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Grate-kiln pelletization of Indian hematite fines and its industrial practice

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Abstract: Indian hematite fines normally have a high iron grade and minor impurities; they are usually used as sinter fines for feeding into a blast furnace. In this work, the grindability properties of two kinds of Indian hematite fines and the roasting behaviors and induration characteristics of pellets made from these fines were revealed through experiments involving dry ball milling and small-scale and pilot-scale tests. In addition, the microstructures of the particles of ground India hematite fines and fired pellets were investigated using optical microscopy. On the basis of the results, a grate-kiln production line with an annual output of 1.2 Mt of oxidized pellets was established in India. This pellet plant operates stably and reliably, further confirming that preparing high-quality pellets with Indian hematite fines pretreated by dry ball milling is an industrially feasible process.

Keywords: hematite; pelletizing; industrial practice

1. Introduction

India, as an emerging nation, has maintained an overall rapid growth of its steel industry because of the booming development of its economy and the acceleration of urbanization in recent years [1–3]. By the year 2020, India's production of steel is expected to reach 110 Mt from the current level of approximately 70–75 Mt [3–4]. The rapid expansion of Indian steel output and remarkable advances in metallurgical technology drive demand for high-quality raw materials. Iron ore pellets are an indispensable component of burdens for blast furnaces given their unmatched advantages of uniform size, high iron grade, excellent metallurgical properties, and high physical strength; iron ore pellets consequently were used more extensively in ironmaking [5]. In addition, as the largest producer of direct reduction iron (DRI), India requires a large quantity of iron ore pellets to supplement the short supply of the natural lump ore stemming from the depletion of Indian high-grade competent iron ore resources. Meanwhile, large amounts of hematite fines are generated and accumulated during the production of the lump ores. However, demand for fines as sintering feeds in the Indian market is weak because the sintering capacity is not commensurate with the rate of generation of fines [6–7]. Thus, to capture possible economic gains of iron ore mining and to solve the potential environmental problems caused by dumping of fines in earlier periods, the pelletizing process has been attracting increasing attention as a method to sustainably utilize hematite fines.

Indian hematite fines, which normally assay at a high iron grade — greater than 62wt% total iron — and a low content of detrimental impurities, are chemically good pellet feeds. Unfortunately, they cannot be used directly in the pelletizing process because of the fact that Indian hematite fines are characterized by a coarse size and a low specific surface area. Even more importantly, such characteristics will inevitably affect the subsequent pelletization process, such as the grindability properties, roasting performance, and induration characteristics; thus, intimate knowledge of their properties and industrial production practice are important. However, previous investigations related to the pelletization of Indian hematite fines have been extremely limited.

In this paper, two Indian hematite fines were adopted as pellet feeds for investigating the grindability properties on

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the basis of Bond work index via ball mill and dry ball milling tests. Moreover, two typical kinds of finely ground Indian hematite fines were used as pellet feeds to reveal the preheating-roasting behaviors by conducting small-scale and pilot-scale tests. On this basis, a pellet plant with an annual capacity of 1.20 Mt of fired pellets was designed and the industrial practice was carried out.

2. Experimental

2.1. Raw materials

The following materials were used for preparing the green pellets: 1# and 2# Indian hematite fines and bentonite. The composition and particle size distribution are listed in Tables 1 and 2, respectively. As evident in Table 1, ore 1# and ore 2# bear a high iron grade and a low FeO content of 0.45wt% and 0.50wt%, respectively, indicating that both are hematite-type iron ores. Meanwhile, both Indian hematite fines contain low silica content and minor detrimental elements such as sulfur, phosphorus, and nonferrous metals. Thus, they are good raw materials for producing pellets from a chemistry viewpoint. However, they must be finely ground before ball milling because of their coarse size of only 31.76wt%–39.17wt% passing 0.074 mm (Table 2).

Bentonite is a hydrous aluminosilicate largely composed of montmorillonite clay mineral. The composition of bentonite and its physical properties are listed in Tables 1 and 3, respectively, all of which indicate that bentonite is an excellent binder for improving pelletization.

Table 1. Chemical compositions of the raw materials wt%

Sample	TFe	FeO	SiO_2	Al_2O_3	CaO	MgO	K_2O
1#	65.31	0.45	3.88	1.89	0.25	0.065	0.180
2#	63.88	0.50	4.62	2.38	0.50	0.068	0.024
Bentonite	10.52	—	46.98	17.09	1.59	2.32	0.090
Sample	Na_2O	Cu	Pb	Zn	S	P	LOI
1#	0.0063	0.00050	0.0025	0.0085	0.020	0.020	1.400
2#	0.0260	0.00150	0.0095	0.0150	0.023	0.032	2.370
Bentonite	2.10	—	—	—	0.013	0.077	12.98

Table 2. Size distributions of the Indian hematite fines wt%

Sample	Size / mm								
	+8	–8+4	–4+3	–3+0.9	–0.9+0.5	–0.5+0.2	–0.2+0.125	–0.125+0.074	–0.074
1#	14.34	7.25	10.67	8.71	2.77	5.33	12.23	6.95	31.76
2#	4.00	6.12	9.92	7.92	5.76	7.82	13.03	6.26	39.17

Table 3. Physical properties of bentonite

Methylene blue uptake per 100 g bentonite / g	Colloid percentage / %	Expanding volume / ($mL \cdot g^{-1}$)	Water absorbency for 2 h / wt%	pH value
39.8	100	23	403.27	9.82

2.2. Methods

2.2.1. Bond work index of the ball mill

The Bond work index (W_i) is widely used in the mineral industry for comparing the resistance of different ores to ball milling and can be used to estimate the energy required for grinding, which can be determined using multiple methods [8–10]. In this paper, the standard Bond method was used to measure the W_i via ball milling conducted in a laboratory.

The grindability tests for determining W_i were conducted at 70 r/min in a Bond ball mill with a diameter and width of 305 mm × 305 mm. The mill was loaded with 285 steel balls of different sizes and with a total mass of 20.125 kg. The size distribution of the grinding medium is shown in Table 4.

Table 4. Size distribution of the grinding medium for Bond work index measurements

Diameter of steel balls / mm	36.5	30.2	25.4	19.1	15.9
Numbers of balls	43	67	10	71	94

First, 200 g of iron ore collected from the bulk sample using a divider was sieved into many size fractions; the size fraction with 80wt% passing was used in subsequent expe-

riments. The bulk density of the iron ore was then measured by using a 700 cm^3 graduated flask, and the average value was calculated as the final result. The first batch sample, which was measured using the 700-cm^3 graduated flask, was placed into the ball mill, which was then rotated for 100 revolutions to grind the first batch sample. Screening of the first ground batch sample was carried out to determine the aperture of the comparative screen (P_1) and to weigh the undersize. Afterwards, the second batch sample was fed into the ball mill, which consisted of two parts: the total oversize of the first batch grinding and the original iron ore possessing the equal mass of the undersize of the first batch grinding. The feed mass of the batch ball mill was kept constant each time. The revolutions for the second batch milling were estimated with a circulating load at 250% on the basis of the amount of newly formed undersize of the first batch milling (G_{bp}). Similarly, the third batch feed was then determined after screening and weighing the undersize from the second batch ground product. Finally, the aforementioned batch milling was performed in turn until the grinding circulating load was stabilized at 250%. Generally, ten batch millings were required and the average value of the last three G_{bp} was recorded as the final G_{bp}. However, the deviation between the maximum and minimum G_{bp} must be less than 3%. G_{bp} is usually defined as grindability [8–13].

W_i can be calculated as

$$W_i = 1.1 \times \frac{44.5}{P_1^{0.23} G_{bp}^{0.82} \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)} \quad (1)$$

where W_i is the Bond work index of ball milling, kW·h/t; P_1 is the aperture of the comparative screen, μm; G_{bp} is the net mass of the newly screened undersize produced per mill revolution, g/r; P_{80} is the size with 80wt% of the mill product passing, μm; F_{80} is the size with 80% of the mill feed passing, μm.

2.2.2. Ball milling of iron ores

In this work, a dry ball milling process was conducted to pretreat Indian hematite ore fines. The grinding tests of the iron ore fines were carried out in a ball mill for dry milling. The ball mill contained steel balls with a total mass of 160 kg; the mill's drum size was 460 mm in diameter and 620 mm in length, and the drum was rotated at a constant speed of 50 r/min. The size distribution of the grinding medium is shown in Table 5.

Table 5. Size distribution of balls of mill

Diameter of steel balls / mm	10–25	25–50	50–80	80–100	<100
Percentage / wt%	15	20	25	20	20

2.2.3. Green balls preparation

Green balls were prepared from the mixture of the finely ground hematite fines and 0.5wt% bentonite in a disc pelletizer with a diameter of 0.8 m and a rim depth of 0.2 m, rotated at 38 r/min and inclined 47° horizontally. The time required for pelletization was fixed at 15 min, and the moisture of green balls was approximately 8wt%–9wt%. The green balls were obtained with diameters from 9 to 16 mm by screening, and all characterizations were conducted using this size fraction. The drop numbers and compression strength of green balls were measured using 10 green balls to evaluate the ability of the green balls to remain intact and retain their shape during handling, respectively. The drop strength of green pellets was measured by the drop numbers from the height of 0.5 m. Green balls were dried at 105°C for 3 h in an oven to prepare dry balls for further induration.

2.2.4. Small-scale tests of firing pellets

The small-scale roasting of dry pellets was conducted in an electric tube furnace with a diameter of 35 mm. The effects of the roasting system, including the effects of the preheating temperature and duration, and the firing temperature and duration on the fired pellet strength were investigated. The temperature profile of preheating and firing is shown in Fig. 1. The dried pellets were indurated through four stages of temperature variation, including heating up, preheating at 1000–1100°C, firing at 1300°C, and heat soaking from 1300 to 1000°C for some time. The fired pellets were then cooled to room temperature in air for measurement of their compressive strength.

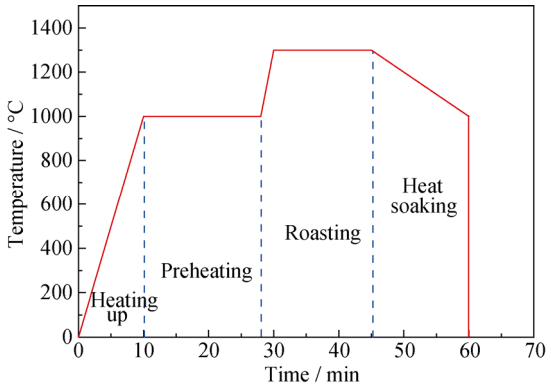

Fig. 1. Temperature profile of preheating and firing in an electrical tube furnace.

2.2.5. Pilot-scale tests of firing pellets

On the basis of small-scale tests, pilot-scale tests were conducted in a grate pot (ϕ300 mm × 500 mm)–rotary kiln (ϕ500 mm × 1000 mm) firing system to verify the technical feasibility of the grate-kiln pelletization process. In each batch, approximately 20 kg of green pellets were loaded into

the grate pot for drying and preheating; a schematic of the operation system of the pot grate tests is shown in Fig. 2. In the pot grate tests, updraft drying, downdraft drying, and preheating were simulated through control of different valves and the temperatures of the burning chamber. The preheated pellets were transferred into the rotary kiln with a diameter and length of 500 mm and 1000 mm, respectively. The heat of firing was supplied by the combustion of natural gas. Approximately 15 kg of preheated pellets were loaded into the kiln for each firing batch. The temperature profile for operating the rotary kiln is shown in Fig. 3. When the firing stage was finished, the fired pellets were removed from the kiln and allowed to naturally cool in the air.

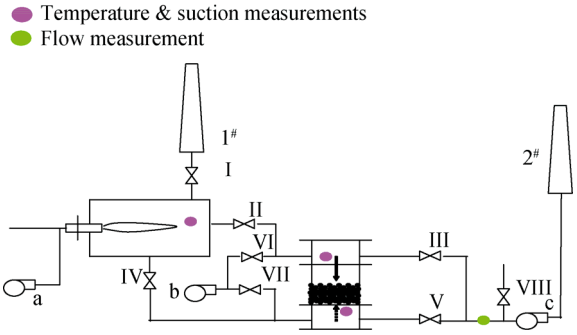

Fig. 2. Schematic of the operation system of pilot pot grate tests. Chimney: 1# and 2#; fan: a, b, and c; valves: I–VIII.

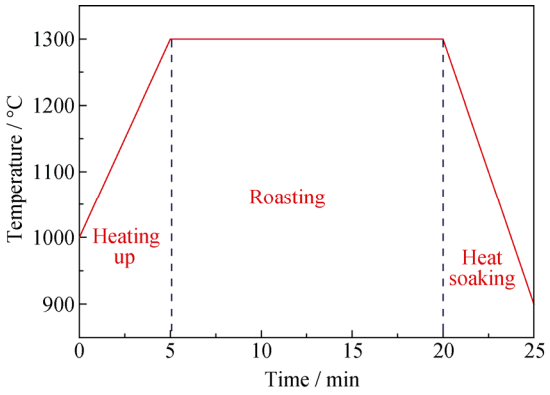

Fig. 3. Temperature profile of the pilot rotary kiln for pellets firing.

The compressive strength and metallurgical performance of the fired pellets were measured to evaluate their suitability for use as blast-furnace burden. The compressive strength of the preheated and fired pellets was determined according to standard ISO4700. Their metallurgical properties, including their reducibility index (RI), reduction degradation index (RDI), reduction swelling index (RSI), and softening and melting temperatures, were measured in a specially designed apparatus according to standard ISO7215 [14–15].

2.2.6. Microstructure observations

The microstructure of the ground products was observed under a Leica DMLP optical microscope, an FEI Quanta-200 scanning electron microscope, and an EDAX32 Genesis energy-dispersive X-ray spectrometer. Scanning electron microscopy (SEM) images were recorded in backscatter electron mode, and the microscope was operated in low-vacuum mode at 66.661 Pa and 20 keV [16–17].

3. Results and discussion

As previously mentioned, the two types of Indian hematite fines were not suitable for balling directly because of their initial coarse size with only 31.76wt%–39.17wt% passing 0.074 mm. In general, the optimum fineness of concentrates as pellet feed is within the range from 80wt% to 90wt% passing 0.074 mm as well as 50wt%–60wt% passing 0.044 mm; the corresponding specific surface areas (SSAs) are 1500–2000 cm^2/g [18]. Therefore, further fine dry ball milling is required to reach the target fineness for balling.

3.1. Bond ball mill work index

In the practice of comminution, the Indian hematite fines are coarse, with a size of 85.66wt%–96.00wt% below 8 mm; however, the Bond tests require samples with a standard size. Therefore, to obtain the correct W_i, the hematite samples were crushed to a size below 3.35 mm. The W_i data were measured for the samples following the standard Bond work index procedure; the results are given in Table 6.

Table 6. Summary of W_i data for the two kinds of hematite

Sample	P_1 / μm	F_{80} / μm	P_{80} / μm	G_{bp} / ($g \cdot r^{-1}$)	W_i / ($kW \cdot h \cdot t^{-1}$)
1# hematite	98	630	80	4.12	7.437
2# hematite	98	560	78	3.98	7.726

As shown in Table 6, the Indian hematite fines had an extremely low W_i from 7.437 to 7.726 kW·h/t. Generally, the W_i data of iron ores are within the range from 10 to 15 kW·h/t, which means the two kinds of Indian hematite fines exhibit better grindability than common iron ores, resulting in less energy consumption during the balling process [9]. There-

fore, pretreating the Indian hematite fines by ball milling is relatively economically viable.

3.2. Dry ball milling

According to our previous experiments, the finely ground Indian hematite is characterized by poor dewatering characteristics, high moisture content of the filter cake, and low processing capacity. Consequently, dry ball milling is more appropriate than wet ball milling for processing the Indian hematite fines.

3.2.1. Size distribution

The dry open-circuit grinding tests were performed in a laboratory, and the size distribution of the dry ground products of the Indian hematite fines with a fineness of 80wt%–90wt% passing 0.074 mm is shown in Table 7. As evident from the results in Table 7, when the 1# and 2# Indian hematite fines were ground to the size of approximately 85% below 0.074 mm, the percentage of ground products below 0.043 mm was 51.25wt% and 54.65wt%, respectively, which satisfies the requirement for the subsequent balling process [18–19]. In addition, the 2# ground Indian hematite concentrates contained more particles below 0.043 mm than did the 1# concentrates.

Table 7. Size distribution of dry grinding products of Indian hematite wt%

Size / mm	–0.074 mm 90%		–0.074 mm 85%		–0.074 mm 80%	
	1#	2#	1#	2#	1#	2#
–0.043	57.25	63.59	51.25	54.65	48.05	52.47
+0.043–0.074	33.50	27.47	34.00	30.45	33.55	27.58
+0.074–0.104	3.15	3.80	4.85	4.35	4.90	7.88
+0.104–0.125	3.35	0.86	3.75	1.50	3.50	2.19
+0.125–0.154	2.50	4.04	5.40	8.20	8.50	8.93
+0.154–0.180	0.05	0.03	0.35	0.45	0.65	0.04
+0.180–0.280	0.05	0.14	0.25	0.35	0.65	0.35
+0.280	0.15	0.07	0.15	0.05	0.20	0.20

3.2.2. Specific surface areas

In the balling process, the specific surface areas of the raw materials are one of the most important factors that influence the properties of the green pellets, such as their drop strength, compressive strength, and thermal stability. Generally, the raw materials should have specific surface areas (Blaine index) in the range from 1500 to 1900 cm^2/g to ensure good balling characteristics [19–20]. Hence, the specific surface areas of the ground products were determined by the Blaine method [21]; the results were shown in Fig. 4, which reveals that these two typical kinds of Indian hematite concentrates ground to the size of 80wt%–90wt% passing 0.074 mm possessed very high SSAs, approximately 2100–4900 cm^2/g, well above the desired level for balling.

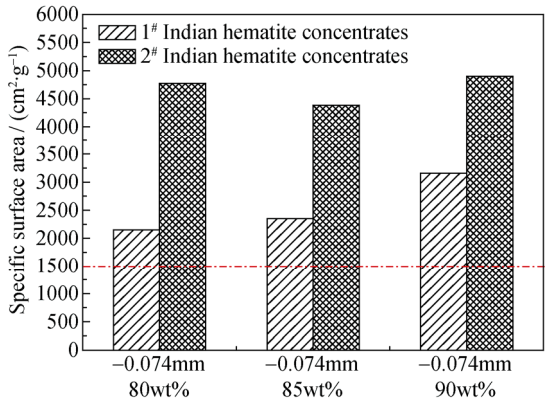

Fig. 4. Specific surface areas of ground products with different sizes.

3.2.3. Microstructure of particle of ground India hematite fines

SEM micrographs of the particle morphologies of hematite concentrate ground to the size of 90wt% passing 0.074 mm are depicted in Fig. 5; the energy spectra of flocs in the 1# and 2# Indian hematite concentrates are shown in Fig. 6. Numerous flocs adsorbed onto the surface of the coarser Indian hematite particles, which mainly contained Fe, Si, and Al (as shown in Fig. 6). We inferred from this observation that the surface flocs consisted of ultrafine hematite and clay mineral particles, which was beneficial to improving ballability. Moreover, the surface of the Indian hematite particles was relatively rough.

3.3. Small-scale tests

3.3.1. Green ball preparation

To optimize the balling parameters and prepare superior-quality green balls, green ball preparation experiments were carried; the results are shown in Fig. 7, which reveals that the optimum balling parameters were a bentonite content of 0.5wt%, a balling time of 15 min, and a balling moisture content of 7.5wt%. Under these optimum conditions, the drop numbers, compressive strength, and cracking temperature reached 33.2 times, 22.43 N per pellet, and 330°C for the 1# green pellets and 38.3 times, 23.41 N per pellet, and 324°C for the 2# green pellets; all of these values satisfy the requirements for the subsequent firing process. The high drop numbers (greater than 30 times) of the 1# and 2# green pellets are mainly due to the very high SSAs of these two typical ground Indian hematite concentrates, as shown in Fig. 4. In addition, with increasing content of 1#

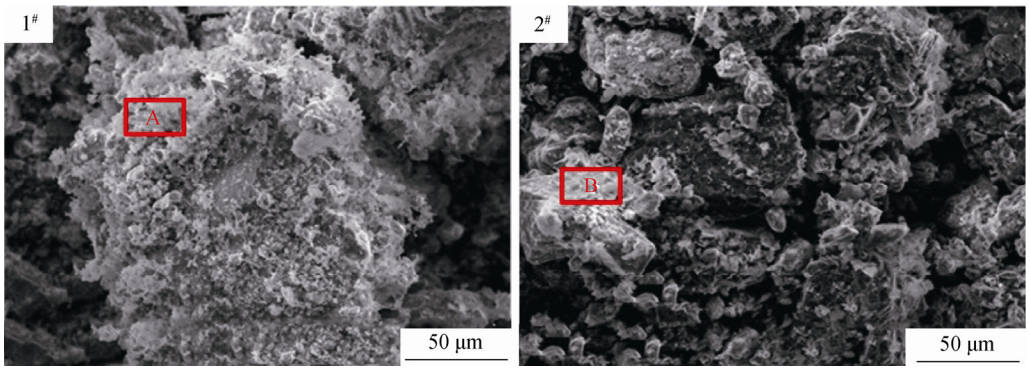

Fig. 5. Particle morphologies of two types of hematite concentrates after being ground to a size of 90wt% passing −0.074 mm.

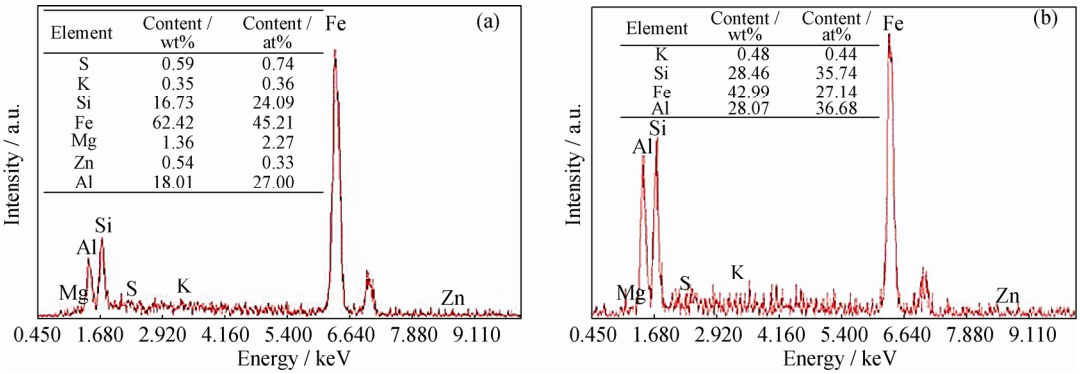

Fig. 6. Energy spectra of surface flocs adhering onto 1# and 2# Indian hematite particles: (a) area A in Fig. 5; (b) area B in Fig. 5.

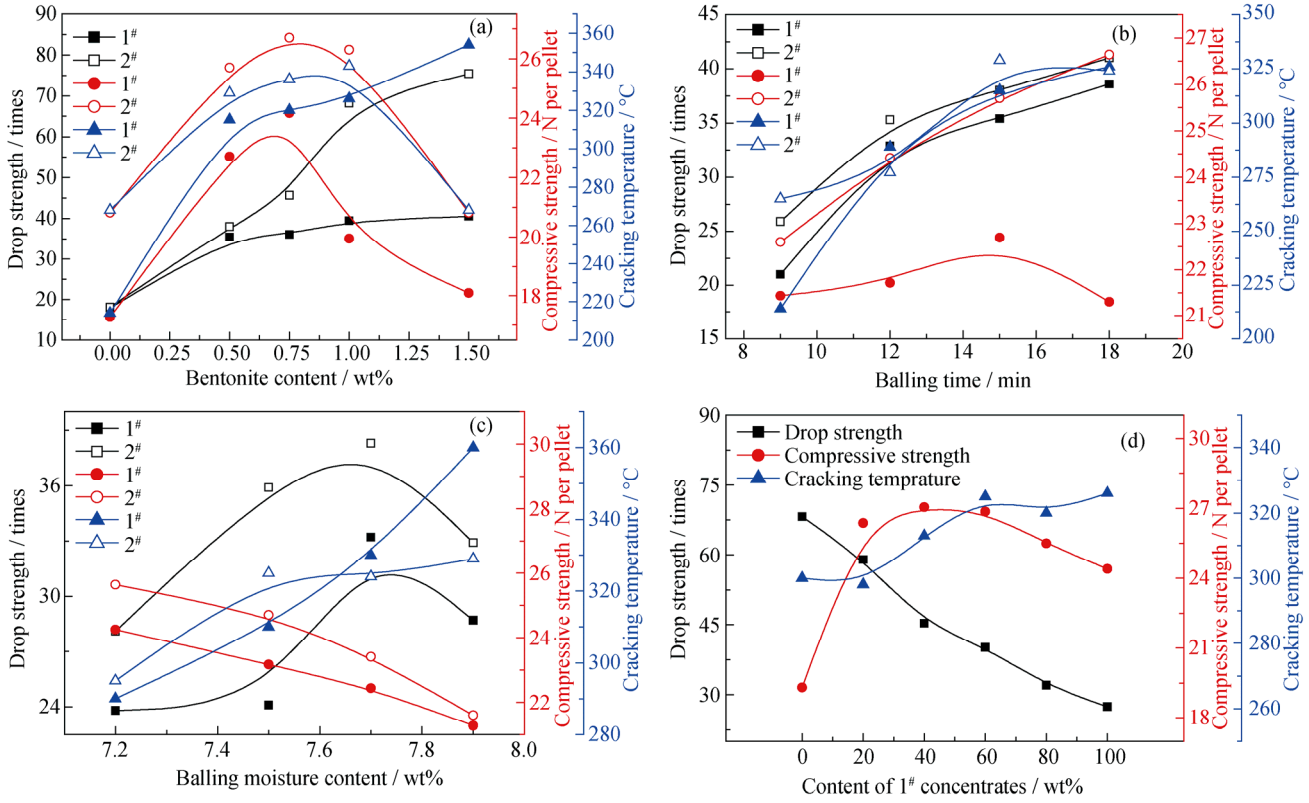

Fig. 7. Effects of different parameters on the strength and cracking temperature of green pellets: (a) bentonite content; (b) balling time; (c) balling moisture content; (d) content of 1# Indian hematite concentrates.

ore in the blends, the drop numbers of the green pellets decreased, the cracking temperature of the green pellets increased, and the compressive strength of the green pellets exhibited a trend of first increasing and then decreasing. However, superior-quality green balls were obtained irrespective of the proportion in which the 1# ore and 2# ore were mixed.

3.3.2. Tests of firing pellets

Using the optimized balling parameters and the prepared superior-quality green balls, we carried out small-scale firing tests with an electric tube furnace. Investigations on the influence of preheating and firing variables on the preheated and fired pellets were conducted; the results, which are shown in Figs. 8 and 9, guided the large-scale tests.

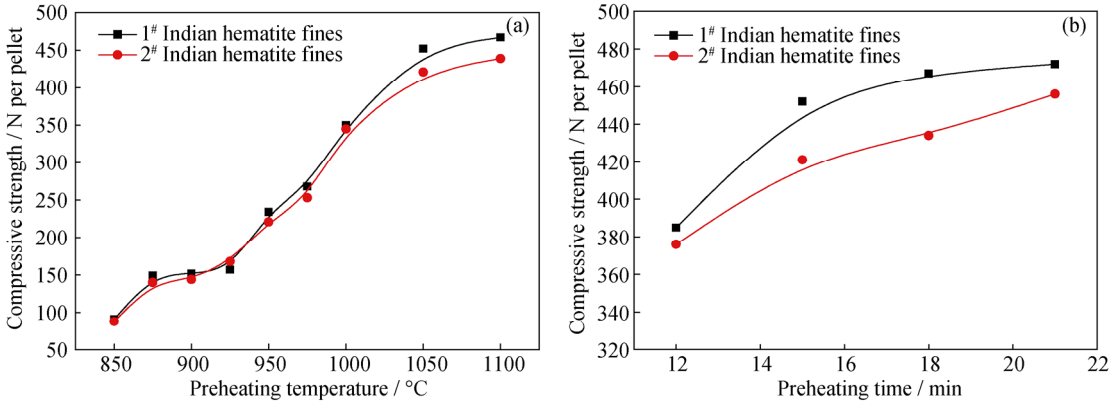

Fig. 8. Effects of preheating conditions on the compressive strength of preheated pellets: (a) preheating temperature (preheating for 15 min); (b) preheating time (preheating at 1050°C).

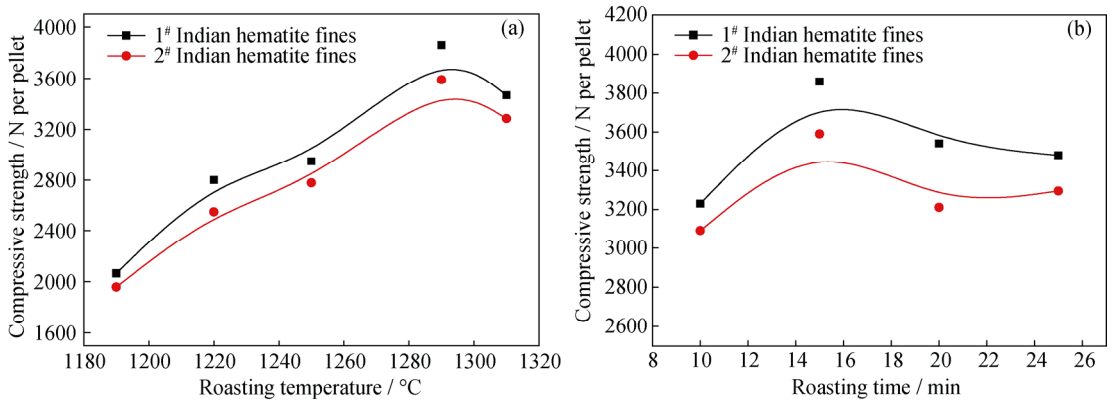

Fig. 9. Effects of roasting conditions on the compressive strength of fired pellets: (a) roasting temperature (preheating at 1050°C for 15 min and roasting for 15 min); (b) roasting time (preheating at 1050°C for 15 min and roasting at 1290°C).

As evident from the results in Figs. 8 and 9, the optimum preheating and firing parameters included preheating at 1050°C for 15 min and firing at 1290°C for 15 min; correspondingly, the compressive strength of the preheated and fired pellets reached 421–452 N and 3860–3590 N per pellet, respectively, which satisfies the requirements for use in a large blast furnace. Moreover, we concluded that two types of finely ground Indian hematite fines possess superior induration properties after being finely ground. However, they require a higher preheating and firing temperature and a longer preheating and firing duration compared to magnetite pellets.

3.4. Pilot-scale test

3.4.1. Full flowsheet test

On the basis of the small-scale tests, pilot-scale tests of pellets 1# and 2# were conducted under the following optimized conditions: bed height of 150 mm, updraft drying at 200°C for 8 min with an air flow rate of 0.8 m/min, downdraft drying at 300°C for 4 min with an air flow rate of 0.8 m/min, preheating at 1050°C for 15 min with an air flow rate of 1.9 m/min, and firing at (1290 ± 10)°C for 20 min. Three types of pellets prepared using 1#, 2#, and 3# hematite fines (where 3# fines were a mixture of 1# and 2# ores at a mass ratio of 60:40), were indurated through full flowsheet test under the aforementioned optimum conditions, including proportioning, mixing, balling, drying, preheating, firing, and cooling. The experimental conditions are shown in Table 8 and the results are shown in Table 9 and Fig. 10.

Table 8. Experimental conditions in a full flowsheet of pilot tests

Stage	Bed height / mm	Air flow rate / ($m \cdot s^{-1}$)	Induration / min	Temperature / °C
Updraft drying	180	0.8	8	150
Downdraft drying	180	0.8	7/4	150/300
Preheating	180	1.9	15	1050
Firing	180	—	20	1290

Note: Green balls were prepared by adding 1% bentonite.

Table 9. Results of the full flowsheet of pilot tests

Index	1#	2#	3#
AC tumble index of preheated pellets (+3 mm) / wt%	99.32	99.44	99.24
Compressive strength of preheated pellets / N per pellet	689.5	650.1	678.9
Compressive strength of fired pellets / N per pellet	3350	3170	3260
Tumble index of fired pellets (+6.3 mm) / wt %	97.8	96.2	95.6
Abrasion index of fired pellets (–0.5 mm) / wt%	1.25	1.47	1.41

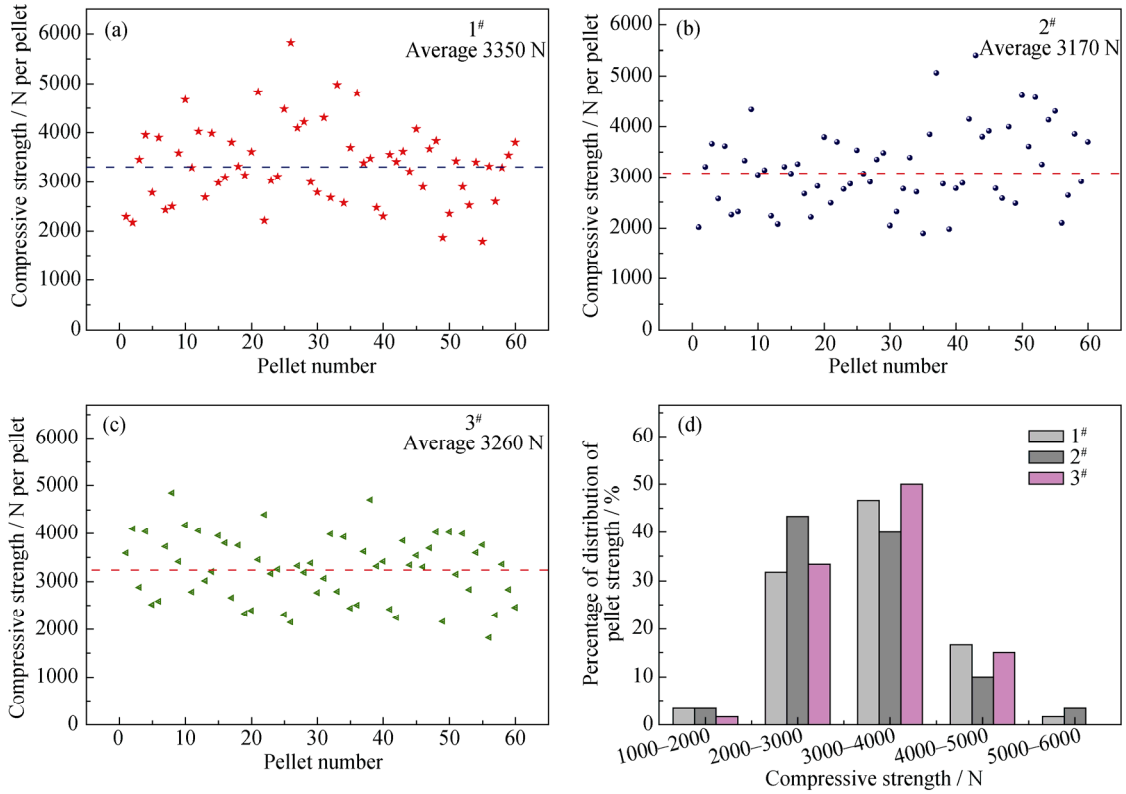

Fig. 10. Strength distribution of fired pellets obtained in the full flowsheet of pilot tests: (a) 1# fired pellets; (b) 2# fired pellets; (c) 3# fired pellets; (d) three types of fired pellets.

The results in Table 9 reveal that all three types of fired pellets exhibited excellent physical characteristics, with compressive strengths of 3170–3350 N per pellet, a high tumble index greater than 95%, and a low abrasion index of less than 1.5%. Meanwhile, the results of pilot-scale tests agreed well with those of small-scale tests; in particular, the compressive strength of the pellets obtained in large-scale tests was much higher than that obtained in small-scale tests. In addition, as evident in Fig. 10, the compressive strength of the product pellets was primarily distributed in the range from 2000 to 4000 N per pellet, and no pellets exhibited a compressive strength less than 2000 N, indicating that the product pellets prepared by the rotary kiln

process have reliable and uniform quality.

3.4.2. Metallurgical performance of product pellets

The chemical composition of the product pellets obtained from full flowsheet tests is given in Table 10. The compositions of all of the pellets are in accordance with the target values and are characterized by a high iron grade and low silica and alumina contents, indicating that the pellets should be good burdens for blast furnace operation.

The metallurgical performances of the products are summarized in Table 11. The results show that the three kinds of pellets exhibit superior metallurgical performance, including a high RI, a low RSI and $RDI_{-3.15\ mm}$, a proper softening temperature, and a narrow range of softening and melting; these properties are beneficial to permeability in a blast furnace. In China, the standards for high-grade roasted pellets are RI ≥ 65%, $RDI_{+3.15\ mm}$ ≥ 90%, and RSI ≤ 15% according to standard YB/T005—91.

Table 10. Chemical composition of the fired pellets of the Indian hematite fines wt%

Sample	TFe	FeO	SiO_2	Al_2O_3	CaO	MgO	K_2O	Na_2O	S	P	Mn
1#	65.23	0.44	4.46	1.47	0.094	0.045	0.027	0.033	0.020	0.021	0.14
2#	64.87	0.54	5.49	1.86	0.160	0.049	0.031	0.034	0.012	0.032	0.16
3#	65.02	0.42	4.85	1.92	0.098	0.043	0.031	0.034	0.011	0.028	0.13

Table 11. Metallurgical performance of the fired pellets of Indian hematite

Sample	RI / %	RSI / %	RDI / %			Softening and melting temperature / °C			Compressive strength of reduced pellets / N per pellet
			+6.3 mm	+3.15 mm	–0.5 mm	T_{bs}	T_{fs}	T_{md}	
1#	66.26	13.45	94.12	95.69	4.40	1130	1350	1470	483.1
2#	70.51	11.25	95.03	95.87	3.91	1090	1342	1456	411.3
3#	70.03	13.58	94.56	95.44	4.12	1120	1344	1455	448.6

Note: T_{bs}—softening temperature; T_{fs}—melting temperature; T_{md}—droping temperature.

3.5. Induration characteristics of Indian hematite pellets

The three samples of fired pellets obtained from the full flowsheet of pilot-scale tests were made of 1#, 2#, and 3# hematite fines, respectively, where the 3# sample is a mixture of 1# and 2# ores at a mass ratio of 60/40.

3.5.1. Mineral compositions

The mineralogy of the fired pellets was determined using optical microscopy; the main mineral compositions are listed in Table 12. The fired pellets are mainly composed of hematite, minor magnetite, calcium fayalite, magnesium fayalite, and a glassy phase. In addition, we inferred that the predominant binding phase of the fired pellets contains hematite recrystallized by solid diffusion, with the minor liquid phase as a complementary phase.

Table 12. Mineral compositions of fired pellets vol%

Sample	Hematite	Magnetite	Ferrous/calcium fayalite	Magnesium fayalite	Glass phase	Others
1#	93.3	0.3	2.2	1.1	2.5	0.6
2#	92.1	0.3	2.9	1.1	2.8	0.8
3#	92.5	0.3	2.7	1.1	2.7	0.7

3.5.2. Microstructures of product pellets

The microstructures of the three kinds of fired pellets are demonstrated in Figs. 11 and 12, which reveal that hematite, as the main bonding phase, fully recrystallized in the surface and nuclear layer of the fired pellets and that all of the hematite crystals grew together to form a full interlinkage, which is beneficial to the mechanical strength of the fired pellets [22–23]. Moreover, some granule fayalite occurred as a liquid phase among hematite crystals, which tends to reshape the grains by dissolving their sharp corners into the liquid phase, eliminating their pores, and consolidating the particles into a denser structure [18,24–25]. We also observed more large-sized pores in the 2# pellets than in the 1# pellets because 2# Indian hematite fines possessed more combined water, with a 2.37wt% LOI, which resulted in lower mechanical strength. However, some coarser fayalite

appeared in the nuclear layer of all of the pellets, which resulted from the lower oxygen potential due to the diffusion resistance of the bulk gas into the nuclear layer. The SEM–energy-dispersive X-ray spectroscopy (EDS) analysis results for the 3# fired pellets are presented in Fig. 13. A clear boundary is observed between the Fe_2O_3 and the other minerals. Other minerals, such as fayalite, existing as chemical compounds and as solid solutions, fill the gaps of the Fe_2O_3 grains. In addition, the Fe_2O_3 grains are very pure, exhibit a mean size greater than 30 μm, and are uniformly distributed, densely crystallized, and closely bonded, implying a high compressive strength of the roasted pellets.

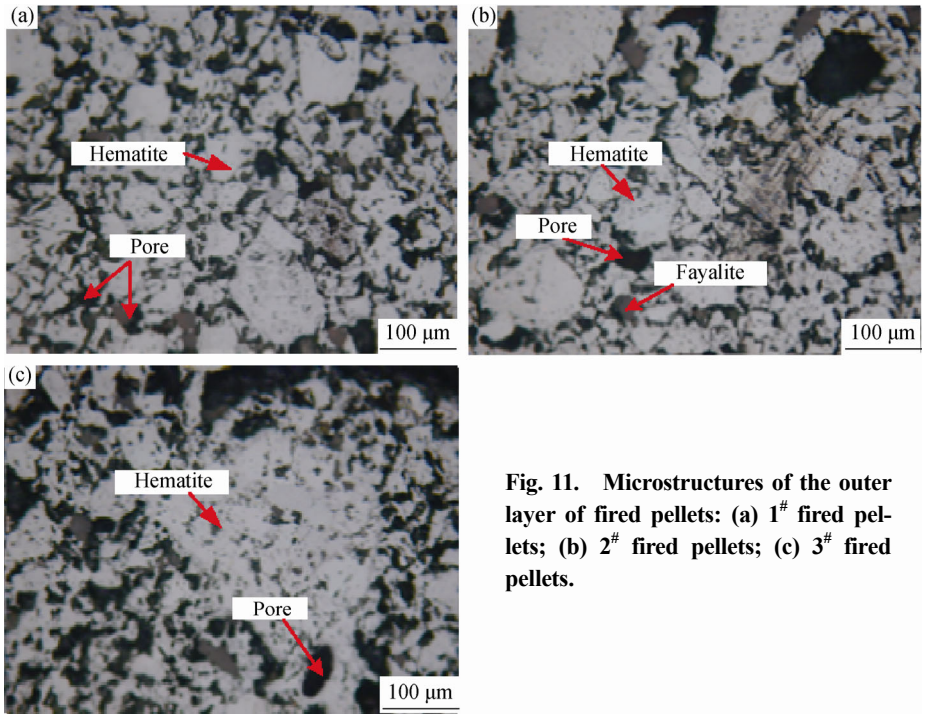

Fig. 11. Microstructures of the outer layer of fired pellets: (a) 1# fired pellets; (b) 2# fired pellets; (c) 3# fired pellets.

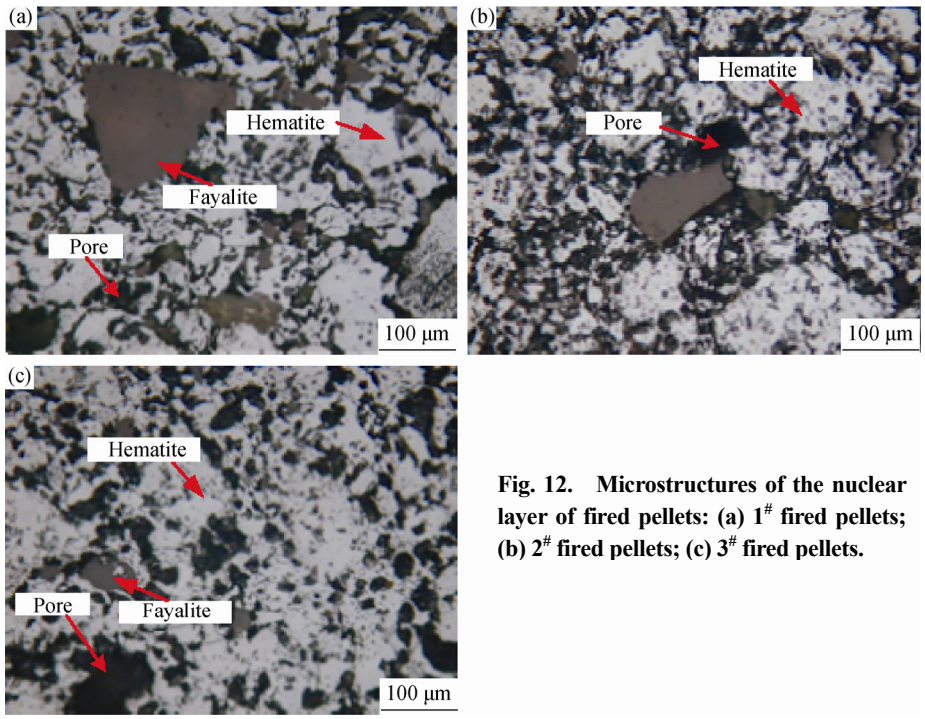

Fig. 12. Microstructures of the nuclear layer of fired pellets: (a) 1# fired pellets; (b) 2# fired pellets; (c) 3# fired pellets.

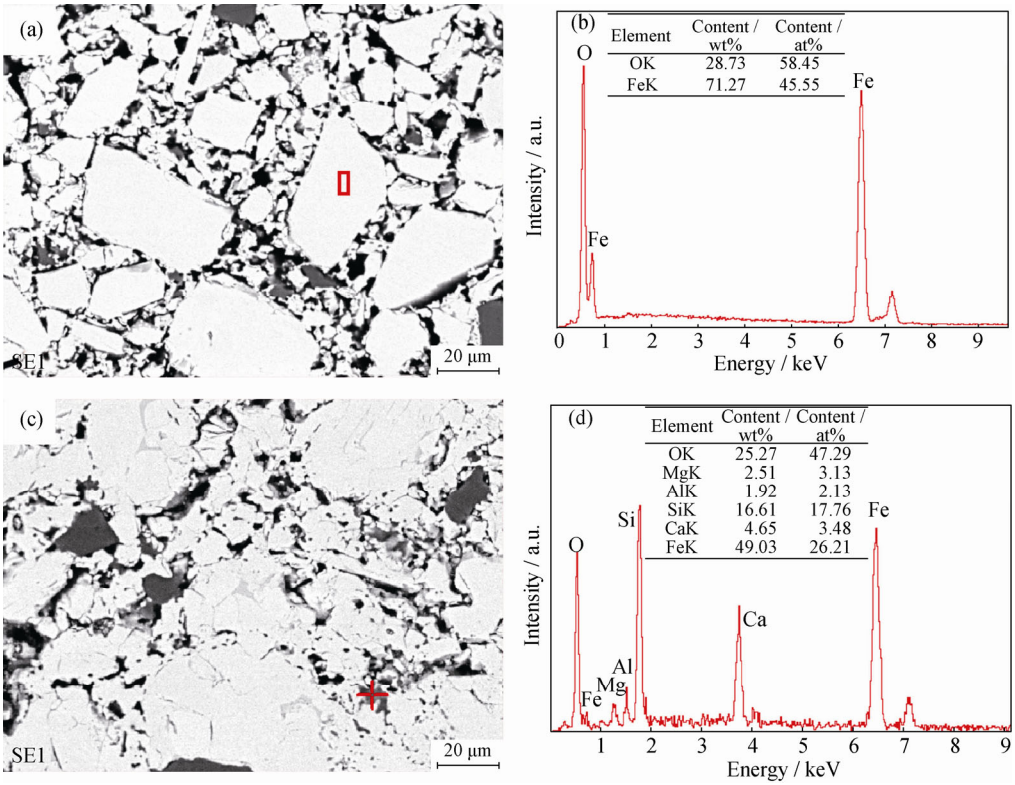

Fig. 13. SEM images (a,c) of the 3# roasted pellets and EDS spectra of the hematite area (b) and the fayalite area (d) of the 3# roasted pellets.

3.6. Industrial trial

On the basis of the results of small-scale and pilot-scale tests, a grate-kiln production line with an annual output of 1.2 Mt of fired pellets to satisfy the operation of a BF was constructed in India. The results of industry pre-production are shown in Table 13. The data presented were collected from an industrial field, with a maintenance availability of 97.5%.

Regarding the quality of fired pellets and the stability of the raw materials, the mixture of 60wt% 1# hematite fines and 40wt% 2# hematite fines (3#) was used to prepare an industrial trial. In the steady production stage, good-quality fired pellets were made, consistent with the results of the pilot-scale tests. The metallurgical performances of the fired pellets were within the desired limits for the RSI, the RDI, and the reduction index.

Table 13. Performance of fired pellets of industry pre-production

Index	Commissioning stage	Steady production stage
Compressive strength / N per pellet	2570	2925
Tumble index (+6.3 mm) / wt%	91.5	94.3
Iron grade / %	63.52	64.01
RI / %	68.14	69.32
RSI / %	13.10	12.79
Output of product pellets / ($t \cdot d^{-1}$)	3220	3690
Operation rate / %	70.50	93.20

All of the designed plant specifications, including pellet production, iron ore blend composition, and pellet quality, among others, have been reached since startup and are being maintained at a good level, demonstrating that the plant was well designed and also well supported by the studies presented in this paper.

4. Conclusions

The grinding properties of two kinds of Indian hematite fines and the roasting behaviors and induration characteristics of pellets made from finely ground Indian hematite fines were studied using dry ball milling tests and small-scale and pilot-scale tests. On the basis of the aforementioned results, feasible production parameters were recommended for an industrial trial. The following conclusions were drawn.

(1) The Indian hematite fines ($1^{\#}$ and $2^{\#}$ samples) exhibit perfect grindability. Their Bond ball mill work indices are only 7.437 and 7.726 kW·h/t, respectively, which means that ball milling is suitable for pretreating Indian hematite fines at lower energy consumption and cost. The dry-ground products had a relatively high SSA and an appropriate size distribution for use in the balling process. Meanwhile, superior-quality green balls were prepared using the dry-ground products, further confirming that dry ball milling is an excellent way to pretreat Indian hematite fines.

(2) The roasted pellets were prepared under the conditions of preheating at 1050°C for 15 min and roasting at 1290°C for 20 min; the resulting pellets satisfy the requirements for roasted pellets intended for use in a large blast furnace. The three types of fired pellets are mainly composed of hematite and are indurated through interlinkage recrystallization of hematite along with minor slag-phase binding.

(3) The two types of Indian iron ore fines are feasible for producing fired pellets using the grate-kiln process, and the resulting pellets are good-quality burden for a blast furnace because of their high mechanical strength, uniform size distribution, and superior metallurgical performance. All of the aforementioned achievements were demonstrated through an industrial process in a new pellet plant with an annual capacity of 1.2 Mt of fired pellets.

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