1. Introduction

Sinter is the most important iron-bearing material in most blast furnaces in the Asia-Pacific region. It is produced from a blended mix of iron ore fines, imported predominantly from Australia and Brazil. The proportion of sinter used is dependent on factors such as blast furnace performance, overall ironmaking costs, sinter properties and chemical composition and the production capability of the sinter machines. The Pilbara iron ore industry was built around Brockman ores, which are porous hematite–martite ores. Over the last decade, there has been a significant shift in the type of iron ores exported from Australia. Currently, the region exports around 50 million tonnes of hematite–goethite pisolite ores. Mining plans are also underway to supply the market with Marra Mamba ores, which also contain significant hematite and goethite. There are concerns that ores containing goethite have a detrimental influence on sinter plant productivity.

The material flow streams in and out of a sinter machine is shown in Fig. 1 and through balancing the mass flow of the streams, sinter plant productivity can be expressed as follows:

\[ P = \frac{(hw(1-\phi)(1-\varepsilon)v-R)(1-\lambda)}{1} \]  

where,

- \( P \) is sinter plant productivity (tonnes/hr),
- \( h \) is the height of the bed (m),
- \( w \) is the width of the bed (m),
- \( \rho \) is the average density of the particles forming the bed (kg/m³),
- \( \phi \) is the mass fractional moisture content,
- \( \varepsilon \) is the fractional voidage,
- \( v \) is the sinter machine speed (m/hr),
- \( R \) is the return fines load (tonnes/hr),
- \( \lambda \) is the mass fractional volatile content or loss-on-ignition of the bed.

For a sinter machine operating at a constant bed height, return fines load and strand speed, decreasing the average particle density and increasing the loss-on-ignition value—as with the introduction of hematite–goethite ores—will cause \( P \) to decrease. Increasing the water content of the sinter mix—as is required for porous ores to achieve the same granulation efficiency—will decrease \( P \). From this analysis, it is clear that introducing hematite–goethite ores will cause deterioration in productivity if sintering time is not shortened so that machine speed can be increased.

There is also another view that sintering time in fact increases because the excessive formation of melts from hematite–goethite ores reduces permeability in the flame.
front (a full discussion has been given\textsuperscript{1}). The purpose of this paper is to measure the resistance to airflow during sintering in a laboratory pot for a number of ore blends, to understand the factors—including mix goethite content— influencing sintering bed permeability. While the experimental procedure used in this study is an improvement on the one described\textsuperscript{3}, the basis for the study is similar: involving the measurement of airflow rates before and after ignition of the bed at the same suction value. With the establishment of the flame front regions such as the drying and calcination zones are formed in the bed. It has been argued that the flame front, because of its high temperature, is the controlling zone in a sintering bed.\textsuperscript{2,4} In this study, it is assumed that this is the case and flame front properties will be used generally to reflect sintering bed properties. The difference between pre and post-ignition (or green and sintering) airflow rates provides information on the resistance of the flame front to airflow.\textsuperscript{3} The program also involved experiments to understand the parameters that influence flame front properties. In addition to determining if hematite–goethite ores have a detrimental effect on productivity, this study could also identify conditions whereby the permeability of the flame front could be improved to compensate for potential decreases in productivity caused by lower $\rho$ and higher $\lambda$.

2. Experimental Technique

Results of the initial laboratory work to measure sintering airflow rates showed quite large variability in results.\textsuperscript{3} The main contributor to variability was identified as the leakage of air between the cylindrical block of green mix/sinter and the pot wall.\textsuperscript{3} This varied between tests depending on the goethite content of the mix (which influenced the level of bed shrinkage), and possibility factors such granule size distribution and initial bed voidage. Following that test program, improvements in procedures were made to eradicate leakage so that only air flowing through the green and sintering beds is measured.

A schematic diagram of the modified loaded sinter pot prior to ignition is shown in Fig. 2. A distinctive feature is the presence of an annular layer of fine sand between the green mix and the sinter pot wall.\textsuperscript{3} This varied between tests depending on the goethite content of the mix (which influenced the level of bed shrinkage), and possibility factors such granule size distribution and initial bed voidage. Following that test program, improvements in procedures were made to eradicate leakage so that only air flowing through the green and sintering beds is measured.

As in the last program,\textsuperscript{3} airflow rate through the bed ($\text{m}^3/\text{hr}$) was determined at the inlet to the pot using a hot wire anemometer. The hood containing the anemometer sat on top of the pot and extreme care was taken to ensure that a good seal was obtained between the hood and the pot (see Fig. 2). After determining the pre-ignition bed permeability ($V_i$), the hood was removed and the bed ignited. The hood was then re-introduced to determine post-ignition airflow values ($V_s$). As the granulated mix sintered and shrank away from the pot wall, the free flowing sand ensured that no air flowed between the pot wall and the cylindrical block of material. All the measured air was forced through the flame front and un-sintered sections of the bed. The return sinter fines layer at the bottom of the annulus ensured that the voids in the hearth layer were filled and the free flowing sand did not run down into the wind box.

This method of sealing is extremely effective and Fig. 3 shows the influence of the layer of sand on the structure of the sintered cylindrical block removed from the pot. The same ore blend was used but the right-hand-side block had an annular layer of fine sand.
rough outer surface texture because the annular layer of sand had flowed downward to fill the space occupied by the thin sleeve as it was being withdrawn from the bed. Figure 3 indicates that a stronger and more homogeneous block of sinter is formed because of reduced in-leakage. Without the sand layer the shape of the flame front, toward the end of sintering, is an inverted-V. Waste gas temperature profiles are much broader and maximum temperatures are much higher with the sand layer because of reduced dilution/cooling of the air caused by in-leakage. For the same coke addition level, forcing all the air through the bed resulted in a longer sintering time and the formation of much stronger sinter. It is clear that coke rates could be decreased using this particular technique while still producing a sinter of adequate strength.

3. Materials

Table 1 shows the composition of the three ore blends used in the study. The first, HAEM, contained 93% hematites. The magnetite was included to help achieve a desired sinter chemical composition. The second blend, PISO, contained 35% pisolite ore and the third blend, PIMM, contained both pisolite and Marra Mamba ores. From earlier sinter pot tests it was found that a balanced return fines operation (i.e. returns fines balance of between 0.95 and 1.05) at comparable productivity and sinter strength could be achieved for the three blends at a return sinter fines level of 40 wt%, on ore basis. Coke requirement for the third blend was higher by 0.25 wt%, to obtain a sinter of comparable strength to HAEM and PISO for the same productivity. This is not entirely surprising considering that this blend contains 60 wt% hematite–goethite ores, which require energy for calcination. The theoretical compositions of the three sinters produced from the blends are given in Table 2. It is seen that they have very comparable chemical compositions.

Granulation of the sinter mixes was carried out in a large rotating drum. Water addition was varied to produce granules of different size distributions and, consequently, beds with different pre-ignition permeability values. The granulated mix was loaded into the sinter pot using standard procedures, which have been described in previous publications. In this program tests were carried out to determine the effect of the following on the resistance of the flame front and associated regions to airflow:

a) changing the proportion and type of hematite–goethite ore in the blend,

b) altering the ultrafines (minus 0.15 mm) content of Marra Mamba ore,

c) reducing coke level in all the sinter mixes by 0.5%,

d) coarsening the coke through using only plus 0.25 mm material,

e) increasing basicity from ~1.8 to ~2.2 with increased limestone addition,

f) increasing basicity from ~1.8 to ~2.2 with increased hydrated lime addition,

g) reducing suction from 16 to 12 kPa.

4. Results

All the results are presented graphically as plots of pre-ignition airflow rate, $V_i$ (m³/hr), versus post-ignition airflow rate, $V_s$ (m³/hr), in Figs. 4 to 8. As indicated in the earlier paper 3) the gap between the experimental results and the $V_i–V_s$ line is a function of the properties of the flame front, in particular its resistance to airflow i.e. denoted as $f(R_f)$ in Fig. 4. The experimental results showed a definite asymptotic trend, unlike the earlier results 3)—most probably because of the inclusion of an annular layer of sand between the sinter mix and the pot wall. It is possible that the

| Blend   | Hematite ore Australia | Pisolite ore Brazil | Marra Mamba ore | Magnetite | Coke (ore basis) | Return fines (ore basis) |
|---------|------------------------|---------------------|-----------------|-----------|------------------|-------------------------|
| HAEM    | 65                     | 28                  | 0               | 0         | 7                | 6.5                     | 40                      |
| PISO    | 40                     | 25                  | 35              | 0         | 0                | 6.5                     | 40                      |
| PIMM    | 26                     | 13                  | 31              | 30        | 0                | 6.75                    | 40                      |

| Blend   | Fe (total) | CaO | SiO₂ | Al₂O₃ | MgO | Basicity |
|---------|------------|-----|------|-------|-----|----------|
| HAEM    | 57.86      | 8.69| 4.82 | 1.72  | 1.51| 1.80     |
| PISO    | 57.90      | 8.78| 4.83 | 1.48  | 1.50| 1.80     |
| PIMM    | 57.75      | 8.91| 4.90 | 1.52  | 1.51| 1.82     |

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earlier results showed quite linear trends because the ingress of air at the pot wall increased with increasing grain mean size distribution (i.e. increasing $V_i$ value).

Figure 4 shows that a very similar relationship between $V_i$ and $V_s$ is obtained for the three blends, indicating that the goethite content of the mix did not influence the value of $R_f$. The gap between the experimental results and the $V_i/H_{11005}V_s$ line is also a measure of ore blend sinterability. One blend can be considered to be better than another blend in sinterability if a higher $V_s$ value is obtained at the same $V_i$ value.

Figure 5 shows that increasing the proportion of fine material—which should enhance the melt formation process—also did not alter the sinterability of the blend. Figure 6 shows that decreasing coke rate has a beneficial effect on sinterability. There are two possible reasons for this: firstly reducing coke rates reduces gas velocities and, secondly, the reduction in temperature can alter the structure of the flame front because of a reduction in melt volume and/or fluidity. It is to be expected that the dilation of gas channels in the flame front is more difficult with reduced melt volume and fluidity. If this is true reducing temperatures
should increase the value of $R_c$; but this is not the case. Results suggest that at a lower temperature, flame front resistance is lower because of lower gas velocities. The effect of using coarser coke at the lower coke addition level is also given in Fig. 6. Previous studies suggest that the use of coarser coke increases flame front temperatures but has the effect of narrowing the flame front width.\(^{1,6}\) Obtained experimental results suggest that the latter is more important, and that factors other than temperatures can influence flame front resistance.

The next set of experiments involved increasing basicity, which reduces melt viscosity and enhances melt formation. From Fig. 7, it is clear that a more sinterable mix is obtained at higher basicity. However, this could be a temperature reduction effect rather than a flame front structural effect, since energy is spent in calcining the additional limestone. To provide more information in this area, the additional lime required to increase basicity, from 1.8 to 2.2, was added in the form of hydrated lime. The results, also shown in Fig. 7, indicate that a further improvement in sinterability is obtained through the replacement of limestone with hydrated lime. These results would indicate that increasing basicity reduces the value of $R_c$ but a definitive conclusion cannot be made because it is well-known that burnt lime (which is converted to hydrated lime during granulation) improves sinter plant productivity for reasons which have not yet been fully determined.

Figure 8 shows that airflow rate decreased when suction was reduced from 16 to 12 kPa. It is clear that, as with flame front temperature, the force applied across the bed also influences the sinterability of a mix.

5. Quantifying Sinterability

For a particular ore blend, water addition during granulation was varied to produce granules of different size distributions and, hence, different $V_i$ values. To obtain the equivalent $V_i$ values for the three blends, water requirements were higher for PISO and PIMM because of the porous nature of pisolite and Marra Mamba ores. With the exception of results shown in Fig. 8, airflow rate results were determined under constant suction conditions. Coarser granules were produced at higher mix moistures and this resulted in increased bed voidage, a more permeable bed and a higher airflow rate across the bed.

In our experiments, beds are prepared to a pre-determined green bed permeability and the flame front was then introduced into the bed by ignition. Airflow velocity dropped with the introduction of the flame front because the pressure drop across the bed was kept constant and additional work was done or energy was dissipated per unit time in pushing the gases through the high temperature flame front. The drop in airflow could be used to provide a measure of the permeability of the flame front—which, in turn, provided a measure of the ‘sinterability’ of an iron ore blend i.e. of defined ore, flux and coke types and levels in the blend.

5.1. Ergun Equation

Under turbulent flow conditions (as is obtained during sintering), flow through a bed is expressed as a function of pressure drop per unit length of the bed ($\Delta p/l$) and bed properties by the Ergun equation (this is discussed in an earlier paper\(^3\)):

$$\frac{\Delta p}{l} = k \rho_g (1-\varepsilon) \frac{v^2}{D_p \varepsilon^3}$$

where $k$ is a constant, $\rho_g$ is the gas density, $\varepsilon$ is the bed voidage, $D_p$ is the granule effective diameter, and $v$ is the superficial gas velocity. For a bed of fixed length under isothermal conditions, Eq. (2) can be seen as relating the pressure drop across a bed to a bed resistance term and superficial gas flow velocity i.e.

$$\frac{\Delta p}{l} = \mathcal{R} v^2 = \frac{v^2}{\mathcal{P}}$$

where $\mathcal{R}$ and $\mathcal{P}$ are the resistance and permeability of the bed respectively. The equation indicates that when the driving force across the bed is increased, airflow velocity will increase if bed permeability remains unchanged. If bed permeability is increase while the driving force remains unchanged, flow rate will decrease. When pressure drop is kept constant, bed permeability is a function of the square of gas velocity.

If flow through both the green bed and sintering bed can be described by the Ergun equation, then the value of $\mathcal{P}$ can be determined from Eq. (3). Figure 9 shows plots of pre-ignition permeability against post-ignition permeability using the NCR and LCR data. The scatter in results is quite large around the best-fit straight lines. If the lines are assumed to have a similar slope, the intercept on the $y$-axis could be a possible indicator of blend sinterability.

5.2. Permeability Equations

As discussed in the earlier paper,\(^3\) the following equation is widely used to determine bed permeability:
Depending on the units of the variables, a BPU (British Permeability Unit) or JPU (Japanese Permeability Unit) is determined. Sintering studies also indicated that the equation could also be used for sintering beds if the value of the power coefficient is reduced to 0.5. Using these coefficients, bed permeabilities were recalculated using the NCR and LCR data and results are shown in Fig. 10. Compared to Fig. 9, the best-fit straight lines using this technique gave some improvements in $R^2$ values. Again if the lines are assumed to or made to have similar slopes the intercept could be used to provide a measure of blend sinterability.

5.3. Energy Approach

This aim of this approach is to derive an equation for the curve in Figs. 4 to 7. The gap between the experimental line and the 45° line, which is the loss in airflow per unit time, can be expected to be a function of the energy dissipated per unit time (or power, $\Omega_t$) in flowing through the flame front. If $\Delta p_t$ is pressure drop across the flame front and $V_f$ is gas flow velocity through the flame front of constant thickness then,

$$V_f - V_i = f(\Omega_t) = k_5 \Delta p_t V_f$$

since power is equivalent to the product of driving force and flow velocity, and $k_1$ is constant. If it can be assumed that $\Delta p_t = k_2 \Delta p$ (where $k_2$ is a constant smaller than unity) in all these experiments and that $V_f = V_s$ i.e. ignoring the contribution of carbon added to the flowing gases during combustion, then

$$V_f - V_i = k_3 \Delta p V_s$$

The physical significance of the constant $k_3$ (with units of m$^3$/kg) is obviously very complex and unclear at this stage. If flow through the flame front can be expressed by Eq. (2) with $l$ assumed constant, or by Eq. (4) with a power coefficient of 0.5, then

$$V_i - V_s = k_2 \Omega^3$$

In the flame front, it is possible that the gas channels can be dilated because of the presence of liquid (melts). The dilution of the channels would be a function of gas flow velocity in the channels. However, it is to be expected that a direct proportional relationship would not exist because the solid–melt mixture in the flame front would reach an incompressible state. The resistance of the flame front could be expressed as:

$$R = f(V_s^m)$$

where $m$ is likely to be a small number less than unity. Based on this evaluation the experimental curve could be described by:

$$V_i - V_s = k_3 \Delta p V_s$$

where $n=3+m$. Figure 11 indicates that, through manipulating the value of $k_s$, an $n$ value of 3 or 4 could fit the experimental NCR data quite well. For these three curves, the values of $k_s$ are shown in Table 3. If the value of $n$ is assumed constant for a range of iron ore blends, the value of $k_s$ could be used to provide a measure of blend sinterability at defined sintering conditions e.g. suction, coke rate and basicity. If it is assumed that $m=0$, values of $k_s$ that give the best-fit curve for the experimental results can be determined. Particularly good fits were obtained for the high basicity, hydrated lime, low suction and coarse coke results and $k_s$ values for $n=3$ are shown in Fig. 12. The value of $k_s$ is zero when there is no flame front in the bed, and increas-

![Fig. 10.](image1)

![Fig. 11.](image2)

| $n$ | $k_s$   |
|-----|--------|
| 2   | 4.0x10$^3$ |
| 3   | 3.2x10$^3$ |
| 4   | 3.3x10$^3$ |
as bed sinterability decreases.

6. Conclusions

In iron ore sintering, concerns have been expressed about the effect of reactive ores on the sintering bed permeability. A novel technique was used to measure the in-situ airflow rate through the beds before and after ignition, to provide information on the permeability of the flame front. A previous study indicated that in-leakage at the pot wall was a major problem, and fine sand and sinter was used to seal this region. With these changes, only air flowing through the bed was determined.

Results show that, at optimized coke and return fines level, increasing the levels of goethite in the sinter mix, sourced from pisolite and Marra Mamba ores, did not change the permeability of the flame front. This indicates that reactive ores do not have a negative impact on the permeability of the flame front. Increasing the fines content of Marra Mamba fines also did not alter flame front permeability. However, decreasing flame front temperatures improved the permeability of the flame front because of reduced gas volumes. Increasing the basicity of the blend, using limestone to source the addition lime, from 1.8 to 2.2, also improved the permeability of the flame front. Tests carried out using hydrated lime to source the additional lime showed further improvements in sintering bed permeability. The use of coarser coke benefited flame front permeability. The study also showed that the resistance of the flame front is dependent on the applied suction across the bed.

The study identified three techniques to generate single parameters, which could be used to assess the sinterability of a sinter mix. Just as the JPU is used widely to assess the granulability of a blend, sinterability could provide a measure of the resistance of the flame front and, therefore, a comparative indication of sintering time for sinter mixes granulated to the same JPU value.

Acknowledgement

The authors would like to thank BHP Billiton Iron Ore for supporting the work and David Alchin for preparing the figures.

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