The Effect of Raw Mixture Properties on Bed Permeability during Sintering

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Raw mixes of iron ore sinter feed were prepared under a variety of conditions. The permeability of mixes before ignition and during sintering was examined using a conventional permeameter and a small instrumented sinter pot, respectively. The sinter pot consisted of a gas preheater and a sample bed 29 mm high so that pressure drop of high temperature zones could be measured precisely and easily.

As expected, the pre-ignition permeability of the mixes was related to the mean size of the granules which in turn was related to the amount of water used for granulating. The order of permeability of mixes having different moisture contents did not change during or after sintering. Late-addition of coke during granulation resulted in a higher pre-ignition permeability. During sintering, however, the permeability deteriorated considerably. Use of larger particles of coke or limestone resulted in improved permeability before and during sintering. The basicity and coke content of mixes had little effect on the permeability of a bed during and after sintering under the condition of constant total amount of flux (SiO₂ + CaO).

It was concluded that the permeability of the produced sinter cake depended predominantly on the pre-ignition permeability, for mixes of the same ore type and the same total amount of flux. This suggests that some aspect of the structure of a bed of granulated sinter feed is preserved during sintering.

KEY WORDS: agglomeration; iron ore; sintering; permeability; granulation; mixing; high temperature zone; late coke addition.

1. Introduction

Iron ore sinter is the major source of iron in the burden to the modern blast furnace. Consequently, appropriate metallurgical properties of sinter in the blast furnace are essential to its efficient and stable operation. Properties of sinter such as reducibility, reduction degradation, softening and melt-down characteristics are determined by various process factors during sintering which are highly interactive. In this context, the permeability of a sintering bed plays a vital role in controlling sinter properties and productivity, since it governs bed-temperature profiles by determining gas flow rate through the bed.

The state of a sintering bed can be represented by several zones in a vertical direction: the wet (or water condensed), dry, combustion, melt and sintered zones. Several studies have been done on the permeability of mixtures of raw materials in connection with moisture content,1-3) particle size distribution of granules4,5) and so forth. A few attempts6,7) have been made to measure the pressure drop of each zone during sintering. These measurements yielded some fundamental information on bed permeability. For instance, zones at high temperature lead to high pressure drop because of the high velocity of gas due to volume expansion, and the sintered zone has extremely low pressure drop because of its porous structure and lower temperature. The wet zone is a relatively permeable zone,7) as the temperature of the gas is low. However, its permeability dominates that of the whole bed in the early stage of sintering since it occupies most of the bed in that stage. In the latter stages, the high temperature zones, in turn, become dominant as the thickness of the wet zone decreases and the more permeable sintered zone enlarges.

In this paper, the results of experiments to measure the permeability before ignition and during sintering are compared for various mixes prepared with different materials and under different granulating conditions. Changes in pressure drop of the high temperature drying, combustion and melt zones are analyzed, and differences between the mixes are discussed in order to obtain information of use in practical processes.

2. Experimental

2.1. Raw Materials

A hematite ore from Australia and Japanese limestone was used for the experiments. Metallurgical coke was supplied by an Australian steel works. The particle size distribution and chemical composition of the materials used in the experiments are listed in Tables 1 and 2, respectively. The ore has relatively high percentages of silica and alumina. Sinter for producing the “return fines” was prepared using the raw materials in a conventional sinter port. Basicity (CaO/SiO₂: C/S) of “return fines” was 1.85. Pure silica sand was used to adjust the basicity of test mixes.
of ore, limestone, coke and "return fines" when required. The return fines were added to the sinter mix in two size fractions: two-thirds as 3.2–6.4 mm and one-third as 0.5–2.0 mm by mass.

2.2. Preparation of Sinter Feed

Weighed amounts of the raw materials were charged into a drum-type mixer of 0.5 m inside diameter and 0.25 m width and dry-mixed for 2 min at 23 r.p.m. A pre-weighted amount of water was then added homogeneously through a spray. Further mixing was continued for 2 min at the same rotation speed. Finally, the mixture was rotated at 6.6 r.p.m. for 10 min in order to granulate the materials.

The following properties of the mixes were measured on samples taken after granulation.

(i) Water Content:

The average percent of water was determined by the mass difference before and after 2 h drying at 110±5°C and expressed on a dry mixture basis.

(ii) Mean Granule Diameter:

Two diameters, arithmetic mean diameter* and surface-volume diameter,** were obtained for each mix. The size distribution of granules in the mix was determined by freezing a sample in liquid nitrogen then screening it with laboratory sieves in the manner described previously by one of the authors.***

(iii) Pre-ignition Permeability:

A small conventional down draft permeameter of 0.25 m in height and 0.125 m inside diameter was used to measure the permeability. The permeability was expressed in terms of the Japanese Permeability Unit (J.P.U.), calculated by Eq. (1), by taking the average of several measurements of pressure drop for different flow rates from 200 to 800 l/min.

\[ \text{J.P.U.} = \frac{F}{A} \frac{(h/s)^{0.5}}{h} \]  

where, \( F \): the air flow rate (Nm³/min)  
\( A \): the cross-sectional area of the bed (m²)  
\( h \): the bed height as charged (mm)  
\( s \): the suction pressure at the bottom of bed (mmHg).

2.3. Procedure for High Temperature Tests

A small sinter pot with a sample bed 29 mm high and 151 mm diameter was used to measure changes in the pressure drop of the sintering bed. The equipment consisted of a preheater and a pot as illustrated in Fig. 1.

The preheater consisted of a combustion chamber

![Schematic diagram of a small sinter pot with a gas preheater.](image)

Fig. 1. Schematic diagram of a small sinter pot with a gas preheater.

### Table 1. Particle size distribution of raw materials used in the experiments. (mass%)

| Size     | Iron ore | Limestone | Coke |
|----------|----------|-----------|------|
| -8.00 mm | 18.2     | 0.6       | 6.5  |
| -4.00 mm | 21.5     | 26.5      | 22.7 |
| -2.00 mm | 14.7     | 28.3      | 21.4 |
| -1.00 mm | 8.5      | 13.5      | 12.7 |
| -0.50 mm | 8.4      | 13.8      | 16.0 |
| -0.25 mm | 7.5      | 6.1       | 9.9  |
| -0.175 mm| 6.1      | 3.4       | 7.1  |
| < 0.063 mm| 15.1    | 7.8       | 3.7  |

Surface-volume mean diameter (mm) | 0.16 | 0.26 | 0.33 |
Arithmetic mean diameter (mm) | 2.08 | 1.43 | 1.58 |

### Table 2. Chemical composition of raw materials used in the experiments. (mass%)

|         | CaO | SiO₂ | T.Fe | Al₂O₃ | MgO | Loss on ignition |
|---------|-----|------|------|-------|-----|-----------------|
| Iron ore| 0.07| 4.38 | 62.45| 2.57  | 0.11| 3.18            |
| Return fine | 8.04| 4.70 | 58.57| 3.10  | 0.25| -               |
| Limestone| 55.22| 0.76 | 0.13 | 0.35  | 0.88| 42.4            |
| Coke    | 1.03| 9.03 | 4.09 | 3.44  | 0.19| 79.4            |

* \( \sum (m_i d_i) \)  
** \( \frac{1}{\sum (m_i d_i)} \)  

where, \( m_i \): mass of granules of size fraction \( d_i \)  
\( d_i \): diameter of granule size fraction \( i \).
in which propane and hydrogen were burned above a packed bed of alumina spheres. The alumina bed was insulated from the outer steel wall by alumina fiber 25 mm thick so that a uniform temperature distribution of the bed could be obtained in the radial direction. A suction pyrometer and a thermocouple were located in the combustion chamber and alumina bed, respectively, in order to control the preheating gas temperature.

Fig. 2 shows the construction of experimental beds in the sinter pot. The sample bed was placed on the hearth layer, 20 mm in height, of return fines. Two suction pyrometers to measure the inlet and outlet gas temperatures, a thermocouple for measuring the temperature at the bottom of the sample, and 3 stainless steel tubes to measure the pressures at the top and bottom of the sample bed and in the windbox were used for most experiments. The position of the measurements are illustrated in Fig. 3. Extra thermocouples and a suction pyrometer were used occasionally to assess the variation in temperature both radially and vertically.

To perform an experiment, the alumina bed was first heated to about 1250°C by burning the gas mixture. The gas mixture was then turned off and the preheater was immediately positioned on the top of the pot. The suction was controlled manually with a needle valve so as to keep a predetermined flow rate of air passing through the bed during the experiment. The gas and bed temperatures and pressure drops were logged every second and recorded on a computer diskette for subsequent off-line analysis.

3. Results and Discussion

Sintering experiments were carried out on 21 raw mixes. The composition and characteristics of the granulated mixes are shown in Table 3. The term ‘Normal’ for coke and limestone size indicates that these were used without sizing.

The experiments were designed to examine several effects and can be grouped as follows:

(I) Coke Concentration (Mixes 02 to 04):
Coke was mixed in 3 levels from 4.5 to 5.5 mass% on a dry mix basis.

(II) Moisture Content (Mixes 03, 05 to 06R, 12 and 12R):
Moisture content was varied from 5.7 to 7.6 mass% on a dry mix basis.

(III) Coke Size Distribution (Mixes 03 and 07 to 09):
Sized coke fines, −0.5, 1.0−2.0 and 3.0−4.0 mm, were added to the mixes.

(IV) Late Coke Addition (Mixes 03, 01 and 11):
Two methods of the late addition were examined. In one method, all coke was charged after 7 min granulation of the other raw materials and granulated for a further 3 min, (Method 1). In the other method, the −0.5 mm fraction of the coke was added after the 7 min granulation (Method 2).

(V) Basicity (Mixes 12R to 15):
4 levels of basicities, from 0.8 to 1.8 were examined.

(VI) Limestone Size Distribution (Mixes 12R and
Table 3. Sinter feed mixtures prepared for small pot experiments.

| Mix No. | Coke (mass%)<sup>1</sup> | Coke size (mm) | Limestone size (mm) | Basicity (→) | Moisture (mass%)<sup>1</sup> | Permeability (J.P.U.) | Diameter | Void fraction calculated (→) |
|---------|--------------------------|----------------|---------------------|-------------|----------------------------|-----------------------|----------|-----------------------------|
| 02      | 4.5                      | Normal         | Normal              | 1.6         | 6.96                       | 86.0                  | 2.34     | 4.02                        | 0.47     |
| 03      | 5.0                      | Normal         | Normal              | 1.6         | 6.99                       | 85.7                  | 2.34     | 3.87                        | 0.47     |
| 04      | 5.5                      | Normal         | Normal              | 1.6         | 7.11                       | 81.6                  | 2.40     | 3.87                        | 0.46     |
| 05      | 5.0                      | Normal         | Normal              | 1.6         | 6.34                       | 72.2                  | 2.09     | 3.64                        | 0.46     |
| 06      | 5.0                      | Normal         | Normal              | 1.5         | 6.68                       | 75.5                  | 2.45     | 4.05                        | 0.45     |
| 07      | 5.0                      | Normal         | Normal              | 1.5         | 7.58                       | 93.8                  | 3.35     | 4.85                        | 0.44     |
| 08      | 5.0                      | Normal<sup>2</sup> | Normal              | 1.6         | 7.16                       | 70.7                  | 2.41     | 4.16                        | 0.43     |
| 09      | 5.0                      | Normal<sup>3</sup> | Normal              | 1.6         | 7.22                       | 71.8                  | 2.37     | 4.06                        | 0.44     |
| 10      | 5.0                      | 1.0—2.0        | Normal              | 1.6         | 7.06                       | 89.6                  | 2.77     | 4.06                        | 0.46     |
| 11      | 5.0                      | Normal         | Normal              | 1.6         | 7.17                       | 99.7                  | 3.19     | 4.88                        | 0.46     |
| 12      | 5.0                      | Normal         | Normal              | 1.6         | 7.12                       | 91.3                  | 2.93     | 4.47                        | 0.45     |
| 13      | 5.0                      | Normal<sup>1</sup> | Normal              | 1.6         | 6.56                       | 93.4                  | 1.53     | 3.10                        | 0.44     |
| 14      | 5.0                      | Normal<sup>1</sup> | Normal              | 1.6         | 6.82                       | 85.2                  | 2.83     | 4.23                        | 0.46     |
| 15      | 5.0                      | Normal<sup>1</sup> | Normal              | 0.8         | 6.78                       | 87.9                  | 2.77     | 4.17                        | 0.45     |
| 16      | 5.0                      | Normal<sup>1</sup> | Normal              | 1.2         | 6.98                       | 81.8                  | 2.42     | 3.87                        | 0.46     |
| 17      | 5.0                      | Normal<sup>1</sup> | Normal              | 1.2         | 7.07                       | 79.8                  | 2.51     | 4.08                        | 0.45     |
| 18      | 5.0                      | Normal<sup>1</sup> | Normal              | 1.6         | 7.00                       | 72.7                  | 2.52     | 3.90                        | 0.44     |
| 19      | 5.0                      | Normal<sup>1</sup> | Normal              | 1.6         | 6.92                       | 73.4                  | 2.47     | 3.93                        | 0.44     |

<sup>1</sup>Coke and moisture contents are on dry mixture basis.

<sup>2</sup>Method I: All coke was added after 7 min granulation for a further 3 min granulation.

<sup>3</sup>Method II: +0.5 mm coke was mixed with other materials and -0.3 mm coke was added after 7 min granulation for a further 3 min granulation.

mm high, 910 g of mix was charged onto the hearth layer and this formed a bed of 1.75 g/cm³ bulk density.

A few different gas flow rates were used in the experiments, however, results at 500 N/min, 0.47 m/s superficial velocity, were used for the analyses in this paper. The temperature of the inlet gas was not controlled during an experiment because the alumina bed was heated before an experiment started. However, the inlet gas temperatures were reasonably constant: 1015±25°C for runs 0016 to 0046 and 1135±25°C for runs 0048 to 0066, as shown in Table 4. The difference of the inlet gas temperature was caused by the different gas mixture (the ratio of hydrogen and propane) used for the two series of the experimental runs.

3.1. Pre-ignition Permeability

The permeabilities of the raw mixes, in terms of the J.P.U., are shown as a function of the moisture contents of the mixes in Fig. 4. As expected, permeability increases with increasing moisture content. However, the mixes prepared using late additions of coke deviate considerably from the line. This is likely due to the different amounts of moisture available for granulation before the coke was added. Because there is less material at that stage, water would contribute more to the granulation of the mixes. The difference between Methods 1 and 2 can be also explained as due to the different relative amounts of water in the mix before the coke addition.

In the cases for different particle size distributions of the coke and limestone, the addition of coarser fines lead to more permeable mixes. This was caused by the increase in mean particle size of the raw materials. More specifically, the ratio of nucleus particles to adhering particles in the mixes was increased by adding coarse materials.<sup>4</sup>

The above phenomena relate closely to the physical characteristics of packed beds of the sinter mixes, in particular the mean granule* diameter and void fraction. Fig. 5 shows the relationship between moisture content of the mixes and mean diameters of granules which were calculated from the measured granule size distributions. Both the "arithmetic" and "surface-volume" mean diameters increase with increasing moisture content of the mixes. A slight deviation from the correlation is observed for the mixes prepared with the late coke addition. The relation of permeability to the mean diameters of granules for all mixes is shown Fig. 6. Within a certain scatter, the permeability is strongly affected by the mean diameters.

Difference of permeability can be caused by changes in not only the mean diameter but also the void fraction of the bed. Accordingly, the void fractions were calculated by substituting the applied flow rates and the surface-volume diameters into Eq. (2).

\[ \Delta P/L = 150(1 - \varepsilon)^3 \frac{d_p^2}{d_v^2} \cdot \rho_d + 1.75(1 - \varepsilon) \frac{d_p^2}{d_v^2} \cdot \rho_d \varepsilon \]

* The term granule is used in this paper to indicate an agglomerate or quasi-particle composed of particles of the raw materials.
Table 4. "Sintering time" and average heating rate from 100 to 600°C of outlet gas.

| Mix No. | Run  | Preheat temperature* (°C) | Sintering time (s) | Average heating rate (°C/s) |
|---------|------|---------------------------|--------------------|-----------------------------|
| 01      | 016  | 1020                      | 114                | 10.2                        |
| 02      | 018  | 1010                      | 106                | 10.0                        |
| 03      | 020  | 1010                      | 103                | 10.9                        |
| 04      | 023  | 1000                      | 103                | 10.6                        |
| 05      | 024  | 1000                      | 103                | 9.9                         |
| 04      | 025  | 1010                      | 125                | 9.6                         |
| 05      | 027  | 990                       | 91                 | 10.9                        |
| 06      | 028  | 1020                      | 101                | 10.0                        |
| 06R     | 030  | 990                       | 108                | 8.9                         |
| 06R     | 035  | 1010                      | 104                | 10.1                        |
| 06R     | 040  | 1010                      | 105                | 9.2                         |
| 07      | 042  | 1000                      | 97                 | 10.8                        |
| 07      | 034  | 1010                      | 101                | 9.6                         |
| 07R     | 044  | 1000                      | 91                 | 10.1                        |
| 08      | 035  | 1010                      | 94                 | 9.8                         |
| 09      | 037  | 1030                      | 140                | 6.5                         |
| 10      | 044  | 1000                      | 91                 | 10.3                        |
| 11      | 046  | 1000                      | 91                 | 10.1                        |
| 12      | 048  | 1150                      | 121                | 8.5                         |
| 12R     | 049  | 1160                      | 122                | 8.4                         |
| 12R     | 050  | 1150                      | 116                | 8.8                         |
| 12R     | 051  | 1160                      | 115                | 8.6                         |
| 13      | 052  | 1110                      | 112                | 9.4                         |
| 14      | 054  | 1140                      | 115                | 8.7                         |
| 15      | 056  | 1110                      | 105                | 10.1                        |
| 16      | 058  | 1110                      | 120                | 8.1                         |
| 17      | 060  | 1110                      | 113                | 9.5                         |
| 18      | 063  | 1120                      | 123                | 7.0                         |
| 19      | 065  | 1120                      | 162                | 4.7                         |
| 19      | 066  | 1110                      | 169                | 4.8                         |

* Preheating temperature is the initial temperature of gas introduced into the sample bed; value falls by 70 to 90°C at the end of the experiment.

Fig. 4. Relationship between moisture content in raw mix and bed permeability (in J.P.U.).

where, $JP$: pressure drop of bed
$L$: bed height
$\varepsilon$: void fraction

Fig. 5. Relationship between moisture content in mix and diameter of granules.

Fig. 6. Relationship between mean diameter of granules in mix and bed permeability.

$d_p$: particle diameter
$\mu$: viscosity of gas
$u_0$: superficial gas velocity
$\rho_g$: density of gas.

For simplicity, the shape factor of granules was taken as unity though previous work indicates that the value would probably lie in the range 0.6 to 0.7. The calculated values are presented in Table 3. As in the calculation of the J.P.U., each value represents the average of 7 results obtained for a range of different flow rates. The values vary over a small range only, 0.44 to 0.48, but there appears to be a relation with the moisture content. As shown in Fig. 7, there is a maximum value at a moisture content of around 6.8 mass%. This finding is consistent with previous work in which direct measurement of void
fraction using kerosene impregnation was attempted.

3.2. Reproducibility of the Pot Experiments and Homogeneity of Sample Beds

A certain structural inhomogeneity in bed is a characteristic of the sintering process. Accordingly, an experimental bed should be of sufficient size that reproducible values of pressure drop can be measured. The largest granules in the mixes were about 8 mm and the diameter of the bed was approximately 20 times that size while the height was nearly 4 times. Fig. 8 shows the changes in gas and bed temperatures and in pressure drop of sample beds in experiments, 0050 and 0051, which were prepared under the same conditions. The inlet and outlet gas temperatures and pressure drops agree fairly well and it is considered that the dimensions of the sample bed are sufficiently large to minimize the effects of the structural inhomogeneity.

Temperatures in the bed, especially those at the bottom, are scattered significantly. Dotted lines in the figure indicate bed temperatures measured in the plane at the bottom of the sample bed \(T_b\) at different radial positions. The lines in Fig. 8(a), run 0050, are significantly different from each other; however, those in Fig. 8(b), run 0051, are in good agreement. Measured values of bed temperature can be affected by the structural inhomogeneity. A thermocouple at the same position can give different readings in different experiments depending on the nature of the raw material adjacent to the bead; burning coke, limestone, melt, or void space. Accordingly, it is not surprising that the measured bed temperature is unreliable and independent of the dimension of the bed. Taking this fact into account, measured bed temperature can not be used in a precise analysis unless a representative temperature is obtained by taking the average of several values. In this study, the bed temperature was not directly employed for the analyses.

3.3. Temperature Pattern in the Sintering Bed

Sintering time is usually defined as the time from the start of sintering to when the bottom of the sample bed reaches a maximum temperature. However, since the measured bed temperatures were not re-

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**Fig. 7.** Calculated void fraction of the bed consisting mixes prepared with different moisture content.

**Fig. 8.** Examples of changes in bed and gas temperatures, and in pressure drop of sample bed during experiment.
producing, the time to when the temperature of the outlet gas (\(T_s\)) reached 625°C was taken as the "sintering time" in these experiments. The value of 625°C was chosen because it was the average of the outlet gas temperatures for all the experiments when the corresponding bed temperatures at the bottom reached a maximum value. The "sintering time" is a convenient criterion to estimate the usual sintering time for this experiment as seen in Fig. 9. The "sintering time" can not, of course, be referred directly to an actual process, as a specified and unchanged gas flow rate was applied during the experiments.

The values of the "sintering time" are listed in Table 4. Significant differences are observed for the mixes with different size distributions of coke (runs 0032 to 0037) and limestone (runs from 0058 to 0066) from those used in the standard mix. Fig. 10 shows the relationship between "sintering time" and surface-volume mean diameter of coke and limestone fines. It is interesting that both lines have the same trend and indicate a minimum value at a diameter of about 1 mm despite the fact that combustion of coke is an exothermic reaction but calcination of limestone is endothermic. It can be thought that this trend caused by the difference of the extent of changes in heat exchange area, in other words, specific surface area of the particles in the sintering bed when different particle size of coke and limestone are used. It suggests, therefore, certain optimum particle sizes of coke and limestone lie around 1 mm for promoting change in the sintering bed structure. It was reported that coke size in the range from 0.6 to 1 mm has the highest maximum bed temperature\(^{13}\) and this seems to be one of reasons to promote the structure change of bed.

It is evident from Fig. 8 that the shape of the temperature profile in a sintering bed is strongly reflected in that of the outlet gas in these experiments. This is because a thin sample bed and thin hearth layer was used. The average heating rate where the rate was reasonably constant, that is, the temperature from 100 to 600°C of the outlet gas in the windbox, was calculated for each experiment and the values are listed in Table 4. The sharpness of the temperature profile in the sintering bed may be judged from the magnitude of the heating rate. The relationship between the "sintering time" and the heating rate is shown in Fig. 11 and is inversely linear.

The results of mathematical consideration\(^{12}\) suggests that low heating rates produce a wide bed temperature profiles and, usually, low maximum temperatures when a constant gas flow rate is applied. These trends were observed in the measurements of bed temperature \(T_s\). Such phenomena seem to occur because larger particles have slower reaction rate due to less specific surface area, regardless of whether the reactions are exothermic or endothermic. This explanation is consistent with the observation that mixtures with late coke addition (runs 0044 and 0046) had short sintering times. The coke presented at the surface of the granules or without uncombustible particles around it reacted fast and uniformly.

### 3.4. Influence of Mix Property on Pressure Drop of Sintering Bed

It is a characteristic of sintering beds that the bed temperature stays at a stable value at any point, normally between 50 and 70°C, before the heat front passes through the point. This phenomenon was observed in these experiments, as shown in Fig. 12. In the figure, "sintering time" has been normalized so that at a value of 1 the waste gas temperature is
625°C. This procedure makes it possible to compare the results of different experiments. The temperature at the center and bottom of bed was about 55°C and stable for a certain period. During that period, the structure of the bed does not change significantly except due to the effect of moisture condensation. Since the bed in these experiments was extremely shallow, it can be assumed that the condensation effect is relatively small.

Pressure drop over the wet zone where the bed temperature is stable was estimated substituting surface-volume diameters as \( d_p \) and calculated void fractions as \( \varepsilon \) of the mixes listed in Table 3 into Ergun's equation. The heat front was assumed to progress at a constant rate, calculated as the height of the bed divided by the time when the temperature of the bottom of the bed started to rise. Therefore, the bed height of the high temperature zones (\( L_o \)), the drying, combustion, melting and sintered zones, was defined as the height of the upper bed of the heat front. The pressure drop over the high temperature zones (\( \Delta P_h \)) was calculated by subtracting the value estimated for the wet zone from the pressure drop measured for the whole sample bed. An example of the calculated pressure drop per unit height of bed (\( \Delta P_h / L_h \)) is shown as a function of the normalized time lapse in Fig. 12. Initially, the high temperature region is thin and is a zone in which bed temperature rises rapidly. The melting and sintered zones become involved successively in the region. In spite of the increase in bed temperature, \( \Delta P_h / L_h \) decreases rapidly in the early stages, then continues to decrease more gradually. This is a similar result to that found in the previous work.

The pressure drop across the high temperature zones decreases with time because the proportion of the high temperature zones occupied by the highly permeable sintered zone progressively increases from an initial value of 0%. The initial rapid decrease in pressure drop implies that the permeability of the drying zone is very low compared with the other high temperature zones.

Comparisons of the values of \( \Delta P_h / L_h \) are shown in Fig. 13 for various experimental conditions. Fig. 13(a) shows that higher moisture contents brought higher final permeabilities. Because high moisture contents give high pre-ignition permeabilities, this result suggests that some aspects of the initial bed structure survive the rearrangement of the structure in the high temperature zones. Fig. 13(b) shows that high coke concentrations led also to high permeability at the end of sintering although the mixes had contrary pre-ignition permeabilities. However, this was not so over the whole high temperature region because of higher bed temperature. Higher concentration of coke results in more heat being evolved in the bed. Consequently, a greater change in the bed structure can occur as the result of a greater degree of melting.

Fig. 13(c) shows that mixes with larger coke sizes yielded higher final permeability. This trend is consistent with the results of pre-ignition permeability of the mixes. Moreover, conversion of coke volume to "macro" void during combustion may occur to a greater extent in the case of larger coke sizes. A wide size distribution, as in the standard mix, gave lower pressure drop in the earlier stage. Both mixes prepared by late addition of coke had lower permeabilities during and after sintering than the standard mix even though the initial permeabilities were higher (Fig. 13(d)). This suggests that the coke adhering around granules detached in the course of sintering. Since coke used in the experiment was coarser than the other materials (Table 1), it might be difficult for the outer coke particles to remain on granules after drying and some might detach and block channels in the bed before combustion. Shorter "sintering times" were obtained for these mixes because of the improved combustion efficiency of coke particles at the surface of the granules. Higher maximum bed temperatures, therefore, are expected in these experiments. This contributed to the lower permeability during sintering.

There was only a small difference between mixes of different basicity in spite of the different amount of heats of calcination and melt-formation for each mix (Fig. 13(e)). A slightly lower pressure drop was observed for the mix with highest basicity (1.8) compared with the mix of lowest basicity (0.8). Since the total amount of flux (SiO2+CaO) was constant.

* A shorter "sintering time" is not consistent with a higher permeability during sintering in these experiments since the flow rate was kept constant rather than the suction in the windbox as in practical sintering.
this result suggests that the composition of the melt has only a small effect on permeability during sintering and on the final sinter cake. The effect of the amount of melt produced was not directly examined in these tests other than in the variable coke experiments but will be considered in future work. The use of larger limestone sizes resulted in higher permeability over the entire experiment (Fig. 13(f)). However, differences between -0.5 and 0.5—1.0 mm and between 1.0—2.0 and 2.0—4.0 mm, respectively, were small. This trend was the same as obtained for the pre-ignition permeability and it suggests that, as for the effect of moisture and size of materials, some structural aspects of the original bed are preserved during sintering.

4. Implications for the Sintering Process

It is known that the gas volume required for sintering is independent of flow rate, within a certain range, for a particular mixture. In other words, the propagation rate of the heat front is almost in proportion to the flow rate of the gas which is the medium of heat transfer. Therefore, the permeability of a sintering bed directly affects productivity under conditions of a practical operation because the suction pressure at windboxes is constant. Increase in the productivity can be achieved by improving the permeability of both wet and high temperature zones.

For the permeability of the wet zone, it has been reaffirmed in this work that size distribution of granules is significant. Control of moisture content in the mix seems to be reliable and convenient for controlling the size distribution. Addition of materials such as limestone and coke having a larger mean size also is effective, although it is rather difficult in practice because of constraints on supply of such materials. It was found that the late addition of coke to the granulating mix made a large improvement to the permeability of wet mix. In order to obtain an optimum permeability of given materials, it can be worthwhile considering the order of material additions, including the timing of water addition in the granulation process.

The trends observed in the results for pre-ignition permeability were substantially the same for the high temperature zones. Mixes having high pre-ignition permeability showed less pressure drop during and after sintering in the case of varying moisture content in the mixes. The effects of particle size of coke and limestone on high temperature permeability were also similar to that on pre-ignition permeability. Improvements in the permeability of sintering beds and resultant productivities which have been obtained in a practice using coarse limestone have been mainly explained by the high permeability of raw mixes.
However, an extremely high pressure drop during the present experiments was found for the mixes prepared with late coke addition technique. This is due likely to considerable detachment of coke particles from granules in the drying zone because most of the coke is present at their surfaces. To eliminate the phenomenon, a small amount of fine material could be added with the coke to act as a binder.

It had been supposed that the amount and composition of melt formed during sintering would significantly affect the bed structure during sintering. The results of the experiments, however, show that the effect of coke content and basicity on the permeability was relatively small when the total amount of flux was kept constant. This suggests that there is not much possibility of controlling the permeability of the high temperature zones by means of controlling the thermal conditions and property of the melt under the limited condition of actual sintering processes. Pre-ignition permeability, therefore, is the most important criterion for evaluating mixes for sintering.

When a large amount of “easily-melting” ore such as limonite ore, is present in a sinter mix, considerable decrease in productivity occurs. This has been found from operating experience and, as well, significant changes in bed structure have been observed in fundamental experiments. The influence of the type of ore on permeability during sintering will be examined in a subsequent series of experiment.

5. Conclusions

Raw mixes of iron ore sinter feed were prepared under a variety of conditions. The permeability of mixes before ignition and during sintering was examined using a conventional permeameter and a small sinter pot with a shallow bed, respectively. The conclusions obtained from this study are as follows:

(1) Pre-ignition permeability of the mixes was unequivocally related to the mean size of the granules irrespective of the granulating conditions. Control of moisture content in the mix is a reliable and convenient way to obtain an appropriate pre-ignition permeability. The order of permeability of mixes having different moisture contents did not change during or after sintering.

(2) The late addition of coke during granulation resulted in a higher pre-ignition permeability. This was caused by the larger amount of water contributing to granulation before the coke addition. During sintering, however, the permeability deteriorated considerably relative to mixes in which coke was granulated with the other raw materials.

(3) Use of larger particles of coke and limestone resulted in improved permeability both before ignition and during sintering.

(4) The basicity and coke content of mixes had only a small effect on the permeability of a bed during and after sintering under the condition of constant total amount of flux (SiO₂ + CaO).

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