1. Introduction

Recently, the increase of limonite ore in sintering bed causes the lowering of permeability and yield. It is believed that collapse of pores in the sintering bed causes it although the sintering bed has porous structure. Control of pores in the sintering bed to increase permeability by the permeability rods or permeability slits, etc.\(^1\)\(^-\)\(^3\) is carried out. Also, control of layer structure\(^4\)\(^,\)\(^5\) by the particle size of the sinter mixture\(^6\) or making low-density area and high-density area in the sintering bed\(^7\) is discussed. However, the permeability rods and permeability slits need many plant investments.

Further, there are few discussions about the specific way to control the density distribution in the sintering bed. Therefore, the way for making a high and low-density area in the sintering bed by using ordinary sinter mixture was studied.\(^8\)\(^,\)\(^9\) Theconcept of large particle placed sintering method is illustrated in Fig. 1. The sizes of large particles are 10–20 mm. They are agglomerates of ordinary sinter feed, lumpy ore, etc. and placed in the sinter mixture. The density around the large particles may decrease by a kind of wall effect. By these low-density areas, the permeability may increase. Also, the strength of the large particles supports the load from their upper part so that the shrinkage of the sinter cake may be restrained and the permeability may be kept during sintering.

The permeability before ignition and during sintering, sintering speed and yield were measured in pot tests so as to evaluate this method. The cross sections of sinter cakes were observed after crushing and the properties of large particles and sinter mixture were studied.

2. Experimental

2.1. Test Conditions

In order to understand the effect of the difference of raw material contents in the large particle on the yield separately from the effect of the permeability, it is necessary that FFS (Frame Front Speed), [bed height before ignition/time from ignition to beginning of the rise in exhaust gas temperature], and heat pattern are kept constant. If an examination is carried out under a constant exhaust gas flow rate, FFS is controlled as almost constant. Also, sinter mixture weight is constant to keep the amount of reaction and heat capacity constant, so that the heat pattern in the sintering bed becomes constant. On the other hand, the examination under the same bed height and suction pressure is similar to the ordinary sinter making process. This examination is useful for evaluation of yield or productivity. Therefore two types of examinations, the gas flow rate constant test, defined as Test A, and the suction pressure constant test, defined as Test B, were carried out. Properties of large particles and sinter mixture were studied in Test A.

![Fig. 1. Concept of the large particles placed sintering method.](image_url)
Permeability, yield and productivity were studied under a similar condition to the ordinary sinter making process in Test B. Also, sintering behavior of raw material bed placed large particles was discussed based on results of Test B.

2.2. Test Samples

2.2.1. Samples for Test A

The blending conditions of large particles and fine material are shown in Table 1. The characteristics of each material are given in Table 2. Table 3 gives the characteristics of large particles. Marra Mamba fine (Ore W) was contained 30% in the Base (I). The large particles were not placed in this case. There were 6 types of large particles. The characteristics and the diameter of large particles, and the CaO content in sinter mixture were changed in those types. GB (B) means that large particles contained 5.9% BF dust, and GB means that large particles did not contain BF dust as shown in Table 3. Also, there was a case in which the diameter of green balls was 5–10 mm described as small.

According to the idea that the assimilation and melt reaction in the large particles is restrained so that they keep strength against the load from upper part during sintering, the CaO content in green balls decreased and the basicity of them was controlled as 1.0. Hence, CaO/SiO2 of sinter mixture decreased described as Low CaO in Table 1. The cases described as High CaO means that the additional limestone was added in sinter mixture to promote the assimilation and melt reaction. In addition, fired pellets (FP) were used as large particles in order to clarify the effect of the particle strength. In this case, additional limestone was added in the sinter mixture, too.

2.2.2. Samples for Test B

Properties of large particles, such as density, strength or moisture, are expected to have great influence on the permeability during sintering. Therefore, dense alumina balls and pisolite ore Y lump, whose characteristics are shown in Table 2, were used as the large particles to omit the influence of the properties of large particles. The alumina ball acts as inert and rigid stuff because they will not lose strength during sintering and will never be sintered owing to low wettability and reactivity. On the other hand, the pisolite lump ore collapsed during heating and is easy to assimilate into sinter matrix. Therefore, the structure of sinter cake may differ when using alumina ball and pisolite lump ore.

Table 1 shows the blend of Test B. In case of Pisolite, ore Y fine was replaced with its lump, and adjusted the amount of other materials so that the contents of sinter made from Base (II) and from Pisolite were almost same as shown in Table 5. In case of Alumina, alumina ball was added in the same blending of Base (II).

2.3. Procedure

The schematic view of pot test apparatus is shown in Fig. 2. The size of the pot is 300 mm in diameter and 500 mm in height. 2.0 kg of sinter, whose diameters were 10–15 mm, were used as the hearth layer and the thickness was 20 mm. The experimental procedures are shown in Table 6.
Because the suction pressure was kept constant during sintering, the procedure of it was little different from that of Test A. In addition, to evaluate the effect of cooling condition on yield, the sinter cake was crushed soon after the termination of sintering in Test A, which is similar to ordinary sinter making process.

In order to analyze the experimental results, apparent densities of large particles are calculated. The diameters and weights of green balls, fired pellets and alumina balls were measured after drying. Also the volume of dried pisolite lump ore was measured by oleate-kerosine-volumetric method.10)

### 3. Experimental Results

#### 3.1. Results of Test A

The results of Test A were shown in Table 7. In this table, Eq. (1) can be used to calculate the shrinkage ratio.

\[
\text{Shrinkage ratio (\%)} = \frac{\text{bed height before ignition} - \text{bed height after sintering}}{\text{bed height before ignition}} \times 100
\]

Also the permeability is described as Eq. (2). The permeability during sintering was calculated with sinter cake height and average suction pressure from the ignition through the stop of suction.

\[
\text{Permeability (JPU)} = \frac{\text{exhaust gas flow rate (Nm}^3/\text{min})}{\text{cross sectional area of pot (m}^2)} \times \left(\frac{\text{bed height (m)}}{\text{suction pressure (mmH}_2\text{O)}}\right)^{0.6}
\]

#### 3.1.1. Permeability, Shrinkage and Sintering Speed

When the large particles were placed in the sintering bed, the permeability before ignition increased (Table 7). The permeability during sintering tended to increase when the large particles were placed, too. The relationship between bulk density of sinter mixture and shrinkage ratio is shown in Fig. 3. When the large particles were placed in the sintering bed, the bulk density of it increased. Also increase of the bulk density tended to restrain the shrinkage of the cake. Figure 4 shows the relationship between shrinkage ratio and permeability during sintering. When the shrinkage ratio decreased, the permeability during sintering increased. Hence the sintering speed, which described as FFS, was almost the same or slightly increased when the large particles were placed even if the bulk density of sinter mixture increased as shown in Fig. 5. It was because that the large particles might restrain the shrinkage of the sinter cake and improve the permeability.

#### 3.1.2. Yield and Productivity

There were great differences in yield between cases. The yield of Base (I) was about 83%. The cases with placed green balls had a lower yield than Base (I). However, fired pellet case and smaller green balls case had a slightly lower yield than Base (I). The fired pellets already hardened be-
Table 6. Experimental procedures of Test A and of Test B.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Test A</th>
<th>Test B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Making green balls</td>
<td>Raw materials shown in Table 3 were agglomerated in pan pelletizer (1000mm in diameter).</td>
<td>(None)</td>
</tr>
<tr>
<td>2. Granulation</td>
<td>Raw materials described as fine layer in Table 1 were mixed in 2 min, and then granulated with water in 5 min in a drum mixer (1000mm in diameter).</td>
<td>Raw materials described as fine layer in Table 4 were mixed in 4 min, and then granulated with water in 4 min in a drum mixer (1000mm in diameter).</td>
</tr>
<tr>
<td>3. Mixing</td>
<td>Green balls or fired pellets were fed into the mixer. They were mixed in 15 sec. Pisolith lump ore or alumina balls were fed into the mixer. They were mixed in 1 min.</td>
<td>Pisolith lump ore or alumina balls were fed into the mixer. They were mixed in 1 min.</td>
</tr>
<tr>
<td>4. Charging into a pot</td>
<td>53.0kg of sinter mixture was supplied by hand. Sinter mixture was supplied which layer height was 500mm by hand.</td>
<td></td>
</tr>
<tr>
<td>6. Ignition</td>
<td>For 1 min under a suction pressure of 4.9kPa by a LPG burner.</td>
<td>For 1 min under a suction pressure of 20 kPa by a LPG burner.</td>
</tr>
<tr>
<td>7. Sintering</td>
<td>Exhaust gas flow rate was kept at 1.5 wet-Nm³/min.</td>
<td>The suction pressure was kept at 9.8kPa.</td>
</tr>
<tr>
<td>8. End of sintering</td>
<td>1 min after the exhaust gas rose to a maximum temp.</td>
<td>3 min after the exhaust gas rose to a maximum temp.</td>
</tr>
<tr>
<td>9. Measuring yield</td>
<td>Hot cake was dropped 4 times from a height of 2m, and then +5mm sinter products were weighed. Cake was cooled to room temp. in air, and then dropped 4 times from a height of 2m. The +5mm sinter products were weighed.</td>
<td></td>
</tr>
</tbody>
</table>

Table 7. Results of constant exhaust gas flow rate test (Test A).

<table>
<thead>
<tr>
<th></th>
<th>Brand</th>
<th>Base (I)</th>
<th>GB (B) Low CaO</th>
<th>GB (B) High CaO</th>
<th>GB (B) Small Low CaO</th>
<th>GB (B) Low CaO</th>
<th>GB (B) High CaO</th>
<th>GB (B) High CaO</th>
<th>FP High CaO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinter mix. moisture (mass%)</td>
<td>7.9</td>
<td>7.9</td>
<td>8.0</td>
<td>8.1</td>
<td>8.5</td>
<td>8.3</td>
<td>6.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charged weight (wt-kg)</td>
<td>57.6</td>
<td>57.4</td>
<td>57.4</td>
<td>57.4</td>
<td>57.4</td>
<td>57.4</td>
<td>56.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charged weight (dry-kg)</td>
<td>53.0</td>
<td>52.9</td>
<td>52.8</td>
<td>52.8</td>
<td>52.5</td>
<td>52.5</td>
<td>53.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinter cake weight (kg)</td>
<td>46.1</td>
<td>45.9</td>
<td>45.8</td>
<td>46.0</td>
<td>47.3</td>
<td>46.5</td>
<td>48.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+5mm sinter (kg)</td>
<td>38.3</td>
<td>33.5</td>
<td>32.5</td>
<td>36.7</td>
<td>27.4</td>
<td>30.7</td>
<td>39.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer height</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>before ignition (mm)</td>
<td>462</td>
<td>437</td>
<td>437</td>
<td>451</td>
<td>433</td>
<td>431</td>
<td>403</td>
<td></td>
<td></td>
</tr>
<tr>
<td>after sintering (mm)</td>
<td>368</td>
<td>382</td>
<td>401</td>
<td>373</td>
<td>406</td>
<td>403</td>
<td>362</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shrinkage ratio (vol %)</td>
<td>20</td>
<td>13</td>
<td>8</td>
<td>17</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>before ignition (JPU)</td>
<td>25.3</td>
<td>27.3</td>
<td>33.2</td>
<td>33.0</td>
<td>31.1</td>
<td>31.1</td>
<td>26.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>during sintering (JPU)</td>
<td>14.2</td>
<td>14.2</td>
<td>19.1</td>
<td>14.4</td>
<td>17.4</td>
<td>20.7</td>
<td>19.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exhaust gas temp. rising time (min)</td>
<td>19.2</td>
<td>18.1</td>
<td>19.1</td>
<td>19.4</td>
<td>17.5</td>
<td>18.3</td>
<td>16.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFS (mm/min)</td>
<td>24.1</td>
<td>24.1</td>
<td>22.9</td>
<td>23.2</td>
<td>24.7</td>
<td>23.6</td>
<td>24.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinter mixture (dry-t/m³)</td>
<td>1.64</td>
<td>1.73</td>
<td>1.73</td>
<td>1.68</td>
<td>1.74</td>
<td>1.75</td>
<td>1.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sinter cake (t/m³)</td>
<td>1.80</td>
<td>1.72</td>
<td>1.64</td>
<td>1.77</td>
<td>1.67</td>
<td>1.65</td>
<td>1.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield (+5mm) (mass %)</td>
<td>83.1</td>
<td>73.0</td>
<td>71.0</td>
<td>79.8</td>
<td>57.9</td>
<td>66.0</td>
<td>82.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Productivity (t/(d·m³))</td>
<td>27.9</td>
<td>26.4</td>
<td>23.1</td>
<td>26.7</td>
<td>22.4</td>
<td>22.9</td>
<td>32.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Relationship between the bulk density of sinter mixture and shrinkage ratio.

Fig. 4. Relationship between shrinkage ratio and permeability during sintering.

Fig. 5. Relationship between the bulk density of sinter mixture and FFS.
fore test, so that they might collect as +5 mm sinter products. Smaller green balls might be sintered strongly, so the yield achieved near 80%. There was a slightly difference between Low CaO case and High CaO case when the green balls contained BF dust, but High CaO case had a better yield than Low CaO case when the green balls did not contain BF dust. Also, the cases using green balls containing BF dust had a higher yield than those using green balls without BF dust. It is believed that the green balls containing BF dust sintered stronger than those without BF dust. In addition, influence of the increase of CaO content in sinter mixture was not clear because it was effective when the green balls did not contain BF dust, but it was ineffective when the green balls contained BF dust.

Since the effect of yield was much bigger than that of sintering speed, the productivities of sintering placed the large particles were not improved very much in Test A except the case using fired pellets.

3.2. Results of Test B

3.2.1. Coke Contents

It is expected that promotion of the assimilation in sinter mixture may restrain the decrease of the yield. Therefore, coke content in the sinter mixture increased and the content, which the decrease of the yield could be restrained when the large particles were placed, was defined in Test B. The coke content was changed from 2.2 to 2.7 kg in the same blending shown in Table 5. Figure 6 shows the relationship between the coke contents and yields.

The yields of Pisolite were lower than those of Base (II) when they had the same coke content. However, when the coke content increased from 2.3 to 2.7 kg, the yield of Pisolite increased greatly though that of Base (II) did not increase very much. The yield of Pisolite at 2.7 kg coke content came close to that of Base (II) at 2.3 kg coke content.

The assimilation and melt reaction might increase by the increase of the coke so that the sinter mixture was sintered strongly. It may be expressed in other word that the coke content should be increased to maintain the yield when the large particles like pisolite lump ores are placed.

Therefore, the coke content for rest of the tests was decided to be 2.3 kg in Base (II) and as 2.7 kg in Pisolite based on Fig. 6. On the other hand, the coke content in Alumina was decided that the weight of coke was the same as that of Base (II) because blending of it except alumina ball was the same as that of Base (II).

3.2.2. Permeability, Yield and Productivity

Table 8 gives the results of Test B. In Test B, the permeability during sintering was calculated by Eq. (2) for each seconds. The permeability during sintering in this table was the average of them between 2 min after ignition and FFS. In addition, the bed height during sintering was calculated by proportional allotment of height of sinter mixture and that of sinter cake. The packed bed densities increased when the large particles were placed. However, the permeability before ignition and during sintering increased, hence FFS increased. Since, the yields were kept almost constant by increase of coke in Pisolite, the productivities increased. The yield of Alumina, whose coke content was the same as Base (II), was also as same as that of Base (II). All alumina balls weighed as +5 mm sinter product. Therefore the corrected yield was recalculated with the weight of the sinter cake excluding weight of alumina balls and the weight of +5 mm sinter product particles without alumina balls. The corrected yield was 72%. This was slightly lower than yields of Base (II) and of Pisolite.

The tendency of changes in permeability, yield and productivity for Test B were similar to that for Test A. Nevertheless, the shrinkage ratio of Pisolite was larger than that of Base (II) though all other cases placed large particles restrained shrinkage. In order to clarify this difference, the cross sections of the sinter cakes were observed.

3.2.3. Observation of Cross Section

Figure 7 shows the cross sections of the sinter cakes placed pisolite ore lumps and alumina balls after crushing by a drill. Nearly all the lumps placed in the sintering bed assimilated into sinter cake according to the visual observation. In addition, the lumps placed at the top and side of the bed did not assimilate and remained in its original form in the sinter cake. It is believed that the heat quantity might not be enough for the assimilation and melt reaction there.
On the other hand, the sinter cake placed alumina balls was broken into blocks, which were about 200 mm long when it was crushed. 1 162 of 1 269 placed in the bed alumina balls were collected without any sticks. As shown in Fig. 7(b), there were voids under the balls and they were connected each other. It is believed that the cake was divided into blocks because these connected voids decrease the strength of the cake. Also increase of the permeability and decrease of corrected yield might be affected by these connected voids. E. Kasai\(^6\) reported the similar phenomena that large particles form such connected voids using the X-ray CT observation.

4. Discussions

4.1. Bulk Density and Permeability

Both in Test A and Test B, when the large particles were placed in the sintering bed, the bulk densities of the bed increased. However, the permeability of the bed increased before ignition and during sintering. The apparent densities and weights of the large particles were measured, so that Eq. (3) could be used to calculate the density of the sinter mixture.

\[
\rho_B^{\text{sinter mixture}} = \frac{W^{\text{sinter bed}} - W^{\text{large particles}}}{V^{\text{sinter bed}} - V^{\text{large particles}}} \\
\rho_A^{\text{large particles}}
\]

**Fig. 8.** Relationship between bulk density of sinter mixture and that of sinter mixture.

\[\text{Total surface area of large particles (calc.) (m}^2\]\n
The connected voids observed in the cake where alumina balls were placed. It is believed that this low-density area is formed because the difference of diameter between large particles and sinter mixture causes the difference of behavior of them at charging, such as charge speed or landing order. This low-density area formation behavior may be similar to formation of low-density area around the wall in the pot test, what is called “the wall effect”.

4.2. Sintering Behavior of Raw Material Bed Placed Large Particles

The difference of sintering behaviors of the raw material beds placed two kinds of large particles was discussed as illustrated in **Fig. 10**. When the large particles were placed in the bed, the low-density areas were formed around the particles. Therefore, the gas flow rate around the particles might be faster than other part, so that the frame front speed around the particles might be faster. As a result, the assimilation and melt reaction might occur earlier around the particles, and then the melt might moves under the particles because of the gas flow and the gravity. The melt might assimilate with sinter mixture and then be absorbed under the particle. Hence the void might be formed beneath the particle.

When the large particles were alumina balls, they never assimilate or melt during sintering and were not broken by the rapidly rising temperature, so they could keep their shapes and strength for resistance against the load from upper part. Therefore, the voids might remain after sintering.
On the other hand, when the large particles were pisolite ore lumps, their strength might decrease because of the cracking during heating or the assimilation and melt reaction. As a result, the lumps might not support the load and fell into the voids at some period. Hence, the sinter cake shrank.

It is suggested that the corrected yield recalculated without alumina balls decreased based on Fig. 10. The voids formed in the low-density areas caused the decrease of yield. The low-density areas might be sintered softly because the alumina balls were strong enough to keep the layer structure. Therefore, the softly sintered areas were easy to brake and caused the decrease of yield. According to this consideration, it should be necessary to keep the yield that the quantity of the melt is increased by some countermeasures such as increase of coke and/or CaO contents in sinter mixture, and the low-density areas around the large particles be sintered strongly.

5. Conclusions

The pot tests placing the large particles in the sintering bed were carried out. The results are summarized as follows:

(1) When the large particles are placed in the sintering bed, the bulk density of sintering bed increases. However the bulk density of sinter mixture decreases. The bulk density of sinter mixture tends to be in inverse proportion to the surface area of large particles. This result suggests that low-density areas are formed around the particles.

(2) When the large particles are placed in the sintering bed, the permeability before ignition and during sintering is highly improved. It is believed that permeability is improved because the low-density areas are formed around the large particles.

(3) The sintering speed of the sintering bed placed large particles increases because the permeability during sintering increases.

(4) In order to keep the yield when the large particles are placed in the sintering bed, the large particles should contain carbon source such as BF dust that enhance sinter strength, or they should be very hard so that they become sinter product particles. Also, increase of coke or CaO content in sinter mixture to promote assimilation and melt reaction is effective for yield.

Acknowledgment

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REFERENCES