Suspension Magnetization Roasting with Low-Intensity Magnetic Separation Process for Iron Recovery from Red Mud

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Abstract

In order to solve the problems of poor quality and low yield of iron concentrate from direct magnetic separation of high-iron red mud, a technology of "suspension magnetization roasting combined with low-intensity magnetic separation " was developed. The effects of magnetization roasting temperature, magnetization roasting time, CO concentration, grinding fineness and low intensity magnetic separation field strength were studied. The raw high-iron red mud, with a total iron (TFe) content of 43.51 %, yielded an iron concentrate of 67.69 % with a TFe grade of 56.21 % under optimal conditions, alongside tailings with a 22.51 % yield and 24.26 % TFe grade. X-ray diffraction (XRD) and chemical phase analyses confirmed that weakly magnetic hematite and limonite were selectively reduced to strongly magnetic magnetite during roasting, while aluminum-bearing phases (diaspore, gibbsite, boehmite) dehydrated into Al_2O_3, and gangue minerals (quartz, rutile) remained stable. This process enhanced the magnetic contrast, enabling efficient separation and high-value utilization of red mud.

Keywords: High-iron red mud, Suspension magnetization roasting, Mineral phase reconstruction, Low-intensity magnetic separation, Iron ore concentrate

1. Introduction

Red mud, a byproduct of alumina production, presents significant disposal challenges due to its high alkalinity, fine particle size, and complex mineralogy. In China, approximately 107 Mt were generated in 2023, contributing to a stockpile exceeding 1.6 Gt [1–3]. Rich in valuable metals such as iron, titanium, lithium, gallium, and rare earth elements, red mud represents both an environmental liability and an underutilized resource [4, 5]. However, its comprehensive utilization rate in China was only 9.80 % in 2023, well below the 60 % target outlined in the National Development and Reform Commission's "Guiding Opinions on the Comprehensive Utilization of Bulk Solid Waste in the 14th Five-Year Plan" document. The steel industry is an important industry in the national economy. China has abundant reserves of iron ore resources, but the endowment is poor. Most of them belong to low-grade complex and difficult to select ores, which are difficult to meet the needs of China's steel industry and social development. As a result, the import volume of iron ore in China has been increasing year by year. In 2023, the import volume of iron ores will be 1.16 Gt, and the external dependence will exceed 80 % [6, 7]. Therefore, the recovery of iron minerals from red mud can not only achieve the goal of reduction on the environmental remediation cost of red mud, but also increase the added value of red mud solid waste. Apart from that, iron concentrate can also provide raw materials for regional steel enterprises, meeting the national strategic needs of ecological civilization construction and ensuring the safe supply of iron resources, which is of great significance.

This study introduces a "suspension magnetization roasting combined with low-intensity magnetic separation" process to recover iron from high-iron red mud, investigating its effects on mineral phase reconstruction and separation efficiency to support industrial-scale application.

2. Study on the Properties of Red Mud

2.1 Composition Analysis of Red Mud

Multi-element and phase composition analyses were conducted on low-temperature dissolved red mud derived from imported bauxite at an alumina plant in Henan Province. These analyses aimed to guide the subsequent separation and enrichment of valuable minerals. The analysis results of the X-ray Fluorescence Spectrometer (XRD) and X-ray Diffusion (XRF) are shown in Table 1 and Table 2, respectively.

Table 1. Multi-element analysis results of red mud (%).

Element	Al_2O_3	SiO_2	Fe_2O_3	TFe	TiO_2	K_2O	Na_2O	CaO	MgO	Cr_2O_3
Content	13.48	3.55	62.15	43.51	3.79	0.17	1.22	3.1	0.19	0.19
Element	P	S	Loss on Ignition							
Content	0.077	0.049	9.96							

Table 2. Phase composition analysis results of red mud (%).

Phase	Limonite	Hematite	Perovskite	Diaspore	Quartz	Rutile	Boehmite
Content	34.51	35.50	3.07	2.03	1.70	2.13	3.08
Phase	Gibbsite	Calcite	Sodium-silicon residue		Hydrated garnet		
Content	5.11	1.63	6.85		2.08		

According to the analysis results of Table 1, the main valuable metal element of red mud is iron, and its TFe grade is 43.51 %, which belongs to high iron red mud; the amount of Al_2O_3, SiO_2 and TiO_2 is 13.48 %, 3.55 % and 3.79 %, respectively. The amount of harmful elements sulphur and phosphorus is low, 0.077 % and 0.049 % respectively. It can be seen from the phase analysis results in Table 2 that the valuable element iron in the high-iron red mud is mainly in the form of hematite (limonite), and the red mud also contains sodium silicon slag, hydrated garnet, gibbsite, diaspore, calcite, rutile, perovskite, quartz, and other gangue minerals. Among them, the useful mineral limonite accounts for 49.29 %. Because the magnetism of limonite is weaker than that of hematite, it is more difficult to recover iron-bearing minerals by direct magnetic separation.

2.2 Red Mud Particle Size Analysis

The high-iron red mud samples were analysed by laser particle size analyser. The particle size distribution of high-iron red mud is shown in Fig.1 and Table 3. According to the analysis results of Figure. 1 and Table 3, it can be seen that the particle size distribution of high-iron red mud is bimodal, and the particle size distribution is wide. The volume of -30 µm particle size distribution accounts for 37.71 %, and -10 µm accounts for 20.50 %. There are more fine-grained distribution and a certain amount of coarse-grained distribution, +150 µm accounts for 19.29 %. It can be seen that the fluidization velocity of gas needs to be controlled to avoid the loss of fine particles in the process of suspension magnetization roasting.

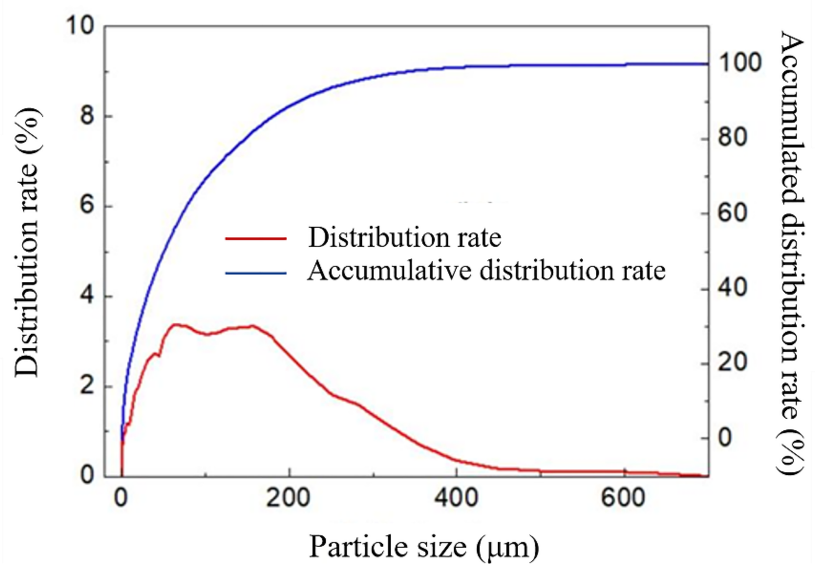

Figure 1. Grain size distribution of red mud materials.

Table 3. The main particle size distribution of high iron red mud.

Grade	Distribution (%)	Positive cumulative (%)	Negative cumulative (%)
+150 μm	19.29	19.29	100
-150 – +74 μm	20.00	39.29	80.71
-74 – +45 μm	13.68	52.97	60.71
-45 – +38 μm	3.99	56.96	47.03
-38 – +30 μm	5.33	63.29	43.04
-30 – +20 μum	7.75	71.04	37.71
-20 – +10 μm	9.46	80.50	29.96

3. Results and Discussion

Dried red mud was ground, screened, and roasted in a suspension furnace preheated to the target temperature. After purging oxygen with N_2, red mud was introduced, and fluidizing (N_2) and reducing (CO) gases were supplied at 0.3 m/s through a distribution plate. Post-roasting, samples were water-cooled, ground, and subjected to low-intensity magnetic separation. The iron concentrate and tailings were quantitatively analyzed to determine their total iron (TFe) content and recovery rate (Figure 2). Single-factor experiments were conducted to evaluate the effects of key parameters, including roasting temperature (700–900 °C), CO concentration (5–25 %), roasting time (1–3 min), grinding fineness (-0.038 to -0.010 mm), and magnetic field strength (0.10–0.30 T).

3.1 Magnetic Roasting Temperature Test

Under the conditions of suspension magnetization roasting fluidization speed of 0.3 m/s, roasting time of 1.5 min, reducing gas CO concentration of 15 %, grinding fineness of -0.023 mm content of 72 %, magnetic separation field strength of 0.20 T, the effect of magnetization roasting temperature on the index of high iron red mud suspension magnetization roasting-low intensity magnetic separation iron was investigated according to the process referred in Figure 2. The results are shown in Figure 3.

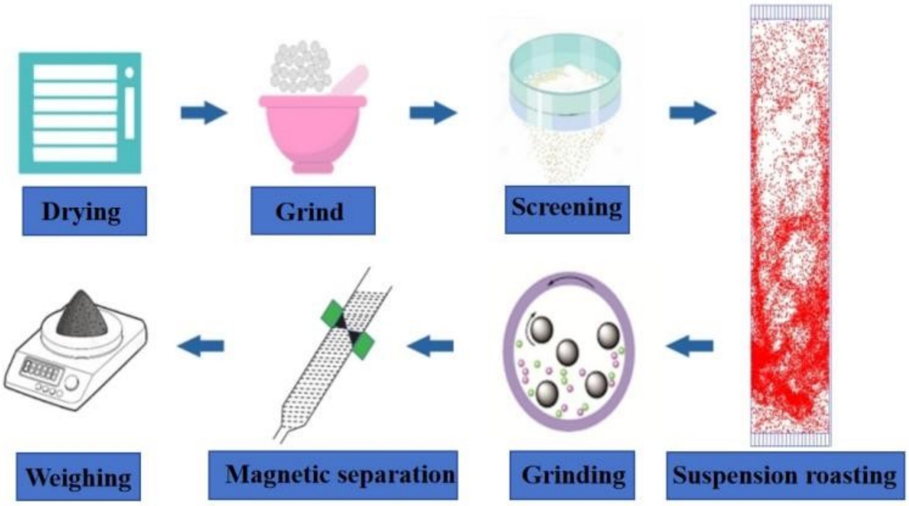

Figure 2. The diagram of the combined suspension magnetization roasting and low magnetic separation process for high iron red mud utilization.

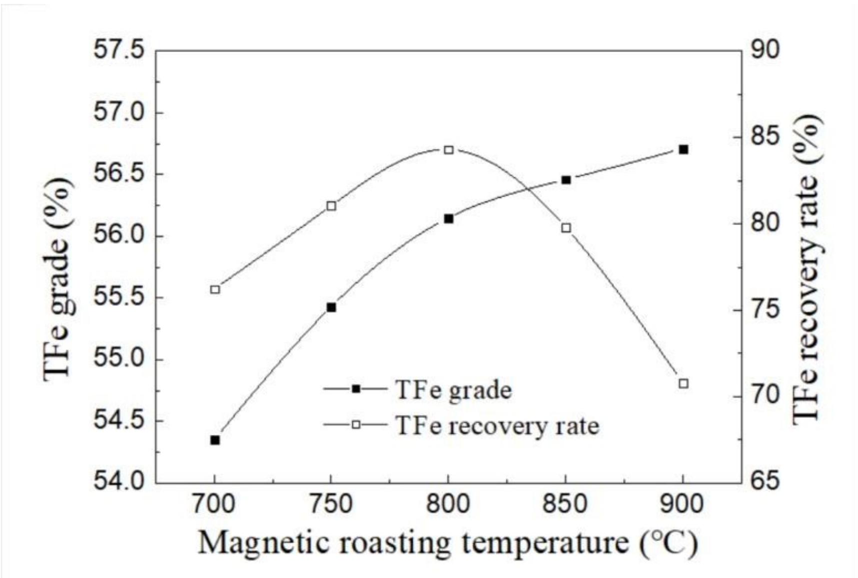

Figure 3. Experimental results of magnetization roasting temperature.

It can be seen from the test results in Figure 3 that the temperature has a significant influence on the suspension magnetization roasting-low intensity magnetic separation index of high-iron red mud. The TFe grade of iron concentrate increases with the increase of suspension roasting temperature. This is because the rise in temperature accelerates the reaction rate of reduction of hematite (limonite) to magnetite, and the magnetism of roasted ore is continuously enhanced. The TFe grade of iron concentrate fluctuates between 54.35 and 56.71 %. The recovery rate of TFe in iron concentrate increases first with the temperature increase, and the recovery rate begins to decrease significantly when the magnetization roasting temperature exceeds 800 °C. The reason is that the strong magnetic mineral magnetite (Fe_3O_4) generated by the magnetization reaction continues to react with CO to form relatively weak magnetic FeO (wustite), which causes the loss of some valuable minerals in the tailings of weak magnetic separation [8, 9]. Considering the TFe grade, recovery rate, and roasting cost of iron concentrate, it is found that when the temperature is 800 °C, the iron index of suspension magnetization roasting-low intensity magnetic separation is better. Currently, the yield of iron concentrate is 65.33 %, the TFe grade is 56.15 %, and the TFe recovery rate is 84.31 %.

3.2 CO Concentration Test

Under the conditions of suspension magnetization, roasting fluidization speed of 0.3 m/s, roasting time of 1.5 min, roasting temperature of 800 °C, reduction gas CO concentration of 15 %, a grinding fineness of 72 % passing 0.023 mm, and magnetic separation field strength of 0.20 T, the effect of fluidization reduction gas CO concentration on the index of high-iron suspension magnetization roasting-low intensity magnetic separation iron was investigated and the test results are shown in Figure 4.

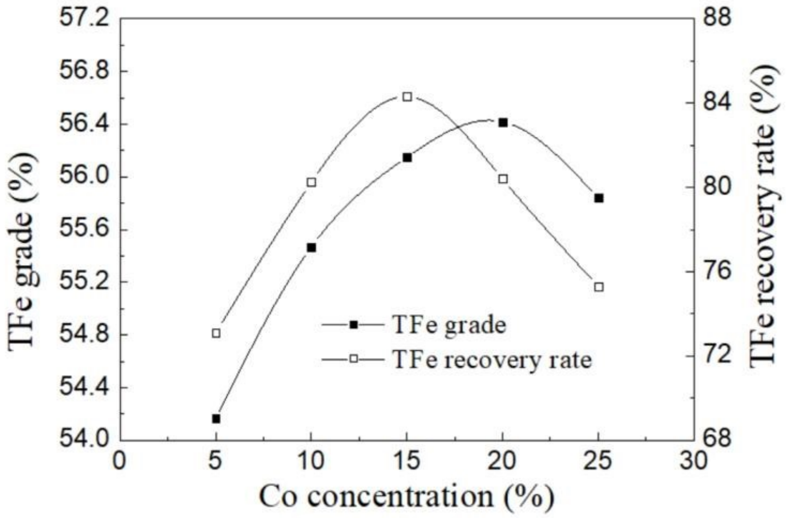

Figure 4. Experimental results of CO concentration in magnetized roasting.

According to the test results in Figure 4, with the continuous increase of the concentration of reducing gas CO, the TFe grade and recovery rate of iron concentrate increased first and then decreased. The TFe recovery of iron concentrate begins to decrease when the CO concentration exceeds 15 %, while the TFe grade of iron concentrate decreases when the CO concentration exceeds 20 %. When the CO concentration increased from 15 to 20 %, the TFe grade of iron concentrate risen from 56.15 to 56.42 %. The TFe recovery rate of iron concentrate decreased from 84.31 to 80.41 %, indicating that when the CO concentration exceeded 15 %, the reaction rate accelerated and the over-reduction phenomenon began to occur [10]. Considering the TFe recovery rate and economic cost of iron concentrate, it was determined that the reduction gas CO concentration of 15 % was more suitable for the suspension magnetization reaction of high-iron red mud.

3.3 Magnetization Roasting Time Test

Under the conditions of suspension magnetization, roasting fluidization speed of 0.3 m/s, roasting temperature of 800 °C, reducing gas CO concentration of 15 %, a grinding fineness of 72 % passing 0.023 mm, magnetic separation field strength of 0.20 T, the effect of suspension roasting time on iron index of suspension magnetization roasting-low intensity magnetic separation process for the high iron red mud was investigated and the results are shown in Figure 5.

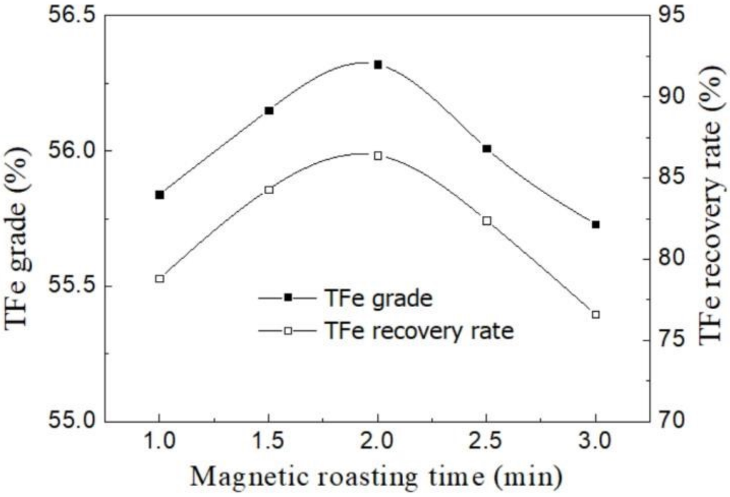

Figure 5. Results of magnetization roasting time test.

According to the test results in Figure 5, the roasting time significantly affects the treatment efficiency of the suspension roasting-low intensity magnetic separation process. With the continuous extension of the suspension roasting time, both the iron concentrate's TFe grade and recovery rate first increase and then decrease. When the roasting time was extended from 1 to 2 min, the TFe grade of iron concentrate increased from 55.84 to 56.32 %, and the TFe recovery rate rose from 78.81 to 86.39 %. It shows that increasing magnetization roasting time is beneficial to the directional transformation of weak magnetic hematite (limonite) to strong magnetic magnetite, and therefore improve the TFe grade and recovery rate of iron concentrate. When the roasting time continues to increase to 3.0 min, the TFe grade of the iron concentrate decreases from 56.32 to 55.73 %, and the TFe recovery rate of the iron concentrate decreases from 86.39 to 76.61 %, which indicated that the reduction of the strong magnetic minerals that have been magnetized and reduced to produce weak magnetic FeO (wustite). Therefore, the suspension magnetization roasting time was determined to be 2 min. At this time, the yield of iron concentrate was 66.74 %, the TFe grade was 56.32 %, and the TFe recovery rate was 86.39 %.

3.4 Grinding Fineness Test

Under the conditions of suspension roasting fluidization speed of 0.3 m/s, roasting time of 2 min, roasting temperature of 800 °C, reducing gas CO concentration of 15 %, and magnetic separation intensity of 0.20 T. The effect of grinding fineness was investigated and the results are shown in Figure 6.

According to the test results in Figure 6, the TFe grade of iron concentrate increases first and then tends to be stable with the increase of grinding fineness. In contrast, the TFe recovery rate of iron concentrate decreases with the increase of grinding fineness. When the grinding fineness of red mud after roasting is -0.023 mm and the content is 72 %, the TFe grade of iron concentrate is 56.32 %, and the TFe grade of iron concentrate with increasing grinding fineness tends to be stable. In contrast, the TFe recovery rate of iron concentrate is significantly reduced. Given that the magnetic capture force is weak for the fine grains, and therefore a grinding fineness of 72 % passing 0.023 mm should be controlled to avoid the tailing lost.

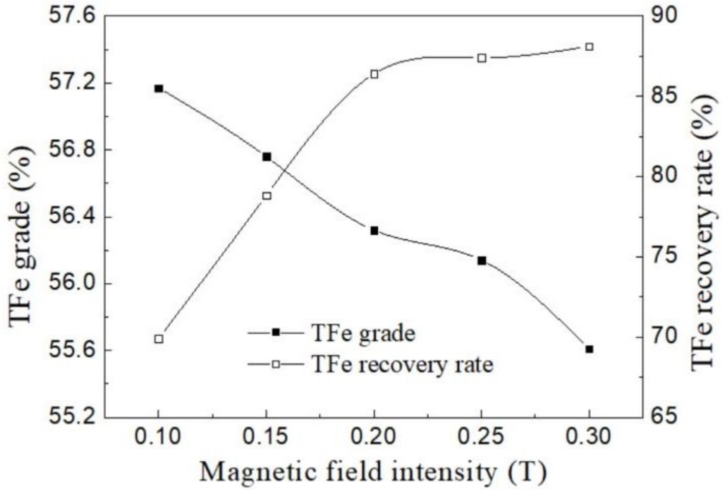

Figure 6. Grinding fineness test results.

3.5 Field Strength Test of Weak Magnetic Separation

Under the conditions of suspension magnetization roasting fluidization speed of 0.3 m/s, suspension roasting time of 2.0 min, roasting temperature of 800 ℃, reducing gas CO concentration of 15 %, a grinding fineness of 72 % passing 0.023 mm, the effect of low-intensity magnetic separation field strength on the index of high-iron red mud suspension magnetization roasting-low-intensity magnetic separation iron was investigated according to the process shown in Figure 2. The results are shown in Figure 7.

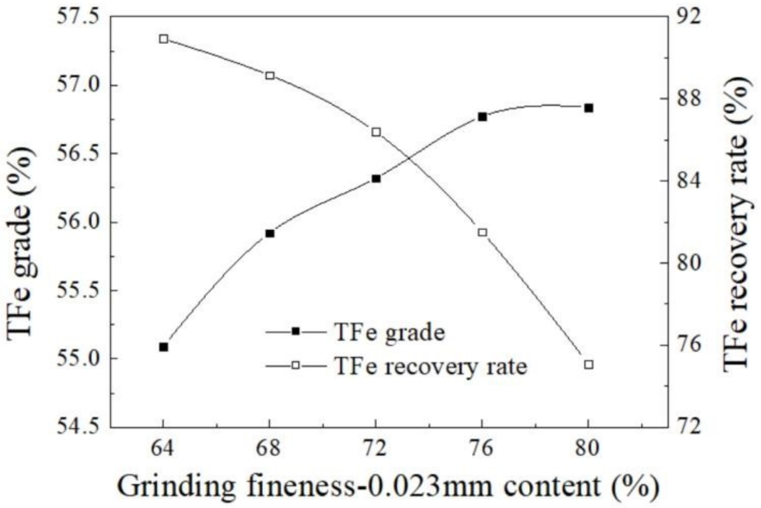

Figure 7. Field strength test results of weak magnetic separation.

According to the test results of Figure 7, with the increase of magnetic separation field strength, the TFe grade of iron concentrate decreases gradually. In contrast, the TFe recovery rate of iron concentrate increases continuously and then tends to be stable. When the magnetic field strength of the magnetic separation tube exceeds 0.25 T, the recovery rate increase of the iron concentrate tends to be little. Still, the TFe content of the iron concentrate continues to decrease, and the decrease is relatively significant, from 56.14 to 55.61 %. Considering the TFe grade and recovery rate of the iron concentrate, the magnetic field strength of the weak magnetic separation is determined to be 0.25 T.

3.6 Verification Test

Under the conditions of suspension magnetization, roasting fluidization speed of 0.3 m/s, roasting time of 2.0 min, roasting temperature of 800 °C, reduction gas CO concentration of 15 %, a grinding fineness of 72 % passing 0.023 mm, and weak magnetic separation field strength of 0.25 T, the verification test was carried out according to the process shown in Figure 2 to investigate the feasibility and reliability of the red mud "suspension magnetization roasting combined with low-intensity magnetic separation" technology. The results are shown in Table 4, from which it can be seen that an iron concentrate with a yield of 67.69 %, a TFe content of 56.21 % and a recovery rate of 87.45 % can be obtained after the combined Suspension magnetization roasting and low-intensity magnetic separation treatment. The iron tailings with a TFe content of 24.26 % have stated the high-quality utilization of high-iron red mud, which provided a technical reference for the industrial utilization of this type of high-iron red mud in China.

Table 4. Verification test results of high iron red mud "suspension magnetization roasting combined with low-intensity magnetic separation" (%).

Product name	Yield	TFe content	TFe recovery rate
Iron concentrate	67.69	56.21	87.45
Iron tailings	22.51	24.26	12.55
Burning loss	9.80		
Red mud	100.00	43.51	100.00

3.7 Phase Analysis of Red Mud and Roasted Sample

To investigate the phase change of high-iron red mud before and after suspension magnetization roasting, XRD analysis, and iron chemical phase analysis were carried out on the red mud and the roasted samples obtained under optimal conditions. The analysis results are shown in Figure 8 and Table 5, where it can be seen that the TFe grade of the original red mud is 43.01 %, the iron minerals mainly exist in the form of hematite (limonite), and the distribution rate is 97.63 %. The TFe grade of the roasted sample is 48.61 %, the iron minerals mainly exist in the form of magnetite, and hematite accounts for 95.60 %. It can be seen that the high-iron red mud completed the mineral phase reconstruction of iron-containing minerals in the process of suspension magnetization roasting; the weak magnetic hematite (limonite) was directionally reduced to a strong magnetic magnetite. At the same time, according to XRD analysis, it was also found that some gibbsite, and boehmite were transformed into alumina after suspension roasting dehydration, while minerals such as quartz, rutile, perovskite, and sodium silicon slag did not change. The increased magnetic difference between iron-containing and gangue minerals laid a foundation for the subsequent recovery of high-grade iron concentrate from roasting samples by low-intensity magnetic separation.

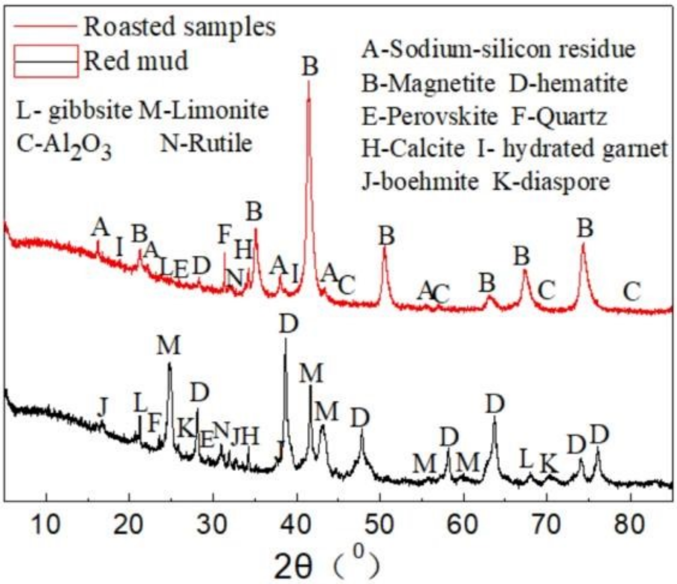

Figure 8. XRD analysis of raw red mud and roasted samples.

Table 5. Results of iron chemical phase analysis in roasted samples.

Iron chemical phase	Red mud (%)		Roasted samples (%)	
Iron chemical phase	Content	Distribution rate	Content	Distribution rate
Iron in magnetite	0.19	0.44	46.47	95.60
Iron in iron carbonate	0.28	0.64	0.22	0.45
Iron in red (brown) iron	41.98	97.63	1.35	2.78
Iron in iron sulphide	0.12	0.28	0.13	0.27
Iron in iron silicate	0.44	1.01	0.44	0.91
Total	43.01	100.00	48.61	100.00

3.8 Reaction Mechanism of Red Mud Suspension Magnetization Roasting

According to the experimental results and the phase analysis results, the reaction of hematite (limonite) in high-iron red mud-generating magnetite mainly undergoes the following four links: (A) Red mud particles are suspended and heated in a hot reducing airflow; (B) When the reaction temperature is reached, CO diffuses and adsorbs on the surface of hematite (limonite), and reacts with the surface of hematite (limonite) to form magnetite Fe_3O_4 and CO_2. (C) CO continues to adsorb on the surface, and the outer Fe^{2+} and electrons diffuse to the inner Fe_2O_3 through the lattice vacancies. After lattice reconstruction, it is transformed into magnetite Fe_3O_4. The inner O^{2-} diffuses to the outer layer and interacts with CO to form CO_2, which is continuously removed. (D) The former process is in-depth, and the reaction is constantly pushed to the inner layer. Finally, the particles are entirely reduced to magnetite particles, thus completing the mineral phase reconstruction of iron-bearing minerals in high-iron red mud. The reaction formula is shown in Equations (1), (2) and (3).

$$CO + O^{2-} = CO_2 + 2e \quad (1)$$

$$2Fe^{3+} + 2e^- = 2Fe^{2+} \quad (2)$$

$$4Fe_2O_3 + Fe^{2+} + 2e^- = 3Fe_3O_4 \quad (3)$$

4. Conclusion

In this paper, "Suspension Magnetization Roasting and Low-Intensity Magnetic Separation" technology was applied to recover iron-bearing minerals from high-iron red mud, and the effect of suspension magnetization roasting on the phase reconstruction of iron minerals in high-iron red mud was studied. The key findings of this study are summarized as follows:

1. The study on the properties of high-iron red mud shows that the amount of TFe in the original red mud is 43.51 %. The valuable element iron is mainly red (brown) iron ore, and its distribution rate reaches 97.63 %. The high-iron red mud also contains sodium silicon slag, hydro garnet, gibbsite, diaspore, calcite, rutile, perovskite, and quartz.

2. The high-iron red mud with a TFe grade of 43.51 % was subjected to suspension magnetization roasting process combined with low-intensity magnetic separation under the conditions of roasting fluidization speed of 0.3 m/s, magnetization roasting temperature of 800 °C, roasting time of 2.0 min, CO concentration of 15 %, a grinding fineness of 72 % passing 0.023 mm, and low-intensity magnetic separation field of 0.25 T. The iron tailings for preparing cement with a yield of 67.69 %, a TFe grade of 56.21 %, a recovery rate of 87.45 %, a yield of 22.51 %, and a TFe grade of 24.26 % were obtained, which realized the high-value comprehensive utilization of red mud.

3. It was found that the weak magnetic hematite (limonite) iron ore was directionally converted into strong magnetic magnetite during the suspension magnetization roasting process of red mud. Some gibbsite, and boehmite were dehydrated and converted into Al_3O_2, while the gangue minerals such as quartz, rutile, perovskite, and sodium silicon slag did not change. The specific magnetization coefficient gap between iron minerals and gangue minerals was expanded, which laid a foundation for the recovery of high-grade iron concentrate from roasted red mud by weak magnetic separation.

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