REDUCTION AND SWELLING BEHAVIOUR OF FIRED IRON ORE PELLETS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF TECHNOLOGY

IN

METALLURGICAL AND MATERIALS ENGINEERING

BY

HIMANSHU BAGHEL

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MUKUL GUPTA

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UNDER THE GUIDANCE OF

PROF. M. KUMAR

DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING

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CERTIFICATE

This is to certify that the thesis entitled "**Reduction and Swelling Behaviour of Fired Iron Ore Pellets**" submitted by Mr Himanshu Baghel and Mr Mukul Gupta in partial fulfilment of the requirements for the degree of Bachelor of Technology in Metallurgical and Materials Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any degree or diploma.

Date: 10th May, 2005

Prof. M. Kumar

Department of Metallurgical and Materials Engg.

National Institute Of Technology

Rourkela-769008

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Himanshu Baghel

Mukul Gupta

ABSTRACT

The present project work on "**Reduction and Swelling Behaviour of Fired Iron Ore Pellets**" was undertaken with a view to promote the effective utilization of iron ore and coal fines in sponge iron making. Presently, India has become the world leader in sponge iron production and the production of steel by DR-EAF route is increasing day by day. In the present project work, the effect of addition of concentrated sugarcane juice binder on the physical properties of fired iron ore pellets was investigated. The crushing strength and drop number were found to be maximum at 2% binder addition, followed by a decrease with further increase in binder concentration. A reverse trend was observed in the case of porosity, i.e. porosity of fired pellets increased with rise in binder concentration from 2% to 6%. The pellets fired at 1300^0C were processed for reduction and swelling studies in different types of coal. The degree of reduction of fired iron ore pellets increased with increase of reduction temperature and time up to the range studied. The extent of swelling in fired iron ore pellets during their production increased with increase of reduction time, most probably due to the structural changes and fibrous growth of iron particles. SEM images of few reduced iron ore pellets were also taken.

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INTRODUCTION

As India progresses towards higher level of growth and greater and more concentrated efforts in the development of Infrastructure and manufacturing sector, the Iron and Steel industry is poised for a rapid growth in the coming years. Steel demand in the country is increasing at the rate of 10% and is likely to remain in the same range at least for the next 10-15 years. In order to meet this continuous growth of Steel demand in the country, domestic Steel producing capacity is required to be higher than 150 MT per annum by 2017 [1].

India ranks fourth in terms of iron ore production and sixth in terms of iron ore reserves in the world with approximately 28.53 MT of iron ore reserves comprising hematite (58%), magnetite (42%). NMDC (government owned) and SESA GOA (private sector) are India's largest producer and exporter of iron ore [1].

In India due to the Sponge Iron sector the overall percentage of lump uses in steel making (approx.47%) is higher than most of the countries. India is the only country where over 30% of steel comes from the Induction Furnace sector using sponge iron [1]. Sponge iron plants use only lumps and are located in areas in near vicinity of iron ore mines. As hard ore reserves are depleting, lump generation suitable for blast furnace operation is coming down which results in large amount of access production of fines.

The world production of sponge iron has increased from 17.68 MT in 1990 to 69.95 MT in 2010. Presently, India has emerged as the largest producer of DRI (26.30 MT in 2010) in the world. Out of this 26.30 MT, the contribution of coal-based sponge iron plants was 19.10 MT and rest of gas-based plants [2]. This large difference is due to scarcity of natural gas and abundant supply of non-coking coal in India.

Presently a lot of emphasis is being given to the DR process in the country, for the utilization of lower grade coal. This change in technology for production of steel may lead to change in feed stock causing a significant shift in respective share of lumps and agglomerated iron ore for hot metal in furnace, which will enable the use of ore fines which could not be utilized earlier. The steel plants are looking towards the use of Iron ore pellets sinters and lumps as this strategy opens up the opportunity of utilization of fines and are less energy intensive.

Coal Reserves of India [2]

India is having some of the largest coal reserves in the world (approx. 285 billion tonnes or 10% of the world). It is the third largest producer and has the fourth largest coal reserves in the world. Indian coal is broadly classified into two categories – Coking and Non-Coking. Coking coal reserves in India amounts to 33474.26 million tonnes (12%) whereas non-coking coal reserves amounts to 250895.31 million tonnes (88%).

The coal reserves in India are widely distributed over 14 states in India located as far as Maharashtra in the west, Madhya Pradesh and Chhattisgarh in Central India, Tamil Nadu in the south and Assam in the northeast. However, the eastern states of West Bengal, Orissa, Jharkhand, etc. are the principal coal- bearing states in the country.

Indian coal generally has a low calorific value and high ash content (up to 35%) which are important parameters in governing the use of coal in making metallurgical coke to be used in blast furnace. Besides poor quality, Indian coal has adverse washability characteristics, i.e. even after undergoing extensive crushing before washing the removal of ash becomes difficult without a significant loss in yield.

The details of state-wise geological resources of coal as on April 1, 2011 are given in Table 1.

Table 1: State-wise distribution of coal of India

Gondwana Coalfields				(In Million Tonnes)
State	**Geological Resources of Coal**			
	Proved	**Indicated**	**Inferred**	**Total**
Andhra Pradesh	9296.85	9728.37	3029.36	22054.58
Assam	0	2.79	0	2.79
Bihar	0	0	160	160
Chhattisgarh	12878.99	32390.38	4010.88	49280.25
Jharkhand	39760.73	32591.56	6583.69	78935.98
Madhya Pradesh	8871.31	12191.72	2062.7	23125.73
Maharashtra	5489.61	3094.29	1949.51	10533.41
Orissa	24491.71	33986.96	10680.21	69158.88
Sikkim	0	58.25	42.98	101.23
Uttar Pradesh	866.05	195.75	0	1061.8
West Bengal	11752.54	13131.69	5070.69	29954.92
Total	**113407.79**	**137371.76**	**33590.02**	**284369.57**
Tertiary Coalfields				(In Million Tonnes)
State	**Geological Resources of Coal**			
	Proved	**Indicated**	**Inferred**	**Total**
Arunachal Pradesh	31.23	40.11	18.89	90.23
Assam	464.78	42.72	3.02	510.52
Meghalaya	89.04	16.51	470.93	576.48
Nagaland	8.67	0	306.65	315.41
Total	**593.81**	**99.34**	**799.49**	**1492.64**

Source: Ministry of Coal, Govt. of India

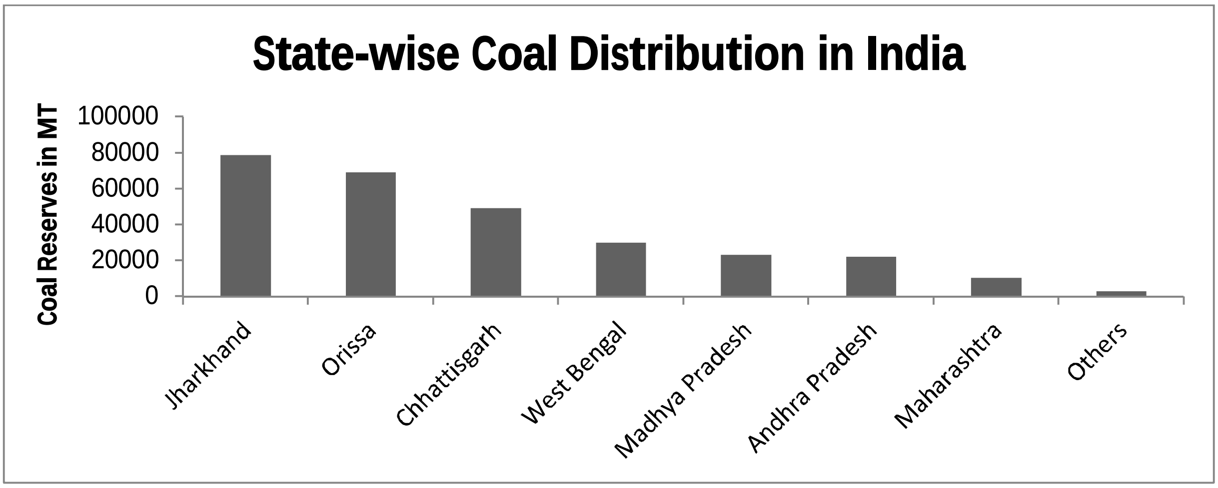


Figure 1: Coal reserves in different states of India

Iron Ore Reserves of India [3] [4]

Iron ore reserve estimates for world is around 170 billion tonnes with average iron content of 47%. India has the sixth largest reserves of iron ore in the world, and these are some of the best quality iron ore reserves in the world. India along with Ukraine, Russia, China and Australia accounts for about 75% of the world reserves. India's resources of iron ore as per UNFC system as on 1.4.2010 are estimated at 28.53 billion tonnes.

The details of state-wise distribution of iron ore reserves in India are given in Table 2.

Table 2: State-wise distribution of Iron Ore in India

(In Thousand Tonnes)

State	Hematite Reserves	Magnetite Reserves
Andhra Pradesh	381477	1463541
Assam	12600	15380
Bihar	55	2659
Chhattisgarh	3291824	0
Goa	927171	222673
Jharkhand	4596621	10542
Karnataka	2158677	7801744
Kerala	0	83435
Madhya Pradesh	231445	0
Maharashtra	283208	1360
Meghalaya	225	3380
Nagaland	0	5280
Orissa	5930233	199
Rajasthan	30561	526830
Tamil Nadu	0	507037
Uttar Pradesh	38000	0
India	**17882097**	**10644061**

Source: Indian Bureau of Mines, Ministry of Mines, Govt. of India

Direct Reduction Technique of Iron Making

The DR technique is one of the alternative methods of Iron making. Direct reduced iron is produced from direct reduction of iron ore by a reducing gas produced either from natural gas or coal. This process produces 97% pure iron which is called solid sponge iron or direct reduced iron or hot briquetted iron.

The various processes of DR technique based on coal and gas are: [1]

- Coal based rotary kiln process.
- Gas based shaft furnace process.
- Coal/gas based rotary hearth furnace process.
- Multiple hearths furnace based processes.
- Coal based DR in Tunnel kilns.
- Fluidised bed processes.

Importance of DR Process

The DR process of iron making is fast gaining importance in the country because it eliminates the dependence on coking coal and is cost effective. Irrespective of the DR process adopted, the cost of raw materials adds up to approximately 65-75% of the total cost of producing direct reduced iron. Hence to curtail costs, the trend in all the recently developed DR processes is to shift from lump ore to fine ore and to use the less-expensive energy resources like coal fines, waste gases, etc.

Advantages of DR process over blast furnace iron making process are: [5]

- Elimination of dependence on Coking-coal.
- Smaller module size.
- Lower capital investment.

- Superior environmental friendliness.
- Easier process control.

Production of Direct Reduced Iron in India and World

From a worldwide production of 7.8 million tonnes in 1981, world total output of DRI has reached 69.9 million tonnes in 2010. It is clear from the Table 3 that the DRI production has increased and been on an increasing trend. India is now the largest producer of DRI in the world with a production of around 26.3 million tonnes per annum. Out of the total DRI produced in India in 2010 around 19 million tonnes was produced in coal based units while the rest 7 million tonnes was produced in gas based units [6]. This large difference is due to the scarcity of natural gas and abundant supply of non-coking coal in India.

A year-wise production of Direct Reduced Iron in the world including India is given in Table 3.

Table 3: Year-wise production of DRI in India and World

	Production of DRI (In Million Tonnes)	
Year	**World**	**India**
2001	37.787	5.72
2002	43.18	5.731
2003	45.858	7.051
2004	53.437	9.121
2005	56.68	12.052
2006	56.375	15.032
2007	66.756	20.11
2008	66.094	20.916
2009	64.481	23.444
2010	69.949	26.302

Source: Steel Statistical Yearbook 2011, World Steel Association

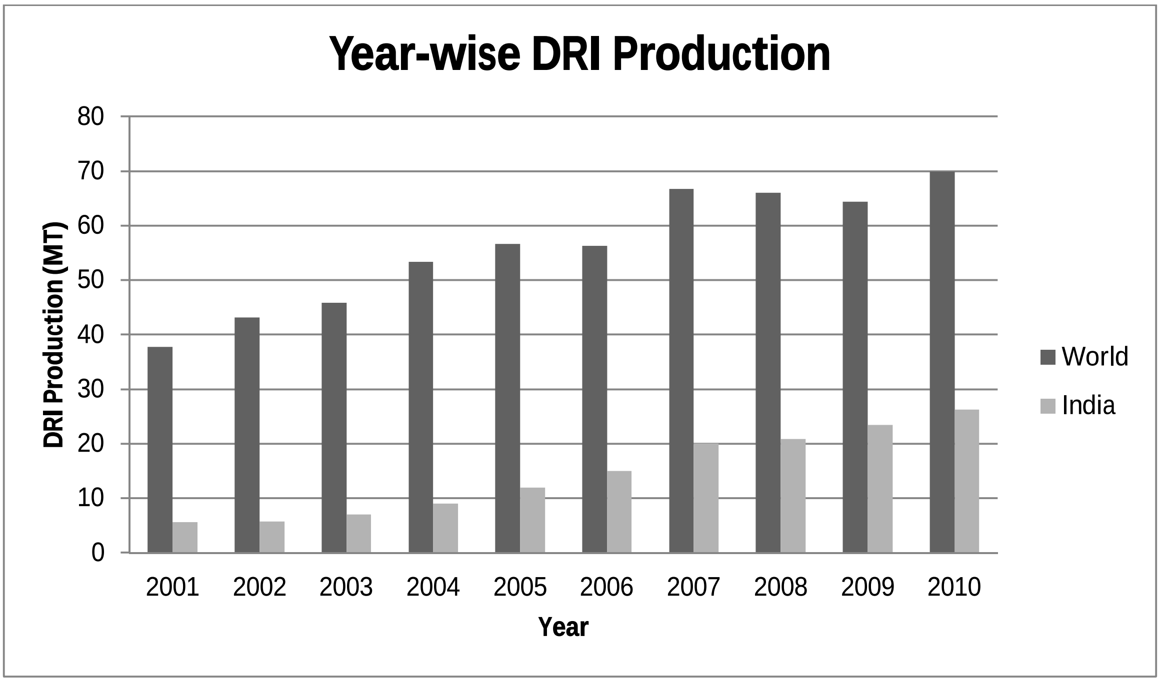


Figure 2: Production of Direct Reduced Iron in World and India in the period 2001-2010

OBJECTIVES OF THE PROJECT WORK

The objectives of the present project work have been the followings:

- To see the potential of utilization of +100 mesh size particles to some extent in the manufacture of pellets.
- To develop an alternative binder to get a better substitute of costly bentonite. In the present work an attempt has been made with concentrated sugarcane juice as an alternative binder.
- To study physical properties (crushing strength, porosity and drop number) of fired iron ore pellets made under different conditions.
- To study the effect of reduction temperature and time on the reduction behavior of fired iron ore pellets in non-coking coal.
- To study the effect of quality of coal (particularly CO_2 reactivity) on reduction behavior of fired iron ore pellets.
- To study the effect of reduction temperature and time on the swelling behavior of fired iron ore pellets during reduction in coal.

LITERATURE SURVEY

During mining and ore dressing operations a large amount of (-0.5mm) fines are generated which cannot be sintered because of very low permeability of the bed. According to the industry the high grade domestic lumpy ore will be exhausted in the next 10 years. Because of these reasons value addition to the iron ore fines by various processes such as pelletisation is the need of the present scenario, which will be economically beneficial for the long run. The fines can be agglomerated by balling them up in the presence of moisture and suitable binders such as Bentonite, lime etc. into 8-20 mm or larger size. This process of agglomeration of fines is known as pelletisation. These green pellets are further hardened by firing at temperatures of 1200-1350 ^{0}C.

Mechanism of Pelletisation

The formation of pellets consists of two processes – Ball formation and Induration (Heat Hardening).

Ball Formation – Surface tension of water and gravitational force creates pressure on particles, so they coalesce together and form nuclei which grow in size into ball.

Induration (Heat Hardening) – Solid state diffusion take place at particle surfaces when the balls are subjected to higher temperature causing recrystallization and growth. This process provides strength to the green pellets.

Advantages of Pellets

- Very good reducibility due to high micro porosity (25-35 %)
- Spherical shape and uniform size give very good bed permeability

- High strength (about 150-250 kg) or more for acid pellets
- Heat consumption is much less than that of sintering.
- High Iron content and uniform chemical composition hence lower flux and fuel requirement in the furnace.
- Ease of handling

Disadvantages of Pellets

- High cost of production due to grinding and firing
- Swelling and loss of strength inside the furnace
- Difficulty in producing fluxed pellets
- Resistance to the flow of gas more than that in sinter for the same size range due to lower void ratio.

Thermodynamics and Kinetics of Iron Oxide

Chemical reactions involved

$Fe_2O_3(s) + 3C(s) \rightarrow 2Fe(s) + 3CO\ (g)$

Reduction of Hematite

$Fe_2O_3(s) + CO\ (g)\ /\ H_2\ (g) \rightarrow 2\ Fe_3O_4(s) + CO_2\ (g)\ /\ H_2O\ (g)$……………………… (1)

Reduction of Magnetite

$Fe_3O_4(s) + CO\ (g)\ /\ H_2\ (g) \rightarrow 3FeO(s) + CO_2\ (g)\ /\ H_2O\ (g)$…..………………….…… (2)

Reduction of Wustite

$FeO(s) + CO(g) / H_2(g) \rightarrow Fe(s) + CO_2(g) / H_2O(g)$………………………….…… (3)

Other possible reactions

$C(s) + CO_2(g) \rightarrow 2CO(g)$…………………………… (4)

$C(s) + H_2O(g) \rightarrow H_2(g) + CO(g)$……………….. (5)

It could be said that the most probable reaction is (1), followed by reactions (2) and (3). The reactions (4) and (5) are highly endothermic and possible only at high temperatures. In comparison to CO gas, the reduction reactions with H_2 gas are mostly endothermic and favoured at higher temperatures.

Steps involved in Reduction Kinetics

Before the formation of Metallic Layer

The kinetic steps involved in reduction of hematite iron ore by CO/H_2 gas are as follows:

- Transport of CO/H_2 gas from bulk gas phase to Fe_2O_3 - CO/H_2 interface.
- Adsorption of CO/H_2 gas at the Fe_2O_3 - CO/H_2 interface.
- Chemical reaction between Fe_2O_3 and CO/H_2 gas at the Fe_2O_3- CO/H_2 interface and desorption of the product gas CO_2/H_2O from this interface.
- Transport of product gas from Fe_2O_3- CO/H_2 interface to the bulk gas phase.

After the Formation of Metallic layer

- Transport of CO/H_2 gas from bulk gas phase to the Fe-CO/H_2 interface.
- Adsorption of CO/H_2 gas at the Fe- CO/H_2 interface.

• Transport of CO/H2 gas from Fe- CO/H_2 interface to the Fe_2O_3 - Fe interface.

• Chemical reaction b/w Fe_2O_3 and CO/H_2 at Fe_2O_3 - Fe interface.

• Desorption of the product gas CO_2/H_2O from this interface.

• Transport of CO_2/H_2O gas from Fe_2O_3 - Fe interface to Fe-CO/H_2 interface.

• Transport of the product gas from Fe-CO/H_2 interface to the bulk gas phase.

The steps involved are either diffusional or chemical and the slowest of these control the overall rate of reaction.

Factors Affecting the Rate of Reduction

- Temperature of reduction
- Time of reduction
- Pellet Size
- Presence of catalyst
- Reactivity of coal
- Chemical nature of ore

Factors Responsible for Swelling of Fired Iron Ore Pellets

Pellets in the reduction furnace swell and hinders its operation. Two main disadvantages of swelling are: reduced strength and disintegration of compact during reduction. However an increase in volume up to 20% is tolerable and is considered as normal swelling which is the characteristics of compact. As in literature the reasons for swelling as proposed are:

- Degradation of Iron grains

- Whisker or Fibrous growth of iron
- Crack generated during reduction
- Recrystallization of iron grains
- Structural changes during reduction
- Physical properties of pellets (crushing strength, porosity etc.)
- Briquetting parameters (fine size, Compaction pressure, binders etc.)
- Firing parameters (temperature, time etc.)
- Reduction parameters (mode of heat, gas composition, time, temperature)

Degradation of Iron grains

Swelling can be as high as 130% without whisker formation, when reduced up to temperature about 900^0C, which is explained as: carbon deposition and consequent evolution of large amount of CO/CO_2 gases, causing expansion and disintegration of iron grains [7]. However at such a high temperature about 1100^0C, disintegration decreases and completely disappeared due to recrystallization.

Whisker or fibrous growth of iron

Most of the researchers in their work claimed whisker or fibrous growth of iron grains as the major cause of swelling behaviour observed during reduction [8][9][10][11][12]. In the recent study, the dense whiskers and plates in porous structure are formed during abnormal swelling in fired hematite compact.

Crack generated during reduction

Inter-granular and trans-granular cracks are generated during reduction are responsible for the change in volume of iron ore pellets during the transformation from hematite to wustite when swelling is marked as 20-27% [13]. Cracking in the pellets is also due to the combined effect of thermal and volume strains (lattice disturbance) during the transformation from hematite to wustite [14] [10]. Growth of iron whiskers favoured by cracks and voids generated.

Recrystallization of iron grains

Sintering is favoured by greater degree of metallization, high reducing temperature and large amount of whiskers formation which further lead to shrinkage. The newly formed iron surface is more reactive and has a greater tendency to stick together because of high energy [15]. The sticking tendency of particles is mainly due to adhesive force, area of contact, and pellet's iron content, however greater will be the size and its mass higher will be the momentum, henceforth lower will be the agglomeration [16].

Structural changes during reduction

Sintering of iron ore pellets results and its volume change is mainly due to the changes in crystal structure during reduction. During the first stage of reduction hexagonal hematite lattice transforms into cubic magnetite lattice and results in about 25% increase in volume [16]. However lattice remains unchanged and is accompanied by a small increase (7-13%) in volume during the transformation of magnetite to wustite.

Physical Properties of Pellets

Crushing strength and porosity of pellets more strongly influence its swelling characteristics than geometry [12][17]. Also with increase in crushing strength and decrease in its porosity, the swelling index of pellets decreases. Lower crushing strength and higher porosity gives more active sites for nucleation and growth of iron whiskers. The high strength of pellets is mainly due to presence of slag bonds, these whiskers hence, are not able to push mechanically the grains adjacent to it and therefore results into decrease in volume (lower swelling) [10][18][19][20]. However according to some studies pellets having higher porosity indicates less swelling because more stresses can be accommodated which is produced during the course of reduction and formation of iron whiskers [21].

Briquetting parameters

Addition of gangue such as MgO, SiO_2, CaO, Al_2O_3, bentonite, molasses etc. reduces the growth of iron whiskers and hence swelling of iron ore pellets during reduction, which is further explained as addition of these constituents increases its crushing strength and hence do not allow the iron ore whiskers to grow sufficiently during reduction, as a result lower swelling is obtained [22] [23] [12] [24] [19] [7]. Sequence of constituents, decreasing the swelling indices of fired iron ore pellets is MgO, followed by silica, lime and alumina [18].

Firing parameters

With increase in firing temperature the swelling index of iron ore pellets decreases [24] [12] [18] [25]. It is observed that pellets which are fired at high temperatures and for a longer time has higher crushing strength and porosity, due to formation of slag bonds and which resulted into reduced growth of iron whiskers and thus lower swelling. A decrease in number of sites for growth of iron whiskers is observed when it is fired at a high temperature, which resulted into decrease in swelling index of iron oxide compact [26].

Reduction Parameters

Iron oxide compacts reduced with CO gas shows a gradual increase in swelling up to a maximum of 176% with rise in temperature up to 900^0C, which further decreases with increase in temperature up to 1100^0C [7]. Decrease in volume (lower swelling) at higher temperature was due to sintering and recrystallization of Fe grains, whereas carbon deposition and disintegration of iron grains are the main reasons for increase in volume up to 900^0C [4]. Higher swelling in the temperature range of 900-1000^0C and shrinkage in the range 1100-1200^0C is found while working on reduction of hematite and magnetite iron ore pellets containing char. In the temperature range of 700-1000^{0}C swelling increases with reduction temperature and is maximum at around 900-950^{0}C [21] [7]. During reduction of iron oxide compacts by CO gas in the range 800-1100^{0}C and it was found that swelling reaches a maximum value at about 900^{0}C due to larger amount of whiskers at this temperature [26].

Reducing gas containing hydrogen accelerates the rate of reduction and hence reduces the chances of whisker growth [14] [28] [26]. Gas-solid reaction on the iron oxide surface is inhibited due to adsorption of sulphur on it.

EXPERIMENTAL DETAILS

Material Selection

In the present work hematite iron ore was obtained from Sakaruddin mines of Orissa and its physical and chemical characteristics are detailed in Table 4, 5 and 6. Low grade (F) non-coking and other coal used in the study are obtained from Ananta coal mine(India), Australia, South Africa, Indonesia and examined for their proximate analysis (IS: 1350 1969), reactivity towards CO_2 gas (IS : 12381 1994), ash fusion temperatures (DIN : 51730 1984) and caking index (IS : 1353 1993). The results obtained have been listed in Table 7 and 8.

Table 4: Chemical composition of Hematite Iron Ore obtained from Sakaruddin mine of Orissa, India (wt. %, air-dried basis)

Fe (total)	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	MnO	Loss on Ignition
64.51	91.74	3.06	1.43	0.14	0.02	3.61

Table 5: Physical Properties of Hematite Iron Ore obtained from Sakaruddin mine of Orissa, India (wt. %, air-dried basis)

Tumbler Index (wt. % of +6.3mm)	Abrasion Index (wt. % of -0.5mm)	Shatter Index (wt. % of -5.0mm)	Apparent Porosity (%) Lump Ore	Apparent Porosity (%) Fired Pellets
90.0	4.75	0.68	1.5	18.9

Table 6: Mechanical properties of Sakaruddin Iron Ore Pellets

Binder	Binder (%)	Firing Conditions		Drop No.		Crushing Strength (Kg/pellet)	Porosity
		Firing Temp (°C)	Firing Time(hr)	Oven Dried	Fired		
Concentrated Sugarcane Juice	2	1300	1	1	4500	910	8.39
	4	1300	1	2	850	205	19.24
	6	1300	1	4	275	135	26.76

Table 7: Chemical composition, reactivity, caking index and ash fusion temperatures of non-coking coal procured from Ananta mine of Orissa, India

Proximate analysis (wt.%, dry basis)			Sulphur content (wt. %)	Reactivity (cc of CO/g. of C/sec.)	Caking index	Ash fusion temperatures(^{0}C)			
Volatile matter	Ash	Fixed carbon				IDT	ST	HT	FT
25.86	43.0	31.14	0.45	5.88	Nil	1310	1500	1602	1646

IDT – Initial deformation temperature; ST – Softening temperature; HT – Hemispherical temperature; FT – Flow temperature

Table 8: Characteristics of coal selected (proximate analysis) in present study

Type of Coal	Moisture (%)	Ash (%)	Volatile Matter (%)	Fixed Carbon (%)	Reactivity (cc of CO/g of C. sec)
Australian	4	29.5	1	65.5	2.93
Indonesian	2	21	5	72	3.72
South African	3	30	2	65	3.11

Sample Preparation

The Iron ore fines -100 mesh size approx. 84%, -16+25 mesh size approx. 16% were thoroughly mixed with the addition of concentrated sugarcane juice as binder with varying amount as 2%, 4 %, 6% and little amount of water in it. Pellets were then made by Hand Rolling method. The pellets were dried in electric oven at 110 ^{0}C for more than 5 hours. The dried pellets were fired by heating them in muffle furnace from room temperature to 1300^{0}C at a rate of about 4^{0}C/min and soaking at this temperature for 1 hour, followed by furnace cooling.

Reduction and Swelling Behaviour

Separate reductions were carried out in coal fines of -4+6 mesh size. In the present investigation, single pellet type reduction experiments, on the weighed fired iron ore pellets which were embedded centrally inside the packed bed of coal particles in each of the stainless steel reactors (size: 75mm height x 40 mm diameter), have been carried out by heating the reactors from room temperature to the predetermined temperature of 950^{0}C, 1000^{0}C at a rate of about 4^{0}C/min. Each reactor was tightly closed with an air tight cover having an outlet for the release of gas. The temperature was controlled within ± 5^{0}C. After soaking for predetermined period of time the reactors were taken out of the furnace after an interval of 15 minutes and cooled to room temperature in air. The reduced pellets were weighed and the degree of reduction was calculated by the wt. % of oxygen removed from each of them.

Using Vernier Calliper the diameter of the pellet before and after reduction were measured three times each and averaged for determination of volumes. The swelling/shrinkage at different intervals of reduction was calculated by using the formula:

Swelling index (%) = $\{(V_f - V_i)/V_i\} \times 100$

Where,

V_i– Initial Volume of the Pellet, and

V_f – Final Volume of the Pellet after reduction for a given time.

Weight losses in pellets were recorded by an electronic balance to calculate to calculate the Degree of Reduction.

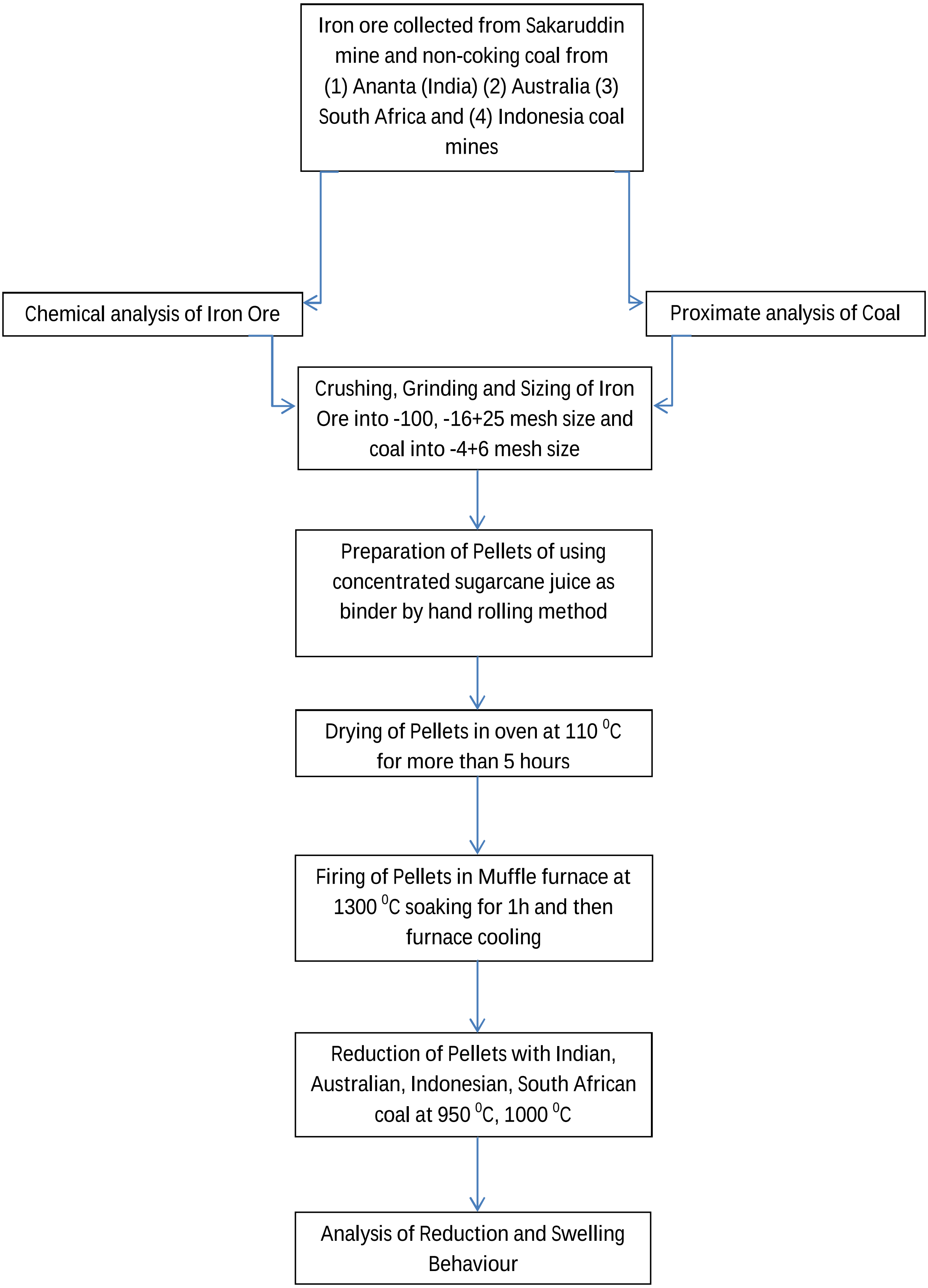
Degree of Reduction was calculated by following formula:

Degree of Reduction = (Weight loss in pellets / total oxygen content in the pellets) x 100

Scanning Electron Microscope Observation

In order to assess the surface characteristics and structural changes in some of the reduced iron ore pellets JEOL scanning electron Microscope (6480 LV model) is used. In this study, fractured surfaces of reduced pellets were gold coated to produce a conductive path and examined at magnifications increasing to 2000.

Process Flow Chart



Results and Discussion

Characteristics of Iron Oxide feed suitable for use in Rotary Kiln

In general, the oxide feed (hematite and magnetite) must have iron content more than 62% and the allowable amount of silica plus alumina should not exceed 4% for producing a sponge iron as shown in Table 9. Iron ores with Fe contents > 66% are not easily reducible and higher amount of FeO is retained in the produced DRI. While ores of lower grade (Fe content: 62 – 66%) are likely to be more suitable for sponge iron production. Higher Titania (TiO_2) content may have a deleterious effect on the reducibility of the oxide feed and hence, a lower degree of metallization could be achieved in the reduced product. In general, the Titania content in the oxide feed should not exceed 0.15% (Table 9)

Table 9: Characteristics of Iron Oxide feed suitable for use in Rotary Kilns

Chemical Properties	Physical Properties
(a) Composition (wt. %) Fe: 62-66, $SiO_2 + Al_2O_3$: $\leq$ 4.00, CaO + MgO: $\leq$ 2.00, S: ≤ 0.02, P : ≤ 0.03, TiO_2 $\leq$ 0.15, Pb+Zn+Cu+Sn+Cr+As: $\leq$ 0.02 (b) Reducibility (% min^{-1}) (dR/dt) at 40% reduction: $\geq$ 0.5	(a) Tumbler index (wt.% of +6.3mm): $\geq$ 90.0 (b) Abrasion index (wt.% of -0.5mm): $\leq$ 7.0 (c) Shatter index (wt.% of +5mm): $\geq$ 95.0 (d) Thermal degradation index : ≤ 5.0 (wt.% of – 6.3mm)

In general, coals with high reactivity values are preferred as they allow kiln operations at relatively lower temperatures with enhanced productivity and decreased tendency towards ring formation. Another important characteristic of coal is the initial deformation temperature (IDT) of its ash. In order to ensure no agglomerate formation in the charge bed, the caking index of coal should be preferably below 1 (however, tolerable up to 3). However, lower fixed carbon and higher ash contents in this coal may increase its consumption during DRI production in rotary kiln.

Table 10: Characteristics of non-coking coal for use in rotary kilns

Chemical Properties	Physical Properties
a) Composition (wt.%, air-dried basis) Moisture: 4-7, Volatile matter : 27-32, Ash : 21-25, Fixed carbon : 38-42, Sulphur : < 1.0 b) Reactivity (cc of CO/g of C/sec): **>** 2.0	(a) IDT of ash : > 1250^{0}C (b) Caking Index : ≤ 3.0 (c) Swelling index : ≤ 1.0 (d) Bulk Density (Kg/mm^3): ≥ 800

Reduction and Swelling Behaviour of Fired Hematite Iron Ore Pellets

Data on the degree of reduction versus time (Table 11) for fired Sakaruddin hematite iron ore pellets, reduced in Indian (Ananta), Indonesian, South African, and Australian Coal (size: -4+6 mesh size) at temperatures of 950 and 1000^{0}C, have been presented graphically in figure 3 and 4.

Table 11: Reduction and Swelling Characteristics of Sakaruddin Fired Iron Ore Pellets

Binder	Binder (%)	Reduction Temp (°C)	Coal Type	Time (min)	Degree of Reduction (%)	Swelling (%)
Concentrated Sugarcane Juice	4	950	Indian	5	42.36	7.84
				10	52.14	14.54
				15	68.24	14.98
			Indonesian	10	42.7	33.1
				15	50.16	35.27
			South African	10	32.5	30.3
				15	40.23	32.68
			Australian	10	41	15.76
				15	49.38	24.32
		1000	Indian	10	76.25	15.25
				15	87.32	21.57
			Indonesian	10	38.5	15.76
				15	46.31	17.39
			South African	10	31.5	9.27
				15	41.24	14.32
			Australian	10	23.8	12.49
				15	35.26	13.85

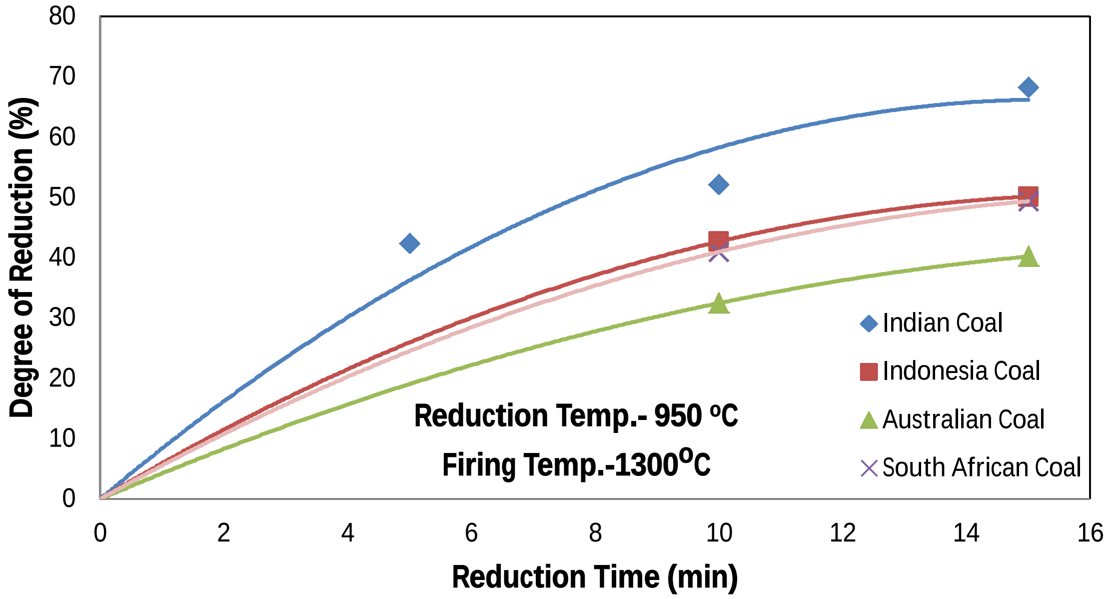


Figure 3: Degree of Reduction vs. Time Plots for the reduction of fired Sakaruddin Hematite Iron Ore Pellets fired at 1300^{0}C and reduced in coal (-4+6 mesh size) at a temperature of 950^{0}C

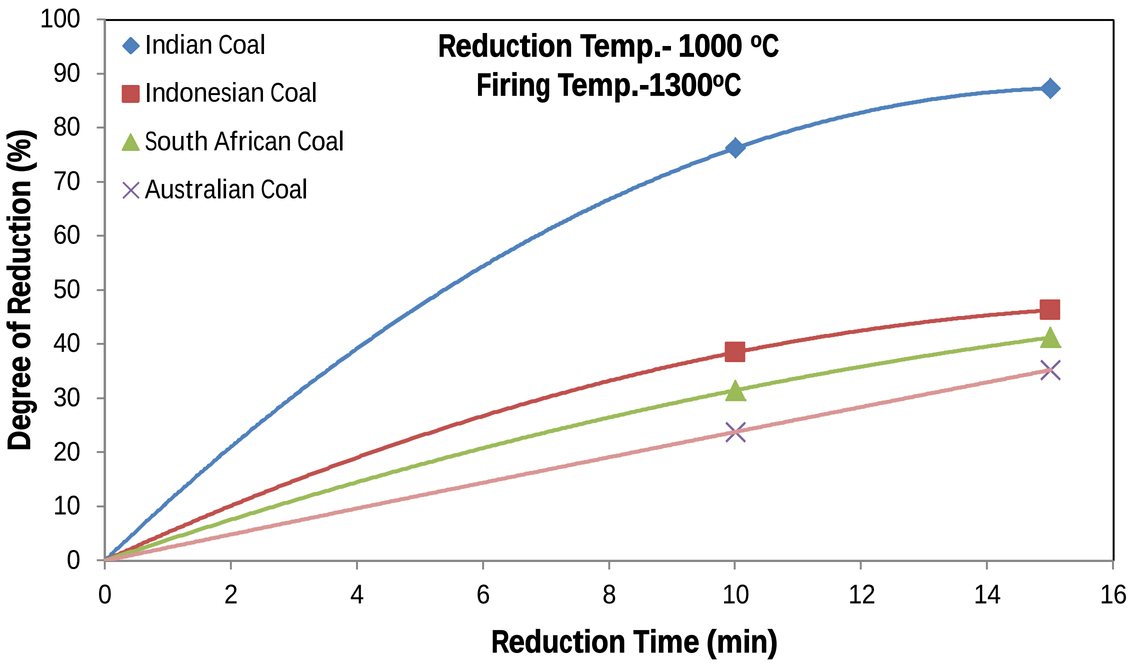


Figure 4: Degree of Reduction vs. Time Plots for the reduction of fired Sakaruddin Hematite Iron Ore Pellets fired at 1300^{0}C and reduced in coal (-4+6 mesh size) at a temperature of 1000^{0}C

The results (figure 3 and 4) established that in all the studied fired iron ore pellets, the reduction rate improved greatly with increase of temperature up to (950^{0}C, 1000^{0}C). As shown in this figure, the degree of reduction also increased with time at all the studied temperatures.

Effects of Temperature and Time

As depicted in the figure 5 and 6, swelling is found to be strongly dependent on reduction temperature and time. As shown in figure 5 and 6, pellets were reduced at 950 and 1000^{0}C and swelling is slightly higher at 950^{0}C. On the basis of researches, literature available and observations made in the scanning electron micrographs (SEMs), all the volume changes at reduction temperatures of 950 and 1000^{0}C appear to be due to the combined effects of creation of cracks and voids, formation of iron whiskers and their growth, and phase transformation in the reduced products. Typical scanning electron micrographs of fired pellets reduced at temperature of 1000^{0}C have been presented in figure 12. They clearly indicate the presence of cracks / voids and iron whiskers in the reduced structures. More carbon deposition (through thermal decomposition of CO gas) and evolution of large amounts of CO / CO_2 gases from inner zones of the pellets, reduced at temperatures of 950 and 1000^{0}C, are also expected to contribute to their swelling. Thus, the availability of more porous structure and higher carbon deposition appear to be the most probable reasons for slightly higher swelling in the pellets reduced at 950^{0}C.

As can be seen in figure 5 and 6, all the fired pellets reduced at temperatures of 950 and 1000^{0}C exhibit shrinkage (being more at 1000^{0}C) and the extent of this shrinkage, in general, increased with the progress of reduction time / degree of reduction. The higher degree of sintering of iron fibres / grains and their densification may be held responsible for shrinkage in the pellets reduced at temperatures of 950 and 1000^{0}C. As observed in scanning electron micrographs shown in figure 12, the high temperatures of reduction (i.e. 1000^{0}C) caused sintering (fusion) of adjacent whiskers / grains resulting in the formation of densified masses and the extent of sintering increased with an increase of reduction temperature. A reduction temperature of 1000^0C greatly increases the ability of iron whiskers/grains to sinter and re-crystallize – a matter which would increase the shrinkage. However, it must be emphasized that a higher amount of carbon (through increased mobility and migration from coal) gets dissolved in the dense iron layers, which in turn causes distortion in iron lattice and thus increase in volume [23].

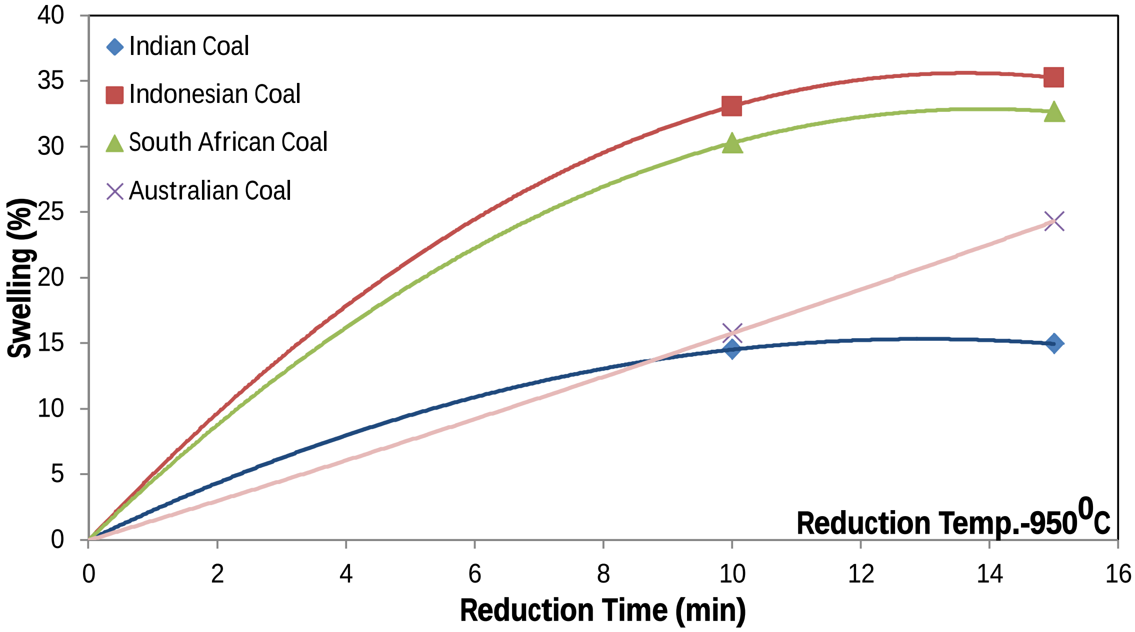


Figure 5: Swelling vs. Time Plots for the reduction of fired Sakaruddin Hematite Iron Ore pellets fired at 1300^0C and reduced in coal (-4+6 mesh size) at a temperature of 950^0C.

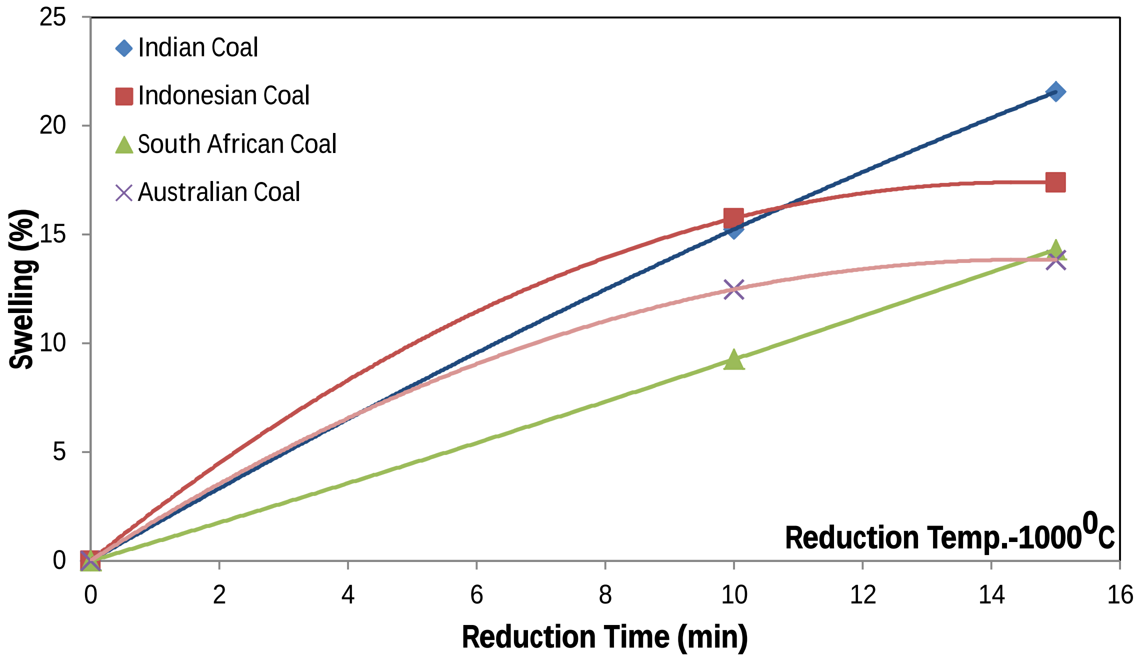


Figure 6: Swelling vs. Time Plots for the reduction of fired Sakaruddin Hematite Iron Ore pellets fired at 1300^{0}C and reduced in coal (-4+6 mesh size) at a temperature of 1000^{0}C

Effect of Binder %

It is observed from the experiments that crushing strength and Drop no. both decreases with increase in binder %, as shown in figure 7 and 8.

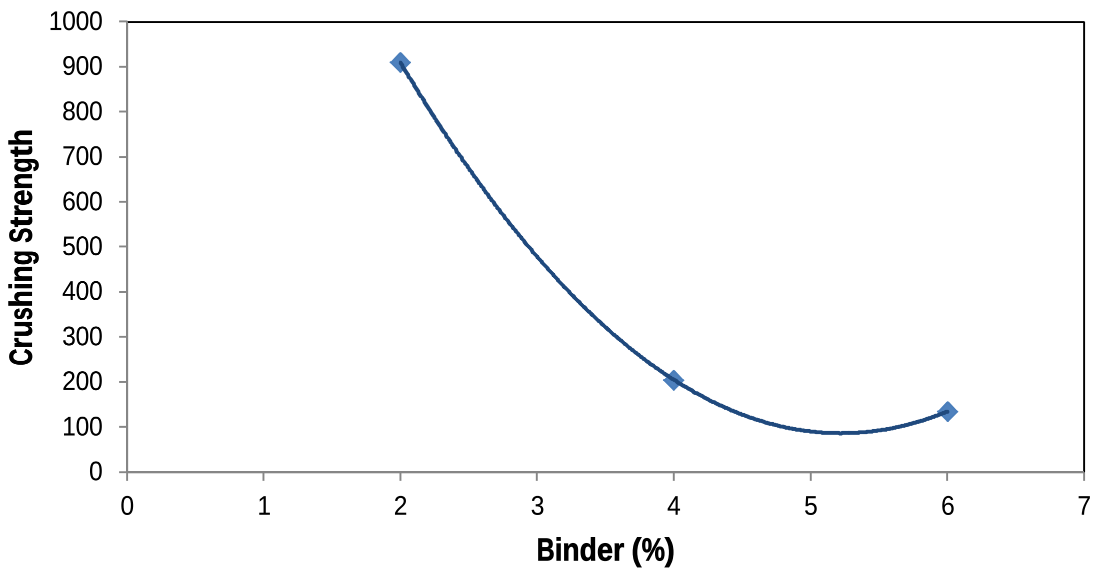


Figure 7: Crushing Strength vs. Binder (%)

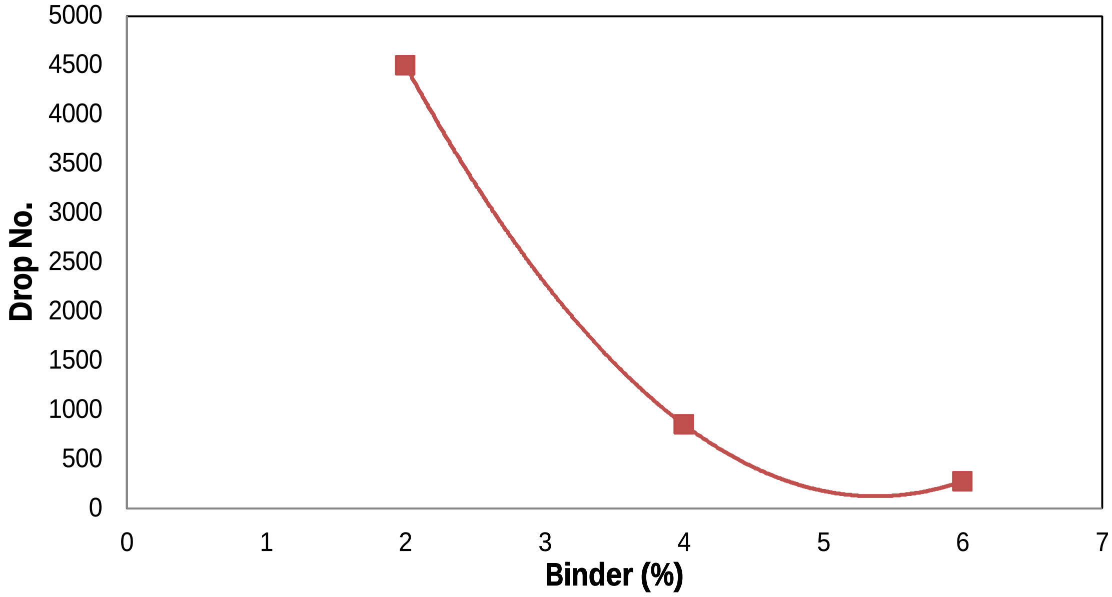


Figure 8: Drop Number vs. Binder (%)

Effect of Coal Reactivity

It is also observed form the experiments that the extent of reduction depends on reactivity of Coal which is depicted graphically in the figure 9.

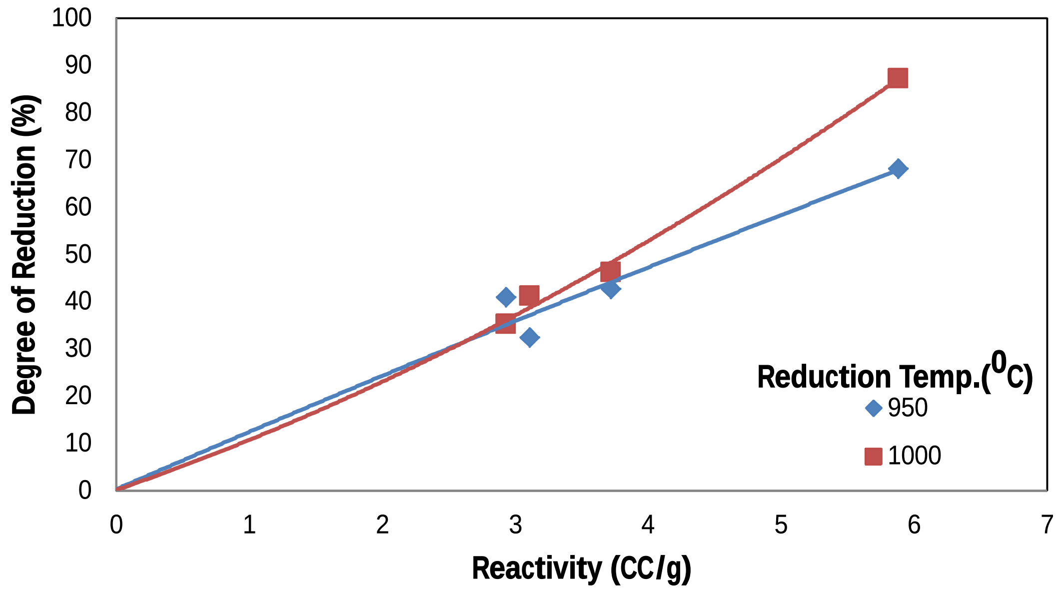


Figure 9: Degree of Reduction vs. Reactivity plots for the reduction of fired Sakaruddin Hematite Iron Ore pellets fired at 1300^{0}C and reduced in coal (-4+6 mesh size) at a temperature of 950^{0}C and 1000^{0}C.

Variation of Degree of Reduction and Swelling with change in Reduction Temperature

Degree of Reduction increases with increase in volume of the pellets when reduced at 950, 1000^{0}C as shown in figure 10 and 11. Also it is visible that with the increase in reduction temperature the degree of reduction of iron ore pellets increases.

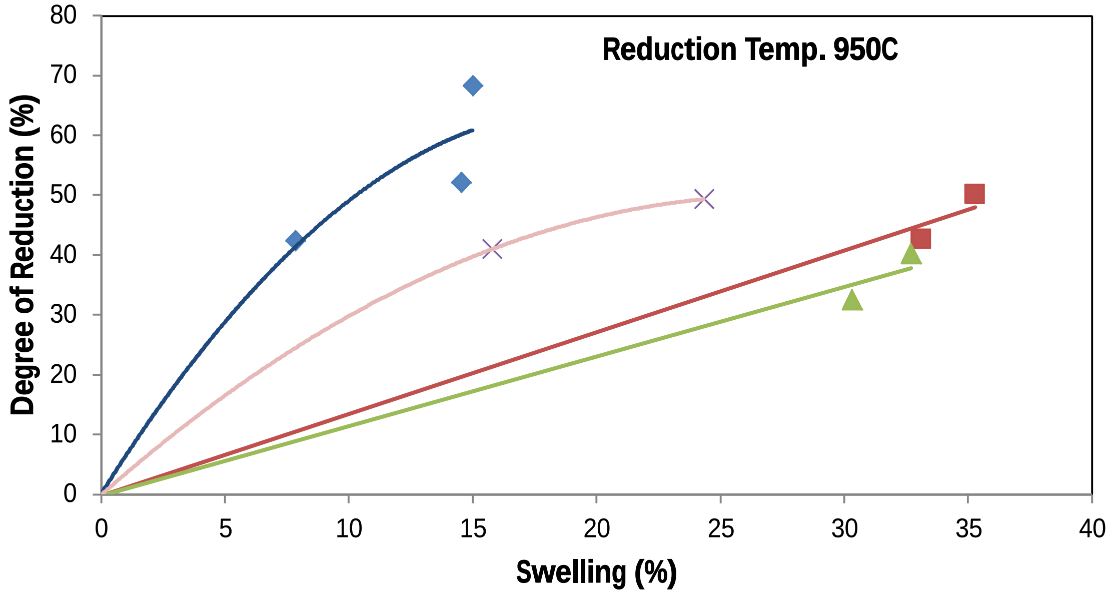


Figure 10: Degree of Reduction vs. Swelling Plots for the reduction of fired Sakaruddin Hematite Iron Ore pellets fired at 1300^{0}C and reduced in coal (-4+6 mesh size) at a temperature of 950^{0}C

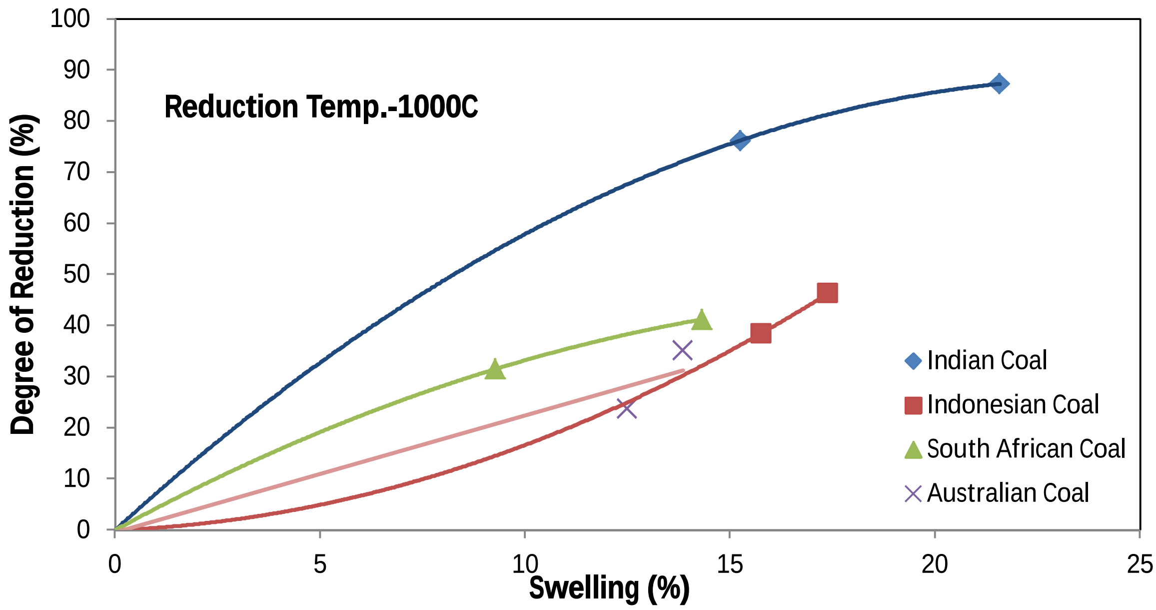
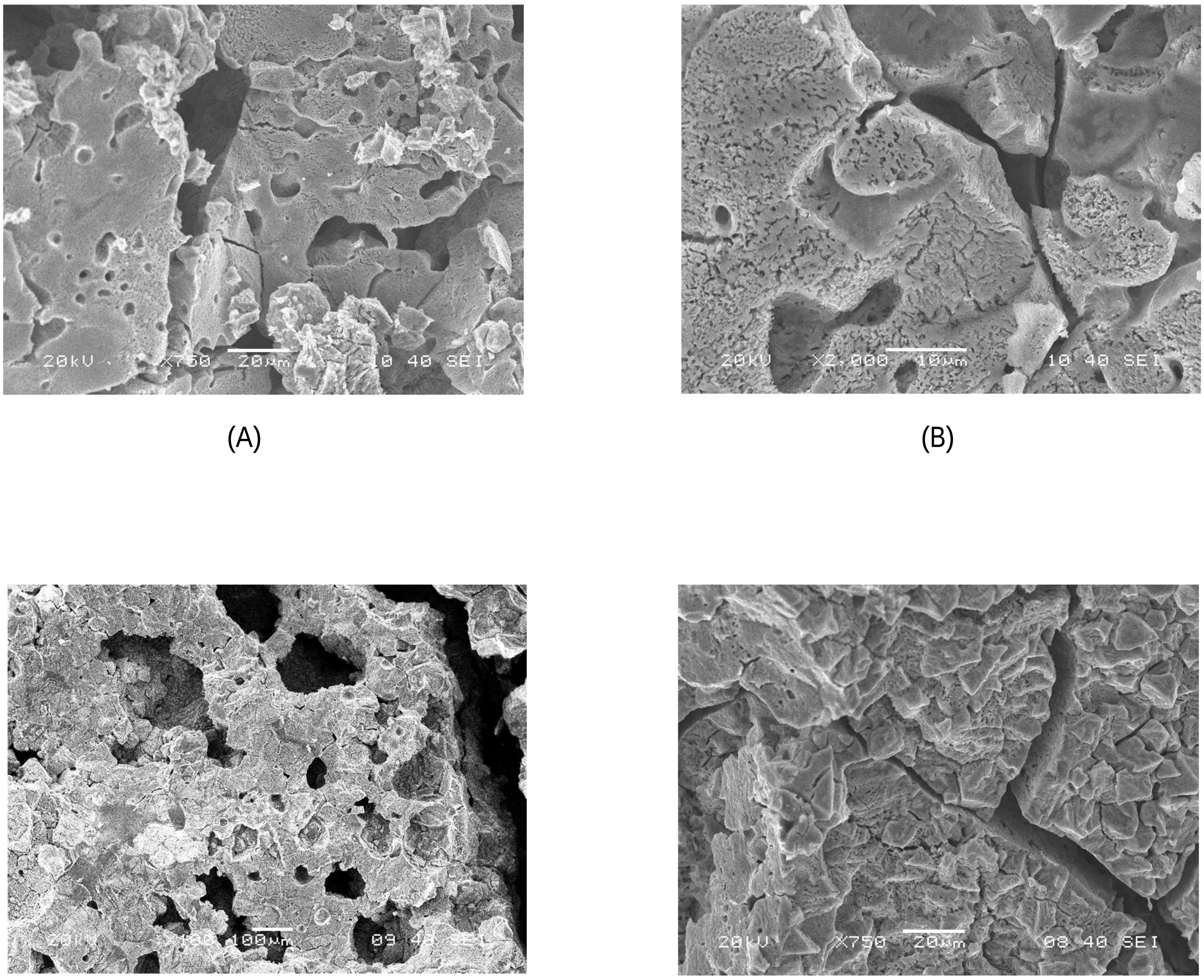


Figure 11: Degree of Reduction vs. Swelling Plots for the reduction of fired Sakaruddin Hematite Iron Ore pellets fired at 1300^{0}C and reduced in coal (-4+6 mesh size) at a temperature of 1000^{0}C

SEM Images



(A) (B)

(C) (D)

Figure 12: SEM Images of reduced Sakaruddin iron ore pellets fired at 1300^{0}C reduced in [A] Australian Coal at 750X [B] Indian Coal at 2000X [C] Indonesian Coal at 100X [D] South African Coal at 750X at a reduction temperature 1000^{0}C with a reduction time 10 minutes

CONCLUSIONS

- The crushing strength and drop number of the fired iron ore pellets decrease with the addition of concentrated sugarcane juice binder from 2% to 6%.
- The porosity of the fired iron ore pellets increase with the addition of concentrated sugarcane juice binder from 2% to 6%.
- The degree of reduction increases with increase in temperature in the studied temperature range (950 – 1000^{0}C).
- The degree of reduction of pellets increases with increase in reduction time up to the range studied.
- The degree of reduction of fired pellets increased with increase in the reactivity of the coal.
- The swelling in the fired iron ore pellets increased with increase in reduction time.

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