation distance in high MF coals shown in Fig. 10 prompted us to examine the effect of blending high MF coals whose maximum permeation distance was different on coke strength. In order to clarify the effect, carbonization tests and evaluations for obtained coke were carried out as below.

At first, the effects of the maximum permeation distance of high MF coal in coal blend on the coke strength and structure were evaluated (Test1). The detailed characterization data of the coal blends are shown in **Table 2**. In the Test1, CoalA2, B2 and F1 were chosen as the high MF coal. Then those high MF coal were blended so that the blending ratio in sample coal blend became 20 wt%. The coal blends were carbonized in an electric furnace under the conditions shown in **Table 3**. After carbonization, the produced coke was cooled under nitrogen. The coke strength (drum Index) of the obtained coke was determined based on JIS K2151. In addition, the coke made from coal blend No.1–3 was

embedded into resin and polished. Then the pictures of those samples were taken by optical microscope at 100-fold magnification. For quantifying the pore-wall structure of the coke, the pore-wall thickness was measured by image analysis software (Nippon Roper: Image-Pro Plus version4.0) as follows. Firstly, all the shot microscopic images ($700 \times 900 \mu\text{m}$) were binarized based on a set RGB threshold value so that the coke matrix and pore were discriminated. Secondly, the vertical lines were arranged on the every image at equal intervals ($66 \mu\text{m}$). Thirdly, the coke matrix length just on the lines was measured by image analysis technique. Then the

Table 3. Carbonization test conditions.

	Test1	Test2
Coal size (wt%)	–3 mm: 100	–3 mm or –6 mm: 100
Moisture content (wt%)	8	8
Bulk density (kg-dry/m ³)	750	750
Dimensions (mm)	W250 × H600 × L413	W273 × H300 × L260
Wall temperature (°C)	1 050	1 050
Coking time (min)	500	380

Table 2. Coal blending conditions.

Coal brand	Test1			Test2						
	Blend1	Blend2	Blend3	Blend4	Blend5	Blend6	Blend7	Blend8	Blend9	Blend10
CoalF1	20.0									
CoalB2		20.0							20.0	5.0
CoalA2			20.0							
CoalI1	12.0	11.0	19.0						14.0	
CoalQ1	20.0	18.0	3.0						19.0	
CoalR1	20.0	19.0	18.0							
CoalS1	10.0	8.0	20.0						13.0	
CoalC2	6.0	9.0	9.0						11.0	
CoalW1	8.0	10.0	6.0						8.0	
CoalZ1	4.0	5.0	5.0						4.0	
CoalE1				15.0	10.0	5.0				
CoalN1				15.0	15.0	15.0				
CoalP1				20.0	20.0	20.0				
CoalQ2				25.0	25.0	25.0				
CoalU1				10.0	7.0	6.0				
CoalC3				15.0	18.0	19.0				
CoalG1					5.0	10.0		5.0		
CoalV1									11.0	
CoalQ3							18.0	17.1		
CoalO1							16.0	15.2		
CoalX1							18.0	17.1		13.0
CoalR2							20.0	19.0		22.0
CoalP2							19.0	18.1		30.0
CoalJ1							9.0	8.6		19.0
CoalT1										11.0
$\bar{R}_o$ (%)	0.99	0.99	0.99	1.00	1.01	1.01	1.05	1.03	0.98	0.99
logMF (log/ddpm)	2.2	2.2	2.1	2.8	2.8	2.8	2.2	2.3	2.2	2.2
Coal size	–3 mm	–3 mm	–3 mm	–3 mm or –6 mm	–6 mm	–3 mm or –6 mm	–3 mm	–3 mm	–3 mm	–3 mm

measured length of each image was averaged as mean pore-wall thickness.

Next, the effect of the blending ratio of high MF coal in coal blend on the coke strength was also evaluated (Test2). The detailed characterization data of the coal blends and the carbonization test conditions are also shown in Tables 2 and 3. In the Test2, CoalB2, E1 and G1 were chosen as the high MF coal. Blends4–8 are the levels for evaluating the effect of long permeation distance coal, CoalG1. In order to clarify the MF impact on coke strength, the mean logMF of Blends4–6 were set to 2.8 and the one of Blends7, 8 were set to 2.2–2.3. In more detail, the blending ratio of CoalG1 in Blends4–6 was decreased in return for increasing the ratio of CoalE1 whose maximum permeation distance was short. Blend8 consisted of 95 wt% of Blend7 and 5 wt% of CoalG1. Blends9, 10 are the levels for evaluating the effect of short permeation distance coal, CoalB2. After carbonization and cooled, the coke strength (drum Index) of the obtained coke was determined based on JIS K2151.

3.2. Results and Discussions

Figure 12 shows the relationship between the maximum permeation distance of high MF coal included in coal blends (Blend1–3) and the strength of coke obtained from Test1. It clearly shows that when the longer maximum permeation distance coal is in a coal blend, the strength of the obtained coke becomes lower. **Figure 13** shows the relationship

Fig. 12. Effect of maximum permeation of high MF coal on coke strength (Blend1–3).

between the blending ratio of the high MF coal brand (CoalB2 or CoalG1) and the coke strength. It was observed that coke strength decreased with increasing CoalG1 in coal blend though averaged logMF levels of coal blend was changed from 2.2 to 2.8. On the other hand, the coke strength did not decrease when the blending ratio of the short maximum permeation distance coal (CoalB2) was increased. These results suggest that the cause of deterioration of coke strength is the long maximum permeation distance coal itself.

Figure 14 shows the effect of size of coal blend on coke strength. The coke strength was more drastically decreased with increasing CoalG1 in case coal size was bigger. In general, it is well known that size of high caking property coal should be kept larger for making high strength coke because caking property is decreased with decreasing coal size.¹⁷⁾ However as shown in Fig. 14, it is suggested that the strength of coke produced from coal blend including the long permeation distance coal could be maintained by more pulverizing the coal blend.

Figure 15 shows optical microscopic images of the coal Blend1 and 2. It was observed that the thickness of the pore-wall of coke derived from Blend1 including the long maximum permeation distance coal (CoalF1) was thinner than photo(b) where the short maximum permeation distance CoalB2 was blended. The relationship between the mea-

Fig. 14. Effect of size of coal blend on coke strength with increasing amount of long maximum permeation distance coal (Blend4–6).

Fig. 13. Relationship between blending ratio of high MF coal and coke strength ((a) Long maximum permeation distance coal: CoalG1 (Blend4, 6–8), (b) Short maximum permeation distance coal: CoalB2 (Blend9, 10)).

sured mean pore-wall thickness and the maximum permeation distance of high MF coal is shown in **Fig. 16**. This relationship strongly suggests that the long maximum permeation distance coal produces the coke structure having thinner wall and produces weaker coke structure as a result.

The presumed behavior of high MF coal with thermally plastic state is shown in **Fig. 17**. In **Fig. 17(a)**, the long maximum permeation distance coal permeates into gaps between packed particles or void upon heating. After per-

Fig. 16. Effect of the maximum permeation of high MF coal on mean pore-wall thickness (Blend1–3).

meation is completed, thin pore-walls are formed and large pores are left in places in which the particles have been originally present, which result in the decrease in the coke strength. On the other hand, **Fig. 17(b)** shows the structure formed from coal blend including the short maximum permeation distance coal. The coal permeates into the void less than the long maximum permeation distance coal does. Consequently, thick pore-walls are formed and no large pore is left. According to the previous studies about relationship between coke strength and coke structure, it was reported that large pores especially having the mm-scale diameter behave as the defects of coke and decrease the coke strength.^{18–20)} It was also reported that coke strength is decreasing as the pore-wall thickness becomes thin.²¹⁾ Therefore it is considered that the difference of void left after permeation and pore-wall thickness are critical for understanding the difference of the effect of the long maximum permeation coal and the short maximum permeation coal on coke strength. Based on these results, the cause of coke strength decrease in excessively high MF coal blend is suggested to be the existence of the long maximum permeation distance coal in a coal blend. Furthermore it is proposed that the permeation distance can supplement the Gieseler fluidity as the caking property especially for evaluating high fluidity coal and contribute to improving the anticipation of coke strength, namely blending technique.

Fig. 15. Polarizing microscope images of coke structure ((a) Blend1, (b) Blend2).

Fig. 17. Schematic illustration of behavior of long and short maximum permeation distance coal.

4. Applications of Permeation Distance to Commercial Plant

4.1. Experiments

For verifying the commercial-scale impact of the permeation distance on coke strength, a plant trial was implemented at Keihin No.1 coke oven battery (124 chambers, $W0.45 \times H7.55 \times L17.0$ m). The working rate was 125% during the trial. The blending ratio of the long maximum permeation distance CoalA2 in commercial coal blend was decreased in return for increasing the ratio of the short maximum permeation distance CoalH1. Then the variation of coke strength was evaluated. During the trial, average $\bar{R}_o$ and logMF of coal blend were kept constant.

4.2. Results and Discussions

Figure 18 shows the variations of coke strength, $\bar{R}_o$, logMF and blending ratio of CoalA2 and CoalH1. With replacing CoalA2 to CoalH1, the coke strength enhanced. Averaged coke strength while the blending ratio of CoalA2 was more than 10 wt% (1–9 day) was 84.3. On the other hand, averaged coke strength while the ratio was not more than 10 wt% (10–16 day) was 84.7. The difference was statistically-meaningful in consequence of two-sample t-test under the conditions that the two-sided 95% confidence interval was used and the dispersion of each level was assumed same. Therefore it is clarified that the permeation distance is effective and important as the caking property because it indeed affects on the coke strength under the conditions of commercial operations. By employing the permeation distance method, contribution to the production of high strength coke and effective usage of caking coal will be expected.

Fig. 18. Variations of coke strength with changing the blending ratio of long and short maximum permeation distance coal at commercial plant.

5. Conclusions

A novel method for evaluating coal thermoplasticity is developed. The method includes measuring the permeation distance of thermally plastic coal into glass beads layer placed adjacent to the coal sample. Following findings and implications were obtained in terms of the permeation distance;

(1) Rough correlations between the maximum permeation distance and conventional coal thermoplasticity (Gieseler maximum fluidity (MF) and total dilatation (TD)) were observed, however large deviation from the correlation was observed especially in higher MF coals. Permeation distance measurement is an improved method especially for evaluating thermoplasticity of high MF coal and can supplement the Gieseler Fluidity by overcoming idling of stirring rod.

(2) Coal that has the long maximum permeation distance forms large pore and thinner pore-wall structure in coke, which induces deterioration of coke strength when the coal blend includes the long maximum permeation distance coals.

(3) The coke strength deterioration caused by the long maximum permeation distance coals was reduced as the grain size of coal blend becomes smaller.

(4) The difference of the maximum permeation distance in high MF coals rationalizes the decrease of coke strength in case that high MF coal is used in a coal blend.

(5) By employing the permeation distance method, more precise evaluation of coal thermoplasticity is realized, which enables us more effective usage of coal resources and to produce high strength coke.

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