CHARACTERIZATION OF PROPERTIES AND REDUCTION BEHAVIOR OF IRON ORES FOR APPLICATION IN SPONGE IRONMAKING

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CHARACTERIZATION OF PROPERTIES AND REDUCTION BEHAVIOUR OF IRON ORES FOR APPLICATION IN SPONGE IRONMAKING

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ABSTRACT

Studies on chemical and physical properties, and reduction behaviour (in coal) of hematite iron ores, procured from ten different mines of Orissa, were undertaken to provide information to the iron and steel industries (sponge iron plants in particular). Majority of the iron ores were found to have high iron and low alumina and silica contents. All these iron ores were free from the deleterious elements (S, P, As, Pb, alkalies, etc.). The results indicated lower values of shatter and abrasion indices, and higher values of tumbler index in all the iron ore lumps except Serazuddin (previous) and Khanda Bandha OMC Ltd.. For all the fired iron ore pellets, the degree of reduction in coal was more intense in the first 30 minutes after which it became small. Slow heating led to higher degree of reduction in fired pellets than rapid heating. All the iron ores exhibited more than 90% reduction in their fired pellets in 2 hrs. time interval at a temperature of 900^0C. Iron ore lumps showed lower degree of reduction than the corresponding fired pellets.

Keywords : Chemical and physical properties, coal, iron ores, reduction.

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1. INTRODUCTION

In view of increasing demand of pre-reduced pellets or sponge iron in the manufacture of different varieties of steel, a lot of emphasis is being given to promote direct reduction processes. The world production of sponge iron has increased from 17.68 MT in 1990 (Sindwani 2006) to 55.90 MT in 2005 (SIMA 2006). As reported in the literature (World Direct Reduction Statistics 2000), the world DRI production may reach up to 75 MT by the year 2010. Presently, India has emerged as the largest producer of sponge iron (11.82 MT in 2005-06) in the world (Patnaik 2006). In this total production of 11.82 MT, the contribution of coal-based sponge iron plants was 7.10 MT and rest of gas-based plants.

Bountiful iron ore and coal deposits in the state of Orissa (India), constituting 26 and 24% of the country's total reserves (Das etal. 2004), have attracted many companies in the recent past for setting up of various sponge iron and steel making plants in this state. At present, there are 18 sponge iron plants (coal-based) in Orissa producing about 0.90 MT of sponge iron per annum (Das etal. 2004) and few more are likely to be commissioned very soon. This has brought riot of colors in the mining industries around potential iron zones of Keonjhar, Sundergarh and Mayurbhanj districts of the state. A detailed characterization of these iron ores is essential for their effective utilization.

In selecting iron ore for iron and steel industries, the properties which need to be considered are tumbler, abrasion and shatter indices, porosity, chemical composition, loss on ignition, reduction behaviour, thermal degradation, etc. In the present investigation, 10 different types of hematite iron ore (obtained from different mines of Orissa) having the possibility to be exploited by sponge iron plants have been examined for their above mentioned chemical and physical properties. The aims have been: (1) to ascertain the behaviour of these iron ores in advance, and (2) to provide sufficient technical information to the iron and steel industries, particularly to those which do not have R & D facilities. This work will certainly help in assessing the cost and selection of iron ore for a particular sponge iron industry.

2. EXPERIMENTAL

2.1 Materials Selection

In this investigation, ten types of hematite iron ore samples were collected from different mines of Orissa. Non-coking coal, used in the reduction studies, was collected from Brajrajnagar mine of Orissa and examined for its proximate analysis (Indian Standard 1350: 1969), sulphur content, caking index and reactivity towards carbon dioxide (Indian Standard 12381 : 1994). The results obtained indicated (i) volatile matter : 39.25 wt. %, (ii) ash : 40.25 wt %, (iii) fixed carbon : 20.50 wt. %, (iv) sulphur : 0.55 wt. %, (v) caking index : nil, and (vi) reactivity : 5.17 cc of CO/g.sec on dry basis.

2.2 Determination of Chemical Composition and Loss on Ignition Values of Iron Ores

The chemical compositions and loss on ignition values of all these iron ores were determined by X-ray fluorescence technique at Rourkela steel plant. The results obtained have been listed in Table 1.

2.3 Determination of Physical Properties of Iron Ores

Assessments of physical properties of all these selected iron ores were carried out by determining their tumbler, abrasion and shatter indices, and apparent porosity.

2.3.1 Tumbler and abrasion indices

These indices were determined by tumbling a standard weight of oven dried lump iron ore of size −40 + 10 mm in a standard drum, as per Indian Standard Specification (Tupkary and Tupkary 2003). The % weight of material passing through 0.5 mm screen represented its abrasion index, while the % weight of iron ore retained on 6.3 mm screen was taken as its tumbler index.

2.3.2 Shatter index

In shatter test, a dried lump iron ore sample (10 kg) of size −40 + 10 mm was dropped four times from a height of 2 m on a cast iron floor. The iron ore was then screened and the shatter index was expressed as the wt.% passing through 5 mm screen (i.e. -5 mm fraction) (Tupkary and Tupkary 2003).

2.3.3 Apparent Porosity

The apparent porosity values of iron ore lumps and pellets were determined by the hot test boiling water (HTBW) method (Chesters 1973).

2.4 Preparation of Iron Ore Pellets

The pellets (size: 15 mm dia. approx.) were made by prolonged hand rolling of moistened (12% water) iron ore fines of -100 mesh size. The pellets were dried at 110°C for 2 hours and then indurated in a muffle furnace at 1200^0C for one hour to attain workable strength. These indurated pellets were then kept in a desicator for subsequent reduction experiments.

2.5 Procedure for Reduction Studies

Majority of the reduction experiments were carried out under rapid heating condition at a temperature of 900°C for varying time periods in the range 30 – 120 minutes. Few experiments under slow heating condition were carried out for comparison. The weighed amount of oven dried pellet (size: 15 mm diameter approx) was placed centrally on a packed bed of non-coking coal in a stainless steel reactor (size: 77 mm height $\times$ 40 mm inside diameter) tightly closed with an air tight cover having an outlet for the exit of gas.

In case of reduction studies under rapid heating condition, usually four stainless steel reactors were inserted inside the muffle furnace maintained at the predetermined reduction temperature of 900°C. In doing so, the furnace first cooled down to 850^0C and then took nearly 10 minutes in reaching to the required reduction temperature of 900^0C. Each reactor was taken out one by one at an interval of 30 minutes and cooled to room temperature in air. The weight loss in each of the pellet was recorded. Reduction under slow heating condition was carried out by heating the stainless steel reactor containing the iron ore pellet/lump in coal from room temperature to the required temperature of 900°C at a rate of about 7°C min^{-1} and kept there for one hour. The reactor was then taken out and cooled in air. The pellets thus reduced were weighed and the degree of reduction was expressed as the wt.% of oxygen removed from the iron ore pellet.

3. RESULTS AND DISCUSSION

3.1 Characteristics of Iron Ores

Qualities of burden materials affect the economy, output and efficiency of the furnace operation. The chemical and physical characteristics of iron ores under investigation have been listed in Tables 1 and 2. Data for the mineralogical composition (Table 1) indicated that the gangue materials in these iron ores mainly consisted of alumina and silica with a negligible amount of TiO_2 and MnO. The ores were found to be free from deleterious elements S, P, As, Pb, alkalies, etc. The results (Table 1) established that the iron ores obtained from Zenith, Sakaruddin, Serazuddin (current), M.G. Mohanty, G.M. OMC Ltd. and D.R. Pattnaik mines were rich in iron (> 64%) and poor in alumina (1.6 - 3.0 %) and silica (0.9 - 2.6 %) contents, whereas other ores contained higher amounts of these gangue materials. Hence, more slag formation is expected during melting of sponge irons produced from Khanda Bandha OMC Ltd., BPJ OMC Ltd. Nos. 6 and 7, and Serazuddin (previous) iron ores. Alumina raises the melting point of slag and increases fuel consumption in the furnace.

Data for the porosity values and strength properties (tumbler, abrasion and shatter indices) of these iron ores have been presented in Table 2. These are the most popular properties to assess the resistance of an iron ore to degradation. As shown in Table 2, all the iron ores except Serazuddin (previous) and Khanda Bandha OMC Ltd. offered high resistance to abrasion and tumbling, most probably due to their hard fine grained structure and lower porosity. Furthermore, results obtained (Table 2) indicated lower value of shatter index (for −5 mm size fraction) in all of them except Serazuddin (previous) and Khanda Bandha OMC Ltd. iron ores. Based on the tumbler, abrasion and shatter indices results, the iron ores procured from Sakaruddin, Serazuddin (current), BPJ OMC Ltd. Nos.6 and 7, M.G. Mohanty and D.R. Pattnaik mines appear to be hard and strong. On the other hand, all these tests ascertained Serazuddin (previous), Khanda Bandha OMC Ltd., and Zenith iron ores to be more porous, soft and friable, and hence are liable to produce more deleterious fines (−5 mm fraction) during handling or in iron blast furnaces, rotary kilns, etc. As evident from Table 2, no definite correlation between porosity and strength properties (tumbler, abrasion and shatter indices) exists due to wide scattering of points (data). The loss on ignition values (2–4 wt.% in general), associated with these hematite iron ores, are believed to be due to removal of physically combined moisture in them.

3.2 Reduction Behaviour of Iron Ores

The degree of reduction values of these iron ore lumps and fired pellets, reduced at 900°C for different time periods in the range 30 −120 minutes under rapid and slow heating conditions, have been summarized in Tables 3 and 4. Reduction studies of pellets were carried out with a point of view of utilization of fines generated from these iron ores. The observations made during this study are discussed below.

3.2.1 Effect of time on degree of reduction

Data listed in Table 3 (rapid heating) indicate that the reduction time has an approximately identical effect on the reduction behaviour of almost all the iron ore pellets studied. As shown in Table 3, all the fired iron ore pellets showed highest degree of reduction in the first 30 minutes (i.e. up to about 40 − 50 % reduction) and thereafter the rate of reduction decreased with increasing reduction time up to the range studied (i.e. 120 minutes) . It was also observed that all the fired iron ore pellets were almost completely reduced (more than 90% reduction) in about 120 minutes. This indicates that the utilization of these iron ores in sponge ironmaking is likely to allow the rotary kiln operations to be carried out at low temperatures (i.e. less than 1000^0 C) resulting in greater savings of energy and kiln life.

As suggested by Bodsworth and Taheri (Ironmaking and Steelmaking 1987), the excessively high degree of reduction in the first 30 minutes is mainly associated with the release of volatiles from coal, their reformation into H_2 , CO, etc. and major participation of these reducing gases in the reduction of iron oxide (i.e. an appreciable presence of H_2 and CO in the reduction chamber gives a boost in the reduction rate). The decrease in reduction rate with increasing time above 30 minutes is undoubtedly due to the combined effects of an increase in product metallic layer thickness and diminished evolution of volatile matter from coal. An increase in the thickness of product iron layer offers greater resistance in the diffusion of carbon and reducing gas to the surface of unreduced iron oxide.

3.2.2 Effect of heating mode on degree of reduction

In order to study the effect of mode of heating, the fired iron ore pellets were reduced in coal at 900°C (soak time at this temperature: 1 hr.) under rapid and slow heating conditions. The results obtained have been listed in Tables 3 and 4. It is fairly clear from these tables that in comparison to rapid heating, the slow heating to reduction temperature gives appreciably higher degree of reduction.

It is more likely that rapid heating to 900°C causes a higher rate of volatile matter escape from coal, thereby providing less time for H_2 and CO (reducing gases) to be in contact with iron ore pellet. The result is thus lower degree of reduction in rapid heating. During slow heating operation, volatile matters are released from coal at a slower rate and hydrocarbons get sufficient time to undergo the process of cracking (C_nH_m = nC + mH). The more deposition of highly reactive pyrolytic carbon, and increased time of contact of carbon and reducing gases (H_2 and CO) with the pellet appear to be the obvious reasons for the higher degree of reduction. As suggested in the literature (Dutta and Ghose 1994), heating of hematite pellet from room temperature to the required reduction temperature (900°C) in reducing atmosphere, to some extent, is also responsible' for higher degree of reduction under slow heating condition.

3.2.3 Comparison of reduction characteristics of pellets (fired) and lumps

In this study, reduction behaviours of dried hematite iron ore lumps (size: 15 mm approx.) have been compared with those of corresponding fired pellets reduced (in coal) under identical slow heating conditions (heating rate: $7^0C\ min^{-1}$, temperature: 900^0C, soak time: 1 hr.). Data for their degree of reduction values have been recorded in Table 4 and plotted as a function of their total iron contents in Fig. 1. The results (Table 4 and Fig. 1) established lower degree of reduction in lumps than the corresponding fired pellets.

Table 2 clearly indicates that the dried iron ore lumps have much lower porosity values than those of corresponding fired pellets. The appreciably lower porosity in iron ore lumps appears to be the most likely reason for their lower reducibility. As outlined in the literature (Moinpour and Rao 1988), hematite pellets tend to form disordered and hence more reactive/easily reducible wustite (FeO) . This may be the another reason for relatively higher reducibility of pellets, as observed in the present investigation. It was noted that Khanda Bandha OMC Ltd., BPJ OMC Ltd. No.6, Zenith, and D.R. Pattnaik iron ore lumps cracked into fine fragments during reduction at 900^0C, and hence their degree of reduction values could not be measured. The breakdown in these lumps may be attributed to the higher rate of Fe_2O_3 - Fe_3O_4 transformation and generation of higher therma1 strain. An increased degree of Fe_2O_3 - Fe_3O_4 transformation increases the volumetric strain (abnormal swelling) and thus the cracking tendency.

3.2.4 Comparison of the degree of reduction values of different fired hematite iron ore pellets

Tables 3 and 4 give the comparison of reduction characteristics of 10 different hematite iron ore pellets (fired) reduced in coal under identical conditions. As can be seen in these Tables, Zenith, Sakaruddin, Serazuddin (current), BPJ OMC Ltd. No.6, M.G. Mohanty and D.R. Pattnaik iron ore pellets, in general, have shown higher degree of reduction than others for the same reduction conditions. The higher rates of reduction in these iron ore pellets could be attributed, at least in part, to their higher reducibilities and generation of greater thermal and volumetric strains in these pellets during Fe_2O_3 - Fe_3O_4 transformation.

Fig. 1 shows the correlation between degree of reduction (%) and total iron content (%) for these hematite iron ores (fired pellets and lumps both) reduced in coal at 900^0C (soak time: 60 min.) under slow heating condition. It can be seen in this figure that despite considerable scatter in the data, there is, in general, a trend of improvement in reducibility of an iron ore with increase of its iron content. This could be ascribed to the decrease in total gangue (Al_2O_3, SiO_2, etc.) content with increasing iron content, as shown in Table 1. These gangue minerals are notoriously distributed in the matrixes of Indian iron ores and offer a lot of hindrance in the diffusion of reducing gases to the reaction sites. The result is thus less reduction of iron ore having more gangue / less iron content.

4. CONCLUSIONS

The following results are concluded from the studied iron ores:

1. Zenith, Sakaruddin, Serazuddin (current), M.G. Mohanty, G.M. OMC Ltd and D.R. Pattnaik iron ores were found to be rich in iron (> 64%) and poor in alumina and silica contents.

2. Chemical analyses established that all the iron ores under investigation were free from the deleterious elements S, P, As, Pb, alkalies, etc.

3. The results obtained indicated higher values of tumbler, abrasion and shatter resistance in all the iron ore lumps except Serazuddin (previous) and Khanda Bandha OMC Ltd.

4. The rates of reduction in all the fired iron ore pellets were higher up to 30 minutes (i.e. up to about 40 - 50 % reduction) and then decreased.

5. For the same reduction temperature and time, slow heating revealed higher degree of reduction in all the fired iron ore pellets than rapid heating.

6. The results established more than 90% reduction in all the fired iron ore pellets at a temperature of 900^0C in 2 hrs. time interval, indicating their higher reducibilities. This may result in significant reduction in energy consumption during sponge ironmaking.

7. The results demonstrated that iron ore lumps were less reducible than their corresponding fired pellets.

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Table 1 : Chemical composition and loss on ignition values of hematite iron ores (wt.%, air-dried basis)

Iron ore source	Fe (Total)	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	MnO	Loss on ignition
Serazuddin mine (previous)	61.40	88.15	6.21	1.65	0.22	0.00	3.77
Khanda Bandha OMC Ltd.	57.80	82.65	5.10	4.70	0.00	0.12	7.43
Zenith mine	64.51	92.25	2.34	1.55	0.14	0.03	3.69
Sakaruddin mine	64.51	91.74	3.06	1.43	0.14	0.02	3.61
Serazuddin mine (current)	65.04	93.01	2.38	1.36	0.15	0.02	3.08
BPJ OMC Ltd. No.6	62.63	89.56	4.09	3.80	0.11	0.01	2.43
BPJ OMC Ltd. No.7	61.54	88.00	4.55	4.48	0.12	0.00	2.85
M.G. Mohanty mine	64.52	92.27	2.11	1.81	0.08	0.02	3.71
G.M.OMC Ltd.	64.06	91.60	2.52	2.61	0.10	0.01	3.16
D.R. Pattnaik mine	65.22	93.26	1.62	0.92	0.07	0.06	4.07

Table 2 : Physical properties of hematite lump iron ores (dried basis)

Iron ore source	Tumbler index (wt.% of + 6.3mm)	Abrasion index (wt.% of -0.5mm)	Shatter index (wt.% of -5.0 mm)	Apparent porosity (%) (lump ore)	Apparent porosity (%) (fired pellet)
Serazuddin mine (previous)	76.0	13.6	1.79	5.2	34.4
Khanda Bandha OMC Ltd.	82.0	9.5	1.64	4.5	26.2
Zenith mine	85.3	8.9	0.87	2.0	22.8
Sakaruddin mine	90.0	4.75	0.68	1.5	18.9
Serazuddin mine (current)	92.0	3.16	0.86	1.3	22.2
BPJ OMC Ltd. No.6	88.7	4.27	1.32	2.3	26.1
BPJ OMC Ltd. No.7	86.1	4.76	1.01	1.2	21.4
M.G. Mohanty mine	91.0	3.24	1.00	2.5	11.8
G.M. OMC Ltd.	90.0	5.56	0.70	2.3	21.5
D.R. Pattnaik mine	86.7	5.01	0.98	2.1	19.5

Table 3 : Degree of reduction values of different hematite iron ore pellets (fired) reduced under rapid heating condition in coal: Effect of reduction time

Iron ore pellet	Reduction temperature (^{o}C)	Reduction time (minutes)			
		30	60	90	120
		Degree of reduction (%)			
Serazuddin mine (previous)	900	40.7	70.6	82.4	90.6
Khanda Bandha OMC Ltd.	900	37.8	68.7	80.2	92.6
Zenith mine	900	52.0	78.2	90.5	94.5
Sakaruddin mine	900	48.6	72.6	90.7	95.4
Serazuddin mine (current)	900	39.5	62.3	84.2	93.8
BPJ OMC Ltd. No.6	900	49.7	66.5	86.7	94.2
BPJ OMC Ltd. No.7	900	40.0	59.8	84.4	94.3
M.G. Mohanty mine	900	42.5	70.4	79.6	89.7
G.M.OMC Ltd.	900	38.5	67.0	86.8	94.7
D.R. Pattnaik mine	900	50.4	71.3	89.6	96.0

Table 4 : Degree of reduction values of different hematite iron ore pellets (fired) and lumps reduced in coal under slow heating condition

Iron ore source	Reduction conditions		Degree of reduction (%)	
	Temperature (°C)	Soak time (min)	Pellet	Lump
Serazuddin mine (previous)	900	60	85.1	73.9
Khanda Bandha OMC Ltd.	900	60	75.4	Broken into fine fragments
Zenith mine	900	60	87.8	Broken into fine fragments
Sakaruddin mine	900	60	88.0	77.4
Serazuddin mine (Current)	900	60	90.2	83.5
BPJ OMC Ltd. No.6	900	60	85.2	Broken into fine fragments
BPJ OMC Ltd. No.7	900	60	84.6	65.3
M.G. Mohanty mine	900	60	91.0	70.7
G.M.OMC Ltd.	900	60	90.8	72.3
D.R. Pattnaik mine	900	60	88.1	Broken into fine fragments

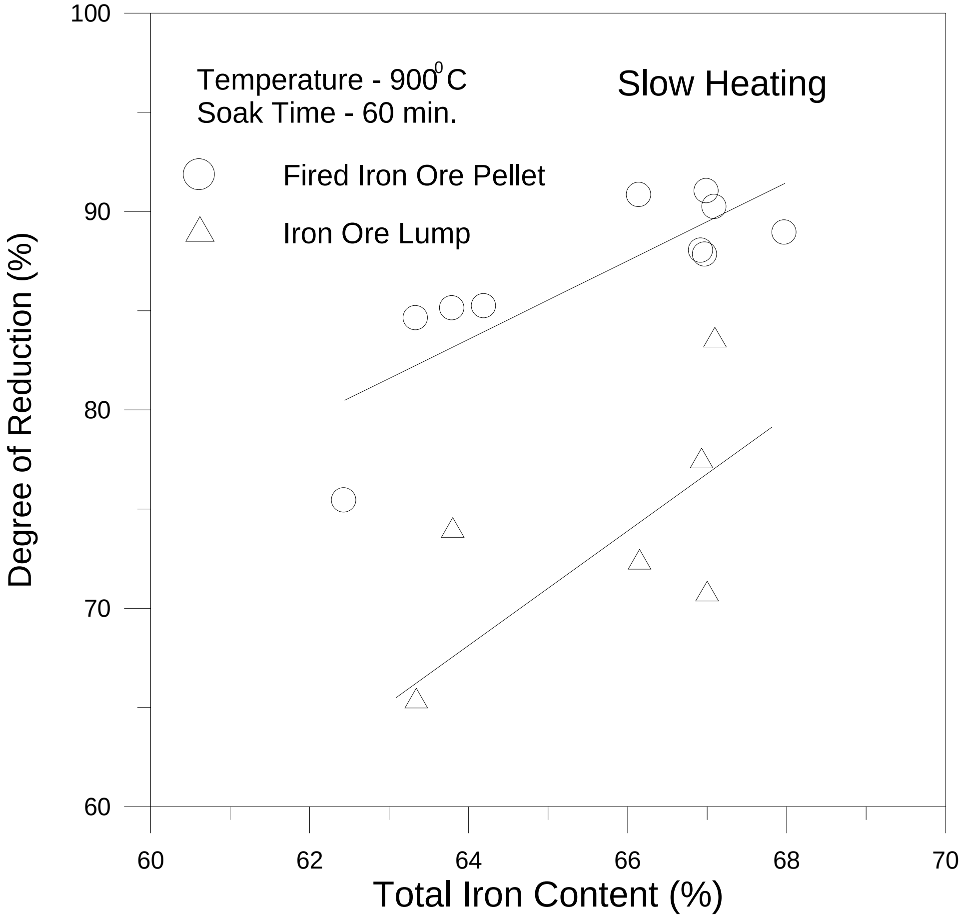

Fig. 1 : Relation between degree of reduction and total iron content for hematite iron ore pellets (fired) and lumps reduced under slow heating condition