In recent years, it is an urgent issue to get high-grade iron ores and establish the adequate pre-treatment technology based on the characteristics of iron ores against the gradual deterioration of quality. In some ores, slag components and fine ratio have been increasing gradually. An increase in fine ratio reduces the sinter permeability and results in decreasing productivity. In addition, an increase in slag components decreases the reduction speed in the blast furnace, which leads to increase in expensive lump coke. In order to solve these problems, pellet feeds and concentrates have been focused as high grade iron ores. The pellet feeds have an average particle size of 150 μm or less, therefore particles are likely to form granules in the presence of moisture and remained with less moisture. In the sintering process, strong agglomeration (granulation) structure is required to achieve the permeability in the sintering bed. However, in the conventional drum mixer, mixing ability is not as high as pelletizer, so the permeability and productivity deteriorates with increase in pellet feed ratio. HPS (Hybrid Pelletizing Sinter) was developed to utilize the pellet feed by using the disk pelletizer and coating mixer for coke breeze to improve the combustion efficiency. It was reported that pellet feed was blended by 60 mass%. Kamijo et al. stated that large amount of pellet feed could be used without loss of permeability by producing high strength semi-pellet in P-type separate granulation system using pulverized ore, high-speed mixer and pelletizer. Shiozaki and Sassa stated that pellet feed could be blended by 20 mass% by controlling the moisture added in high-speed mixer, contributing to optimization of particle size distribution of quasi-particle. In the case of concentrate, the particle size distribution is quite uniform. Therefore, the water holding capacity and granulation property are lower than conventional sinter feeds. In order to improve the granulation property, it is effective to mix the concentrate with limonite ore. In the light of mineralogical properties of magnetite, FeO forms the lower liquidus phase, contributing to improvement of melt fluidity. It is reported that segregation of the magnetite components contributes to sinter quality in the upper area of sinter bed by magnet plate. Disk pelletizer and high speed mixer are effective pre-treatment equipment to improve the granulation property of fine particles. Regarding the granulation behavior, various researches were reported so far such as matrix analysis, theoretical analysis of optimum operating conditions, DEM (discrete element method) and so on. In terms of high speed mixer, Matsumura and Kawaguchi introduced the concept of limiting moisture which is necessary for adhering fine powder. They showed the mechanism that the
size distribution of granules become narrow under the high speed mixing. However, the influence of high speed mixing and raw material conditions on particle size distribution of granules have not been investigated well so far compared to drum mixer and pelletizer. In addition, the high speed mixer works as a granulator or kneader, but this functional differences have not been discussed well. In order to utilize much amount of high grade ores, it is necessary to control the granule’s structure based on the understanding of granulation and collapse phenomenon in high speed mixer.

In the present study, the influence of the mixing and raw material condition on the moisture and particle size distribution of the wet granules was investigated with respect to the initial mixing state when the granulation and collapse phenomenon compete simultaneously, and then the mixing rate coefficient was obtained. Next, in order to evaluate the effect of granulation and collapse separately, the changes in particle size distribution was analyzed with matrix model. Focusing on the parameters for collapse phenomena, the relationship between the strength of granules and the impact force of impeller was discussed. After that, the influence of the degree of collapse on the change in the average particle diameter was examined. Finally, the internal growth rate was defined as an indicator of long-term granulation performance and granulation behavior was compared under the various conditions.

2. Experimental

2.1. Raw Material and Apparatus

Table 1 shows the chemical composition of ores used in the present study. Two kinds of hematite Ores A and B were used. Table 2 shows the blending conditions of raw materials. All raw materials were dried at 105°C, 24 hours in oven. In order to clarify the size effect, Ore A was screened to −1 mm and another sample was pulverized to −150 μm. The proportions of −150 μm were set as 9.5 and 19.1 mass% without changing the Ore A ratio in the case of T2 and T3, respectively. The blending ratios of the return fine, auxiliary materials and coke breeze were fixed.

The moisture contents of ores are not constant values at the actual process. In order to simulate the pre-wetting condition, raw material was pre-wetted by the following method. First, 60 kg of dried raw material was divided into 5 equal parts. Next, the moisture of 1.5, 3.5, 5.5, 7.5 and 9.5 mass% were added in addition to dry material for each group in the case of the average moisture of 5.2 mass%. The moisture of 0, 1.0, 3.5, 6.0 and 7.5 mass% in case of total moisture as 3.5 mass%, while 3.5, 5.5, 7.5, 9.5 and 11.5 mass% in case of 7.0 mass%. The optimal granulation moisture in case of T1 was around 6.0 mass%, indicating that the total moisture values of 3.5 and 5.2 mass% were lower than optimum moisture, while that of 7.0 mass% was over the optimum moisture. After that, small samples were collected and evaluated as the condition before mixing. Five sets of pre-wetting samples were loaded into a high speed mixer, followed by mixed under various conditions. The samples of 1 kg were picked up from mixer and sieved in a wet state. Particle size distribution and moisture content for each particle size were measured. Sieve meshes were 11.2, 9.52, 8.0, 4.75, 2.8, 1.0 and 0.5 mm. There were no

2.2. Evaluation of Collapse Behavior by Degree of Mixing

In general, the degree of mixing $\sigma$ (mass%) is calculated by multiplying the concentration $C_i$ (mass%) in the sample collected at $N$ locations in the system and the average concentration $C_0$ (mass%) as shown in Eq. (1):\(^{13}\)

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (C_i - C_0)^2$$

### Table 1. Chemical composition of iron ore A and B used in experiments (mass%).

| Material | T.Fe | FeO | SiO₂ | CaO | Al₂O₃ | MgO | LOI |
|----------|------|-----|------|-----|-------|-----|-----|
| Ore A    | 64.0 | 0.12| 3.40 | 0.08| 1.90  | 0.06| 2.10|
| Ore B    | 62.5 | 0.95| 6.50 | 0.04| 1.30  | 0.16| 1.70|

### Table 2. Blending condition of sinter mix (mass%).

| Material | T1 (base) | T2   | T3   |
|----------|-----------|------|------|
| Ore A (−1 mm) | 46.5      | 37.0 | 27.4 |
| Ore B (−8 mm) | 18.6      | 18.6 | 18.6 |
| Ore A (−150 μm) | 0        | 9.5  | 19.1 |
| Silica sand | 1.9       | 1.9  | 1.9  |
| Return fine | 15.9      | 15.9 | 15.9 |
| Limestone  | 12.4      | 12.4 | 12.4 |
| Coke breeze | 4.7       | 4.7  | 4.7  |

### Table 3. Experimental condition.

| Condition | Unit | Range              |
|-----------|------|--------------------|
| Raw Material | Blending | T1 (base), T2, T3 | |
| Moisture content | mass% | 3.5, 5.2 (base), 7.0 |
| Agitator | Rotation speed | rpm | 0, 60, 125, 250, 500, 1 000 |
|          | Rotational direction | – | Counter-clock-wise |
| Pan | Rotation speed | rpm | 28 |
|     | Rotational direction | – | Clock-wise |
| Mixing time | s | 0 to 600 |

particles larger than 11.2 mm, and the representative particle diameter was 10.4, 8.8, 6.4, 3.8, 1.9, 0.75 and 0.25 mm, respectively as the arithmetic mean value size. Average particle diameter was calculated based on representative particle size and the weight ratio. The water content was calculated by dividing the weight difference before and after drying by the total moisture weight before drying. In order to evaluate the structure of the particles, some samples was filled with resin to provide the block sample for optical microscope observation.

A high speed mixer (inner diameter: 750 mm, internal volume 0.075 m³, batch type) was used in the present study. The charging weight, rotation speed of pan and direction of pan were fixed. The rotation speed of impeller was changed from 0 to 1 000 rpm, and the mixing time was changed from 0 to 600 s. Table 3 shows mixing and raw material conditions.
In the present study, the changes in particle size and moisture distribution were focused as shown in Fig. 1(a). It is assumed that the weight ratio and the moisture of the representative particle size, \( j \), before mixing are constant irrespective of mixing conditions. The sampling amount was set to 1 kg so that a statistically sufficient number of particles were included. As the moisture of the particles were almost the same value in the same particle size, it was assumed that they have the same moisture contents. The degree of mixing, \( \sigma \), from the initial distribution before mixing at a certain mixing time, \( t \), is defined:

\[
\sigma(j)^2 = \frac{1}{N} \sum_{i=1}^{N} (C(j)_a - C(j)_r)^2 \quad \text{.................. (2)}
\]

Where

- \( \sigma(j)_a \): Deviation of moisture in particle size \( j \) (mass\%),
- \( C(j)_a \): Pre-mixing moisture of particle size \( j \) (mass\%),
- \( N \): Number of particles (–),
- \( j \): Particle size classification.

Equation (2) was integrated over the whole particle size, and the deviation of moisture at a certain mixing time was defined:

\[
\sigma_{at}^2 = \sum_j \sigma(j)_a^2 \quad \text{.......................... (3)}
\]

Where \( \sigma_{at} \) is the deviation of moisture at mixing time \( t \) (mass\%).

The deviation of particle size distribution, \( \sigma_{pt} \), is defined as Eq. (4):

\[
\sigma_{pt}^2 = \sum_j \sigma(j)_{pt}^2 = \sum_j \left( f(j)_a - f(j)_r \right)^2 \quad \text{.................. (4)}
\]

Where

- \( \sigma(j)_{pt} \): Deviation of the dry weight ratio in the representative particle size \( j \) (mass\%),
- \( f(j)_a \): Dry weight ratio for mixed sample of particle size \( j \) (mass\%),
- \( f(j)_r \): Dry weight ratio for pre-mixing sample of the particle size \( j \) (mass\%).

The changes of \( \sigma_{at} \) and \( \sigma_{pt} \) to the mixing time are assumed to show the exponential function as shown in Fig. 1(b). In the present study, the changing rates of \( \sigma_{pt} \) and \( \sigma_{at} \) at the initial mixing was focused.

2.3. Evaluation of Agglomeration and Collapse Process by Population Balance Model

Time dependence of size distribution was analyzed using matrix model. Assuming that the collapse/granulation system follows a simple Markov process, the particle size distribution vector, \( G_N \), during mixing is expressed by Eq. (5):

\[
G_N = \left( (1 - \pi) \cdot E + \pi B \right)^N \cdot F \quad \text{..................... (5)}
\]

Where

- \( F \): Particle size distribution before mixing,
- \( \pi \): Granulation and collapse probability,
- \( B \): Granulation and collapse matrix
- \( E \): Unit vector,
- \( N \): Number of agitation steps.

\( G_N \) and \( F \) vector are expressed by Eq. (6):

\[
G_N = \begin{pmatrix} g_1 \\ g_2 \\ \vdots \\ g_N \end{pmatrix}, \quad F = \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_N \end{pmatrix}, \quad \sum_i g_i = 1, \quad \sum_i f_i = 1 \quad \text{............. (6)}
\]

Where the weight ratio in each mesh section is \( g_1, g_2, \ldots, g_n \) and \( f_1, f_2, \ldots, f_n \) from the finer particle side.

The granulation and collapse matrix \( B \) is represented by Eqs. (7) and (8).

\[
B = \begin{pmatrix} q_{11} & q_{12} & \cdots & q_{1n} \\ q_{21} & q_{22} & \cdots & q_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ q_{n1} & q_{n2} & \cdots & q_{nn} \end{pmatrix} \quad \text{............. (7)}
\]

\[
\sum_{i=1}^{n} q_{ij} = 1.0 \quad (j = 1, 2, \ldots, n) \quad \text{............. (8)}
\]

Here \( q_{ij} \) is 0 or a positive number. The matrix \( B \) is expressed by the sum of \( B_G \) and \( B_D \) as shown in Eq. (9).

The coefficients of \( B_G \) matrix mean the degree of residual to the same grain size, and degree of migration of adhered powder from finer grain components. The coefficients of \( B_D \) indicates the residual one and the degree of migration of fine particle from the coarser particle components. In the present study, the residual probability to the same particle size was set to 0.5 as shown in the diagonal components.

\[
B = B_G + B_D
\]

\[
B_G = \begin{pmatrix} 0.5q_{11} & \cdots & 0 \\ q_{21} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ q_{n1} & \cdots & 0.5q_{nn} \end{pmatrix} \quad \text{............. (9)}
\]

\[
B_D = \begin{pmatrix} 0.5q_{11} & q_{12} & \cdots & q_{1n} \\ 0 & 0.5q_{22} & \cdots & q_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0.5q_{nn} \end{pmatrix}
\]

Matrix elements were determined by multiple regression calculation using a conjugate method. The time step was set in increments of 10 s, and the matrix elements \( q_{ij} \) and
were determined so that the square sum of the difference between the experimental value and the calculated value was minimized.

3. Results

3.1. Influence of Agitation and Raw Material Condition on Granule Size

Figure 2 shows the influence of mixing and raw material conditions on the average particle diameter. The lines in the figure show the calculated values obtained by matrix analysis. In Fig. 2(a), when no mixing condition (0 rpm), the average particle diameter gradually decreased. Under the mixing conditions, the average particle diameter sharply decreased at the mixing time of 50 s, and showed the minimum value. Except for 1 000 rpm, the average particle diameter gradually increases after mixing time of 100 s. Figure 2(b) shows that the average particle diameter before mixing increased from 4.3 to 4.9 mm as the fine powder ratio increased. The time when the particle diameter starts to increase after mixing time of 50 s tended to be delayed as the fine powder ratio increases. This is because it takes time to disperse the moisture to the whole raw material. In terms of moisture contents, as the initial moisture content increased, the average particle diameter before mixing also increased to 2.8, 4.3, and 5.9 mm, respectively. Furthermore, the starting time of particle size increase started to be faster 480, 120, 20 s, respectively. This is because the contact between powder and moisture is promoted.

3.2. Influence of Agitation and Raw Material Condition on Moisture and Size Distribution

Figure 3(a) shows the moisture contents and size distribution with various mixing time. The average moisture content was slightly lower than the initial moisture content due to the adhesion to the inner wall of the machine. At a mixing time of 0 s, the moisture contents of coarse particles (>8.8 mm) were higher and that of small particle (<3.8 mm) were lower than the average moisture content of 5.2 mass%. As the mixing time increased, the moisture of the coarse particles decreased remarkably while the moisture of the small particle around 1.9 mm increased to near 5 mass%. Regarding the particle size distribution (Fig. 3(b)), the ratio of coarse particles (>6.4 mm) sharply decreased as the mixing time increased, and conversely the ratio of the small particle (<1.9 mm) increased significantly from 26 to 60 mass%. Aggregation and adhesion to the coarse nuclei occur when water is added. During mixing, the granules with fine particles are peeled from the nuclei particle, and then redistributed to other particles. It shows the similar moisture and particle size distribution after the mixing time of 300 s. Figure 4 shows the effect of rotation speed on the moisture and particle size distribution. Moisture with a particle size over 1.9 mm decreased as compared with the average moisture (5.2 mass%), and the width of the particle size distribution also decreased with the increase in rotation speed. Figure 5 shows the effect of fine ore (Ore A: -150 μm) ratio and initial moisture. There was no clear difference in the particle size distribution (Fig. 5(b)) against the increase...
in the fine ore ratio. However, Fig. 5(a) shows that moisture content with the particle size of 8.8 mm or more decreased sharply and that with 0.75 mm or less increased. Moisture distributed to unit fine powder particles decreases with the increase in fine powder. If the moisture content is below the critical moisture, it may remain as fine powder without adhering.\(^{(12)}\) The peak position of the moisture and the particle size distribution tend to shift to the coarser particle side as the initial moisture increased. This means that adhesion between the particles is promoted.

### 3.3. Time Dependence of Granule Size Distribution

Figures 6(a) to 6(d) show the changes in weight ratio by particle size. At the rotation speed of 60 rpm, the ratio of the 6.4 mm (Fig. 6(a)) was almost constant at 7.6 mass\%, the ratio increased in the case of 3.8 mm (Fig. 6(b)). Therefore, the increase in the average particle size is due to the increase in the particle size of 3.8 mm ratio. At the rotation speed of 500 rpm, the changes in ratio of the 3.8 mm is attributable to the average particle size. Meanwhile, at rotation speed of 1,000 rpm, both the ratios of 6.4 and 3.8 mm were low, and the ratio of 0.75 mm increased after mixing time 50 s, indicating that collapse is progressing.

#### 3.4. Influence of Agitation on the Internal Structure of Granules

Figure 7 show the cross sectional microphotographs of granules of 3.8 mm. Before mixing (Fig. 7(a)), the two-layer structure consisting of the core particles and adhering layer, mixture with fine and nucleus particles, and bare nucleus particles were observed. After the mixing time of 300 s (Fig. 7(b)), the ratio of the particles with the two-layer structure increased and the thickness of adhering layer also decreased. The particle shape also showed a spherical form after mixing.

Consequently, the mixing behavior of the granules is presumed as follows. The granules with fine particles and high moisture are collapsed by mixing. Fine particles are separated from the nucleus particles and adhered to other particle size portion.

### 4. Discussions

#### 4.1. Influence of Conversion Coefficient on Initial Agitation Behavior

The mixing behavior by the high-speed mixer is characterized by a sharp decrease in the average particle size within the mixing time of 100 s, followed by increase in particle size. In order to discuss the mixing speed at the beginning of mixing, the variation of particle size ($\sigma_{\text{pt}}$) was evaluated according to Eq. (4). Figure 8 shows the time dependence of $\sigma_{\text{pt}}$. As the mixing time increased, $\sigma_{\text{pt}}$ increased at first and then decreased gradually after showing maximum value around 50 to 100 s. The higher the rotation speed, the higher the local maximum value of $\sigma_{\text{pt}}$. In the case of 0 rpm, no clear maximum value was observed. This is because the mixing speed is very low and disaggregation of the fine powder is not completed. Yano et al.\(^{(14)}\) reported that deviation of components during mixing shows the individual values depending on the operating conditions, and the deviation gradually converges to a fixed value with repeating dispersion and mixing. In this result, the deviation increased again due to the progress of the granulation after reaching convergence state around the mixing time of 100 s.

Figure 9 shows the relationship between $\sigma_{\text{pt}}$ and average particle diameter. In Fig. 9(a), the average particle diameter decreased with $\sigma_{\text{pt}}$ except for the result of 0 rpm. A regression line excluding the data of 0 rpm is shown in the figure. In Fig. 9(b), the results of the same water content of 5.2...
mass% show the consistency. The results of 7.0 and 3.5 mass% shifted to larger and lower average particle diameter than 5.2 mass%, respectively. The regression line was calculated by the conditions (T1, T2, T3) with a moisture content of 5.2 mass%.

The maximum value of $\sigma_{pt}$ on the regression line was defined as a standard value ($\sigma_r$). The mixing degree $M$ was defined as Eq. (10):

$$M = 1 - \frac{\sigma_{pt}}{\sigma_r} \quad \text{(10)}$$

Where

- $k_t$: Mixing rate coefficient (1/min),
- $t$: Mixing time (min).

The value of $M$ converges to 0 as $\sigma_{pt}$ approaches $\sigma_r$. Under the water content of 5.2 mass% (60 to 1 000 rpm (T1) and T1 to T3 (250 rpm)), $\sigma_{pt}$ and $\sigma_r$ are 4.8 and 64, respectively. The average particle size is 2.4 mm. In the case of 3.5 mass%, $\sigma_{pt}$ and $\sigma_r$ are 3.7 and 50, respectively. The average particle size of 2.2 mm. In the case of 7.0 mass%, $\sigma_{pt}$ and $\sigma_r$ are 5.4 and 70, respectively. The average particle size of 3.6 mm.

**Figure 10** shows the time dependence of degree of mixing in the case of T1 and moisture of 5.2 mass%. Behavior of the rotation speed 0 rpm is greatly different from the other conditions, so it was exclude to discuss. The degree of mixing sharply decreased within the mixing time of 50 s, and the higher the rotation speed, the more the mixing progresses.

**Figure 11** shows the relationship between the mixing rate coefficients of powder ($k_s$), moisture ($k_w$) and Froude number. Mixing rate coefficients were calculated based on the time between 0 and 50 s when the average particle size displayed the minimum value. The values of $k_s$ and $k_w$ were almost the same with various rotation speed. Therefore, fine particles and moisture move together during mixing process. As the ratio of fine particles increased, $k_s$ decreased. This is because the number of particles that can contact with moisture per unit time decreases. As the moisture content increased, the mixing rate coefficients increased. Contrary to the above, this is because the contact probability of moisture and particles increases with increasing moisture, resulting in increasing the dispersion rate of moisture to the whole particles.

It has been reported that the conventional mixing rate coefficient, $k_1$, is expressed as the function of Froude number ($RN^2/g$) as shown in Eq. (11):

$$k_1 = K \left( \frac{RN^2}{g} \right)^n \quad \text{(11)}$$

Where

- $K$: Constant (1/min),
- $N$: Rotation speed (1/s),
- $R$: Rotation radius (m),
- $g$: Gravitational acceleration (m/s$^2$).

In the present study, both $k_s$ and $k_w$ increased in proportion to the three-tenth power of Froude number. The values of $k_s$ and $k_w$ were in the range of 1.5 to 11 (1/min). The mixing rate constant of a ribbon mixer having high kneading performance is reported to be 4 to 6 (1/min), similar order to present study. The definition of degree of mixing in the present study is different from past research. However, initial mixing behavior can be expressed by degree of mixing. Consequently, the rapid decrease in the average particle size is characterized by the increasing rate of deviation (mixing rate) of moisture and particle size distribution. The mixing rate constant is proportional to the power of the Froude number and influenced by the fine ore ratio and the initial moisture.
4.2. Evaluation of Collapse and Granulation Behavior

In order to evaluate the collapse and granulation individually, degree of collapse was introduced based on population balance model. Next, the internal growth rate was introduced to evaluate the transition of the long term average particle diameter.

4.2.1. Evaluation of Collapse Effect in the Initial Agitation Process

Figure 12 shows an example of the parameter $q_{ij}$ of the matrix $B$ for each rotation speed. Figure 12(a) corresponds to the condition of 60 rpm. Degree of collapsed powder from coarser size and adhering powder from finer size in 3.8 mm is indicated by the $q_{4j}$ from coarser size and adhering powder from finer size in 3.8 mm. The value of $q_{4j}$, which means the residual possibility to the same grain size, is large and the value of the $q_{4j}$, which means granulation growth from finer particle region, is quite small. The probability that this particle size shifts to another size is indicated by $q_{ij}$ ($i=1, 2, ..., 7$). It is composed only of $q_{4j}$. Therefore, it can be said that the weight ratio of the particle size, is large and the value of the $q_{4j}$, which means granulation growth from finer particle region, is quite small. The probability that this particle size shifts to another size is indicated by $q_{ij}$ ($i=1, 2, ..., 7$). It is composed only of $q_{4j}$. Therefore, it can be said that the weight ratio of the particle diameter 3.8 mm increased as a result of granulation growth of particles of 1.9 mm.

In addition, the granulation and collapse probability $\pi$ was approximately 1.0, higher than previous report of particles of 1.9 mm. The degree of collapse $S_{ij}$ was introduced based on population balance model. Next, the internal growth rate was introduced to evaluate the transition of the long term average particle size, is large and the value of the $q_{4j}$, which means granulation growth from finer particle region, is quite small. The probability that this particle size shifts to another size is indicated by $q_{ij}$ ($i=1, 2, ..., 7$). It is composed only of $q_{4j}$. Therefore, it can be said that the weight ratio of the particle diameter 3.8 mm increased as a result of granulation growth of particles of 1.9 mm.

The degree of granulation $S_{ij}$ was defined for the column element $j$ which corresponds to granulation region in the matrix element $B$.

\[
S_{ij} = 0.5q_{ij} + \sum_{j=1}^{7} q_{ij} (j = 1, 2, ..., 6) \quad \quad \quad (12)
\]

\[
S_{ij} = 0.5q_{ij} (j = 7)
\]

The degree of collapse $S_{ij}$ is defined by the following equation Eq. (8).

\[
S_{ij} = 1 - S_{ij} \quad \quad \quad (13)
\]

$S_{ij}$ shows the ratio of transition to a particle size region with a smaller particle size. When $S_{ij}$ is larger than 0.5, granule size distribution is dominated by collapse phenomena.

Figure 13 shows the relationship between $S_{ij}$ and rotation speed with various particle sizes. $S_{ij}$ sharply increased with rotation speed. On the other hand, in fine powders with a particle diameter of 0.75 mm, $S_{ij}$ decreased with rotation speed. This is because this particle size is likely to adhere to coarser particle.

Next, the relationship between $S_{ij}$ and the strength of granules and impact force by impeller was examined. The tensile strength $S$ (Pa) was calculated from the crushing strength $P$ (N). The particles were assumed to be spheres of diameter $d$ (m).

\[
S = \frac{2.8P}{\pi d^2} \quad \quad \quad (14)
\]

The particles after 600 s of mixing with moisture 5.2 mass% and 250 rpm were subjected to the evaluation. Some granules with the size of 1.9 mm or less are present as nucleus without adhering layer, making it difficult to measure the crush strength. In the present study, wet granules with an average particle size of 3.8 mm or more were subjected to the crushing strength test. The impact force $P_{\text{max}}$ (Pa) by the impeller was calculated from Eqs. (15) and (16).

\[
P_{\text{max}} = \frac{K}{\pi r^2} \left( \frac{5M}{8K} V_0^2 \right)^{3/5} \quad \quad \quad (15)
\]

\[
K = \frac{4\sqrt{r}}{3 \left( \frac{1-\nu_i^2}{E_i} + \frac{1-\nu_w^2}{E_w} \right)^{-1}} \quad \quad \quad (16)
\]

Where

- $M$: Weight of particle (kg),
- $r$: Radius of particle (m),
- $V_0$: Relative velocity at impact (m/s),
- $\nu_i$: Poisson’s ratio of particle (–),
- $\nu_w$: Poisson’s ratio of impeller (–),
- $E_i$: Young’s modulus of particle (Pa),
- $E_w$: Young’s modulus of impeller (Pa).

The values of $\nu_i$ and $E_i$ were obtained by measuring the displacement in the longitudinal and transverse direction during the strength measurement. The values of $\nu_w$ (0.3) and $E_w$ (210 GPa) were used by referring to ordinary steel properties.

Figure 14 shows the tensile strengths and impact force...
Particle size and the relationship between the minimum value of the average more significantly decreased. Therefore, in order to evaluate of 7.0 mass%. This is because particle size of 3.8 mm or sharply decreased to about 3 mm by the mixing time of 50 discussed. As shown in Fig. 2, the average particle diameter

\[ d_{\text{calc}} = \frac{\ln d_0}{\ln \frac{d_0}{d_{\text{min}}}} \]

\[ \text{Intensity ratio} = \frac{\text{Tensile strength of wet particle}}{\text{Tensile strength of dry particle}} \]

\[ 1 - \Sigma (0.5 x_j f_j S_{DJ}) / d_0 \]

\[ f_j : \text{frequency} \]

\[ S_{DJ} : \text{collapse index} \]

\[ d_{\text{calc}} : \text{initial average particle diameter (mm),} \]

\[ d_{\text{min}} : \text{minimum particle diameter (mm)} \]

\[ S_{DJ} : \text{collapse index} \]

\[ d_0 : \text{initial average particle diameter (mm)} \]

\[ d_{\text{calc}} : \text{calculated by Eqs. (15) and (16). The tensile strength decreased as the particle size increased. The fine particles and the coarse particles showed a large difference of strength nearly 100 times. In addition, the impact force increased with rotation speed. The impact force at 1 000 rpm showed 4.8 MPa, exceeding the tensile strength value of the whole granules.} \]

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\[ S_{DJ} : \text{collapse index} \]

\[ d_0 : \text{initial average particle diameter (mm)} \]

calculated by Eqs. (15) and (16). The tensile strength decreased as the particle size increased. The fine particles and the coarse particles showed a large difference of strength nearly 100 times. In addition, the impact force increased with rotation speed. The impact force at 1 000 rpm showed 4.8 MPa, exceeding the tensile strength value of the whole granules. Figure 15 shows the relationship between the ratio of the impact force to the tensile strength (intensity ratio: \(P_{\text{max}}/S\)) and \(S_{DJ}\). The finer granules had higher tensile strength than the coarser ones. \(S_{DJ}\) sharply increased from 0.5 to 1.0 as the intensity ratio increased from 1 to 20. When the intensity ratio became several tens of times, \(S_{DJ}\) became almost 1.0, and collapse was completely dominated.

Next, the relationship between the average particle diameter change and \(S_{DJ}\) at the beginning of mixing will be discussed. As shown in Fig. 2, the average particle diameter sharply decreased to about 3 mm by the mixing time of 50 s except for rotation speed of 0 rpm and the water content of 7.0 mass%. This is because particle size of 3.8 mm or more significantly decreased. Therefore, in order to evaluate the relationship between the minimum particle diameter and \(S_{DJ}\) at the initial stage of mixing, the following calculation was considered: First, the product of the particle size \(d_0\), initial weight ratio \(f_j\) and \(S_{DJ}\) is defined for the particle size of 3.8 mm or more. This value was divided by the initial particle size \(d_0\). As an influence factor of \(S_{DJ}\), coefficient of 0.5 was used. This dimensionless number \((1 - \Sigma (0.5 x_j f_j S_{DJ})/d_0)\) represents how the initial particle size was shrunk by collapse. In terms of different blending and moisture, calculation was made by assuming the same value of \(S_{DJ}\) shown in Fig. 15.

4.2.2. Evaluation of Granulation Process

In the present study, the maximum eigenvalue \(\lambda\) is obtained by assuming the matrix element \(((1 - \pi) E + \pi B)\) is the transition matrix in order to predict the transition of the average particle size. The internal growth rate \((= \ln \lambda)\) was defined for the purpose of evaluating the increasing rate of the average particle size. The positive value of \(\ln \lambda\) means the positive growth of the system. To calculate the eigenvalue \(\lambda\), Eq. (5) was solved iteratively until the difference of \(\lambda\) is less than \(10^{-8}\) while the magnitude of vector \(G_{\text{bin}}\) was normalized to 1. When the number of calculations is sufficiently large, \(\lambda\) was expressed by Eq. (17).

\[ (1 - \pi) E + \pi B \]

\[ G_{\text{bin}} = \lambda \cdot G_{\text{bin}}' \]

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\[ G_{\text{bin}}' \]

\[ \lambda \]

\[ G_{\text{bin}} \]

\[ d_{\text{calc}} : \text{calculated by Eqs. (15) and (16). The tensile strength decreased as the particle size increased. The fine particles and the coarse particles showed a large difference of strength nearly 100 times. In addition, the impact force increased with rotation speed. The impact force at 1 000 rpm showed 4.8 MPa, exceeding the tensile strength value of the whole granules.} \]

\[ d_{\text{calc}} = \frac{\ln d_0}{\ln \frac{d_0}{d_{\text{min}}}} \]

\[ 1 - \Sigma (0.5 x_j f_j S_{DJ}) / d_0 \]

\[ f_j : \text{frequency} \]

\[ S_{DJ} : \text{collapse index} \]

\[ d_{\text{calc}} : \text{initial average particle diameter (mm),} \]

\[ d_{\text{min}} : \text{minimum particle diameter (mm)} \]

\[ S_{DJ} : \text{collapse index} \]

\[ d_0 : \text{initial average particle diameter (mm)} \]

\[ d_{\text{calc}} : \text{calculated by Eqs. (15) and (16). The tensile strength decreased as the particle size increased. The fine particles and the coarse particles showed a large difference of strength nearly 100 times. In addition, the impact force increased with rotation speed. The impact force at 1 000 rpm showed 4.8 MPa, exceeding the tensile strength value of the whole granules.} \]

\[ d_{\text{calc}} = \frac{\ln d_0}{\ln \frac{d_0}{d_{\text{min}}}} \]

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\[ f_j : \text{frequency} \]

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\[ d_{\text{calc}} : \text{initial average particle diameter (mm),} \]

\[ d_{\text{min}} : \text{minimum particle diameter (mm)} \]

\[ S_{DJ} : \text{collapse index} \]

\[ d_0 : \text{initial average particle diameter (mm)} \]
$d_{\text{calc}}/d_{\text{min}}$ increased as $\ln \lambda$ increased. In addition, as the rotation speed increased, $\ln \lambda$ and $d_{\text{calc}}/d_{\text{min}}$ decreased. The values of $\ln \lambda$ were approximately 0, and $d_{\text{calc}}/d_{\text{min}}$ were 1.0 and 1.06 in the case of 1 000 and 500 rpm, respectively. It indicates that granulation growth hardly occurs at 1 000 rpm, but growth proceeds about 6% at 500 rpm. The growth rate is 0.03 to 0.05% when the rotation speed is less than 250 rpm, and the value of $d_{\text{calc}}/d_{\text{min}}$ shows the growth rate of 15 to 18%. When the moisture reduction (3.5 mass%) and the fine powder ratio increase (T2 and T3), both $\ln \lambda$ and $d_{\text{calc}}/d_{\text{min}}$ decreased. It means that the granulation speed decreases as the contact probability of moisture and powder particles decreases. When the moisture increased (7.0 mass%), $\ln \lambda$ became 0, but $d_{\text{calc}}/d_{\text{min}}$ showed a higher value of 1.65. This is because the mixing and granulation are completed in a shorter time than other conditions due to enough amount of moisture.

Consequently, the transition of the long-term mixing process can be predicted by matrix element. In the actual process, however, moisture evaporation and collapse of granules need to be considered during mixing procedure. As future research subjects, it is necessary to investigate the influence of mixing treatment on sintering properties, contributing to granulation flow design and scaling up to tackle with the changes in raw material properties.

**5. Conclusion**

The influence of the mechanical mixing on the collapse and granulation behavior of the wet iron ore granules was examined under various mixing and raw material conditions.

1) The rapid decrease of the average particle diameter is characterized by the increasing rate of the deviation of the particle size distribution from initial state. The mixing rate constant is proportional to the power of the Froude number and influenced by the fine powder ratio and the initial moisture. It was found that powder and moisture move simultaneously as the wet granules.

2) The granules have different strengths depending on the particle size, and therefore have different degree of collapse depending on the impact force from impeller. The degree of collapse increases with the ratio of the impact force to the granule’s strength. The decrease in the average particle size at the initial stage of mixing is strongly relating to the degree of collapse. The long-term behavior of granulation can be predicted by the internal growth rate defined by the maximum eigenvalue of the matrix element.

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