

Article

Relationship and Mechanism Analysis of Soft-Melt Dropping Properties and Primary-Slag Formation Behaviors of the Mixed Burden in Increasing Lump Ore Ratio

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Abstract: At present, cost reduction and environmental protection are the mainstream of blast furnace (BF) development and the high lump ore ratio is an effective means. Therefore, it is significant to explore the relationship and mechanism of burden soft-melt dropping and its primary-slag formation behaviors under increasing lump ore ratio. In this paper, the melt-drop test is carried out on the single ore and mixed burden, and obtained primary-slag properties are subjected to analysis. The experimental results show that the primary-slag of lump ore contains a large amount of FeO and SiO₂, so it simply produces many low melting point compounds, which cause terrible soft-melt dropping properties and primary-slag formation behaviors. Notably, mixing with sinter and pellet can effectively improve both the properties. With the increase in lump ore ratio, the CaO in the primary-slag decreases, FeO and SiO₂ increase, resulting in the melting temperature of the primary-slag sequentially decreasing and the cohesive zone moves to the low temperature zone. In addition, the maximum pressure difference increases, and the gas permeability deteriorates. Increasing the sinter ratio can overcome the defect of high lump ore ratio that can effectively improve the poor softening performance, melting performance and the position and thickness of the cohesive zone. However, because of the pulverization performance, the maximum pressure difference and gas permeability of the burden become worse.

Keywords: lump ore ratio; soft-melt dropping properties; primary-slag formation behaviors; slag phase transformation; formation mechanism

1. Introduction

At present, blast furnace (BF) is a high-efficiency mainstream ironmaking process that cannot be replaced and the problems it faces mainly include cost and environmental protection. The reasonable burden structure and BF slag system optimization play significant roles in stabilizing BF operation, reducing the production cost and improving the level of productivity [1–4]. However, increasing the ratio of lump ore into the BF can effectively reduce costs and pollution [5–8]. However, during the conversion of ferric oxide to trioxide, the unit cell will expand by 21%, resulting in pulverization, which will affect the permeability by increasing the lump ore ratio. What is more, the reduction in high sinter ore ratio will certainly affect the soft-melt dropping behaviors.

The ratio of lump ore used by companies in Japan and other Asian countries generally exceeds 15% and some even exceed 20%, which fully demonstrates that the ratio of high-quality lump ore into

the furnace between 10% and 20% will not have a large impact on the operation of the BF. It further proves the feasibility of the high-ratio lump ore into the furnace [5–8]. In Baosteel and Shougang, the ratio of lump ore directly entering the BF can reach 20%. However, some other domestic BFs find it difficult to reach 15% and some even produce full clinker smelting [9–11]. This is due to the lack of high-grade lump ore in our country. In recent years, the quality and grade of imported ore have also decreased, which leads to the reduction in the smelting economy of lump ore resources.

The ratio of lump ore has an important influence on the metallurgical properties of the burden and BF operation. In recent years, there are a large number of researchers exploring the function mechanisms of lump ore on softening–melting behaviors of mixed burden. Wu et al. considered that different types of lump ore have different effects on the soft-melt dropping properties and high-quality lump ore has a small impact on the soft-melt dropping properties of the mixed burden. Simultaneously its high temperature metallurgy can meet the requirements of the BF [12,13]. Zhang et al. found that, compared with a single burden, the reduction properties and low-temperature reduction pulverization properties of the mixed burden are superimposed, but the soft-melt dropping properties are not superimposed. In addition, a proper amount of high-quality lump ore ratio will not have a large impact on the ironmaking process [14–16]. Naito et al. revealed that raw materials smelting has a terrible impact on the BF operation, but the metallurgical properties can meet the requirements of BF smelting [17]. Besides, some researchers deem that the temperature range of the single ore primary-slag is wide and the interaction between mixed burden can improve the primary-slag formation behaviors. In addition, others explored the influence of different chemical components on the metallurgical properties of slag [18–25]. However, predecessors have not conducted a comprehensive study on the relationship between softening–melting and primary-slag formation behaviors on the cohesive zone under high lump ratio.

It is of great significance to explore the high-temperature metallurgical properties under high ratio lump ore ratio. This work systematically analyzes the soft-melt dropping properties and primary-slag formation behaviors of the charge under the condition of increasing the lump ore ratio and further analyzes their internal relations and the mechanism. It mainly uses large-scale soft-melt dropping equipment to select lump ore ratios of 15%, 20% and 25%, respectively. Then the obtained primary slags are subjected to chemical composition, slag phase composition and melting properties. Finally, the soft-melt dropping properties and primary-slag formation behaviors are explored, as well as their internal connections. This will provide a theoretical basis for exploring the influence of the ratio of lump ore on the whole BF ironmaking process.

2. Materials and Methods

2.1. Materials

The iron ores in the experiment are used in actual BF production, including sinter (S-1) with basicity of 1.80, pellet (P-1) and lump ore (O-1). The specific chemical compositions of the samples are shown in Table 1. The Fe_T mass fraction of S-1 is 58.51% and SiO_2 mass fraction is only 4.84%, which is a typical sinter with high iron, low silicon and high basicity. In addition, for P-1 with the contents of Fe_T , SiO_2 mass fraction sets as 66.54% and 2.03%, respectively. What is more, the Fe_T mass fraction of O-1 is 63.38% and the content of SiO_2 is 3.14%, which has high quality and can satisfy the normal smelting requirements.

Table 1. Chemical compositions of iron ore samples (mass fraction, %).

Sample	Fe_T	FeO	SiO_2	CaO	Al_2O_3	MgO	TiO_2	MnO	S
S-1	58.51	9.32	4.84	9.05	1.68	1.48	0.10	0.23	0.01
P-1	66.54	0.31	2.03	1.48	0.58	0.17	0.04	0.13	0.02
O-1	63.38	0.48	3.14	0.04	1.25	0.06	0.14	0.18	0.02

2.2. Experimental Procedure

The test uses a large-capacity iron ore soft-melt dropping detection device with independent intellectual property rights, which is shown in Figure 1. At present, the method for measuring iron ore high temperature load reduction soft-melt dropping properties (GB/T 34211—2017) only regulates the relevant operations and parameters of the experimental process of small drip equipment (500 g); this article, however, refers to large drip equipment (2000 g). The experimental dosage is more, the experimental results are more representative, and the reproducibility is better [26]. The test conditions are determined as follows: The specification of graphite crucible is $\varnothing 95 \text{ mm} \times 210 \text{ mm}$ and loads 1 kg/cm^2 of iron-bearing burden. In addition, 80 g of coke is laid under the burden layer, 60 g of coke is laid above and the full particle size is 8–12 mm. The heating system and ventilation system of the equipment are shown in Figure 2.

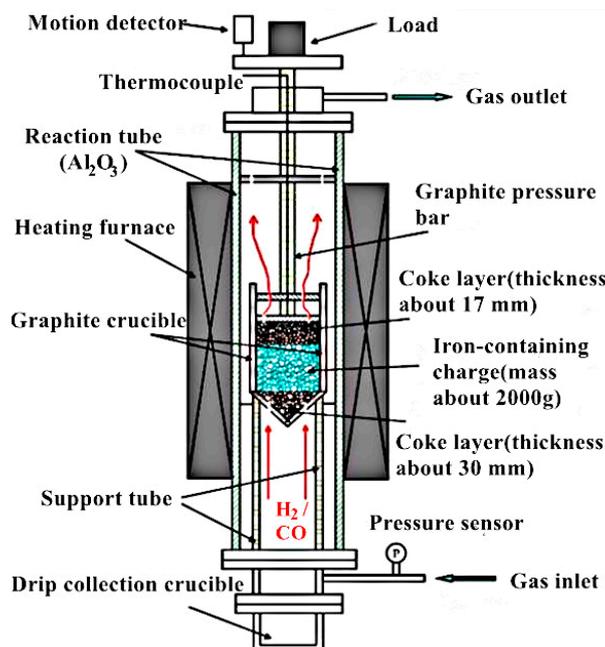


Figure 1. Schematic diagram of iron ores melting and dropping measuring device.

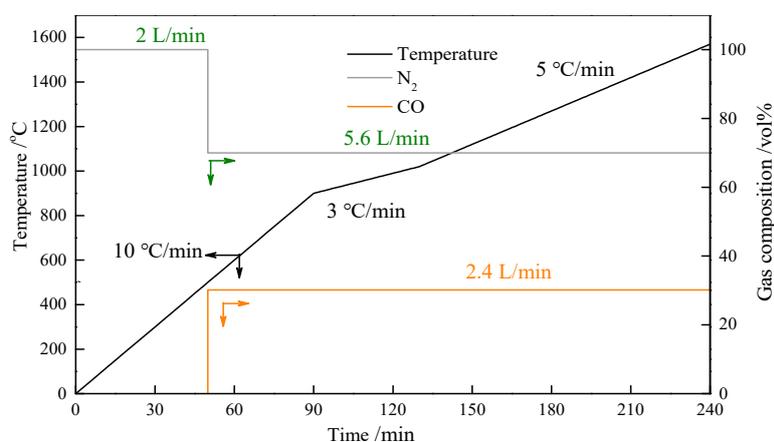


Figure 2. Heating and ventilation program.

2.3. Melting and Dropping Test Schemes

According to the actual production of BF burden alkalinity ($w(\text{CaO})/w(\text{SiO}_2)$) is generally 1.3–1.5 [27,28], the melt-drop experiment scheme selected in this work is shown in Table 2. Schemes 1–3 are three kinds of

single ore. Schemes 4–6 are the mixed burdens with the sinter ratio unchanged, the pellet ratio decreased, and the lump ore ratio increased. Schemes 7 and 8 keep the lump ore ratio constant at 25% and change other burdens' ratios.

Table 2. The schemes of melting and dropping experiment.

Scheme	S-1 Ratio	P-1 Ratio	O-1 Ratio	Basicity
1	100	0	0	1.87
2	0	100	0	0.73
3	0	0	100	0.01
4	55	30	15	1.44
5	55	25	20	1.40
6	55	20	25	1.36
7	65	10	25	1.45
8	75	0	25	1.54

3. Results and Discussions

3.1. Analysis of Softening and Melting Behaviors of Iron-Containing Burden after Increasing Lump Ore Ratio

3.1.1. Analysis of the Softening Behaviors

Shrinkage occurs in the softening process of the burden and the shrinkage rate of the burden can be calculated by Equation (1).

$$\Delta H = \frac{H_0 - H_T}{H_0} \quad (1)$$

where ΔH is the shrinkage rate of the burden at a certain temperature, %; H_T is the displacement of the displacement sensor at a certain temperature, mm; H_0 is the original height of the burden, mm.

The changes in the softening properties of the burden under different burden are shown in Figure 3.

Comparing the shrinkage curves a, b and c in Figure 3a, it can be seen that for the single ore, the T_0 (temperature at which the burden begins to shrink) and T_{10} (the temperature at which the burden shrinks 10% of the lump O-1) and T_{40} (the temperature at which the burden shrinks by 40%) are the smallest, and ΔT (the softening temperature range of the burden, $\Delta T = T_{40} - T_{10}$) is the widest at 169 °C. In comparison, T_0 and T_{10} of sinter are the largest, T_{40} is similar to pellet at 1300 °C and ΔT is the narrowest at only 94 °C. Pellet has the highest T_{40} at 1302 °C and T_0 , T_{10} and ΔT are between the other two types of single ore. In summary, the softening properties of sinter is the best, pellet is second and lump ore is the worst. This is because lump ore is mainly composed of limonite with loose structure and higher crystal water content. At the same time, it contains higher Al_2O_3 , which causes it to soften at a lower temperature [24]. High-basicity sinter and self-dissolving pellet have excellent metallurgical properties, strong resistance to deformation and relatively high softening temperature [27].

Comparing the shrinkage curves d, e and f in Figure 3b, when the S-1 ratio is constant: the O-1 ratio increases from 15% to 20%; T_0 increases by 9 °C; T_{10} decreases from 1172 °C to 1161 °C; T_{40} increases from 1290 °C to 1315 °C; ΔT increases by 36 °C. When the O-1 ratio increases from 20% to 25%: T_0 rises to 1099 °C; T_{10} , T_{40} , ΔT all decrease, but the change value is small. In summary, as the ratio of lump ore increases, the T_0 increases and T_{10} decreases in turn. Under the influence of lump ore, the softening properties first deteriorate sharply and as the ratio of lump ore further increases, its influence gradually weakens. The first reason is that as the high softening temperature pellet ratio decreases and the low softening temperature lump ore ratio increases; the second is that the SiO_2 content of the lump ore is higher. The increasing ratio makes it easier to react with FeO at lower temperatures and generate a large amount of low melting point compounds, resulting in a decrease in the T_{10} of the mixed burden [22,28].

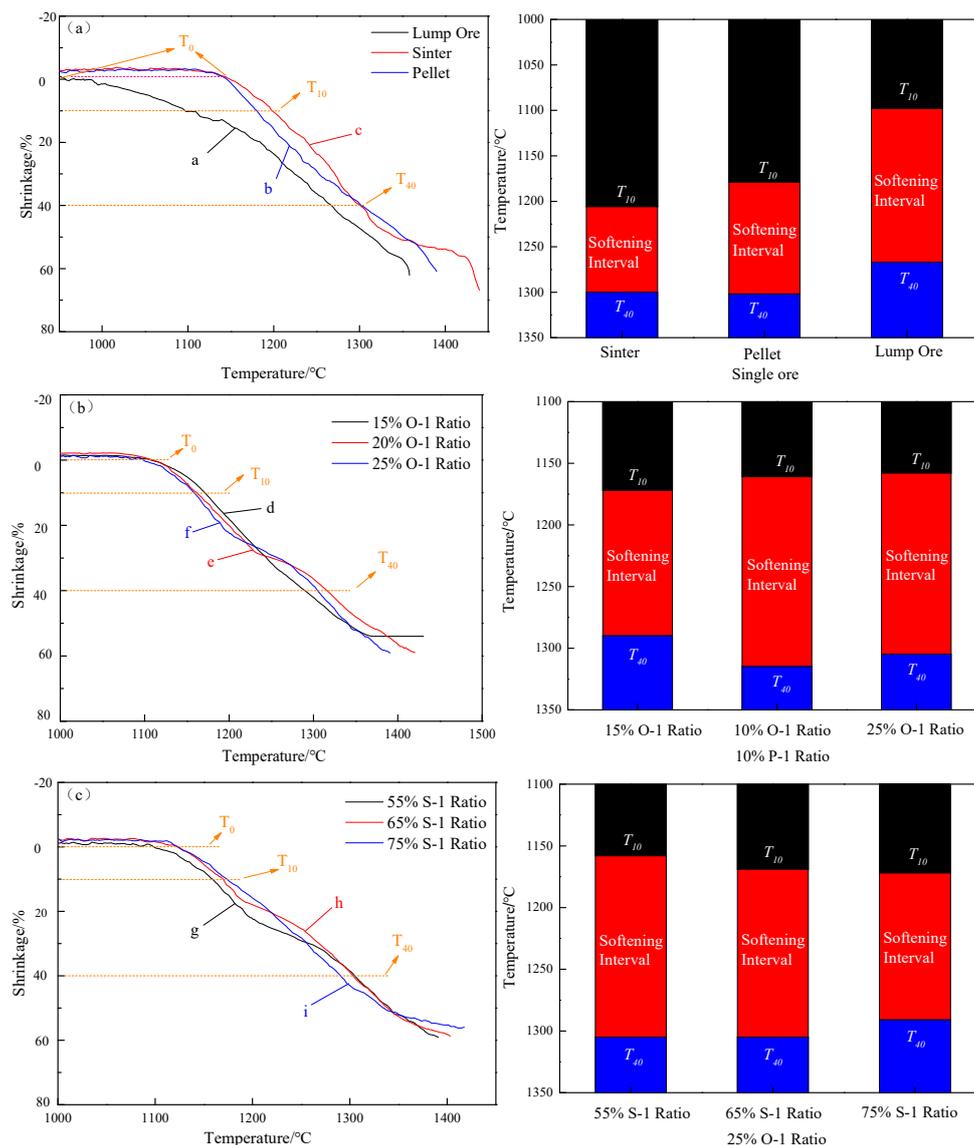


Figure 3. Changes in the softening properties of different burdens. (a) single ores; (b) 55% sinter ratio; (c) 25% lump ore ratio.

Comparing the shrinkage curves g, h and i in Figure 3c, it can be seen that when the O-1 ratio is 25%: the S-1 ratio increases from 55% to 65%; T_0 changes little; T_{10} increases by 11 °C; T_{40} of both is 1305 °C; ΔT is narrowed by 11 °C. When the S-1 ratio increased from 65% to 75%: T_0 rises to 1099 °C; T_0 drops 7 °C; T_{10} only increased 3 °C; T_{40} decreases 14 °C; ΔT reduces from 136 °C to 119 °C. In summary, as the sinter ratio increases successively, the T_0 of the mixed burden decreases, but the amplitude is not large; T_{10} increases; T_{40} , ΔT decreases. Properly increasing the sintering ratio can effectively improve the softening properties of the high lump ore ratio burden. The reason may be that as the high softening temperature sinter increases, the lower softening temperature pellet ratio decreases. The second is that the sinter phase is mainly calcium ferrite, which has better reduction properties. With the increase in its ratio, the FeO content is reduced. At the same time, the sinter contains higher MgO and CaO that can form a large number of high melting point compounds, which leads to the increase in the T_{10} of the mixed burden [20–22,28].

In summary, due to its own defects, lump ore has a lower softening temperature, a wide softening range and poor softening performance. However, the performance can be effectively improved by mixing ores, because the interaction between the burden has a positive effect on the softening

performance [12,13]. As the lump ore ratio increases, the T_{10} gradually decreases due to the increase in low melting point compounds. Under the condition of high lump ore ratio, increasing the high alkalinity sinter ratio can effectively suppress the disadvantages of lump ore.

3.1.2. Analysis of the Melting Behaviors

The changes in melting properties of the three single ore are shown in Figure 4a. O-1 has the lowest T_s (pressure difference steep rise temperature) and T_d (temperature at which the slag and iron drips), which are 1247 °C and 1358 °C, respectively. Additionally, ΔT_{ds} (burden melting temperature range, $\Delta T_{ds} = T_d - T_s$) is 111 °C. The maximum T_s of P-1 is 1321 °C, ΔT_{ds} is only 69 °C and T_d is between the other two. The T_d of S-1 is as high as 1439 °C, ΔT_{ds} is the largest and T_s is second only to pellet. Lump ore containing low melting point compounds has a lower melting temperature [11,16]. Thus, the charge melts at a lower temperature and blocks the gap of the material layer, causing the pressure difference to rise sharply at a lower temperature. At the same time, the high melting point compounds contained in it make its dropping temperature higher, so its melting range is wider. However, sinter and pellet containing a large amount of high melting point have a higher melting temperature and narrow melting range.

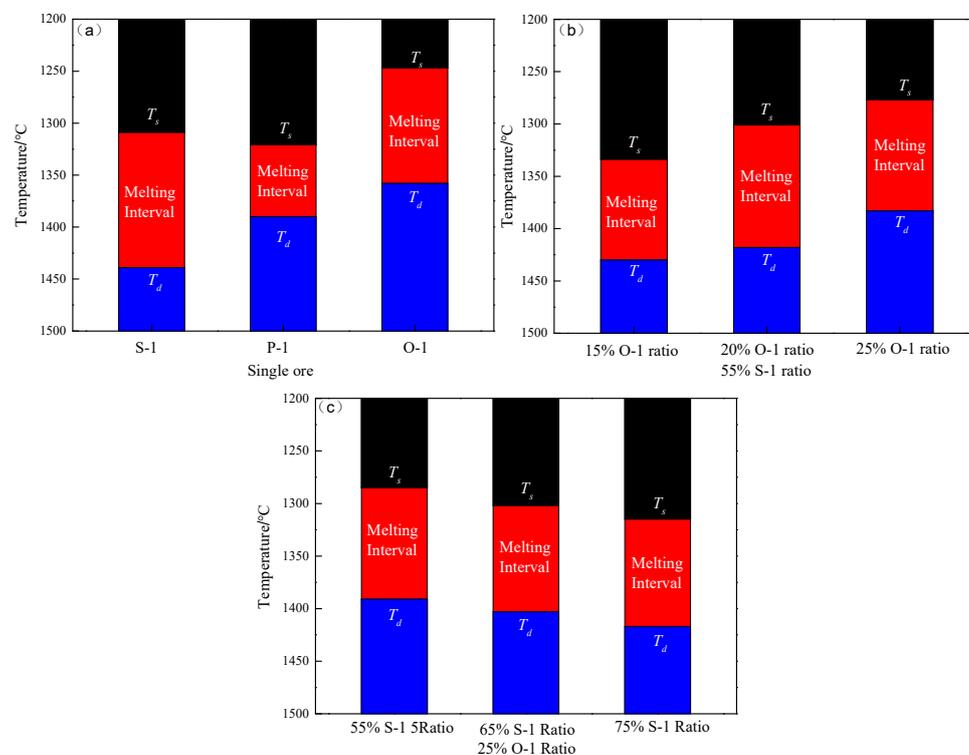


Figure 4. ΔT_{ds} of the different burdens. (a) single ores; (b) 55% sinter ratio; (c) 25% lump ore ratio.

The lump ore ratio increases from 15% to 25% and the melting characteristics of the mixed burdens are shown in Figure 4b. When the O-1 ratio increases from 15% to 20%, the T_s of the mixed burden decreases by 33 °C, the T_d decreases from 1430 °C to 1418 °C, the ΔT_{ds} increases by 21 °C. Meanwhile, the O-1 ratio increased from 20% to 25%, T_s dropped to 1285 °C, T_d dropped by 16 °C, ΔT_{ds} dropped from 117 °C to 106 °C. As the proportion increases, due to the increase in low melting point compounds, the melting start temperature decreases and the temperature at which molten iron appears is lower, which in turn leads to lower dropping temperature.

The sinter ratio increases from 55% to 75% and the melting characteristics of the mixed burden are shown in Figure 4c. When the S-1 ratio increases from 55% to 65%, the T_s of the mixed burden rises from 1285 °C to 1302 °C, T_d increases by 12 °C, ΔT_{ds} decreases by 5 °C and the melting properties

improve. When the S-1 ratio increased from 65% to 75%, T_s increased by 13 °C, T_d rose to 1417 °C, ΔT_{ds} only increased by 1 °C. With the increase in sinter with greater high melting point compounds, the melting temperature and dropping temperature of the mixed charge likewise increased.

In summary, the lump ore phase is complex, and the melting points of the compounds contained are quite different, so it has a lower T_s and a wider ΔT_{ds} . Further, mixed charge can also effectively improve its performance. When the O-1 ratio increases, the ΔT_{ds} moves to the low temperature area and the melting temperature interval becomes wider. This may be due to the decrease in P-1 with better melting properties and the formation of a large amount of low melting compounds. Under the condition of high lump ore ratio, appropriately increasing the sinter ratio can improve the melting properties of the mixed burden to a certain extent. This may be because the increase in S-1 has better melting properties. At the same time, the sinter contains higher MgO and CaO, forming a large amount of high melting point compounds, which leads to the increasing T_d of the mixed burden [27].

3.1.3. Analysis of the Maximum Pressure Difference

The change of ΔP_{max} (maximum pressure difference) of different burdens is shown in Figure 5. As shown in Figure 5a, the ΔP_{max} of lump ore is as high as 12.93 kPa, followed by sinter and pellet, which are the smallest at only 3.02 kPa. The thermal explosion performance of lump ore and the low-temperature reduction and pulverization performance of sinter are poor, resulting in more powder produced during the high-temperature reduction process, which seriously affects the air permeability of the ore layer. Meanwhile, the self-dissolving pellet has better metallurgical properties and strong toughness.

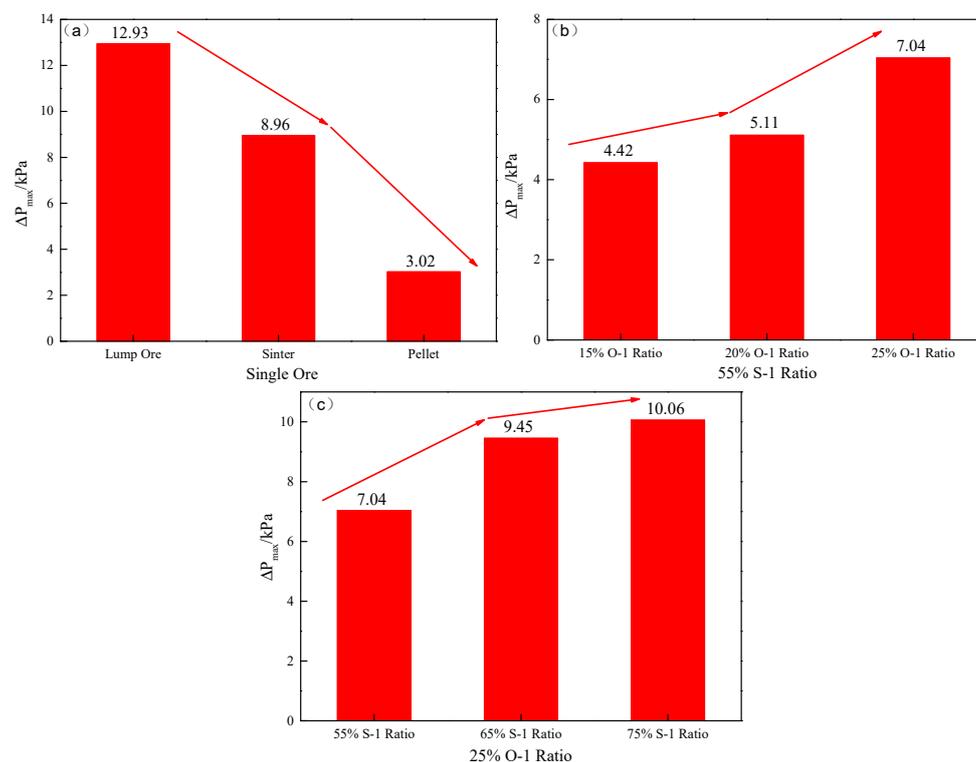


Figure 5. ΔP_{max} of the different burdens. (a) single ores; (b) 55% sinter ratio; (c) 25% lump ore ratio.

As shown in Figure 5b, when the sinter ratio is constant and the lump ore ratio increases from 15% to 20%, the ΔP_{max} of the mixed burden only increases by 0.69 kPa; while the lump ore ratio rises to 25%, the ΔP_{max} of the mixed burden further increases by 1.93 kPa. As the lump ore ratio increases, the powder produced by thermal explosion increases, which blocks the gaps in the material layer and increases the maximum pressure difference.

The control of the lump ore ratio at 25%, the sinter ratio increasing from 55% to 75% and the change of the mixed burden ΔP_{\max} is shown in Figure 5c. When the sinter ratio increased from 55% to 65%, ΔP_{\max} increased from 7.04 kPa to 9.45 kPa. However, as the sinter ratio continues to increase to 75%, the change range of ΔP_{\max} becomes smaller—only 0.61 kPa. As the ratio of sinter increases, the powder produced by low-temperature reduction and pulverization increases, which blocks the gaps in the material layer and increases the maximum pressure difference.

To sum up, due to its poor thermal explosion performance, lump ore produces more powder in the high-temperature reduction, resulting in a larger maximum pressure difference. However, the mixture can effectively reduce the maximum pressure difference. As the lump ore ratio increases, more powder is produced by high-temperature reduction and the maximum pressure difference increases sequentially. As the sinter ratio increases, the powder produced by low-temperature reduction powder further increases and the maximum pressure difference further increases.

3.1.4. Analysis of the Comprehensive Air Permeability

The comprehensive air permeability of the cohesive zone can be expressed by its index (S) and its calculation formula is as shown in Equation (2):

$$S = \int_{T_s}^{T_d} (\Delta P_T - \Delta P_s) dT \quad (2)$$

where ΔP_T is the pressure difference at temperature T and ΔP_s is the pressure difference at temperature T_s .

The change of the comprehensive air permeability index of different burdens is shown in Figure 6. The S value of the three kinds of single ore is shown in Figure 6a. The maximum S value of lump ore is 680 kPa·°C; the air permeability is the worst. The S value of pellet is only 221 kPa·°C; the air permeability is the best, and sinter is located between pellet and lump ore. Lump ore has a large ΔP_{\max} , while its melting temperature is low and the interval is wide, so its S value is large. Although the ΔP_{\max} of sinter is second only to lump ore, it has a higher T_s , T_d and a narrow ΔT_{ds} , so its S value is smaller than that of lump ore. However, the ΔP_{\max} of pellet is smaller, the melting performance is higher, and the gas permeability is the best.

As shown in Figure 6b, when the sinter ratio is constant and the lump ore ratio increases from 15% to 20%, the S value changes little, which has little effect on its air permeability. When the lump ore ratio increases from 20% to 25%, the S value increases from 273 kPa·°C to 434 kPa·°C and the air permeability becomes worse. According to the above, as the lump ore ratio increases, the maximum pressure difference increases successively, the melting performance successively deteriorates, and the S value successively increases.

The lump ore ratio is controlled to be 25%, the sinter ratio increases from 55% to 75% and the change of the S value of the mixed burden is shown in Figure 6c. When the sinter ratio increased from 55% to 65%, the S value increased by 93 kPa·°C. As the ratio increases to 75%, the S value continues to increase to 613 kPa·°C. According to the above, as the sinter ratio increases, although the melting performance becomes better, the change range is smaller than the pressure difference and the air permeability worsens.

In summary, because lump ore has a larger pressure difference, a lower melting temperature and a wider melting range, its air permeability is poor. Being mixed with sinter and pellet can effectively improve its air permeability. With the increase in lump ore ratio, the pressure difference gradually increases, the melting temperature decreases, the interval becomes wider and the air permeability becomes worse. When the sinter ratio increases, its influence on the maximum pressure difference is greater than that on the melting performance, so the gas permeability worsens.

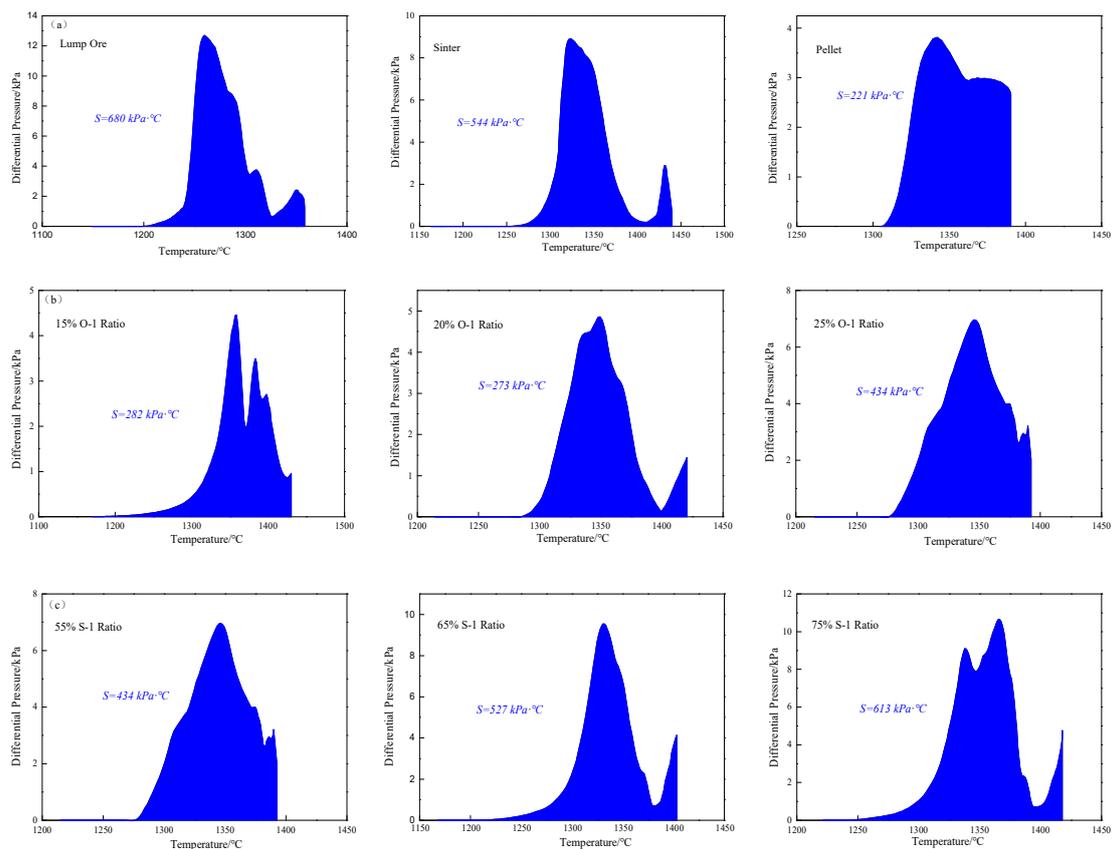


Figure 6. S value of the different burdens. (a) single ores; (b) 55% sinter ratio; (c) 25% lump ore ratio.

3.1.5. Analysis of the Cohesive Zone Position

The position change of the cohesive zone in different burdens is shown in Figure 7. The position of the cohesive zone of the three single ore is shown in Figure 7a. The cohesive zone of the lump ore is the thickest, up to 260 °C. Further, it is in a very low temperature zone, so its air permeability of the burden is very poor. In comparison, the cohesive zone of sinter ranges from 1206 °C to 1439 °C and the temperature zone of the cohesive zone is the highest with a thickness of 233 °C. The cohesive zone of pellet is the thinnest, with a temperature range of 1179 °C–1390 °C and the melting temperature range that has the greatest influence on gas permeability is the smallest and has the best gas permeability. Based on the above, it can be seen that the lump ore contains more complex compounds, has a lower T_{10} and a higher T_d , so the thickness of the cohesive zone is wider.

As shown in Figure 7b, when the sinter ratio is constant and the lump ore ratio increases from 15% to 20%, the thickness of the cohesive zone changes very little. However, the range of melting temperature increases, the air permeability worsens and the cohesive zone moves to the low temperature area. When the lump ore ratio increased from 20% to 25%, although the thickness of the cohesive zone decreased by 24 °C, it moved further to the low temperature zone. As the lump ore ratio increases, due to the increase in low melting point compounds, the T_{10} is lower. Additionally, the sinter and pellet play leading roles in the T_d , so the variation range of T_d is less than the T_{10} and the cohesive zone becomes thicker.

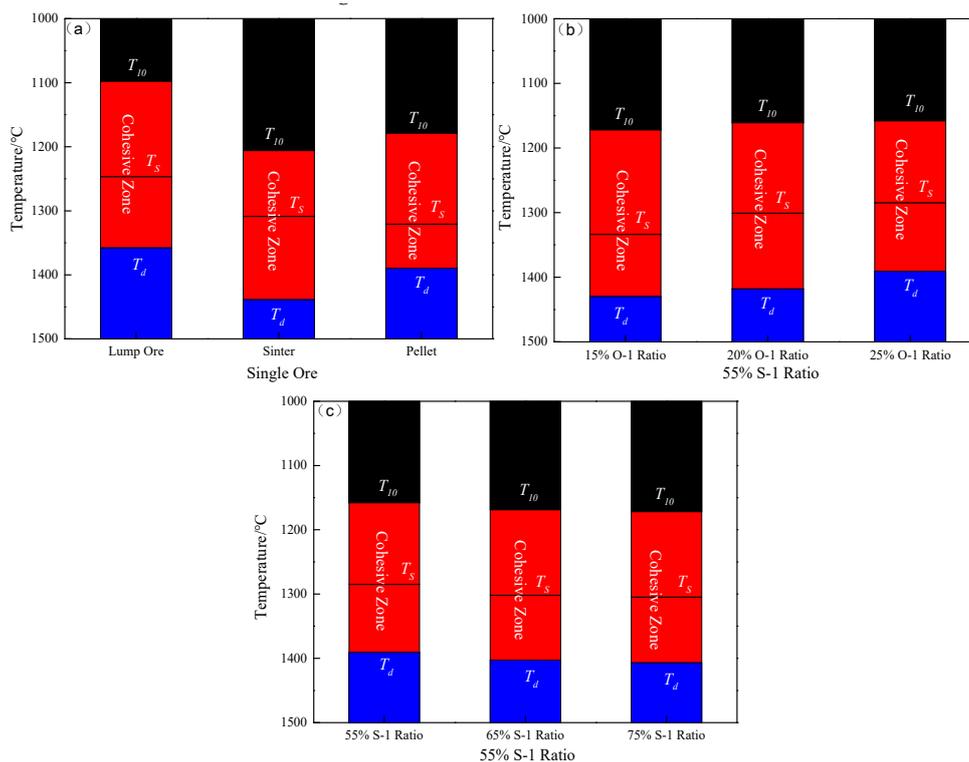


Figure 7. Temperature range of the cohesive zone in different burdens. (a) single ores; (b) 55% sinter ratio; (c) 25% lump ore ratio.

The control of the lump ore ratio is 25%, the sinter ratio increases from 55% to 75% and the change in the mixed burden cohesive zone temperature range is shown in Figure 7c. When the sinter ratio increases from 55% to 65%, the thickness of the cohesive zone changes very little and the melting temperature range only narrows by 5 °C, and the whole cohesive zone moves to the high temperature zone by 8 °C. While the sinter ratio increases to 75%, although the cohesive zone thickens by 11 °C, its melting temperature range only increases by 1 °C, T_d increases by 14 °C and the cohesive zone moves to the high temperature zone. Increasing the sinter ratio, the softening performance and melting performance improve, so the performance of the cohesive zone likewise improves.

In summary, the lump ore has a lower soft-melt temperature and a thicker cohesive zone. Mixed charge can effectively improve the performance of lump ore cohesive zone. As the lump ore ratio increases, the performance of the cohesive zone worsens, and increasing the sinter ratio has a certain positive effect on the formation of the cohesive zone.

3.2. Analysis of Primary-Slag Formation Behavior of Iron-Bearing Burden after Increasing Lump Ore Ratio

In order to further explore the change and mechanism of the soft-melt dropping properties of the mixed burden with increasing lump ore ratio, the maximum pressure difference and the temperature at the maximum pressure difference are determined according to the above-mentioned test. Then the test is stopped at this temperature and the graphite crucible is dissected to extract the primary slag. The dissecting result is shown in Figure 8. We used Rigaku D/MAX-2500 X-ray diffractometer (Tokyo, Japan) to analyze its mineral composition; the results are shown in Figure 9. The XRF-1800 X-ray fluorescence analysis equipment is used for chemical composition analysis. The results of the chemical composition of the primary slag formed by six groups of burden are shown in Table 3. At the same time, the melting point was detected by the HRHN-5F melting point equipment. The melting process is shown in Figure 10. Among them, deformation temperature is the temperature at which the tip end of the cone is rounded or the cone begins to tilt; the softening start temperature is when the tip of the cone becomes curved; hemispherical temperature is the time when the cone turns into a

hemisphere; when the cone reaches the flow temperature, it is completely flat on the cone holder with no obvious shape. The results of the melting properties are shown in Table 4.

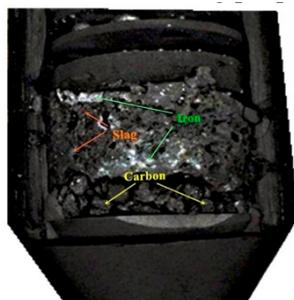


Figure 8. Morphology of the dissecting crucibles.

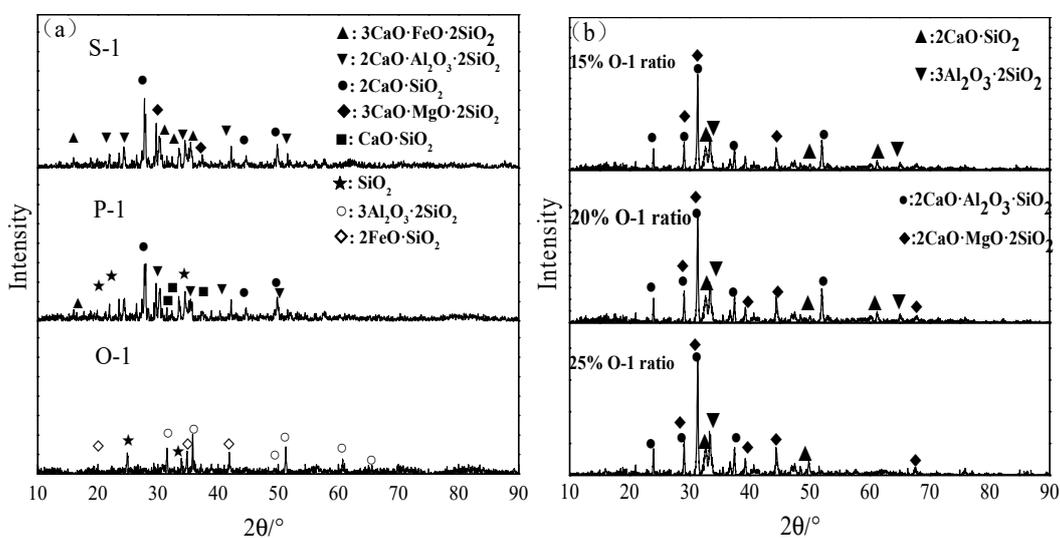


Figure 9. The XRD diffraction pattern of the primary slag. (a) single ores; (b) 55% sinter ratio

Table 3. Chemical composition of no dropping slag samples, %.

Sample	FeO	CaO	SiO ₂	Al ₂ O ₃	MgO
1	8.61	46.17	27.92	12.20	5.10
2	8.52	45.87	27.75	11.69	6.17
3	48.49	2.06	37.24	10.76	1.45
4	5.56	47.06	32.15	8.58	6.27
5	6.66	43.06	35.08	8.71	6.50
6	8.78	39.74	36.66	8.34	6.48

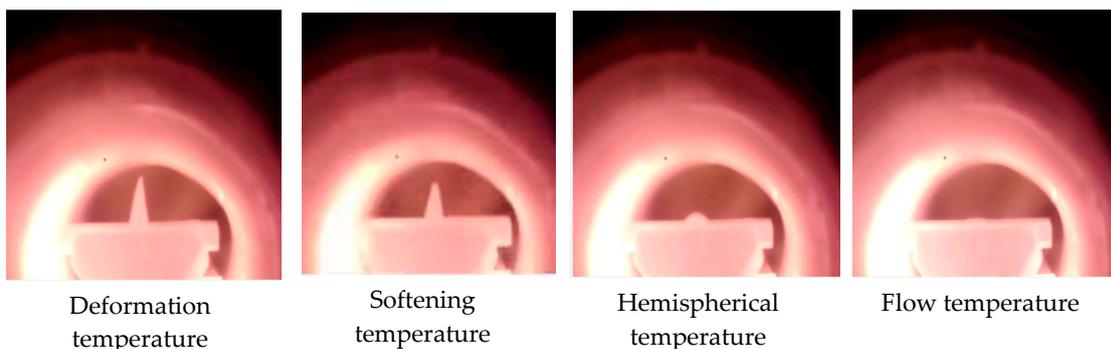


Figure 10. The change behaviors of sample in the heating process.

Table 4. The melting temperature of the slags with different furnace burden.

Scheme	Deformation Temperature/°C	Softening Temperature/°C	Hemispheric Temperature/°C	Flow Temperature/°C
1	1310	1367	1386	1423
2	1185	1203	1220	1235
3	1089	1098	1107	1125
4	1219	1313	1315	1326
5	1205	1305	1310	1328
6	1185	1280	1286	1310

According to the detection results of the primary slag of the single ore, it can be seen that both sinter and pellet are alkaline iron-containing burden; therefore, the formed primary slag has a higher CaO content. At the same time, due to their better reducibility, the formation of primary-slag FeO content is lower than other acid burden [27]. For sinter, the FeO content of the primary slag is relatively low. This is because the sinter is loose and porous and the iron-containing mineral composition is mainly calcium ferrite, which has high reducibility and reduces the FeO content of the primary slag. In addition, due to the addition of more CaO and MgO in the production process of sinter, the content of CaO and MgO in the primary slag is relatively the highest, forming high melting point minerals, such as $2\text{CaO}\cdot\text{SiO}_2$, etc., which makes the melting temperature and T_d of sinter increase, as well as the melting zone to move to the high temperature zone and the thickness of the cohesive zone to increase. The pellet has a high content of Al_2O_3 , but because it is a self-fluxing pellet, it has better reduction properties and low FeO content in the primary slag, which makes its cohesive zone properties better than the other two.

On the other hand, the content of CaO in lump ore is extremely low and the oxides that begin to form slag are mainly FeO, SiO_2 , Al_2O_3 . Although the slag phase contains high melting point compounds such as mullite ($3\text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$, 1940 °C) and silicon dioxide (SiO_2 , 1723 °C). However, the melting point of iron olivine ($2\text{FeO}\cdot\text{SiO}_2$, 1205 °C) is very low, resulting in lump ore drips having a lower temperature. The sinter and self-fluxing pellet primary-slag phase contain a large amount of CaO and the melting point of the compounds is higher, which makes the upper edge temperature of the cohesive zone of the basic iron-containing burden higher than the lump ore. As the reduction progresses, the FeO content in the slag phase decreases and the mineral composition of the slag phase also changes. The newly produced slag phase is magnesia feldspar ($2\text{CaO}\cdot\text{MgO}\cdot 2\text{SiO}_2$, 1454 °C), chrysotile ($2\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{SiO}_2$, 1593 °C), calcium olivine ($2\text{CaO}\cdot\text{SiO}_2$, 2153 °C), monocalcium silicate ($\text{CaO}\cdot\text{SiO}_2$, 1550 °C). Therefore, the primary slag of sinter and pellet has a high melting temperature and high viscosity and needs to be able to flow freely and separate from the molten iron at a higher temperature, thus exhibiting a higher lower edge temperature of the cohesive zone.

According to the detection results of the primary slag of the mixed burden, when the sinter is matched with different ratios of pellet and lump ore to form a mixed burden, the main mineral compositions of the primary slag, such as feldspar ($2\text{CaO}\cdot\text{MgO}\cdot 2\text{SiO}_2$), calcite ($2\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{SiO}_2$), dicalcium silicate ($2\text{CaO}\cdot\text{SiO}_2$) and mullite ($3\text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$) change little. However, as the lump ore ratio increases successively, the content of CaO in the primary slag decreases, the contents of FeO and SiO_2 increase and the contents of Al_2O_3 and MgO are similar. Therefore, the high melting point slag phase decreases and the primary-slag melting temperature decreases, resulting in reductions in the softening start temperature, melting temperature and dropping temperature. The cohesive zone moves to the low temperature zone and the properties deteriorates successively.

4. Conclusions

1. The ore phase of lump ore is more complicated and the primary slag contains a large amount of FeO and SiO_2 . During the high temperature reduction process, it is easy to produce a large amount of low melting point compounds, resulting in lower softening temperature and melting

temperature, thicker cohesive zone, larger maximum pressure difference, poor air permeability and poor melting performance of the primary slag. On the other hand, by being mixed with sinter and pellet, all the properties can be effectively improved.

2. With the increase in lump ore ratio, the CaO in the primary slag decreases, and FeO and SiO₂ increase, resulting in the decrease in high melting point compounds in the primary slag. The melting temperature of the primary slag sequentially decreases, resulting in the softening temperature and melting temperature being reduced. The cohesive zone moves to the low temperature zone. Meanwhile, the maximum pressure difference increases, and the gas permeability deteriorates.
3. Under the condition of high lump ore ratio, increasing the sinter ratio can raise the high melting point compounds produced during the high temperature reduction process, so it can effectively improve the poor softening performance, melting performance and the position and thickness of the cohesive zone. However, due to its own metallurgical properties that easily produce a large amount of powder, which leads to the deterioration of the maximum pressure difference and gas permeability of the burden.

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