Effect of Pre-wetting Treatment on the Granulation Behavior of Iron Ore Fines

Xiaobo HUANG,1) Xuewei LV,1)* Chenguang BAI,1) Guibao QIU1) and Liming LU2)

1) College of Materials Science and Engineering, Chongqing University, Chongqing, 400044 China.
2) CSIRO Minerals Down Under Flagship, Queensland Centre for Advanced Technologies, QLD, 4069 Australia.

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Together with the conventional granulation, a proposed pre-wetting granulation for two commercial sinter mixtures consisted of six different iron ores and other auxiliary materials has been investigated under controlled laboratory conditions. A method to describe the size variation of the granules between different granulation trials was proposed and studied in the granulation of this study. It is a method by drawing a cumulative undersized curve (CUS curve) and a differential cumulative undersized curve (Δ-CUS curve) into one figure. The results indicated that (1) with more water available for granulation, more particles in a sinter raw mixture would behave as the layering fines in granules and the upper size for these layering fines would increase from 1 mm to 4.5 mm in conventional granulation; (2) compared to the results from conventional granulation, the granulation with pre-wetting treatment on iron ore fines resulted in a tighter particle size distribution and a higher permeability before ignition. At similar moisture content, more particles can be shifted into the layering fines in pre-wetting granulation than in conventional granulation; (3) Due to the preferential granule growth and the deformation of the granules, a further increase in pre-wetting degree (PWD) from 65% to 80% had little influence on the optimal permeability before ignition. Furthermore, a sinter mixture with more materials that are high in moisture absorption capacity would lead to higher optimum moisture content in granulation.

KEY WORDS: pre-wetting granulation; granulation behavior; particle size distribution; permeability.

1. Introduction

As a very important step in iron ore sintering, granulation is a process where fine particles are adhered onto coarser nuclei particles1,2) and the quasi-particles are formed under mechanical forces and interaction forces between particles in a granulating device.3,4) Compared to the sinter feed, the granules are usually larger in size and narrower in size distribution.5) The permeability of granules in a sinter bed before ignition is strongly affected by the granule particle size distribution (PSD) and the granule strength, so are the productivity and the quality in sintering process.2) It is known that the operation in ore-blending on a sinter mixture based on particle sizes and other physical properties is essential to the product quality in the subsequent process, like granulation and sintering.6) However, the production cost and chemical composition are usually the main factors considered in the ore-blending in Chinese sintering plants. The quality deterioration in iron-bearing materials used in sinter plants would become serious year by year. It is time to give a full consideration in the design of a sinter mixture, especially the consideration on granulating properties of iron ore fines.7)

The granulation behavior of a sinter mixture is largely determined by its mineral composition, initial particle size distribution, the amount of water inside the granules, and so forth. In selective granulation8) or separated granulation,9–11) the granule properties can be improved more than that in the conventional two-stage granulation,8,12) with respect to the distributions of mineral phases, chemical components and particle sizes of the quasi-particles. Not like the process in selective granulation, pre-wetting granulation proposed here is a granulation, by which the granulation performance of a sinter mixture can be improved a lot without too much additional investment on equipment. The granulation with pre-wetting treatment on return fines of a mixture has been studied by researchers13,14) However, little information on the pre-wetting treatment on iron ore fines in granulation was investigated and reported in the literature.

In order to investigate the effect of pre-wetting treatment of iron ore fines on the resulting granulation result, the pre-wetting granulation and conventional granulation on two sinter mixtures with 8 different iron ores and other auxiliary materials were conducted experimentally under controlled laboratory conditions. The conventional granulation described in an earlier work15) is not the main topic of this work. By introducing a graphical method with a cumulative undersized curve (CUS curve) and a differential cumulative undersized curve (Δ-CUS curve) in one figure, we figured out the evolution of particle sizes in conventional granulation with moisture content increased, and also determined to

* Corresponding author: E-mail: lvxuewei@163.com
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what extent the granulation can be improved by the pre-wetting treatment on iron ore fines.

2. Principle of Pre-wetting Treatment

Due to special climate conditions (dry seasons with low vapor content in atmosphere, like Autumn and Winter in the north of China) and the low wetting rate of sinter returns, Chinese iron and steel mills sometimes had to carry out pre-wetting operation on sinter return fines before they were mixed with other materials and granulated further in a drum granulator. Experimental and industrial research demonstrated a significant improvement in the granulation and sintering behavior via this pre-wetting operation.1,13,14,16–18

To enhance the granulation behavior, the effect of pre-wetting of iron ore fines in a sinter mixture on granulation was proposed and researched here.

Pre-wetting treatment is a process where selected raw materials in a sinter mixture, particularly like some relatively coarse ores, are partially wetted before being mixed and granulated in the subsequent process. In the proposed pre-wetting granulation technology, the pre-wetted coarse ore particles are preferentially encapsulated or layered by fine particles due to the capillary force and mechanical forces in a granulating drum. By optimizing the amount of water available on the surfaces of different particles via pre-wetting treatment, the granulation characteristics, especially the physical properties and the packed bed properties of the granules, can be improved.

Before carrying out pre-wetting treatment, some operational issues need to be considered. Firstly, for each material in a sinter mixture, the water-related properties (water absorption and wettability) have to be determined. The key blend components with high moisture absorption capacity values19 (M$_{w}$, the dry ore basis percentage of water absorbed by an ore when it is saturated) and high content of nuclei particles are the preferred materials in the pre-wetting treatment. The next step is to determine the amount of water required to pre-wet the materials selected. Supposing that the wet mass of ore $i$ in a sinter mixture is W$_{ori}$-w (kg) and the initial moisture content of this ore is M$_{0}$ (mass%), then the initial weight of water (W$_{H2O-o i}$, kg) in the ore can be calculated as follows.

$$W_{H2O-o i} = W_{ori}-w \times \frac{M_0}{100} \hspace{1cm} (1)$$

The moisture saturation content of this ore (M$_{s}$, mass% wet basis) can be calculated from its moisture absorption capacity (M$_{abs}$, mass% dry basis) by Eq. (2).

$$M_s = \frac{M_{abs}}{100 + M_{abs}} \times 100 \hspace{1cm} (2)$$

The pre-wetting moisture content (M$_{p-w}$, mass% wet basis) of this ore is then calculated from its saturation moisture content (M$_{s}$) and the pre-wetting degree (PWD, %) required, by Eq. (3).

$$M_{p-w} = M_s \times \frac{PWD}{100} \hspace{1cm} (3)$$

Together with Eqs. (1) and (3), the weight of water (W$_{H2O-p-i}$, kg) added onto ore $i$ in pre-wetting treatment can be calculated by Eq. (4).

$$W_{H2O-p-i} = \frac{W_{ori}-w + W_{H2O-o i}}{100} \hspace{1cm} (4)$$

Rearranging Eq. (4) yields the weight of water required in the pre-wetting of ore $i$ calculated by Eq. (5).

$$W_{H2O-p-i} = \frac{W_{ori}-w \times M_s \times (PWD/100) - M_{p-i} \times (PWD/100)}{100 - M_s} \hspace{1cm} (5)$$

Finally, according to Eq. (5), the pre-wetting treatment on iron ore $i$ was carried out by spraying the amount of water (W$_{H2O-p-i}$) onto the particles in the iron ore bed in 3 min. After that, the pre-wetted materials can be added into the mixture in a high speed mixer. During the spraying of water, the iron ore bed was located inside a cylinder-shaped container with 300 mm in a diameter and 500 mm in height. The spraying of water onto the iron ore bed was operated by setting the spray parameters of a hand-operated sprayer (WBD-16 type with 18 L in volume) at a fixed value (working pressure of 0.3 mPa, spray angle of 65–72°, flow rate of 2.4 l/min) and keeping the spray nozzle (round openings with 0.8 mm diameter) 40 cm above the surface of the iron ore bed, then scanning the iron ore surface when the water was sprayed out.

3. Materials and Experiment

3.1. Materials

Two sinter mixtures consisting of six commercial iron ore fines (Ores A – F) and other auxiliary materials were studied here. The compositions of the two ore blends and corresponding sinter mixtures were given in Tables 1 and 2, respectively. Sample G in Table 2 is a mixture of recycled ferrous materials from downstream iron and steelmaking processes, while Sample H is the return fines generated in the sintering process. As the proportion of these two materials is almost the same in the two sinter mixtures, their impact on the pre-wetting granulation is not considered here. As shown in Table 2, the fuel and quicklime contents of the mixtures are fixed at 3.23% and 2.87%, respectively and the contents of other fluxes are varied to keep the sinter basicity (ratio of mass%CaO to mass%SiO$_2$) and MgO content constant at 2.0 and 1.45 mass%, respectively.

The size distributions of the six iron ores are presented in Fig. 1. In particle size measurement, by using hand-made

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**Table 1.** Composition of the Iron ore blends (mass%).

<table>
<thead>
<tr>
<th>Ore blends</th>
<th>Ore A</th>
<th>Ore B</th>
<th>Ore C</th>
<th>Ore D</th>
<th>Ore E</th>
<th>Ore F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>20.55</td>
<td>41.96</td>
<td>0.00</td>
<td>25.01</td>
<td>6.24</td>
<td>6.24</td>
</tr>
<tr>
<td>2#</td>
<td>52.02</td>
<td>0.00</td>
<td>2.35</td>
<td>10.01</td>
<td>25.00</td>
<td>10.62</td>
</tr>
</tbody>
</table>

**Table 2.** Composition of the sinter mixtures with the basicity = 2.0 (mass%).

<table>
<thead>
<tr>
<th>Sinter mixtures blend</th>
<th>Ore G</th>
<th>Ore H</th>
<th>Limestone</th>
<th>Dolomite</th>
<th>Serpentine</th>
<th>Quick lime</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>49.83</td>
<td>10.86</td>
<td>26.64</td>
<td>3.91</td>
<td>2.05</td>
<td>0.78</td>
<td>2.87</td>
</tr>
<tr>
<td>2#</td>
<td>49.66</td>
<td>10.86</td>
<td>26.64</td>
<td>3.91</td>
<td>2.05</td>
<td>0.78</td>
<td>2.87</td>
</tr>
</tbody>
</table>
screens (200 mm in diameter and 50 mm in height) with a screen type of woven mesh, all the samples were sized at its received moisture content (no pre-treatment for drying the sample) for 5 min. Except for the impacts between the particles moving on the screen, no other impacts were involved in the measurement. As for the nuclei particles reported by Loo, C. E,20) Ores A and B contained a similar high proportion of >2 mm particles (the nuclei particles, >55 mass% for Ore A and >60 mass% for Ore B). Compared with Ores A and B, the other ores had a much less proportion of >2 mm particles (the nuclei particles, about 40% for the other ores). Based on the nuclei particle size proposed by others,21–24) the similar conclusions on the particle sizes of the iron ores used can be made.

Moisture absorption capacity of the ores are also measured and presented in Fig. 2. Ores A and C had the highest moisture absorption capacity of approximately 18%, which was almost twice as much as that for Ores E and F. The moisture absorption capacity of Ores B and D was moderate approximately at 14 mass%. The water absorption kinetics of the ores can be obtained by fitting the absorption curves in Fig. 2 using the following empirical exponential equation.25)

\[
M_t = M_{ac} \times \left(1 - \exp \left(-\frac{k \rho A P_t}{M} \right)\right)
\]

Where \(M_t\) is the percentage (mass% dry basis) of water absorbed at \(t\) seconds after absorption starts; \(M_{ac}\) is the percentage (mass% dry basis) of water absorbed when the sample is saturated; \(k\) is the overall water transfer coefficient (mm/s); \(A\) is the cross-sectional area of the sample bed for water penetration (mm²); \(\rho\) is the density of water (10⁻³ g/mm³); \(M\) is the dry mass of the sample (g). In addition, \(t_c\) is defined as the time when the sample reaches 98% of its saturation value. As summarized in Table 3, Ores D, E and F were quite fast in water absorption \((k > 2.8 \text{ mm/s})\) and had moderate to low water absorption capacity, they are expected to be easily wetted in the granulation process. However, Ores A, B and C required the longer absorption time (>120 s) to achieve 98% saturation due to their low water transfer coefficient (<2.1 mm/s). Therefore, Ore A, B and C were chosen for pre-wetting treatment.

### 3.2. Granulation Experiment

Conventional granulation of the same sinter mixtures has been reported in our earlier research.15) Here, as shown in Fig. 3, the pre-wetting granulation was carried out in three stages:
1) pre-wetting treatment of iron ore fines selected to achieve 65 or 80% saturation (pre-wetting degree);
2) Mixing of pre-wetted ores with other components of the mixture and partial wetting of the mixture in a high speed mixer. After deducting all the water used in pre-wetting operation, the rest in the 80% of the granulation water required was added in the mixing and partial wetting stage.
3) Continuous growth and densification of the granules in a horizontal rotating drum granulator. The balance (20%) of the granulation water required was added during the granule growth stage.

The moisture content of the granules for the two mixtures in pre-wetting granulation was varied between 5.8 and 6.2 mass%. The moisture content of the granules was determined by measuring the mass of the granules before and after the wet granules were dried at 105±5°C for 3 hours.26) The detailed information of the apparatus to measure granulation behavior was discussed elsewhere.15) The process parameters used in different stages of pre-wetting granulation were given in Table 4. The water required (\(W_{(2G+P)}\)) for pre-wetting Ores A, B and C at 65% pre-wetting degree (PWD=65%) in Sinter Mixture 1 was calculated and listed in Table 5.

After pre-wetting granulation, the granules were sized by manual sieve method27) with the same set of sieves in Fig. 1. The quasi-particles with a size larger than 3 mm are the desired part in the granules before ignition in sintering. Since it is not preferable to have too much super-coarse particles, the part of granules in size of 3 to 7 mm is the most important part to be considered in the evaluation of granulation. The particle size indices (e.g. \(W_{+3}, W_{+3,-7}\)) and the

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ore A</th>
<th>Ore B</th>
<th>Ore C</th>
<th>Ore D</th>
<th>Ore E</th>
<th>Ore F</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M_{ac})/mass%</td>
<td>18.21</td>
<td>14.33</td>
<td>17.80</td>
<td>14.20</td>
<td>8.55</td>
<td>10.35</td>
</tr>
<tr>
<td>(t_c)/s</td>
<td>185.0</td>
<td>131.0</td>
<td>162.0</td>
<td>73.0</td>
<td>40.0</td>
<td>94.0</td>
</tr>
<tr>
<td>(k)/(mm/s)</td>
<td>1.93</td>
<td>2.03</td>
<td>1.27</td>
<td>3.35</td>
<td>6.60</td>
<td>2.82</td>
</tr>
</tbody>
</table>

Table 3. Water absorption characteristics of iron ore fines used.
cumulative particle size curves of the granules were calculated and plotted into a figure. To measure the bulk density\(^2\) of granules, the granulated mixture was charged into a container of 223.9 cm\(^3\) under the influence of gravity. As shown in Eq. (7), the permeability \((JPU)\) was calculated by measuring the pressure drop \((\Delta P, \text{mm H}_2\text{O})\) of a packed granule bed of 234 mm in height and 210 mm in diameter under an air flow rate of 60 m\(^3\)/h.

\[
JPU = \frac{Q}{A} \left( \frac{H}{\Delta P} \right)^{0.6} \]

Where, \(A\) is the sectional area (m\(^2\)) of the packed granule bed; \(Q\) is the air flow rate across the bed (m\(^3\)/min); \(H\) is the bed height (mm) and \(\Delta P\) is the pressure drop across the packed bed (mm H\(_2\)O).

### 3.3. Particle Size Distribution Curve

Particles in a sinter mixture are generally divided into two or three groups depending on their sizes that are believed to have different impacts on granulation. No consensus was made in the literature\(^2\) on the exact boundaries of different size groups. As described in Eq. (8), the differential cumulative undersized curve (\(\Delta\text{CUS}\) curve) is plotted according to the difference between two cumulative undersized curves (CUS curves).

\[
\Delta W'_D(< D) = W'_D(< D) - W'_D(> D) \]

Where \(D\) is the aperture size (mm) of sieves from the set of sieves in Fig. 1; \(W'_D(< D)\) and \(W'_D(> D)\) are the corresponding cumulative weight percentages of the undersized granules from the reference and the studied granulation trials, respectively. With the \(\Delta\text{CUS}\) curve (differential cumulative undersized curve) of the studied granules and the CUS curve (cumulative undersized curve) of the reference granules, a graphical method was formulated, by which the role of particles with different sizes in granulation can be described.

By referring to the granules prepared at the lowest moisture content (4.32 mass%), the \(\Delta\text{CUS}\) curves of the granules prepared at different moisture contents from Sinter Mixture 1 in the conventional granulation\(^1\) were presented in Fig. 4. As the moisture content increased from 5.44 mass% to 7.68 mass%, the upper limit of size range of the particles which can act as the adhering fines appeared to shift from 1 mm to about 4.5 mm. With increasing moisture content, the amount of coarse +10 mm and –10+5 mm granules increased by 7 mass% to 14 mass% and by 3.2 mass% to 19.3 mass%, respectively. Similar to the observations in the literature\(^3\), two groups of particles are identified in Fig. 4 to play a distinct role in granulation with the increase of moisture content. It is well accepted\(^4\) that at any moisture content, particles in the finest size fractions can be classified solely as layering particles and the ones in the largest size fractions acted only as nuclei particles. As for the particles between the two extreme size fractions, a proportion of particles less than a certain size behaved as layering particles, the rest of them being nuclei particles.

### 4. Results and Discussion

#### 4.1. Effect of Pre-wetting Degree

The pre-wetting granulation was conducted at two levels of PWD (65% and 80%) for Sinter Mixture 1 at a moisture content of 5.83% (W\(_{\text{MC}}\) = 5.83 mass%). As shown in Fig. 5, pre-wetting granulation showed a great potential in decreasing the fine particles (<3 mm) and increasing the relatively coarse particles of the granules at both two PWD levels tested. The granules prepared at PWD = 65% contained more –10+3 mm granules, however less content of super coarse particles (+10 mm), compared with the granules prepared at PWD = 80%. The preferential granule growth\(^5\) can be responsible for the significant increase in the super coarse particles of the granules prepared at a high-
er PWD level of 80%.

The effect of pre-wetting degree (PWD) on the amounts of +3 mm granules (W+3, mass%) and the –7+3 mm granules (W–7+3, mass%) was presented in Fig. 6. At the similar moisture content, the proportion of the +3 mm granules increased from around 80% in conventional granulation to about 95% in pre-wetting granulation at PWD = 65%. While the proportion of the +3 mm granules increased with PWD, there was only marginal difference in the proportion of the +3 mm granules between the two pre-wetting granulations at different PWDs. A huge difference in the proportion of –7+3 mm granules between the two pre-wetting granulations at different PWDs was observed. Pre-wetting granulation with PWD = 65% generated a higher proportion of –7+3 mm granules, and a lower proportion of super coarse granules (+7 mm). This is due to the preferential granule growth of the super coarse particles in the sinter mixture.

The permeabilities (JPU) of the granules prepared at different PWDs were analyzed by comparing to that prepared without pre-wetting treatment in Fig. 7. Compared with the conventional granulation at the same moisture content, pre-wetting granulation has improved the bed permeability of granules considerably by 1.25 times. Further increase in PWD from 65% to 80% had little impact on the permeability of the packed bed. Although pre-wetting granulation with a higher PWD has led to the further growth in granule size, it also resulted in granules with a broad size distribution. In overall, non-significant increase in permeability was observed for the granules prepared from pre-wetting granulation at a higher PWD.

4.2. Pre-wetting Granulation of Different Mixtures

The analyses in the section on “Effect of pre-wetting degree” suggested that the pre-wetting treatment on Ores A, B and C at PWD = 65% has considerably improved the granulation performance of Sinter Mixture 1. Similar tests were also conducted on Sinter Mixture 2 with a PWD of 65% to examine the effect of raw materials on the efficiency of pre-wetting granulation. Comparing with Sinter Mixture 1 in Table 1, Ore B was completely replaced by the other ores in Sinter Mixture 2. The proportion of Ore A increased a lot, and Ores E and F also increased a bit in Sinter mixture 2. Ores E and F are characterized by a fast rate of water absorption and low water requirement for granulation.

The size analysis of the granules prepared with and without pre-wetting treatment from Sinter Mixture 2 was presented in Fig. 8. Like Sinter mixture 1, pre-wetting granulation had a great potential in improving the granule size distribution for Sinter Mixture 2. According to the principal mechanism in iron ore granulation, compared to the conventional granulation at the same moisture content, more fine particles can be coated onto or coalesced with coarse particles in pre-wetting granulation. Even at a slightly lower moisture content (WMC = 6.09 mass%), granules prepared...
after the pre-wetting treatment on iron ores contained more coarse particles (3 to 10 mm) than those obtained from conventional granulation ($W_{MC} = 6.45$ mass%).

The effect of pre-wetting treatment on the size distribution and packed bed properties (for instance, JPU and bulk density) of the granules from the two sinter mixtures was summarized in Figs. 9 and 10. The amount of +3 mm granules ($W_{+3}$) increased gradually with the moisture content of the granules increased. Compared with the conventional granulation at similar moisture contents in Fig. 9, the proportions of $–7+3$ mm granules ($W_{–7}$) and $+3$ mm granules ($W_{+3}$) for the two mixtures after pre-wetting granulation increased at least by 20% and 15%, respectively. The permeability of the two mixtures after pre-wetting granulation was improved by more than 22%, as evidenced in Fig. 10(a). Furthermore, pre-wetting treatment on iron ores improved more on the permeability of the granules for Sinter Mixture 2.

A similar permeability – moisture trend was observed for the two mixtures in conventional granulation. The bed permeability in Fig. 10(a) initially increased with moisture, and then decreased at higher moisture contents after passing through a maximum. In contrast, the bulk density showed the exactly opposite relationship with the moisture content of the granules. We found that the improvement in bulk density by pre-wetting granulation for the two cases with respective moisture content are similar, while we cannot get the same conclusion for the permeability of the packed bed. We believe the difference in physical properties of the granules (especially the true density) and the difference in the effective porosity of the packed bed between the two cases (case (1#) and case (2#) in Fig. 10) will account for such difference between the two indices with the moisture content of the granules changed. Considering the researches by Ergun, S.34) and Yoshinaga, M., et al.,29) the permeability is
largely determined by the porosity, especially by the effective porosity of the bed. Variance in true density of the granules can change value of the porosity significantly. And, the effective porosity of the packed bed is determined not only by the packing state (with respect to the porosity or bulk density), but also by some other parameters of the packing structure. The similar phenomenon was also observed by Yoshinaga, M., et al.29) and Ooi, T. C., and Lu, L. M..35)

It was observed that the granulation performance was also dependent on the composition of the sinter mixtures. When Ores B (41.95%) and D (25.01%) in Sinter Mixture 1 were replaced by Ores A, C, E, F in Sinter Mixture 2 (Table 2), a significant loss in permeability and W⁻⁻⁻,⁻⁻ was observed for Sinter Mixture 2. Furthermore, higher moisture content was required for Sinter Mixture 2 to achieve the maximum permeability. Increase the proportion of the materials with a lower moisture absorption capacity should lead to lower optimum moisture content for the sinter mixture in granulation.36) Compared to iron ores used in Sinter Mixture 1, the increment in the proportion of Ore A (the highest moisture absorption capacity) in sinter mixture 2 is the highest (from 20.55 to 52.03). And a slight increase in optimum moisture was observed in the granulation of Sinter Mixture 2 in Fig. 10(a). This indicated that a sinter mixture with more materials that are high in moisture absorption capacity would lead to higher optimum moisture in granulation.

5. Conclusions

In this study, the pre-wetting granulations on two sinter mixtures consisting of several commercial iron ores were studied by comparing to the results from conventional granulation. A graphical method to describe the size variation of the granules between different granulation trials was proposed and studied in this study. From the results and analyses, the conclusions are summarized as following:

(1) With this graphical method, it is easy to understand the role and the evolution of the particles with any given size ranges from a sinter mixture in the granulation process with the moisture content increased.

(2) The upper size of the layering fines shifted from 1 mm to 4.5 mm with more water available in conventional granulation. At the similar moisture content in conventional granulation, more particles in a sinter mixture would behave as the layering fines in pre-wetting granulation.

(3) The pre-wetting degree (PWD) played a crucial role in the pre-wetting granulation of a sinter mixture. Due to preferential granule growth and the deformation of the granules, a further increase of PWD from 65% to 80% had little influence on the permeability before ignition.

(4) A sinter mixture with more materials that are high in moisture absorption capacity would lead to higher optimum moisture in granulation. Pre-wetting on iron ore (Ore A) with higher moisture absorption capacity showed a deterioration effect on the permeability before ignition.

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