Iron ore sintering blends in the Asia-Pacific contain significant levels of Australian ores which are lower in bulk density compared to Brazilian ores. This study explores the impact of further decreasing the bulk density of a fairly typical ore blend. This was done by introducing small amounts of a very porous ore into the blend. Measured decreases in bulk density were up to 3%. All the sinter quality parameters could be maintained or improved without the need to increase coke rate. Changes in sinter density results were not significant, indicating that the changes in bed bulk density did not have a significant effect on sinter porosity. The study was then extended to include a comparable blend and two hematite blends of higher bulk density. Decreasing green bed bulk density, bed shrinkage and sinter density did not have a detrimental effect on sinter tumble strength. The associated increase in porosity with the measured changes in sinter density is estimated to be up to 10%. Results showed that sinter density values obtained for the low bulk density mixes at increased coke addition were still lower than equivalent values for the hematite mixes. As expected flame front speed was dependent on post-ignition airflow rate and both these parameters influence sinter strength. Many blends studied have binders and results indicated that their inclusion into sinter mixes gave increased post-ignition airflow values.

**KEY WORDS:** iron ore sintering; pot test; bed bulk density; binders; sinter strength.

1. **Introduction**

Over the last decade, iron ore mines around the world have expanded production and new mines have also been developed to meet the unprecedented increase in steel demands, particularly in China. Generally, ores exported from Australia are lower in bulk density compared to Brazilian ores. This is because hematite is the predominant mineral in Brazilian ores while Australian ores can contain significant levels of goethite (lower in density than hematite), have higher intra-particle porosity, or both. As to be expected, the bulk density of beds formed for sintering is strongly dependent on the composition of the ore blend. The importance of bed bulk density on sinter plant performance has been discussed in many earlier publications. The basic issue is that a sinter plant operates on a fixed bed volume basis — which is the volume of the green bed laid down on the strand — but sinter production is quantified on a weight basis. To maintain sinter production tonnage, a machine operating with a lower bulk density bed will need to have a faster strand speed. Detailed discussions of whether this can be done without pushing the burn-through point beyond the sinter stand discharge end have been given in several papers. The answer is essentially affirmative because decreasing bed bulk density will increase flame front speed.

An area of concern associated with increasing flame front speed is the impact on sinter strength and size. This is because material in the bed is subjected to increasingly shorter residence times at high temperatures. Plant and sinter pot test results do not always support this concern as they show no deterioration in sinter strength, possibly, because porous ores are highly reactive and significant melt is generated very quickly and early. This also means that in the flame front the formed solid-melt-void mix has high melt volume and low solids content, which should enhance the rate of material coalescence. In contrast, dense ore particles are less reactive and the higher solids to melt ratio in the flame front will retard the coalescence process. Nonetheless, when porous ore levels have exceeded a certain limit (the value of which is dependent on the properties of the other ore components) small increases in coke addition are usually necessary to maintain sinter strength. This additional coke will restore the amount of total heat imparted to the material - essentially increasing maximum sintering temperature to compensate for the decreased residence time.

The first part of this study is aimed at determining the consequences of further decreasing the bulk density of a fairly typical ore blend. These tests were carried out a fixed burnt lime addition level. In addition to understanding the effect of decreasing bed bulk density on productivity, coke...
rate and other performance parameters, the properties of the sinter product were also characterized. This included the common quality parameters such as tumble strength, low-temperature reduction-disintegration (RI) and petrographic composition, and also the less common parameters such as particle density and porosity. The study was then extended to include three other ore blends – one very similar to the one considered but the other two have much higher bulk densities – to provide more understanding on the effect of bulk density and sintering conditions on sintering performance and sinter quality. For all the four blends, binders (burnt lime and sugar) were used in some tests.

2. Experimental

Sintering studies were carried out using the BHP Billiton sinter pot located at Newcastle, Australia. The standard technique used to assess sintering performance has been described in several publications.5–7) Airflow during sintering was determined, and to reduce leakage around the pot walls an annular layer of fine iron ore was used to seal this region.7) The composition of the four ore blends studied is given in Table 1. Blends B and P are very similar in composition. The major difference between Blends H1 and H2 is the number of porous hematite ores used: H1 has one while H2 has two. Both Blends H1 and H2 contain 7 wt.% magnetite concentrate, which would oxidise during sintering to generate heat. For this reason, coke rates obtained for these blends cannot be meaningfully compared with those for Blends B and P.

The composition of Blend B given in Table 1 can be considered to be the base case. To reduce bed bulk density a very porous ore (VPO) was introduced into this blend. As the chemical composition of VPO is very similar to the low-alumina pisolith ore in the blend (Table 1), directly substituting VPO for this pisolith ore gave no significant changes in sinter chemical composition. However, introducing even small levels of this ore had an impact on the physical properties of the ore blend and the bulk density of the green granulated bed. VPO addition rates ranged from 2.4 to 6.0 wt.% on a blended ore basis. There are five blends with different VPO levels and each has been allocated separate notations e.g., blends containing 0, 2.4 and 6.0 wt.% VPO are referred as Blends B, B2.4 and B6.0 respectively.

For the Blend B series, burnt lime addition was 2.0 wt.% on a dry total blended material basis i.e., including return fines. This is equivalent to around 3.2 wt.% burnt lime on a sinter product basis, depending on the yield of the test. The granulated mix was charged into the pot using a standard technique and bed ignition was carried out at 6 kPa. Following 1.5 minutes of ignition the suction across the bed was raised to 16 kPa. At the end of sintering, bed vertical shrinkage was determined. The granulated mix in the pot was prepared flush with the top of the pot wall for ignition. After sintering, the vertical distance between the top of the sintered block and the top of the pot wall was measured using a ruler. Shrinkage at positions adjacent to the pot wall - conforming to the four cardinal directions - and at the centre of the pot was determined. From these five values an average was calculated.

The sintered block was then gently emptied out of the pot, the fines from the annular layer removed before it was shattered by dropping from a height of two metres. The shattered sinter was a further three times from two metres to complete the stabilization process. For all these tests, return fines balanced conditions were achieved using the same level (35 wt.% on ore basis) of return fines in the sinter mix.

The same pot test procedure was used to study the sintering properties of Blends P, H1 and H2. However, an important difference in sintering condition is that the Blend B series used a lower bed height of 570 mm compared to 600 mm for Blends P, H1 and H2. For these three blends, return fines balanced operation was achieved in every case at a fixed addition level (of 39 wt.% on an ore basis) in the sinter mix – higher than the Blend B series even though the bed height was higher. For all the tests involving burnt lime addition, levels were fixed at 0.5 wt.% on a dry total blended material basis, which is equivalent to around 0.75 wt.% on a sinter product basis. This level of burnt lime is much lower than that used in the Blend B series. For tests involving sugar as binder, a 10 wt.% sugar solution was used in place of plain water for granulation. This meant that the total level of added sugar was not fixed on a blended material weight.
basis but depended on the amount of water added during granulation.

For the Blend B series representative aliquots of the shattered sinter particles were removed for characterization. Sinter tumble strength, low-temperature reduction degradation and reducibility were quantified, as was the density of sinter particles. A microscopy technique was used to determine the volumetric composition of the phases and minerals in sinter. This involved setting a crushed sample, representing material from a range of size fractions, in resin and polishing to obtain a smooth surface for modular analysis under a microscope. Sinter particles in the size range of plus 10 minus 12.5 mm were also characterized for density. The reported technique of weighing a large number of particles in air and then submerged in peanut oil was used. Reducibility, low-temperature reduction-disintegration and mineralogy were not characterized for the sinters produced from Blends P, H1 and H2. A total of 41 acceptable sinter pot tests are considered in this study. In every case the sintering results and tumble strengths of these tests are discussed. Particle density was not determined for every product sinter.

3. Blend B Series

3.1. Sintering Performance

Table 2 summarizes all the results for the Blend B series.

Table 2. Results for Blend B series.

<table>
<thead>
<tr>
<th>Blend</th>
<th>B</th>
<th>B2.4</th>
<th>B3.6</th>
<th>B4.8</th>
<th>B6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Green bed properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mix moisture, wt.%</td>
<td>6.4</td>
<td>6.8</td>
<td>6.9</td>
<td>6.9</td>
<td>6.9</td>
</tr>
<tr>
<td>Coke level in sinter mix, wt.% ore basis</td>
<td>4.01</td>
<td>3.82</td>
<td>3.82</td>
<td>3.86</td>
<td>4.01</td>
</tr>
<tr>
<td>Green bed bulk density, t m⁻³</td>
<td>1.93</td>
<td>1.90</td>
<td>1.90</td>
<td>1.89</td>
<td>1.87</td>
</tr>
<tr>
<td><strong>Sintering results</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flame front speed, mm min⁻¹</td>
<td>23.6</td>
<td>24.4</td>
<td>25.0</td>
<td>25.2</td>
<td>25.2</td>
</tr>
<tr>
<td>Average bed shrinkage, mm</td>
<td>85</td>
<td>95</td>
<td>105</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>Yield, wt.%</td>
<td>63.8</td>
<td>64.5</td>
<td>62.8</td>
<td>65.9</td>
<td>65.0</td>
</tr>
<tr>
<td>Productivity, t m⁻³ day⁻¹</td>
<td>37.0</td>
<td>37.7</td>
<td>37.7</td>
<td>36.5</td>
<td>38.7</td>
</tr>
<tr>
<td>Coke rate, kg t⁻¹</td>
<td>62.8</td>
<td>59.1</td>
<td>60.8</td>
<td>60.8</td>
<td>61.6</td>
</tr>
<tr>
<td><strong>Bulk sinter quality parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tumble strength, wt.% +6.3 mm</td>
<td>68.4</td>
<td>67.0</td>
<td>68.3</td>
<td>68.5</td>
<td>68.8</td>
</tr>
<tr>
<td>RI, % R</td>
<td>77.5</td>
<td>78.6</td>
<td>76.9</td>
<td>75.2</td>
<td>75.1</td>
</tr>
<tr>
<td>RDI, wt.% -3 mm</td>
<td>29.6</td>
<td>26.4</td>
<td>27.5</td>
<td>24.9</td>
<td>25.1</td>
</tr>
<tr>
<td>Sinter density, t m⁻³</td>
<td>3.64</td>
<td>3.60</td>
<td>3.64</td>
<td>3.65</td>
<td>3.61</td>
</tr>
<tr>
<td><strong>Sinter mineralogy (vol.%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary hematite</td>
<td>24</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>Secondary hematite</td>
<td>14</td>
<td>17</td>
<td>16</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>Magnetite</td>
<td>11</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>SFCA</td>
<td>39</td>
<td>40</td>
<td>40</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>Dicalcium silicate</td>
<td>8</td>
<td>6</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Glass</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Others</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

On completing the base case test (Blend B), VPO was introduced into the blend at varying levels. The aim of all the tests involving VPO was to achieve productivity and sinter strength values comparable to those for Blend B, under return fines balanced condition. The three variables manipulated to achieve this aim were mix moisture, coke addition level and return fines level in the sinter mix. Clearly, with increasing levels of VPO, mix moisture had to be increased to maintain green bed permeability and obtain a productivity value comparable to the base case. On meeting this requirement, coke and return fines levels were sometimes altered to produce sinters of comparable strength to the base case sinter and achieve balanced return fines condition. In most cases, the accepted test for each blend was repeated to ensure that results were reproducible. Reported results are averaged values for the two tests.

The sintering results shown in Table 2 were obtained without the need to alter the return fines level established for the base case i.e., for all the tests the ratio of return fines in mix to return fines generated on stabilizing the product sinter was in the region of 0.95 to 1.05. Coke addition levels in the green sinter mix were only slightly different between the blends. This was done primarily to obtain sinter strength values more comparable with the base case. Table 2 confirms that with increasing levels of VPO the bulk density of the green bed decreased.

The expectation that a lower green bed bulk density would result in increased flame front speed is corroborated. Productivity values for blends containing VPO were generally slightly higher than the base case which meant that the increase in flame front speed more than compensated for the decrease bed bulk density. Coke rates for the tests with VPO were slightly lower, and results generally corresponded to coke addition levels in the sinter mix. In Table 2, sinter strength values can be assumed comparable with the exception of the test with 2.4 wt.% VPO. Higher sinter strength would have been obtained if coke addition level was higher than that used in the test. Overall, it is clear that with finer adjustments to mix moisture and coke level in the sinter mix more comparable productivity, coke rate and sinter strength vis-à-vis the base case would have been obtained.

3.1.1. Flame Front Resistance

An important measure carried out during sintering was the determination of airflow rates through the bed before \(V_g\) and after \(V_s\) ignition. Through graphing these two parameters, flame front resistance can be determined. The airflow results for the Blend B series are shown as filled circles in Fig. 1. There were other balanced tests where mix moistures were outside the target values, resulting in productivity values that were unacceptably different compared to the value obtained for the base case. Airflow rates for these tests are also shown (unfilled circles in Fig. 1) but all other results from these tests will not be considered in further discussions.

The developed theoretical expression below shows the relationship between \(V_g\) and \(V_s\).

\[
V_s = V_g - k_5 V_g^3
\]

On assuming various values for the single variable \(k_5\), a
increases with increasing pre-ignition airflow rates. The $k_5 \times x = y$ line. It is seen that the resistance of the flame front and can be quantified by the value of $k_5$. Graphically the value of $k_5$ determines the gap between the data points and the $x = y$ line. It is seen that the resistance of the flame front increases with increasing pre-ignition airflow rates. The $k_5$ value of the drawn curve is lower than values reported in recent studies but is comparable to that obtained in an earlier study for a sinter mix with 1.8 wt.% burnt lime addition on a dry material blended basis. In that study, it was concluded that burnt lime reduced the resistance of the flame front to airflow, resulting in a lower $k_5$ value. A direct consequence of reducing flame front resistance was increased airflow rate and flame front speed.

### 3.1.2. Sinter Quality

Table 2 shows that the reducibility results of all the sinters are excellent as are their RDI values. Sinter phase and mineral compositions are shown in the same table. A common characteristic of these sinters is their high SFCA content. A large proportion of these are the fine fibrous types, which would have contributed towards the reducibility of the sinters. Increasing flame front speed would reduce the amount of heat imparted to the solids but this did not have an impact on sinter mineralogy. As a major cause of sinter RDI is the level of porous hematite present, it is not surprising that these sinters have comparatively low RDI values. Without further study it is not possible to explain how sinter RDI improved with increasing VPO addition.

Sinter particle density results obtained using the plus 10 minus 12.5 mm sample are also shown in Table 2. Approximately 500 g of sinter is used in the determination of sinter density. There are no significant differences between the results suggesting that at the bulk or macro-level the lower bulk density beds did not produce more porous sinters. It is possible that more accurate techniques may be able to pick up differences between these sinters. On the other hand, it is important to note that the variability in results will be large because the batch of sinter used for characterization would contain particles originating from different regions of the bed and, therefore, formed under different temperatures. Possibly, the only accurate method of determining if sinter density has changed for the tests is to use samples from the same known positions in all the beds. This technique was adopted in a recent study.

### 4. All Blends

Two approaches will be used to discuss all the other results obtained in this study. Some will be segmented to provide a clear direct comparison between Blends B and P. This analysis will be aimed at understanding the effects cause by differences in sintering conditions for two ore blends of comparable compositions. The second analysis used will consider all the results (Blends B, P, H1 and H2) simultaneously to determine how major changes in bed bulk density, resulting from ore blend compositional differences, altered results.

#### 4.1. Airflow

Although the ore blend compositions of Blends B and P appear not very different there are important subtle differences in sintering conditions. These are summarized in Table 3. It is to be expected that the differences in return fines, coke and burnt lime levels, flux types and bed height will have an impact on flame front temperature, bed permeability and the value of the flame front resistance.

**Figure 2** compares airflow rates for the two blends. Results for Blend P tend to be below those for the Blend B series. As discussed, the curve shown in Fig. 2 is for the Blend B series and has a $k_5$ value of $1.8 \times 10^{-5}$. For a fixed abscessa value, Blend P has a lower ordinate value indicating that the flame front generated during the sintering has a higher resistance (i.e., a larger $k_5$ value). Studies have shown that flame front resistance is independent of ore blend composition but is a strong function of coke level in the sinter mix and process conditions such as suction. The higher bed height used for Blend P would have an impact on increasing the flame front resistance (Table 3). The airflow results for Blends H1 and H2 are available but not shown in this paper. In every case the positions of the data points are below the drawn line, indicating that airflow resistance values are higher than that determined for the Blend B series. Likewise, the high bed heights used for Blends H1 and H2 would have contributed towards this.

**Figure 3** shows the strong proportional relationship between post-ignition airflow rate and flame front speed. A line is drawn through the data points to illustrate the trend indicated by the data. This is an expected relationship because convective heat transfer drives the flame front down the bed. A close examination of the results indicates that, of the seventeen data points on or below the drawn line, three are for the Blend B series while the rest are results for either Blends H1 or H2. That for a fixed post-ignition airflow, blends containing denser ores have lower flame front speeds is to be expected.
4.2. Bed Shrinkage

All beds shrink during sintering, some more than others. To form sinter of comparable porosity, lower bulk density beds will have to shrink more. Bed shrinkage is an outcome of material coalescing and densifying at high temperatures. The process is a function of temperature and properties of the solid-melt-gas/void mix formed in the flame front. Increasing coke addition will increase melt volume and reduce the viscosity of the melt formed in the flame front. Both these factors will enhance coalescence resulting in more severe bed shrinkage and the formation of sinter of higher particle density. At the same flame front temperature, low bulk density beds will shrink more because the (porous) ores assimilate more readily, leading to increased melt formation.

For the Blend P tests, obtained bed bulk density values (1.86 to 1.92 t m$^{-3}$) are within the range observed for the Blend B series (1.86 to 2.02 t m$^{-3}$). These values are lower than those obtained for Blends H1 and H2, which are 1.98 to 2.07 and 2.07 to 2.12 t m$^{-3}$ respectively. Bed shrinkage results for the four blends are given in Fig. 4. As the Blend B series used a lower bed height of 570 mm, shrinkage results obtained for 600 mm beds were normalized by multiplying with a factor of 570/600. The Blend B series and Blend P used different coke addition levels (Table 3) and this is expected to have an influence on bed shrinkage results. The two high bulk density ore blends H1 and H2 did not shrink as much, which is to be expected.

4.3. Sinter Density

Sinter density results are expressed as a function of green bed bulk density in Fig. 5. These results are consistent with the shrinkage results given in Fig. 4. The green bed bulk density values for Blends H1 and H2 are the highest and in spite of low shrinkage values resulted in the production of denser sinters. On comparing the Blend B series results with Blend P, it is seen that their starting green bed densities are not too different but higher shrinkage resulted in the formation of denser sinter particles. In an earlier study it was

Table 3. Differences between the Blend B series and Blend P and their effect on the flame front resistance.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Blend P compared to the Blend B series</th>
<th>Effect on flame front property</th>
<th>Effect on flame front resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke</td>
<td>↓ – 0.5 wt.%</td>
<td>↓ temperature</td>
<td>↓</td>
</tr>
<tr>
<td>Sinter basicity</td>
<td>limestone, ↑ 0.3 kg per 100 kg of dry mix</td>
<td>↓ temperature</td>
<td>↓</td>
</tr>
<tr>
<td>Sinter MgO</td>
<td>dolomite, ↑ 1.0 kg per 100 kg of dry mix</td>
<td>↓ temperature</td>
<td>↓</td>
</tr>
<tr>
<td>Return fines</td>
<td>↑ 5 wt.%</td>
<td>↓ temperature (already considered under ‘Coke’)</td>
<td>–</td>
</tr>
<tr>
<td>Burnt lime</td>
<td>↓ 1.5 wt.%</td>
<td>↓ permeability</td>
<td>↑</td>
</tr>
<tr>
<td>Bed height</td>
<td>↑ 30 mm</td>
<td>↓ suction gradient</td>
<td>↑</td>
</tr>
</tbody>
</table>
pointed out that the density of ore particles (mineral type and intra-porosity) and inter-particle porosity determine bed bulk density. Denser sinter is produced when both these forms of pores are removed during the coalescence process. For beds of comparable inter-particle porosity and heat input during sintering, increasing intra-porosity will result in the formation of more porous sinter. For this reason, it is to be expected that denser sinters will be always be obtained from hematite ores because of their lower ore intra-porosity values.

4.4. Sinter Strength

Figure 6 shows that there is no general relationship between sinter tumble strength and sinter porosity. This figure could suggest that fine pores in sinter particles have an impact on sinter particle density but not necessarily its tumble strength. A firmer conclusion cannot be made because tumble strength is determined using the plus 6.3 minus 40.0 mm fraction while sinter density was determined using only the plus 10 minus 12.5 mm particle size range.

Sinter tumble strength will also be influenced by sinter mineralogy. For the Blend B series sinters, Table 2 shows that they have very similar petrographic composition results.

A close examination of the results obtained for the Blend B series - data points for ‘Burnt lime (2.0 wt.%)’ in Fig. 6 - suggests that it may be reasonable to draw a straight line through them. There are, nonetheless, some data points that are quite far from this line.

5. Discussions

5.1. Differences between Blends B and P

The major differences between these two blends are given in Table 3. Blend B uses a higher coke addition level and this should increase flame front temperature and its resistance to airflow. The basicity and MgO contents of a sinter have an impact of flame front temperature because limestone and dolomite both require calcination. Even though Blend P has a lower basicity compared to Blend B (by 0.2), the amount of limestone in the mix for Blend P is higher. This is because a high proportion of lime for Blend B is added in the form of burnt lime – 2.0 compared to 0.5 wt.% burnt lime for Blend P. The net effect of this is that Blend P uses higher limestone level, of 0.3 kg in 100 kg of dry charge. The MgO in sinter is sourced equally from dolomite and serpentine. As for limestone, energy is utilized to calcine dolomite. Blend P sinter is higher in MgO and this is achieved by additional 1.0 kg more dolomite (from 0.3 to 1.3 kg) in 100 kg of the dry sinter mix. Increasing limestone and dolomite levels will reduce flame front temperatures and decrease flame front resistance.

Return sinter fines addition expressed on an ore basis will have an impact on bed temperatures because higher addition levels will reduce coke levels on a total blended ore basis. However, this aspect has been taken into consideration through expressing coke addition on a total blended ore basis. Return fines balance and sinter strength were not controlled but allowed to float. Such tests were directed at understanding the fundamentals of sintering rather than simulate a commercial operation. The clear advantage of such tests is that results are easy to interpret because only one variable is altered at a time. The sintering conditions for the four blends in this study are not similar. Results from this study and a previous study show that small changes in return fines level, basicity can have an impact on factors such as flame front resistance values. This means that if such differences are not taken into consider-
ation, it will be impossible to interpret sinter pot test results with a view to understand the fundamental factors controlling the process.

5.3. Effect of Binders

Burnt lime is used very widely throughout the world to improve sinter plant productivity. In particular, ore blends containing significant fine materials (e.g., concentrates) need burnt lime to achieve reasonable productivity levels. Generally, the law of diminishing returns holds in that productivity increases diminish with increasing burnt lime levels and beyond a certain level no further benefits are obtained. Some papers have reported improvements in granulation with burnt lime addition but others have suggested no benefits in this area. The study of flame front resistance strongly indicates that the benefit of burnt lime is related to improvements in the permeability of the flame front. How this is achieved is not clear. It is very likely that at inter-particle contact points burnt lime (in a transformed state) bridges and reduces the disintegration of granules e.g., during drying and calcination and, thereafter, in the flame front. If this is true then it is not surprising that burnt lime addition will result in the formation of a more permeable flame front during sintering.

The effect of binders on sinter density is shown in Fig. 7. These results do not indicate that binders caused the formation of lower density i.e., more porous, sinters. This means that the higher bed porosity in the flame front has not resulted in increased sinter porosity. A possible reason is that with the departure of the flame front the material continues to coalesce and this has wiped out these small differences in porosity in the flame front.

5.4. Shrinkage and Sinter Density Measurement

This study has shown that bed shrinkage can vary quite significantly between tests. Differences in bed shrinkage are only evident and significant between the blends i.e., Blends B or P compared to Blend H1 and H2. For a particular ore blend shrinkage results do not reflect changes in test conditions, possibly because the variability in shrinkage results is high. When the structure of a sintered bed is examined very large horizontal (layered) shrinkage cracks are often observed (Fig. 8). During sintering the continuous or continual dropping of the top sintered section to fill such cracks will manifest as vertical shrinkage. Figure 8 indicates that not all horizontal shrinkage cracks are filled. A likely reason is that these cracks do not run across the entire cross section of the pot because the flame front does not stay perfectly horizontal and uniform right down the bed. When this happens, at any position down the bed there is an ample amount of sufficiently strong solidifying sinter around these cracks to help hold up the upper sintered section. Of course, the chances of the upper sintered section dropping will be higher if the formed shrinkage cracks are larger or more numerous. Larger cracks will also form if original bed porosity is higher (i.e., low bulk density mix) or if coalescence is increased (e.g., because of higher temperatures). It is, therefore, not surprising that bed shrinkage is a strong function of coke level in the sinter mix (Fig. 9) and also the properties of the ore blend. However, it is to be noted that the equivalent coke in mix values for Blends H1 and H2 would be higher than values indicated in Fig. 9 because both blends contain 7 wt.% magnetite concentrates (Table 1), which would oxidise during sintering to generate heat.

Fig. 7. Sinter density results for Blends P, H1 and H2 with and without the use of binders.

Fig. 8. Photograph of a binary image sintered bed (pores are black and solids are white) to show near-horizontal large cracks in its structure. Width of figure 300 mm.

Fig. 9. Relationship between coke in the sinter mix and the average bed shrinkage after sintering.

9)
5.5. Sinter Tumble Strength

Figure 6 indicates that there is no strong correlation between sinter density and tumble strength. Tumble strength is a very complex parameter and depends on factors such as the ores and fluxes in blend, the heat treatment process and reactions in the flame front, the phases and minerals that precipitate out of the melt, and cooling rate. This suggests that it is difficult to correlate sinter strength to ore blend or process variables independently. In the literature, arguably the most successful correlation has been obtained between tumble strength and the sintering temperature profile parameters, as the profile is basically what the material ‘sees’ as the flame front passes over it. The properties of the flame front is determined by many parameters such as coke level in the sinter mix, airflow through the bed (which strongly influences convective heat transfer down the bed) and flame front speed (a function the rate of heat transfer down the bed, the thermal capacity of the solids and bed bulk density).

In Fig. 4 it is seen that the lowest and highest green bed bulk densities are 1.82 and 2.11 t m\(^{-3}\), a difference of around 16.5%. These beds produced sinters particles with particle densities ranging from 3.41 to 3.68 t m\(^{-3}\) (Fig. 6), an 8% difference between the lowest and highest values. It is clear that blend properties is not the only reason for this; coke level in the sinter mix clearly had an influence. However, from Fig. 6 it is clear that Blend P which uses lower coke rates produced the low density sinters. This change in sinter density did not have a discernible effect on sinter tumble strength (Fig. 6). On assuming the solid in sinter has a density of 4.42 t m\(^{-3}\), the change in sinter density value is equivalent to an increase in sinter porosity of around 20 to 30%. In spite of this large change, there is no indication that there is any relationship between sinter tumble strength and sinter density, probably because the addition pores in the low density sinters are fine and did not weaken the sinter structure.

Attempts were made to explore the other factors that influence tumble strength. Parameters that determine heat generation and the thermal treatment experienced by the solids were chosen for consideration. Results are given in Fig. 10, with airflow rate and flame front speed chosen as the independent variables. Another measure of sinter strength could also be yield which is the percent competent sinter.
(plus 5 mm) generated after the stabilization process. As correlations against yield are not as good, only results involving tumble strength are shown in Fig. 10. Even then the scatter in results is quite large; for this reason lines are included in the figure to show only indicative trends.

It is not surprising that Fig. 10(a) shows no correlation between coke in the mix and tumble strength. In this figure only the results for the Blend B series and Blend P are shown. The range in tumble strengths for the two blends is very similar in spite of the differences in sintering conditions shown in Table 3 and sinter density (Fig. 5). For low bulk density blends it appears that changes in sinter porosity only has a small impact on tumble strength. In Fig. 10(b) the results for all the sinter tests are shown and confirm that coke level in a sinter mix alone does provide any indication of sinter strength.

For the Blend B series, decreasing the bulk density of the bed by around 3% did not result in significant changes in sinter density or tumble strength. The spread in sinter density results shown in Table 2 would suggest that the variation in sinter density from the top to the bottom of a sintered bed is larger than the effect of bed bulk density. In Table 2 measured sinter density ranged from 3.61 to 3.65 t m$^{-3}$. On assuming the material in sinter has a density of 4.42 t m$^{-3}$ (obtained from an earlier study), this range in sinter density is equivalent to a sinter porosity range of around 21.0 to 22.5%. Even if this change is significant, it is to be expected that many of these additional porosity is present as fine pores which are not detrimental to sinter bulk properties.

Figures 10(c) and 10(d) shows that post-ignition airflow rates correlate better with tumble strength compared to flame front speed. This is somewhat surprising because flame front speed directly influences the time that solids are subjected to high temperatures. The longer the residence time the stronger the sinter and this is fully in line with expectations. While airflow rate has a major influence on flame front speed, for the same airflow rate (i.e., same bed porosity) flame front speed will be higher for a lower bulk density bed. This means that flame front speed should incorporate more of the factors that determine the solids heat treatment process compared to post-ignition airflow rate.

The final two figures in Fig. 10 are attempts to take into consideration the quantity of heat generated from coke combustion and the rate at which this is transferred out by convection. Increasing coke in the mix should increase heat generation in the flame front and sinter strength. On the other hand increasing both airflow rate and flame front speed will increase the rate at which heat is transferred out of the front, which should have the opposite effect on tumble strength (Figs. 10(c) and 10(d)). The abscissae of Figs. 10(e) and 10(f) reflect proportional relationship with one variable (coke level) and inversely proportional relationship with the other variable (post-ignition airflow rate). However, it does not appear that this more complex approach improved the correlations. Figures 10(c) and 10(e) involving airflow rates probably gave the best relationships. Studies on the factors that determine sinter tumble strength will be explored further in future studies.

6. Conclusions

A. Blend B series work involved decreasing the bulk density of an ore blend through substituting a porous ore with a very porous ore.

i) With no changes in coke addition levels, decreasing bed bulk density increased flame front speed but this did not have any significant impact on sinter mineralogy or any detriment effect on sinter properties. Sinters of excellent strength, reducibility low-temperature reduction degradation properties can be produced from low bulk density blends.

ii) Decreasing the bulk density of the bed by about 3% did not have a significant effect on sinter density. A likely explanation is that the variation in sinter density from the top to bottom of a sintered bed (caused by differences in temperature) is much greater than the effect of bed bulk density changes. Measured bed shrinkage results are too variable and cannot confirm if bed shrinkage increases at decreasing bed bulk density.

iii) When sintering these blends the formed flame front has a very low resistance to airflow value. A major contributor to this is the 2 wt.% burnt lime in the sinter mix. Past studies have shown very similar values at burnt lime addition levels of 1.8 wt%. A lower flame front resistance means improved sintering bed permeability and the outcome is higher plant productivity.

B. The ore types and their levels in Blend P are very similar to that of the Blend B series. However, there were major differences in processing conditions between the two blends.

i) The lower levels of burnt lime (0.5 c.f. 2.0 wt.%), and higher bed height for Blend P (570 c.f. 600 mm) would have the effect of increasing its flame front resistance value. On the other hand, Blend P has a lower level of coke in the sinter mix (by about 0.5 wt.%) and lower limestone level (0.3 kg less limestone in 100 kg of sinter mix), which should result in a lower flame front resistance value. Experimental results show that Blend B has a lower flame front resistance compared to Blend P, possibly indicating that the influence of burnt lime and suction gradient are greater than the contribution of the other parameters.

C. There are major differences in bed bulk density between the four blends studied because they contain different levels of dense Brazilian hematites and Australian hematites.

i) Higher bulk density blends gave reduced bed shrinkage on sintering. For the two lower bulk density blends, bed shrinkage increased with increasing coke addition rates.

ii) Bed shrinkage and sinter density results can be quite variable. Nonetheless the differences in values are large enough to indicate that there is some relationship between these two parameters.

iii) Results indicate that binders decreased flame front resistance through increasing the porosity of the three-phase mix in the flame front. However, this did not appear to have any impact on bed shrinkage and sinter density.

iv) From the range in results obtained, estimates indicate that decreasing the bulk density of the bed by 16.5% resulted in 8% decrease in sinter density (from 3.68 to 3.41
to $t \text{m}^{-3}$). On assuming the solid in sinter has a density of $4.42 \text{t m}^{-3}$, a 3% decrease in sinter density is equivalent to an increase in sinter porosity of around 20 to 30%. No discernible decreases in sinter tumble strength accompanied this increase in porosity. An important conclusion of this finding is that for low bulk density beds, attempts should not be made to produce sinter of the same density as those from high bulk density bed. Lower bulk density sinters are preferred blast furnace feeds because of their higher reducibilities.

v) Many of the factors that influence sinter quality are not quantified in this study. Results of this study show that a factor which has a strong influence on tumble strength is the post-ignition airflow rate. This indicates that the rate of convective heat transfer down the bed influences heat imparted to the bed and, therefore, the strength of the product sinter.

Acknowledgements
The authors are grateful to BHP Billiton for funding the work and permission to publish this paper and Mr Gareth Penny for preparing the figures.

REFERENCES