STUDY OF REDUCTION KINETICS OF IRON ORE PELLETS BY NONCOKING COAL

A

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

MASTER OF TECHNOLOGY

In

Metallurgical and Materials Engineering
By

Subhasisa Nath

Roll No: 207MM104

DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA
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CERTIFICATE

This is to certify that the thesis entitled, “STUDY OF REDUCTION KINETICS OF IRON OXIDE PELLETS BY NONCOKING COAL” submitted by **Mr. Subhasisa Nath** in partial fulfilment of the requirements for the award of Master of Technology Degree in **Metallurgical and Materials Engineering** with specialization in **“Metallurgical and Materials Engineering”** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him 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.

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(SUBHASISA NATH)

ABSTRACT

Demand of sponge iron and pre-reduced pellets for the manufacture of different varieties of steel is increasing day by day and new solid reductant based sponge iron plants 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. Also majority of fines which are generated during the course of handling, mining, transportation etc are exported at a through away price which need to be utilized by making iron ore pellets for sponge iron making.

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 some mines of Orissa. In the present project work, an attempt has been made to study the reduction behavior and kinetics of fired iron ore pellets. The effect of different reduction parameters such as temperature (850-1000^{0}C), time (15-120 min.), reductant quality, pellets Vs lump, mixing of particles of different sizes at different ratios for pellet preparation etc. on the reduction behavior of iron ore pellets. These form the subject matter of the thesis.

First chapter gives the introduction of the subject. It speaks about the need of DRI industry, scope, present status and future planning of DRI industry in India, world wise DRI production, etc. It also presents the mechanism of direct reduction process.

The second chapter shows the literature review.

The third chapter deals with planning of experiments, selection of raw materials, preparation of samples, preparation of iron ore pellets, experimental procedure for characterization of different chemical and strength properties of the selected iron ore lump, proximate analysis of selected noncoking coals, evaluation of reduction and activation energies, study of swelling behavior, evaluation of strength properties of pellets, etc.

The results obtained and the discussions made from these observations have been outlined in chapter four. The result for fired iron ore pellets indicated an increase in degree of reduction with increase in reduction temperature (850-1000^{0}C). Fired iron ore pellets

showed higher degree of reduction of iron ore pellets than iron ore lump. The reduction behavior of iron ore was identical in all the selected coals.. Abnormal swelling was observed at temperature 850^0C and 900^0C; whereas shrinkage in the pellets was observed at 950^0C and 1000^0C. The reduction kinetics of Zenith iron ore pellets were studied in the temperature range of 850-1000^0C. None of the data were found to fit to the kinetic models. So the activation energies of all the iron ore – coal combinations were calculated using Integration method. Pellets made from fines of (-100#) 100% + (-18+25#)10% + (-10+16#)% were showing reduction in activation energy as compared to the pellets made from fines of -100#. In all the studied coal size, least activation energy was observed with coal of -6+16# size.

Results obtained from chapter four have been summarized in chapter five. Lastly, these conclusions have been followed by the list of references.

a) The degree of reduction increased with increase in reduction temperature from 850-1000^0C
b) There was no effect of type of coal on the degree of reduction of iron ore pellets
c) Iron ore lumps were less reducible than their corresponding iron ore pellets.
d) The reduction behavior of iron ore pellets made from fines of different sizes were comparable with pellets made from fines of -100#.
e) At 850^0C and 900^0C, the iron ore pellets were showing abnormal swelling after reduction, whereas at 950^0C and 1000^0C, shrinkage was observed in the reduced iron ore pellets

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CHAPTER-1

INTRODUCTION

1. INTRODUCTION

DRI 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 verities 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 it's nascent form the later half of the 20th century, until then steel scrap constituted the major part of our import, next to petroleum product. Then Indian government imposed some curtailment measure and search for the alternatives began, and direct reduced 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 a good flexibility 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, in India.

Being enriched with good quality Iron ore along with vast reserves of non coking Coal, which likely last for another 200 years or so India is in an adventitious for 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 behavior 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 YEAR-WISE 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 recent analysis, it has been observed that beginning with a meager production of 0.79 million tones in 1970, the world sponge iron production went upto 55.85 million tones in 2005, as shown 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 tonne 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. And out of this around 45% of steel is coming from the DRI-EAF route.

As such today DR is definitely on a strong ground. Future growth is guaranteed and driven by growth of steel making and insufficient supply of prime scrap especially in terms of quality.

1.2 PRODUCTION, CONSUMPTION, EXPORT AND SURPLUS AVAILABILITY OF IRON ORE LUMPS AND FINES IN INDIA

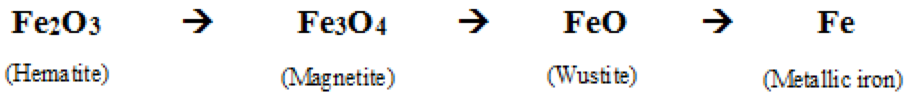
Some datas of Production, Consumption, Export and Surplus availability of Iron Ore in India, in the year 2003-04, 2004-05, 2005-06 are given in the Table-2. [1]

From the Table it is quite clear that, the ratios of fines in total export are increasing year by year. About 78.50% in year 2003-04 and has increased to around 84% in the year 2005-06. So it is quite obvious that the fines generated don’t find there market in India. After meeting the entire domestic demand and export demand, there was still Iron Ore surplus of 15.30 MT, 19.65 MT, and 12.93 MT, in the year 2003-04, 2004-05 and 2005-06 respectively.

Moreover, around 84% of fines are exported to foreign countries at a throw away price which causes huge economic loss to our countries. If these fines can find their utilization in the country, it would be a great contribution towards our economic growth.

1.3 MECHANISM OF DR PROCESS

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



$$\underset{\text{(Hematite)}}{Fe_2O_3} \rightarrow \underset{\text{(Magnetite)}}{Fe_3O_4} \rightarrow \underset{\text{(Wustite)}}{FeO} \rightarrow \underset{\text{(Metallic iron)}}{Fe}$$

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

1.3.1 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.

1.3.2 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.

1.3.3 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.

1.3.4 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.

1.5AIMS AND OBJECTIVES

Efforts have been made during the course of this present study to meet the following objective

- Characterization of the chemical and physical properties of selected iron ore.
- Characterization of the properties of selected noncoking coals.
- Study of the effect of time on the degree of reduction of iron ore pellets.
- Study of the effect of temperature on the degree of reduction of iron ore pellets.
- Study of the effect of coal type on the reduction characteristics of iron ores
- Study of effect of time on extent of swelling of iron ore pellets.
- Study of effect of temperature on extent of swelling of iron ore pellets.
- Study of Correlation between Degree of reduction and Percentage swelling of iron ore pellets.
- Reduction studies of iron ore lumps in coal- For comparison with the pellet reduction result.
- Study of effect of mixing of iron ore particles of different sizes in different ratios on the reduction characteristics of the resulting iron ore pellets.
- Kinetics study of reduction of selected iron ore pellets by selected coals.

TABLES

Table-1.1

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

Table-1.2

Year wise production, consumption, export and surplus availability of iron ore lump and fines in India

In Million tons

Year	Iron Ore Production	Domestic Consumption of Iron Ore	Export Of Iron Ore			Surplus Availability of Iron Ore
			Lump Ore	Fines	Total	
2003-04	122.84	44.97	13.45 (21.50)	49.12 (78.50)	62.57 (100)	15.30
2004-200	145.95	48.15	13.54 (17.33)	64.60 (82.67)	78.14 (100)	19.65
2005-200	154.43	52.23	14.30 (16.01)	74.97 (83.99)	89.27 (100)	12.93

(Figures in parenthesis are the percentage of total export)

Source: Indian Bureau of Mines, Nagpur, GMOEA, KIOCL, NMDC, MMTC

CHAPTER-2

CHAPTER-2

LITERATURE SURVEY

2. LITERATURE SURVEY

The investigation on the reduction of iron ore pellets (mixed or composite) with coal fines has been made by a number of workers [2 – 20].The reduction behavior of hematite and magnetite pellets containing coal char has been studied by Seaton et al [3], where they have observed higher reduction rate during the initial stage of reduction. This stage comprises the pyrolysis of the remaining volatile matter in char, the reduction of hematite and magnetite to Wustite and part if Wustite to iron. In fact, they confirmed the presence of the phases by X-ray diffraction analysis. They have indicated that the steps $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO$ and $Fe_3O_4 \rightarrow FeO$ took place rapidly during early stages of reduction.

Seaton et al [3] also studied the effect of heat transfer on the reduction behavior of the pellet and proposed that reduction of iron ore-coal char mixed pellet is controlled by the heat transfer rate in the samples. They observed temperature difference between the centre and surface of the pellet and this gap decreased with increase in degree of reduction. In their observations,15 and 27 minutes are needed for pellets to reach thermal equilibrium at 1000^0C and 1100^0C respectively and 10 minutes was sufficient to reach at 1200^0C. The reduction was not found to be stepwise throughout the pellet, where the presence of magnetite, wustite and iron at the early stages was confirmed by metallographic observations. Also the kinetic analysis of the result confirmed the reduction reaction to be under chemical control. The used the following equations for data analysis.

$\ln(1-f) = -kt$ ----- (1)

The value of activation energy obtained for magnetite pellets was 38 Kcal/mole while for hematite it varied in the range 57 to 30 Kcal/mole.

These values were comparatively less than those obtained by Rao [4] (72 Kcal/mole), Fruhen [5] (70-80 Kcal/mole) and Shrinivasan and Lahiri [21] (99 Kcal), but comparable to Walker [6]. The reason for low values of activation energy was reported to be due to catalytic effect of iron and alkaline compound on the rate of carbon gasification reaction [5] . Finally Seaton et al [3] have concluded the solid-solid reduction of oxide pellets containing coal char to proceed via gaseous intermediate CO/CO_2. In an extensive study by El-Guindy and Devanport [7] on the reduction behavior of ilmenite with graphite, it has been inferred that below 1020^0C, the reduction is controlled by solid-solid reduction at contact points. Above 1020^0C, however it was suggested to be controlled by diffusion of CO through product layer towards the unreacted ilminite core. The rate equation proposed was the Ginstling-Brounchtein equation,

$1- 2/3\ R- (1-R)^{2/3} = kt$ ----- (2)

Where ‘R’ denotes the fractional conversion.

The reduction behavior of cylindrical column of iron ore surrounded by coal/char in the temperature range of 850-1050^{0}C has been studied by Mukharjee et al [8] , where they have reported that the reduction and carbon gasification follow Ginstling – Brounshtein Equation. The values of activation energy calculated for iron ore reduction and carbon gasification were 168.4 and 176.7 KJ/mole respectively. They further concluded that both the reactions i.e. iron ore reduction and carbon gasification are essentially coupled and a common rate controlling mechanism prevails in. Similar observations have been made by Majumdar et al [9], who have studied the reduction of iron ore pellet in non coking coal bed. The values of activation energies reported for reduction and carbon gasification were 208.6 and 200.3 KJ/mole respectively. They have also found the data to fit in the Ginstling –Brounshtein equation.

The result obtained by Sharma [10] for reduction of iron ore-char mixed pellet has been found to fit in kinetic equation ln (1-f) = kt and both the reactions, i.e. reduction and carbon gasification, have been reported to be coupled in controlling the reaction rate of reactions. The values of activation energies obtained were 166.38 and 160.9 KJ/mole for reduction and carbon gasification respectively.

Shrinivasan et al [21], Otasuka et al [22] and Abraham et al [23] have studied the reduction behavior 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 catalyzed 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.

Bryk and Lu [11] studied the reduction behavior of commercial magnetite concentrate and carbon mixture in the temperature of 900-1300^{0}C. They have concluded that reaction kinetic was affected by furnace temperature, heat transfer, particle size of coal, coal: ore ratio and the reducing agent.

Coal and graphite have been reported to behave differently. Further replacement of coal by graphite has been reported to slow down the metallization process [11].

In a separate investigation [24] the pyrolysis of blends of bituminous coal and 30 wt% of magnetite or hematite has been studied using thermogravimetry and analysis of gases, where heating rate was 3.2^0K / minute. The state of iron in ferrocoke has been established by X-ray diffraction. A primary reduction by H_2 and CO of the hematite has been observed at between 400 and 500^0C, but hidden in thermogravitimetric measurements by primary volatilization of the coal. At 600^0C magnetite is progressively reduced to wustite and then to iron. This reduction starts a little earlier if the heating rate is slow and the coal rank is low and progresses more rapidly on using hematite. Except for higher heating rates in coal – magnetite blends; the reduction is complete at 1000^0C. When the temperature is increased, the reduction by CO becomes of increasing importance, being mainly produced from coke by Boudouard reaction. Further lignite was considered to be a better reducing agent than the other coals, because if large quantity of CO produced from start of it's pyrolysis, and good reactivity of it's char towards CO_2 and H_2O.

The reduction of iron ore pellets with domestic lignite coal in a semi pilot scale rotary tube furnace with variables such as coal consumption ratio (C_{Fix}/Fe_{Tot}), temperature of the environment and the residence time has been established by Narchin et al [15]. At temperature 1000^0C and coal consumption ratio of 0.40, reduction process was completed in about 90 minutes residence time with 93% average metallization of pellets. Thus, the result of experimental study showed similarities with industrial practice.

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 1050^0C 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 1000^0C fractional reaction increased with increasing carbon content up to a critical value of the ratio and then decreased. At temperatures above 1000^0C fractional reaction increased linearly with increasing carbon content.

Shoji Hayashi et al have investigated the abnormal Swelling during Reduction of Binder Bonded Iron Ore Pellets with CO–CO_2 Gas Mixtures [26]. He found that Abnormal swelling during reduction of iron ore pellets with CO–CO_2 gas mixtures was investigated in the temperature range of 700 to 1000°C. Influence of addition of gaseous sulfur COS at low partial pressures to inlet gas mixtures, CO_2/ (CO_CO_2) 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 sulfide, 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 sulfur 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 sulfur 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 sulfur species in exit gas to evaluate the sulfur activity in gas near the reaction front inside cement bonded pellets.

T. Sharma studied the effect of Firing Condition and Ingredients on the Swelling Behaviour of lron 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.

CHAPTER-3

CHAPTER-3

EXPERIMENTAL

3. EXPERIMENTAL

3.1 Selection of Materials

For packed bed reduction studies, iron ore sample was collected from Zenith iron ore mine of Orissa and non coking coals were collected from Lingaraj Mine, Ananta Mine, and Jagannath Mine in Orissa.

3.2 Determination of Chemical Composition and Loss on Ignition of Iron Ore

The chemical composition of the iron ore was determined by X-ray fluorescence technique. The loss on ignition values of the iron ore is determined by heating 1gm. of air dried samples at a temperature of 900^0C for 1hr, followed by air cooling. Loss in weight was taken as the % loss in ignition.

3.3 Proximate Analysis of Non-Coking Coal and Coal Char

Analysis for moisture, volatile matter, ash and fixed carbon contents were carried out on samples ground to pass through 72 mesh B.S. test sieve as follows.

3.3.1 Moisture Determination

1 gm. of air dried sample was placed in an air oven maintained at a temperature of 110^0C and kept there for 1 hour. The loss in weight, expressed as the percentage of initial weight of coal/coal char, gives the percentage of moisture content in the sample [27].

3.3.2 Volatile matter determination

1 gm. of air dried sample was taken in a volatile matter crucible (made of silica) covered with a lid**.** The crucible was introduced in the furnace maintained at a temperature of 925^0C and kept at this temperature for 7 minutes. The crucible was then taken out and loss in weight of sample was determined. The % loss in weight minus % of moisture content in the sample gives the value of percentage volatile matter in the sample on air dried basis.

3.3.3 Ash determination

1 gm. of air dried sample was taken in a Silica disc and placed in the furnace maintained at a temperature of 775^0C, and kept there till complete burning. The weight of ash obtained expressed as the % of initial weight of the sample gives % of content in the sample on air dried basis.

3.3.4 Fixed carbon determination

It was simply calculated as follows:

% Fixed Carbon = 100 - % (moisture + volatile matter + ash)

3.4 REACTIVITY MESUREMENT OF COAL CHAR

Reactivity values of chars to carbon dioxide gas were determined as per the standard method (Indian standard: 12381, 1994), which simulates the conditions in the rotary kiln based sponge iron plants. In this laboratory test, 5gm of the dried char sample 0.5-1.0mm in size were held in a perforated crucible made of 100 mesh stainless steel screen and kept in a silica reaction tube of the tubular furnace so that sample was in uniform temperature zone . The test sample was brought to the required temperature of 1000^0C under nitrogen atmosphere (50cc min^{-1}). After the stabilization of temperature, a stream of dry carbon dioxide gas was admitted to the reactor at a flow rate of 100cc min^{-1} for 25 minutes. The power was then switch off and the sample was then cooled to 150^0C in nitrogen atmosphere. The reacted char sample was then weighed and the reactivity was calculated by using the following equation (Indian Standard: 12381 1994).

Reactivity = $11.61 \times W / (5 \times C_{fix} – W/2)$ cc of CO gas/gm.sec

Where W denotes the weight loss in char and C_{fix} is the fraction of fixed carbon in the hare ore reaction.

3.5 EVALUATION OF PHYSICAL PROPERTIES OF IRON ORE

3.5.1 Determination of cold strength

Assessments of cold strength of the selected iron ore was carried out by determining their tumbler, abrasion and shatter indices.

(i) Tumbler and Abrasion Indices:

The tumbler tests for lump ore, sinter and pellets were carried out for the determination of resistance to degradation or breakage by impact and abrasion.

15 kg of oven dried lump iron ore was placed in circular drum of 100cm inside diameter and 50 cm inside length and the door of the drum was closed tightly. The drum was rotated at 25 rpm for a total 200 revolutions. Al the materials were removed gently from the drum by slowly opening the door and sieved on a 6.3 mm and 500µm sieves. The weight of the fraction retained on and passing through 500µm were taken. The tumbler index (T) and Abrasion index (A) values were calculated by using the following formula.

$T = (m_1/m_2) \times 100$

and $A = m - (m_1 + m_2)/m \times 100$

Where,

m = weight of the sample before test;

m_1 = weight of sample retained on 6.3 mm sieve after the test;

m_2 = weight of sample passing through 6.3 mm and retained on 500µm sieves after the test.

(ii) Shatter index:

A 10 kg dried iron ore sample of size 25 to -40 mm was dropped from a height of 2m on cast iron floor. The material was then screened and shatter index was expressed as the percentage of – 0.5mm fraction produced.

3.5.2 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 [28]

Apparent porosity = W – D/ W- (S-s)

Where, ‘D’ is the weight of dried piece;

‘W’ is the weight of oil saturated;

‘S’ is the weight of the piece + wire cage while immerse in oil;

and ‘s’ is the weight of wire cage only while immerse in oil

3.6 PREPARATION OF IRON ORE PELLET

Iron ore pellets were made of the fines of size -100 mesh and some the pellets were also made by mixing the Zenith iron ore fines of different sizes(-100 #, -18+25 #, -10+16 #) at different ratios(80% : 10% : 10% , 70% : 15% : 15%). The pellets were made by prolonged hand rolling (by adding approximately 12% moisture) and then they are placed on a glass plate. The size of the pellets was kept in a very close range (approximately 15mm diameter). The pellets were dried at 110^0C in an air oven for 2 hours and then fired at 1300^0C for 1 hour by heating from room temperature to the firing temperature (1300^0C) and were left for furnace cooling in a silicon carbide rod furnace to attain workable strength in pellets.

3.7 EVALUATION OF PHYSICAL PROPERTIES OF INDURED IRON ORE PELLETS

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

3.7.1 Determination of apparent porosity

The porosity values of the fired pellets were obtained by the same procedure as outlined in section 2.5.2.

3.7.2 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 [35].

$$\sigma_c = W/A$$

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 cm^2

3.8 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, 1000^{0}C at a rate of about 7^{0}C per minute and were soaked at these temperatures for varying time periods in the range 15 - 120 minutes. The 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: 77mm height × 40 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 center. This ensures complete surrounding of pellet by solid reductant. The char produced after reduction was again used for the further reduction to determine the reduction potential of the char.

During the reduction at a particular temperature each container was taken out at an interval of 15 minutes up to 30 minutes of residence, then at an interval of 30 minutes up to 120 minutes of residence in the furnace. 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.

$$\text{Degree of Reduction} = \frac{\text{Weight loss}}{\text{Total weight of removable oxygen in iron oxide}} \times 100$$

3.9 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 [31].

Percentage swelling can be calculated as:

$$\% \text{ Swelling} = \frac{V_f - V_i}{V_i} \times 100$$

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 Fe_2O_3--Fe_3O_4 (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 Na_2O, K_2O, 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. .

3.10 PROCEDURE FOR EVALUATION OF ACTIVATION ENERGY

Activation energy can be calculated by several methods. In this project work, the data obtained do not fit to the models proposed by different researchers. So the activation energies were calculated by Integration method as outlined by Dey et al [25]. In this method, plots of ln t Vs 1/ T were plotted and the slopes of the straight lines obtained give the activation energies, where‘t’ is the time at a particular degree of reduction.

CHAPTER-4

CHAPTER-4

RESULT & DISCUSSION

4. RESULT AND DISCUSSION

The results obtained during the course of this project work have been summarized in table 4.1 – 4.30 and present graphically in figures 4.1-4.76.

4.1 CHARACTERISTICS OF IRON ORE

The chemical compositions and loss on ignition values of the Zenith iron ore have been listed in table 4.1, which indicates that the gangue materials in this iron ore is mainly Alumina and Silica[30]. Data for the porosity value and strength properties (tumbler, abrasion, shatter indices) of this iron ore have been presented in table 4.2. Tumbler, abrasion and shatter indices are the most popular properties to assess the resistance of iron ore to degradation.

As shown in table 4.2 the iron ore offers higher resistance to abrasion and tumbling, most probably due to their hard fine grained structure and higher porosity value.

4.2 CHARACTERISTICS OF NON COKING COALS

The non coking coal samples under investigation has been characterized in terms of their proximate analysis values, Reactivity values, Caking indices, Gross calorific values and Ash Fusion Temperatures. The respective data have been shown in table 4.4.

The caking indices results in table 4.4 clearly indicate that all the studied coals have no caking index. This is no doubt due to the high contents inertinite (fusinite, semifusinite etc.) in these coal samples. The proximate analysis result reveals the fixed carbon contents in these coals are in the range of 37 – 44 % and ash contents are in the range of 13 – 22%.

The ash fusion temperatures for the three different coals have been shown in table 4.4.

From the table 4.4, it can be seen that all the three types of coals are having high ash fusion temperature; which in good agreement with the data for sponge iron making. Higher ash fusion temperatures are expected to be due to the presence of Al_2O_3, SiO_2, TiO_2, and K_2O.

From the table 4.4, it can be seen that the gross calorific value for Ananta coal is higher than the other two types of coal.

The proximate analysis of coal char Table 4.4 shows that the carbon contents are in the range of 61 – 68% and the ash contents are in the range of 27 – 33%.

4.3 COMPRESSIVE STRENGTH OF FIRED IRON ORE PELLET

The compressive strength results for fired Zenith iron ore pellets have been reported in table 4.3.

It can be seen from the table that, strength of fired iron ore pellets ranges from 165 – 520 kg. The pellet made from fines of (-100#) 80% + (-18+25#) 10%+ (-10+16#) 10% is showing poor crushing strength. It may be due to weak bonding between ore particles due to very less slag generation. Rest types are comparable with those reported (200 kg min.) for pellets made by adding binding agent such as bentonite, lime etc. The higher compressive strength of these (fired at 1300^0C) appear to be due to the slag bond formation within the pellets, which usually occur at a temperature of 1300^0C and above [33].

4.4 APPARENT POROSITY OF FIRED IRON ORE PELLET

Apparent porosity of fired Zenith iron ore pellets have been shown in the Table-4.3. It can be seen that the apparent porosity of fired Zenith iron ore pellets lies between 13-20%.

4.5 EFFECT OF REDUCTION TIME ON DEGREE OF REDUCTION OF IRON ORE PELLETS

Data presented graphically in figure 4.2 – 4.19 illustrate the effect of time for different reduction temperature of 850, 900, 950 and 1000^0 C for Zenith iron ore reduced by three types of different non coking coals under non-isothermal condition. It can be observed from the figures 4.2 – 4.19 that the reduction time has an approximate identical effect on the reduction behavior of almost all the studied iron ore-coal combination. With increase in reduction time, the degree of reduction increased at every temperature under consideration. The rate of reduction in general was observed to be high up to about 70 – 80 % reduction and then it decreased.

The reduction of iron ore pellet with solid reductant starts at the point of contact on the surface of pellet which produces CO/CO_2 gas. The CO_2 produced combines with solid carbon and gets converted into CO gas. The CO gas diffuses into the pellet and takes part in the reduction. 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 suggested by Bodsworth et al [29]. The released volatile matters of coal get almost completely reformed into H_2, H_2O and CO during the initial stage of reduction. It might be expected that the pressure of H_2 and CO in reducing gas gives boost in the reduction rate. As the reduction progress with time, the thickness of the product iron layer increases and offers greater resistance to the diffusion of carbon and reducing gas onto the surface of unreduced iron oxide. This is the reason for lower rate of reduction in the later stages at all the temperatures.

4.6 EFFECT OF REDUCTION TEMPERATURE ON DEGREE OF REDUCTION OF IRON ORE PELLETS.

The reduction curves (% reduction Vs time) for indurated Zenith iron ore pellets reduced by non coking coals (Lingaraj mine, Ananta mine, Jagannath mine) at temperatures of 850, 900, 950 and 1000^0C are shown in figures 4.2 – 4.73. It is clear from the figures that the reduction is faster up to about 70-80 % reduction and then slows down at the latter stages. This is undoubtedly due to formation a dense metallic iron layer over unreduced iron oxide. On the other hand, reduction (%) was enhanced with the increase in temperature. Reduction at 850 and 900^0C was not complete within the studied time period (i.e. up to 2hr.) and stopped at about 86% reduction at 850^0C and 96% reduction at 900^0C, except for Zenith iron ore pellet (-100#)80%+(-18+25#)10%+(-10+16#)10% reduced in Lingaraj coal, where reduction stopped at about 95% at 850^0C and about 98% at 900^0C. This may be due to the catalytic effect of newly formed metallic iron layer on the reduction rate of the iron ore pellet. The greater influence of temperature was observed up to 60-70 minutes time period.

It is believed that as the temperature increases, the initially formed iron layer grow through further reduction leading to higher degree of reduction at higher temperatures.

4.7 EFFECT OF COAL TYPE ON THE DEGREE OF REDUCTION OF IRON ORE PELLETS

To study the effect of coal type on the degree of reduction of iron pellet, the degree of reduction of Zenith iron ore pellet in the three different coals (Lingaraj, Ananta, Jagannath) at different times were presented graphically in figure 4.2–4.19 at four different temperatures (850, 900, 950 and 1000^0C)**.** The proximate analysis and reactivity data of three types coals were given in table 4.4.

It is clear from the figure 4.2–4.19 that, the reduction behavior of Zenith iron ore in is nearly identical in these three non coking coals at the four different temperatures. This most probably may be due to generation of sufficient amount reducing gas (CO) in case of all the studied coals. Hence, the effect of reactivity of coal appears to be not pronounced. But however the effect of reactivity may appear if, the time interval of reduction at a particular temperature is reduced.

4.8 COMPRISION OF REDUCTION BEHAVIOR: PELLET Vs LUMP

This study provides more reliable information on the reduction behavior of lumps and pellet and better simulate the actual industrial reactors. In this study, reduction behavior of dried iron ore lumps have been compared with those of indurated iron ore pellets reduced under identical non isothermal condition. The result (Degree of Reduction) obtained have been given in table 4.30. It is evident from the table that the iron ore lumps have lower degree of reduction than the corresponding indurated iron ore pellets.

The data listed in tables 4.2 and 4.5 clearly indicate that the dried iron ore lumps have much lower porosity values than those of corresponding iron ore pellets. The appreciably lower porosity in iron ore lumps appear to be most likely reason for it's lower reducibility.

As outlined in the literature [27], hematite pellets tend to be more disordered and hence more reactive wustite, which enhance the rate of wustite reduction**.** This may be another reason for relatively higher reducibility of pellets, as observed in the present investigation.

4.9 EVALUATION OF ACTIVATION ENERGY

Activation energy can be calculated by several methods. In this present project work, different kinetic models were applied to calculate the activation energy. But none of them was found to be fitting to the reduction data. So calculation of activation energy was done by Integration method as outlined by Dey et al [25]. In this method, slopes of the plots ln t Vs 1/T as shown in the figures (4.56-4.73), give the apparent activation energies table (4.24-4.26).

From the results obtained from table (4.24-4.26), it is clear that highest activation energy was observed for the reduction of pellets (made from fines of -100#) reduced by Lingaraj coal of size -16+25#, whereas other studied coal size gave approximately the same activation energy for reduction of the same pellets. This variation in activation energy is expected to be related with the reducibility of the pellets.

For the iron ore pellets made from fines of (-100#)80%+ (-18+25#)10%+(-10+16#) 10% and reduced in Lingaraj coal, the activation energy reduced drastically in comparison to the pellets made from -100# size. This appears to be due to the higher rate of reduction in the pellets made from fines of (-100#) 80%+ (-18+25#) 10%+ (-10+16#) 10%.

For pellets made from fines of (-100#) 70%+ (-18+25#) 15%+ (-10+16#) 15%, the activation energy observed was in between the other two.

In all the types of pellets, the least activation energy was observed with coal of size -6+16#.

4.10 REDUCTION BEHAVIOR OF PELLETS MADE BY MIXING IRON ORE FINES OF DIFFERENT SIZES AT DIFFEREN RATIO

The variation in percentage reduction of iron ore pellets made by mixing the iron ore fines (Zenith Mine) of different sizes (-100#) 80%+ (-18+25#) 10%+(-10+16#) 10% ; (-100#) 70%+ (-18+25#) 15%+(-10+16#) 15%;-100#) 60%+ (-18+25#) 20%+(-10+16#) 20% with time at different temperatures, by Lingaraj coal, Ananta coal and Jagannath coal have been shown in figure (4.2- 4.19) and in table (4.6-4.23).

From the above stated figures and tables, it can be observed that the degrees of reduction of the mixed iron ore pellets are very much comparable to those of the pellets made by using -100# size iron ore fines. This is expected to be due to the higher porosity of these mixed iron ore pellets made by mixing the iron ore fines of sizes -100#, -18+25# and -10+16#. The higher porosity allows easy access of reducing gases to the inner core of pellets. This is of greatest advantage in the use of such pellets in the rotary kiln for sponge iron making. The use of such type of pellets will definitely lead to saving greater amount of energy. The higher reducibility of these pellets will certainly encourage the industrialist in going for pellets rather than lumps.

4.11 EFFECT OF TIME ON THE EXTENT OF SWELLING OF IRON ORE PELLETS

It can be seen from Figure (4.20 – 4.37) and table (4.6–4.23) that as reduction time increases, the extent of swelling increases at 850^0C and 900^0C and at 100-120 minutes, swelling more than 30% was observed. This is due to the growth of iron whiskers at 100-120 minutes. At higher temperatures (950^0C and 1000^0C), reduction in volume of reduced iron ore pellets were observed with increase in reduction time. This shrinkage in reduced iron ore pellets is due to the nucleation and sintering of iron with time at high temperatures [31].

4.12 EFFECT OF TEMPERATURE ON THE EXTENT OF SWELLING OF IRON ORE PELLETS

From figure (4.20–4.37) and from table (4.6–4.23), it can be seen that at low temperatures such as 850^0C and 900^0C, the abnormal swelling of reduced iron ore pellets were observed. This is due to that these temperatures promote the growth of iron whiskers. At higher temperatures (950^0C and 1000^0C), decrease in volume of reduced iron ore pellets were observed. This shrinkage in reduced iron ore pellets is due to the nucleation and sintering of iron at high temperatures [31].

4.13 CORRELATION BETWEEN DEGREE OF REDUCTION AND PERCENTAGE SWELLING

The variation of Swelling (%) Vs Degree of Reduction (%) has been shown in figures (4.38-4.55) and in table (4.6-4.23). From the figures, it can be seen that abnormal swelling (25-30%) was observed at around 90-95% reduction ($FeO \rightarrow Fe$) at temperature 850^0C and 900^0C. It is expected to be due to the growth of iron whiskers as shown in figure 4.75 at $FeO \rightarrow Fe$ reduction step at 850^0C and 900^0C. However Shrinkage in the reduced iron ore pellets was observed at 950^0C and 1000^0C. This is expected to be due to the sintering of iron at high temperatures as shown in figure 4.76.

4.14 XRD PATTERN ANALYSIS OF REDUCED IRON ORE PELLETS

The XRD patterns of Zenith iron ore pellets reduced at temperatures of 850, 900, 950 and 1000^0C for a time period of 15, 90 & 120, 60 and 45minutes respectively by Lingaraj coal, have shown in figure 4.74 and the major & minor phases at various temperatures have shown in table 4.27.

It can be seen from these figures that, no peaks of any of the oxides of iron is present in the XRD pattern of the reduced iron ore pellets, soaked for 60 minutes at temperatures of 950^0C, indicating complete reduction of the iron ore pellet before 60 minutes at 950^0C. At 850^0C and a reduction time of 15 minutes, peaks of FeO appeared in the XRD pattern of the reduced iron ore pellet. At 900^0C, 1000^0C and reduction time up to 120 & 45 minutes, peaks of iron oxide are present. This shows that the reduction step $FeO \rightarrow Fe$ is a lengthy one. It is expected to be due to resistance to diffusion of CO gases to the interior of pellet.

FIGURES

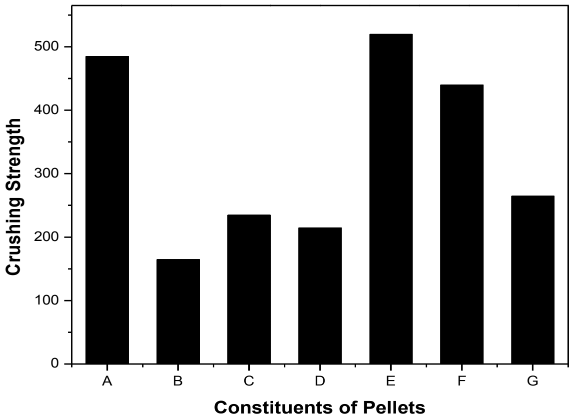


Fig- 4.1 **Variation of crushing strength of fired iron ore pellets with constituents of pellets**

A = (-100#)100%, B = (-100#)80% + (-18+25#)10% + (-10+16#)10%,
C = (-100#)70% + (-18+25#)15% + (-10+16#)15%,
D = (-100#)60% + (-18+25#)20% + (-10+16#)20%, E = (-100#)80% + (-18+25#)20%,
F = (-100#)70% + (-18+25#)30%, G = (-100#)60% + (-18+25#)40%

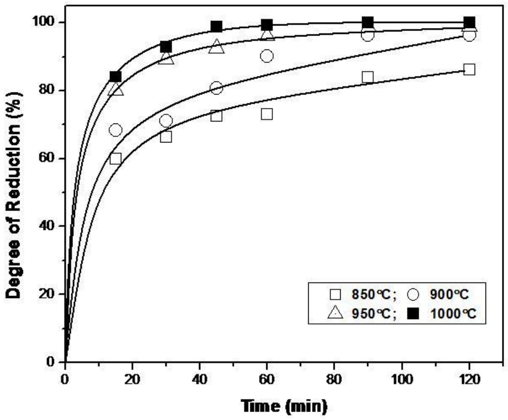


Fig-4.2 **Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj Coal of -6+16# size**

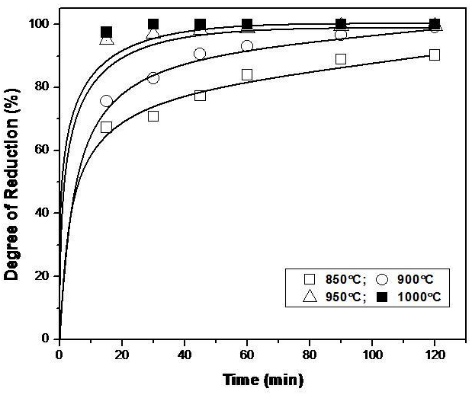


Fig-4.3 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj Coal of -16+25# size

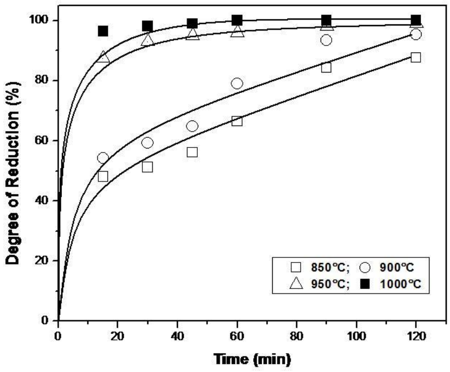


Fig-4.4 Effect of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj Coal of -72# size

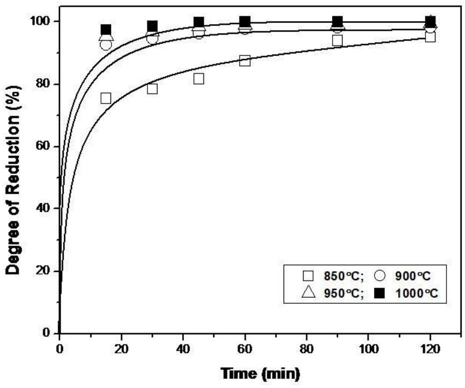


Fig-4.5 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10% +(-10+16#)10% and reduced by Lingaraj Coal of -6+16# size

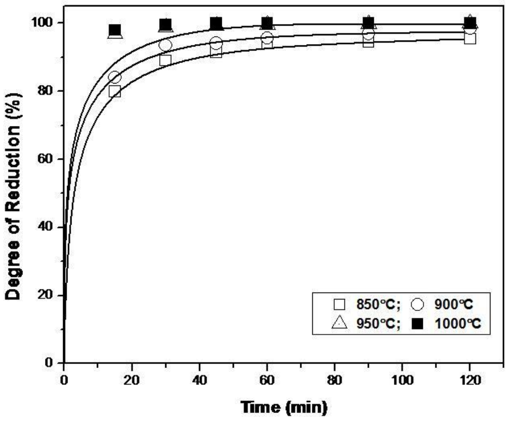


Fig-4.6 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10% +(-10+16#)10% and reduced by Lingaraj Coal of -16+25# size

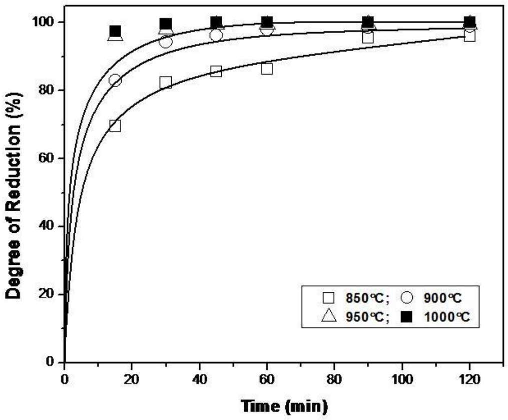


Fig-4.7 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#) 80%+(-18+25#) 10% + (-10+16#) 10% and reduced by Lingaraj Coal of -72# size

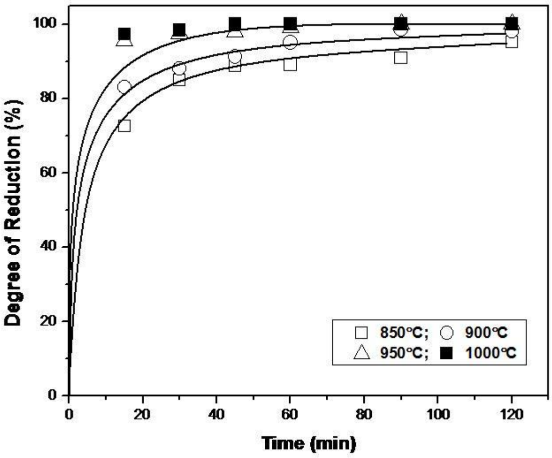


Fig-4.8 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#) 70%+(-18+25#) 15% +(-10+16#)15% and reduced by Lingaraj Coal of -6+16# size

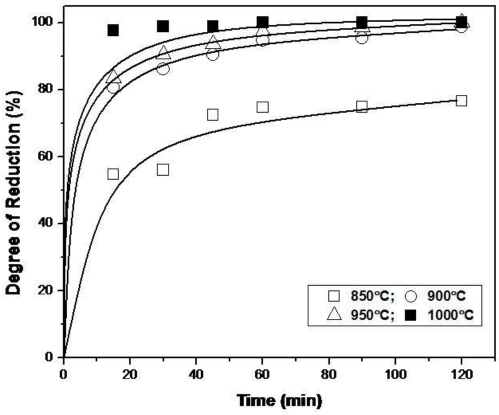


Fig-4.9 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#) 70%+(-18+25#) 15% +(-10+16#)15% and reduced by Lingaraj Coal of -16+25# size

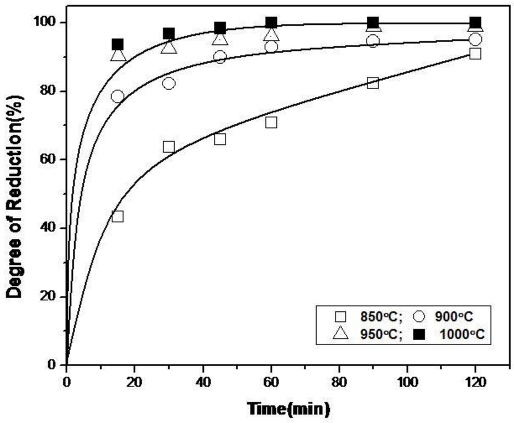


Fig-4.10 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#) 70%+(-18+25#) 15% + (-10+16#) 15% and reduced by Lingaraj Coal of -72# size

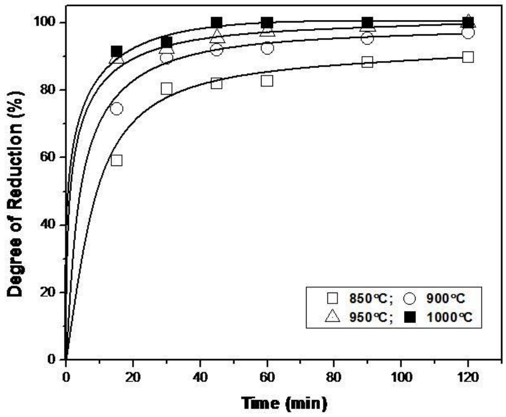


Fig-4.11 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of -100# and reduced by Ananta Coal of -6+16# size

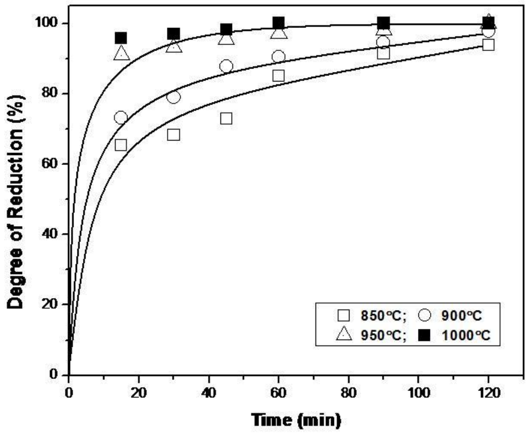


Fig-4.12 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of -100# and reduced by Ananta Coal of -16+25# size

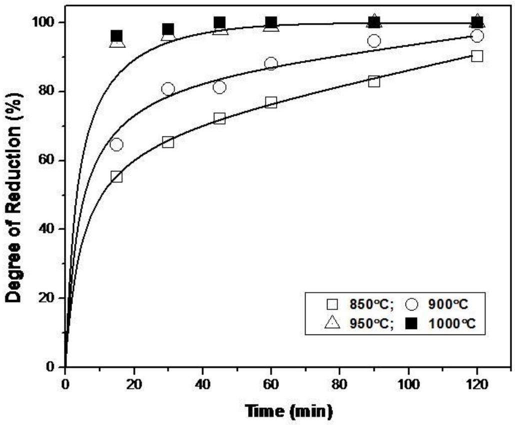


Fig-4.13 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10% +(-10+16#)10% and reduced by Ananta Coal of -6+16# size

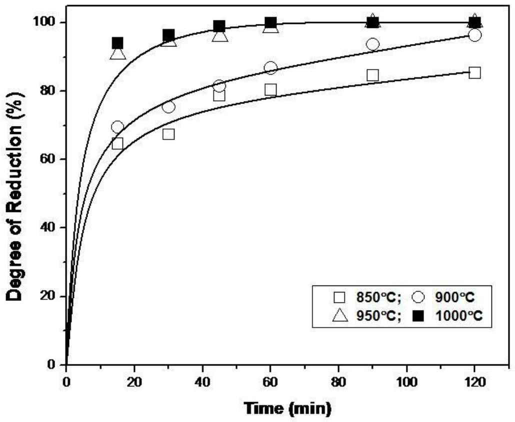


Fig-4.14 Effect of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#) 80%+(-18+25#) 10% +(-10+16#)10% and reduced by Ananta Coal of -16+25# size

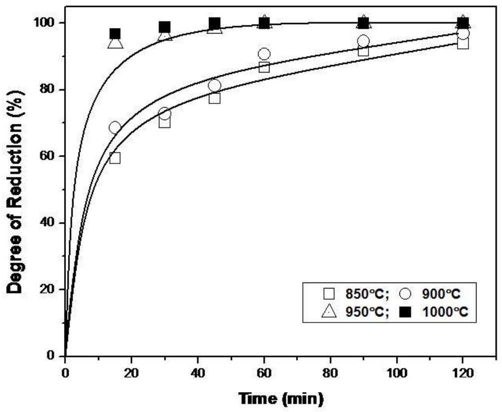


Fig-4.15 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#) 70%+(-18+25#) 15% +(-10+16#)15% and reduced by Ananta Coal of -6+16# size

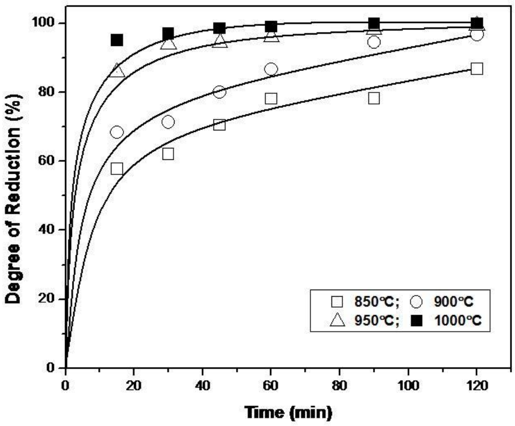


Fig-4.16 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#)70%+(-18+25#)15% +(-10+16#)15% and reduced by Ananta Coal of -16+25# size

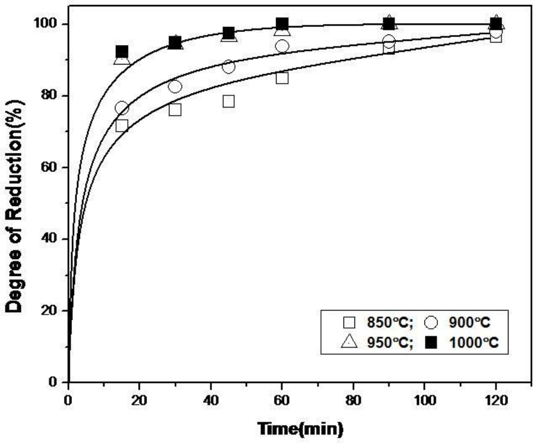


Fig-4.17 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of -100# and reduced by Jagannath Coal of -6+16# size

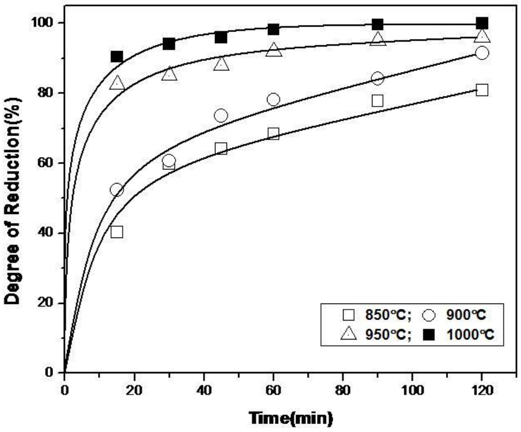


Fig-4.18 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#) 80%+(-18+25#) 10% +(-10+16#)10% and reduced by Jagannath Coal of -6+16# size

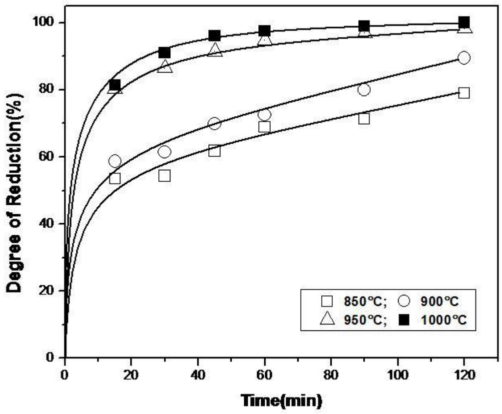


Fig-4.19 Effects of Time and Temperature on Degree of Reduction of Zenith iron ore pellets made from fines of (-100#) 70%+(-18+25#) 15% +(-10+16#)15% and reduced by Jagannath Coal of -6+16# size

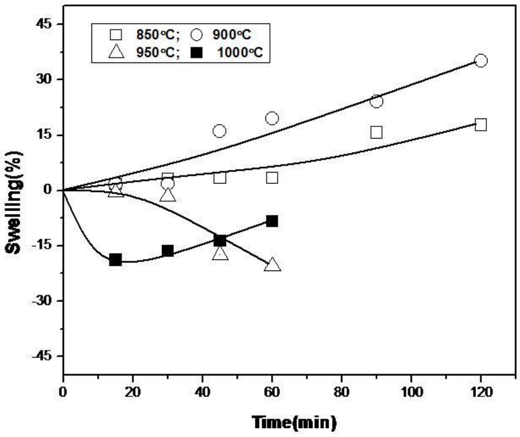


Fig-4.20 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj coal of -6+16# size

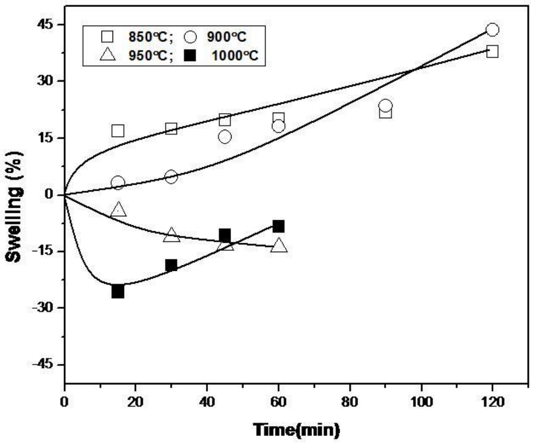


Fig-4.21 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj coal of -16+25# size

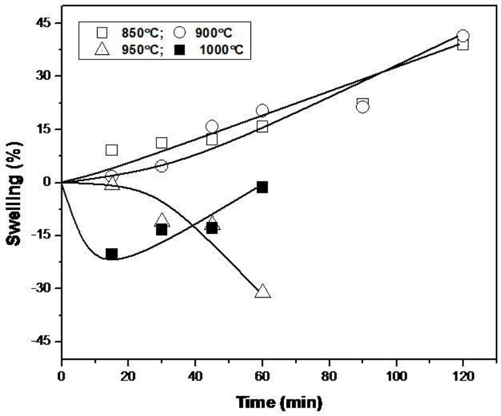


Fig-4.22 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj coal of -72# size

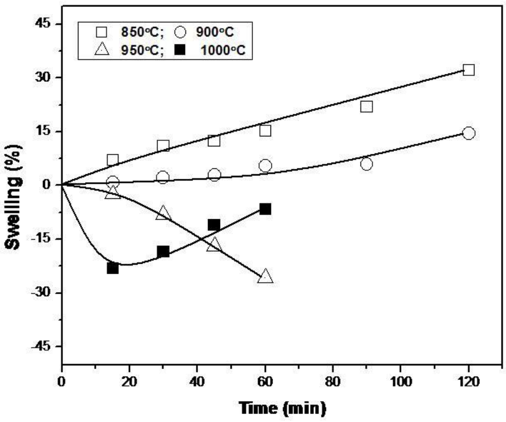


Fig-4.23 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)80%+ (-18+25#)10%+(-10+16#)10% and reduced by Lingaraj coal of -6+16# size

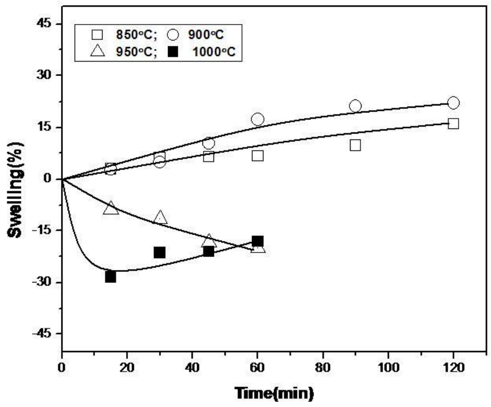


Fig-4.24 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)80%+ (-18+25#)10%+(-10+16#)10% and reduced by Lingaraj coal of -16+25# size

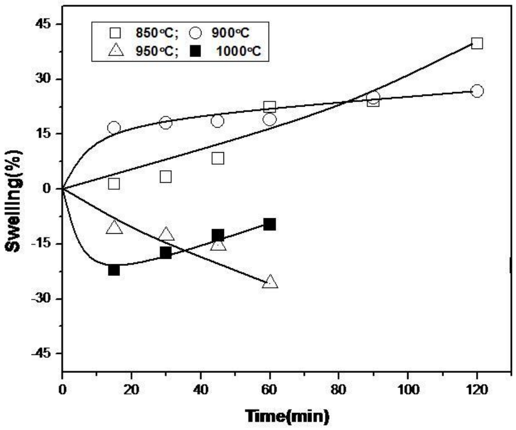


Fig-4.25 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)80%+ (-18+25#)10%+(-10+16#)10% and reduced by Lingaraj coal of -72# size

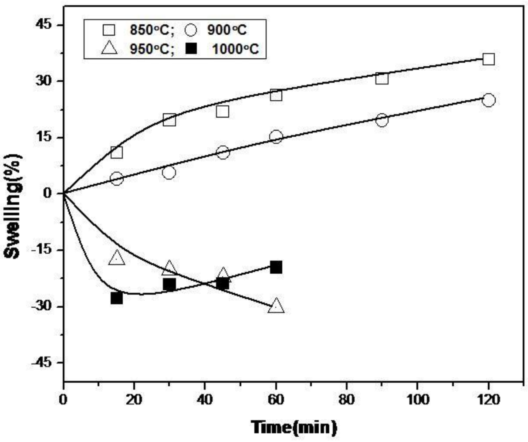


Fig-4.26 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)70%+ (-18+25#)15%+(-10+16#)15% and reduced by Lingaraj coal of -6+16# size

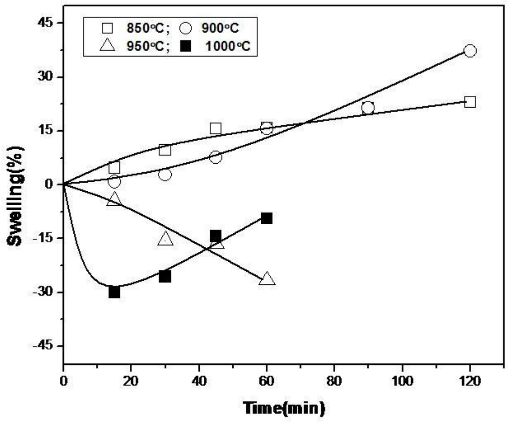


Fig-4.27 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)70%+ (-18+25#)15%+(-10+16#)15% and reduced by Lingaraj coal of -16+25# size

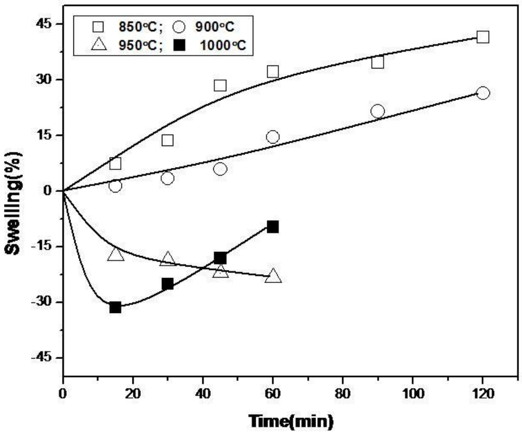


Fig-4.28 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)70%+ (-18+25#)15%+(-10+16#)15% and reduced by Lingaraj coal of -72# size

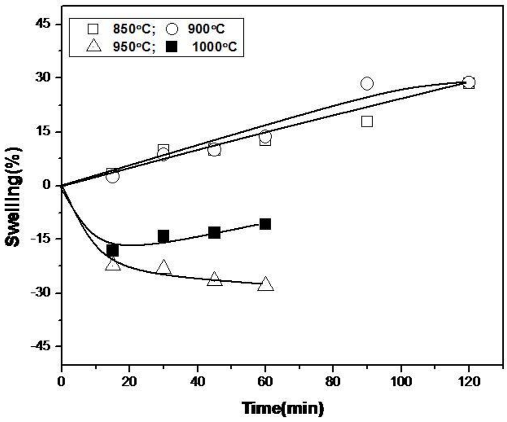


Fig-4.29 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Ananta coal of -6+16# size

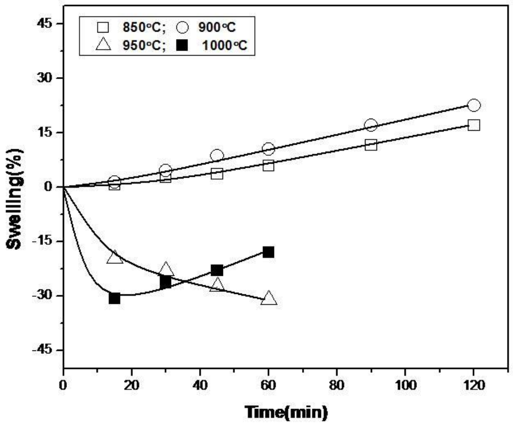


Fig-4.30 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Ananta coal of -16+25# size

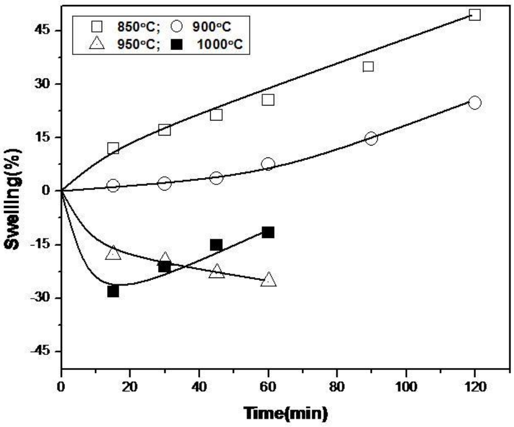


Fig-4.31 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10% +(-10+16#)10% and reduced by Ananta coal of -6+16# size

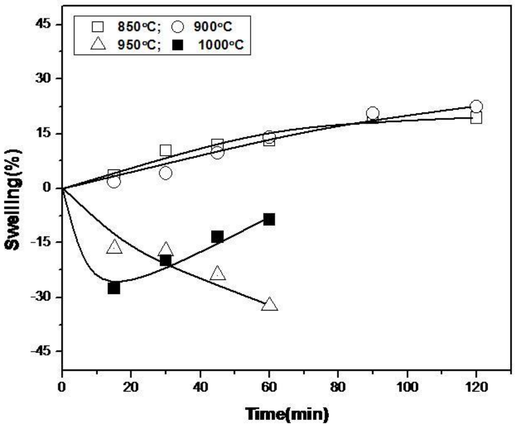


Fig-4.32 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10% +(-10+16#)10% and reduced by Ananta coal of -16+25# size

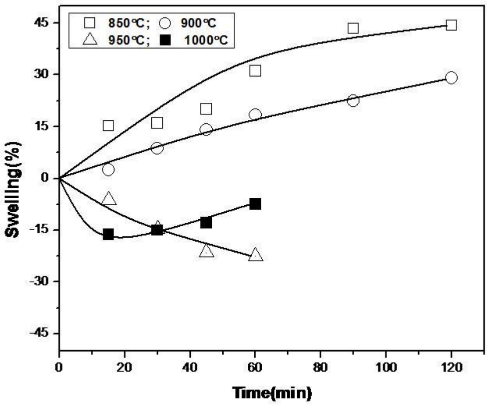


Fig-4.33 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)70%+(-18+25#)15% +(-10+16#)15% and reduced by Ananta coal of -6+16# size

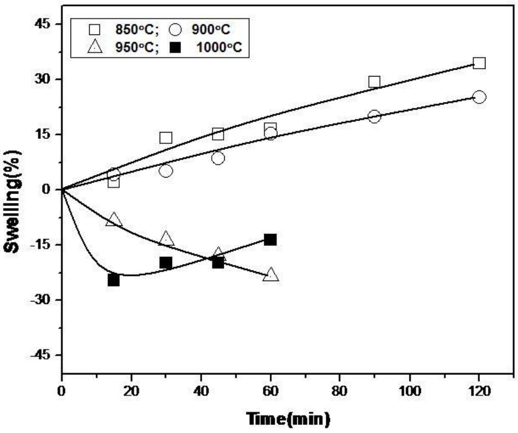


Fig-4.34 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)70%+(-18+25#)15% +(-10+16#)15% and reduced by Ananta coal of -16+25# size

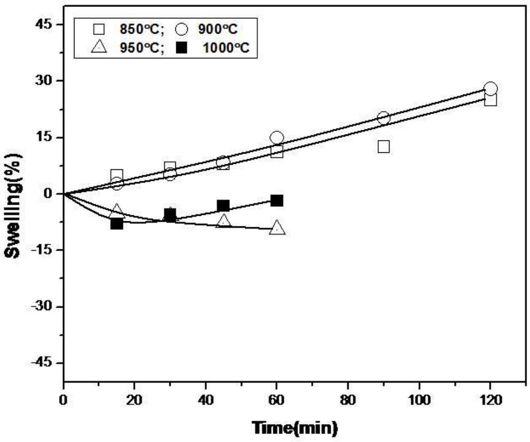


Fig-4.35 Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Jagannath coal of -6+16# size

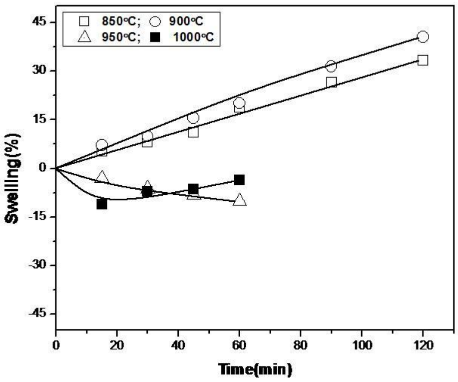


Fig-4.36 **Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10% +(-10+16#)10% and reduced by Jagannath coal of -6+16# size**

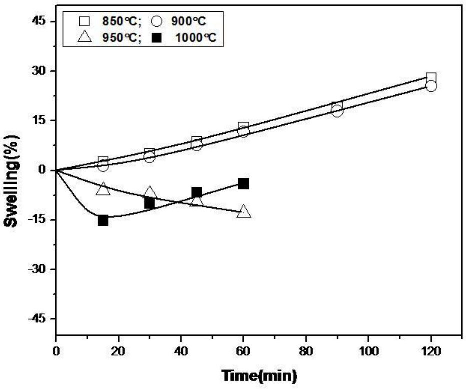


Fig-4.37 **Effects of Time and Temperature on Extent of Swelling of Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10% +(-10+16#)10% and reduced by Jagannath coal of -6+16# size**

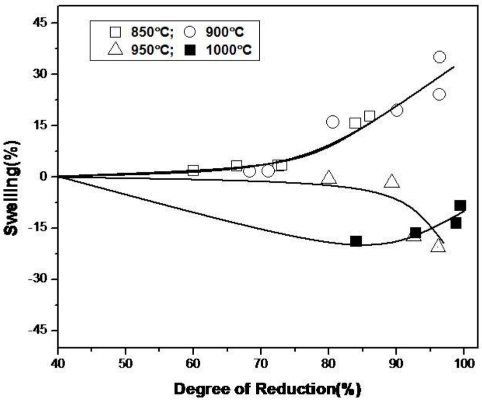


Fig-4.38 **Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj coal of -6+16# size**

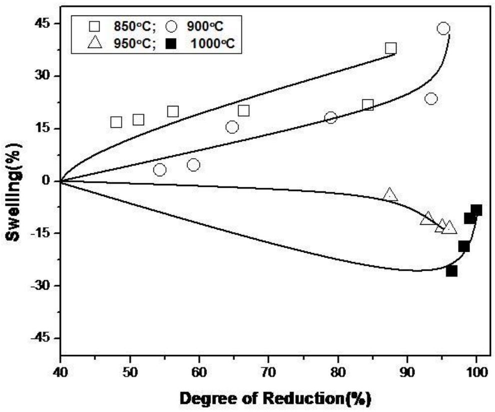


Fig-4.39 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj coal of -16+25# size

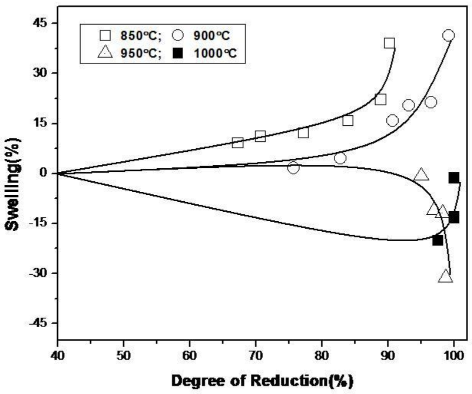


Fig-4.40 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj coal of -72# size

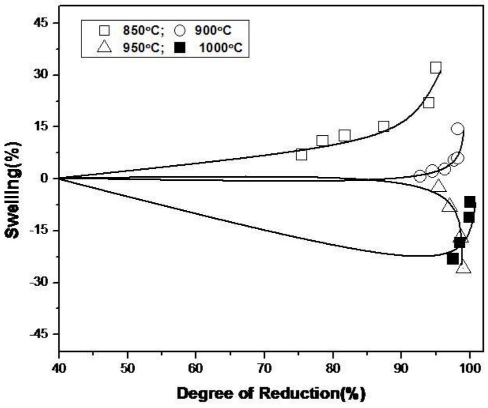


Fig-4.41 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)80%+ (-18+25#)10%+(-10+16#)10% and reduced by Lingaraj coal of -6+16# size

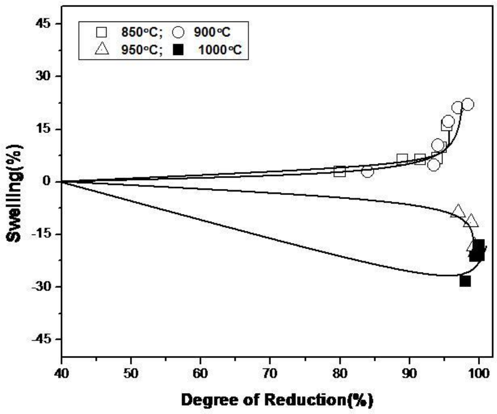


Fig-4.42 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)80%+ (-18+25#)10%+(-10+16#)10% and reduced by Lingaraj coal of -16+25# size

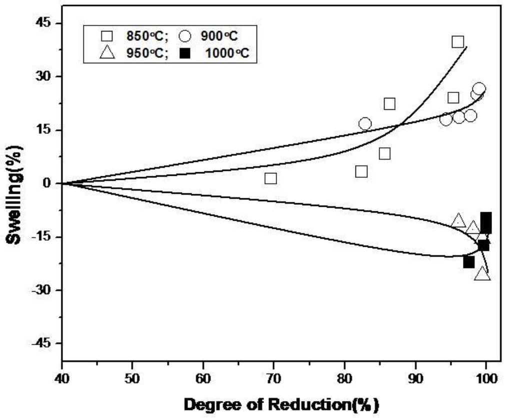


Fig-4.43 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)80%+ (-18+25#)10%+(-10+16#)10% and reduced by Lingaraj coal of -72# size

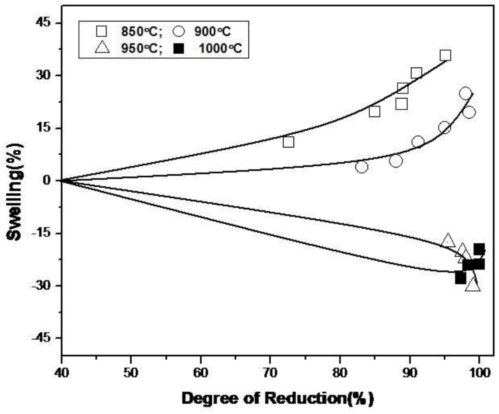


Fig-4.44 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)70%+ (-18+25#)15%+(-10+16#)15% and reduced by Lingaraj coal of -6+16# size

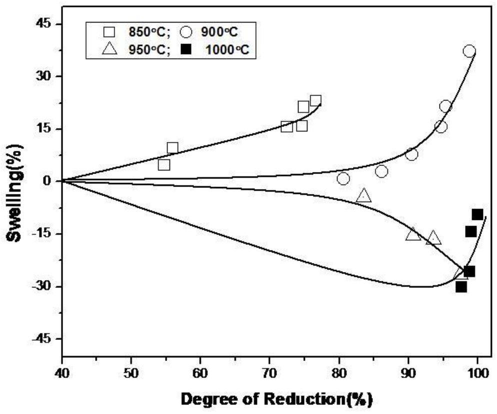


Fig-4.45 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)70%+ (-18+25#)15%+(-10+16#)15% and reduced by Lingaraj coal of -16+25# size

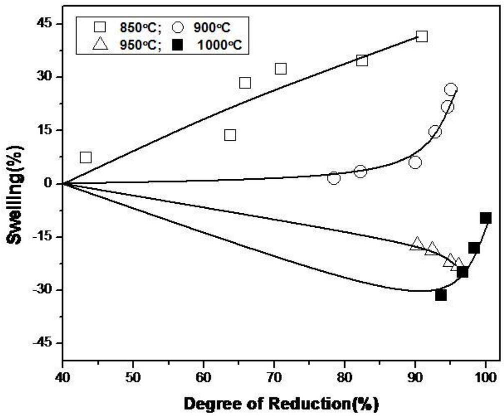


Fig-4.46 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)70%+ (-18+25#)15%+(-10+16#)15% and reduced by Lingaraj coal of -72# size

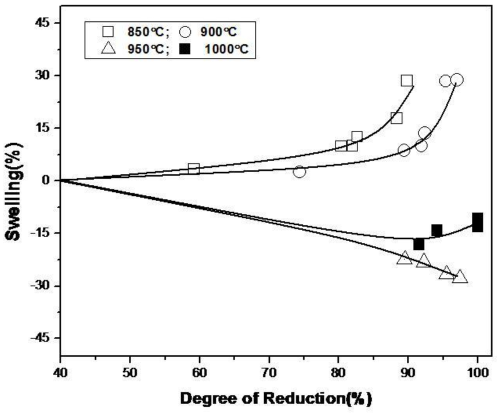


Fig-4.47 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Ananta coal of -6+16# size

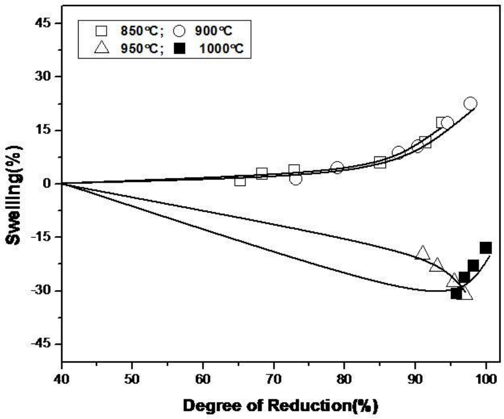


Fig-4.48 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Ananta coal of -16+25# size

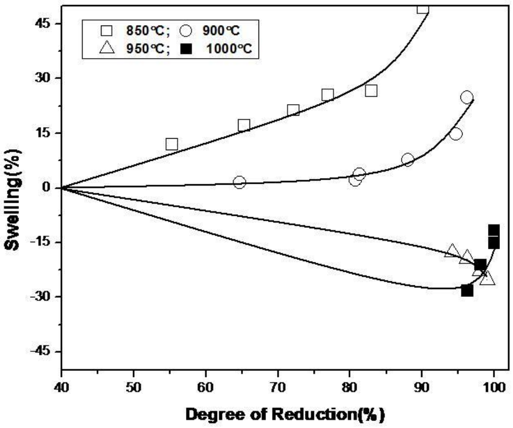


Fig-4.49 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10% +(-10+16#)10% and reduced by Ananta coal of -6+16# size

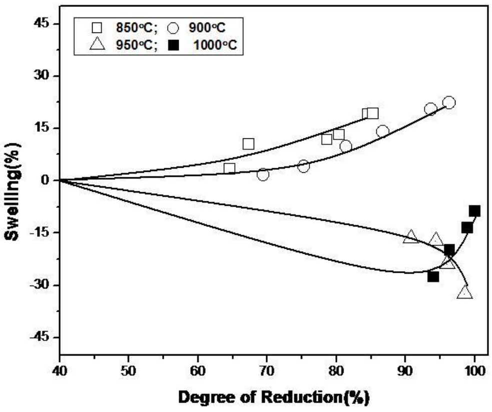


Fig-4.50 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10% +(-10+16#)10% and reduced by Ananta coal of -16+25# size

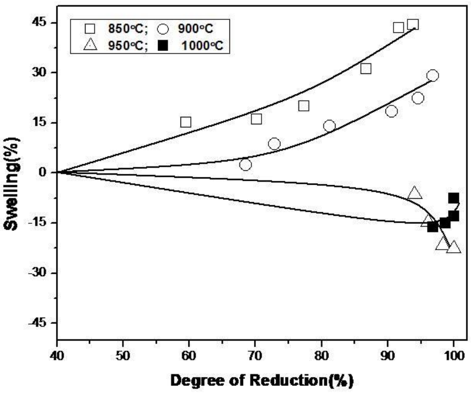


Fig-4.51 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)70%+(-18+25#)15% +(-10+16#)15% and reduced by Ananta coal of -6+16# size

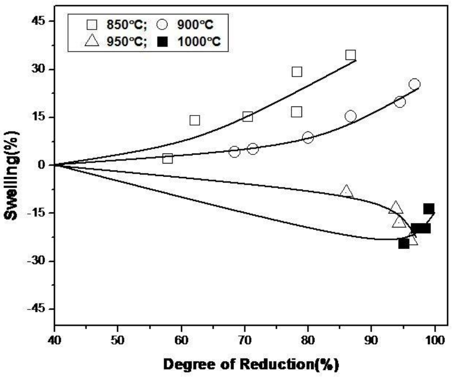


Fig-4.52 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)70%+(-18+25#)15% +(-10+16#)15% and reduced by Ananta coal of -16+25# size

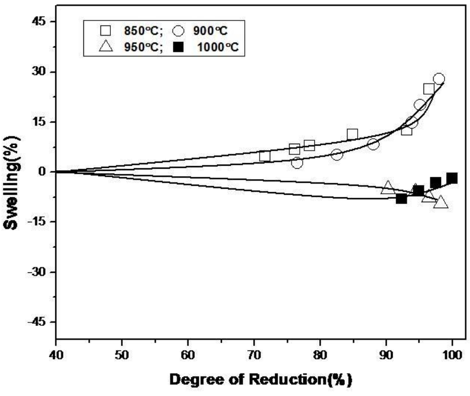


Fig-4.53 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of -100# and reduced by Jagannath coal of -6+16# size

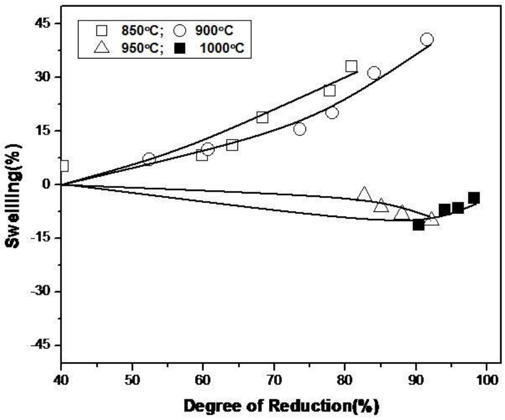


Fig-4.54 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10% +(-10+16#)10% and reduced by Jagannath coal of -6+16# size

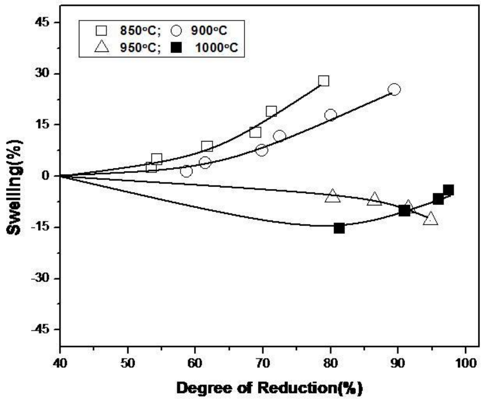


Fig-4.55 Correlation between Degree of Reduction and Percentage Swelling of Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10% +(-10+16#)10% and reduced by Jagannath coal of -6+16# size

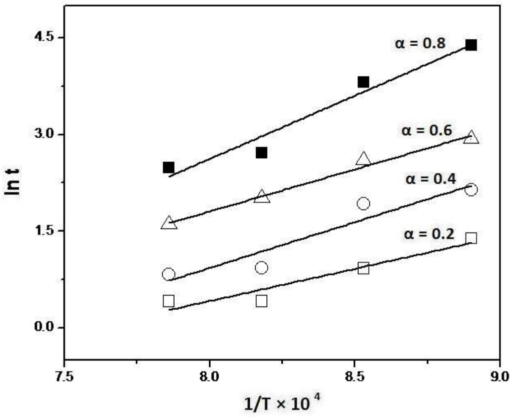


Fig-4.56 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj coal of -6+16# size

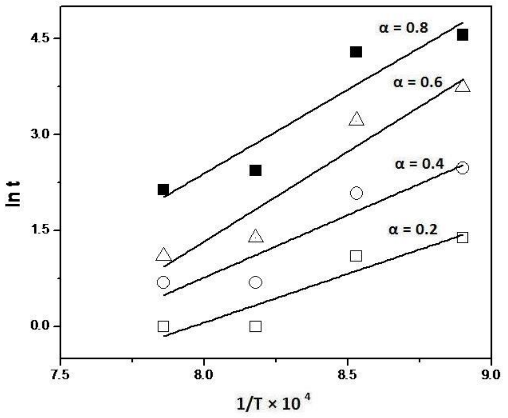


Fig-4.57 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj coal of -16+25# size

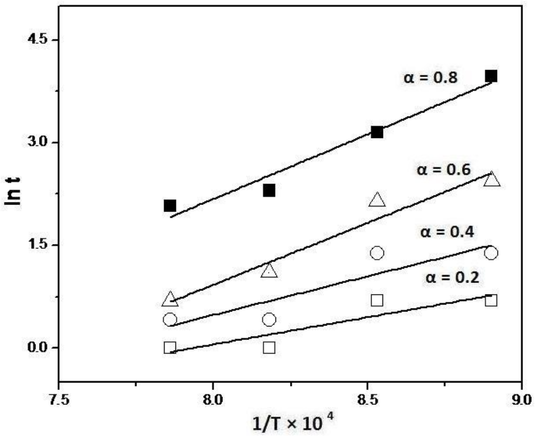


Fig-4.58 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of -100# and reduced by Lingaraj coal of -72# size

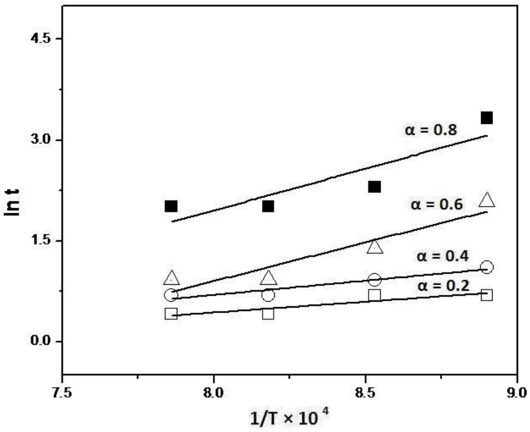


Fig-4.59 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of (-100#)80%+ (-18+25#)10%+(-10+16#)10% and reduced by Lingaraj coal of -6+16# size

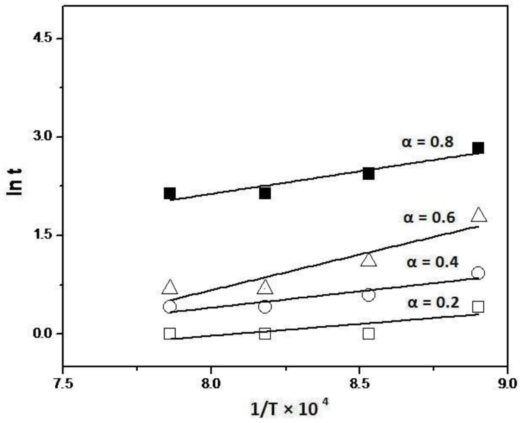


Fig-4.60 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#) 10%+(-10+16#)10% and reduced by Lingaraj coal of -16+25# size

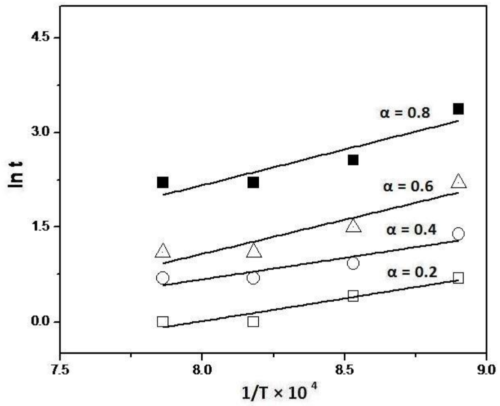


Fig-4.61 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of (-100#)80%+ (-18+25#)10%+(-10+16#)10% and reduced by Lingaraj coal of -72# size

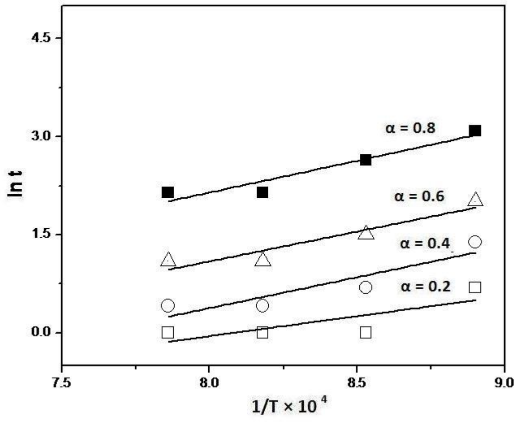


Fig-4.62 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of (-100#)70%+ (-18+25#)15%+(-10+16#)15% and reduced by Lingaraj coal of -6+16# size

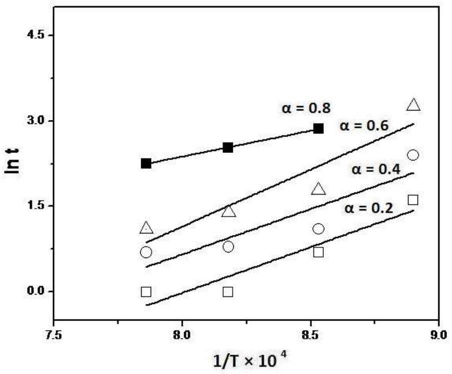


Fig-4.63 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of (-100#)70%+(-18+25#)15%+(-10+16#)15% and reduced by Lingaraj coal of -16+25# size

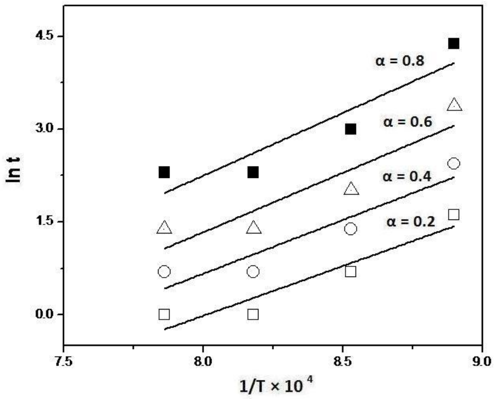


Fig-4.64 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of (-100#)70%+(-18+25#)15%+(-10+16#)15% and reduced by Lingaraj coal of -72# size

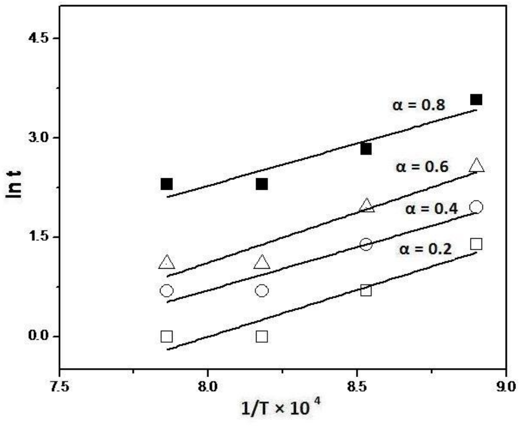


Fig-4.65 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of -100# and reduced by Ananta coal of -6+16# size

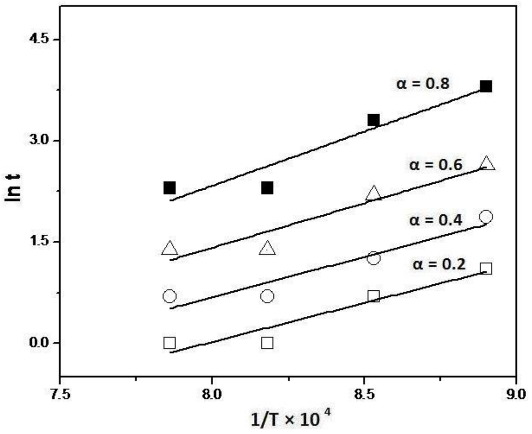


Fig-4.66 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of -100# and reduced by Ananta coal of -16+25# size

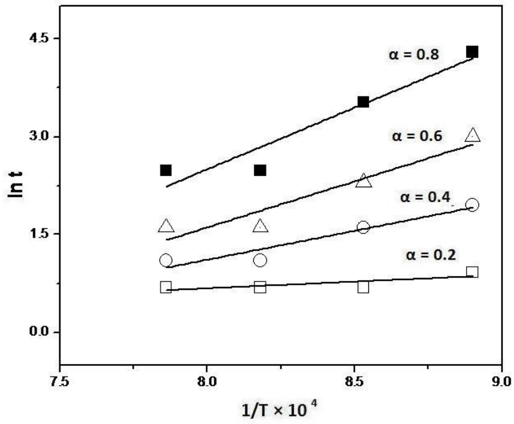


Fig-4.67 Plots of ln t Vs 1/T for Zenith iron ore pellets made from fines of (-100#)80%+(-18+25#)10%+(-10+16#)10% and reduced by Ananta coal of -6+16# size

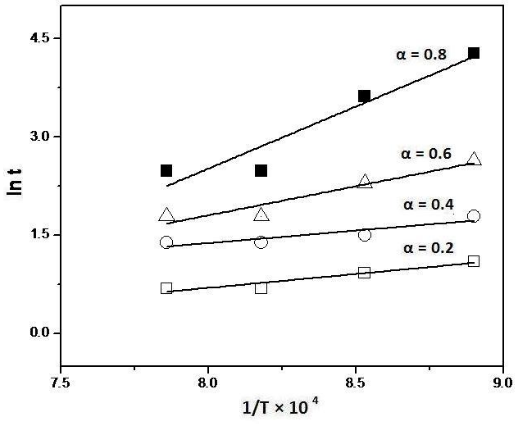


Fig-4.68 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of (-100#)80%+ (-18+25#)10%+(-10+16#)10% and reduced by Ananta coal of -16+25# size

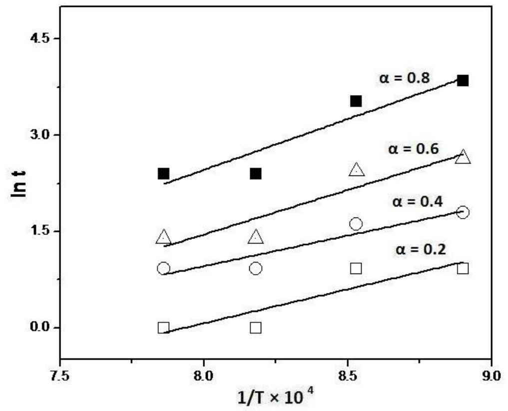


Fig-4.69 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of (-100#)70%+ (-18+25#)15%+(-10+16#)15% and reduced by Ananta coal of -6+16# size

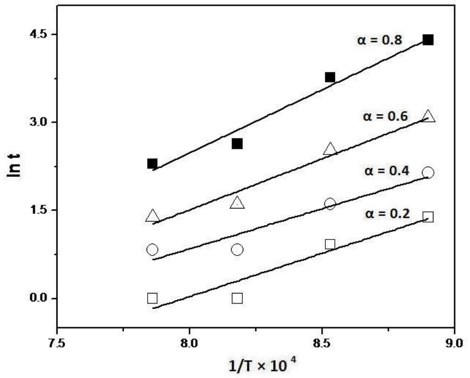


Fig-4.70 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of -100#)70%+ (-18+25#)15%+(-10+16#)15% and reduced by Ananta coal of -16+25# size

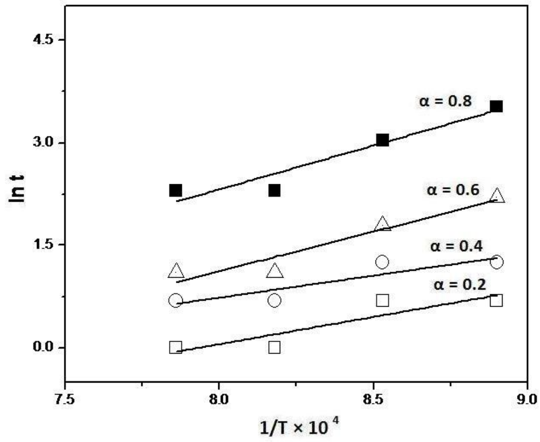


Fig-4.71 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of -100# and reduced by Jagannath coal of -6+16# size

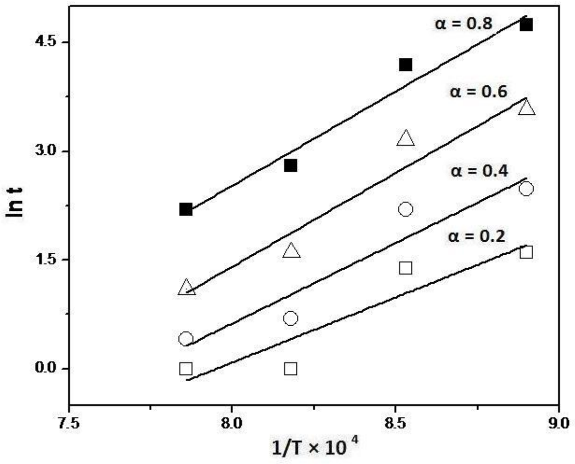


Fig-4.72 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of (-100#)80%+ (-18+25#)10%+(-10+16#)10% and reduced by Jagannath coal of -6+16# size

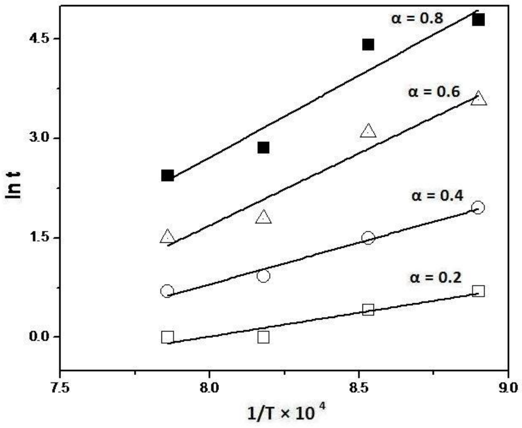


Fig-4.73 Plot of ln t Vs 1/T for Zenith iron ore pellets made from fines of (-100#)70%+(-18+25#) 15%+(-10+16#) 15% and reduced by Jagannath coal of -6+16# size

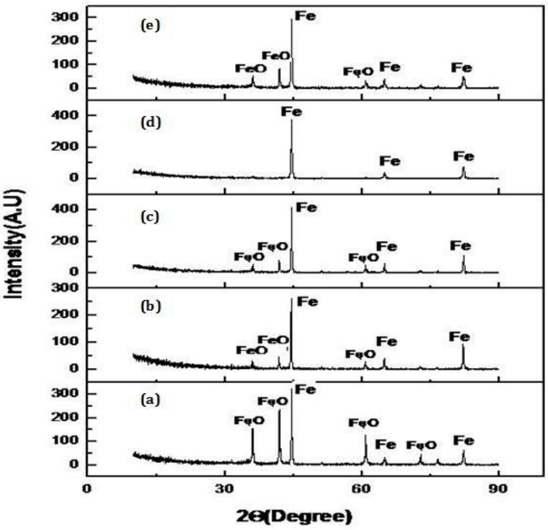


Fig-4.74 XRD Patterns of Zenith iron ore pellets made from fines of -100# reduced at different temperatures and times with Lingaraj coal of -6+16# size (a)Temp.-850^{0}C, Time- 15 min (b)Temp.-900^{0}C, Time- 90 min (c) Temp.-900^{0}C, Time-120 min (d) Temp.-950^{0}C, Time- 60 min (e) Temp.-1000^{0}C, Time- 45 min

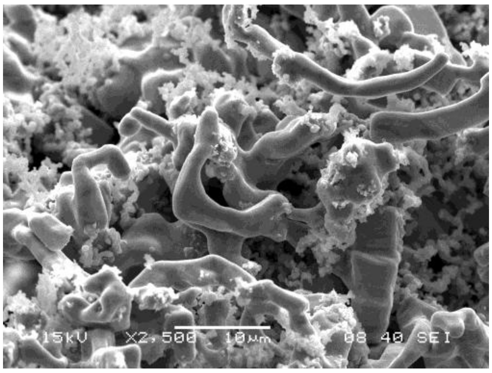


Fig-4.75 SEM image of Zenith iron ore pellet reduced at temperature 900^{0}C , showing iron whisker formation

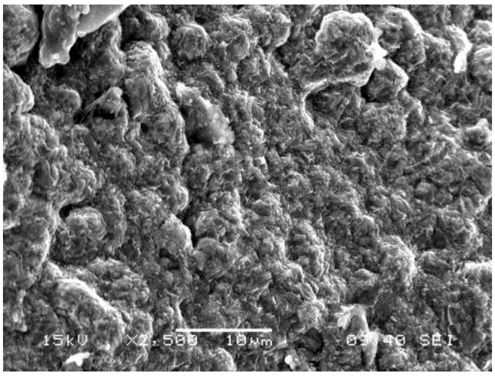


Fig-4.76 SEM image of Zenith iron ore pellet reduced at temperature 1000^{0}C, showing dense structure due to sintering

TABLES

Table- 4.1

Chemical Composition and Loss on Ignition of Iron ore

Iron Ore	**Chemical Composition (weight percent on dry basis)**						
	Fe (Total)	**Fe_2O_3**	**Al_2O_3**	**SiO_2**	**TiO_2**	**MnO**	**LIO[*]**
Zenith Iron ore Mine	64.51	92.25	2.34	1.55	0.14	0.03	3.69

LOI[*] = Loss on Ignition

Table- 4.2

Strength Properties and Porosity Value of Lump Iron Ore (Dried Basis)

Iron Ore	**Tumbler Index (% of +6.3mm)**	**Abrasion Index (% of – 0.5mm)**	**Shatter Index (% of – 5mm fraction)**	**Apparent Porosity**
Zenith Iron ore Mine	85.3	8.9	0.87	2

Table-4.3

Crushing Strength and Porosity of Fired Iron ore pellets

Iron ore Mine	Constituents of Different phases in Iron ore pellets	Crushing Strength (Kg)	Apparent Porosity (%)
Zenith Mine	-100#	485	18
	(-100#)80% + (-18+25#)10% + (-10+16#)10%	165	13.3
	(-100#)70% + (-18+25#)15% + (-10+16#)15%	235	16.3
	(-100#)60% + (-18+25#)20% + (-10+16#)20%	215	20
	(-100#)80% + (-18+25#)20%	520	13.4
	(-100#)70% + (-18+25#)30%	440	19.3
	(-100#)60% + (-18+25#)40%	265	17.9

Table-4.4

Proximate Analysis of Noncoking coal char

Non Coking Coal Char	Moisture (%)	Volatile Matter (%)	Ash (%)	Fixed Carbon (%)
Lingaraj Mine	3	2	27	68
Ananta Mine	2	4	33	61
Jagannath Mine	2	4	32	62

Table- 4.5

Proximate Analysis, Reactivity, Caking Indices, Gross Calorific value and Ash fusion temperature of Noncoking Coals

Non-coking Coal	Moisture (%)	Volatile Matter (%)	Ash (%)	Fixed Carbon (%)	Reactivity (cc/gm.sec)	Caking Index	Gross Calorific value (Kcal/Kg)	Ash Fusion Temperature (ºC)
Lingaraj Mine	5	29	22	44	1.196	Nil	5015	IDT = 1152 , ST= 1346, HT > 1400, FT > 1400
Ananta Mine	12	38	13	37	1.061	Nil	5742	IDT = 1110 , ST= 1238, HT > 1400, FT > 1400
Jagannath Mine	9	36	17	38	1.246	Nil	5499	IDT = 1122 , ST= 1260, HT > 1400, FT > 1400

Table- 4.6

Zenith iron ore pellet Constituents: (-100#) 100%, Lingaraj coal (size = -6+16#),

Crushing Strength = 485 Kg

Temperature (°C)	**Time (minutes)**	**Degree of reduction (%)**	**Swelling (%)**
850	15	60	1.84
	30	66.48	3.15
	45	72.56	3.33
	60	73.08	3.37
	90	83.97	15.72
	120	86.09	17.77
900	15	68.33	1.66
	30	71.08	1.74
	45	80.61	16.04
	60	90.05	19.46
	90	96.32	24.04
	120	96.34	35.07
950	15	80	-0.45
	30	89.29	-1.66
	45	92.49	-17.42
	60	96.13	-20.55
	90	98.6	
	120	99	
1000	15	84.07	-18.83
	30	92.82	-16.4
	45	98.77	-13.57
	60	99.4	-8.36
	90	100	
	120	100	

Table- 4.7

Zenith iron ore pellet Constituents: (-100#) 100%, Lingaraj coal (size = -16+25#),

Crushing Strength = 485 Kg

Temperature(°C)	Time(minutes)	Degree of reduction(%)	Swelling (%)
850	15	48.03	16.92
	30	51.23	17.5
	45	56.21	19.84
	60	66.45	20.11
	90	84.29	21.89
	120	87.59	37.93
900	15	54.29	3.16
	30	59.18	4.67
	45	64.8	15.38
	60	78.99	18.12
	90	93.43	23.52
	120	95.23	43.68
950	15	87.43	-4.31
	30	92.92	-11.06
	45	94.99	-13.3
	60	96	-13.69
	90	98.2	
	120	99	
1000	15	96.4	-25.75
	30	98.11	-18.57
	45	99	-10.65
	60	100	-8.41
	90	100	
	120	100	

Table- 4.8

Zenith iron ore pellet Constituents: (-100#) 100%, Lingaraj coal (size = -72#)

Crushing Strength = 485 Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	67.26	9.13
	30	70.69	11.1
	45	77.25	12.14
	60	83.93	15.8
	90	88.89	22.12
	120	90.28	39.02
900	15	75.66	1.64
	30	82.83	4.57
	45	90.71	15.83
	60	93.11	20.36
	90	96.56	21.28
	120	99.21	41.38
950	15	95	-0.66
	30	97	-10.98
	45	98.2	-11.9
	60	98.7	-31.16
	90	99.5	
	120	99.5	
1000	15	97.5	-20.19
	30	100	-13.34
	45	100	-12.89
	60	100	-1.36
	90	100	
	120	100	

Table- 4.9

Zenith iron ore pellet Constituents: (-100#) 80%+(-18+25#)10%+(-10+16#)10%, Lingaraj coal (size = -6+16#), Crushing Strength = 165 Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	75.4	6.95
	30	78.48	10.96
	45	81.7	12.49
	60	87.43	15.15
	90	94	22
	120	95	32.07
900	15	92.73	0.67
	30	94.5	2.21
	45	96.3	2.82
	60	97.7	5.39
	90	98.2	5.93
	120	98.2	14.45
950	15	95.4	-2.46
	30	97	-8.11
	45	98.6	-16.92
	60	99	-25.83
	90	99	
	120	99.5	
1000	15	97.5	-23.11
	30	98.5	-18.55
	45	99.9	-11.12
	60	100	-6.71
	90	100	
	120	100	

Table- 4.10

Zenith iron ore pellet Constituents: (-100#) 80%+ (-18+25#) 10%+ (-10+16#) 10%, Lingaraj coal (size = -16+25#), Crushing Strength = 165 Kg

Temperature (°C)	**Time (minutes)**	**Degree of reduction (%)**	**Swelling (%)**
850	15	80	2.99
	30	89	6.31
	45	91.5	6.4
	60	94	6.72
	90	94.5	9.73
	120	95.4	16.05
900	15	84.01	2.86
	30	93.53	4.85
	45	94.11	10.4
	60	95.63	17.28
	90	97	21.13
	120	98.4	22.02
950	15	97	-8.77
	30	98.8	-11.56
	45	99.3	-18.34
	60	99.5	-19.93
	90	99.7	
	120	100	
1000	15	98	-28.36
	30	99.5	-21.32
	45	100	-21.01
	60	100	-18.01
	90	100	
	120	100	

Table- 4.11

Zenith iron ore pellet Constituents: (-100#) 80%+(-18+25#)10%+(-10+16#)10%, Lingaraj coal (size = -72#), Crushing Strength = 165 Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	69.54	1.4
	30	82.35	3.38
	45	85.63	8.41
	60	86.34	22.39
	90	95.4	24.07
	120	96	39.78
900	15	82.89	16.76
	30	94.33	17.98
	45	96.2	18.52
	60	97.82	19.03
	90	98.7	25.03
	120	99	26.67
950	15	96	-10.88
	30	98.1	-12.76
	45	99.4	-15.38
	60	99.4	-25.73
	90	99.5	
	120	99.5	
1000	15	97.5	-22.1
	30	99.6	-17.43
	45	100	-12.62
	60	100	-9.71
	90	100	
	120	100	

Table- 4.12

Zenith iron ore pellet Constituents: (-100#) 70%+(-18+25#) 15%+(-10+16#)15%, Lingaraj coal (size = -6+16#), Crushing Strength = 235 Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	72.59	10.96
	30	84.93	19.69
	45	88.83	21.95
	60	89.03	26.3
	90	90.97	30.66
	120	95.14	35.78
900	15	83.08	3.94
	30	88	5.65
	45	91.22	11.07
	60	95.03	15.14
	90	98.54	19.46
	120	99	24.87
950	15	95.42	-17.41
	30	97.54	-20.16
	45	98	-22.11
	60	99.02	-30.1
	90	100	
	120	100	
1000	15	97.32	-27.82
	30	98.36	-24.04
	45	100	-23.86
	60	100	-19.53
	90	100	
	120	100	

Table- 4.13

Zenith iron ore pellet Constituents: (-100#) 70%+(-18+25#)15%+(-10+16#)15%,

Lingaraj coal (size = -16+25#), Crushing Strength = 235 Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	54.76	4.73
	30	56	9.67
	45	72.46	15.61
	60	74.64	15.86
	90	74.83	21.35
	120	76.61	23.08
900	15	80.69	0.86
	30	86.13	2.79
	45	90.44	7.69
	60	94.7	15.63
	90	95.45	21.36
	120	98.76	37.3
950	15	83.51	-4.43
	30	90.63	-15.46
	45	93.58	-16.46
	60	97.43	-26.58
	90	98.7	
	120	100	
1000	15	97.66	-30.61
	30	98.83	-25.6
	45	99	-14.36
	60	100	-9.4
	90	100	
	120	100	

Table- 4.14

Zenith iron ore pellet Constituents: (-100#) 70%+(-18+25#)15%+(-10+16#)15%,

Lingaraj coal (size = -72#), Crushing Strength = 235 Kg

Temperature (°C)	**Time (minutes)**	**Degree of reduction (%)**	**Swelling (%)**
850	15	43.29	7.39
	30	63.78	13.67
	45	65.87	28.4
	60	70.95	32.26
	90	82.44	34.7
	120	91	41.56
900	15	78.44	1.46
	30	82.23	3.42
	45	90	5.96
	60	92.83	14.61
	90	94.67	21.55
	120	95.09	26.43
950	15	90.31	-17.45
	30	92.42	-18.8
	45	95	-22.03
	60	96.11	-23.32
	90	98.9	
	120	99	
1000	15	93.71	-31.42
	30	96.8	-25.01
	45	98.4	-18.11
	60	100	-9.72
	90	100	
	120	100	

Table- 4.15

Zenith iron ore pellet Constituents: -100# (100%),Ananta Coal (size = -6+16#), Crushing Strength = 485 Kg

Temperature(°C)	Time(minutes)	Degree of reduction (%)	Swelling (%)
850	15	59.17	3.23
	30	80.39	9.89
	45	81.98	9.96
	60	82.67	12.59
	90	88.36	17.91
	120	89.83	28.53
900	15	74.36	2.53
	30	89.4	8.65
	45	91.89	10.01
	60	92.35	13.64
	90	95.39	28.45
	120	97	28.76
950	15	89.47	-22.37
	30	92.22	-23.17
	45	95.53	-26.61
	60	97.43	-27.83
	90	98.83	
	120	100	
1000	15	91.54	-18.17
	30	94.11	-14.09
	45	100	-13.11
	60	100	-10.77
	90	100	
	120	100	

Table-4.16

Zenith iron ore pellet Constituents: -100# (100%), Ananta Coal (size = -16+25#), Crushing Strength = 485 Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	65.29	0.84
	30	68.33	2.83
	45	72.92	3.71
	60	85.07	5.9
	90	91.42	11.68
	120	93.76	17.1
900	15	73.12	1.36
	30	79.01	4.51
	45	87.66	8.66
	60	90.32	10.53
	90	94.57	17.09
	120	97.83	22.45
950	15	91	-19.73
	30	93.05	-23.11
	45	95.45	-27.46
	60	97	-31.03
	90	98.1	
	120	100	
1000	15	95.83	-30.79
	30	97	-26.28
	45	98.23	-22.89
	60	100	-17.96
	90	100	
	120	100	

Table-4.17

Zenith iron ore pellet Constituents: (100#) 80%+(-18+25#)10%+(-10+16#)10%

Ananta Coal (size = -6+16#), Crushing Strength = 165 Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	55.32	12.01
	30	65.33	17.14
	45	72.14	21.35
	60	76.92	25.47
	90	82.96	26.65
	120	90.14	49.4
900	15	64.71	1.39
	30	80.77	2.08
	45	81.29	3.67
	60	88	7.67
	90	94.68	14.7
	120	96.22	24.76
950	15	94.15	-17.73
	30	96.23	-19.48
	45	98	-22.93
	60	98.99	-25.28
	90	100	
	120	100	
1000	15	96.23	-28.2
	30	98.11	-21.16
	45	100	-15.09
	60	100	-11.63
	90	100	
	120	100	

Table-4.18

Zenith iron ore pellet Constituents: (100#) 80%+(-18+25#)10%+(-10+16#)10%

Ananta Coal (size = -16+25#), Crushing Strength = 165 Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	64.62	3.42
	30	67.32	10.43
	45	78.63	11.76
	60	80.4	13.19
	90	84.56	19.16
	120	85.31	19.31
900	15	69.44	1.73
	30	75.32	4.11
	45	81.43	9.67
	60	86.73	14.01
	90	93.67	20.53
	120	96.3	22.53
950	15	90.78	-16.5
	30	94.37	-17.15
	45	96	-23.89
	60	98.55	-32.35
	90	100	
	120	100	
1000	15	94	-27.63
	30	96.39	-19.83
	45	99	-13.39
	60	100	-8.67
	90	100	
	120	100	

Table-4.19

Zenith iron ore pellet Constituents: (100#) 70%+(-18+25#)15%+(-10+16#)15%

Ananta Coal (size = -6+16#), Crushing Strength = 235 Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	59.54	15.24
	30	70.15	16.02
	45	77.37	20.11
	60	86.72	31.1
	90	91.66	43.37
	120	93.83	44.34
900	15	68.54	2.43
	30	72.83	8.69
	45	81.17	14.11
	60	90.65	18.3
	90	94.57	22.49
	120	96.83	29.16
950	15	94	-6.34
	30	96.11	-14.8
	45	98.34	-21.56
	60	100	-22.61
	90	100	
	120	100	
1000	15	96.79	-16.23
	30	98.68	-15.03
	45	100	-12.91
	60	100	-7.52
	90	100	
	120	100	

Table-4.20

Zenith iron ore pellet Constituents: (100#) 70%+(-18+25#)15%+(-10+16#)15%

Ananta Coal (size = -16+25#), Crushing Strength = 235 Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	57.79	2.08
	30	62.09	14.07
	45	70.5	15.13
	60	78.17	16.69
	90	78.22	29.22
	120	86.75	34.41
900	15	68.4	4.12
	30	71.32	5.09
	45	80.01	8.66
	60	86.72	15.34
	90	94.5	19.85
	120	96.82	25.26
950	15	85.97	-8.43
	30	93.8	-13.61
	45	94.32	-17.93
	60	96.1	-23.44
	90	98.22	
	120	99.3	
1000	15	95.12	-24.48
	30	97	-19.7
	45	98.56	-19.69
	60	99.05	-13.61
	90	100	
	120	100	

Table-4.21

Zenith iron ore pellet Constituents: -100#

Jagannath Coal (size = -6+16#), Crushing Strength = 485Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	71.58	4.86
	30	76.12	6.9
	45	78.4	7.98
	60	84.93	11.24
	90	93.14	12.51
	120	96.44	24.93
900	15	76.53	2.73
	30	82.5	5.15
	45	88.04	8.3
	60	93.87	14.86
	90	95.11	20.11
	120	98	27.86
950	15	90.2	-5.03
	30	94.37	-5.85
	45	96.43	-7.69
	60	98.23	-9.48
	90	100	
	120	100	
1000	15	92.33	-7.96
	30	94.86	-5.58
	45	97.5	-3.17
	60	100	-1.83
	90	100	
	120	100	

Table-4.22

Zenith iron ore pellet Constituents: (100#) 80%+(-18+25#)10%+(-10+16#)10%

Jagannath Coal (size = -6+16#), Crushing Strength = 165 Kg

Temperature (°C)	Time (minutes)	Degree of reduction (%)	Swelling (%)
850	15	40.23	5.23
	30	59.84	8.11
	45	64.13	11.06
	60	68.36	18.7
	90	77.82	26.42
	120	80.9	33.16
900	15	52.33	7.13
	30	60.69	9.83
	45	73.62	15.6
	60	78.18	20.09
	90	84.12	31.3
	120	91.54	40.6
950	15	82.66	-3.13
	30	85.06	-6.24
	45	88	-8.29
	60	92.11	-10.14
	90	94.96	
	120	96.1	
1000	15	90.43	-11.23
	30	94.02	-7.11
	45	96	-6.54
	60	98.17	-3.66
	90	99.62	
	120	100	

Table-4.23

Zenith iron ore pellet Constituents: (100#) 70%+(-18+25#) 15% + (-10+16#) 15%

Jagannath Coal (size = -6+16#), Crushing Strength = 235 Kg

Temperature (°C)	**Time (minutes)**	**Degree of reduction (%)**	**Swelling (%)**
850	15	53.52	2.62
	30	54.32	4.93
	45	61.75	8.66
	60	68.89	12.84
	90	71.24	18.98
	120	79	27.83
900	15	58.67	1.36
	30	61.43	3.93
	45	69.82	7.54
	60	72.46	11.63
	90	79.98	17.88
	120	89.44	25.44
950	15	80.3	-6.22
	30	86.47	-7.13
	45	91.47	-9.44
	60	94.75	-12.89
	90	97	
	120	98.23	
1000	15	81.32	-15.23
	30	90.94	-10.11
	45	95.98	-6.73
	60	97.47	-4.11
	90	99	
	120	100	

Table-4.24

Estimated Activation Energy of Zenith Iron Ore Pellets reduced by Lingaraj Coal (Temp.range: 850-1000^{o}C)

Constituents of Pellets	Coal Size	Fractional Reduction (α)	Activation Energy (KJ/ mole)
(-100#)100%	-6+16#	0.2	78.98
		0.4	124.71
		0.6	123.88
		0.8	166.28
	-16+25#	0.2	126.37
		0.4	162.95
		0.6	233.62
		0.8	217.83
	-72#	0.2	66.51
		0.4	93.95
		0.6	150.48
		0.8	157.13
(-100#)80%+ (-18+25#) 10% + (-10+16#)10%	-6+16#	0.2	45.73
		0.4	41.57
		0.6	103.93
		0.8	94.78
	-16+25#	0.2	29.93
		0.4	41.57
		0.6	89.79
		0.8	57.37
	-72#	0.2	59.86
		0.4	56.54
		0.6	89.79
		0.8	93.95
(-100#)70%+ (-18+25#) 15% + (-10+16#)15%	-6+16#	0.2	50.72
		0.4	78.15
		0.6	75.66
		0.8	80.65
	-16+25#	0.2	133.86
		0.4	132.19
		0.6	166.28
		0.8	75.66
	-72#	0.2	133.86
		0.4	143.83
		0.6	159.63
		0.8	168.77

Table-4.25

Estimated Activation Energy of Zenith Iron Ore Pellets reduced by Ananta Coal (Temp.range: 850-1000^oC)

Constituents of Pellets	**Coal Size**	**Fractional Reduction (α)**	**Activation Energy (KJ/ mole)**
(-100#)100%	-6+16#	0.2	117.23
		0.4	108.08
		0.6	126.37
		0.8	105.59
	-16+25#	0.2	96.44
		0.4	98.94
		0.6	109.74
		0.8	133.02
(-100#)80%+ (-18+25#) 10% + (-10+16#)10%	-6+16#	0.2	16.63
		0.4	73.99
		0.6	117.23
		0.8	157.13
	-16+25#	0.2	35.75
		0.4	31.59
		0.6	73.99
		0.8	157.97
(-100#)70%+ (-18+25#) 15% + (-10+16#)15%	-6+16#	0.2	88.13
		0.4	78.98
		0.6	115.56
		0.8	132.19
	-16+25#	0.2	123.05
		0.4	113.90
		0.6	144.66
		0.8	178.75

Table-4.26

Estimated Activation Energy of Zenith Iron Ore Pellets reduced by Jagannath Coal (Temp.range: 850-1000^oC)

Constituents of Pellets	Coal Size	Fractional Reduction (α)	Activation Energy (KJ/ mole)
(-100#)100%	-6+16#	0.2	66.51
		0.4	54.04
		0.6	96.44
		0.8	107.25
(-100#)80%+ (-18+25#) 10% + (-10+16#)10%	-6+16#	0.2	149.65
		0.4	185.40
		0.6	215.33
		0.8	216.16
(-100#)70%+ (-18+25#) 15% + (-10+16#)15%	-6+16#	0.2	59.86
		0.4	104.76
		0.6	181.25
		0.8	206.19

Table- 4.27

XRD analysis of Zenith Iron ore pellets made from fines of -100# reduced by Lingaraj coal of -6+16#

Temperature (^{0}C)	Time (minutes)	Major Phase	Minor Phase
850	15	Fe	FeO
	30	Fe	FeO
	45	Fe	FeO
900	15	Fe	FeO
	30	Fe	FeO
	45	Fe	FeO
	60	Fe	FeO
	90	Fe	FeO
	120	Fe	Nill
950	15	Fe	FeO
	30	Fe	FeO
	45	Fe	FeO
	60	Fe	Nill
1000	15	Fe	FeO
	30	Fe	FeO
	45	Fe	FeO

Table- 4.28

Comparison of Degree of Reduction (%)

Pellet Vs Lump

Zenith Iron ore Mine, Reductant: Lingaraj Coal

Reduction Condition		Degree of Reduction (%)	
Temp (^{0}C)	**Soak Time (Hr.)**	**Pellet**	**Lump**
850	01	73.08	48.53
900	01	90.05	58.05
950	01	96.13	70.05
1000	01	99.4	76.59

CHAPTER-5

CHAPTER-5

CONCLUSION

5. CONCLUSION

From the results of the present study, the following conclusions may be drawn.

1) The caking indices of the noncoking coals were found to be nil, which may be due to their inertinite content.
2) The crushing strength of fired iron ore pellets were in good agreement with the reported values of 200Kg minimum, except for the iron ore pellets made from fines of (-100#)80% + (-18+25#) 10% + (-10+16#) 10% size.
3) Reduction time and temperature had marked influence on the degree of reduction. The degree of reduction increased with increase in reduction temperature from 850-1000^{0}C. In studied time period of 15-120 minutes the rate of reduction was higher up to 70-80% reduction and decreased in latter stages.
4) There was no effect of type of coal on the degree of reduction of iron ore pellets. The reduction behavior of iron ore pellets was identical in all the studied coals. However pellets reduced by noncoking coal of -72# size are showing greater degree of reduction than other studied coal size.
5) The result demonstrated that, iron ore lumps were less reducible than their corresponding iron ore pellets.
6) The reduction behavior of mixed iron ore pellets of different composition (-100#) 80% + (-18+25#) 10% + (-10+16#) 10%; (-100#) 70% + (-18+25#) 15% + (-10+16#) 15% were found to be identical with the iron ore pellets made by -100# iron ore fines. 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.
7) The iron ore pellets made from fines of (-100#)80% + (-18+25#) 10% + (-10+16#) 10% reduced by Lingaraj coal were showing reduction in activation energy in comparison to the pellets made from fines of -100#. This may be due to higher rate of reduction in the pellets made from fines of (-100#) 80% + (-18+25#) 10% + (-10+16#) 10%.
8) In all the types of studied iron ore pellets, the least activation energy was observed with coal of size -6+16#.

9) At 850^0C and 900^0C, the iron ore pellets were showing abnormal swelling after reduction, whereas at 950^0C and 1000^0C, shrinkage was observed in the reduced iron ore pellets.
10) At 850^0C and 900^0C, abnormal swelling was observed around 90-95% of reduction, while at 950^0C and 1000^0C, decrease in volume (shrinkage) was observed with increase in the extent of reduction.

CHAPTER-6

CHAPTER-6

FUTURE WORK

6. SUGGESTIONS FOR FUTURE WORK

The following works are suggested to be carried out in future.

I. Detailed study of reduction kinetics of remaining iron ores of Orissa by different coals of Orissa and Jharkhand

II. Reduction study of iron ore pellets made up of +100# iron ore particles need to be carried out.

III. Studies on the reduction kinetics of all these iron ore pellets by coal-char mixture.

IV. Studies on the reduction kinetics of ore-coal composite pellets for all these iron ores.

V. Studies on the kinetics of carbon pick-up during reduction of all these iron ores under different condition need to be carried out.

VI. Effect of using binders on the reduction and swelling behavior of iron ore pellets.

CHAPTER-7

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REFERENCES

7. REFERENCES

1. Sengupta S., “Indian Iron ore Industry in Global Perspective”, Steel World, October 2006, pp. 10- 17
2. Fillipov S., “Theory of Metallurgical Process”, Mir Publisher, MOSCOW, (1975)153-163.
3. Seaton, C.E., Foster, J.S. and Velasco, J., 1983. “Reduction kinetics of hematite and magnetite pellets containing coal char”. Trans. ISI Japan. **23**, pp. 490–496
4. Rao Y.K., Met.Trans. 2(1971)1439.
5. Fruhen R.J., “The rate of reduction of iron oxides by carbon” Met.Trans. 8B (1977)270.
6. Walker P.L., Shelef M., Anderson R.A., “Chemistry and Physics of Carbon”, Marcel Dekker, New York (1968)287-383.
7. M.I.E.T. – Guindy, Devnport W.G., Met.Trans. 1(1970)1729.
8. 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.
9. Majumdar A.K., Sharma T., Reddy G.V., “Reduction kinetics of iron ore pellets by non-coking coal”, Trans. I. I. M., 42, (1989), 461
10. Sharma T., “Reduction of iron ore pellets by char fines”, Trans.II M, 43(1990)380-77
11. Bryk and Lu, 1986. C. Bryk and W.-K. Lu, Reduction phenomena in composites of iron ore concentrates and coals. Ironmaking Steelmaking **13** (1986), pp. 70–75.
12. 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
13. Sharma T., “Pre-reduced pellets as blast furnace feed stock”, Steel Time International, 16(1992)28.
14. Sharma T., “Composite Pre – Reduced Pellet. A New Feed for Iron and Steel Industry (In Press)” Iron Making and Steel Making.
15. Narcin N., Aydin S., Sesen K., Dikec F., “Reduction of Iron Ore Pellets with Domestic Lignite Coal in a Rotary Tube Furnace”, Intl.J. Minner, Process, 43(1995)49-59.

16. Indian Standard 1350; Part-1, “Method of Test for Coal and Coke”, Bureau of Indian Standards, Delhi, (1969)3.
17. Chesters J.H., “Refractories; Production and Properties”, The Iron and Steel Institute, London (1973)472.
18. Indian Standard 1528; Part-IV, “Determination of Cold Crushing Strength of Refractory Materials”, Delhi (1974)4.
19. Bodsworth C., Taheri S.K., Progressive changes in iron ore and coal char during direct reduction with coal gasificationIron Making and Steel Making, 14(1987)278.
20. Nasr M.I., Ommar A.A., Hessien M.M, EI- Geasy A.A., ISIJ (1996)164.
21. Shrinivasan N.S., Laheri A.K., “Studies on the reduction of hematite by carbon”, Met.Trans. , 8B (1997)175.
22. Otsuka K.I., Kunni D., Reduction of powdery ferric oxide mixed with graphite particles”,J.Chem. Engg. Japan, 2(1969)46-50.
23. Abraham M.C., Ghosh A., “Kinetics of reduction of iron oxide by carbon”, Iron Making and Steel Making, 6(1979)14-23.
24. Cypress Rene, Soudan Clere, Moinet, “Pyrolysis of Coal and Iron Oxide Mixture, 2.Reduction of Iron Oxides”, Fuel, 60(2003)33.
25. Dey S.K, Jana B., Basumallick A., “Kinetics and Reduction Characteristics of Hematite-noncoking Coal Mixed Pellets under Nitrogen Gas Atmosphere” , ISIJ International, Vol. 33 (1993), No. 7, pp. 735-739
26. Hayashi S., “Abnormal Swelling during Reduction of Binder Bonded Iron Ore Pellets with CO-CO_2 Gas Mixtures”, ISIJ International, Vol. 43 (2003), No. 9, pp. 1370–1375
27. Biswas A.K., Principle of Blast Furnace Iron Making , SBA Publication, 1st Edition,(1996)
28. Dutta S.K., Ghosh A., Met. And Materials Trans., 25B (1994)15.
29. 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
30. Kumar, M., Jena, S. and Patel, S. K. (2008), “Characterization of properties and reduction behavior of iron ores for application in sponge ironmaking”, Mineral Processing and Extractive Metallurgy Review, 29:2, 118 — 129

31. Takano, Cyro and Mourão, Marcelo B. “Self-Reducing pellets for ironmaking: Mechanical Behavior”, Mineral Processing and Extractive Metallurgy Review,24(2003):3,233 — 252