Effect of the Separation of Large Limonite Ore Particles in the Granulation Process of Sinter Raw Materials

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Sintering with large amount of limonite generally requires higher fuel consumption, either due to the dehydration of combined water or the evaporation of more added water. Although limonite can accelerate melt formation, the sintering strength indexes are in lower level on the contrary, proved to have much to do with the excessive assimilation.

In order to improve the sintering behavior of sintering mix when large amount of limonite were used, a simplified method named separating large particles of limonite from granulation was investigated by measuring the bonding strength using quasi-particles on the base of confirming influence of excessive assimilation on effective liquid phase of limonite, and calculating changes in properties of sintering mix for moisture transferring. The results obtained were summarized as follows:

Limonite nuclei adversely influenced bonding strength of quasi-particles mainly by the effective liquid phase, which was determined by volume decrease for penetration and viscosity increment by less fluxed melt, separation of limonite nuclei to reduce the contact interface is helpful in improving bonding of sintered body, and the separation ratio was suggested be within certain range by melt distribution in the whole bed. Less accumulation of condensed water and partial absorption by ungranulated dry limonite resulted in smaller increment in effective mean size and less decrement in void fraction, indicating better bed permeability.

KEY WORDS: sintering; limonite; separation; effective liquid phase; moisture condensation.

1. Introduction

Since pisolite was exploited in the 1980s, it has been one of the most important raw materials in most iron and steel companies, especially in Asia. It is well known that pisolite known as limonite, which has comparatively high combined water content is characterized with the property of higher moisture addition to gain good green bed permeability,1–3) very porous after dehydration4–6) leading to higher assimilation degree or amount7–9) and special penetration behavior.10,11) The application of limonite results in lower strength and higher fuel consumption,1,12–14) affected the sintering indexes to some extent.

In order to produce high quality sinter with large amount of limonite, several studies has been conducted to realize effective sintering, known as pretreating of raw materials,15) for example, densification and etc., granule design16,17) and the MEBIOS,18–21) and they are verified to be effective for structure or strength improvement. However, above measures had some requirement for the raw materials and would increase complexity of practical production, which increased difficulty in application under present conditions for many companies. Some researchers22) reported separately adding return fines to the granulated sinter mixtures (RF-MEBIOS process) to improve bed permeability and sinter productivity, suggesting that it is a good and simple method to separate dry particles from sinter mixture to achieve more granule water and lower bulk density of packed bed. Since there’s considerable percentage of large particles in limonite, the author proposed a simplified means named separation of large limonite particles in the granulation process by considering the characteristics of limonite based on fundamental results.

In this research, the method to separate large particles of limonite was studied by evaluating the influence of limonite assimilation on effective bonding phase, and calculating the structural change of quasi-particles and green bed in condensation zone. The technique could be useful in improving sintering behavior of limonite and obtaining better sintering indexes.

2. Fundamental Experiments

2.1. Experimental Procedures

Limonite Ore A, hematite Ore B and Ore C, and practical sintering blend Ore D were used in the present experiment. Chemical compositions of iron ores are listed in Table 1. Ore A was a typical Australian limonite characterized with high CW content and porous structure. Ore B and C were Brazilian hematite with different silica content and compar-
Porosity of single ore before and after dehydration (%).

<table>
<thead>
<tr>
<th>Material</th>
<th>Before Dehydration</th>
<th>After Dehydration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore A</td>
<td>22.36</td>
<td>25.31</td>
</tr>
<tr>
<td>Ore B</td>
<td>4.16</td>
<td>4.81</td>
</tr>
<tr>
<td>Ore C</td>
<td>1.47</td>
<td>2.07</td>
</tr>
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</table>

Table 2.

Chemical compositions of iron ores (mass%).

<table>
<thead>
<tr>
<th>Material</th>
<th>TFe</th>
<th>FeO</th>
<th>SiO₂</th>
<th>CaO</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>MnO</th>
<th>P</th>
<th>S</th>
<th>Ig</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore A</td>
<td>57.99</td>
<td>0.19</td>
<td>5.40</td>
<td>0.04</td>
<td>1.61</td>
<td>0.05</td>
<td>0.05</td>
<td>0.10</td>
<td>0.01</td>
<td>10.17</td>
<td>limonite</td>
</tr>
<tr>
<td>Ore B</td>
<td>65.36</td>
<td>0.17</td>
<td>1.78</td>
<td>0.02</td>
<td>1.31</td>
<td>0.03</td>
<td>0.03</td>
<td>1.17</td>
<td>0.06</td>
<td>0.01</td>
<td>2.09 hematite</td>
</tr>
<tr>
<td>Ore C</td>
<td>64.89</td>
<td>0.55</td>
<td>4.55</td>
<td>0.02</td>
<td>0.73</td>
<td>0.07</td>
<td>0.07</td>
<td>0.27</td>
<td>0.09</td>
<td>0.01</td>
<td>1.36 hematite</td>
</tr>
<tr>
<td>Ore D</td>
<td>60.93</td>
<td>1.27</td>
<td>3.98</td>
<td>1.25</td>
<td>1.45</td>
<td>0.34</td>
<td>0.38</td>
<td>0.13</td>
<td>0.02</td>
<td>5.55</td>
<td>blend</td>
</tr>
</tbody>
</table>

Fig. 1. Sketch of assimilability experiment.

Fig. 2. Experimental conditions and measurement positions of the melt penetration test.

\[
\text{Fluidity} = \frac{A_{\text{after}} - A_{\text{before}}}{A_{\text{before}}} \quad \text{(1)}
\]

Where, \(A_{\text{after}}\) is the vertical projection area after sintering experiment, mm², \(A_{\text{before}}\) is the vertical projection area before sintering experiment, mm².

In the experiment of limonite nuclei separation, original cores were mixed with the separated and uncoated iron ore A, B and C as main ores. The porosity of single ore measured with gas absorption method before and after dehydration is shown in Table 2. The assimilability of iron ores was evaluated by the lowest assimilated temperature, defined: Unassimilated, Assimilated and Over-Assimilated. The measurement, particles were dried at 105°C for 24 h, then put into distilled water for certain time, after that took it out, wiped water on the surface and measure the weight. Then dried the particle and measured the weight after water absorption with longer time, repeated above operations until the weight did not change.

In the measurement of the assimilability, iron ores were crushed into the size less than 100 mesh, Fig. 1 shows a sketch of the assimilability test. Firstly, a compressed tablet of iron ore was placed over a compressed tablet of CaO reagent. In sequence, the material was sent to an infrared image furnace to simulate sintering thermal profile. After experiment, three assimilating states for the sample were defined: Unassimilated, Assimilated and Over-Assimilated. Finally, the temperature at which the material starts to assimilate was defined as the lowest assimilated temperature to evaluate the assimilability.

In the experiment of secondary melt properties, Ore A, B, C and D were crushed to the size less than 100 mesh, then Ore A, B and C were pressed to cylinder with height of 5 mm and diameter of 20 mm at 15 MPa to simulate iron ore. Ore D was mixed with 20 mass% of CaO reagent (analytically pure) and the mixture was pressed to tablet with height of 5 mm and diameter of 8 mm. The tablet was set on the surface of iron ore cylinder, shown in Fig. 2, and sintered in the infrared image furnace. After that, fluidity of the melt formed on the surface of iron ore cylinder was measured with projection method.

The fluidity is defined as the increase of vertical projection area after melt flowed, it is calculated according to Eq. (1).
2.2. Experimental Results

2.2.1. Water Adsorption Rate

Figure 3 shows the water adsorption rate of iron ores when time prolongs, it is seen that iron ore can absorb water to approximately 80% in two minutes, and almost saturated in five minutes, indicating that water would generally be absorbed during the period when mix still stayed in drum mixer. It is in good accordance with the fact that porous limonite needs more water to be well granulated, since much water enters the pores and residual capillary water in interstice of adhering fines became less.

Although it is difficult for limonite gaining saturated state in sintering process, due to some content of small pores in which it takes longer for compressed air discharging, absorbed water content is very close to the saturated value, and the change is slight, so in present study, water absorbing ability was simplified as saturated in short time. And the water adsorption rate \( W_t \) is gained by logarithmic fitting with time, and written by

\[
W_t = 0.474 \times \ln t + 5.063
\] ................. (2)

Where, \( W_t \) is the water adsorption rate, mass%. \( t \) is water absorbing time, min.

2.2.2. Characteristics of Effective Liquid Phase after Assimilation

Figure 4 shows the fluidity of effective liquid phase by Ore D after assimilated with different ore tablet, it can be seen that melt fluidity reduced after the primary melt reacted with acid iron ore, and largest decrement is gained in the case of limonite, then comes hematite Ore B and Ore C, indicating bonding capability deterioration in sintering process with limonite.

Figure 5 shows penetrated reaction depth at different positions in assimilated zone with different iron ores. Penetrated reaction depth at each numbered position decreased in the order of Ore A, Ore B and Ore C. It is approximately half the depth of limonite when it comes to Ore B, and Ore C is the most difficult to be assimilated and penetrated.

Figure 6 shows the microstructure of assimilated zone at the interface of assimilated nuclei and adhering layer. Structure of assimilated zone was different with nuclei, for limonite Ore A, it’s characterized by rather porous with thinner matrix. In the case of Ore B, structure with much smaller pores and more uniform matrix were observed, and minerals in assimilated zone are mainly calcium ferrite, suggesting higher bonding capability. Ore C had circle shaped large pores in the assimilated zone, but there was much hematite residual of large grains since Ore C was typical Brazilian specularite with large densely combined hematite grains.

Table 3. Ratios of iron bearing materials when limonite was separated (mass%).

<table>
<thead>
<tr>
<th>Number</th>
<th>Cores Ore A separated</th>
<th>Ore A granulated</th>
<th>Ore B granulated</th>
<th>Adhering fines</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>0</td>
<td>40</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>A</td>
<td>10</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>20 20 20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>30 10 40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>40 0 0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Water absorption rate of limonite.

Fig. 4. Fluidity of primary melt.

Fig. 5. Fluidity of effective liquid phase after nuclei assimilation.

Fig. 6. Penetration depth at different position in the assimilated zone.

Fig. 7. Penetrated reaction depth at each reactor position decreased in the order of Ore A, Ore B and Ore C.

Fig. 8. Shattered strength of sintered body, it was shown that when limonite Ore A was used as nuclei, sintered body seemed to be less sufficiently bonded with much voids left on the surface compared with Ore B and C, and there were clear interstices between particles.

Fig. 9. Shattered strength of sintered body.
is seen that sintered body with limonite cores had the lowest shattered strength, while it was much higher for sintered body with hematite cores, and the differences were approximately 20 percentage at four times and counted larger when shattered times increased. For sintered body with hematite cores, the shattered strength for Ore B seemed to be a bit higher than Ore C, possibly due to the different characteristics of liquid phase and mineral structure after assimilation mentioned above.

2.2.3. Influence of Separating Ratio on Bonding Strength

Figure 9 shows change of bonding strength when particles of limonite were separated. Since excessive assimilation of limonite is not advantageous to gaining bonding melt with high fluidity, the strength of sintered body was low in base measurement (see J in Fig. 9) when all limonite was coated with adhering fines. After part of limonite, 25 mass% or 50 mass% in the present research, were separated not to granulate with adhering fines, the bonding strength increased to some extent. However, if separated ratio of limonite increased to more than 50%, shattered strength of sintered body decreased on the contrary.

3. Modeling of Moisture Transfer by Limonite Separation

3.1. Theoretical Concept of Model

In sintering process, since drying of sintering mix takes places, lots of moist enters the hot gas in form of vapor, the flowing gases generally are of high humidity, when partial pressure of vapor in gas is higher than the saturated pressure on the surface of solid, the moist in gas condenses and enters into the raw materials, resulting in higher moisture content than original.

If the sintering bed is divided into many layers, besides the moisture taken out by exhaust gas, certain content of moisture would accumulated in the sintering bed, the maximum moisture of the condensation zone can be simply calculated with the following equation.

\[ W_{\text{max}} = nW_0 + (n-1)W_{CW} - (n-1)W_a \]  .......... (3)

Where, \( n \) is the number of divided layer, \( W_0 \) is original moisture in each layer, mass%. \( W_{CW} \) is the combined water content in each layer, mass%. \( W_a \) is moist taken away by exhaust gas, mass%.

It was found that excessive moisture would cause release of adhering fines and collapse of granulated quasi-particles, leading to bad effect in bed structure. According to W. J. Rankin, condensed water won’t be free to move either upwards or downwards, it is part of the quasi-particles and will cause swelling in the adhering layer, the effective mean diameter of the quasi-particles increased, changing
shape and voidage subsequently. The particles are assumed to be sphere, is given by

$$d = \left(\frac{6V}{\pi}\right)^{1/3} \quad \text{(4)}$$

Where, $d$ is the effective mean diameter of the quasi-particles, cm. $V$ is the volume of a quasi-particle, cm$^3$.

The volume of quasi-particle after condensed moisture enters is given by

$$V = V_0 + \Delta V \quad \text{.......................... (5)}$$

Where, $V_0$ is the initial volume of a quasi-particle, cm$^3$. $\Delta V$ is the volume of condensed water entering quasi-particle, cm$^3$.

The mass of a quasi-particle as raw materials before condensation happens is given by

$$M = \frac{100}{100 - \frac{W_{\text{separate}}}{\rho_0} + \frac{W_{\text{w}}}{\rho_0}} \times V_0 \quad \text{.......................... (6)}$$

In which, $M$ is the mass of a quasi-particle before condensation, $g$. $\rho_0$ is the density of the dry mix, the value was 3.52 g/cm$^3$ which was measured experimentally with materials in this research. $\rho_s$ is the density of water, the value is 1.0 g/cm$^3$. $W_s$ is the original moisture content, mass%.

Mass balance of one quasi-particle after condensed water entering is written

$$W_q = \frac{W_s \times M + M_w \times 100}{M + M_w} \quad \text{........................ (7)}$$

Where, $M_w$ is the mass of condensed water, g. $W_q$ is moisture content after moist condensation, mass%.

The volume of condensed water that enters the quasi-particles is calculated by

$$\Delta V = \frac{W_c \times M}{(100 - W_s) \times \rho_0} \quad \text{........................ (8)}$$

Where, $W_c$ is the incremental increment of moisture content caused by moist condensation, mass%. It is written

$$W_c = W_q - W_s \quad \text{........................ (9)}$$

Overall volume of sintering green bed will not increase during condensation, and calculated by

$$\varepsilon = 1 - \frac{V}{V_0} (1 - \varepsilon_0) \quad \text{........................ (10)}$$

Where $\varepsilon_0$ is original void fraction of green bed, experimentally measured of 0.45.

In the case of limonite separation, moisture transfer between dry particles of limonite and the original moist quasi-particles before condensation is ignored, and in each layer, condensed moisture is assumed to be absorbed by the dry or unsaturated limonite particles prior to wet quasi-particles, since moisture gradient in originally dry limonite is much higher. In addition, because quasi-particles absorbing moisture would cause cubical expansion, there would possibly be thin water film or through channels of moisture on the surface, and if the contacted limonite particle has less moisture content, water will transfer into the internal pores and onto the surface, so the condensed moist will prior to be absorbed into the separated particle which is comparatively dryer.

Since water absorption in limonite wouldn’t cause volume swelling, so the volume increased should be calculated with correction in equation of (6) to (9).

Where, density of the dry mix that would swell after condensation is written in

$$\rho_s \times (1 - w_{\text{separate}}) + \rho_s \times w_{\text{separate}} = \rho_0 \quad \text{........................ (11)}$$

In which, $\rho_s$ is the density of limonite, measured as 3.18 g/cm$^3$. $w_{\text{separate}}$ is the percentage of separated large particles in the sintering mix, set at 8.6 mass% in present research.

Moisture that would cause swelling is reduced for limonite absorption, given by

$$W_s = W_q - W_s - W_L \quad \text{........................ (12)}$$

In which, $W_L$ is moisture absorbed by dry limonite, treated as saturated water absorbing capacity in this study, and calculated by saturated water and the ratio of separated limonite in the layer. Effective mean size and void fraction is computed with Eqs. (3) to (10) and (11) to (12) in correction.

Above equations are established on the condition that internal open cylindrical and closed cylindrical pores are full of water, results shown in Fig. 3 suggested that as 80% of saturated water is absorbed in two minutes, only few of pores has residual gases in pores, and were ignored in this research.

Original effective mean size of the granulated quasi-particles is 3.37 mm, which is calculated by

$$d = d_{\text{p}} \times \phi \quad \text{........................ (13)}$$

Where, $d_p$ is the average of quasi-particles after granulation, the value is 4.21 mm. $\phi$ is the shape factor of quasi-particles, the value is 0.8.

Table 4 shows the compositions of Ore A, B and C in sintering blend, limonite had quite high percentage of particles larger than 5 mm, which is the lower limiting value of sintering sieving to gain sinter product. For this blend, original water addition was 7.5 mass%, gained for optimal permeability of green bed with high usage of limonite. The value is thought to be decided by the water absorbing properties of composed single ore of the sintering blend.

For the case in present research, besides approximately 25 mass% of return fines, 13 mass% of fluxes, 4 mass% of fuel, blend takes part of about 60 mass% in sintering mix, and if particles larger than 5 mm are separated to keep dry, according to limonite using ratio and the ratio of large particles, the value of the mix would be reduced by 0.5 mass%, and it was calculated

$$\Delta_{\text{water}} = w_{\text{5mm}} \times (100 - W_{\text{fule}} - W_{\text{return fluxes}}) \times SWR_{\text{Ore A}} \times \eta \quad \text{........................ (14)}$$

Where, $SWR_{\text{Ore A}}$ is the saturated water absorption rate, the value is 7.18 mass%. $\eta$ is the degree of water absorption in

<table>
<thead>
<tr>
<th>Material</th>
<th>Ore A</th>
<th>Ore B</th>
<th>Ore C</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio in blend</td>
<td>52.8</td>
<td>9.8</td>
<td>18.0</td>
<td>19.4</td>
</tr>
<tr>
<td>$w_{\text{5mm}}$%</td>
<td>15.1</td>
<td>1.8</td>
<td>2.8</td>
<td>4.0</td>
</tr>
</tbody>
</table>

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five minutes, the value is 83.30%. $W_{\text{return fines}}$, $W_{\text{flux}}$ and $W_{\text{fuel}}$ are adding rate in sintering mix, the value is 25 mass%, 13 mass% and 4 mass%. $w_{-5 \ mm}$ is the ratio of Ore A particles larger than in iron ore blend, the value is 15.10 mass% as shown in Table 4.

Moisture content of new sintering mix would be set as 7.0 mass%, and the accumulated moisture at different depth of green bed were calculated.

3.2. Calculated Results

Figure 10 shows the calculated results of water content increased for accumulation of condensed moisture. Water content increased with sintering proceeding to lower depth of the bed in both cases, the maximum moisture accumulation near the bottom approach to about 2.0 mass%. In the condition of the same height, the maximum moisture content was smaller with less original water addition, indicating lower extent of excessive moisture, and as a result lower resistance and fuel consumption.

Figure 11 shows calculated change in effective mean size of quasi-particles when large limonite was separated. In the upper region of the sintering bed, since the accumulated moisture entered from condensation is lower, and can be absorbed by limonite, so little moisture entered the quasi-particles, and no swelling was observed. But when condensation happened in middle or low position of the green bed, some residual water entered the quasi-particles, and cause slighter increase in effective mean size, but the degree was about 2/3 of conventional no separation.

After limonite being separated, swelling caused by entering moisture was alleviated, mainly ascribing to the positive effect caused by preferentially absorbing ability of separated dry limonite, as well as the less accumulated moisture content. According to Rankin and Roller, the effect on shape factor of quasi-particles with the same condensed water content seemed to be greater with higher original moisture. So by separation large particles of limonite, the shapes of limonite won’t change in one hand, and swelling of granulated quasi-particles decreased on the other hand, the void fraction slightly reduced, as shown in Fig. 12.

4. Discussions

Figure 13 shows the relation between saturated water absorption rate and porosity, Limonite gains as much as 7 mass% of water while hematite absorb much lower moisture content at 3 mass% for Ore B and 1 mass% for Ore C, mainly due to the differences in porosity since linear relation was observed. Therefore, it is clear that if limonite is added in
sintering blend to absorb water, higher water addition will be required. So when limonite was separated to keep dry, water addition reduced.

**Figure 14** shows the relation between fluidity of effective liquid phase and the lowest assimilated temperature of different nuclei. Linear relation was observed, expressing that the lower temperature iron ore reacted with calcium oxide and generated calcium ferrite, the lower fluidity of secondary liquid phase would be, possibly due to the penetration of melt and the increment of apparent viscosity of liquid phase.

When Melt generated on interface of simulated nuclei is set the same in this paper, penetration of depth mainly depends on the structural and chemical characteristics of iron ore tablet. Although both of Ore B and Ore C are comparatively dense in the structure, the penetrated reaction depth were different as it was much higher with Ore B, possibly due to the much lower silica content which is a hindering factor reported by J. Okazaki. For limonite, although gangue minerals are much higher, it still got the deepest penetration depth, as promoting effect of high porosity seemed to be far more influential than the hinder effect of gangue minerals.

With respect to apparent viscosity of liquid phase, judging from the microstructure, secondary melt in assimilated zone seemed to have higher apparent viscosity with Ore A, as pores are of irregular shape and much are left with much higher porosity, possibly due to the less fluxed compositions. Viscosity is inferred to be higher with ore C, for the solid hematite coexistence in melt.

**Figure 15** shows the relation between fluidity of effective liquid phase and penetrated depth of iron ores, it took on adverse linear relationship, showing that if more melt penetrated into the contacting nuclei, less would leave in the adhering layer to act as bonding media, predicting lower bonding strength.

**Figure 16** shows the relation between shattered strength of sintered body and the fluidity of effective liquid phase. Limonite gained the lowest strength when shattered, which was in accordance with the insufficiently bonded appearance and the lower bonding ability of effective liquid phase. Sintered body of hematite Ore B was a bit higher than Ore C although the penetrated depth was higher and fluidity of secondary melt was lower, it was possibly caused by the mineral generating characteristics known as uniform structure and more calcium ferrite. Generally, the shattered strength of sintered quasi-particles was in linear relation with fluidity of effective liquid phase.

Consequently, limonite is easily to be assimilated with both CaO and calcium ferrite, so the volume of bonding melt will decrease and the apparent viscosity go up, leading to high decrement in fluidity of liquid phase, resulting in low bonding capability, more voids and inferior strength.

When certain percentage of large limonite ore particles was separated not to be coated, contact interface with primary melt can be reduced to some degree, so that there’s less assimilation and as a result, more flowing bonding melt would effectively bond quasi-particles. But if separated ratio exceeded certain degree, 50% in present laboratory experiment, the number of separated particles increased, although the bad effect of excessive assimilation was further weakened in the conditions, distribution of primary melt generated from adhering fines would be excessively concentrated and led to thin-matrix or just no bonding between particles in sintering bed.

As a result, it is indicated that in order to achieve the largest improvement, separation ratio of limonite not granulating should not be more than 50%, considering the contact conditions and melt fluidity of adhering fines. Besides, control the lower limit to be 5 mm in case of insufficient bond-
would be the method with more insurance.

**Figure 17** shows the mechanism of bonding improvement after separation of large limonite. When limonite was conventionally coated with adhering fines, effective bonding ability of melt decreased a lot, resulting in inferior strength. By separating limonite, the contacting interface greatly reduced, limonite assimilates with melt form adhering layer of adjacent quasi-particles at the rim, so bad effect on bonding melt reduced, and at the same time, since large particles needn’t to be well bonded, a little melt generated at the assimilated zone was possibly enough for the strength, and pores excluded from thin melt layer may be easier to gain thick matrix, sintering behavior of limonite at high temperature is improved.

It is clear that the advantage of limonite separation is obvious from the view of keeping original effective mean size of quasi-particles and void fraction. **Figure 18** shows mechanism of structural improvement in condensation zone after separation of large limonite. Compared with conventional practice (see (a) in Fig. 18), water addition in sintering mix reduced, resulting in less transferring moist. When the humid gases come to the front of condensation zone, condensed water priors to condense on the surface of dry limonite, then residual condensed water enters adhering layer in quasi-particles, since limonite has strong moist absorbing ability possibly due to the porous structure, change in effective mean size or particle shape of quasi-particles and void fractions of green bed comes to the least extent, reducing phenomena of water filling the interstice or particle collapse, so moisture condensation can be weakened or even avoided by separation large particles of limonite.

Limonite ores are reported to disintegrate after dehydration in sintering process. Disintegration may be greater if there’s no coating with higher heating rate when large limonite ore particles are separated in this paper. Although it hardly causes influence on moisture absorbing behavior of dry limonite particles in condensation zone before disintegration took place, it would affect the strength of sintered body at high temperature. Since disintegration of large particle limonite may increase the number of separated particles, causing adverse effect on melt distribution, the proper ratio of separated limonite would decrease, for example, less than 50% in present research.

5. **Experimental Proof by Pot Test**

Sinter pot test was carried out to check the effect of separation of large limonite. Proportioning of sinter raw materials in sinter pot test was shown in **Table 5**. Limonite particles large than 5 mm were separated, detailed information was listed in **Table 6**. Sinter pot test parameters in this paper were as follows: sinter pot was 300 mm in diameter and 700 mm in height, ignition time was 120 seconds, suction pressure during sintering was 14.71 kPa. Results of sinter pot test were shown in **Table 7**.

It is shown that by separating large particles of limonite
not to granulate, vertical sintering speed increased from 29.0 to 29.9 mm·min⁻¹, indicating improvement in permeability due to both decrement in condensation degree in sintering bed and less flowing melt generation by assimilation of limonite at high temperature. Yield of sinter increased by 0.5 percent even though the high-temperature holding time was shortened, due to higher effectively bonding degree of secondary melt. Productivity went up from 42.9 to 44.2 t·m⁻²·d⁻¹. Fuel consumption reduced a little, and tumbler index of sinter increased by 0.5 percent even though the high-temperature holding time was shortened, due to higher effectively bonding degree of second-
ary melt. Productivity went up from 42.9 to 44.2 t·m⁻²·d⁻¹. Fuel consumption reduced a little, and tumbler index of sinter increased by 0.5 percent even though the high-temperature holding time was shortened, due to higher effectively bonding degree of secondary melt. Productivity went up from 42.9 to 44.2 t·m⁻²·d⁻¹. Fuel consumption reduced a little, and tumbler index of sinter increased by 0.5.

Overall, the results confirmed the improvement of proposed method, known as separation of large particles of limonite from granulation. When large amounts of limonite are used, it could also be a possible means for gaining better sintering indexes, besides, it is also helpful in heat transfer downward the bed which is thought to be one of the aim of MEBIOS process.30)

### 6. Conclusions

In order to improve the sintering behavior of mix when large amount of limonite were used, a new method was proposed and basic study was conducted on the influence from the view of the improvement in effective liquid phase as a result of nuclei assimilation, and structural change of quasi-particle and the green bed caused by moisture transferring. Following results were obtained:

1. Limonite nuclei had adverse effect on bonding strength of quasi-particles as they can either cause liquid decrement by penetration or viscosity increament by less fluxed composition, resulting in sharp decrease in fluidity of effective liquid phase, which was in linear relation with bonding strength of sintered quasi-particles.

2. By separating large particles of limonite, higher bonding strength can be achieved by less assimilation of limonite with decreased contacting interface, the separated ratio should be determined considering uneven of melt distribution.

3. By separating large particles of limonite not to be coated, water addition would reduce due to increment in granulated water ratio with no absorption into porous limonite, and the dry limonite absorb part of condensed moisture to reduce moisture that entered quasi-particles, resulting in smaller degree of increament in effective mean size caused by swelling and as a result lower decrement in void fraction, suggesting better bed permeability.

### Acknowledgement

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### Table 5. Proportioning of sinter raw materials in sinter pot test (mass%)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Sintering blend</th>
<th>Return fines</th>
<th>Lime</th>
<th>Limestone</th>
<th>Dolomite</th>
<th>Serpentine</th>
<th>Coke fines</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage</td>
<td>61.18</td>
<td>25.00</td>
<td>5.00</td>
<td>2.58</td>
<td>2.02</td>
<td>0.72</td>
<td>3.50</td>
<td>100</td>
</tr>
</tbody>
</table>

### Table 6. Detailed information of limonite separation in sinter pot test.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Granulated limonite</th>
<th>Separated limonite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Less than 5 mm</td>
<td>Larger than 5 mm</td>
</tr>
<tr>
<td>Percentage</td>
<td>23.7%</td>
<td>8.6%</td>
</tr>
<tr>
<td>Dispose</td>
<td>Granulated together with other materials</td>
<td>Mix with granulated materials for 1 min</td>
</tr>
</tbody>
</table>

### Table 7. Result of sinter pot test by separation of limonite.

<table>
<thead>
<tr>
<th>Name</th>
<th>Vertical sintering speed (mm·min⁻¹)</th>
<th>Yield (%)</th>
<th>Productivity (t·m⁻²·d⁻¹)</th>
<th>Fuel Consumption (kg/t)</th>
<th>TI (10⁻⁶mm) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>29</td>
<td>76.4</td>
<td>42.9</td>
<td>51.6</td>
<td>53.8</td>
</tr>
<tr>
<td>S</td>
<td>29.9</td>
<td>76.9</td>
<td>44.2</td>
<td>51.3</td>
<td>53.6</td>
</tr>
</tbody>
</table>

### Reference