Fundamental Insights into the Sintering Behaviour of Goethitic Ore Blends

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The main purpose of this paper is to examine the effect of altering the sintering parameters—viz., bed height, suction, and the levels of return fines, coke, mix moisture, and limestone—of two blends, one containing over 50 mass% pisolite ore and the other 50 mass% pisolite ore and 30 mass% Marra Mamba ore. Pre- and post-ignition airflow rates were determined together with the traditional performance measures i.e., sintering time, yield, productivity, coke rate and sinter tumble index. Results from such a study provide useful information on tolerable variations in the sintering process parameters and insights into which are the more important parameters controlling sinter plant performance. Sinter pot test results show significant changes in airflow rates and sintering performance when the sintering parameters were altered, although the two blends did not always respond in the same manner. Many of the obtained relationships (e.g. increasing bed height results in the formation of stronger sinter) are well known, but in this study explanations on why and how the relationships exist are given. It is clear from this study that the temperature of the flame front, which has a significant influence on flame front permeability and the melt formation process, has a very large influence on sintering performance and the strength of the ensuing sinter product.

KEY WORDS: sinter pot test; goethitic ore blends; productivity; coke rate; sinter strength.

1. Introduction

Over the last fifteen years, two attractive iron ores containing significant levels of goethite have been made available to the marketplace. Iron ore sintering blends used in Asia have changed dramatically and most now include a very high level of pisolite ore. Marra Mamba ores have come onto the marketplace more recently and most mills are using or intent to use a significant level of the ore type as well.

Sinter pot testing is an extremely important means of obtaining relevant information on the sintering properties of ore blends before they are evaluated on a full-scale plant. Pot tests are also widely used to provide information on how sinter plant performance can be improved. At the Newcastle Technology Centre (NTC) of BHP Billiton Technology, pot tests are mainly used to understand the link between fundamental iron ore properties and sintering performance, and also as a research tool to understand the sintering process. To meet these specific requirements, which are more demanding that normally expected of pot tests, all our experiments have to be carefully controlled and executed. In addition, adopted standard procedures have to simulate commercial plant operations reasonably well.

This paper is an extension of studies reported in the accompanying paper, “Fundamental Factors Determining Laboratory Sintering Results”, published in this ISIJ International issue. The reader is asked to refer to this paper for details of the sinter pot test procedure used at NTC, and definition of terminologies e.g., return fines balance and the difference between coke level in a sinter mix and coke rate. It is important to note that the addition levels of sinter return fines and coke in a sinter mix are all carried out on ore basis. Earlier work carried out at NTC\(^2\),\(^3\) has shown that the permeability of the flame front is an extremely important variable in sintering and can be used to define the ‘sinterability’ of a sinter mix, just as Japanese Permeability Units (JPU) is widely used to characterise the permeability of a green bed. The ‘sinterability’ of a blend can be quantified if the difference in airflow rates through the bed before and after ignition is known.

To accurately measure airflows during sintering, a modified laboratory sintering technique,\(^1\)\(^2\)\(^3\) was used. This technique is different to conventional pot tests in that it incorporates an annular layer of fines around the pot walls to reduce the ingress of air there—thereby giving more accurate measures of pre- and post-air volumes flowing through the bed. A hot wire anemometer located in a hood seated on top of the sinter bed measures both the pre- and post-ignition airflow rates. It is important to note that sintering results obtained with and without the annular layer of fines are very different.\(^1\)

In a sinter pot test, the controllable variables are the sinter mix moisture, the mass% coke and return fines added to the sinter mix. During a test, suction, airflow rate and waste gas temperature are monitored continuously. After burn-through, indicated by the peak in the waste gas temperature profile, the sinter block is stabilized by dropping four times...
from two metres. The sinter is screened to determine yield, and appropriate aliquots from the different size fractions are then removed for strength characterisation in a tumble drum. Productivity (tonnes per square metre of grate per day) and coke rate (kg coke required to produce a tonne of sinter) are calculated using the obtained information.

The main purpose of this paper is to provide information on the sintering behaviour of a two blends—one containing 50 mass% pisolite ore (Blend P), and the other 50 mass% pisolite ore and 30 mass% Marra Mamba ore (Blend M30). The composition of the two blends is given in Table 1, while conditions used in sintering these blends are given in Table 2. Table 1 also shows that the sinters formed from the two blends have very similar chemical composition. For all the pot tests carried out in this study, the fundamental parameters together with productivity, coke rate and sinter strength results are presented as bar charts. It has been shown that changes in the fundamental parameters—viz., mix moisture, coke and return fines level in the sinter mix, pre- and post-ignition airflow rate—can explain changes in sinter pot productivity and coke rate, and sinter strength.1)

2. Effects of Varying Control Parameters

In the accompanying paper,1) it was shown that when Marra Mamba ore was introduced into a blend containing 50 mass% pisolite ore increases in mix moisture and coke additions were required to maintain pre-ignition airflow rate, productivity and sinter strength. On an operating sinter machine, sinter return fines level, coke addition and mix moisture are controlled but daily variations can be significant. In this section, the effect of variations in these parameters on sintering performance is assessed. As sinter plants operate using different bed heights and suction, the influence of these two parameters were also studied to determine if certain plant conditions favour the performance of one blend over the other.

2.1. Effect of Return Fines Level

Sinter return fines is an interesting blend component. It contains significant low-temperature phases formed from reactions between ores and fluxes. It is possibly that the energy required to bond this material into the sinter structure could be lower than that required for ore particles of similar mass. To obtain a greater understanding of how return fines influence the sintering process, the level of return fines in the granulated mix was altered while keeping green and sintering airflow rates constant and maintaining return fines balance.

Two sets of results for Blend M30 are given in Fig. 1. Both tests are in balance: 0.96 and 1.03 for the tests with 29 and 27 mass% return fines addition respectively. This means that for the test containing lower return fines the mass% coke per unit mass of sinter mix is higher and this...
should result in higher maximum flame front temperatures (a discussion of what is the flame front and the effect of flame front temperature on its permeability and speed has been given\(^1\)). A 2 mass% change in return fines addition did not alter the green and sintering airflow rate, suggesting comparable maximum flame front temperature. This can come about because only a small amount of energy is required to melt and bond return fines into the sinter structure. This energy is the irrecoverable energy component of the assimilation process, principally that required to break down the solid ore lattice structure and does not include the recoverable sensible heat used to raise material to assimilation temperatures.\(^3\)

The sintering time was slightly faster at increased return fines level even though the sintering airflow rates were similar, probably because return fines have a lower density and thermal capacity compared to the materials it displaced in the sinter mix. Even though the change is not very significant, Fig. 1 shows that the increased yield did not improve the tumble index.

The information in Fig. 1 is a good example of two acceptable tests giving slightly different results because of slight changes in the level of return fines. For this reason, it was suggested that comparable sinter strength and a balanced operation can be achieved using more than one combination of coke level in the sinter mix, return fines and mix moisture levels.\(^2\) Tightening the specification for return fines balance, for example from 0.95–1.05 to 0.98–1.02, will certainly improve the ability to measure differences in performance between blends.

These results show that plants should aim to control return fines addition rates as stably as possible because small fluctuations in return fines addition will have an impact on yield, productivity and tumble strength.

### 2.2. Coke Level

The level of coke in a sinter mix has been shown to be very important because of its influence on flame front temperatures.\(^2\) For both the blends, three different coke addition levels (on ore basis) were studied. For Blend P, Fig. 2 shows that when coke addition level was decreased, an increase in return fines addition was required. It is important to note that in doing this the mass% coke in the sinter mix will reduce further. It is, therefore, not surprising that decreasing coke levels resulted in a large decline in sinter strength and yield. However, reducing coke addition level decreased sintering time because sintering airflow rates were much higher for the same green bed permeability. This was a direct result of reduced flame front temperature\(^2,3\) and, therefore, the formation of a more permeable flame front. Reducing coke addition level improved productivity because the shortened sintering time had a greater impact than the reduction in yield.

The results given in Fig. 3 for Blend M30 are not as definitive. The variations in green bed permeability were larger and, for this reason, the impact of flame front temperature on sintering airflow rate is not as clear. However, the direct relationship between green and sintering airflow rates, and the inverse relationship between sintering airflow rate and sintering time are clearly evident. Decreasing sintering coke rate clearly affected yield, but did not appear to have a significant impact on sinter strength. As with Blend P, sintering time had a greater impact on productivity than yield.

These findings are most probably applicable to all ore blends, not just blends high in goethitic ores. They confirm that coke addition level in a sinter mix has a very significant impact on return fines generation, sinter strand speed, yield, productivity and sinter strength. To effectively control coke addition level in a sinter mix, coke moisture and ash values must be held as constant as possible.

### 2.3. Mix Moisture

This variable is often quite difficult to control, especially during rainy seasons when the blend components arrive at the sinter plant comparatively wet. It is clear that a certain amount of water is required for effective granulation and to achieve high green bed permeability. However, the relationship between mix moisture and green bed permeability is extremely complex, and results have been presented to show that the same permeability value can be achieved at lower mix moisture if the ore blend components are drier.\(^4\)

In addition to granulation, increasing mix moisture could also have an affect on flame front temperature. In the accompanying paper,\(^1\) it was shown that flame front temperature, \(T_f\), is dependent on the amount of heat generated by coke combustion \(i.e.,\) coke level in the sinter mix, and also the temperature of the calcined layer, \(T_T\), when it is positioned adjacent to the flame front, just prior to coke in the layer combusting spontaneously. For the same coke addition level, increasing the limestone content of a sinter mix will decrease the value of \(T_f\) and, consequently, \(T_T\) because of additional calcination requirements. In the same way, but to a lesser extent, increasing the water load in the system will also lower the value of \(T_f\) and \(T_T\).

For each ore blend three mix moisture levels were studied. Figure 4 shows that increasing the mix moisture of Blend P decreased green bed airflow rate. Factors which could contribute to this unexpected behaviour are: the different moisture content of the components in the blend prior to granulation; the different atmospheric conditions (temperature and humidity) at which the tests were carried out, resulting in greater evaporation in some tests; and, decreased bed voidage at increased mix moisture because of greater bed compaction during charging. However, the changes in green bed permeability did not have an impact on sintering bed permeability—possibly because the relationship between these two parameters is not linear once green bed permeability has exceeded a certain value.\(^2,4\)

With decreasing mix moisture a slightly lower return fines level was required to obtain balanced return fines operation, which meant that coke levels in the sinter mix was increased slightly. Overall, results indicate that increasing mix moisture from around 7.2 to over 7.6 mass% did not alter productivity, but decreasing its value to around 6.8 mass% caused deterioration in productivity because of increased sintering time. The reason for this is not apparent at this stage.

For Blend M30, Fig. 5 shows no clear trend in green bed airflow with increasing mix moisture. It is most likely that at the highest mix moisture value, the granules became very compressible,\(^5\) resulting in a sharp decline in green bed
Fig. 2. Effect of altering the coke addition level for Blend P.

Fig. 3. Effect of altering the coke addition level for Blend M30.

Fig. 4. Effect of altering mix moisture for Blend P.

Fig. 5. Effect of altering mix moisture for Blend M30.
permeability. It is to be expected that the granules formed from Blend M30 would have a thicker adhering fines layer and, therefore, are more compressible since Marra Mamba ore contains a higher level of ultrasilines compared to pisolite ore and most hematite ores. The trends obtained for green and sintering bed airflows, sintering time and tumble strength are consistent. These results further support the view that mix moisture is not a good indicator of green bed permeability and that plants should be operated to meet green bed permeability targets rather than mix moisture targets.

The results for the two blends would indicate that mix moisture control is not as important for Blend P, possibly because Blend M30 contains a higher level of fine material, sourced from Marra Mamba ore.

2.4. Bed Height

It is well known that increasing bed height will improve yield since a significant amount of return fines is generated from the upper bed region, which is sintered at a lower temperature. It is also well established that lower coke rate is the other benefit obtainable from increasing bed height.

For the two blends, two bed heights were examined and results are shown in Figs. 6 and 7, respectively. The trends obtained for the two blends are identical. Increasing bed height increased the total resistance of the bed to airflow and, consequently, airflow rate decreased for the same pressure drop across the green bed. Increasing bed height also reduced sinter return fines generation, which meant that the amount of coke per unit mass of sinter mix was increased. The effects of reducing airflow rates and increasing coke levels are reduced rate of convective heat transfer and higher flame front temperatures—resulting in very significant increases in sintering time. Although yield and sinter strength both improved, productivity dropped because of increased sintering time. The increase in coke mass per unit mass of sinter mix also resulted in slightly higher coke rates.

These results show that if bed permeability remained unchanged, increasing bed height will have a negative impact on productivity. These days, most plants in the Asia Pacific would operate at bed heights in excess of 600 mm. In spite of this, plants are able to achieve high productivities because of the use of higher suctions and strong emphasis on forming highly permeable beds.

2.5. Suction

The effects of increasing suction and decreasing bed height on the sintering parameters should not be too dissimilar, if bed properties remain unchanged. Studies at different suctions are useful because they can provide information on the rigidity of the granulated beds. At higher suction, less rigid beds could undergo compaction giving reduced bed voidage.

To examine this variable the pressure drop across the bed was decreased from 16 to 13 kPa and then increased to 19 kPa. For Blend P, Fig. 8 shows that reducing suction reduced green and sintering bed airflow rates, and this led to increased sintering time and decreased productivity. The level of return sinter fines altered slightly and this affected coke rate. In line with expectations, yield and sinter strength improved as suction and flame front speed decreased.

Figure 9 shows that the results for Blend M30 at 13 kPa are quite different to those obtained at higher suctions. Green and sintering airflow rates were particularly low and this resulted in a very long sintering time. It is possible that a certain airflow rate is necessary to keep the gas channels in the flame front fully dilated because the melts generated from this blend are more viscous. The test at 16 kPa used a higher level of return fines compared to the test at 19 kPa, so decreases in flame front temperature could explain the shorter than expected sintering time. The lower yield and tumble index obtained at this suction is consistent with a shorter sintering time.

These results would indicate that at a bed height of 550 mm, if productivity is the major driver in a plant, Blend P should be sintered at a suction close to 19 kPa, while the more appropriate value for Blend M30 is 16 kPa. At higher bed heights, it is possible that productivity can be maintained if suction is increased to maintain the same pressure drop per unit height of bed.

2.6. Combination of Bed Height and Suction

Both suction and bed height were altered in these tests. For the high bed height and high suction experiment the pressure drop per unit length was 0.032 kPa/mm, while the equivalent value for the standard test carried out at 16 kPa on a 550 mm bed was 0.029 kPa/mm. The trends in results for the two blends, given in Figs. 10 and 11, are identical. Even though the pressure gradient is higher for the 19 kPa test, green and sintering airflow rates are lower. A possible explanation for this is that high suction in combination with high bed height caused a reduction in bed voidage through increased bed compaction.

The reduced airflow during sintering resulted in increased sintering time and a decrease in productivity. Yield was lower for the higher bed operation but sinter strength was higher. These two experiments further confirmed that yield was highly dependent on the layer of weak sinter at the top of the bed (thickness of which is independent of bed height), while sinter strength is more dependent on flame front speed.

3. Effect of Limestone Addition Levels

Fluxes play an extremely important role in sintering because of their participation in melt formation and their effect on melt properties. Fluxes in the form of carbonates also influence the sintering parameters because they require substantial heat for calcination, and as discussed earlier they result in lower flame front temperatures, and this leads to increases in flame front speed. In this section the mass of limestone was altered to understand its influence on the sintering parameters.

Sinter basicity was reduced from 1.8 to 1.5 and then increased to 2.1. For Blend P, Fig. 12 shows that the level of sinter return fines in the mix had to be increased as sinter basicity increased. The most likely cause of this was the decrease in flame front temperature caused by additional calcination requirements. This view is supported by the increase in sintering airflow rate when basicity was increased.
Fig. 6. Effect of altering bed height for Blend P.

Fig. 7. Effect of altering bed height for Blend M30.

Fig. 8. Effect of altering suction for Blend P.

Fig. 9. Effect of suction for Blend M30.
Fig. 10. Effect of altering suction and bed height for Blend P.

Fig. 11. Effect of altering suction and bed height for Blend M30.

Fig. 12. Effect of sinter basicity on the sintering behaviour of Blend P.

Fig. 13. Effect of sinter basicity on the sintering behaviour of Blend M30.
The increased airflow rate, in turn, reduced sintering time and increased productivity. Sinter quality did not deteriorate significantly even with the large changes in sintering time, probably because lime lowers melt formation temperature and enhances melt properties.

Figure 13 shows the results for Blend M30. The variations in return fines levels for the three basicity levels are much less compared to the values shown in Fig. 12. At a basicity of 1.5, sintering airflow rate was unusually low even though the green bed airflow rate was high. This could also be a result of increased melt viscosity, except that the high basicity test also gave an unusually long sintering time. Tumble strength appears to be more a function of basicity than flame front speed. The trend obtained for yield is opposite to that observed for tumble strength.

The results shown in Figs. 12 and 13 show no consistent relationship between green and sintering bed permeabilities. This is not entirely surprising because increasing limestone addition would lower the value of $T_i$ and could also affect the properties of the gas channels in the flame front—the importance of which has been discussed in some detail. On reacting, limestone particles would leave behind a void and the higher basicity tests would have more of such voids in the flame front. This variable, if important, will influence the structure of the flame front and add another level of complexity to the interpretation of test results.

The two figures also show clear general differences in trends and this is most probably a function of the differences in assimilation behaviour between pisolite ore and Marra Mamba ore. Fundamental studies have shown that melts penetrate into calcined goethite very easily and this explains their high reactivity in sintering. Goethite is uniformly distributed between the pisolite ore particles, but is more abundant in some size fractions of Marra Mamba.

The other important difference between the two ores is their size distribution. Marra Mamba is finer and a large part of this ore would be layered on the surface of nuclear ore particles (predominantly pisolite ore particles). Their close proximity with limestone and their high reactivity (fine size and high porosity) would mean that they have a significant influence on the primary melt formation process. Increasing basicity would form more melt and the melt would also be more fluid. This should alter: the melt penetration process, the secondary melt formation process, the coalescing of melt, and the properties of gas channels in the flame front.

4. Sinter Size

In the accompanying paper, it was shown that pot sinters, prepared from blends containing different levels of goethitic ores, did not vary much in size distribution even though they had significantly different tumble strength. Sinter size distributions were also determined for all the tests from which Sauter Mean Diameters (SMD) were calculated. SMD is a characteristic diameter based on the surface area to volume of particles and is particularly relevant in the assessment of packed bed (e.g., blast furnace stack or sinter bed) permeability. SMD results are generally in line with expectations. Only a selection of results will be presented to demonstrate that this parameter can be determined accurately, and that it can change in a pot test to reflect sintering conditions.

The effect of coke rate on Blends P and M30 is shown in Figs. 14 and 15. With Blend P, increasing coke rate increased the proportion of coarser sinter resulting in a larger SMD. A coarser sinter size distribution was also produced with increasing coke rate for Blend M30 but the effect was not as pronounced.

For the two blends, Figs. 16 and 17 show that increasing bed height significantly increased the mass% of minus 40 mm plus 25 mm sinter and reduced the two finer fractions. Sinter SMD increased significantly with these changes.

5. Discussions and Conclusions

Recent studies aimed at characterising airflow rates through a sintering bed have given important insights into the role of the flame front in sintering. This pot test study was carried out to further current understanding of the influence of blend composition and test conditions on sintering performance and sinter strength. Emphasis was given to understanding the fundamental cause of changes in sintering time, yield, productivity, coke rate and sinter tumble index for two blend containing very high levels of goethitic ores.
ores. The major findings of this study are:

(1) When return sinter fines level was increased by 2 mass%, sintering time shortened even though pre- and post-airflow rates were comparable indicating that this small change has affect the thermal and melting properties of the bed. In addition, changes to yield and sinter strength were recorded. These results indicate the importance of controlling return fines addition rate in a sinter plant. Fluctuating addition rates will have an impact on burn-through point, the level of on-strand cooling, waste gas temperatures and sinter properties.

(2) Reducing coke addition level, on an ore basis, resulted in increased return fines generation. Both these factors resulted in lower flame front temperatures, which increased sintering airflow rate and shortened sintering time. It is, therefore, to be expected that there would be deteriorations in sinter strength and yield. Experimental results indicate that reductions in yield were obtained for the two blends, but for the blend containing Marra Mamba ore there were no changes in sinter strength. Reducing coke addition level did not always result in lower productivity because this parameter is strongly dependent on sintering time.

(3) It is well-established that granulation efficiency is dependent on the volume of water available to bind particles together into granules. As granules grow in size bed permeability increases, but there is a trade-off between granule size and granule strength. When a certain mix moisture value is exceeded, bed permeability will not increase with increasing mix moisture. Results obtained in this study would suggest that with Marra Mamba ore in the blend, there is greater need for better mix moisture control to avoid granule deformation.

(4) At constant suction, increasing bed height improved yield and sinter strength but productivity dropped because of reduced pressure gradient, which led to decreased airflow rates and increased sintering time. As expected, there were coke rate benefits associated with increasing bed height.

(5) At constant bed height, increasing suction increased airflow rate and this decreased sintering time and improved productivity. For the blend containing Marra Mamba ore, 16 kPa appears to be optimum for productivity but higher suction can be tolerated for the blend without Marra Mamba ore. Results obtained also suggest that the volume and properties of melts generated could determine the optimum suction value. A larger pressure difference across the flame front may be required when viscous melts are generated to ensure that gas velocities are high enough to keep gas channels in the front dilated.

(6) A combination of high suction and high bed height can have an adverse effect on the sintering behaviour of these blends, possibly because of bed compaction leading to reduced bed voidage.

(7) Basicity had a very significant effect on sintering results and the response of the two blends to basicity changes was quite different. It was suggested that increasing limestone content not only altered flame front temperatures and melt properties, but also the structure of the flame front. There is a need to obtain greater understanding into these areas.

(8) Observed changes in sinter size distribution were
consistent with changes in heat availability and sintering temperatures.

These results show that sinter machine performance is extremely sensitive to changes in blend composition, bed height and suction. Several relationships observed in this study—such as the effect of bed height on return fines level—are not new and have been observed in plants. In some cases, experimental test results obtained in this study could not be explained fully. Some irregularities in results could be caused by limitations in test procedure. During the course of sintering, the material in the pot could not be observed because of the hood placed over the sinter pot. In some tests, it is possible that some fines from the annular layer could have flowed through the hearth layer into the windbox, resulting in the formation of gas channels within the annular layer. If this occurred measured airflow rates would be higher than expected. For the next program, experimental procedures will be further refined so that changes in results can be quantified even more definitively.

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