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IRON ORE SINTERING WITH CHARCOAL[1]

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Abstract

The use of charcoal as an alternative fuel to coke breeze in a simulated Japanese Steel Mills (JSM) sinter blend was investigated. The influence of four charcoal types, with different volatile matter and density characteristics, on the granulating and sintering characteristics of the JSM sinter blend was investigated. Compared with coke breeze, higher mix moisture contents were required for sinter mixtures containing charcoals to achieve optimum granulation. The sinter mixtures containing charcoals also needed higher fuel rates. Although initial experiments produced weaker sinter, the mechanisms responsible for the weakening of sinter structure were identified. The volatile content and density of charcoals were found to be important parameters. As the residual volatile content of charcoals decreases and the density increases, the sinter fired at the same fuel addition level becomes stronger, reflected by the return fines balance, sinter yield, sinter tumble strength and mean product sinter size. The experimental results showed that it is possible to achieve a return fines balance and adequate sinter quality while maintaining high sintering productivity by controlling the volatile content and density of charcoals. At slightly higher fuel rates, the quality of sinter made from the two low volatile charcoal types was comparable to the sinter made using coke breeze. The slightly higher fuel rate required for the sinter blends containing charcoals may be justified by their advantages in improving sintering productivity and reducing greenhouse and other harmful gaseous emissions.

Key words: Charcoal; Renewable fuel; Iron ore sintering; Greenhouse gas emission.

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1 INTRODUCTION

Iron and steel production accounts for about 70% of world greenhouse gas emissions generated from primary metal production[1]. While there are a number of short term approaches to reducing CO_2 emissions from iron and steel production, the longer term approach will require gradual substitution of fossil fuel-based energy and reductants such as coke and coal with renewable sources such as biomass materials[1]. However, the challenges are:

- to develop and manage the renewable sources on a sustainable basis;
- to develop a high capacity production technology that produces charcoal from the renewable sources at a low cost and low environmental impact; and
- to achieve the qualities ideally suited to product applications, such as iron ore sintering and blast furnace ironmaking.

There is an ongoing collaboration between BlueScope Steel, OneSteel and CSIRO investigating ways to substitute charcoal, derived from biomass, for coal and coke to reduce net CO_2 emissions from existing operations[2]. This way carbon is recycled through the atmosphere as CO_2 in a 5-30 year cycle compared with fossil carbon which was deposited in geological time. Charcoal is also much lower in sulphur and nitrogen, hence lowering SO_X and NO_X emissions. Previous experimental and plant-based work has shown that charcoal is a feasible alternative to coal in many steelmaking operations. Somerville et al[3,4] have demonstrated that specially prepared charcoal is a viable alternative to calcined anthracite for recarburising liquid steel, although issues of moisture absorption and low density remain. In mathematical modelling and experimental studies, Mathieson[5] and Rogers and Mathieson[6] showed that charcoal can be a viable alternative to coal as a blast furnace injectant.

Limited work[7-9] has been conducted to substitute biomass for coke breeze in the sintering process, with this work mainly focused on its enviromental impacts and low substitution rate. In a previous study[7], substitution of charcoal for coke breeze resulted in higher sintering productivity, but with much higher fuel rates and weaker sinter. Therefore, the properties of charcoal, especially its combustion characteristics, need to be optimised to ensure adequate sinter strength is achieved while increasing the substitution of charcoal. It is well known that the reactivity of coal char depends heavily on its pyrolysis temperature and source[10-12]. Coal chars prepared at higher temperatures are often less reactive than those prepared at lower temperatures. It may also be possible to reduce charcoal reactivity by increasing its density. This paper investigates the effects of three Red Gum charcoals prepared at different pyrolysis temperatures, as well as a dense charcoal prepared from a commercial high-density wood pellet, on the sinter quality and sintering performance. This work was conducted using CSIRO's pilot scale sintering facility.

2 MATERIALS AND METHODS

2.1 Materials

Table 1 summarizes the chemical analyses of the component ores used in the base ore blend, which was based on typical JSM sinter blends. The base ore blend consisted of a balanced mixture of ore types from very dense to moderately microporous Brazilian hematitic ores, to moderately and highly microporous, reactive Australian Marra Mamba and pisolitic ores. The aim was to achieve balanced sintering performance, i.e. the return sinter fines produced equal to those added to the blend (at 19 or 23% in the current study). It will be observed that the base ore blend (Table 1) is quite low in SiO_2 (3.71%) and Al_2O_3 (1.48%), and moderately high in Loss on Ingition (LOI) (5.13%). The size distribution of the base ore blend contained 42% +2 mm material as potential nuclei and 26% -0.25 mm material as potential adhering fines. As a result, it showed a quite coarse mean size of about 2.5 mm. Overall, the base ore blend was designed to perform well in granulation and sintering due to its favourable chemical, physical and mineralogical characteristics.

A commercial charcoal, herein called ‘red gum charcoal’, and densified biomass fuel (DBF) pellets were purchased as biomass sources for the preparation of different charcoals as renewable fuels for the subsequent sintering tests. The proximate and ultmate analyses of these materials are shown in Table 2.

Table 1. Chemistry of the component ores used and the base JSM ore blend tested (wt% db)

Ore	**Fe_{Total}**	**SiO_2**	**Al_2O_3**	**P**	**LOI total**	**CaO**	**MgO**	**H_2O**
WAF	61.73	3.14	2.05	0.062	5.88	0.05	0.02	3.62
CRJ	67.07	0.94	0.93	0.019	1.40	0.02	0.02	4.58
NPF	63.43	4.09	2.04	0.062	2.46	0.1	0.1	4.81
SSF	65.78	3.47	0.73	0.027	0.86	0.14	0.03	1.83
YDF	57.96	5.41	1.38	0.037	9.66	0.07	0.06	5.60
MAC	61.48	3.43	2.08	0.062	6.18	0.02	0.08	7.39
PBF	62.44	3.57	2.03	0.070	4.36	0.07	0.06	2.87
Base Ore Blend	62.22	3.71	1.48	0.04	5.13	0.07	0.05	4.51

Table 2. Proximate and ultimate analyses of the two biomass sources used to prepare different types of charcoal

Analyte	Red Gum Charcoal	DBF pellets
Moisture (%ar)	6.8	10.1
Ash (%ad)	2.7	0.66
Volatile Matter (%ad)	19.7	79.3
Fixed Carbon (%ad)	77.6	20.0
N (%daf)	0.28	0.03
S (%daf)	0.02	0.01
Gross Calorific Value (ad, MJ/kg)	30.5	16.4

2.2 Experimental Methods

Charcoals were prepared using a modified rotary furnace. Figure 1 shows a schematic diagram of the rotary furnace and ancillary equipment. The furnace was heated by electrical resistance elements located between the inconel furnace lining and outer furnace shell. A thermocouple located between the inconel furnace lining and outer shell was used to control the furnace temperature. Nitrogen gas was introduced into the rear of the furnace to provide an oxygen-free environment within the furnace while also carrying away the volatiles generated during pyrolysis. The gases and fumes then passed through to a brass column condenser to remove moisture and oils in the volatiles. A pilot gas burner was placed above the condenser exhaust to combust the non-condensable, flammable gases. Table 3 shows details of the preparation of the charcoal samples. Approximately 30 kg of each charcoal type was prepared for testing as an alternative fuel in iron ore sintering.

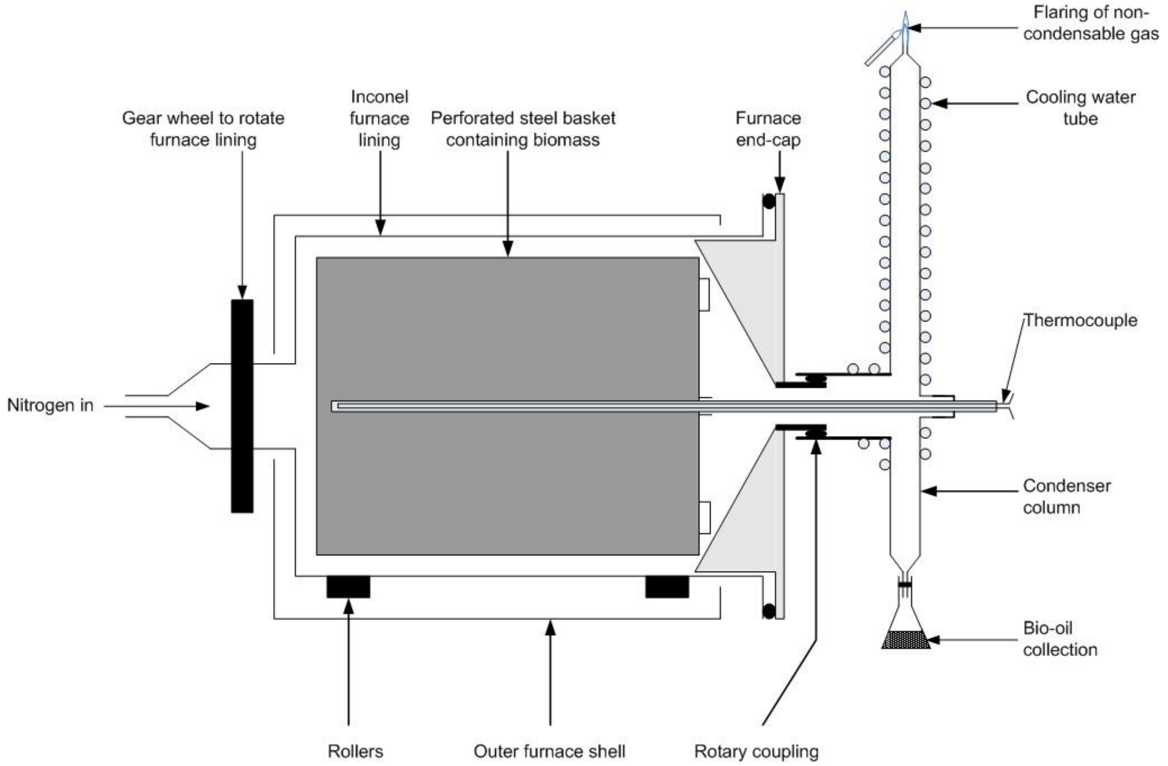


Figure 1. Schematic diagram of the rotary furnace and ancillary equipment used for preparing different types of charcoal at different temperatures.

The granulating characteristics of the JSM sinter blend containing different types of charcoal were studied using a small-scale granulation drum. This was carried out by making up a number of sinter mixtures with different water additions from the component raw materials and measuring the permeability of a packed, green granule bed. The effect of mix moisture and charcoal type on the granulating characteristics of the JSM blend was investigated. The sintering performance of the JSM blend containing different types of charcoal was established using a pilot-scale, pot-grate sintering facility. Table 4 summarises the sintering test conditions used.

Table 3. Biomass sources, pyrolysis temperature and analyses of charcoal samples produced

	High volatile charcoal	Medium volatile charcoal	Low volatile charcoal	Dense low volatile charcoal	Coke Breeze
	Type 1	Type 2	Type 3	Type 4	
Biomass source	Commercial charcoal	Commercial charcoal	Commercial charcoal	DBF pellets	Coking coal
Pyrolysis temperature (°C)	As received	650	800	750	1050
Moisture (%ad)*	6.6	5.4	6.4	6.3	0.8
Ash (%ad)	2.6	4.0	2.8	3.0	13.2
Volatile matter (%ad)	19.9	8.2	3.8	4.1	1.4
Fixed carbon (%ad)	70.9	82.4	87.0	86.6	84.6
C (%daf)	83.4	91.6	94.9	93.9	95.7
H (%daf)	2.38	1.49	0.58	1.35	0.36
N (%daf)	0.29	0.41	0.40	0.27	1.42
S (%daf)	0.06	0.06	0.06	0.06	0.48
O (%daf)	13.8	6.4	4.1	4.5	2.1
Calorific value (ad, MJ/kg)	28.34	30.58	30.76	30.7	28.48

Table 4. Pot-grate sintering test conditions

Parameters		**Sintering Conditions**
Bed height (total)	mm	600
Return fines (dry mix basis)	%	19, 23
Return fines sizing	mm	-5
Hearth layer depth	mm	30
Hearth layer size	mm	-16 + 10
Ignition flame temp	°C	1300
Ignition time	s	90
Ignition suction	kPa	8
Sintering/cooling suction	kPa	16
Basicity (CaO/SiO_2)	kg/kg	1.9
Sinter SiO_2 level	%	4.8
Sinter MgO level	%	1.6

3 RESULTS AND DISCUSSION

3.1 Characteristics of Charcoals

Three charcoals were prepared under different conditions. As shown in Table 3, the Type 1 charcoal was the “as received” commercial Red Gum charcoal purchased and was labelled as “high volatile (HV)” charcoal. The commercial charcoal was further pyrolysed at 650 and 800°C to produce Type 2 and 3 charcoals which were also called “medium volatile (MV)” and “low volatile (LV)” charcoals, respectively. Type 4 charcoal was produced through pyrolysis of the DBF pellets at about 750°C. This charcoal is called “dense, low volatile (LV)” charcoal. The volatile matter of charcoals prepared from the commercial Red Gum charcoal decreased from 19.9% for Type 1 to 3.8% for Type 3 charcoal as the pyrolysis temperature increased. The charcoal made from DBF pellets had a slightly higher volatile content than the low volatile charcoal from the commercial Red Gum charcoal, mainly due to the lower pyrolysis temperature. The high volatile charcoal had a lower calorific value, while the other three charcoals showed similar calorific values. Compared with coke breeze, charcoals are generally lower in ash, N and S contents, with higher volatile matter and calorific value.

The charcoal samples were crushed using a roller crusher to simulate the size distribution of coke breeze which had about 60% -4+0.25 mm, 13.4% +4 mm and 26.6% -0.25 mm materials; with a mean particle size of about 1.67 mm. The HV charcoal showed a size distribution quite close to coke breeze with slightly more -4+0.25 mm materials and less coarse and fine materials. Compared with the coke breeze, the MV and LV charcoal samples had narrower size distributions, both containing about 78% -4+0.25 mm and much less +4 mm (~1.5%) and less -0.25 mm (~20%) materials. The dense LV charcoal was the coarsest sample among the solid fuel samples tested, containing ~9.5% of +4 mm and ~85% of -4+0.25 mm materials. All the charcoal samples tested showed a similar moisture saturation value of ~50%, which was roughly twice that of the coke breeze (25%) and indicative of the extremely porous nature of the charcoal samples.

Therefore, substitution of charcoal for coke breeze is expected to increase the mix moisture content required for achieving efficient granulation and the thermal processes occurring inside the sintering bed, as this depends on the amount of surface moisture added beyond the saturation of the internal pores.

3.2 Granulating Characteristics of Blends Containing Different Types of Solid Fuel

The granulating characteristics of the JSM blend containing different types of solid fuel, plotted as JPU permeability curves, are shown in Figure 2. The blends showed similar permeability versus mix moisture profiles and achieved maximum permeability at specific moisture contents. The optimum moisture content required for efficient granulation was approximately 7.05% for Blend 1 (with coke breeze), much lower than the blends with charcoal samples (8.45%). Substitution of charcoal for coke breeze in the base blend shifted the permeability curve towards the right and increased the moisture requirement for optimum granulation. However, the blends containing HV and MV charcoals showed similar moisture requirement for optimum granulation. This agreed with the moisture saturation measurements, showing that all the charcoal samples tested had similar moisture saturation values and were twice that of the coke breeze.

Also shown in Figure 2, the blends containing different types of solid fuel achieved similar optimum permeability. However, at higher mix moisture contents, the blends containing charcoals showed better permeability while the blends with coke breeze achieved better permeability at lower mix moisture contents. The mean granule size (Figure 3a) and bed voidage (Figure 3b) were also measured for each blend as a function of mix moisture content. The mean granule size and bed voidage are quite comparable at the optimum mix moisture content for the blends containing different types of solid fuel.

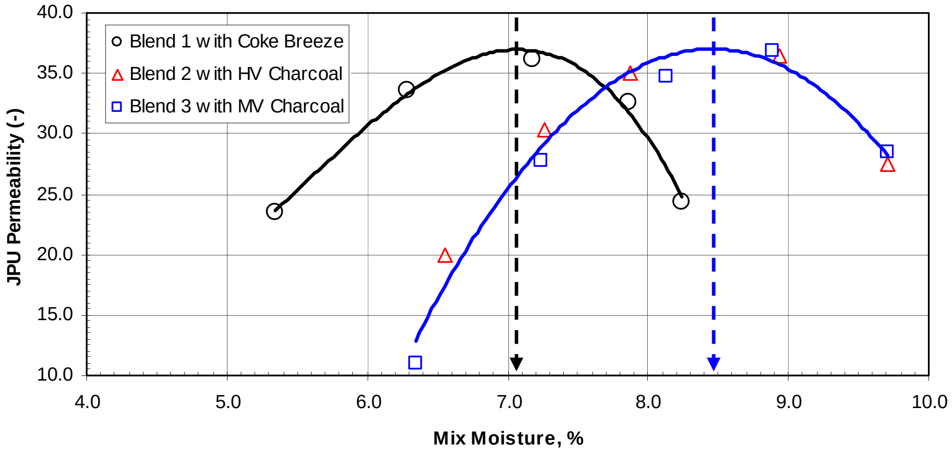
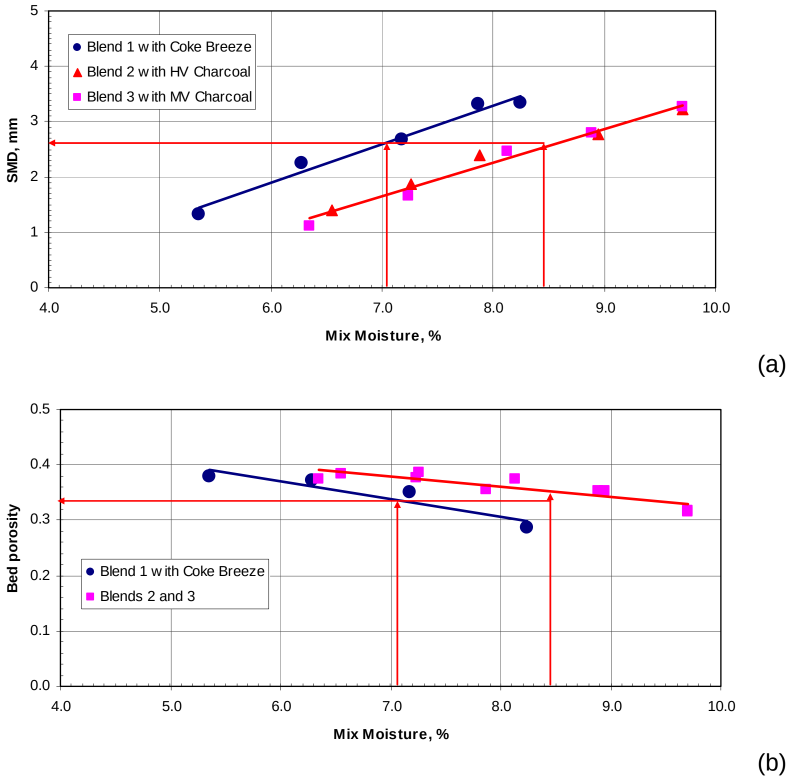


Figure 2. Permeability calculated in JPU and measured at a pressure drop of 6 kPa across the green granule bed.



(a)

(b)

Figure 3. (a) Sauter Mean Diameter (SMD) and (b) bed porosity of granules from the blends containing HV and MV charcoals as well as coke breeze.

3.3 Sintering Characteristics of Blends Containing Different Types of Solid Fuel

3.3.1 Blends containing HV and MV charcoals

High and medium volatile charcoals were first used to substitute for coke breeze in Blends 2 and 3, respectively. Figure 4a compares the sinter return fines balance ratio achieved for the blends containing coke breeze, HV charcoal and MV charcoal, respectively. While increasing the fuel addition level from 4.2 to 4.7% did improve the RFB (Return fines balance) ratio from 2.42 to 1.66 for Blend 2 and to 1.34 for Blend 3, both blends failed to achieve balance even at the fuel addition level of 4.7%. In contrast, Blend 1 containing coke breeze achieved the balanced outcome at a low fuel addition level of 3.9%. As shown in Figure 4a, compared with the sinter from Blend 1, the sinter from both Blends 2 and 3 had a considerably lower sinter FeO content, suggesting substantially lower flame front temperatures. This was not expected as Blends 2 and 3 contained considerably higher amounts of fuel and the charcoal samples had similar or better calorific values compared with the coke breeze used in Blend 1.

Figure 5 shows the waste temperature profiles recorded during the test runs of the different blends containing. Compared with Blend 1 (coke breeze), both Blends 2 and 3 showed narrower waste temperature profiles, suggesting a narrower flame front within the sintering bed. A narrow flame front is expected to reduce the consolidation time of the sintering bed (leading to a weak sinter structure) whilst improving the permeability of the flame front during sintering (resulting in a fast sintering process). Also evident in Figure 5, the blends containing HV and MV charcoals achieved a lot higher waste temperatures than Blend 1. This, together with a highly permeable sintering bed, suggested a large proportion of the combustion energy was carried away from the flame front by the waste gas as sensible heat. As a result, both

Blends 2 and 3 produced a low temperature flame front, as demonstrated by the low FeO content of sinter formed from Blends 2 and 3. A low temperature, narrow flame front will inevitably reduce the degree of melting and consolidation in the sintering bed, consequently decreasing the degree of bonding between granules. As a result, an imbalanced and weak sinter structure was produced. As the HV and MV charcoals had similar or better calorific values than coke breeze, the combustion kinetics, or reactivity of charcoals is likely to be responsible for the low-temperature, narrow flame front observed for the blends containing HV and MV charcoals. Furthermore, a lower green bed bulk density (Figure 4b) would also contribute to a weaker sinter structure for the blends containing high and medium VM charcoals.

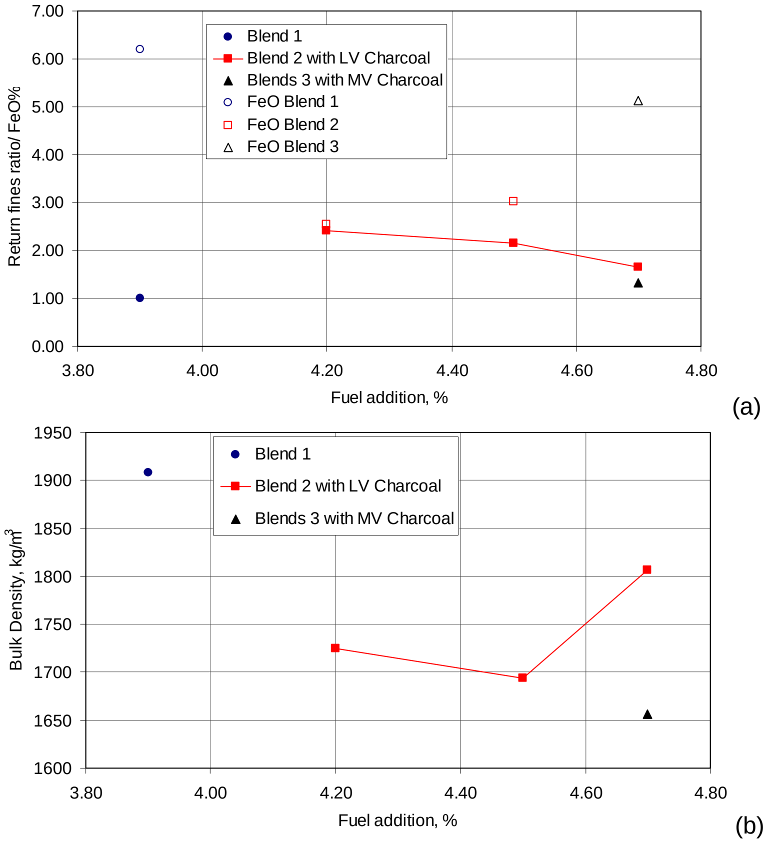


Figure 4. (a) Return fines ratio and FeO content of sinters fired at different fuel addition levels and (b) green bed bulk density achieved, for Blends 1-3.

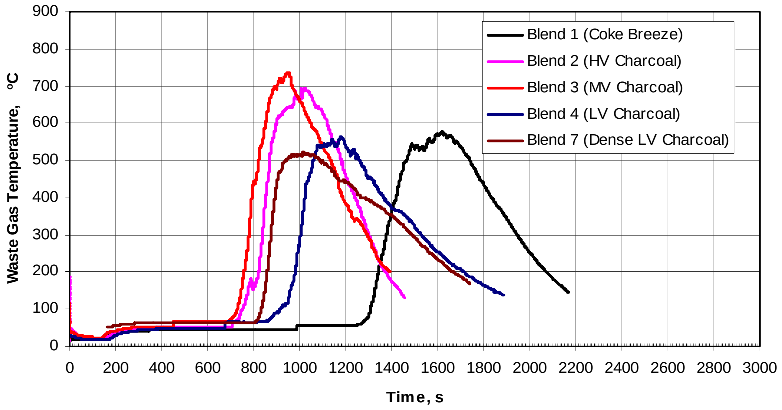


Figure 5. Waste gas temperature profiles recorded during the test runs for the blends containing different types of solid fuel.

3.3.2 Blends containing LV charcoals

The average optimum sintering performance and sinter quality of the blends using coke breeze (Blend 1), LV charcoal (Blend 4) and a dense LV charcoal (Blend 7) are compared in Figure 6. Unlike the HV and MV charcoals, both LV charcoals were able to achieve return fines balance. As shown in Figures 5 and 6, the blends containing both LV charcoals had a waste temperature profile and sinter FeO content close to those for Blend 1, suggesting improved combustion characteristics and flame front temperature. However due to higher mix moisture contents and combustion characteristic, more solid fuel was needed for Blends 4 and 7. As a result, substitution of charcoal increased the fuel rate substantially to achieve balance and sinter quality for Blends 4 and 7. However, compared with Blend 4 (69.8 kg/t-sinter), Blend 7 (dense LV charcoal) was balanced at a fuel rate of 61.8 kg/t-sinter which is reasonably close to that for Blend 1 (55.2 kg/t-sinter).

Compared with the Base Blend (40.5 t/m^2.day), Blends 4 (LV charcoal) and Blend 7 (dense LV charcoal) achieved much better sintering productivities of 45.2 and 53.5 t/m^2.day, respectively. The unique combustion characteristics of charcoals is likely to have contributed to improved productivity for Blends 4 and 7.

Under optimum firing conditions, the resultant sinter from Blends 4 and 7 had excellent reducibility as evidenced by their reducibility index, RI (71.8 for Blend 4 and 74.5 for Blend 7), good resistance to reduction degradation as shown in their reduction disintegration index, RDI (31.0 for Blend 4 and 29.7 for Blend 7) and good to reasonable strength as indicated by the tumble index TI (69.1 for Blend 4 and 65.6 for Blend 7). These are all above the minimum quality required for sinter produced from pilot-scale pot tests. Compared with Blend 1 sinter, Blend 7 sinter was slightly weaker in tumble strength while Blend 4 sinter was slightly stronger.

Hence, it is possible to achieve return fines balance and sinter quality while maintaining high sintering productivity by fine tuning the charcoal structure and combustion characteristics. This was achieved by reducing the volatile matter content of the charcoal. The slightly higher fuel rate may be justified through its advantages in improving sintering productivity and reducing greenhouse emissions from iron ore sintering operations.

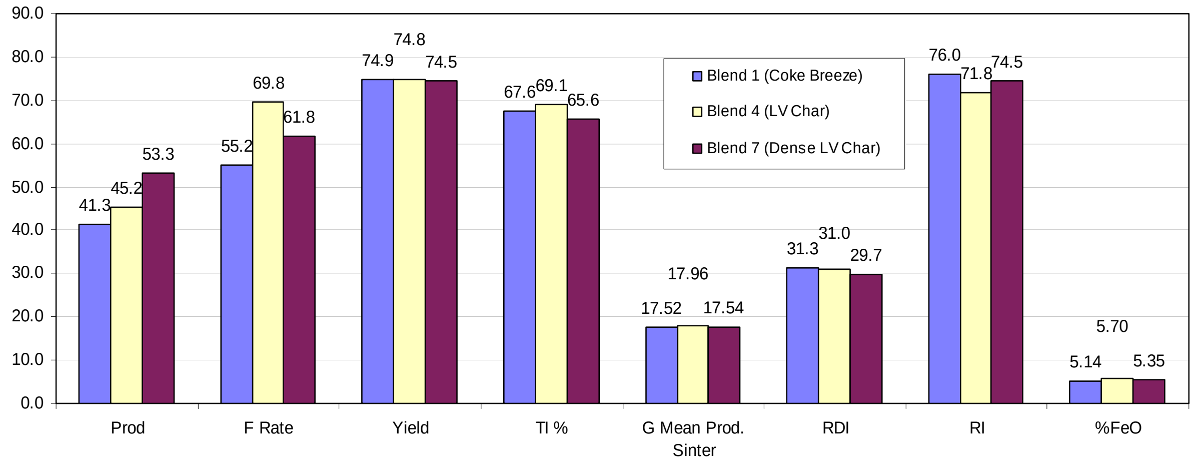


Figure 6. Average sintering performance: yield (%), fuel rate (kg/t-sinter) and productivity (t/m^3 day), and sinter quality: FeO (%), TI (%+6.3mm), RDI (%-2.8mm), RI (%) and mean product diameter (mm).

4 CONCLUSIONS

The use of charcoal as an alternative fuel to coke breeze in a simulated Japanese Steel Mills (JSM) sinter blend was investigated. The results have demonstrated that it is possible to achieve return fines balance and sinter quality, while maintaining high sintering productivity, by fine tuning the charcoal structure and combustion characteristics. The influence of charcoal types on the granulating and sintering characteristics of the JSM sinter blend is summarised below:

- Compared with coke breeze, higher mix moisture contents were required for sinter mixtures containing charcoals to achieve optimum granulation. The sinter blends containing different charcoal types showed similar granulation characteristics.
- Compared with coke breeze, the sinter mixtures containing charcoals generally needed higher fuel rates, sintered faster, and produced weaker sinter. However under the optimum firing conditions, the resultant sinter from Blends 4 (LV charcoal) and 7 (dense LV charcoal) had excellent RI, good RDI and good to reasonable TI, which are all above the minimum quality required for the sinter from pilot-scale pot tests.
- The volatile content and density of charcoals were found to be important parameters. As the residual volatile content of charcoals decreases and the density increases, the sinter fired at the same fuel addition level becomes stronger, reflected by the return fines balance, sinter yield, sinter tumble strength and mean product sinter size.

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