STUDIES ON THE PHYSICAL PROPERTIES AND REDUCTION-SWELLING BEHAVIOR OF FIRED HAEMATITE IRON ORE PELLETS

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

Master of Technology

In
Metallurgical and Materials Engineering
By
Srikar Potnuru
Roll No: 210MM1251

Department of Metallurgical and Materials Engineering
National Institute Of Technology, Rourkela
May 2012

STUDIES ON THE PHYSICAL PROPERTIES AND REDUCTION-SWELLING BEHAVIOR OF FIRED HAEMATITE IRON ORE PELLETS

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

Master of Technology

In
Metallurgical and Materials Engineering
By
Srikar Potnuru
Roll No: 210MM1251

Under the Guidance
of
Prof. M.Kumar

Department of Metallurgical and Materials Engineering
National Institute of Technology, Rourkela
May 2012

ACKNOWLEDGEMENT

The author wishes to express his deep sense of gratitude to Prof. **M.Kumar**, Department of Metallurgy & Materials Engineering, National Institute of Technology, Rourkela for his valuable guidance and meticulous supervision of the work. Without his help, it would not have been possible for the author to complete the work. The author is indebted to him for his affectionate care and valuable suggestion throughout the course of study.

The author extends heartiest acknowledgement to Mr. B.Naik, Mr. K.Tanti and Mr.S.K. Sahoo of Metallurgical & Materials Engineering department for their periodic co-operation during the course of work.

Last but not least the author wishes to acknowledge all who have been connected more or less with this venture and donated their valuable time.

Date

Srikar Potnuru
Roll No.210MM1251S

ABSTRACT

In view of generation of huge amount of iron ore and coal fines there is a need to develop a technique to utilize these fines. The present project work has been undertaken to study reduction and swelling characteristics of hematite iron ore pellets made from iron ore fines under different conditions. The physical properties of fired iron ore pellets were studied. The compressive strength and drop number of fired pellets increased with the increase of firing temperature due to the enhancement in the extent of sintering and consolidation of iron ore fines.

The main objectives of the present work have been to study the effects of (i) Firing temperature (ii) Reduction temperature and time (iii) Addition of concentrated sugarcane juice on the reduction and swelling behaviours of fired iron ore pellets. The results indicated a decrease in the extent of reduction with increase of firing temperature. The reduction rate of fired iron pellets were found to increase with rise of reduction temperature from (850°C-1000°C). The degree of reduction of fired pellet increased with increase of reduction time, the rate being faster in the initial 20-30 minutes followed by a decrease thereafter. Extent of swelling in fired sakaruddin hematite iron ore pellets, in general, was found to be highest in the pellets reduced at 900°C followed by 950-1000°C. Reduction at a temperature of 850°C, in general, gave lowest degree of swelling in the reduced pellets. The highest degree of swelling at a reduction temperature of 900°C appears to be due to fibrous growth of iron in the reduced pellets. Slightly lower values swelling in the fired iron ore pellets reduced at 950°C and 1000°C appear to be due to sintering of iron particles in the pellets, as indicated by their SEM micrographs. Effect of reduction time in the range studied on the extent of swelling was not found to be distinguishable. The Indian coal gave higher rate of reduction than Australian, Indonesian and South African coals because of highest CO2 reactivity of Indian coal.

CONTENTS

CHAPTER-1

CHAPTER-2

CHAPTER-3

CHAPTER-4

CHAPTER-5

CHAPTER-6

CHAPTER-7

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Iron is believed to be the tenth most abundant element in the universe, and the fourth most abundant in the earth‘s crust. Iron is the most commonly used metals, comprising 95% of all the metal tonnage produced worldwide. Iron is extracted from its ore, and is almost never found in the free elemental state. In order to obtain elemental iron, the impurities must be removed.

Directly Reduced Iron or Sponge Iron is a porous solid-state product of direct reduction process, which is produced either in lump or pellet form. DRI is a good substitute for steel scrap for producing steel in EAF, BOF etc, which is resulted in a rapid growth of the sponge Iron Industry. In view of increasing demand of sponge Iron in the manufacturing of different varieties of steel, a good deal of emphasis is being given to promote the study of direct reduction process.

The growth of DRI industry took place in its nascent form the later half of the 20th century, until then steel scrap constituted was being used for production of steel by mini steel plan. The demand of steel was fulfilled by import. Then Indian government imposed some curtailment measure and search for the alternatives began, and the sponge iron was resulted as an alternative to the steel scrap, which is produced by the direct reduction of iron ore in the form of lump or pellet. In direct reduction (DRI) process, there is a good scope of using different kind of reductants like lower grade non coking coal, char coal, natural gas etc. The fast depletion of high grade cooking coal, reserves restricts the use of coke in conventional blast furnace-oxygen steel making route.

Being enriched with good quality Iron ore along with vast reserves of non-coking Coal, there is very good scope of coal based Sponge Iron plants. The total gross reserves of coking and non-coking coal in India are approximately 11,602 and 71,400 million tons respectively. From this prospective, the rotary kiln (coal based) DR process have developed well and vigorously in the country instead of natural gas based Shaft furnace or Retort furnace.

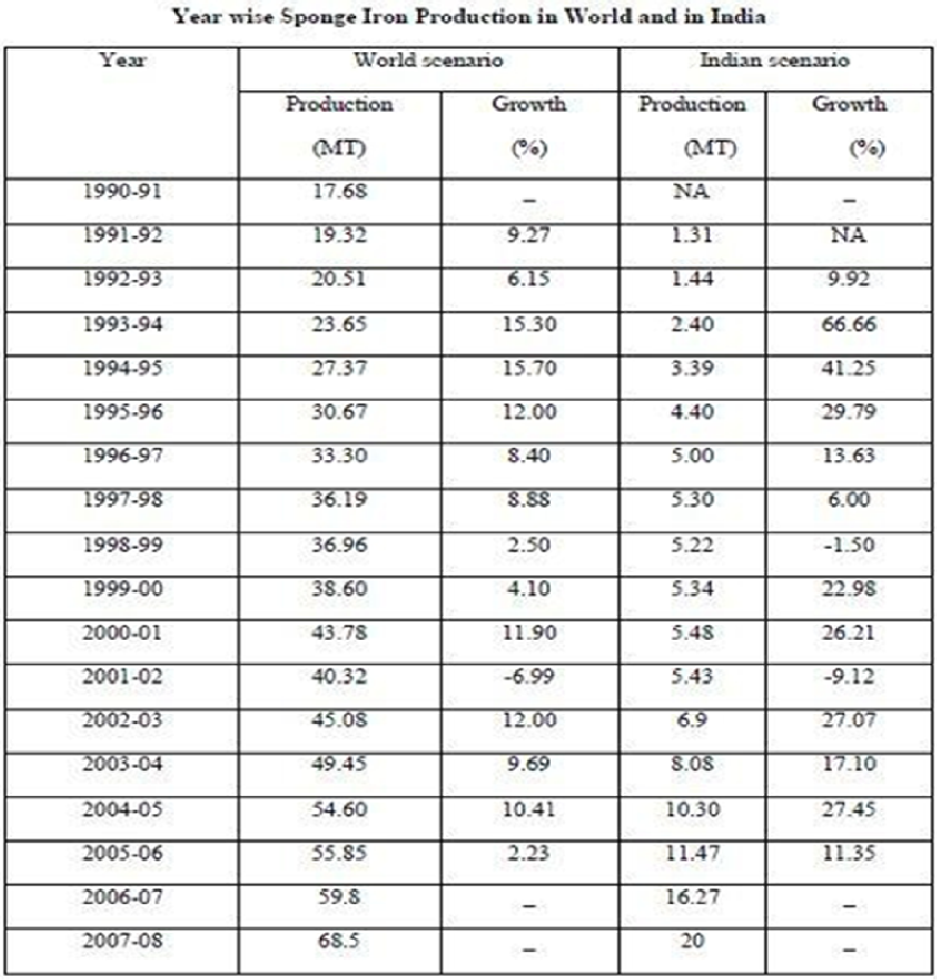
In order to accept the potential of the fact, it is rather imperative to understand the basic mechanism involved in DR process using non coking coal as reductant. The reduction of iron ore by carbon is one of the most important reactions in iron making in blast furnace, rotary kiln and electric smelting furnace. Extensive studies has been carried out on the reduction behaviour of iron ore mixed with carbon/char/graphite/coke etc. , which reveals that the reduction reaction take place via gaseous intermediate like Carbon monoxide and Carbon dioxide. As such it is evident that, the actual direct reduction doesn‘t need any gaseous medium to be carried out. But of late it has been rather well accepted that, the reduction of Iron oxide by carbon in blast furnace and direct reduction process of sponge Iron production is mostly the result of indirect reduction.

Currently a lot of emphasis is being given to direct reduction process because use of pre-reduced pellets or sponge iron as feed for blast furnace, induction furnaces and basic oxygen furnaces, despite some associated drawbacks, offers much scope for improving both productivity and economy in coke consumption.

1.1 DETAILS OF DRI PRODUCTION IN INDIA AND IN THE WORLD

A year-wise production of sponge iron in the world including India is given in Table-1.1. According to current analysis, it has been observed that starting with a meager production of 0.79 million tons in 1970, the world sponge iron production went upto 55.85 million tons in 2005, as given in table-1.it is clear from the table that the world sponge iron production has been increased nearly 225% from the year 1990 to 2005. In the year 2002 India became the largest producer of sponge iron in the world with a production of 5.48 million tones and still it has retained its first slot in the world rating of sponge iron production. Out of 16.27 MT of sponge iron produced in 2006-07 the contribution of coal based sponge iron units is around 11.01 MT and that of has based units are 5.26 MT. This large difference in contribution of G.B.S.I.U. and C.B.S.I.U. is due to scarcity of natural gas and abundant availability of non-coking coal in India. This phenomenal growth of DRI industries is driven by increasing demand of steel in India and as well as in the world. Now India is the 6th largest steel producer in the world with a production of 42 MT/Annum.

Table 1: Total Dri Production In India



Year wise Sponge Iron Production in World and in India

Year	World scenario		Indian scenario	
	Production (MT)	Growth (%)	Production (MT)	Growth (%)
1990-91	17.68	–	NA	–
1991-92	19.32	9.27	1.31	NA
1992-93	20.51	6.15	1.44	9.92
1993-94	23.65	15.30	2.40	66.66
1994-95	27.37	15.70	3.39	41.25
1995-96	30.67	12.00	4.40	29.79
1996-97	33.30	8.40	5.00	13.63
1997-98	36.19	8.88	5.30	6.00
1998-99	36.96	2.50	5.22	-1.50
1999-00	38.60	4.10	5.34	22.98
2000-01	43.78	11.90	5.48	26.21
2001-02	40.32	-6.99	5.43	-9.12
2002-03	45.08	12.00	6.9	27.07
2003-04	49.45	9.69	8.08	17.10
2004-05	54.60	10.41	10.30	27.45
2005-06	55.85	2.23	11.47	11.35
2006-07	59.8	–	16.27	–
2007-08	68.5	–	20	–

Source: Steelworld.com

1.2 IRON ORE AND COAL RESERVES IN INDIA

Presently, India is fifth in terms of iron ore reserves. It has got 25 billion tons of reserves, of Which 15 billion tons are reported to be hematite and rest magnetite at cut off grades of 55% iron as per Indian bureau of mines (IBM). India produces around 155 million tons of iron ore (Including both lumps and fines) out of which about 52 million tons were used by the domestic steel manufacturers.

1.2.1 Iron Ore Reserves

India is one of the richest sources of iron ore deposits in the world. Iron ore which is also known as hematite occurs in abundance in the country. Iron ore reserve accounts for almost two third of the entire iron ore reserves in India. India holds the leading position in the list of leading iron ore reserves countries.

Of the total iron ore reserves in the country, Chikkamagaluru in Karnataka, Singhbhum in Jharkhand, Sundargarh and Kendujhar in Orissa, Bellary, Shimoga and Goa accounts for major portion. Further in Bihar and Orissa, huge deposits of iron grade iron ore appears as huge masses that rise above the adjoining plain. Some of them are located within a close proximity to the coal field. Iron ore generally occurs at top of the hillsand thus arial roadways are used by the iron ore companies to bring down the ore and for pumping it directly to the railway carriages. Singhbhum district in Jharkhand and the neighbouring district of Mayurbhang, Sundarand, Keonjhar constitute the richest high grade iron ore reserves.

In India the chief mining centers are Sulaipat and Badampur in Mayurbhang District in Orissa and Gua and Noamundi in Singhbhum in Jharkhand. The iron ore from these mines is supplied to the iron and steel industries.The Rajhara and Dhali Hills located in south of bhillai gives its ore to Bhilai steel works Kemmangundi in the Bababudan hills of Chikmagalur district in Karnataka is the richest source of high grade iron ore. Richest sources of high grade iron ore are Goa, Madhya Pradesh, Maharashtra, Bastar district, Chandrapur District and belt of Orissa Bihar, Andhra Pradesh. The total recoverable reserves of iron ore in India are about 9,602 million tons of hematite and 3,408 million tons of magnetite Madhya Pradesh, Karnataka, Jharkhand, Orissa, Goa, Maharashtra, Andhra Pradesh, Kerala, Rajasthan and Tamil Nadu are the principal Indian producers of iron ore.

1.2.2 Hematite Ores Deposits

Direct shipping iron ore (DSO) deposits (typically composed of hematite) are currently exploited on all continents except Antarctica, with the largest intensity in South America, Australia and Asia. Most large hematite iron ore deposits are sourced from altered banded iron formations and rarely igneous accumulations.

DSO deposits are typically rarer than the magnetite-bearing BIF or other rocks which form its main source or protolith rock, but are considerably cheaper to mine and process as they require less beneficiation due to the higher iron content. However, DSO ores can contain significantly higher concentrations of penalty elements, typically being higher in phosphorus, water content (especially pisolite sedimentary accumulations) and aluminum (clays within pisolites). Export grade DSO ores are generally in the 62-64% Fe range.

1.2.3 Magnetite Ore Deposits

Occasionally granite and ultrapotassic igneous rocks segregate magnetite crystals and form masses of magnetite suitable for economic concentration. A few iron ore deposits, notably in Chile, are formed from volcanic flows containing significant accumulations of magnetite phenocrysts. Chilean magnetite iron ore deposits within the Atacama Desert have also formed alluvial accumulations of magnetite in streams leading from these volcanic formations. Some magnetite skarn and hydrothermal deposits have been worked in the past as high-grade iron ore deposits requiring little beneficiation. There are several granite-associated deposits of this nature in Malaysia and Indonesia.

Other sources of magnetite iron ore include metamorphic accumulations of massive magnetite ore such as at Savage River, Tasmania, formed by shearing of ophiolite ultramafics. Another, minor, source of iron ores are magmatic accumulations in layered intrusions which contain a typically titanium-bearing magnetite often with vanadium. These ores form a niche market, with specialty smelters used to recover the iron, titanium and vanadium. These ores are beneficiated essentially similar to banded iron formation ores, but usually are more easily upgraded via crushing and screening. The typical titanomagnetite concentrate grades 57% Fe, 12% Ti and 0.5% V2O5.

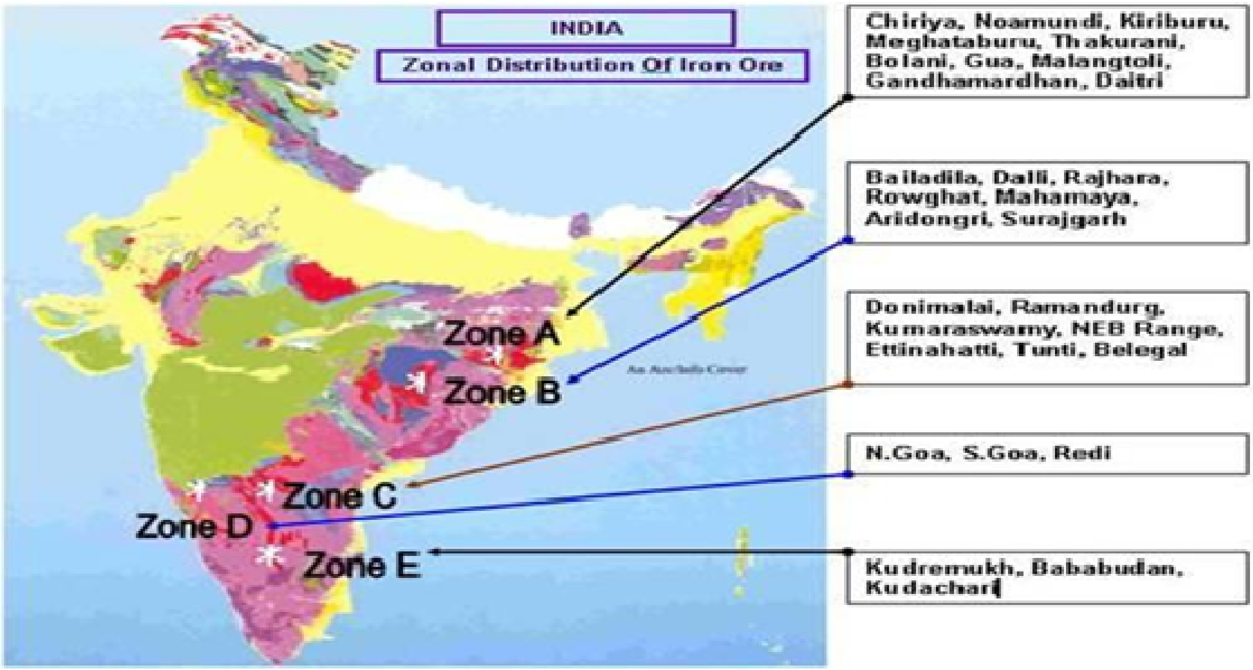
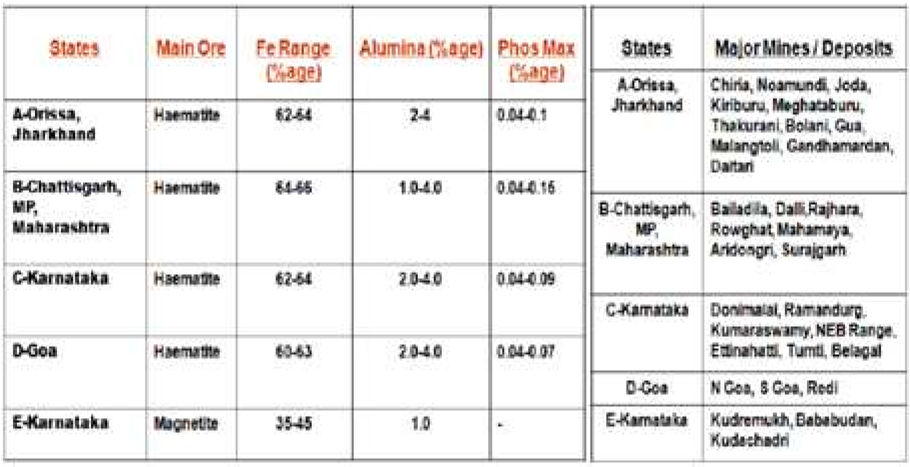


Figure 1: Indian Iron Ore Reserves

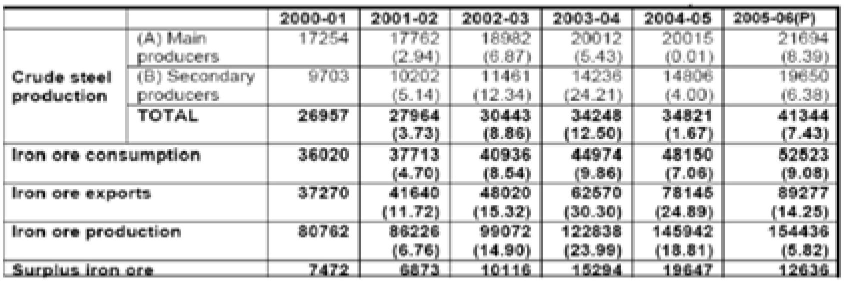
Table 1.2: Iron ore reserves in India



States	Main Ore	Fe Range (%age)	Alumina (%age)	Phos Max (%age)
A-Orissa, Jharkhand	Haematite	62-64	2-4	0.04-0.1
B-Chattisgarh, MP, Maharashtra	Haematite	64-66	1.0-4.0	0.04-0.16
C-Karnataka	Haematite	62-64	2.0-4.0	0.04-0.09
D-Goa	Haematite	60-63	2.0-4.0	0.04-0.07
E-Karnataka	Magnetite	35-45	1.0	-

States	Major Mines / Deposits
A-Orissa, Jharkhand	Chiria, Noamundi, Joda, Kiriburu, Meghataburu, Thakurani, Bolani, Gua, Malangtoli, Gandhamardan, Daitari
B-Chattisgarh, MP, Maharashtra	Bailadila, Dalli,Rajhara, Rowghat, Mahamaya, Aridongri, Surajgarh
C-Karnataka	Donimalai, Ramandurg, Kumaraswamy, NEB Range, Ettinahatti, Tumti, Belagal
D-Goa	N Goa, S Goa, Redi
E-Karnataka	Kudremukh, Bababudan, Kudachadri

Table 1.2.1



		2000-01	2001-02	2002-03	2003-04	2004-05	2005-06(P)
Crude steel production	(A) Main producers	17254	17762 (2.94)	18982 (6.87)	20012 (5.43)	20015 (0.01)	21694 (8.39)
	(B) Secondary producers	9703	10202 (5.14)	11461 (12.34)	14236 (24.21)	14806 (4.00)	19650 (6.38)
	TOTAL	26957	27964 (3.73)	30443 (8.86)	34248 (12.50)	34821 (1.67)	41344 (7.43)
Iron ore consumption		36020	37713 (4.70)	40936 (8.54)	44974 (9.86)	48150 (7.06)	52523 (9.08)
Iron ore exports		37270	41640 (11.72)	48020 (15.32)	62570 (30.30)	78145 (24.89)	89277 (14.25)
Iron ore production		80762	86226 (6.76)	99072 (14.90)	122838 (23.99)	145942 (18.81)	154436 (5.82)
Surplus iron ore		7472	6873	10116	15294	19647	12636

Source: 1. Joint Plant committee, Kolkata.
2. Indian Bureau of Mines, Nagpur.

SOURCE: USGS: Mineral Commodity Summary 2011

Copyright © 2011-12 www.mapsofworld.com (Updated on 6th February, 2012)

Figure 2: World's iron ore deposits

1.3 TYPES OF IRON ORES

1.3.1 Hematite (Fe2o3)

Hematite is widely distributed and is the most important source of iron. When pure, it contains 70% of iron. Much of the hematite mined is high grade, with 64- 68% iron and only small quantities of impurity, mainly silica and alumina. Sulphur and phosphorus contents if any are normally very low. There are also very large deposits of low grade hematite containing only 20-40 % iron with high silica contents, some of which are now being mined. Much of the silica is removed by mineral processing and the product obtained can contains 60-69 % of iron.

1.3.2 Magnetite (Fe3o4)

Deposits of high grade magnetite occur in a number of places in the world. Pure magnetite contains 72.4% iron, whereas the high grade ore normally contains more than 60% iron with some impurities such as silica, phosphorus and apatite, as a common impurity (El Habaak, 2004). Low grade magnetite deposits are also worked in many places, and a product is obtained after mineral processing which has iron content in excess of 60%.

1.3.3 Limonite, Goethite

These are all hydrated iron oxides containing up to 60-63% iron. They can occur as primary minerals and always formed relatively near to the surface as a result of weathering of the exposed ore.

1.3.4 Siderite (Feco3)

This mineral constitutes only a small proportion of the total world iron ore reserves. When pure, it contains 48.3% iron, but it is easily decomposed by heat (calcined) to hematite with 70% iron, siderite is still a commercially important source of ore in some countries.

1.4 COAL BASICS

Coal consists of organic matter from prehistoric times that have been altered chemically during high pressures and long exposure, quite similar to the creation of oil in many ways. The accumulation of silt, muck and similar organic ingredients started in swamps and bogs millions of years ago. Tectonic shifts and movements in the Earth crust buried these areas, sometimes down to enormous depths. The high-pressure environment combined with the heat from the Earth interior transformed the organic matter by altering its chemical nature. First it was transformed into peat and the peat was then refined into coal of different types. The quality of a coal deposit is defined by the pressure and temperature together with the time. A high quality coal has been subjected to the higher pressure, temperature and longer transformation times than coal of lower quality. The quality is often related to as ―organic maturity□. Time timescales for creation of different types of coal vary much. A peat deposit can be created in as little as 9000 years, while anthracite requires millions of years to form.

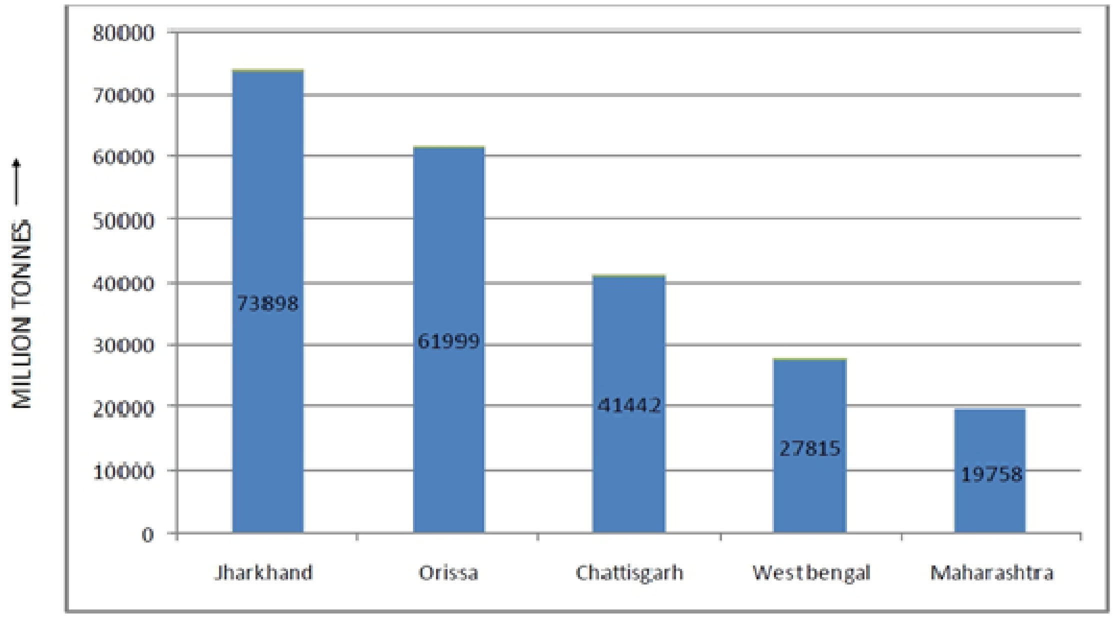


Figure 3: Coal deposits in India

1.4.1 Low-Rank Coals

The first stage in the coal maturity scale is called peat. Due to the acidic conditions the organic material is prohibited from decaying completely. Approximately 60% of the world’s swamp areas are peat. Due to very high water content and the presence of lots of non-carbon materials peat is not as energy-rich as brown coal and limited to local small-scale heating. The stage after peat is called lignite or —brown coal□, with carbon content in the range of 25-35%. The water content is high (up to 66%) and the colour can go from dark black to different shades of brown. This type of coal is mainly used for large-scale power generation. Next stage is sub-bituminous coal. The carbon content is 35-45% with reasonable energy content. It is still quite soft and brittle with quite high water content (20-30%). Used in cement manufacturing and a large array of industrial processes along with power generation.

1.4.2 High-Rank Coals

The following stage forms bituminous coal. The carbon content of bituminous coal is around 60-86%, the rest is composed of water, air, hydrogen, and sulphur. This type is divided into two sub-groups called steam coal and coking coal. Coking coal and steam coal are the two types of coal that is most frequently traded. The steam coal is used as sub-bituminous coal in power generation. It has higher energy content than brown coal and contains less ash, thus making it a better fuel for coal-fired power plants.

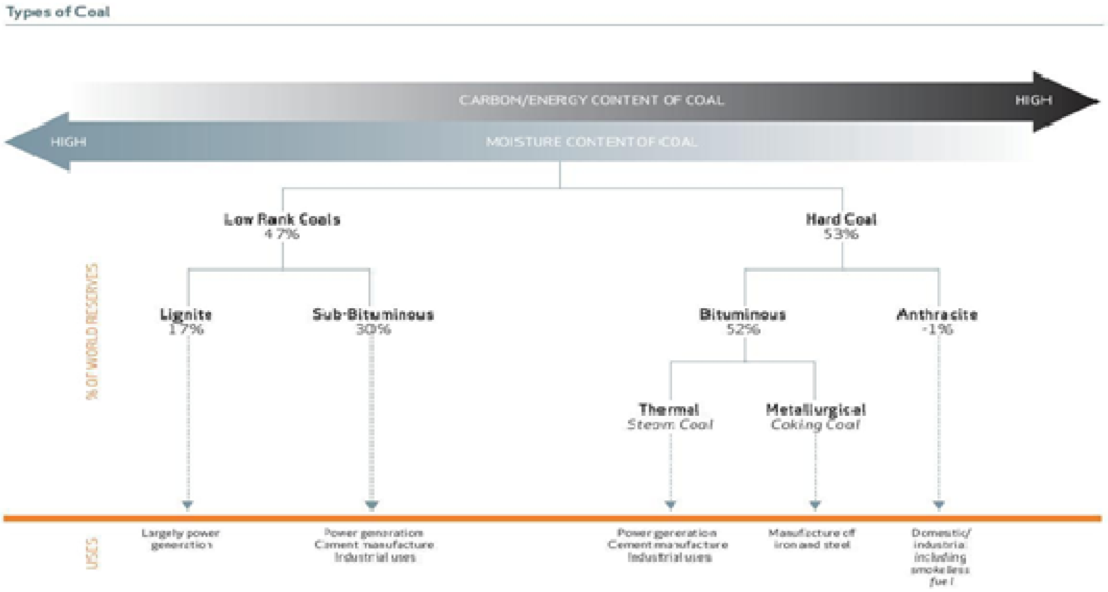


Figure 4: Types of Coals.

1.4.3 Coking Coal:

Coking coals are those varieties of coal which on heating in the absence of air (process known as Carbonisation) undergo transformation into plastic state, swell and then re-solidify to give a Cake. On quenching the cake results in a strong and porous mass called coke.

Coking coal is divided into 3 sub-categories namely,

Primary Coking Coal (Low ash, low Volatile, High Coking property)

Medium Coking Coal (low ash, medium volatile, low caking index) and

Semi/Weak Coking Coal (low ash, high volatile, very low caking index).

Characteristics of Coking coal for Blast Furnace Coke: Coking coal for production of BF Coke (which is the right type of fuel/reductant needed for a BF) is characterised by certain specific properties in terms of appropriate composition (viz low Ash (10% max), Volatile Matter (20-26%), and very low sulphur and phosphorous content, appropriate Rank of coal (1—1.3), good rheological properties, wide range of fluidity, low inert content etc.

Indian Coking Coal: Indian Coking Coal found in Gondwana belt (Bihar &West Bengal region) has very high ash (17% or more) and poor rank and other properties, which results in lower productivity and higher coke consumption in blast furnace. Assam coking coals though, are low in ash have very high sulphur which limits their use in iron making in blast furnace.

1.4.4 Non-Coking Coal (Ncc)

These are coal of poor coking properties i.e. does not soften and form cake like coking coal during carbonization in the coke oven. Such coals with relatively lower ash and higher fixed carbon are used in metallurgical applications viz. COREX technology based iron (pig iron) plants, Coal based DRI Plant etc., while those with higher ash are normally used in thermal Power Plants as steam coal.

1.5 MAJOR ROUTES OF STEEL MAKING

The primary routes of steel making can be divided into two parts:

1) BF-BOF 2) DR-EAF

Now days DR-EAF route is getting momentum over BF-BOF route and is presently contributes to around 35% of the total World's steel production.

1.5.1 Shortcomings of the BF-BOF Route

- Limited availability of coking coal reserves in the World and India in particular.
- Longer gestation period
- Huge investment cost and more emissions of pollutants.
- Costlier import of coking coal.
- Poor flexibility in production capacity

1.5.2Advantages of DR-EAF Route over BF-BOF

- Simplicity of the plant operation.
- Flexibility to operate at smaller capacities, down to 300,000 ton/year with an attractive production cost.
- Best environmental impact compared to coking plants and blast furnaces
- New plants can be realized in phases, to optimize the financial structure of the project.
- Possibility of using local energy sources, as this route can operate with natural gas, non coking coal, petrochemical wastes etc.
- Very attractive investment cost as compared to the blast furnace-BOF route.

1.6 COAL IN THE SPONGE INDUSTRY

Sponge iron is iron reduced directly in solid state using coal gas, natural gas or coal as reductants and is also known as Directly Reduced Iron (DRI). India entered the sponge iron industry only in 1980.

The industry is gaining importance due to proven utility of sponge iron in steel manufacturing processes like Electric Arc Furnaces, L.D. Converters, Open Hearth Furnaces, Blast Furnaces, Basic Oxygen furnaces, Induction Furnaces and Cupolas. The main fuel used for firing preheater cyclone and rotary kiln is coal. Therefore, coal plays an important role in the manufacturing process of cement. Based on the composition of raw feed a wide range of coal is used. In a cement plant two systems of coal firing are used, namely, a) Direct firing and b) Indirect firing.

Coal in an essential component in production of sponge iron. Coal based direct reduction technologies involve reduction of iron oxides in a rotary kiln by using noncoking coal as a reducing agent. Limestone or dolomite is used as desulphurising agent. In normal operating practice the charge is constituted of iron oxide, noncoking coal and limestone or dolomite. The charge is preheated in the preheat zone and the reduction of iron ore is effected by reducing gases derived from coal gasification. The heat for the process is provided by burning coal volatiles and excess carbon monoxide emerging from the charge. This is done by introducing controlled quantity of air in the kiln. Part of coal is introduced from the kiln discharge end to supply energy at discharge end, maintaining reducing atmosphere at discharge end to prevent reoxidation of DRI. The separation of the product is more or less similar in all the coal based processes and involves screening and magnetic separation for removal of non-magnetic ash, char and used de-sulphuriser. Thus the role of coal is to supply heat as well as to act as a reducing agent. For production of quality sponge iron the non-coking coal should be selected in such a way that it would be able to generated desired heat energy.

1.7 THERMODYNAMICS AND KINETICS OF IRON ORE REDUCTION

The reduction of iron oxide in a direct reduction system is known to occur by both solid and gaseous reductants, e.g. solid carbon, CO gas, H_2 gas, in various stages as given below.

The reaction which are involved in the reduction of iron ore is as follows,

Stages of Iron Oxide Reduction by Solid Carbon:

$3Fe_2O_3 + C \rightarrow 2\ Fe_3O_4 + CO$; $\Delta H_1 = 28.38$ Kcal. --- (1)

$Fe_3O_4 + C \rightarrow 3\ Fe + CO$; $\Delta H_2 = 49.98$ Kcal. --- (2)

$Fe + C \rightarrow Fe + CO$; $\Delta H_3 = 37.38$ Kcal --- (3)

The reduction of iron oxides initiated by solid carbon as per the above mention reaction, and the CO gas evolved again participate n the further reduction of iron oxides.

Stages of Iron Oxide Reduction by Co:

$Fe_2O_3 + CO \rightarrow Fe_3O_4 + CO_2$; $\Delta H_4 = -12.85$ Kcal --- (4)

$Fe_3O_4 + CO \rightarrow FeO + CO_2$; $\Delta H_5 = 8.76$ Kcal. ----- (5)

$FeO + CO \rightarrow Fe + CO_2$; $\Delta H_6 = -6.85$ Kcal ----- (6)

$C + CO_2 \rightarrow 2CO$; $\Delta H_7 = 41.22$ K cal ---- (7)

The CO gas produced by, carbon gasification reaction, reduction of oxides by solid carbon , and by oxidation of carbon, reduces the iron oxides to their lower oxidation states, and the CO_2 gas produced again react with solid carbon to form carbon monoxide gas and that carbon monoxide gas again participate in the reduction of iron oxides.

Stages of Iron Oxide Reduction By H_2:

$Fe_2O_3 + H_2 \rightarrow 2Fe_3O_4 + H_2O$; $\Delta H_8 = -3.08$ Kcal ----- (8)

$Fe_3O_4 + H_2 \rightarrow 3\ FeO + H_2O$; $\Delta H_9 = 18.52$ Kcal ----- (9)

$FeO + H_2 \rightarrow Fe + H_2O$; $\Delta H_{10} = 59.20$ Kcal --- (10)

$C + H_2O \rightarrow CO + H_2$; $\Delta H_{11} = 21.71$ Kcal --- (11)

The H_2 gas reduces the iron oxide to their lower oxidation state and produce water vapour as per the reaction (8), (9), (10). The water vapour thus produced react with solid carbon to form H_2 and CO gas as per reaction (11) and the H_2 and CO gas again participate in the reduction of iron oxides.

Oxidation of Solid Carbon

$C + \frac{1}{2} O_2 \rightarrow CO$; $\Delta H_{13} = -94.05$ Kcal ------ (12)

$C + O_2 \rightarrow CO_2$; $\Delta H_{14} = 25.42$ Kcal ------- (13)

The solid carbon present in the charge material is oxidized by the little air present in the kiln to produce carbon monoxide and carbon dioxide .The carbon monoxide formed, reduces the iron oxides, and the carbon dioxide react with solid carbon to form carbon monoxide through carbon gasification reaction.

1.8 THE POSSIBLE WAYS OF IRON ORE REDUCTION:

Industrially iron is produced from iron ores, principally hematite (Fe_2O_3), magnetite (Fe_3O_4) by a carbothermic reaction that is reduction with carbon, in a blast furnace at temperature about 800-1600°C. In blast furnace, iron ore, carbon in the form of coke, and a flux such as limestone are fed into the top of the furnace, while blast of heated air is forced into the furnace at the bottom.

In the blast furnace, the coke reacts with oxygen in the air blast to produce CO.

$C+O_2—CO_2$

$C+CO_2—2CO$

Adding these equations we get the final equation

$2\ C+O_2 \rightarrow 2\ CO$

CO reduces the iron ore to molten iron becoming CO_2 in the process.

Other than this classical route that is blast furnace technology of iron production, the iron also can be produced from its ore by the direct reduction of iron ore by a reducing agent which is coal based or may be a gaseous reducing agent, which is called direct reduced iron (DRI) or SPONGE IRON.

1.9 VARIOUS PROCESSES WHICH PRODUCE DRI

a) Coal based processes:

1) Rotary kiln processes (SL/RN, Krupp-CODIR, DRC, and ACCAR/OSIL)

2) Retort processes (Kinglor Metor)

3) Rotary hearth processes (Inmetco, FASTMET)

b) Gas based processes:

1) Shaft processes (MIDREX, HYL process, Purofer)

2) Fluidized processes (FIOR/FINMET, Iron carbide, Circored)

1.9.1 Coal Based Technologies:

Iron ore (Hematite) and non-coking coal are the prime raw materials for the production of sponge iron. The feed material consisting of pre-determined quantities of iron ore, coal & lime stone is fed continuously to the rotary kiln at the feed end. Due to its inclination and the continuous rotation of the kiln, the charge moves from feed end to discharge end. The temperatures required by the process are maintained and controlled by predetermined quantity of combustion air injected in to the kiln through air tubes along the length of the kiln. The discharge end of the kiln requires high temperatures of 950^0C to 1050^0C to be maintained. For this purpose additional fuels such as oil, gas or fine grained coal along with air are blown through the central burner/ coal throwing pipe at the discharge end of the kiln. The flow of the gases is counter current to the material flow. The kiln is usually operated with slight positive pressure to prevent intrusion of the unregulated air. During the passage of the material through the kiln, iron ore lumps / pellets and coal get dried and preheated to the reduction temperature in the initial stages and progressively iron ore is reduced by carbon monoxide generated from the coal under control combustion conditions. When the charge reaches the discharge end of the kiln the reduction of the iron ore will almost be completed.

The metallised product and excess, un burnt coal normally called char is discharged from the cooler. In the cooler the product is cooled to around 100□C by indirect water spraying before discharging to the open air. The cooler discharge material is taken to product separation system where it is screened and magnetically separated into sponge iron (magnetic) and char (non-magnetic). The hot gases from the kiln pass through dust settling chamber, where heavier particles of dust settles down located below the ABC (After Burner Chamber), where the un burnt carbon monoxide and carbon particles if any are burnt. The gases with finer fraction of dust (P.M. - 30 gm/Nm3) pass directly through waste gases cleaning system or through waste gas heat recovery boiler and cleaning system as the case may be reduction of the iron ore will almost be done.

AIM AND OBJECTIVES OF THE PROJECT

- Characterization of the chemical and physical properties of selected iron ores.
- Characterization of the properties of selected non-coking coals.
- Study of the effect of binder addition on the crushing strength, porosity and reduction characteristics of fired hematite iron ore pellets.
- Study of the effect of firing temperature on the degree of reduction of fired hematite iron ore pellets.
- Study of the effect of reduction temperature and time on the degree of reduction of fired hematite iron ore pellets.
- Study of effect of +100 mesh size iron ore fine in the matrix of -100 mesh size iron ore fine on the crushing strength, porosity and reduction characteristics of fired hematite iron ore pellets.
- Study of effect of reduction time on the extent of swelling of iron ore pellets.
- Study of effect of reduction temperature on the extent of swelling of iron ore pellets.
- Study of Correlation between Degree of reduction and Percentage swelling of iron ore pellets.
- XRD analysis of reduced iron ore pellets.
- Micro structural study of reduced iron ore pellets.

CHAPTER-2

LITERATURE SURVEY

Dutta k Dipak et al4. performed a study on Cold bonded pelletization processes developed for utilization of iron ore fines and slimes require about 10% or more cementitious binders. Reduction of the cost of the pellet and its gangue content require reduction of the amount of binder. This communication reports the results of an investigation on reduction of binder requirement in cold bonded pelletization of iron ore fines by using cement clinker alone or mixed with silica of different characteristics. Pellets with crushing strength of 100–200 kgs pellet could be obtained even using about 4–6% binders consisting of Portland cement clinker cement of appropriate chemical characteristics and fineness either alone or mixed with silica fines. The binder requirement may be curtailed by about 4% by increasing its surface area. The physico-metallurgical properties of the cured pellets indicate potentiality for use as burden material in low/moderate shaft furnaces.

An attempt has been made by B.K Pandey et. Al5. to study the effect of reducing agents (coke, Non-coking coal, Char, Charcoal, etc.) on the reduction behavior of double-layered pellets consisting of a core of iron ore and reducing agent mixture within a shell of iron ore. The reduction tests were conducted under isothermal condition in the temperature range 1000–1200°C. The variables (parameters) studied were the reduction temperature, carbon/iron oxide ratio of the core, and reduction time. The experiments were statistically designed such that the effect of each variable and interactional effect of each variable can be quantitatively assessed and compared. The results show highest degree of reduction with non-coking coal followed by charcoal, char, coke-fines. Among these three parameters, reduction time has the strongest effect when charcoal and non-coking coals are used as reducing agents, whereas in the case of coke and char, reduction temperature has the strongest effect. C: Fe2O3 ratio of core has the least effect in all four types of carbonaceous core double-layered pellets.

T. C. Eisele and S. K. Kawatra6 have found that the majority of iron ores must be grounded to a fine particle size to allow the iron oxides they contain to be concentrated, and the concentrate must then be agglomerated back into large enough particles that they can be processed in blast furnaces. The most common agglomeration technique is pelletization, which requires the use of binders to hold the iron oxide grains together so that the agglomerates can be sintered into high-strength pellets. Although bentonite clay is the most commonly used binder, there are many other possibilities that could be competitive in a number of situations. This article reviews the numerous types of binders (both organic and inorganic) that have been considered for iron ore pelletization, including discussion of the binding mechanisms, advantages and limitations of each type, and presentation of actual pelletization results, so that the performance of the various types of binders can be compared and evaluated.

The Kinetics and Reduction characteristics of Hematite-noncoking coal mixed pellets under nitrogen gas atmosphere have investigated by Dey et al [25]. Hematite-noncoking coal mixed pellets were reduced isothermally at 900, 950, 1000, 1025 and 1050°C under constant flow rate of nitrogen gas. The surface characteristic of the reduced pellets for different time-temperature schedule were examined by a Scanning Electron Microscope (SEM). Analysis of the data and examination of the SEM microphotographs revealed that the mechanism associated with the reduction changed with increasing temperature and fractional reaction. Activation energy values of the reduction at different levels of fractional reaction were calculated with the help of an Integration Method. The effect of Carbon/Hematite molar ratio on the extent of the reduction was also investigated. It was found that at temperatures 900 to 1000°C fractional reaction increased with increasing carbon content up to a critical value of the ratio and then decreased. At temperatures above 1000°C fractional reaction increased linearly with increasing carbon content.

T. Sharma studied the effect of Firing Condition and Ingredients on the Swelling Behaviour of iron Ore Pellets [29]. He found that the swelling of iron ore pellet is controlled by the firing temperature, firing time and additives/ingredients present in the pellet. The growth of iron whisker is controlled by these ingredients. The presence of free lime promotes the swelling index of the pellet.

Shoji Hayashi et.al () have investigated the abnormal Swelling during Reduction of Binder Bonded Iron Ore Pellets with CO–CO2 Gas Mixtures. He found that Abnormal swelling during reduction of iron ore pellets with CO–CO2 gas mixtures was investigated in the temperature range of 700 to 1000°C. Influence of addition of gaseous sulphur COS at low partial pressures to inlet gas mixtures, CO2/ (CO-CO2) in inlet gas and temperature as well as kinds of binders such as Portland cement, bentonite and lime on swelling were examined. When the ratio PCOS/PCO in inlet reducing gas was lower in 10_2 than the equilibrium ratio between iron and iron sulphide, abnormal swelling of pellets was observed for non-cement bonded pellets, in particular, giving maximum around 900°C. Cement bonded pellets provided moderate abnormal swelling independently of adding gaseous sulphur to inlet gas mixtures. Their swelling seemed to be caused by gasification of sulphur species present in cement. These results supported our previous findings that the existence of sulphur is essential to the abnormal swelling and the swelling is mostly accompanied with the formation of fibrous irons. The results are discussed along with previous researches and gas chromatography of sulphur species in exit gas to evaluate the sulphur activity in gas near the reaction front inside cement bonded pellets.

Shrinivasan et.al [8], Otasuka et al [22] and Abraham et. al [23] have studied the reduction behaviour of iron ore oxide-carbon mixture, where higher activation energy value during initial stage and gradual decrease with the progress of reaction were observed. The reaction has been proposed to be controlled by carbon gasification reaction, which is catalysed by the presence of metallic iron. But in case of study made by Mukherjee et al [8], the catalytic effect was because of a particular geometry of the sample. Due to this reason; the values of activation energies were 130.7, 152.1, 144.7 and 146.3 KJ/mole respectively. Mukherjee et al [8] also reported the increase in reaction rate on addition of 5% Na_2CO_3 which is well known catalyst for carbon gasification reaction.

B.K. Pandey et.al [2] the authors made an attempt to study the effect of reducing agents (coke, Non-coking coal, Char, Charcoal, etc.) on the reduction behaviour of double-layered pellets consisting of a core of iron ore and reducing agent mixture within a shell of iron ore. The reduction tests were conducted under isothermal condition in the temperature range 1000–1200°C. The variables (parameters) studied were the reduction temperature, carbon /iron oxide ratio of the core, and reduction time. The results show highest degree of reduction with non-coking coal followed by charcoal, char, coke-fines. Among these three parameters, reduction time has the strongest effect when charcoal and non-coking coal is used as reducing agents, whereas in the case of coke and char, reduction temperature has the strongest effect.

S.P.E. Forsmo et.al investigated the process of sintering mechanism in magnetite iron ore pellets. From their experiments they concluded that Oxidation mechanisms and thermal volume changes in magnetite iron ore pellets as a function of raw material fineness and pellet porosity . When a pellet starts to oxidize, a shell of hematite is formed around the pellet while the core still is magnetite. Dilatation curves were measured under non-oxidizing and oxidizing atmospheres to separately describe thermal volume changes in these two phases. Dilatation measurements showed contraction during oxidation between 3300 and 900 °C by 0.52%. The extent of contraction was not influenced by raw material fineness or the original porosity in the pellets. Simultaneously with the contraction in the hematite shell, linear expansion in the magnetite core took place. Sintering started earlier in the magnetite core (950°C) compared to the hematite shell (1100 °C). The difference in sintering rates increased with increasing fineness in the magnetite concentrate. A finer grind in the raw material would, therefore, promote the formation of duplex structures.

M Kumar et al1. Have performed a comprehensive study over the demand of sponge iron and pre-reduced pellets for the manufacture of different varieties of steel. It is found that demand is increasing day by day and new solid reductants based sponge iron plans are being commissioned. In the existing blast furnace an increase in production by at least 25 to 35% can be achieved by using pre reduced iron ore. Pre-reduced iron ore pellets have been established as a good substitute for steel scrap in an electric arc furnace which enhances the productivity of the arc furnace. A lot of investigations have been carried out on direct reduction process of iron oxides by carbonaceous materials, but little work has been done on the characterization of properties and reduction behavior of iron ore of. In the present project work, an attempt has been made to study the reduction behaviour and kinetics of iron ore fired pellets. The effect of different reduction parameters such as temperature (850-1000ºC), time (15-120 minutes.), mixing of particles of different sizes at different ratios for pellet preparation etc. on the reduction behaviour of iron ore pellets.

\

CHAPTER-3

EXPERIMENTAL

3.1 Evaluation of Physical Properties of Fired Iron Ore pellets

The fired iron ore pellets produced were processed for the determination of their porosity and crushing strength values.

3.1.1 Determination of Cold Crushing Strength

The crushing strength of fired pellets and some of reduced pellets (size 15mm) have been determined by employing a cold uniaxial hydraulic press (capacity 20 tons). The reported values of crushing strength were calculated by using the following formula.

$\sigma c = W/A$

Where, σc is the crushing strength in kg.cm-2;

W is the maximum load at fracture in kg;

And A is the area in cm2

3.2 DETERMINATION OF APPARENT POROSITY

The apparent porosity values of iron ore lumps and pellets were determined by using kerosene oil as a medium in accordance with the following formula

Apparent porosity = W – D/ W- (S-s)

Where, 'D' is the weight of dried piece;

'W' is the weight of oil saturated piece;

'S' is the weight of the piece + thread while immerse in oil;

And's' is the weight of thread only while immerse in oil.

3.3 PREPARATION OF IRON ORE PELLET

3.3.1 Preparation of Iron Ore Pellet

Iron ore fines of two types of ores were generated by means of crushing in a mortar and pestle. The generated fines are screened in 100, 16&325mesh sieves. Minimum 1000 gm of -100 mesh fines and 400gm of – (16+25) mesh fines were collected. The -100 mesh fines are further subjected to sieve analysis. The results of sieve analysis are shown in table 4.2.

Binder: The sugarcane juice was heated at about 150°C for 4 hours inside oven to concentrate it to get better binding properties.

Pellet Preparation: In 1st set of pellet preparation, pellets of 15-17 mm size were made by hand rolling of moistened -100 mesh size iron ore fines only. In the second set of pellet preparation, pellets of 15-17 mm mesh size were made by hand rolling of a mixture of iron ore fines of -100 mesh size and -16+25 mesh size (moistened) in the ratios of 4:1 and 9:1. Pellets were made from iron ores obtained from both the mines. Pellets from both the mines were made without the addition of binder (concentrated sugarcane juice) and with the addition of binder (2, 4 and 6 wt. % of iron ore). . The pellets were kept inside the oven at 110°C for drying and removal of moisture for 2 h. After 2 h the pellets were taken out and kept in separate plastic pouches, and each pouch was marked properly regarding accordingly of their pellet preparation history.

Firing of Pellets:

The iron ore pellets were fired by heating them from room temperature to the predetermined firing temperatures (1000, 1100 and 1300°C) at a rate of about 7°C min-1. The soak time at these firing temperatures was 1 hour. After soaking for 1 hour, the furnace was switched off and the pellets were allowed to cool in the furnace themselves. The pellets were taken out from the furnace and kept separately in different plastic pouches marked with pellet preparation conditions.

3.4 PROCEDURE FOR REDUCTION STUDIES

The reduction experiments were carried out by heating the samples in a muffle furnace from room temperature to the required reduction temperatures of 850, 900, 950, 10000C at a rate of about 10°C per minute and were soaked at these temperatures for varying time periods of 0, 15, 30, 60, 75&90 minutes for the reduction temperatures of 850&9000C and 0, 5, 10, 15, &25 for the reduction temperatures of 950 &1000°C. weighted amount of air dried pellet (size 15mm approximately) was placed on a packed bed of non-coking coal ,crushed into a size of 212 microns, in a stain less steel container (size: 60mm height × 30 mm inside diameter) with a mouth tightly closed by an air tight cover having an out let for exit gas. The position of the iron ore pellet in the packed bed of solid reductant was approximately at the Centre. This ensures complete surrounding of pellet by solid reductant. After attaining the reduction temperature each container was taken out at an interval of 0, 15, 30, 60, 75&90 minutes for 850&900°C temperature and 0, 5, 10, 15, 30, 45 & 60 for 950 &1000°C temperature. Then the containers were cooled to the room temperature in air and the weight losses of the pellets were recorded. The degrees of reduction of pellets were calculated by using the following formula. The degree of reduction was calculated by using the following formula:

Degree of reduction = (weight loss in pellet/total oxygen content in the pellet) ×100.

3.5 DETERMINATION OF PERCENTAGE SWELLING:

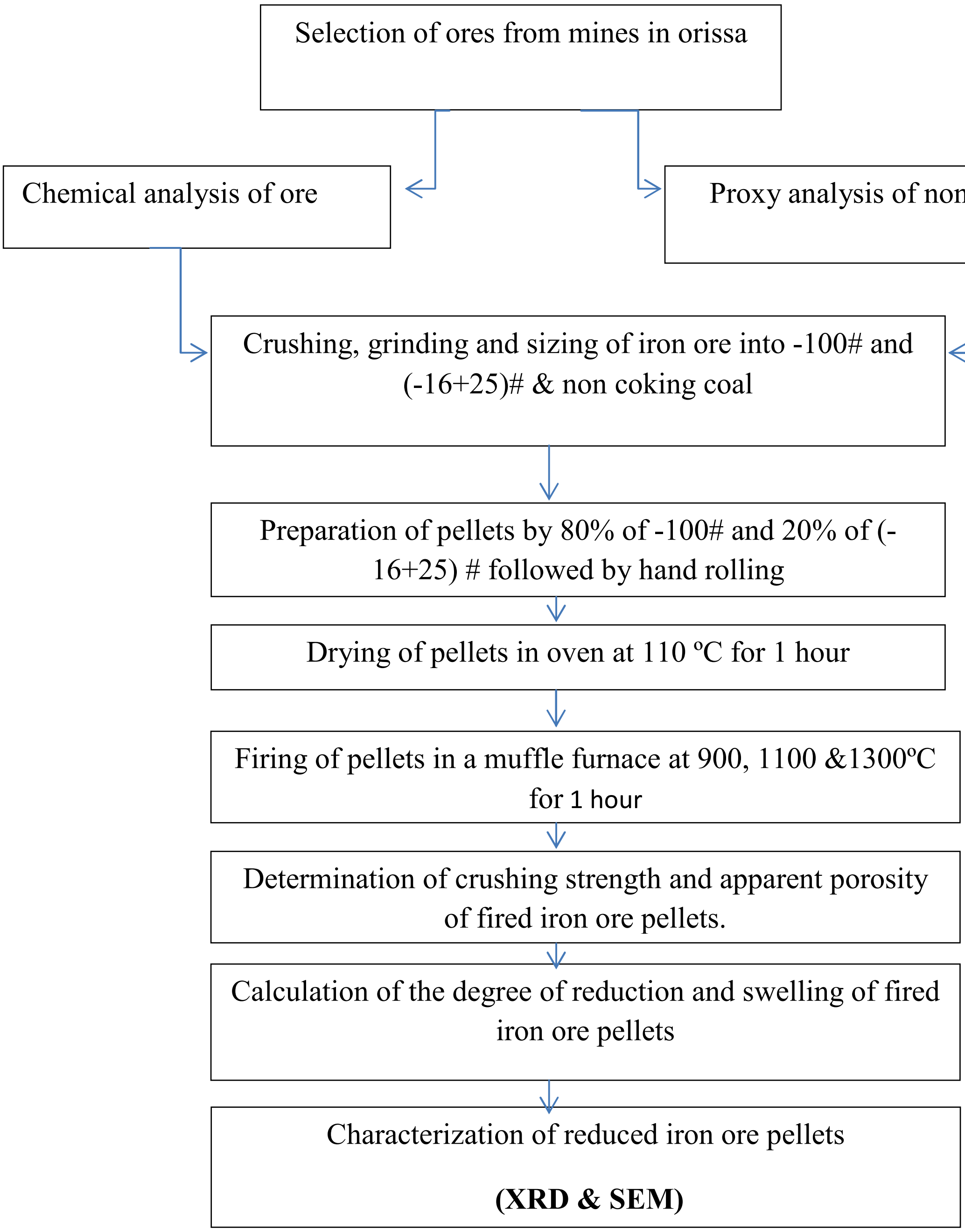
Swelling is a volumetric expansion of the agglomerate during carbothermic reduction of iron oxide. Changes in crystal structure take place during the stepwise reduction of hematite through magnetite and wustite to metallic iron. These changes are accompanied with change in volume. Percentage swelling can be calculated as:

Where, Vf = final volume of the reduced pellet;

Vi= initial volume of the fired pellet

Swelling up to 20% has generally been accepted as “normal‘‘ whereas the high values are called “abnormal swelling‘‘ or even “catastrophic swelling‘ ‘The main causes of abnormal swelling proposed in the literature are as follows[31]: (i) the disruptive stresses set up during the transformation Fe2O3-Fe3O4 (Hayes et al. 1981); (ii) formation of iron whiskers during FeO-Fe reduction step (Nascimento et al. 1997); (iii) iron-bearing material nature (iron ore or dusts containing iron oxide) and the presence of components such as Na2O, K2O, CaO, etc. (Bleifuss 1970; LU 1973); (iv) temperature of reduction and reducing gas composition (Moon and Walker 1975; Nicolle et al. 1979); and (v) disintegration of iron grains during carbon monoxide.

3.6 PROCESS FLOW CHART:



CHAPTER-4

RESULTS

&

DISCUSSIONS

4. RESULTS AND DISCUSSION

The results obtained during the course of this project work have been summarized in table 4.1 – 4.11 and also shown graphically in figures 4.1-4.37.

4.1 Characteristics of Selected Iron Ore and Coal

The chemical compositions and loss on ignition values of the sakaruddin and B.P.J were determined in Rourkela Steel Plant by X-Ray fluorescence have been listed in table 4.1.As outlined in table 4.1 ,the selected iron ore rich in Fe content(>60%). Al_2O_3+ SiO_2 contents are less than 5% so, they are suitable for DRI production .As evident from table 4.2,the selected coal have caking index two Which is suitable for to be used in sponge iron making. The proximate analysis result reveals the fixed carbon content of coal is 40.11, ash content volatile matter is 27.26 and ash content is 32.63.The ash fusion temperature the selected coal is high, which is quite good agreement with the data for sponge iron making.

4.2 Effects of Firing Temperature on Physical Properties of Fired Iron Ore Pellets

In the present project work, pellets were fired at various temperatures (1000, 1100 and 1300°C respectively). As shown in fig 4.1-4.2 the Crushing Strength of fired pellets increased with increase in firing temperature. This appears to be due to increase in the extent of slag bond in the pellets [4]. The effect of firing temperature on the crushing Strength is more pronounced at firing temperature of 1300°C. Tab 4.4 also clearly reveals that the porosity of the fired pellets decrease with increase in firing temperature. The decrease was found to be more pronounced at firing temperature of 1300°C. This appears to be due to slag formation and filling of the pores at a firing temperature of 1300°C.

4.3Effects of Binder Content on the Crushing Strength and Porosity of the Pellets.

In the present project work, the binder used is concentrated sugar cane juice the Crushing Strength of fired pellets decreases with increase in binder content. Maximum Crushing Strength was found for 2wt% binder content. Similarly porosity increase with increases in binder content. This is quite clear from Tab 4.4

4.4 Effects of Firing Temperature on the Extent of Reduction and Swelling of Iron ore pellets.

As shown in fig 4.3-4.5, a decrease in degree of reduction was observed with increase in firing temperature. This appears to be due to lower porosity in the pellets fired at higher temperature.

4.5 Effect of Reduction Temperature on the Degree of Reduction and Extent of Swelling of Fired Iron Ore Pellets.

As shown in fig 4.6 - 4.8, that degree of reduction increases with increase of reduction temperature. An increase in the degree of reduction with reduction temperature appears to be more and more participation of gaseous reducing agents (CO and H_2) released from the devolatilization of coal and C + O2 →2CO reaction. The high rates of diffusion of gases through the metallic layer also contribute to this.

As shown in tab 4.6-4.7 the extent of swelling first increase a little bit with increase of reduction temperature after that it decreases with increase in reduction temperature. The initial increase may be due to high temperature, high degree of reduction and high rate of diffusion of gases. The decrease in the swelling after that with increase in reduction temperature is more likely to be due to sintering of iron whiskers at higher temperature.

4.6 Effect of Reduction Time on Degree of Reduction and Extent of Swelling of Fired Iron Ore Pellets.

As shown in fig 4.3 - 4.5, the degree of reduction increases with increase of time at a particular reduction temperature. This increase in degree is due to the exposure of pellets with the reducing agents (C, CO, and H2) for a longer period of time .The higher reduction rate in initial conditions may be attributed to the combined effect of less resistance offered to the flow of reducing glass into the pellet and significance contribution of volatile matter release initially.

As shown in fig 4.6-4.8 the extent of swelling increases with increase in reduction time at a particular reduction temperature and particular firing temperature. This is believed due to fibrous growth of iron whiskers in the pellet matrix without any restriction in the growth, however the pellets fired at higher temperature showed a decrease in the extent of swelling with increase in reduction time. This appears due to decrease in porosity due to better densification which restricts the fibrous growth of whiskers and prevents volume expansion.

4.7 Correlation between Degree of Reduction and Percentage Swelling

The variation of swelling (%) Vs. Degree of Reduction (%) has been shown in table (4.6-4.7). From the tables, it can be seen that abnormal swelling (28-30%) was observed at around 90-95% reduction (FeO→Fe) at temperature 850°C and 900°C. It is expected to be due to the growth of iron whiskers as shown in SEM figure 4.6 at FeO→Fe reduction step at 850°C and 900°C. However Shrinkage in the reduced iron ore pellets was observed at 950°C and 1000°C. This is expected to be due to the sintering of iron at high temperatures as shown in fig.4.6.

4.8 XRD Analysis of Reduced Iron Ore Pellets.

The XRD patterns of sakaruddin iron ore pellets reduced at temperatures of 850, 900,900, 950 and 1000°C for a time period of 0, 15, 90, 25 and 0 minutes respectively by Basundhara non-coking coal, have shown in figure 4.2 and the major & minor phases at various temperatures have shown in table 4.3 It is quite clear from the fig.4.2 that only one peak of FeO present in the XRD patterns of reduced iron ore pellet, soaked for 90 minute revealing almost complete reduction. For other reduction conditions as mentioned above there is more than one peaks of FeO. It is expected to be due to resistance to diffusion of CO gases to the interior of pellet.

4.9 Scanning Electron Micrographic Study of the Reduced Pellets.

As shown in fig 4.4- 4.3 cracks are developed in the iron ore pellets due to swelling, the cracks are more pronounced at 900°C as compared to 850°C. Cracks at 950°C and 1000°C are finer cracks because of densification due to reduction at high temperatures.

As shown in fig 4.6 - 4.5 densification of the iron ore particles has occurred. Densification is much more in case of reduction at 1000°C as compared to other lower reduction temperatures.

As shown in fig 4.6 the excessive swelling of the iron ore pellet is due to fibrous growth of iron whiskers in the pellet matrix [3].

TABLES

Table 4.1

Chemical Composition and Loss on Ignition of Iron ore

Iron Ore Source	Chemical Composition (weight percent on dry basis)						
	Fe (Total)	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	MnO	LIO*
Sakaruddin Mine	65.50	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

LIO*=LOSS ON IGNITION

Table 4.2

Proximate Analysis, Reactivity, Caking Indices, Gross Calorific Value and Ash Fusion Temperature of Non-coking Coal

Non-coking Coal	Volatile Matter (%)	Ash (%)	Fixed Carbon (%)	Sulfer content (%)	Caking - Index	Ash Fusion Temperature (^{0}C)			
						IDT	**ST**	**HT**	**FT**
Basundhara Mine	27.26	32.63	40.11	0.48	2.0	1253	1428	1524	1600

Table 4.3

XRD Analysis of Reduced Sakaruddin Iron Ore Pellets

Temperature (0C)	Time (minutes)	Major Phase	Minor Phase
850	**0**	**Fe**	**FeO**
900	**15**	**Fe**	**FeO**
900	**90**	**Fe**	**FeO**
950	**25**	**Fe**	**FeO**
1000	**0**	**Fe**	**FeO**

Table 4.4

Results of Physical Properties of Sakaruddin Fired 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	900	01	01	06	55	24.5
		1100	01		27	230	21.7
		1300	01		4000	910	8.39
	4	1100	01	02	400	265	21.58
	6	1100	01	04	222	120	25.4
Portland slag cement	2	1100	01	01	27		
	4	1100	01	01	07		
	6	1100	01	01	04		
Portland ordinary cement	2	1100	01	01	02		
	4	1100	01	01	04		
	6	1100	01	01	05		

Table 4.5

Results of Physical Properties of BPJ Fired 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	900	01	02	27	80	27.45
		1100	01	01	46	110	38.59
		1300	01	01	77	240	38.59

Table 4.6

Results of Degree of Reduction and Swelling Values of Fired Sakaruddin Haematite Iron ore pellets Reduced in Basundhara non-coking coal.

Binder	Binder (%)	Pellet composition: –100# (80%), –16+25# (20%)					
		Firing Conditions		Reduction Conditions		Degree of Reduction (%)	Swelling (%)
		Firing Temp(°C)	Firing Time(hr.)	Reduction Temp(°C)	Reduction Time(Min)		
Concentrated Sugarcane juice	2	900	1	850	15	52.51	5.16
					30	72.20	11.9
					60	82.10	6.40
					75	84.12	3.97
					90	90.85	4.25
				900	15	64.10	4.40
					30	73.50	5.20
					60	77.08	4.16
					75	85.82	2.12
					90	90.12	3.69
				950	15	70.50	6.32
					30	72.50	7.39
					60	79.40	2.92
				1000	15	71.60	6.48
					30	74.30	6.61
					60	97.08	3.30
		1100		850	15	47.3	15.3
					30	49.3	18.8
					45	60.3	22.2
					60	62.3	25.1
					75	67.8	28.8
					90	71.1	24.8
				900	15	53.8	15.7
					30	57.5	4.9
					45	64.2	4.8
					60	72.4	14.1
					75	76.2	16.8
					90	82.2	20.6
				950	10	48.4	2.91

					20	56-4	6.70
					30	72.9	8.94
				1000	10	68.9	3.2
					20	75.1	7.8
					30	97.5	11.3
Concentrated Sugarcane juice	2	1300	1	850	15	45.5	27.2
					30	56.4	25.5
					45	75.7	25.8
					60	49.7	26.6
					75	85.2	28.8
					90	90.1	27.6
				900	10	26.8	27.2
					15	65.8	25.5
					30	66.1	25.8
					60	60	26.6
					90	70.3	28.8
					----	----	----
				950	5	52.1	7.39
					10	58.6	26.3
					15	60.6	8.34
					30	72.9	28.84
					60	75.3	24.39
					90	86.1	---
				1000	5	93.10	10.2
					10	86.70	16.4
					15	92.68	21.2
					30	96.5	27.35
					60	92.38	37.89

Table 4.7

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	10	40.13	5.14
				15	54.54	12.04
				20	64.24	13.88
			Indonesian	15	40.17	29.16
				20	40.66	3.02
			South African	15	30.62	30.0
				20	36.44	28.6
			Australian	15	39.80	15.76
				20	52.63	22.30
		1000	Indian	10	79.32	13.12
				15	90.14	20.46
			Indonesian	10	55.60	12.78
				15	44.31	15.62
			South African	10	29.10	19.07
				15	42.40	11.22
			Australian	10	23.80	14.09
				15	36.12	14.35

\

Table 4.8

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

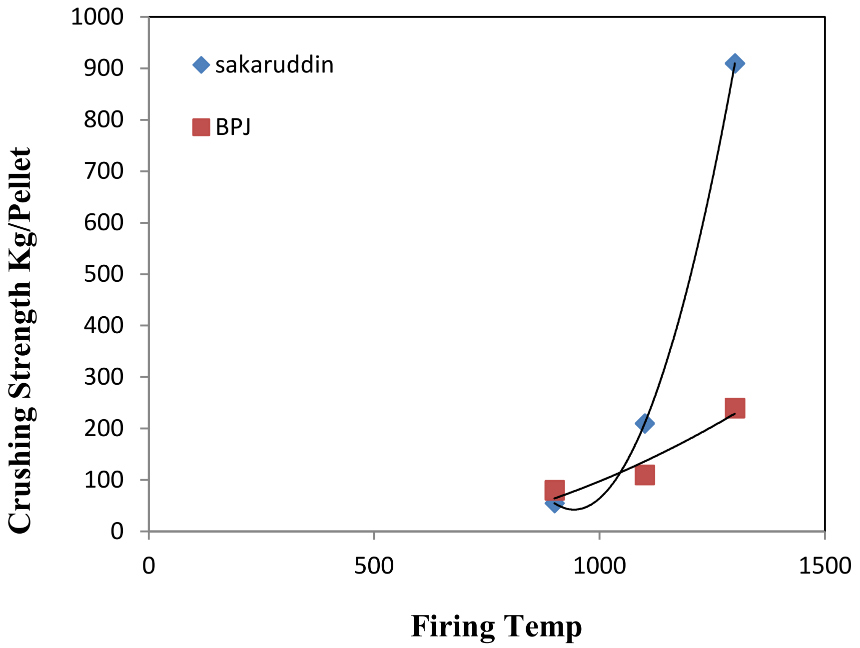


Figure 4.1: Effect of firing temperature on the crushing strength of fired BPJ and Sakaruddin haematite iron ore pellets [2% binder, {-100#(80%), -16+25(20%)}].

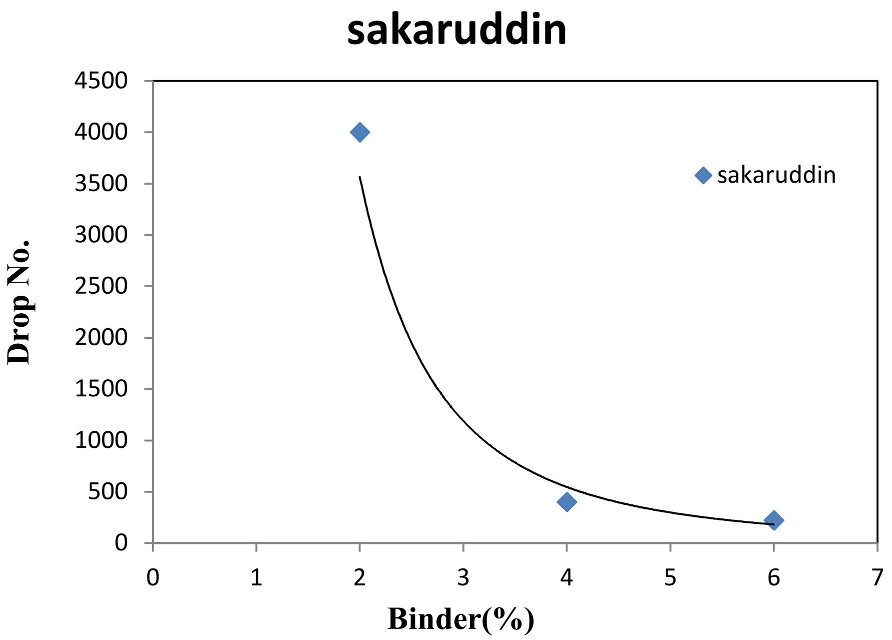


Figure 4.2: Effect of binder content on the Drop No. of fired Sakaruddin haematite iron ore pellets [2% binder, {-100#(80%), -16+25(20%)}].

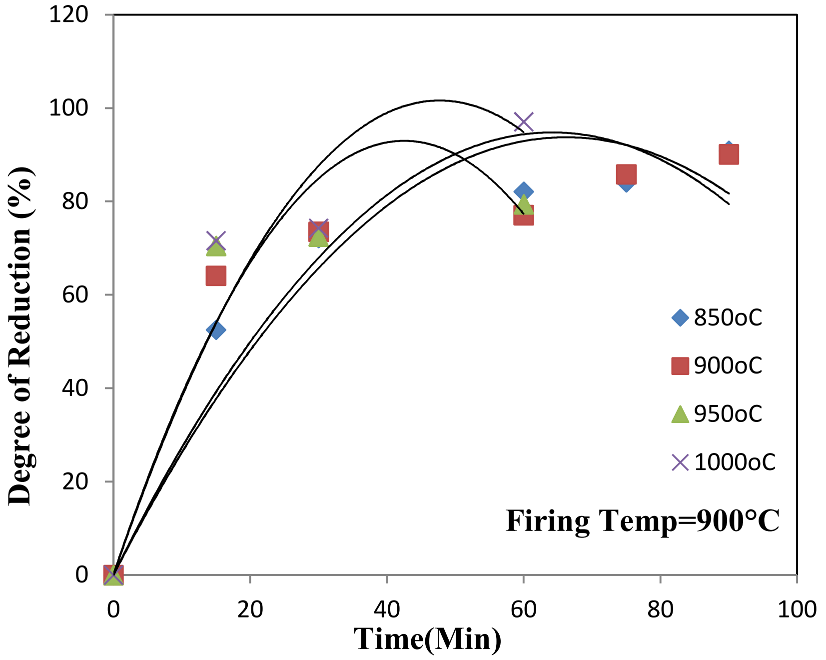


Figure 4.3: Effects of Time and Temperature on Degree of Reduction of Degree of Reduction of Sakaruddin iron ore pellets [2% binder, firing temperature-900°C,{-100#(80%), -16+25(20%) }] ,reduced in Basundhara non- coking coal .

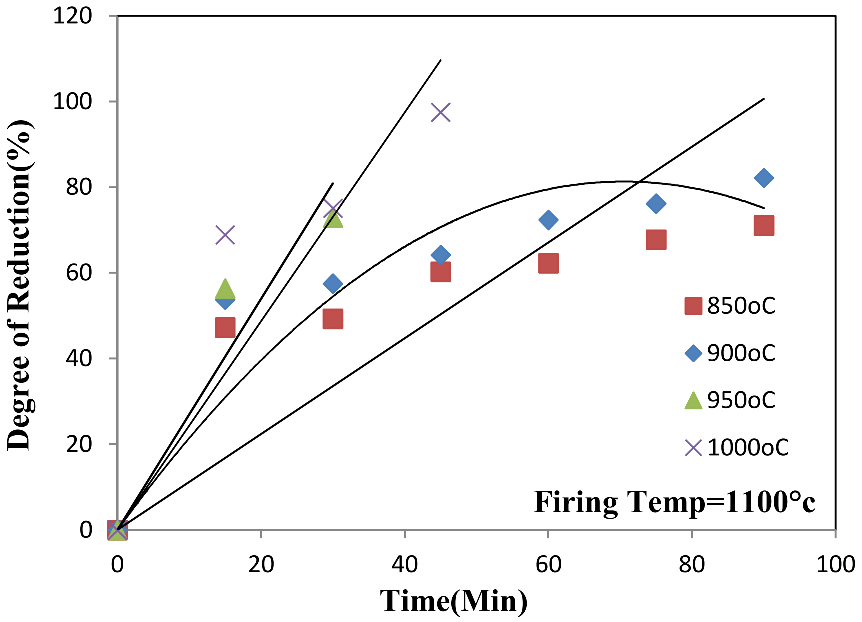


Figure 4.4: Effects of Time and Temperature on Degree of Reduction of Degree of Reduction of Sakaruddin iron ore pellets [2% binder, firing temperature-1100°C,{-100#(80%), -16+25(20%) }] ,reduced in Basundhara non- coking coal .

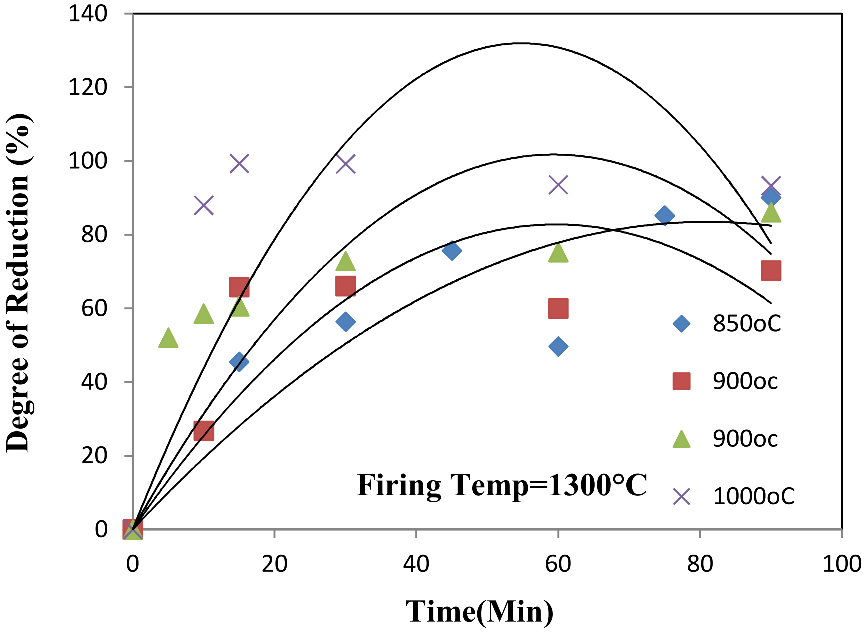


Figure 4.5: Effects of Time and Temperature on Degree of Reduction of Degree of Reduction of Sakaruddin iron ore pellets [2% binder, firing temperature-1300°C,{-100#(80%), -16+25(20%) }] ,reduced in Basundhara non- coking coal .

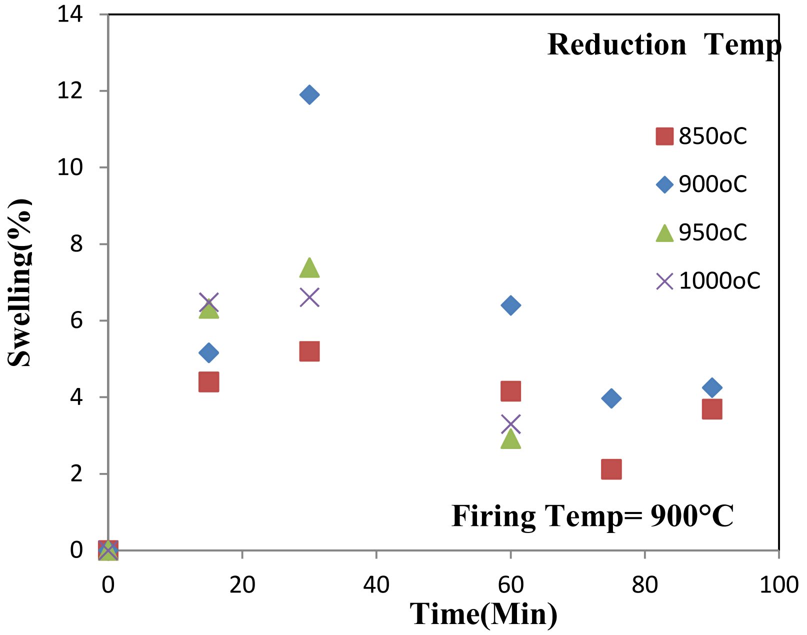


Figure 4.6: Effects of Time and Temperature on Extent of Swelling of sakaruddin iron ore pellets [2% binder, firing temperature-900°C -100#(80%)+{(-16+25)#(20%)}]] ,reduced in Basundhara non-coking coal.

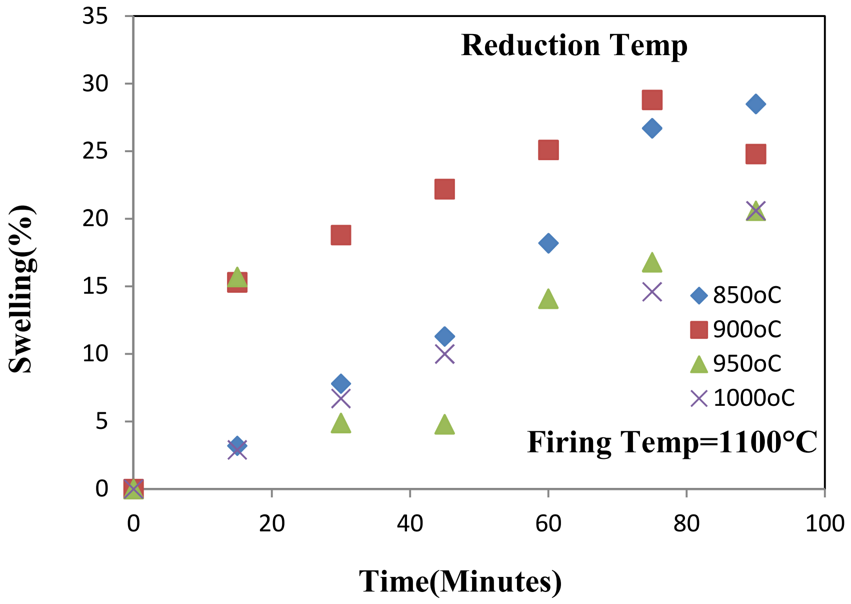


Figure 4.7: Effects of Time and Temperature on Extent of Swelling of sakaruddin iron ore pellets [2% binder, firing temperature-1100°C -100#(80%)+{(-16+25)#(20%)}]] ,reduced in Basundhara non-coking coal.

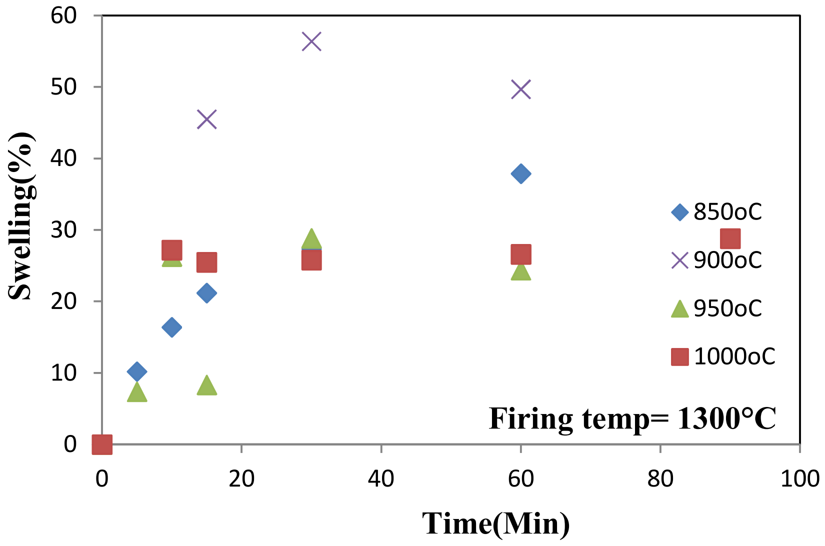


Figure 4.8: Effects of Time and Temperature on Extent of Swelling of sakaruddin iron ore pellets [2% binder, firing temperature-1300°C -100#(80%)+{(-16+25)#(20%)}]] ,reduced in Basundhara non-coking coal.

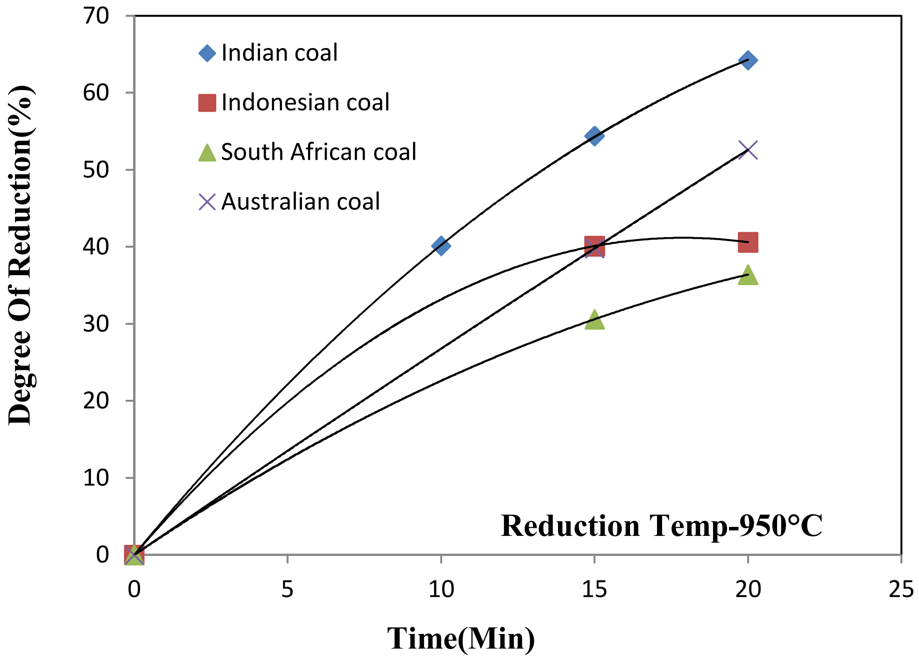


Figure 4.9: Degree of Reduction vs. Time Plots for the reduction of fired Sakaruddin Hematite Iron Ore Pellets fired at 1300^{0}C and reduced in coal (-4+6 mesh size) at a temperature of 950^{0}C.

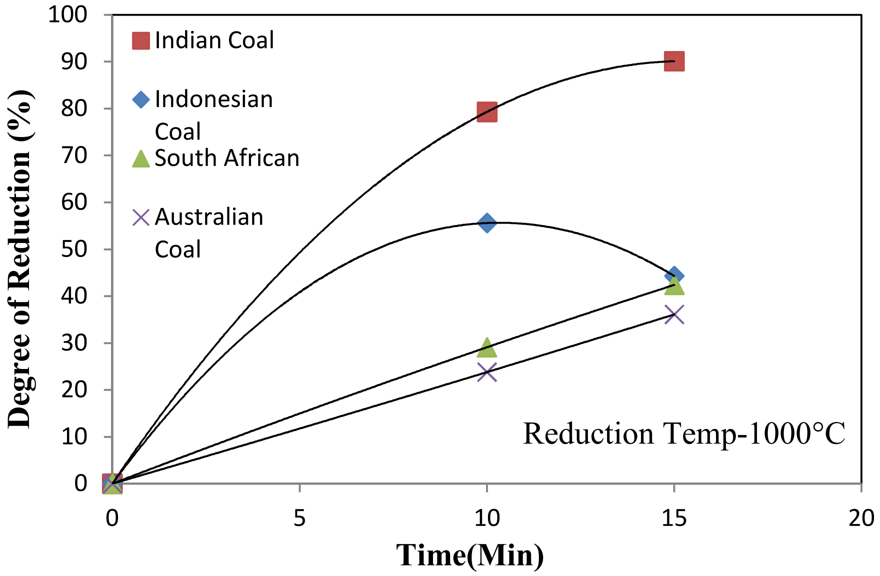


Figure 4.10: Degree of Reduction vs. Time Plots for the reduction of fired Sakaruddin Hematite Iron Ore Pellets fired at 1300^{0}C and reduced in coal (-4+6 mesh size) at a temperature of 1000^{0}C.

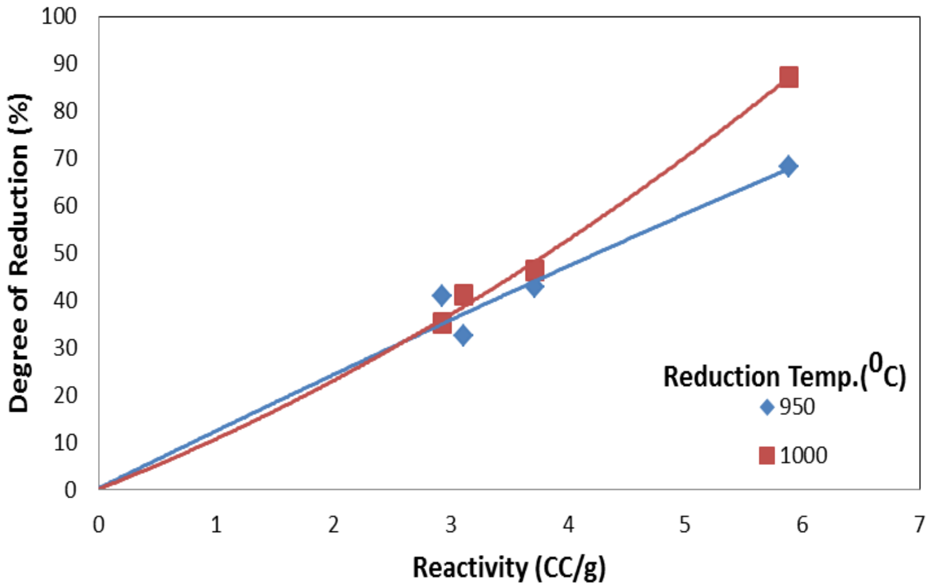


Figure 4.11: Degree of Reduction vs. Reactivity plots for the reduction of fired Sakaruddin Hematite Iron Ore pellets fired at 1300^{0}C and reduced in coal (-4+6 mesh size) at a temperature of 950^{0}C and 1000^{0}C.

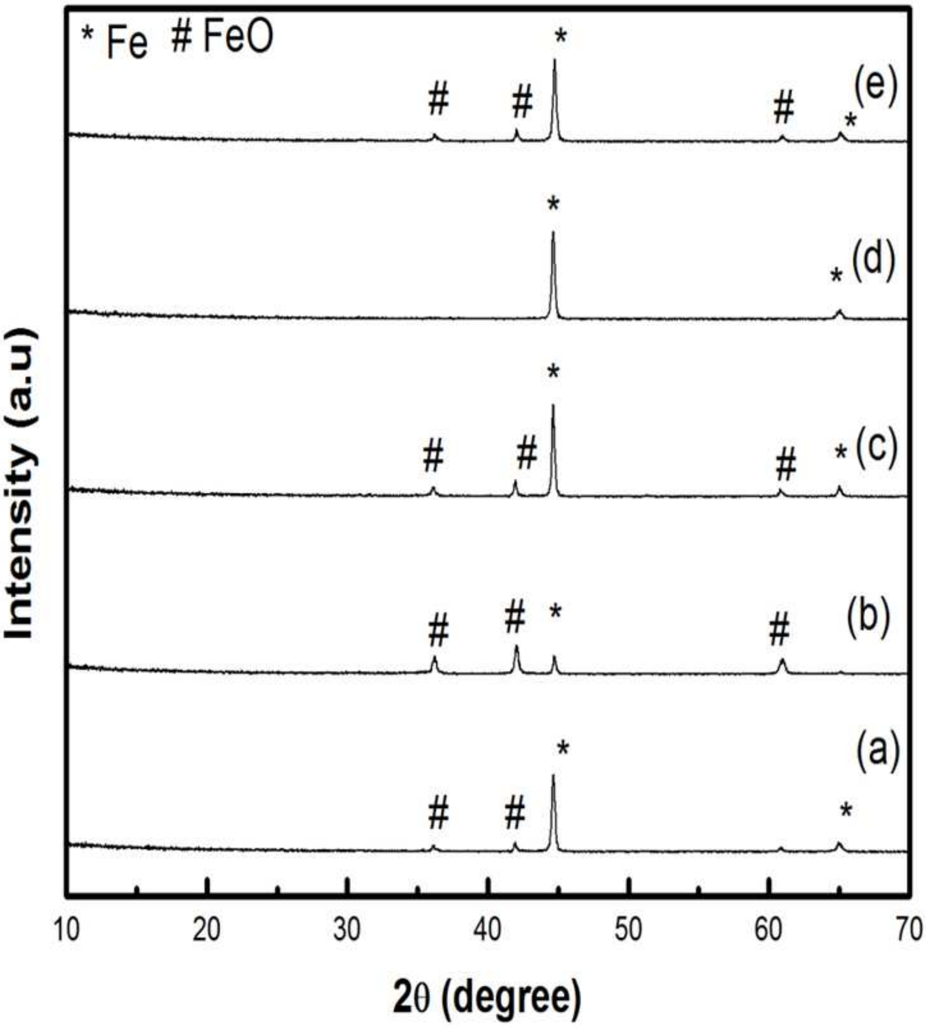


Fig-4.2 XRD Patterns of sakaruddin iron ore pellets reduced at different temperature in Bashundhara non-coking coal (a)Temp.-1000°C, Time- 10 min (b)Temp.-850°C, Time- 10 min (c) Temp.-900°C, Time- 15 min (d) Temp.-900°C, Time- 90 min (e) Temp.-950°C, Time- 15min

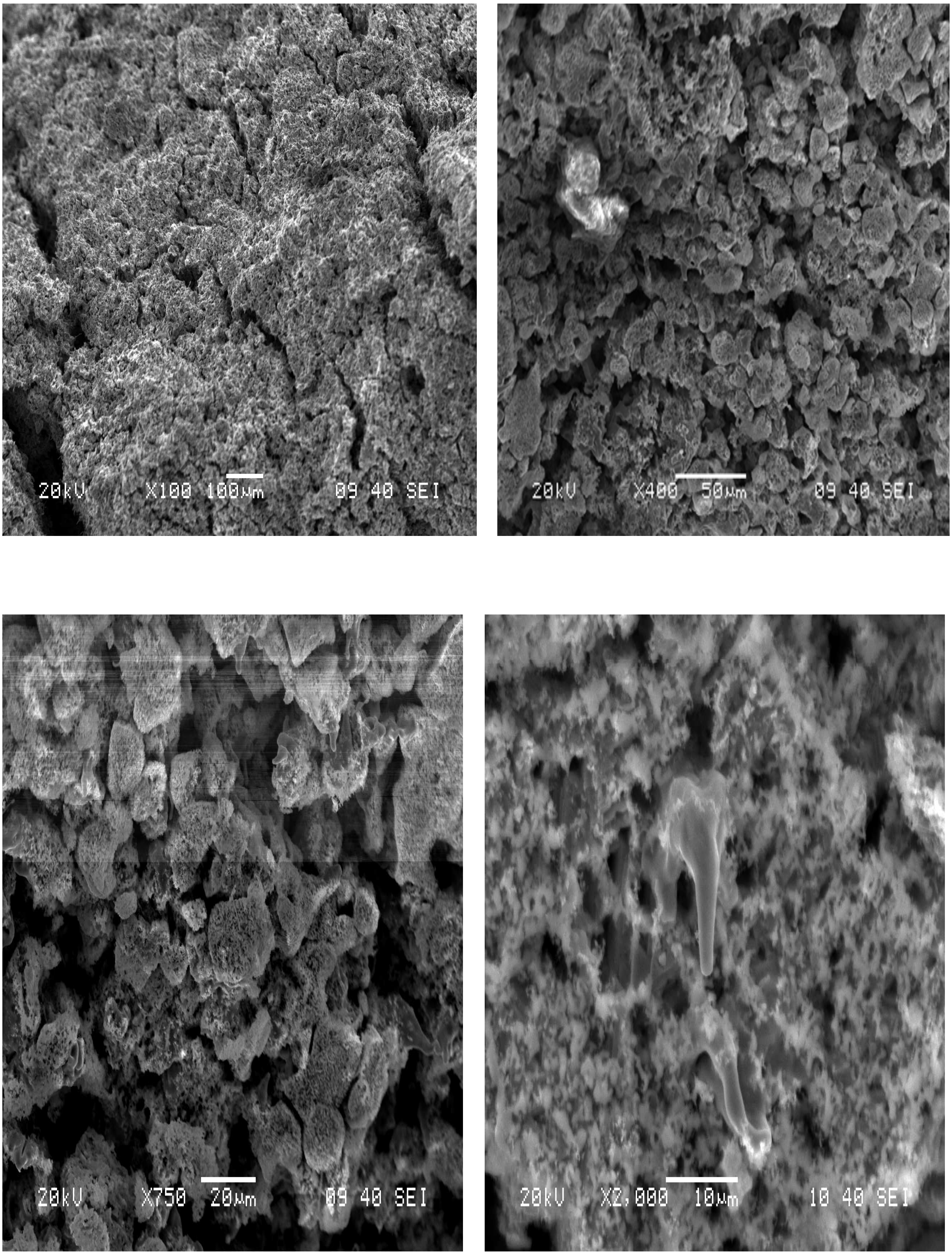


Fig 4.3 SEM photograph of reduced Sakaruddin haematite iron ore pellet fired at 1300°C for 1 hour [reduction temperature-850°C, 2% binder, reduction time-75 min,{-100#(80%),-16+25#(20%)}].

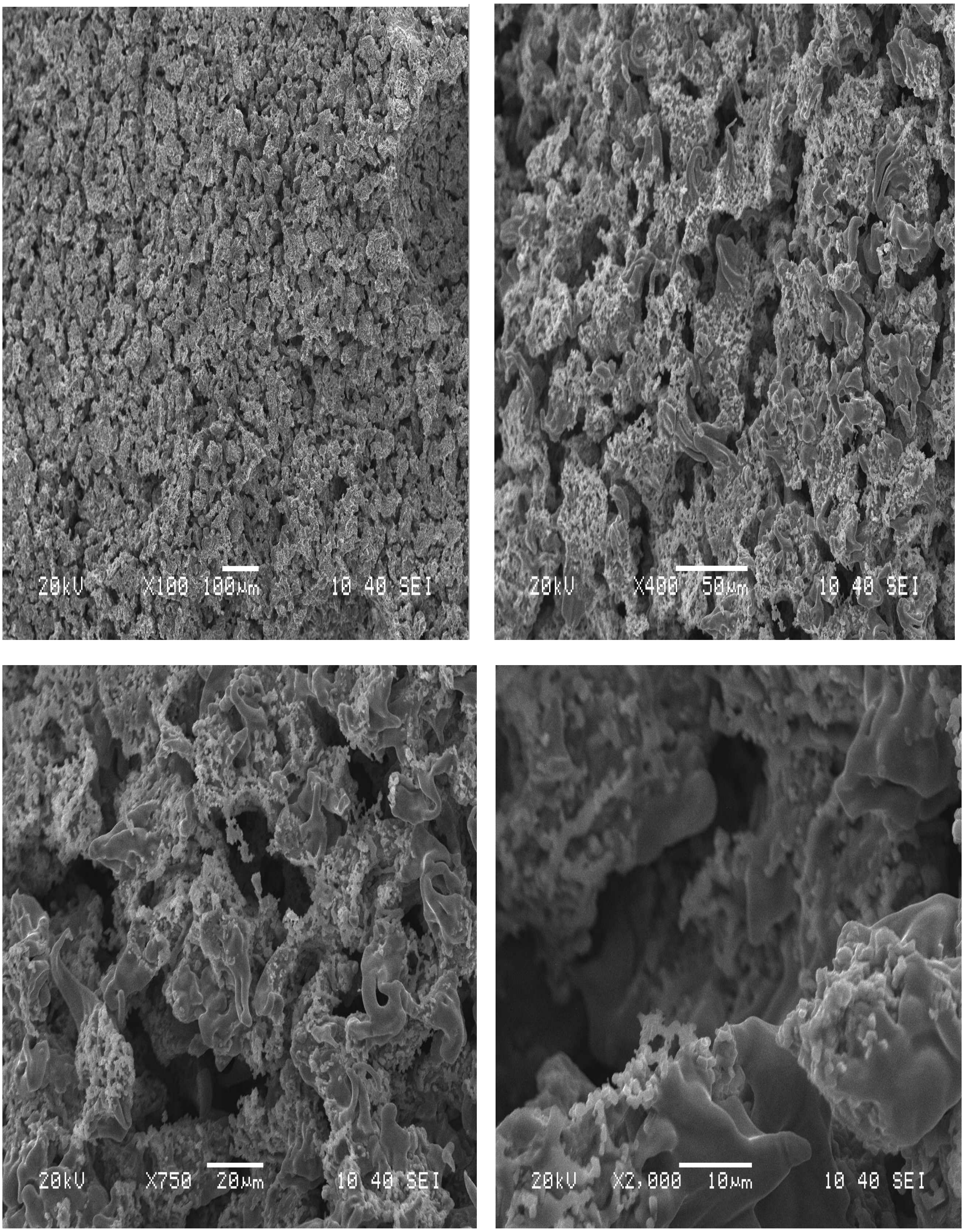


Fig 4.4 SEM photograph of reduced Sakaruddin haematite iron ore pellet fired at 1300°C for 1 hour [reduction temperature-900°C, 2% binder, reduction time-75 min,{-100#(80%),-16+25#(20%)}].

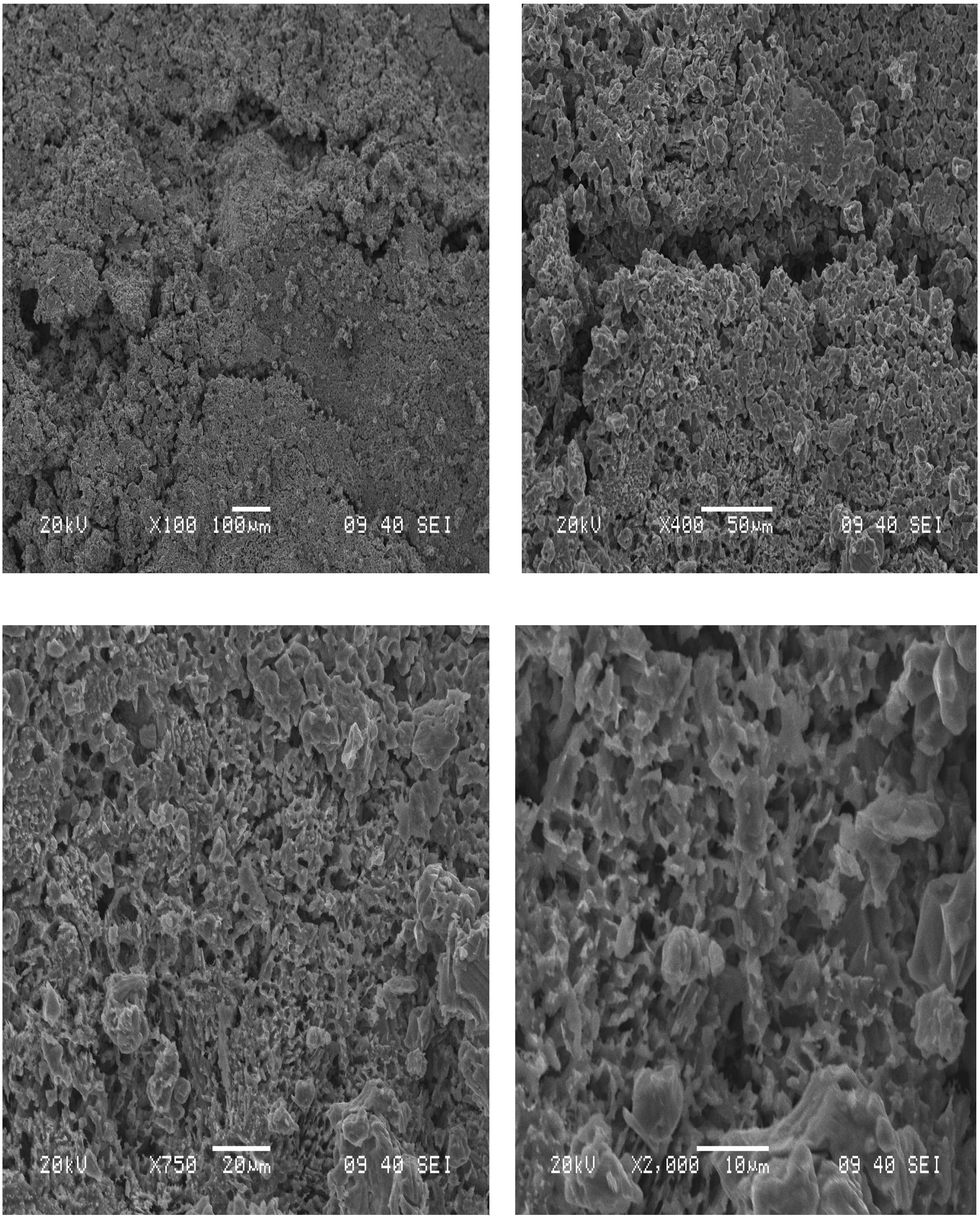


Fig 4.5 SEM photograph of reduced Sakaruddin haematite iron ore pellet fired at 1300°C for 1 hour [reduction temperature-950°C, 2% binder, reduction time-30 min,{-100#(80%),-16+25#(20%)}].

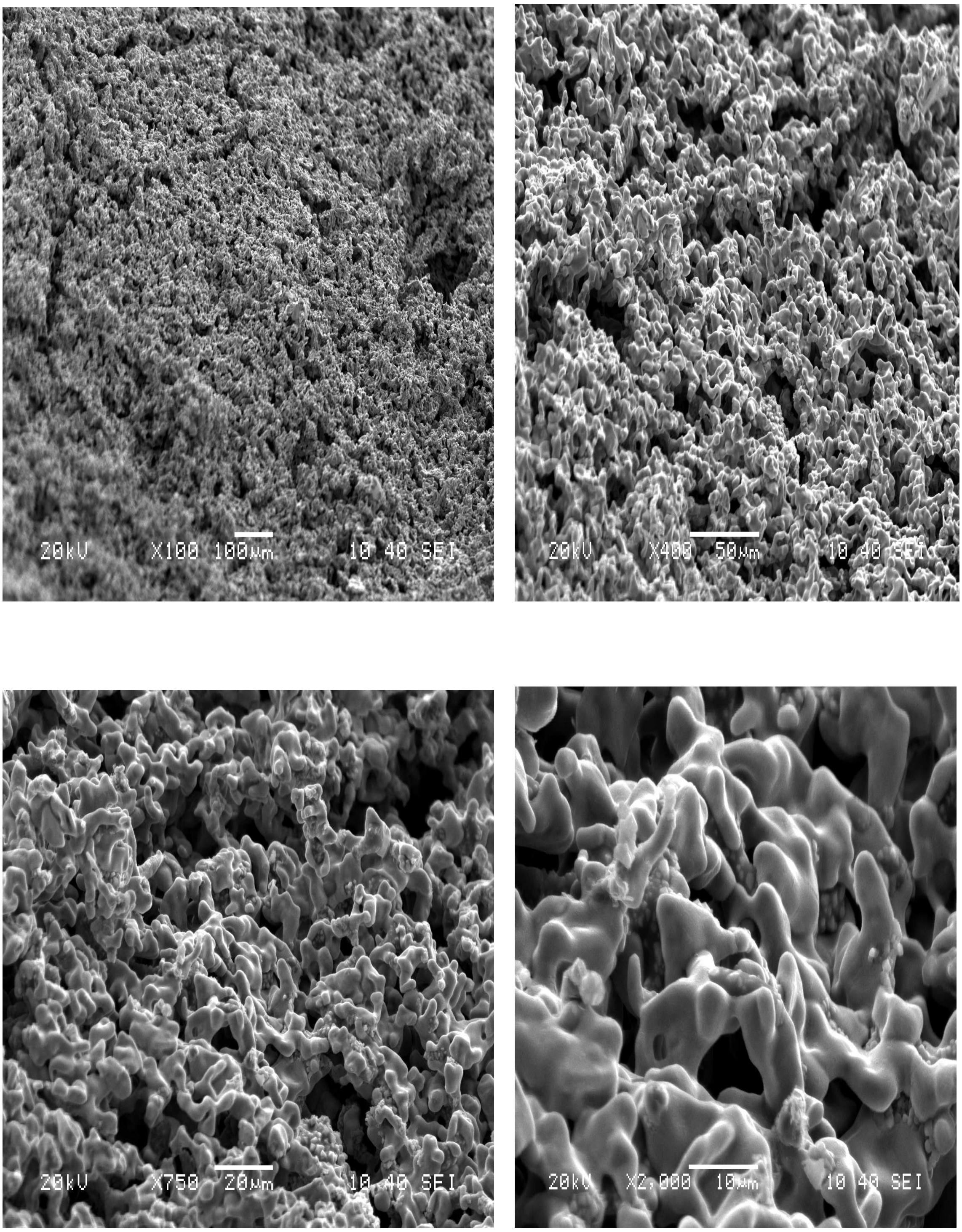


Fig 4.6 SEM photograph of reduced Sakaruddin haematite iron ore pellet fired at 1300°C for 1 hour [reduction temperature-1000°C, 2% binder, reduction time-60 min,{-100#(80%),-16+25#(20%)}].

CHAPTER-5

CONCLUSIONS

5. CONCLUSIONS

From the results of the current project work , the following conclusions can be drawn:

- The Crushing Strength of fired hematite iron ore pellets were found be increasing with increase in firing temperature. The effect of firing temperature on the Crushing Strength was maximum at firing temperature of 1300°C.
- The Crushing Strength of fired hematite iron ore pellets vary with the variation of binder content and maximum strength found for 2%(wt%) and minimum strength found for 6%(wt.%) of binder content.
- Porosity of the fired pellets decrease with increase in firing temperature. The decrease was found to be more pronounced at firing temperature of 1300°C.
- There is a decrease in the degree of reduction observed with increase in firing temperature.
- Degree of reduction increases with increase of reduction temperature.
- The extent of swelling first increases and then decreases with increase in reduction temperature. There abnormal swelling in temperature 850^0C&900^0C whereas shrinkage was found in temperature 950^0C&1000^0C.
- The degree of reduction of fired pellets increased with increase in the reactivity of the coal.
- The degree of reduction increases with increase of time at a particular reduction temperature.
- There is appreciable difference in the crushing strength and drop no. of fired iron ore pellets of sakaruddin and BPJ ore.
- This is of greatest advantage in the use of these iron ore pellets in rotary kiln for sponge iron production, which can lead to a saving of enormous amount of energy.

CHAPTER-6
FUTURE WORK

6. SUGGESTIONS FOR THE FUTURE WORK

The works carried out in this area may be extended in the future by other investigators. The suggested future work is as follows-

1. Detailed studies on reduction and swelling behavior of fired iron ore pellets may be carried out with other non-coking coal of Orissa, Jharkhand, Chattisgarh and nearby areas.

2. This work may be extended for study on reduction and swelling behaviour of iron-ore lumps.

3. Similar studies may be carried out with a mixture of lime and linseed as binder.

CHAPTER-7
REFERENCES

1.Dutta et al., 1992 Dutta, D.K., Bordoloi, D., Gupta, S., Borthakur, P.C.Srinivasan, T.M. and Patil, J.B., 1992. Investigation on cold bonded pelletization of iron ore fines using Indian slag–cement. Int. J. Miner. Process. 34: 149..

2. M. Kumar a; S. Jena a; S. K. Patel a Mineral Processing and Extractive Metallurgy Review, Volume 29, Issue 2 April 2008 , pages 118 – 129

3. M.Kumar and S.K.Patel: Mineral Processing and Extractive metallurgy Review, 29, Characterisation of properties and reduction behavior of iron ores for application in sponge iron making, pg 120-121.

Table 1-4, Steel Statistical Yearbook 2011.

4. Dutta et al., 1993 Dutta, D.K., Bordoloi, D. and Borthakur, P.C., 1993. Cold bonded pelletization of iron ore fines. In: Int. Sem. Miner. Sec. India: Need and Scope of Development under New Economic Policy of Globalization and Technology Up gradation, p. 585.

5. B.K Pandeya, T Sharma International Journal of Mineral Processing Volume 59, Issue 4, July 2000, Pages 295-304.

6. T. C. Eisele and S. K. Kawatra Mineral Processing & Extractive Metall. Rev., 24: 1_90, 2003

7. A.K.Biswas: Principles of blast furnace iron making, pg 233- 236.

8. Dr. R.H. Tupkary and V.R.Tupkary: An Introduction to Modern Iron Making, pg 124-129.

9. KRC research: Weekender, June 11th, 2007, pg 1-4.

10. Basak Anameric and S.Komar Kawatra: Properties and features of direct reduced iron, 2007, pg 63.

11. Prof. L.N.Upadhyaya and Dr. V.K.Saxena, Reduction of iron ore pellets with non coking coal, IE (I) journal MM, pg 34-36.

12. Characterisation of properties and reduction behavior of iron ores for application in sponge iron making, pg 120-121.

13. Shalini Gautam ; Sharma T.; Saxena V K.; Upadhyaya L N., Reduction of Iron Ore Pellets with Non-coking Coal, IE(I) Journal-MM, Vol 86, April 2005, pg 34- 36.

14. Cyro Takano and Marcelo B. Mourão: Mineral Processing & Extractive Metall. Rev24

15. Sharma T., Gupta R.C., Prakash B. ―Effect of Firing Condition and Ingredients on the Swelling Behaviour of lron Ore Pellets, ISIJ International, Vol. 33 (1 993). No. 4, pp. 446-453

16. Mookherjee S., Roy H.S., Mukhuerjee A., —Isothermal reduction of iron ore fines surrounded by coal and char fines. Iron Making and Steel Making, 13(1986)163.

17. Hayashi S., —Abnormal Swelling during Reduction of Binder Bonded Iron Ore Pellets with CO-CO2 Gas Mixtures, ISIJ International, Vol. 43 (2003), No. 9, pp. 1370–1375

18. Otsuka K.I., Kunni D., Reduction of powdery ferric oxide mixed with graphite particles,J.Chem. Engg. Japan, 2(1969)46-50

.

19. Abraham M.C., Ghosh A., “Kinetics of reduction of iron oxide by carbon, Iron Making and Steel Making, 6(1979)14-23.

20. Coetsee T., Pistorius P.C ,. DeVilliers E.E - Rate-determining steps for reduction in magnetite-coal pellets, Minerals Engineering 15 (2002) 919–929.

21. Ghosh A. and Chatterjee Amit, Iron making and Steel making Theory and Practice, Publisher: PHI learning Pvt. Ltd.,New Delhi (2008).

22.Tiwari P., Bandyopadhaya D., Ghosh A., —Kinetics of gasification of carbon and carbothermic reduction of iron oxide, Ironmaking & Steelmaking vol: 19 issue: 6 page: 464-468 year: 1992

23. Chakravorty, S., Reddy, G. V., and Sharma, T., 1991, ‘‘Direct reduction of iron ore by noncoking coals of different compositions.’’ *Transactions of the Indian Institute of Metals*, 44, pp. 1–7.

24. Shrinivasan N.S., Laheri A.K., “Studies on the reduction of hematite by carbon, Met.Trans. , 8B (1997)175.