Effects of coal and iron ore blending on metallurgical properties of iron coke hot briquette

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A B S T R A C T

Utilization of iron coke hot briquette (ICHB), prepared by carbonizing coal-iron ore composite agglomerate, is considered as an effective countermeasure to achieve low carbon emission blast furnace (BF) ironmaking. ICHB shows high reactivity and thereby presents low post-reaction strength, which could have serious impact on the permeability of BF. In this paper, the effects of coal and iron ore blending on the metallurgical properties of ICHB were experimentally investigated and related mechanism were revealed based on Chinese raw material and fuel conditions. The results showed that with increasing coal B addition ratio, the compressive strength of ICHB is slightly improved. The gasification reaction ratio of ICHB is gradually decreased while the post-reaction strength is increased. Furthermore, with increasing coal C ratio, the compressive strength of ICHB tends to slightly increase firstly and then mildly decrease. The reaction ratio of ICHB is decreased firstly and then increased while the post-reaction strength and the crystallite size (L_c) tend to be enhanced initially and then reduced. Additionally, with increasing the addition ratio of iron ore from 0 to 20%, the compressive strength of ICHB is reduced from 5602 N to 4594 N while the porosity of ICHB is increased. The reaction ratio of ICHB is accelerated from 48.22% to 75.02% while the post-reaction strength is reduced from 74.08% to 26.84%. In terms of coal blending and iron ore blending, the reasonable preparation parameters of ICHB are conducted, namely 55% coal A, 10% coal C, 20% coal D, and 15% iron ore. Under the conditions, the compressive strength, the reaction ratio, and the post-reaction strength of ICHB are 4861 N, 63.00%, and 46.45%, respectively.

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1. Introduction

Currently, environmental problems such as global warming and air pollution have become increasingly serious and attracted more attention. Steel industry is supposed to be responsible for reducing CO_2 emission since it consumes substantial fossil fuels. CO_2 emission discharged from steel works accounts for 5%–7% of the global total CO_2 emission [1]. Furthermore, blast furnace (BF)-converter process is dominant for steel production in the long term [2]. As a main sector in steel production, BF produces more than 94% of the total pig iron all over the world, whose energy consumption and CO_2 emission account for about 80% of the whole steel works [3, 4]. Consequently, saving energy consumption and reducing CO_2 emission in BF is greatly important for the sustainable development of steel industry.

Coke is one of the most significant raw materials for BF ironmaking in terms of its effect on hot metal quality and BF operation [5]. Naito et al. [6] proposed that a reduction in coke consumption is an effective measure to mitigate CO_2 emission and energy consumption in a BF, which could be realized by using highly reactive coke (reactivity of

coke refers to the reaction ratio of coke with CO_2) through decreasing the temperature of the thermal reserve zone (TRZ). Highly reactive coke can be prepared by adding minerals with catalytic effect [7]. Simultaneously, Naito et al. [8] reported that the utilization of highly reactive coke can decrease the reducing agent ratio (RAR) by approximately 25–35 kg/ton of hot metal (kg/tHM).

For C-CO_2 reaction, alkali metal, alkaline earth metal, and transition metal have been known as high activity catalyst [9]. It was reported that there are two approaches for the production of highly reactive coke in conventional coke oven. The first one is adding iron- or calcium-inorganic substance to the blend coals and to be carbonized in coke oven (the pre-addition method), while the second method is spraying aqueous solutions of iron- and calcium-salts to coke surface (the post-addition method) [10–12]. By these two methods, such highly reactive coke was successfully produced in commercial coke oven, and it was found that RAR of BF was reduced by 10 kg/tHM with utilizing 8% highly reactive coke [13].

Additionally, Yamamoto et al. [14–16] reported another approach to decrease RAR and CO_2 emission of BF. They proposed and developed an innovative BF burden material, carbon iron composite (CIC), which was produced by carbonizing iron ore-coal briquette made up of iron ore and coal in a shaft furnace. During carbonization, iron oxides are quickly

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Table 1
Characterization data of four coals used in experiments.

Coal	Fixed carbon/%	Ash/%	Volatile matter/%	Moisture/%	Final contraction value/mm	Max thickness of plastic layer/mm	Ash compositions/%				
							CaO	SiO$_2$	MgO	Al$_2$O$_3$	TFe
A	61.52	8.75	28.25	1.48	22.9	12	8.13	40.03	2.46	27.85	6.96
B	72.77	9.45	16.26	1.52	26.1	18	1.59	49.68	0.49	39.31	2.75
C	77.91	9.48	11.38	1.23	18.5	0	3.77	45.96	0.93	33.51	5.88
D	80.63	9.25	8.81	1.31	n.a.	n.a.	4.02	58.96	0.80	21.36	3.64

n.a.: no data available.

reduced to FeO and metallic Fe. With catalytic effects of iron particles and the close arrangement of iron ore and carbonaceous materials, the reactivity towards CO$_2$ of carbon inside the CIC is enhanced by increasing the addition ratio of iron ore. Moreover, blast furnace inner reaction simulator (BIS) test showed that with using CIC having 43% of total iron, the TRZ temperature could decrease about 186 °C and the shaft efficiency could increase 6.8% [17]. Furthermore, industrial test showed that BF operation with 43 kg/tHM charging could cause a decrease in RAR by 13–15 kg/tHM [18, 19].

Highly reactive coke generally shows low post-reaction strength due to its remarkably high reactivity compared with conventional coke, which could have negative effects on the permeability of BF. Nomura et al. [20] investigated the post-reaction strength of highly reactive coke under the condition of fixing two or three parameters (weight loss percentage, reaction time, and reaction temperature), and found that highly reactive coke produced by catalyst post-added method could achieve higher post-reaction strength at lower reaction temperature while catalyst pre-added coke has lower post-reaction strength. In terms of cold strength and post-reaction strength of CIC, Higuchi et al. [17] found that adding iron ore powder could cause a decrease in the cold strength of CIC because the dilatation of coal particles is prevented by iron ore particle, but with adding 30% iron ore powder, CIC has sufficient strength used as nut coke in BF.

Some investigations about the cold strength and post-reaction strength of CIC have been made under different experimental conditions such as reaction temperature and reaction time, but the influences of the composition of coal and iron ore on the post-reaction strength of CIC have not been reported yet. In previous work [21], the preparation process of iron coke hot briquette (ICHB) was proposed depended on the Chinese raw material conditions and optimized. Under the optimized conditions, the compressive strength of ICHB is more than 5000 N. According to the testing method from Chinese National Standard (GB/T 4000-2008; equivalent to ASTM Standard D 5341) [22, 23], the reactivity of ICHB is considerably high while the post-reaction strength is considerably low compared with conventional coke, which could have negative effects on the permeability of BF. Furthermore, operating results from Nippon Steel Corporation (NSC) suggested that the post-reaction strength of coke depends about 70% on the parent coal or the blended coal [24]. In order to improve the post-reaction strength of ICHB simultaneously keeping the compressive strength and the reactivity at relatively higher level based on the previous investigation, the improvement of the post-reaction strength of ICHB by adjusting coal blending and iron ore blending were studied in this paper and other metallurgical properties of ICHB, such as compressive strength, pore structure, and carbon crystallite size (L_c), were also investigated. Simultaneously, the corresponding reaction mechanism was analyzed by means of scanning electron microscope (SEM) with energy dispersive X-ray spectrometer (EDS) examinations and X-ray diffraction (XRD)

analysis. This paper could provide technological support and theoretical basis for the practical application of ICHB.

2. Experimental

2.1. Raw materials

Four types of coals were used in experiments. The characterizations of four coals come from Qitaihe City in China are listed in Table 1. All coals are single coal. Coal A and coal C are slightly caking coals. Coal B is a caking coal and coal D is an anthracite coal. The chemical composition of iron ore concentrate used in tests is shown in Table 2. The total iron content (TFe) and FeO content of iron ore are 66.69% and 26.40%, respectively.

2.2. Experimental procedure

The raw materials were dried at 105 °C for 2 h in a draught drying cabinet. Then coals and iron ore were crushed to 90% < 75 μm and adequately mixed according to the predetermined ratio (as shown in Table 3) to form the mixtures of iron ore powder and coal fines. Afterwards, the mixtures were put into an ellipsoidal mold and heated to 300 °C in a heating furnace, then it was pressed to achieve coal-iron ore composite agglomerate (abbreviated as hot briquette hereinafter) by self-made hot press apparatus with 50 MPa pressure. Finally, the hot briquette was carbonized at 1000 °C for 4 h in a carbonization furnace (heating rate 3 °C/min) under Ar atmosphere. After carbonization, the carbonized product was cooled in N$_2$ atmosphere (cooling rate 15 °C/min) and ICHB was achieved. The external morphologies of hot briquette (21 × 19 × 16 mm) and ICHB (18 × 16 × 14 mm) are shown in Fig. 1.

Based on the previous work [21], to improve the metallurgical properties of ICHB, coal B or coal C were selected and added into the mixtures by partially replacing coal A (test 1–test 9). In terms of coking properties, coal A, B, and C were in the order of B > A > C. The proportions of other materials for test 1–test 9 were kept constant when coal B or coal C was added. Test 1 is the optimized process conditions in the

Table 3
Addition ratios of coals and iron for the preparation of ICHB (mass fraction, %).

Test	Addition ratios of coal and iron ore				
	Coal A	Coal B	Coal C	Coal D	Iron ore
1	65.00	0.00	0.00	20.00	15.00
2	60.00	5.00	0.00	20.00	15.00
3	55.00	10.00	0.00	20.00	15.00
4	50.00	15.00	0.00	20.00	15.00
5	45.00	20.00	0.00	20.00	15.00
6	60.00	0.00	5.00	20.00	15.00
7	55.00	0.00	10.00	20.00	15.00
8	50.00	0.00	15.00	20.00	15.00
9	45.00	0.00	20.00	20.00	15.00
10	64.71	0.00	11.76	23.53	0.00
11	61.47	0.00	11.18	22.35	5.00
12	58.24	0.00	10.59	21.18	10.00
13	51.76	0.00	9.41	18.82	20.00

Table 2
Chemical compositions of iron ore powder (mass fraction, %).

Composition	TFe	FeO	SiO$_2$	CaO	Al$_2$O$_3$	MgO	P	S
Content	66.69	26.40	5.31	0.18	0.31	1.80	0.02	0.05