The Effect of Marra Mamba Ore Addition on the Granulation Characteristics of Pisolite Based and Hematite Based Sinter Blends

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The granulation characteristics of two quite different sinter blends have been studied. One comprises a significant proportion of pisolite ore, and the other is dominated by hematite ores. The effect on granulation of adding a significant proportion of West Angelas, a Marra Mamba type ore, into both blends is also studied. The relationship between blend moisture content and green permeability is measured, as is the size distribution of the granulated blends at different moisture contents. It is clear that when West Angelas ore displaces a denser, less porous ore type in a sinter blend, additional granulation moisture must be added to ensure optimal granulation performance. A petrographic study of granule morphology at different blend moisture contents is reported, with particular reference to the features of the adhering layer. The important role of ultrafines, particularly the $\sim 50\,\mu m$ ‘superfine’ fraction, in the granulation process is discussed. The variations in mineralogical and textural characteristics of West Angelas ore with size are presented. It is proposed that the mineralogical and textural characteristics of the superfine particles are an important factor in the granulation performance of an ore or a blend of ores.

KEY WORDS: iron ore; Marra Mamba; pisolite; hematite; granulation; sinter; permeability.

1. Introduction

The iron ore shipped from Australia will comprise an increasing proportion of Marra Mamba type ores, as the reserves of low phosphorus Brockman type ores are depleted. The successful integration of Marra Mamba iron ore products into existing sinter blends, while maintaining or improving sinter productivity and quality, is a challenge currently facing many steel mills. Effective granulation of a sinter blend is a critical factor in obtaining good green permeability on the sinter strand.

This paper reports the findings of a study into the granulation characteristics of two quite different sinter blends, and the effect on granulation of adding a significant proportion of West Angelas, a Marra Mamba type ore, into these blends. Blend 1 comprises a significant proportion of pisolite ore, with the balance made up of Brazilian and Australian hematite. The pisolite component means that the blend has a relatively high porosity and coarse sizing. Blend 2 is dominated by hematite ores, with the balance being a hematite/magnetite concentrate. This blend is denser in nature, with a finer sizing.

West Angelas iron ore from Robe River Iron Associates was the first commercially available iron ore product to comprise 100% Marra Mamba type ore. Shipments of West Angelas ore commenced in 2002. Marra Mamba type iron ores have a complex range of physical, chemical and mineralogical characteristics.\(^1\) It is important therefore to understand how these characteristics affect the granulation performance of an ore blend. It is well understood that the effect of introducing a new ore into a sinter blend can depend as much on the nature of the ores it displaces, as on the intrinsic properties of the new ore. Therefore, the behaviour of the two different ore blends as West Angelas displaces different ore types is of particular interest.

2. Experimental Procedure

2.1. Raw Materials

All raw materials for this study were blended and homogenised prior to samples being prepared for the measurement of size distribution (Table 1) and chemical composition (Table 2). Ore G (Concentrate) has the most distinctive size distribution, with most of the particles falling between 0.063 and 0.5 mm. A size distribution predominantly below 1 mm is a feature of many iron ore concentrates, reflecting the processing required to beneficiate the ore. The pisolite ores are notably high in $+8\,mm$ particles and low in $-0.5\,mm$ particles. The hematite and West Angelas ores are relatively similar in size distribution, though Ore C does contain a notably lower proportion of $-0.25\,mm$ particles.

The ore blend compositions used in this study are shown in Table 3. When West Angelas was introduced at 30% of...
the ore blend, it displaced all other ores in the same proportion. The 30% West Angelas addition rate was chosen to ensure that a clear effect could be measured, but also with the consideration that rates of Marra Mamba use in sinter blends may well exceed 20% in the future. For both Blends 1 and 2, introducing West Angelas increased the proportion of porous ore types in the blends.

The calculated combined size distributions of the ore components of the four blends are shown in Fig. 1. Blend 1 is coarser, while Blend 2 has notably more material in the 0.063–0.5 mm size fraction due to the concentrate component. The addition of 30% West Angelas does not have a significant impact on the sizing of either blend, though Blend 1 becomes slightly finer, while Blend 2 becomes slightly coarser.

2.2. Granulation Characteristics

The quantity of moisture required to saturate each of the raw materials was measured using a simple gravity filtration technique. A 500 g sample was repeatedly saturated and then allowed to drain under gravity. The moisture content measured when drainage ceased was defined as the saturation moisture.

The granulating characteristics of the four ore blends were examined by making up a number of sinter mixes from the component raw materials, including return sinter fines. The precise composition of the sinter mixes was calculated taking into account the ore blend composition, the sinter chemistry targets (4.9% SiO₂, 1.2% MgO, 1.8 CaO/SiO₂), the composition of the component materials and their inherent moisture level. Sinter return fines were added at a constant rate of 30% of the ore blend.

The effect of mix moisture on the granule properties was then investigated. The procedure involved varying the mix moisture to produce a number of wet granulated sinter mixes of approximately 15 kg (wet) mass.

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**Table 1.** Size distribution of iron ores, fluxes, and coke (mass%).

| Ore                  | Cumulative % passing (size in mm, dry basis) |
|----------------------|---------------------------------------------|
|                      | 8    | 6.3 | 4   | 2   | 1   | 0.5 | 0.25 | 0.125 | 0.063 | 0.038 |
| A Pisolith           | 90.43 | 88.03 | 74.61 | 57.85 | 41.64 | 27.78 | 16.85 | 9.84 | 5.77 | 3.71 |
| B Pisolith           | 88.86 | 82.47 | 68.89 | 53.08 | 39.34 | 28.39 | 20.67 | 15.33 | 11.89 | 10.22 |
| C Brazilian hematite | 100.00 | 93.05 | 75.85 | 60.43 | 45.35 | 33.96 | 23.22 | 13.33 | 6.18 | 2.24 |
| D Brazilian hematite | 98.37 | 97.22 | 78.79 | 57.54 | 44.44 | 37.95 | 33.39 | 28.12 | 19.06 | 12.12 |
| F Australian hematite| 97.08 | 95.07 | 78.51 | 56.81 | 43.47 | 35.36 | 29.22 | 23.06 | 17.54 | 14.66 |
| F Australian hematite| 90.65 | 88.85 | 73.90 | 59.66 | 50.24 | 43.64 | 37.87 | 31.07 | 23.04 | 18.44 |
| G Concentrate       | 100.00 | 100.00 | 100.00 | 99.11 | 93.68 | 69.73 | 25.97 | 2.85 | 0.45 |
| West Angelas        | 96.65 | 95.56 | 81.92 | 63.54 | 49.91 | 39.80 | 31.08 | 22.56 | 12.57 | 7.77 |
| Limestone           | 100.00 | 99.70 | 94.07 | 77.08 | 63.63 | 50.91 | 36.46 | 23.24 | 12.75 | 7.23 |
| Dolomite            | 100.00 | 100.00 | 100.00 | 81.58 | 74.87 | 48.05 | 34.64 | 27.03 | 20.37 | 16.18 |
| Sand                | 100.00 | 100.00 | 100.00 | 99.80 | 73.45 | 0.20 | 0.00 | 0.00 | 0.00 |
| Coke Breeze         | 99.01 | 96.82 | 88.69 | 71.59 | 56.24 | 44.68 | 32.81 | 20.11 | 10.94 | N/A |

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**Table 2.** Chemical analysis of iron ores (mass%).

| Ore                  | Fe | SiO₂ | Al₂O₃ | P | LOI | spec |
|----------------------|----|------|-------|---|-----|------|
| A Pisolith           | 59.1| 4.5  | 1.3   | 0.052 | 9.5 |
| B Pisolith           | 57.2| 5.5  | 2.7   | 0.041 | 9.0 |
| C Brazilian hematite | 67.1| 0.7  | 0.9   | 0.054 | 1.6 |
| D Brazilian hematite | 66.3| 3.7  | 0.5   | 0.02  | 0.5 |
| E Australian hematite| 63.2| 3.5  | 2.1   | 0.068 | 3.3 |
| F Australian hematite| 63.5| 4.2  | 2.2   | 0.069 | 2.2 |
| G Concentrate       | 68.1| 2.3  | 0.1   | 0.004 | -0.6 |
| West Angelas        | 61.3| 3.4  | 2.1   | 0.058 | 6.0 |

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**Table 3.** Composition of ore blends (mass%).

| Ore Type (porous/dense) | Blend 1 | Blend 1W | Blend 2 | Blend 2W |
|-------------------------|---------|----------|---------|----------|
| A Pisolith (p)          | 35      | 24.5     |         |          |
| B Pisolith (p)          | 20      | 14       |         |          |
| C Brazilian hematite (d)| 20      | 14       | 20      | 14       |
| D Brazilian hematite (d)| 10      | 7        | 20      | 14       |
| E Australian hematite (d)| 7.5    | 5.2      | 20      | 14       |
| F Australian hematite (d)| 7.5    | 5.2      | 20      | 14       |
| G Concentrate (d)       |         |          | 20      | 14       |
| West Angelas (p)        | 30      |          |         |          |
| Porous Ore Types        | 35      | 68.5     | 0       | 30       |
| Dense Ore Types         | 45      | 31.5     | 100     | 70       |

**Fig. 1.** Size distribution of the ore component of the blends.
Details of the granulation equipment and procedures are listed in Table 4. They provide the appropriate motion of the solids during the mixing stage (where ‘cataract’ motion is required) and the granulation stage (where ‘cascading’ motion is required) of mix preparation.

After granulation, the permeability of the wet sinter mix was measured as the pressure drop across a 250 mm deep × 150 mm diameter bed. The test was carried out at an air flow rate of 400 L/min, this flow rate being an approximation of the superficial gas velocity in sinter pot testing at CSIRO.

After the general effect of moisture content on permeability was established, three nominal moisture levels were chosen for each blend to produce further batches of granules under conditions of ‘insufficient’, ‘optimum’ and ‘excess’ moisture addition. To measure the size distribution of the granules, the wet granules were poured into liquid nitrogen, which was carefully stirred to avoid the granules clustering together whilst ensuring that there was no damage to the granules. Duplicate 500 g subsamples of the frozen granules were then taken using a sample splitter. These subsamples were screened into size fractions using five sieves of 8, 4, 2, 1 and 0.5 mm on a Ro-Tap sieve shaker for 1 min. Each size fraction was then weighed and the cumulative mass passing each screen size was recorded.

2.3. Petrographic Study

For each blend, two representative samples of granules produced under the insufficient, optimum and excess moisture conditions were taken and then dried at 50°C for 24 h. Once dried these were set in epoxy resin under vacuum and polished sections produced to a 1 μm surface finish. The polished sections were then examined under a petrographic reflected light microscope. The 4–8 mm fraction was selected as the focus of the petrographic study as it best illustrated the features of the granules.

3. Results

3.1. Saturation Moisture

The moisture required to saturate a material gives an indication of its open porosity, and is particularly relevant to the granulation process in which water is the primary binding agent. The measurements in Table 5 indicate that the pisolitic ores and West Angelas ore are the most porous ores in the blends being studied. The introduction of West Angelas ore into both Blends 1 and 2 results in a notable increase in the moisture level required to achieve saturation.

3.2. Permeability

A feature of the moisture vs. pressure drop curve for Blend 1 is a wide zone of minimum pressure drop/maxi-
1 does deteriorate more significantly than Blend 2 at low moisture contents.

Figure 4 shows that the addition of West Angelas ore to Blend 2 has three notable effects: (i) there is a small improvement in green permeability (ii) the moisture content required to achieve minimum pressure drop increases by approximately 0.5% (iii) the shape of the curve is changed—flattening out at higher moisture levels, but steepening at lower moisture levels.

It is interesting to compare the moisture vs. permeability curves for blends 1W and 2W (Fig. 5), which are quite similar following the introduction of West Angelas ore into the respective blends. This is probably due to West Angelas ore now being the main individual component of both blends, and so the curves tend to reflect the characteristics of their main component. However, there is still a clear difference in behaviour at the lowest moisture levels. The presence of 68.5% of highly porous ore types in Blend 1W means that it is more sensitive to sub-optimal moisture addition than Blend 2W, which contains only 30% of highly porous ore types.

3.3. Size Distribution

The size distribution of the granulated blends is an im-
important factor in determining green bed permeability. **Figure 6** shows the change in size distribution of Blends 1 and 1W (i) in the un-granulated state (ii) following granulation with insufficient moisture (iii) following granulation with moisture content close to the optimum level. It is clear that with insufficient moisture addition, very little granulation occurs in this blend that is dominated by porous ore types. There is virtually no formation of granules greater than 1 mm in size. As optimum moisture addition is reached, for both blends there is a significant increase in the quantity of +1 mm, +2 mm and +4 mm granules. At close to the optimum moisture addition, Blend 1W shows a similar size distribution to Blend 1, but additional moisture is required to achieve the same granulation effect.

**Figure 7** shows the size distribution of Blends 2 and 2W (i) in the un-granulated state (ii) following granulation with insufficient moisture (iii) following granulation with moisture content close to the optimum level. The denser ore types in Blend 2 mean that even at low moisture addition there is more free surface moisture available for granulation than with Blend 1, and so more significant granule growth occurs. For similar moisture contents, Blend 2W exhibits a finer size distribution than Blend 2. This reinforces the observation that, when West Angelas displaces denser ore types from a blend, additional moisture must be added to achieve the same level of surface moisture for equivalent
granule growth.

3.4. Granule Morphology

Petrographic study of the 4–8 mm size fraction of the granulated blends clearly demonstrates the effect on the quality of granule formation of different levels of moisture addition. Figure 8 shows the structure of granules from Blend 2 with insufficient, close to optimum, and excess moisture addition. In Fig. 8(a), the nucleus has a discontinuous adhering layer of ultrafines, as there is insufficient free surface moisture to bond more material. Figure 8(b) shows a granule formed with close to optimum moisture addition, with a well rounded coating of 1–2 mm in thickness. The adhering layer is also able to incorporate larger ‘intermediate’ size particles. Optimum moisture addition should also yield the strongest granules, as the capillary action of the free surface moisture is best able to resist any straining forces.2) A granule formed with excess moisture addition is shown in Fig. 8(c). This granule is an agglomeration of smaller granules, with the points of contact between the smaller granules offering potential points of weakness. Excess free moisture tends to reduce permeability, and also weakens the granules.

4. Discussion

There have been several papers in which the role of different size fractions in the granulation process are discussed and categorised. Classically, fines are identified as ‘adhering’, ‘intermediate’ and ‘nucleus’. The precise definition of each size fraction varies between authors,3,5) and there has been some debate about whether intermediate size particles do or do not participate in granule formation.6) However it is generally accepted that intermediate fines are the most problematic in granulation, as they form neither good nuclei nor good adhering fines. Some steel mills use this understanding in the design of their sinter ore blend.7) In this study, it was observed that nucleus-forming particles were typically greater than 1 mm in size. Adhering particles were typically less than 0.5 mm in size, though occasionally up to 0.75 mm. It must be remembered that a section through a particle gives an apparent diameter, and therefore the observed measurements are nominal.

Of particular interest in this study is the behaviour of the ‘ultrafine’ particles within the adhering fines fraction. The definition of ultrafines ranges from −0.125 to −0.25 mm. The possible effect on sintering of the ultrafine component of Marra Mamba fines has been a concern for steel mills since the concept of a standalone Marra Mamba product was first introduced. Previous studies5,8,9) had concluded that increased levels of −0.125 or −0.25 mm particles in the sinter blend have a negative effect on granulation. It was noted, however, that the size distribution of the −0.25 mm fraction was also an important factor in granulation effectiveness, and that a reduced mean size of the −0.25 mm fraction could improve granulation effectiveness.9)

Prior to the commencement of commercial shipments, the quantity of ultrafine particles in Marra Mamba fines products was expected to be as high as 30% −0.15 mm, and it was expected that this would result in poor granulation performance. However, the actual ultrafines levels in shipments of West Angelas fines averaged only 21% −0.15 mm for the first 2 years of commercial shipments. The level of ultrafines in the West Angelas sample used in this study is no higher then several of the other hematite ores (Table 1). Therefore, it is believed that any attempt to understand the effect of Marra Mamba type ore on the granulation process should not focus simply on the quantity of ultrafines, but also on other characteristics of the ultrafines.

It is clear from Figs. 9 and 10 that the adhering fines can be broken down into two sub-groups. The first grouping is −50 μm, and the second grouping is 50–750 μm. The −50 μm ‘superfines’ play two important roles. Firstly in initiating the formation of a coating layer around the nucleus particles, which has also been observed by other authors,5,10) and then in binding together the larger sized adhering fines within the coating. The ultrafines in an ore blend, particularly the finest −50 μm fraction, therefore play a vital role in the granulation process, and so it is important to understand the characteristics of this component for each of the iron ore types.

The relative content of hematite, clay, and goethite mineral types in the ultrafines is likely to affect their behaviour in the initiating and binding roles, and hence have a strong influence on overall granulation behaviour. Samples of West Angelas fines product have been characterised using a system based on the ore group textural classification developed by CSIRO.11,12) This classification has been used to improve understanding of lump ore properties, but is also proving useful in understanding the characteristics and behaviour of sintering fines. For example, the characterisation has demonstrated that the −0.5 mm fraction of West Angelas fines contains a high proportion of martite
(hematite) particles (Fig. 11). However, further subdivision and mineralogical analysis of the \(-0.5\) mm fraction is required, particularly of the \(-100\ \mu\text{m}\) and \(-50\ \mu\text{m}\) fractions, for West Angelas fines and other iron ores. This will give a more complete understanding of the implications for the granulation process.

The mineralogical and textural analysis of West Angelas ore also highlights that the \(+1\) mm particles, that are most likely to form nuclei during granulation, have notably different mineralogical characteristics to the \(-0.5\) mm adhering particles (Fig. 11). This implies that there will be differences in physical characteristics that will affect their behaviour in their respective roles. Such differentiation in properties across the size range may well be seen in other sintering ores, and indicates that analysis of iron ore ‘by size’ should consider more than just chemical grade.

5. Conclusions

The granulation performance of a sinter blend containing a high proportion of porous ore is sensitive to insufficient moisture addition. Green bed permeability deteriorates rapidly with sub-optimal moisture addition. The consequences of insufficient moisture addition are more serious for blends with a high proportion of porous ore than for blends comprising denser ore types.

When West Angelas ore displaces a denser, less porous ore type in a sinter blend, additional granulation moisture must be added to ensure optimal granulation performance.

For a blend dominated by coarse, porous pisolithic ore, addition of West Angelas ore can achieve similar granulation performance and green bed permeability provided that the optimum level of moisture addition is used.

For a blend of dominated by fine, dense ore types, addition of West Angelas ore can achieve similar granulation performance and green bed permeability provided that the optimum level of moisture addition is used.

‘Superfine’ particles (<50 μm) play a very important role in granulation. Firstly by initiating the formation of an adhering layer on the surface of nucleus particles. Secondly by forming a binding matrix in which larger adhering fines sit.

The mineralogical and textural characteristics of the superfine particles are likely to be an important factor in the granulation behaviour of an ore or a blend of ores. Further work to identify the mineralogical and textural characteristics of the superfines in a range of iron ores will improve our understanding of the granulation behaviour of different ore blends.

REFERENCES

1) R. C. Bergstrand, A. G. Waters and J. M. E. Clout: Proc. of the 3rd Int. Cong. on Science and Technology of Ironmaking, VDEh.
Düsseldorf, (2003), 424.
2) P. A. L. Wauters: Ph.D. Thesis, Technical University of Delft, Netherlands, (2001).
3) T. Furui, K. Sugawara, M. Kagawa, S. Uno, M. Kawazu, T. Fujiwara and A. Sawamura: \textit{Nippon Steel Tech. Rep. Overseas}, \textbf{10} (1977), 36.
4) R. Vidal, G. Meunier and E. Poot: Proc. of Agglomeration 85, ISS, Warrendale, PA, (1985), 181.
5) S. Nagano, H. Noda, H. Yanaka, K. Shiobara and Y. Yamaoka: Proc. of Agglomeration 85, ISS, Warrendale, PA, (1985), 191.
6) J. D. Litster, A. G. Waters and S. K. Nicol: \textit{Trans. Iron Steel Inst. Jpn.}, \textbf{26} (1986), 1036.
7) A. Formoso, A. Moro, G. Fernandez Pello, J. L. Menedez, M. Muniz and A. Cores: \textit{Ironmaking Steelmaking}, \textbf{30} (2003), 447.
8) S. Mizukami, H. Murata, K. Shibuta, R. Itoh and K. Tokutake: \textit{Trans. Iron Steel Inst. Jpn.}, \textbf{26} (1986), B-1.
9) J. D. Litster and A. G. Waters: \textit{Powder Technol.}, \textbf{55} (1988), 141.
10) P. W. Roller: \textit{BHP Tech. Bull.}, \textbf{26} (1982), 44.
11) J. M. F. Clout: AusIMM Iron Ore Conf., AusIMM, Carlton, (2002).
12) R. Bergstrand, A. Waters and J. Young: \textit{CAMP-ISIJ}, \textbf{17} (2004), 123.