Improving the Softening and Melting Properties of Ferrous Burden with High Al_2O_3 Content for Blast Furnace by Ore Blending

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(Received on January 6, 2020; accepted on April 2, 2020)

In order to solve the problem of poor gas permeability of blast furnace caused by high Al_2O_3 content in the burden, the softening and melting properties of sinter, pellets and lump ores are studied in this paper. The results show the differences between acid and basic iron ore materials. Based on this, this article study the influence of different kinds of pellets and lump ores blending with sinter on the softening and melting properties of comprehensive burdens. The results show that the self-fluxing pellet and porous lump ore with high aluminium content caused the Al_2O_3 content of comprehensive burden to raise 0.26% compared to acid pellet and dense lump ore with low aluminium content. However, the highest pressure drop of comprehensive burden is reduced from 2.50 kPa to 1.70 kPa, the S-value is decreased from 198 $\text{kPa}\cdot^\circ\text{C}$ to 114 $\text{kPa}\cdot^\circ\text{C}$. Therefore, this method of ore blending will improve the softening and melting properties of integrated burden.

KEY WORDS: blast furnace; permeability; softening and melting property; high aluminium content; primary slag.

1. Introduction

The cohesive zone has significant influence on the blast furnace operational performance and productivity through the dissection of blast furnace.^{1–3)} The softening and melting properties of ferrous burden determines the shape, position and thickness of cohesive zone. It has a signification effect on the distribution of reducing gas, the reduction of iron ore and the fuel rates, which are really important for blast furnace operation.^{4–7)} Much work have been done about the softening and melting behaviors of sinter, pellet, and lump ore, and they are different from one another.^{8–10)} It is generally agreed that the performance of lump ores is inferior to sinter.^{11–13)}

Though the lump ore don't perform as well as sinter in blast furnace, blast furnace may still use a certain amount of lump ore and pellet to reduce the cost of production. However, the increasing scarcity of good quality iron ores has led to the alumina content of iron ore increased year by year and caused many problems on blast furnace operation. It has been found that with the increase of Al_2O_3 content in ferrous burden, the viscosity of slag increased,^{14,15)} the pressure drop became higher and the gas and liquid permeability in blast furnace became worse.^{16–18)} It's important to understand the effect of Al_2O_3 content on softening and melting properties of different ferrous burden and find out how to increase the proportion of high Al_2O_3 content iron ores in the blast furnace.

In present work, softening and melting behaviors of sinter, two kinds of pellets and two kinds of lump ores with different Al_2O_3 content are studied by softening and melting tests. And then sinter blending with different kinds of pellets and lump ores are conducted to understand the effect of Al_2O_3 content on softening and melting properties. According to this, reasonable comprehensive ferrous burden is found out to reduce the bad effects of high Al_2O_3 content on permeability of blast furnace.

2. Experimental

The softening and melting tests are conducted in a softening-melting equipment with load device and the schematic diagram of the experimental apparatus and the heating curve are illustrated in **Fig. 1**. The conditions of raw materials are listed in **Table 1**. Iron ore samples having a layer thickness of 65 mm are charged in a graphite crucible. Coke with a layer thickness of 20 mm is placed over and below the iron ore samples. Subject to the condition of constant layer thickness, sample mass in each experiment is different depending on the apparent density of iron ore. The weight of ore used in each experiment is about 190–210 g. It was impossible to observe the primary slag formation process directly as the internal of the softening-melting equipment is invisible. Therefore some indexes are used to evaluate the softening and melting behavior of iron ores. Typical softening and melting parameters and meanings are shown in **Fig. 2** and **Table 2**. Among them, S-value is the integral of pressure drop over the softening and melting temperature interval, which reflected the permeability of the soften and molten

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DOI: <https://doi.org/10.2355/isijinternational.ISIJINT-2019-833>

Fig. 1. Experimental apparatus (a) and heating curve of softening and melting tests (b).

Table 1. Experimental conditions of the softening and melting tests.

Items	Details
Sample bed diameter	48 mm
Initial sample height	65±5 mm
Ore size	10–12.5 mm
Coke size	6.3–10 mm
Upper/Lower coke layer	20±1 g

Table 3. Chemical compositions and reduction index (RI) of the iron bearing materials.

Samples	Chemical compositions wt%								RI/%
	TFe	FeO	SiO ₂	Al ₂ O ₃	CaO	MgO	LOI	Basicity	
S	57.43	8.24	4.98	1.76	9.41	1.66	–	1.89	82.4
P-A	64.65	0.55	5.93	0.35	0.30	0.59	0.13	0.05	69.8
P-B	65.65	1.29	2.48	0.76	2.73	0.03	0.15	1.10	75.7
L-A	65.57	0.69	4.37	1.01	0.21	0.02	0.55	0.05	54.5
L-B	57.40	1.20	5.10	2.61	0.38	0.01	9.71	0.07	77.9

Table 2. Typical softening and melting parameters and meanings.

Parameters	Meanings
T _{10%}	Softening start temperature (K): Temperature when the shrinkage of samples reaches 10%
T _{pr}	Melting start temperature (K): Temperature of pressure drop rising rapidly (the temperature when the slope of pressure drop-time curve reaches 0.15 kPa/min)
T _{pm}	Melting complete temperature (K): Temperature of pressure drop reaches maximum
ΔT	Temperature interval of softening and melting (K): T _{pm} –T _{10%}
ΔP _m	Highest pressure drop (kPa)
S-value	The integral of pressure drop over the softening and melting temperature interval (kPa·°C)

Table 4. Proportions of respective iron ores/wt%.

Samples	Sinter	Pellet	Lump ore
Integrated burden A	77% S	9% P-A	14% L-A
Integrated burden B	70% S	12% P-B	18% L-B

Table 5. Chemical compositions of the integrated burdens/wt%.

Samples	TFe	SiO ₂	Al ₂ O ₃	CaO	MgO	Basicity
Integrated burden A	59.22	4.98	1.53	7.30	1.33	1.47
Integrated burden B	58.41	4.74	1.79	6.98	1.17	1.47

Fig. 2. A typical set of softening and melting behaviors.

layer.

The equation of S value is shown as Eq. (1).

$$S = \int_{T_{10\%}}^{T_{pm}} P_t dT \dots\dots\dots (1)$$

where P_t is the pressure drop for the samples at intervening temperatures.

Raw materials used in this work are sinter (S), acid pellet (P-A), self-fluxing pellet (P-B), dense lump ore (L-A) and porous lump ore (L-B). The reduction index of five samples is measured according to China's National Standard GB/T 13241-2017. The chemical compositions and reduction index (RI) are shown in Table 3. Based on the chemical compositions of iron ores shown in Table 3, two kinds of integrated burden with different Al₂O₃ content are designed

to study the effect of Al_2O_3 content on softening and melting properties of burdens. The proportions and compositions of integrated burdens are shown in **Tables 4** and **5**.

3. Results and Discussion

3.1. Softening and Melting Test of Different Ferrous Burden

The results of softening and melting tests of single kind of sinter, pellets and lump ores are shown in **Fig. 3**, the detailed typical softening and melting parameters are listed in **Table 6**.

Softening start temperature ($T_{10\%}$) determines the upper position of cohesive zone in blast furnace. The lower softening start temperature means the higher position of cohesive zone, and therefore has bad effects on blast furnace operation. It is found in **Table 6** that the softening start temperature of sinter is the highest, which indicates that the

softening property of sinter is better than the others. The softening start temperature of self-fluxing pellet P-B is obviously higher than that of acid pellet P-A because of higher CaO content. The low softening point minerals of acid pellet P-A in early stage is mainly fayalite ($2\text{FeO}\cdot\text{SiO}_2$). There is much CaO in self-fluxing pellet P-B and the low soft-

Table 6. Typical softening and melting parameters of the ferrous burden materials.

Samples	$T_{10\%}/\text{K}$	T_{pr}/K	T_{pm}/K	$T_{pm}-T_{10\%}/\text{K}$	$\Delta P_m/\text{kPa}$	S-value/ $(\text{kPa}\cdot^\circ\text{C})$
S	1 472	1 758	1 808	336	2.54	155
P-A	1 353	1 618	1 733	380	2.81	255
P-B	1 445	1 672	1 674	229	2.02	27
L-A	1 446	1 655	1 723	277	2.91	191
L-B	1 164	1 743	1 786	622	3.62	176

Fig. 3. The temperature, shrinkage and pressure drop curves of L-A (a), L-B (b), P-A (c), P-B (d) and S (e).

ing point minerals are mainly $2(\text{Fe,Ca})\text{O}\cdot\text{SiO}_2$ and a small amount of dicalcium silicate ($2\text{CaO}\cdot\text{SiO}_2$). The softening start temperature of lump ore L-B is obviously lower than L-A. It is because that L-B is more porous than L-A and it contains much more Al_2O_3 , which would lead to the formation of compound in low melting temperature.¹⁹⁾

The temperature interval of softening and melting ($T_{\text{pm}}-T_{10\%}$) reflects the thickness of the soften and molten layer, which influences the 2-dimension distribution of reduction gas in the blast furnace. Table 6 shows that the thickness of soften and molten layer formed by P-B is thinner than P-A though Al_2O_3 content of pellet P-B is higher than P-A, which indicates that the self-fluxing pellet could accept much more Al_2O_3 while keeping a good permeability. The thickness of soften and molten layer formed by L-B is the thickest due to the lowest softening start temperature ($T_{10\%}$) and higher melting complete temperature (T_{pm}).

The S-value reflects the permeability of soften and molten layer. The smaller S-value is, the better permeability of soften and molten layer is. The S-value of P-B is smaller than P-A which also indicates that the self-fluxing pellets could accept more Al_2O_3 . Though the Al_2O_3 content and the highest pressure drop of L-B is higher than L-A, the time during melting of L-B is shorter according to the Fig. 3 which results in that the S-value of L-B is not the highest.

To figure out the factors affect softening and melting properties further, the primary slag are extracted and analyzed. The experiments are interrupted when the pressure drop reached the highest point, and then collected the primary slags of different iron ore samples. X-ray Fluorescence (XRF-1800) is used to analyze the chemical composition of primary slags. The melting temperature and viscosity at 1 723 K of slags are calculated by software FactSage 6.4 based on the chemical composition of primary slag. The Equilib (Databases: FToxid, FactPS) and Viscosity modules of the software FactSage6.4 are used to calculate the melting temperature and viscosity of the slag, respectively. The results are shown in Table 7. Besides, the diffraction patterns of 5 kinds of iron ore samples are tested by X-ray Diffraction (Rigaku D/MAX-2500) and the results are shown in Fig. 4.

The primary slag of sinter S and self-fluxing pellet P-B contains more CaO because of their basicity compared with other acid samples. The FeO in sinter S and pellet P-B are less than other acid iron ores because of better reducibility. Besides, the viscosity of their primary slag at 1 723 K is lower, so sinter S and pellet P-B performed better softening and melting properties.²⁰⁾

The FeO content in primary slag of P-A is much higher

than other iron ore samples. It is because that the SiO_2 content in gangue is higher and the fayalite ($2\text{FeO}\cdot\text{SiO}_2$) formed during reduction process and then the activity of FeO reduced, restrained the further reduction. With higher content of FeO and higher viscosity of primary slag than P-B, P-A performs worse softening and melting properties though its Al_2O_3 content is lower.²¹⁾

The structure of L-B is porous so that the reduction degree is higher in initial reduction process and produced much liquid phase. The produced liquid phase obstructs the contact between reducing gas and the ore and restrains its further reduction. It results the FeO content and the melting complete temperature of L-B little higher. And the cohesive zone formed by lump ore L-B is the widest and has the highest position in the blast furnace.

Besides, according to the X-ray diffraction patterns of the primary slags shown in Fig. 4, the primary slags of

Fig. 4. X-ray diffraction analysis of the primary slags.

Table 7. The chemical composition and thermodynamic characteristics of the primary Slag.

Samples	$\text{SiO}_2/\%$	$\text{Al}_2\text{O}_3/\%$	$\text{CaO}/\%$	$\text{MgO}/\%$	$\text{FeO}/\%$	Melting Temperature/K	Viscosity/Pa·s
S	26.51	9.31	49.74	6.84	7.60	1 859	0.136
P-A	53.03	6.01	3.47	3.79	33.70	1 680	1.206
P-B	37.85	11.67	44.78	0.66	5.04	1 570	0.307
L-A	63.72	16.76	2.65	0.54	16.33	1 709	92.233
L-B	54.71	23.59	1.92	1.17	18.61	1 576	18.329

acid iron ore samples contains more SiO_2 , some in the form of free SiO_2 and some combining with Al_2O_3 and FeO . There is barely CaO in primary slags of acid iron ore samples but much in basic. Some CaO in primary slags of basic iron ore samples combining with SiO_2 forms dicalcium silicate ($2\text{CaO}\cdot\text{SiO}_2$) and monocalcium silicate ($\text{CaO}\cdot\text{SiO}_2$), some combining with SiO_2 and Al_2O_3 formed melilite ($2\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{SiO}_2$).

According to the phase diagrams of Al_2O_3 - SiO_2 - FeO and CaO - SiO_2 - FeO shown in Figs. 5 and 6, the slag of acid ferrous is mainly formed by FeO , SiO_2 and Al_2O_3 in early stage and the low melting point minerals is mainly fayalite ($2\text{FeO}\cdot\text{SiO}_2$). There is much CaO in basic samples and the low melting point mineral is mainly $2(\text{Fe,Ca})\text{O}\cdot\text{SiO}_2$ (1 503 K), whose melting point is higher than fayalite (1 481 K). So the position of cohesive zone formed by basic iron ore is lower than acid one. Along with the reduction process, the FeO content in slag reduces and the minerals in slag change. New minerals generated in acid iron ore samples are mainly $3\text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$ (2 213 K) and SiO_2 (1 996 K). New minerals generated in basic iron ore samples are $2\text{CaO}\cdot\text{MgO}\cdot 2\text{SiO}_2$ (1 727 K), $2\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{SiO}_2$ (1 866 K), $2\text{CaO}\cdot\text{SiO}_2$ (2 426 K) and $\text{CaO}\cdot\text{SiO}_2$ (1 823 K).^{22,23} So the primary slags formed by acid iron ores have higher melting point and higher viscosity. Higher temperature is needed to separate with hot metal and the thickness of cohesive zone is much thicker. So the acid iron ore materials performs worse softening and melting properties than basic.

3.2. Softening and Melting Test of Integrated Burdens

Based on the tests of softening and melting properties of sinter, pellets and lump ores, the softening and melting prop-

erties of different integrated burdens with different Al_2O_3 content are conducted according to Table 4. The results are shown in Fig. 7 and Table 8.

It must to be noted that the shrinkage ratio of L-B shows 30% shrinkage at 900°C in Fig. 3(b), while Fig. 7(b) which is considered to contain L-B did not shows such behavior. As listed in Table 6, the softening temperature ($T_{10\%}$) of lump ore L-B is 1 164 K, which is lower than that of other iron ores. The reason is that there is plenty of FeO in iron ores at $T_{10\%}$, so the initial phase of primary slag for acid iron ores is fayalite ($2\text{FeO}\cdot\text{SiO}_2$) of lower melting point. What is more, the high porosity makes lump ore L-B easy to reduce and more fayalite is produced at low temperature, so its softening temperature is much lower than other acid iron ores. Therefore, the lump ore L-B shows 30% shrinkage at 900°C. Figure 7(b) shows the softening and melting properties of Integrated burden B consisting of sinter S, lump ore L-B and pellet P-B. As listed in Table 8, the $T_{10\%}$ of the Integrated burden B is 1 382 K. This is because the high temperature interaction between lump ore L-B and sinter S. When sinter mixed with lump ores, the excess CaO from sinter would interact with Al_2O_3 and SiO_2 from lump ores at high temperature, thus the softening and melting behaviors of integrated burdens would be improved. The Al_2O_3 and SiO_2 would diffuse to the interface between sinter and lump ores. And this diffusion would decrease the content of fayalite in lump ores and increase the content of olivine or wollastonite in sinter, thus the initial primary-slugs phases of integrated burdens would be fayalite, wollastonite and olivine. So the results of Fig. 7(b), which contains lump ore L-B, do not shrink at 900°C.

As the results of the test, softening start temperature,

Fig. 5. Phase diagram of Al_2O_3 - SiO_2 - FeO .

 Fig. 6. Phase diagram of CaO-SiO₂-FeO.

Fig. 7. The temperature, shrinkage and pressure drop curves of burden A (a) and B (b).

Table 8. Typical softening and melting parameters of different comprehensive burdens.

Samples	$T_{10\%}/K$	T_{pr}/K	T_{pm}/K	$T_{pm}-T_{10\%}/K$	$\Delta P_m/kPa$	S-value/ (kPa·°C)
Integrated burden A	1 441	1 713	1 786	345	2.50	198
Integrated burden B	1 382	1 692	1 704	322	1.70	114

melting temperature and melting complete temperature of burden B are all lower than those of burden A. The position of cohesive zone formed by burden B is little higher than burden A. But the temperature interval of softening and melting ($T_{pm}-T_{10\%}$) of burden B is lower than that of burden A, the thickness of soft and molten layer formed

by burden B is thinner. Besides, the S-value of burden B is smaller than burden A. The permeability of cohesive zone formed by burden B is better than burden A.

Though the ratio of high Al₂O₃ content pellet and lump ore from burden A to B increased, the permeability of cohesive zone improves. It is because that the self-fluxing pellet and porous lump ore is used in burden B. So the proportion of self-fluxing pellets and porous lump ores should be increased when high Al₂O₃ iron ores be used in the blast furnace.

The chemical compositions and thermodynamic parameters of primary slags formed by composite burdens are listed in Table 9. The X-ray diffraction patterns are shown in Fig. 8.

It must be noted that FeO content in integrated burdens is lower than that in each ore materials. I think there are two

Table 9. The chemical compositions and thermodynamic characteristics of the primary slag.

Samples	SiO ₂ /%	Al ₂ O ₃ /%	CaO/%	MgO/%	FeO/%	Melting Temperature/K	Viscosity/Pa·s
Integrated burden A	31.87	8.25	50.68	7.36	1.84	1 986	0.270
Integrated burden B	29.92	12.25	49.48	7.10	1.25	1 890	0.287

Fig. 8. X-ray diffraction analysis of integrated burden A and B.

possible reasons for this result. One is the “ore window”. The softening and melting behaviors of the five types of raw materials are distinct from each other and one iron ore softens while others almost retain their shape. For instance, P-A softens much earlier than the other two raw materials, and these two samples play the role of coke in the cohesive zone. It is named ore window and helps to guarantee the gas permeability of ore layer in the cohesive zone. The improvement of the permeability of the ore layer is beneficial to the reduction. The second is high-temperature interaction. When sinter mixed with lump ores or pellets, the high temperature interaction would change the primary-slugs formation behaviors of integrated burdens. For instance, the excess CaO from sinter would interact with Al₂O₃ and SiO₂ from lump ores at high temperature. And this diffusion would decrease the content of 2FeO·SiO₂ in lump ores. FeO released from lump ore is easier to reduce than fayalite.

It can be seen that the melting temperature of primary slag of burden B is much lower than A, and the viscosity at 1 673 K of the primary slags are almost the same. The minerals in primary slags are mainly 2CaO·MgO·2SiO₂, 2CaO·Al₂O₃·SiO₂ and 3CaO·MgO·2SiO₂. The minerals of different comprehensive burdens are almost the same, so the existing states of Al₂O₃ don't change the mineral constituent of comprehensive ferrous burdens. According to the results all above, the gas permeability, softening and melting properties of burden B are better than A.

As the above results showed, the softening and melting

behavior of lump ore L-B is worse in single iron ores, but the softening and melting behavior of integrated burden B (consist of sinter, L-B and P-B) is not worse than integrated burden A. This is because that the basic sinter would interact with acid iron ores at high temperature due to the difference of chemical compositions. The detailed procedure of high-temperature interaction has been discussed in former studies^{24–27} and the mechanism of high-temperature interaction is summarised as follows: the sinter of high basicity has more CaO than necessary and the lump ores and acid pellet could supply plenty of SiO₂ and Al₂O₃, obvious diffusion of Ca, Al and Si elements would happen between the interface at high temperature when the sinter is mixed with acid iron ores. The phase compositions of primary slag are changed by the high-temperature interaction, which would improve the softening and melting behavior of integrated burdens.

The high-temperature interaction is largely influenced by the chemical compositions, pore structure and contact condition. The high SiO₂ and Al₂O₃ content provides higher reaction driving force of high-temperature interaction and the high porosity of lump ore L-B offers more ‘channels’ for the diffusion of reactive oxides. Besides, the contact between sinter and lump ores are more sufficient because that there is a ‘surface contact’ between sinter and lump ore, while it is ‘point contact’ between sinter and pellet. Therefore, the high-temperature interaction between sinter and lump ore L-B is much intense than that between sinter and other acid iron ores.

The temperature ranges of cohesive zones for blast furnace burden A and B are almost the same, while the cohesive zone permeability of the latter is much better than that of the former. Although the blast furnace burden B contained 18% poor quality iron ores L-B, its softening and melting behavior is not worse than that of blast furnace burden A (containing 14% high quality lump ores). The main reason is that the strong high-temperature reactivity between sinter and L-B improves the softening and melting behavior of blast furnace burden B. And the softening and melting behavior of self-fluxed pellet P-B is better than other single iron ores, which is also good for the softening and melting behavior of blast furnace burden B. These results show that poor quality lump ores could be properly used by the high-temperature interaction to decrease its disadvantages to blast furnace operation.

4. Conclusions

The softening and melting properties of single kind of iron ores and integrated burdens are studied. Based on this, the influence of different kinds of pellets and lump ores on the softening and melting properties of compositive burden is discussed in this paper. Following conclusions are obtained from the above results.

(1) Though Al_2O_3 content in self-fluxing pellet P-B is higher than acid pellet P-A, the softening start temperature is higher, the highest pressure drop and the value of S are lower. So the softening and melting properties of self-fluxing pellet is better and it could contain more Al_2O_3 than acid pellet and kept good permeability of cohesive zone.

(2) The highest pressure drop of porous lump ore L-B with high Al_2O_3 content is higher than dense lump ore L-A, but the S-value is not worse than dense lump ore due to its better reducibility and shorter time during melting. So the porous lump ore could contain more Al_2O_3 than dense lump ore.

(3) The Al_2O_3 content of sinter blending with self-fluxing pellet and porous lump ore (burden B) is higher than sinter blending with acid pellet and dense lump ore (burden A), but its highest pressure drop and S-value are lower, the permeability of cohesive is improved.

(4) When it had to use high Al_2O_3 content ores for blast furnace, self-fluxing pellet and porous lump ore should be chosen in priority, but the Al_2O_3 content in acid pellet and dense lump ore still should be controlled.

Acknowledgements

This work is financially supported by the National Natural Science Foundation of China (Grant Number: 51904023, 51804027) and Fundamental Research Funds for the Central Universities (Grant Number: FRF-IC-19-004).

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