Research Article

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Effect of K and Na on reduction swelling performance of oxidized roasted briquettes

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Abstract: The presence of potassium oxide (K_2O) and sodium oxide (Na_2O) causes high reduction swelling of pellets of Bayan Obo iron concentrate during reduction and thus affects the permeability of blast gases during blast furnace operations. The influencing mechanism of K_2O and Na_2O on the swelling behavior of reduction reactions (1) $Fe_2O_3 \rightarrow Fe_3O_4$, (2) $Fe_3O_4 \rightarrow Fe_xO$, and (3) $Fe_xO \rightarrow Fe$ was researched by adding ($K_2O + Na_2O$) to Australian fine ore briquettes. The mineral composition and structure of the briquettes, as well as the reduction swelling after the three reactions coupled with the morphology and lattice parameters of the reduced products, were studied. From the results, the swelling index with 0.6% ($K_2O + Na_2O$) added was 8.52%, 7.91%, and 33.81%, respectively, and without were 12.36%, 3.27%, and 12.61%, respectively, for the three reactions. The swelling index of the first reaction ($Fe_2O_3 \rightarrow Fe_3O_4$) is reduced because alkali metal suppresses crystal cracking. The swelling mainly occurs at the third stage ($Fe_xO \rightarrow Fe$), because K_2O and Na_2O enhance the oriented growth of iron whiskers, as well as make them smaller. Crystal transformation does not occur at the second stage ($Fe_3O_4 \rightarrow Fe_xO$) and the reduction swelling is small, but the swelling index of the briquettes with added with K_2O and Na_2O increases (7.91% compared to 3.27%). The main reason is that the alkali metal reduces the melting point of the slag phase and promotes the cascade crystallization of FeO . Therefore, the abnormal

swelling of briquettes caused by K and Na is mainly caused by the growth of iron whiskers at the third stage.

Keywords: Australian ore, briquettes, K_2O and Na_2O , reduction swelling, crystal structure

1 Introduction

With the rapid development of China's iron and steel industry, the output of iron and steel has increased significantly, which creates an iron ore supply issue. Hence, it is necessary to develop and use domestic iron ore. The swelling index of pellets produced by most iron ore concentrate is within the allowable range of normal blast furnace (BF) production. But the composition of Baiyun Obo iron concentrate is complex, and the content of alkali metal oxide is higher than in normal iron ore concentrates. Because of this, the abnormal reduction swelling of the pellet makes BF operation very difficult. The BF cohesive zone becomes wider and with poorer permeability, while the reduction degradation index of raw materials increases. Therefore, the utilization ratio of Bayan Obo iron concentrate is less than 30% in production. Studying the effect of potassium and sodium on the metallurgical properties of the pellets has great significance for the utilization of Bayan Obo ore.

K_2O and Na_2O appear as complex mineral compounds in the ore, such as leucite ($K_2Al_2Si_4O_{12}$), hexagonal potash ($K_2Al_2Si_2O_4$), mirabilite ($Na_2SO_4 \cdot 10H_2O$), and mica ($KH_2Al_2SiO_{12}$). It is difficult to remove these compounds by mineral processing techniques. Potassium and sodium are mainly circulated in the form of aluminosilicate and silicate in the BF. The accumulation of alkali metal brings great difficulties to smelting. The metallurgical properties will deteriorate [1–7] due to the increasing swelling index of the pellets. Previous studies [8–12] have shown that the maximum swelling index should be less than 20%. If it exceeds 20%, it is called “abnormal swelling” or “catastrophic swelling,” which can lead to the disintegration and weakening of the reduced pellets. The appropriate amount of K_2O and Na_2O

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Table 1: Chemical composition of Australian ore (wt%)

Composition	T _{Fe}	FeO	SiO ₂	K ₂ O	Na ₂ O	CaO	MgO	Al ₂ O ₃	S	F	P
Australian ore	61.2	1.4	2.74	0.013	0.08	0.16	0.88	2.02	0.031	0.033	0.069

can increase the content and connection of the slag phase in roasting, which leads to improved strength and the decrease of swelling index [13,14]. When alkaline metals (as Na₂O, K₂O) were added to Fe₂O₃ pellets, abnormal swelling occurred during reduction. It was considered that the swelling may be caused by (1) the cracking of the crystal at the early stage of reduction, (2) the formation of fibrous iron, (3) and/or carbon deposition on reduced iron [15]. With an increase in K₂O, morphologically, the porosity and whisker growth of the produced metallic iron increased, which led to increased swelling and pellets disintegrating [16,17]. K₂O and Na₂O will gradually enter into the FeO lattice and catalyze the reduction reaction so that the iron whiskers grow faster and more cracks are generated which increases the swelling index [18].

Previous [19–23] literature studies into the effect of alkali metal focused on the reduction swelling index at the third stage of reduction (Fe_xO → Fe). Fewer studies have been conducted on the effect of alkali metal on the swelling at the first and second stages. In this work, the effect of alkali metal on the swelling index, slag phase properties, and mineralogy of the iron oxides in the three different reduction stages of briquettes has been investigated, as well as exploring the mechanism of reduction swelling. Meanwhile, the main reason for abnormal reduction swelling of Bayan Obo ore has been recommended based on the experimental results. It can provide a theoretical basis for the control the abnormal swelling of Bayan Obo pellet. The experimental results obtained are important because the use of briquettes with uniform composition guides the developing Baotou self-produced ore and rational utilization of Bayan Obo ore pellet.

2 Experimental

2.1 Raw materials

The raw materials used to prepare briquettes in this work include Australian iron ore and purified Fe₂O₃, K₂CO₃, and Na₂CO₃.

Table 2: Proportion of raw materials (wt%)

Raw materials	Australian ore	Pure Fe ₂ O ₃	K ₂ O	Na ₂ O
1 [#]	100.00	×	×	×
2 [#]	99.40	×	0.30	0.30
3 [#]	×	100.00	×	×
4 [#]	×	99.00	0.50	0.50
5 [#]	×	95.00	2.50	2.50

Note: The “×” stands for no adding of the substance.

The K₂O and Na₂O contents in the Bayan obo ore are approximately 0.25–0.35 wt% and 0.25–0.40 wt%, respectively, but also contain many impurity elements, such as F, P, and S. To avoid being affected by other components, Australian ore with low contents of 0.013 wt% K₂O and 0.08 wt% Na₂O was selected as a raw material shown. The composition of this ore is listed in Table 1.

The samples used in the reduction and swelling experiments included:

- (1) Laboratory briquettes of Australian ore: The Bayan obo ore was simulated by adding (K₂O + Na₂O) into Australian ore. As listed in Table 2, equal amounts of K₂CO₃ and Na₂CO₃ were added.
- (2) Laboratory briquettes of high purified iron oxides: the briquettes were made using chemical reagent hematite with different (K₂O + Na₂O) contents (K₂O:Na₂O = 1:1), as listed in Table 2. The pure reagent experiment (3[#]) was used to explain and analyze the crystal morphology of sample 1[#] and 2[#] observed by SEM. Excluding other factors, the effects of K and Na on the crystal structure can be more directly investigated by pure reagents. The proportion of (K₂O + Na₂O) added is 1.00 and 5.00 wt% in pure reagents.

2.2 Experimental work

2.2.1 Manufacturing briquettes

Producing briquettes: particle size less than 75 microns; mixed time: 5 h; mass: 4 g; pressing force and time:

Table 3: Parameter settings for each reduction stage

Reduction stage	Temperature (°C)	Gas ratio (CO:N ₂)	Flow rate (L/min)	Time (min)
First: Fe ₂ O ₃ → Fe ₃ O ₄	650	30:70	15	60
Second: Fe ₃ O ₄ → Fe _x O	1,000	50:50	15	60
Third: Fe _x O → Fe	1,000	100:0	15	60

15 ± 1 MPa with no binder and water, keeping 120 s; geometry and dimension: cylinder with Φ 20 mm × (4–5) mm.

Drying of briquettes: the raw materials are dried in an oven at 100°C; drying time: 3 h.

Process of roasting: the briquettes were roasted at 1,250°C for 30 min in a muffle furnace.

After the above processes, briquettes without cracks or fissures were selected for experiments.

2.2.2 Reduction-swelling experiment

The reduction condition was determined based on thermodynamic calculations using the FactSage6.4 software. In the first-reduction stage (Fe₂O₃ → Fe₃O₄), the temperature was 650°C and the reducing gas ratio CO:N₂ was 30:70. In the second-reduction stage (Fe₃O₄ → Fe_xO), if the proportion of CO is too high, Fe will appear in the reduced product. Therefore, the temperature was chosen as 1,000°C, and the ratio of reducing gas was 50:50. In the third-reduction stage (Fe_xO → Fe), a pure CO reducing gas was used to ensure a sufficient reduction of Fe_xO. The gas flows for each reduction stage are listed in Table 3.

The reduction swelling test device is shown in Figure 1. Before the start of each reduction experiment, the reduction tube seal was checked, and the computer program was connected with the heating equipment. The heating process for the reduction furnace was set through the computer. During the reduction experiments, the briquettes were placed in the middle zone of the tube. The components of the reducing gas mixture, CO and N₂, were supplied by separate gas bottles, with flow rates monitored by individual flow meters, and, mixed before entering the reduction tube. The furnace tube was flushed with N₂ gas until the isothermal temperature level was reached, which was tested using a thermocouple placed in the middle of the tube. Then, the reducing gas mixture was allowed into the tube proportionally, and the time was counted by an electronic watch. Once the different reduction stage was over, the gas mixture was switched off, and purified

Figure 1: Schematic diagram of the reduction swelling test device. (1) Gas bottle; (2) flow meter; (3) reduction furnace; (4) test vessel; (5) briquettes; (6) reduction tube; (7) gas inlet; (8) gas outlet; (9) thermocouple.

N₂ was allowed to flow, and the briquettes were cooled in the furnace.

2.2.3 Experimental apparatus and procedures

Weighing and volume measurement by the water immersion method (according to the national standard GB/T 13240-1991) were carried out on samples before and after each reduction stage experiments to determine the extents of swelling. The swelling index is defined as the percentage increase of the volume.

In this paper, the slag phase composition and proportion in the briquettes were determined by the calculation using the FactSage6.4 software. The surface distribution of each element was obtained by a SIGMA500 high-resolution field emission scanning electron microscope (SEM), as well as the crystal morphology of iron oxide in different reduction stages. The mineral composition, the crystal cracking of reduction products at the first stage, and the growth of iron

whiskers at the third stage were observed by the DYP-990 mineral microscopy and scanning electron microscopy. This can help reveal the influence of K_2O and Na_2O on the reduction swelling properties of briquettes. The phase compositions of the briquettes and the crystal cell parameters of iron oxides at different reduction stages were analyzed by a MiniFlex 600 X-ray diffractometer, and the crystal parameters were calculated by Jade6.5 software from the data of XRD.

3 Results and analysis

To determine the phase compositions of the briquettes at different stages, XRD analysis was used to determine the reduction products when the temperature and time reached the set value of each stage. A SEM was used to observe the crystal morphology of samples 1[#] and 2[#] at the three reduction stages, while for samples 3[#], 4[#], and 5[#], the swelling index change was determined by XRD.

3.1 Swelling index and mineral composition

The swelling index indicates the volume change of pellets during the reduction of hematite to magnetite and then from magnetite to wustite. According to the water immersion method:

$$V = \frac{m_2 - m_1}{\rho} \times 100\%, \quad (1)$$

where V is the volume of briquette, m_1 is the mass of briquette in water, m_2 is the mass of briquette in the air after water immersion, and ρ is the density of water at the current temperature, and the reduction swelling rate calculation formula is as follows:

$$RSI\% = \frac{V_1 - V_0}{V_0} \times 100\% \quad (2)$$

RSI% is the swelling index, V_0 is the volume of briquette before reduction, and V_1 is the volume of briquette after reduction.

The influence of $(K_2O + Na_2O)$ on the swelling index at different stages is shown in Figure 2. The incremental swelling index changes from stage to stage.

Figure 3 shows the optical microstructure of briquettes with varying $(K_2O + Na_2O)$. Phase analysis of pellets with varying $(K_2O + Na_2O)$ content revealed that hematite (H) and slag (S) are the main phases. With an

Figure 2: Reduction swelling rate of roasted briquettes.

increase in the $(K_2O + Na_2O)$ content, the slag phase increased and the voids decreased. The phase proportion of briquettes with varying $(K_2O + Na_2O)$ is shown in Figure 4. As shown in Figure 3, some smaller pores are filled by the liquid phase or resin. An increase in the slag phase suppresses the continuation of hematite and makes the iron oxide particles smaller.

3.2 The first stage of reduction

When hematite is reduced to magnetite, the hexagonal structure is transformed into an isometric system, and such crystal transformation is the main reason for increasing the swelling of the briquettes during reduction [24].

At the first stage of reduction (Figure 2), the swelling index decreased from 12.36% to 8.52% with an increase in $(K_2O + Na_2O)$. The first stage reduction product was found to be Fe_3O_4 as determined from the XRD pattern as shown in Figure 5.

Figure 6 shows the SEM images of roasting briquettes after the first reduction stage. The number of cracks in Figure 6(b) is significantly greater than that in (d). The cracks in the figures are indicated by “+” (white).

When sample 1[#] was reduced to Fe_3O_4 , the magnetite grains are coarse and the cracking was widespread. However, the magnetite grains in sample 2[#] are fine and the crystal cracking is suppressed significantly. The addition of K_2O and Na_2O has decreased crystal cracking and caused reduction swelling decrease at the first-reduction stage. As shown in Figure 6, the size of Fe_2O_3 grains in roasted briquettes decreased, and making the overall structure of roasted briquettes more uniform,

Figure 3: Micrographs of Australian ore with varying (K₂O + Na₂O): (a) 0 wt% and (b) 0.6 wt% (H-Hematite, L-Slag, P-Voids).

Figure 4: Phase analysis of roasted briquettes with varying (K₂O + Na₂O).

Figure 5: XRD pattern of roasting briquettes at the first stage.

the main reason is that (K₂O + Na₂O) can increase the amount of slag phase (Figure 4).

At the beginning of the reduction, the nucleation of magnetite around hematite will be accompanied by the formation of a stress field. The stress development will lead to cracking of the iron oxide crystal and swelling of the briquettes. After the addition of (K₂O + Na₂O), the size of Fe₂O₃ grains became smaller, and the reduction stress decreased. Therefore, the crystal cracking is not as obvious, and the swelling rate is lower. Many studies [25] have shown that sodium can reduce swelling of roasted briquettes during the reduction from Fe₂O₃ to Fe₃O₄. However, in this experiment, potassium and sodium promoted the alkali metal silicates forming, which enhanced the formation of the slag phase, which inhibited the growth of the Fe₂O₃ grains. These slag phases will not melt at the reduction temperature 650°C and will alternatively bond the iron oxide grains together. Therefore, the smaller iron oxide grains and the more alkali metal silicates slag hindered crystal cracking and the associated volume increase in the iron oxide during reduction.

Figure 7 shows the XRD analysis with varying (K₂O + Na₂O) (3[#], 4[#] and 5[#]), and the crystal parameters calculated from the data of XRD are listed in Table 4.

The samples 3[#] and 4[#] consisting of low (K₂O + Na₂O) are primarily Fe₃O₄. With an increase of (K₂O + Na₂O) in sample 5[#], the reduction product also contains FeO and NaFeO₂ along with Fe₃O₄. When the content of (K₂O + Na₂O) in the sample is higher, NaFeO₂ and K₂Fe₂₂O₃₄ can also be formed in the roasted stage, and Fe₂O₃, NaFeO₂, and K₂Fe₂₂O₃₄ are gradually reduced to Fe₃O₄, causing K₂O and Na₂O to become free compounds. Na⁺ in Na₂O can replace Fe²⁺ in Fe₃O₄, because the ionic size of Na⁺ is satisfied, i.e., $(r_{\text{Fe}^{2+}} - r_{\text{Na}^{+}})/r_{\text{Fe}^{2+}} < 15\%$ [26]. However, since the Na⁺ radius is larger than that of Fe²⁺, the solid solution

Figure 6: SEM images of reduced briquettes at the first stage. (a and b) Mineral structure and morphology of 0 wt% (K₂O + Na₂O); (c and d) mineral structure and morphology of 0.6 wt% (K₂O + Na₂O).

Figure 7: XRD analysis of reduced briquettes with vary (K₂O + Na₂O) at the first stage.

of Na⁺ in Fe₃O₄ causes the crystal volume of the reduced product Fe₃O₄ to increase and the lattice to be distorted, as shown by the increase in lattice volume in Table 4.

Theoretically, (K₂O + Na₂O) promoted the increase of Fe₃O₄ unit cell parameters and crystal volume, leading to an increase in the reduction swelling ratio of the briquettes. However, since (K₂O + Na₂O) significantly suppresses the cracking of Fe₃O₄ crystal, the swelling index is lowered.

Table 4: Lattice parameters of the product Fe₃O₄ after the first-reduction stage

Number	Lattice constant $a = b = c/\text{\AA}$	Lattice volume/ $\text{\AA}^3$
3 [#]	8.3014	572.0764
4 [#]	8.3206	576.0550
5 [#]	8.3397	580.0311

Figure 8: XRD pattern of roasting briquettes at the second stage.

3.3 The second stage of reduction

At the second stage of reduction, the swelling index increased from 3.27% to 7.91% with an increase in ($K_2O + Na_2O$) (Figure 2). The second stage reduction product was determined to be pure FeO from the XRD pattern as shown in Figure 8.

Adding ($K_2O + Na_2O$) to the briquette mix can promote the solid solution of Na^+ into Fe_3O_4 , which can increase the lattice parameter, the crystal volume, and the lattice defects of Fe_3O_4 . The addition of alkalis will decrease the activation energy of $Fe_3O_4 \rightarrow Fe_xO$ and accelerate the process. As a result, the layer spacing of FeO lamellar wafers decreased and the orientated growth trend became obvious (Figure 11). The amount of slag

Figure 9: Typical SEM images and EDS maps of sample 2[#] (0.6 wt%($K_2O + Na_2O$)) (a) H-Metal phase. L-Slag phase; (b) EDS maps of Fe; (c) EDS maps of O; (d) EDS maps of Ca; (e) EDS maps of Al; (f) EDS maps of Si; (g) EDS maps of K; (h) EDS maps of Na.

Figure 10: Calculating the liquid phase curve using Factsage6.4.

phase increases and the melting point of the slag phase decreases with the addition of ($K_2O + Na_2O$). ($K_2O + Na_2O$) can also accelerate the reduction of $Fe_3O_4 \rightarrow Fe_xO$

and dissolution of FeO in the slag phase. Therefore, when the briquettes were reduced in the Fe_xO stage, the resistance to the growth of the reduction product Fe_xO will be significantly reduced, and the boundary of the Fe_xO crystal will clear. Additionally, the directional growth rate will increase. The slag phase content and melting point are the main reasons for the increase in the reduction swelling rate at this stage.

Since the slag phase content and the property play an important role in the second stage, the slag phase properties were studied. The main components and distribution of the slag phase in the 0.6 wt% ($K_2O + Na_2O$) briquettes were obtained by SEM, typical SEM images, and EDS maps as shown in Figure 9. It was observed that Ca, Si, K, Na, and other elements were all concentrated in the slag phase, while Fe was only a small amount in the slag and almost in the metal phase. The alkali metal rarely enters the metallic phase, so a large amount of K_2O and

Figure 11: SEM images of reduced briquettes at the second stage. (a and b) 0 wt% ($K_2O + Na_2O$), (a and c) on macrography, (c and d): 0.6 wt% ($K_2O + Na_2O$), (b and d) on microcosmic.

Table 5: Lattice parameters of the product FeO after the second-reduction stage

Number	Lattice constant $a = b = c/\text{\AA}$	Lattice volume/ $\text{\AA}^3$
3 [#]	4.2613	77.3786
4 [#]	4.2661	77.6414
5 [#]	4.2735	78.0461

Na₂O was added into the slag phase, which combined with the iron oxides to form complex compounds, producing a large number of low-melting compounds such as 2Fe₂O₃·SiO₂ (1,205°C), CaO·FeO·SiO₂ (1,205°C), 2CaO·Fe₂O₃ (1,216°C), etc. Therefore, (K₂O + Na₂O) additions can reduce the melting point of the slag phase, which can promote the dissolution of FeO which has a positive effect on promoting the reduction swelling of the second stage of briquettes.

The Equilib module, FactPS, and FToxid databases in the Factsage6.4 package were used to obtain the slag phase change curve of the briquettes from 900°C to 1,400°C, as shown in Figure 10.

After the addition of (K₂O + Na₂O), the initial temperature of slag formation is lowered, and the amount of slag is increased. Liu et al. [27] used SEM analysis to determine the slag phase composition of the roasted briquettes. These results combined the results with the thermodynamic calculation results of Factsage6.4 were used to obtain the main composition and then used a pure reagent to prepare the slag phase. From this, the slag phase properties and melting properties were analyzed. The results showed the slag phase of the Australian ore did not melt at 1,420°C. With the addition of K₂O and Na₂O, the melting temperature is lower.

Fe₃O₄ and FeO both have a cubic structure; hence, there is no crystal transformation at the second stage of reduction. The slag phase of sample 1[#] has a high melting point and viscosity and does not melt when it is reduced at 1,000°C. As shown in Figure 11, the crystal structure is more regular and the layered structure is more obvious with the addition of (K₂O + Na₂O), and the slag phase melts when it is reduced at 1,000°C and fills-in between iron oxide particles. The liquid phase promotes the directional growth of FeO, leading to an increase in the swelling index.

Table 5 shows the lattice parameters of the product FeO at the second reduction stage. With an increase in (K₂O + Na₂O), there was little change in the unit cell parameters of FeO, compared to the data in Table 4. Figure 12 shows the XRD analysis of reduced briquettes with varying (K₂O + Na₂O) content at the second stage.

Figure 12: XRD analysis of reduced briquettes with vary (K₂O + Na₂O) at the second stage. **Figure 13:** XRD pattern of roasting briquettes at the third stage.

The amount of FeO phase decreased, and some Fe₃O₄ is not reduced. When the content of alkali metal is 5 wt%, NaFeO₂ also appears. With an increase in (K₂O + Na₂O), more solid solution is formed during the first stage of reduction, which can prevent crystal transitions from occurring and stabilize the lattice.

3.4 The third stage of reduction

Figure 2 shows that in the third stage of reduction, the swelling index increased significantly from 12.61% to 33.81% with an increase in (K₂O + Na₂O) due to the fine and long growth of iron whiskers. The third stage reduction product is determined to be Fe from the XRD pattern as shown in Figure 13.

Figure 14: SEM images of reduced briquettes at the third stage. (a and b) 0 wt% (K₂O + Na₂O), (a and c) on macrography, (c and d) 0.6 wt% (K₂O + Na₂O), (b and d) on microcosmic.

Figure 14 shows the SEM image of reduced briquettes at the third stage. The iron whiskers have different lengths and shapes. With an increase in (K₂O + Na₂O), a larger number of metallic iron whiskers were observed with longer shapes, which became finer and longer.

The directional growth of FeO in layered crystals was an important basis for the formation of iron whiskers. The addition of alkali metals (K₂O + Na₂O) generates a solid solution with the FeO, increasing the number of internal defects and promoting the growth of iron whiskers. The effective diffusion coefficient of Fe²⁺ increases in the FeO nucleus. The formation of sharp and fine iron whiskers is due to the accumulation of Fe²⁺ at the tip of the whisker through the crystal defect. The melting point of the slag phase is reduced, which can lead to a rapid growth of iron whiskers. Therefore, the malignant growth of iron whiskers leads to an increase in the swelling index.

Figure 15: XRD analysis of reduced briquettes with vary (K₂O + Na₂O) at the third stage.

Table 6: Lattice parameters of the product Fe after the third-reduction stage

Number	Lattice constant $a = b = c/\text{\AA}$	Lattice volume/ $\text{\AA}^3$
3 [#]	2.6325	18.2434
4 [#]	2.6204	17.9930
5 [#]	2.6311	18.2143

Figure 15 shows the XRD analysis with varying ($\text{K}_2\text{O} + \text{Na}_2\text{O}$) (3[#], 4[#] and 5[#]) at the third stage, and the crystal parameters calculated from the data of XRD are shown in Table 6.

During the third stage, the roasted briquettes of varying ($\text{K}_2\text{O} + \text{Na}_2\text{O}$) were reduced to Fe, and the diffraction peaks of each sample reduction product Fe were similar. The solid solution of an alkali metal with FeO is completely reduced to Fe. The alkali metal and compounds were not detected. From the results of Factsage6.4 calculation, it was found that most of the alkali metal compounds would be reduced to K and Na. The alkali metal evaporated, while the alkali metal compounds were too small (less than 3%) to be detected by XRD. Table 6 shows the ($\text{K}_2\text{O} + \text{Na}_2\text{O}$) content has little effect on the lattice structure of Fe.

4 Conclusions

- (1) With increasing ($\text{K}_2\text{O} + \text{Na}_2\text{O}$) at the first stage of reduction, the swelling index and crystal cracked decreased, and the growth of the Fe_2O_3 grains was inhibited.
- (2) At the second stage of reduction, the swelling index increased with increasing ($\text{K}_2\text{O} + \text{Na}_2\text{O}$). The melting point of the slag phase decreased and the growth rate of the FeO crystals is accelerated.
- (3) A malignant growth of iron whiskers leads to an increase in the third stage of reduction. ($\text{K}_2\text{O} + \text{Na}_2\text{O}$) promotes a rapid increase in swelling index. Inhibiting the growth of iron whiskers is the main way to improve the abnormal expansion of briquettes.

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Data availability statement: Research data refers to the results of observations or experimentation that validate research findings. The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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