AUTOMATIC CONTROL OF THE OPTIMAL GRANULATION MOISTURE OF MIXED RAW MATERIALS FOR IRON ORE SINTER, CONSIDERING THE WATER HOLDING CAPACITY OF EACH IRON ORE TYPE

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Abstract

In the iron ore sintering process, ensuring permeability to allow an appropriate amount of air to pass through the mixed raw material layer in the sintering machine and flow smoothly from top to bottom is crucial for the progress of the combustion zone and sinter productivity. Moisture control is vital for the granulation and air permeability of the mixed raw materials. The water holding capacities of each type of iron ore were measured, and the optimal granulation moisture for return fines, limestone, and solid fuel was determined through a permeability test to achieve the appropriate granulation moisture of the mixed raw materials. Additionally, optimal granulation moistures under various blending conditions were identified through permeability tests. This allowed for the derivation of optimal granulation moisture based on the type and mixing ratio of the raw materials. A system has been established to automatically control the additional moisture amount based on the difference between the real-time moisture measured by the microwave moisture analyzer and the calculated optimal granulation moisture, considering the type of raw materials and blending ratio. When this system was applied to the sintering plant, it was confirmed that iron ore sinter productivity increased by 0.3 t/D.m², and the sinter fuel ratio was reduced by 1.1 kg/t-sinter.

Keywords: Iron ore Sinter, Water holding capacity, Granulation moisture, Microwave moisture analyzer, Permeability test

1. INTRODUCTION

In the sintering process, granulation of the raw materials is important to ensure the permeability of the mixed raw material layer for productivity. Sintering granulation is to make iron ore powder, flux, fuel, and recovered materials into pseudo particles with suitable moisture, reasonable particle size distribution and good bed permeability for sintering. Fundamentally, the sintering granulation is achieved by layering fine particles onto coarser core particles to achieve particle size expansion [1]. This process is usually carried out under the action of water. Therefore, moisture control for the granulation of mixed materials is very important. Matsumura et al. and Lv et al. investigated the moisture content of iron ore particles, suggesting that the optimal moisture content should be adjusted based on the properties and particle size of the iron ore [2-4]. Similarly, Maeda et al. analyzed the factors affecting quasi-particle strength from the perspectives of iron ore properties and granulation conditions, suggesting that increasing water content can enhance the ability of small balls to resist breakage [5,6]. Additionally, Lv et al. provided an equation relating the water content capacity of sintering mixtures to the optimal water content [7]. Khosa and Manuel studied the granulation behavior of iron ore based on particle size distribution and composition, and predicted the relationship equation for the optimal granulation water content of the ore [8].

In this study, the equation was provided to calculate the optimal granulation moisture content in real-time based on the blending ratio of mixed raw materials, considering the inherent water holding capacity (WHC) of the iron ores and the appropriate granulation moisture content for other sub-raw materials such as limestone, quicklime, return fines, and solid fuels. Additionally, a microwave-type moisture measurement device was installed to measure the moisture content of the mixed raw materials in real-time. A system was established to automatically control the amount of moisture based on the deviation between the measured moisture content in real-time and the optimal granulation moisture content of the mixed raw materials. Furthermore, the operational effects of applying this system to the sinter plant were verified.

2. EXPERIMENTRAL

The water holding capacity of iron ores is an inherent characteristic that varies by ore type and is an important factor in determining the optimal granulation moisture for the mixed raw materials. In this test, the water holding capacities were measured for a total of 9 types of iron ores. Each type of iron ore is divided into specific particle size groups (over 2.8 mm, 2.8-1.0 mm, 1.0-0.25 mm and under 0.25 mm) and then washed. After washing, the samples are submerged in water for more than 10 hours. The submerged samples are placed in a 15 ml container equipped with a fine mesh at the bottom. The container is then spun at a speed of 1500 rpm for 5 minutes to centrifuge the water and the sample. After centrifugation, the weight of the sample is measured. The sample is then placed in an oven to be completely dried, and its weight is measured again.

To calculate the water holding capacity, you can use the following Equation 1:

$$\text{Water holding capacity}(\%) = \frac{\text{Weight before drying} - \text{Weight after drying}}{\text{Weight before drying}} \text{ X } 100 \qquad [1]$$

Next, the optimal granulation moistures of various sub-raw materials such as limestone, return fines, and solid fuels used in iron ore sinter production, as shown in **Figure 1**, were calculated through JPU (Japanese permeability unit) tests. Each of these sub-raw materials was placed into a drum mixer, and granulation was carried out for 8 minutes while adding moisture and rotating the mixer. Once granulation was completed, each of the blended materials was charged into a pot with a diameter of 110 mm and a height of 430 mm. Under a constant suction pressure of 1000 mmAq, the velocity of air passing through the layer of blended materials was measured at 10-second intervals for a total of 5 minutes. The same permeability measurement experiment was conducted while varying the moisture content added to the blended materials. Through this process, the optimal granulation moisture content of sub-raw materials that resulted in the best permeability was determined.

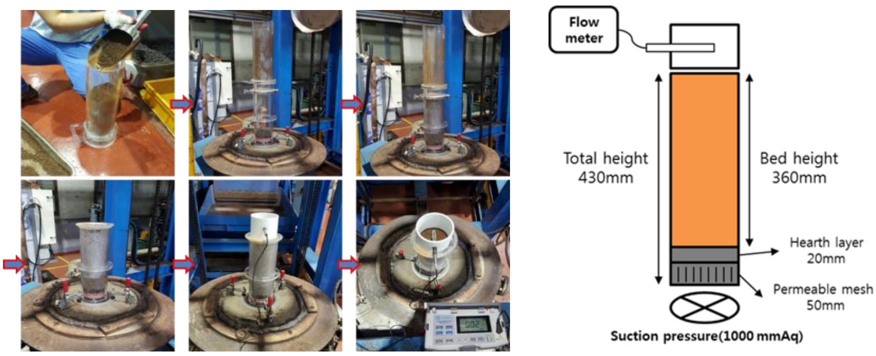

Figure 1 The method for measuring the permeability test (JPU) of mixed raw materials

Using the cross-sectional area of the pot, the height of the mixed raw materials bed, and the average flow rate, the Japanese Permeability Unit (JPU) is calculated as shown in Equation 2 below.

$$\text{JPU} = \frac{F}{A}\left(\frac{L}{\Delta P}\right)^{0.6} \qquad (2)$$

where, JPU : Japanese Permeability Unit, F : Flow rate (m^3/min), A : Cross sectional area of the bed (m^2)
L : Height of the bed (mm), ΔP : Suction pressure across the bed (mmAq)

The permeability measurement tests (JPU) were conducted under a total of seven different blending conditions (Blending A~G) to create the equation for deriving the optimal granulation moisture content according to the blending ratio of raw materials. The equation also uses the water holding capacities for each type of iron ore previously derived, as well as the optimal granulation moisture content of other sub-raw materials, including solid fuel. Additionally, using this equation, the optimal granulation moisture content is calculated in real-time on the sinter plant control room's HMI according to changes in the raw material blending ratio during actual operation.

The microwave-type online moisture analyzer and an auto sampler were installed on the conveyor belt at the exit of the secondary rerolling drum mixer in the sintering plant to measure the moisture content of the mixed raw materials in real-time. To create the calibration curve for the moisture measurement device, samples were taken using the auto sampler while varying the amount of moisture added from the control room, and the readings from the moisture measurement device were recorded simultaneously. The sampled mixed raw materials were dried at 105℃ for a day to measure the actual moisture content. These actual moisture contents were then analyzed for correlation with the readings from the moisture analyzer taken at the same time as the sampling, and a calibration curve was created. Based on the calibration curve created in this manner, the moisture analyzer provided real-time moisture content readings. These readings were compared with the actual moisture analysis values of various samples collected using an automatic sampler installed just behind the moisture analyzer, and the standard deviation between the actual moisture content and the device's measured moisture was analyzed to be almost 0.08%.

3. RESULTS AND DISCUSSION

3.1. Water holding capacity (WHC)

The water holding capacity for each type of iron ore was measured, and the results are provided in **Table 1**. The magnetite series, Ore G showed relatively very low water holding capacity. In contrast, the limonite series, including Ore A, B, C, E, and I, exhibited relatively high water holding capacity. Additionally, the mixtures of hematite and limonite, such as Ore D, F, and H showed a water holding capacity of about 4-5%. It is clear that as the proportion of iron ore with high water holding capacity increases, the optimal granulation moisture should also be increased.

Table 1 The water holding capacity (WHC) of iron ores used in this test according to particle size distribution

Brand	Ratio of particle size (mm), (wt%)				WHC according to particle size (mm), (wt%)				
	+2.8	2.8~1.0	1.0~0.25	-0.25	+2.8	2.8~1.0	1.0~0.25	-0.25	Total
Ore A	20.8	11.3	15.1	52.7	2.23	3.75	3.16	10.60	**6.95**
Ore B	55.5	20.0	14.6	10.0	3.54	4.57	4.29	10.97	**4.60**
Ore C	53.2	28.4	16.2	2.3	5.94	6.17	6.79	9.36	**6.23**
Ore D	41.4	27.1	27.3	4.3	5.90	7.25	9.64	10.76	**7.50**
Ore E	28.8	18.9	23.3	29.0	5.30	7.19	8.32	15.03	**9.18**
Ore F	40.5	29.6	19.2	10.7	4.23	4.90	6.01	10.02	**5.39**
Ore G	-	-	64.5	35.5	-	-	0.95	1.89	**1.28**
Ore H	36.0	25.4	19.8	18.8	3.25	4.37	3.74	9.48	**4.80**
Ore I	51.2	22.9	5.9	20.0	4.25	5.14	5.16	5.20	**4.70**

3.2. Optimal granulation moisture

The results of the permeability test to determine the optimal granulation moisture for other sub-raw materials and the mixed raw materials with various blending conditions are shown in **Figure 2**. The optimal granulation moisture content, which provides the best permeability, was measured as 2.63% for limestone used as flux, 3.24% for return fines, 15.81% for anthracite powder, and 14.98% for coke breeze. And the permeability test was conducted by varying the amount of moisture added under the same blending condition. Based on the results of the permeability measurement experiments as described above, the optimal granulation moisture contents for various blending ratio conditions, along with the water holding capacity and blending ratio of each iron ore, are presented in **Table 2**.

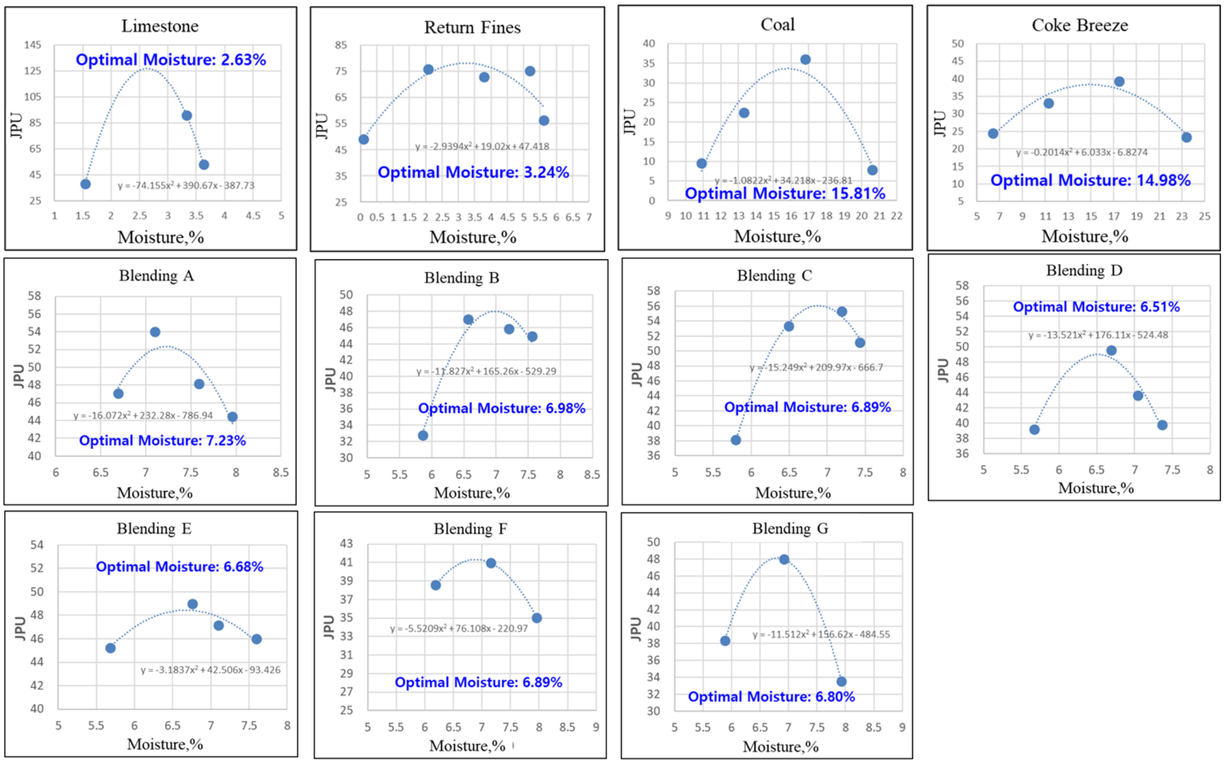

Figure 2 Results of the permeability test based on the moisture content of various sub-raw materials and mixed raw materials with different blending ratios

Table 2 The water holding capacity and blending ratio of each iron ore brand, as well as the optimal granulation moisture content under various blending conditions

Brand	WHC*, %	Blending ratio of each iron ore brand (wt%)						
		Blend. A	Blend. B	Blend. C	Blend. D	Blend. E	Blend. F	Blend. G
Ore A	6.95	2.15	2.15	2.15	2.15	2.15	0.00	0.00
Ore B	4.60	3.96	5.39	5.39	3.95	3.95	6.06	6.06
Ore C	6.23	14.70	12.00	7.05	14.70	0.00	13.00	13.00
Ore D	7.50	26.34	15.84	14.79	4.15	18.85	20.03	11.88
Ore E	9.18	2.69	2.69	2.69	2.69	2.69	2.74	2.74
Ore F	5.39	4.98	2.60	1.20	4.98	4.98	2.04	2.04
Ore G	1.28	4.35	4.35	4.35	4.35	4.35	4.77	4.77
Ore H	4.80	2.77	2.12	2.12	2.77	2.77	3.32	3.32
Ore I	4.70	0.00	14.80	22.20	22.20	22.20	10.35	18.50
**WHCt,%	-	**6.34**	**5.77**	**5.58**	**5.33**	**5.64**	**5.87**	**5.51**
***Mopt,%	-	**7.23**	**6.98**	**6.89**	**6.51**	**6.68**	**6.89**	**6.80**

* WHC : Water holding capacity of each iron ore(%),

** WHCt (%) : Total WHC = (Ore A ratio × Ore A WHC + ... + Ore I ratio × Ore I WHC) / sum (ratio of Ore A+B ...+I)

*** Mopt (%) : Optimal granulation moisture content from JPU test

The relationship between the total water holding capacity and the optimal granulation moisture content according to each blending condition is shown in **Figure 3**. The correlation between the total water holding capacity and the optimal granulation moisture content exhibited an R^2 value of approximately 0.81.

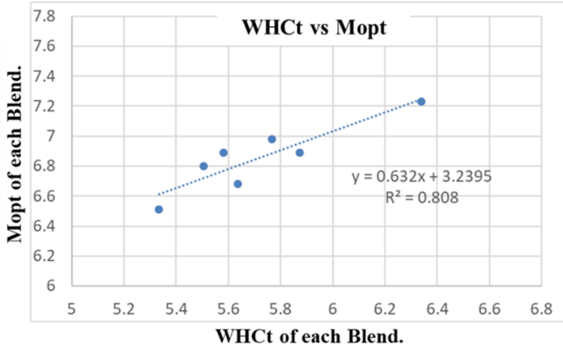

Figure 3 The relationship between the total water holding capacity of iron ores and the optimal granulation moisture content for each blending condition

The optimal granulation moisture content calculation equation, as shown in Equation 3, was derived by considering the total water holding capacity of iron ores as the primary raw materials, the optimal granulation moisture content for each blending condition, the appropriate granulation moisture content for other sub-raw materials including solid fuels, and the amount of water used in the hydration reaction of quicklime.

$$\text{Optimal granulation moisture, } M_{opt} = (0.632 \times WHCt) + B1 + B2 \ldots + B5 + \alpha \qquad (3)$$

where, B1 = 0.321 × quicklime blending ratio (0.321 is the water-to-quicklime ratio required for the hydration reaction of quicklime).

B2~5 = Optimal granulation moisture of each sub-raw material × Blending ratio of each sub-raw material

α = Calibrating constant (selected as 2.31 through actual test operations in the sintering plant)

3.3. Actual test operation results of the sinter plant

For five days, under the same blending file, the operator manually controlled the moisture addition based on the moisture analysis results of the mixed raw materials, which were measured four times a day using the conventional dry method. For the next seven days, the moisture addition was automatically controlled based on the difference between real-time moisture measurements from a microwave-type moisture analyzer and the real-time optimal granulation moisture content calculated in connection with the blending conditions. **Table 3** compares the actual moisture contents of the mixed raw material samples during the 12-day test operation period. The mixed raw materials were sampled four times a day, completely dried, and then the actual moisture was measured.

Table 3 The actual moisture content of the mixed raw material samples during the 12-day test operation period

Test day / Measurement	Moisture contents, (wt%)													
	Manual control (for 5 days)					Automatic control (for 7 days)							Average	
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	Manu.	Auto.
1st	8.5	8.5	7.5	7.2	7.2	7.2	7.4	7.4	6.9	6.4	6.4	6.4	7.8	6.9
2nd	7.5	7.5	7.2	7.3	7.3	7.3	7.1	7.1	7.1	6.3	6.3	6.3	7.4	6.8
3rd	6.5	6.5	6.5	7.2	-	7.2	7.2	6.3	6.3	6.3	6.6	6.8	6.7	6.7
4th	7.1	7.1	7.1	7.1	6.5	7.3	7.3	6.5	6.5	6.5	6.7	6.9	7.0	6.8
Average	7.4	7.4	7.1	7.2	7.0	7.3	7.3	6.8	6.7	6.4	6.5	6.6	7.2	6.8
Standard deviation	0.73	0.73	0.36	0.07	0.36	0.05	0.11	0.44	0.32	0.08	0.16	0.25	0.25	0.13

During the period of using the same blending pile, the average actual moisture of the mixed raw material samples over 5 days of manual control was 7.2%, with a standard deviation of 0.25%. In contrast, during 7 days when the water sprayed into the drum mixer was automatically controlled, the average moisture was 6.8%, with a standard deviation of 0.13%, showing a reduction in moisture standard deviation by approximately 50%. In other words, moisture variation decreased, resulting in more stable moisture control.

Table 4 The results of the sintering operation during the test periods

Operation index / Control method	Standard deviation, (%) (*Mopt-**$M_{M/W}$)	Pallet speed, (m/min)	Productivity, (t/D.m^2)	Fuel Ratio, (kg/t-sinter)
Manual control	0.24	2.68	32.1	51.2
Automatic control	0.11	2.73	32.4(+0.3)	50.1(Δ1.1)

* Mopt : Real time optimal granulation moisture, ** $M_{M/W}$: Moisture from microwave-type moisture analyzer

Table 4 presents the sintering operation results for the periods during the test operation when manual control and automatic control were applied, respectively. Automatic control reduced the standard deviation between the optimal granulation moisture and the real-time moisture measured by the microwave analyzer by approximately 54%, decreasing it from 0.24% to 0.11% compared to manual control. Furthermore, optimizing the overall moisture improved the permeability of the mixed raw material bed, increasing the pallet speed of the sinter plant from 2.68 m/min to 2.73 m/min. Consequently, iron ore sinter productivity increased by 0.3 t/D.m², from 32.1 t/D.m² to 32.4 t/D.m². Additionally, the sinter fuel ratio decreased by 1.1 kg/t-sinter, from 51.2 kg/t-sinter to 50.1 kg/t-sinter, attributed to reduced excessive heat consumption required for moisture removal during the sintering process due to granulation moisture optimization.

4. CONCLUSION

The system has been established to automatically control the additional moisture amount based on the difference between the real-time moisture of the mixed raw materials and the calculated optimal granulation moisture, in order to adjust to the optimal granulation moisture in real-time, considering the type of raw materials and blending ratio. When this system was applied to the sinter plant, the standard deviation of the optimal granulation moisture and the real-time mixed raw material moisture decreased by approximately 54%, from 0.24% to 0.11%. Additionally, iron ore sinter productivity increased by 0.3 t/D.m², from 32.1 t/D.m² to 32.4 t/D.m², and the sinter fuel ratio was reduced by 1.1 kg/t-sinter, from 51.2 kg/t-sinter to 50.1 kg/t-sinter.

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