EFFECT OF FIRING TEMPERATURE AND TIME ON THE SWELLING BEHAVIOUR OF REDUCED IRON ORE PELLETS

A REPORT SUBMITTED IN PARTIAL FULLFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

Bachelor of Technology

In

Metallurgical and Materials Engineering

By

Deepak Patra (107MM013)

Sharath. V (107MM016)

Under the Guidance of

Prof. M.Kumar

Department of Metallurgical and Materials Engineering

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CERTIFICATE

This is to certify that the thesis entitled "**Effect of firing temperature and time on the swelling behaviour of reduced iron ore pellets"** submitted by **Mr. Deepak Patra** and **Mr. Sharath. V** in partial fulfillment of the requirements for the degree of Bachelor of Technology in Metallurgy and Materials Engineering at 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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ABSTRACT

The increasing trend in the prices of steel scrap and its short supply led the steel technologists to find a suitable charge mix in the form of sponge iron or Direct Reduced Iron (DRI).

Sponge Iron or DRI is obtained from the direct reduction of iron ore and has iron content between 84 to 95 percent. Technically and technologically, sponge iron has been found to be a suitable material for charging in blast furnaces. In the existing blast furnace an increase in production by at least 25 to 35% can be achieved by using pre reduced iron ore. Sponge iron is a better substitute for scrap for steelmaking through EAF / IF routes due to its homogenous nature, Improved productivity and lower coke consumption. 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. According to industry experts, the preference for usage of DRI will lead to the use of 80 percent DRI in the charge mix in EAFs by 2009-10 which may even reach the 85 percent level by 2011-12 in the various regions of India.

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 firing temperarure (1000, 1100 and 1300^{o}C), binder (concentrated sugar cane juice) on strength of pellets and the effect of different reduction parameters such as temperature (850-1000°C), time (0-90min.), reductant quality, mixing of particles of different sizes at different ratios for pellet preparation etc. on the reduction, swelling behavior of iron ore pellets. These form the subject matter of the thesis. First chapter gives the introduction about 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. The second chapter deals with the literature survey.

The third chapter deals with selection of raw materials, preparation of samples, preparation of iron ore pellets, experimental procedure. Results and discussions are out lined in fourth chapter. Lastly, these conclusions have been followed by the suggestion for future work and list of references.

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CHAPTER1

INTRODUCTION

1. Introduction

Globally, iron ore is the major feedstock for BF-BOF steelmaking route which produced 65.4 percent of world crude steel in 2005. But the process requires various types of treatment of raw materials, involving high capital costs and substantial investment on infrastructure. It also leads to environmental problems and has a long gestation period. To find a way out of this shortcoming of BF-BOF process, EAF steelmaking was introduced long ago.

The share of EAF steelmaking in the global output of crude steel has increased substantially from 26.6 percent in 1988 to 33.1 percent in 2005. The increasing trend in the prices of steel scrap and its short supply led the steel technologists to find a suitable charge mix in the form of sponge iron or Direct Reduced Iron (DRI).

Table 1.1 Details of DRI production in India

Year	Installed capacity, (Mt)			Production, (Mt)		
	Gas based	Coal based	Total	Gas based	Coal based	Total
2004-05	6.1	6.0	12.1	4.6	5.5	10.1
2005-06	6.1	8.5	14.6	5.7	6.5	12.2
2006-07	7.1	11.0	18.1	7.0	8.5	15.5
2007-08	7.1	13.0	20.1	7.0	10.0	17.0
2008-09	7.1	15.0	22.1	7.0	11.0	18.0
2009-10	7.1	18.0	25.1	7.0	14.0	21.0
Source: JPC						

1.2 Production, consumption, export and surplus availability of iron ore lumps and fines in India

Some data's 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 1.2.

From the Table 1.2 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.

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
2004-05	145.95	48.15	13.54 (17.33)	64.60 (82.67)	78.14 (100)	19.65
2005-06	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

1.3 Future of DRI-EAF route of Steel making in India

There exist in the world two main routes for the production of liquid steel: On one side, the “Classical Route” based on blast furnace iron making and conversion of pig iron to steel. On the other side, the “Modern Route” for the production of steel in electric arc furnaces, using as raw material either scrap or direct reduced iron (DRI).The “Classical Route” is based on iron ore reduction in the blast furnace to a high carbon-primary metal (liquid pig iron), followed by the conversion of this hot metal to steel mainly in oxygen converters (in the past open hearth furnaces were also used). Although this route continues to produce the major percentage of steel in the world, it requires coal preparation, including coking in coke ovens, as well as ore preparation in sintering or pelletizing plants. Economically, it is mandatory to increase the unit size and the production of each plant, so as to work with larger and more efficient blast furnaces, as well as with higher capacity oxygen converters. In this way, the most economical production capacity of an integrated installation, consisting of a sintering plant, a coke oven battery, a blast furnace and an oxygen converter, is between 2 and 4 Million ton/year of liquid steel.

As opposed to the “Classical Route”, the “Modern Route”is based on the melting of metallic iron units in the electric arc furnace. Traditionally, scrap has been used as the main raw material, but the use of direct reduced iron (DRI) is becoming a normal and advantageous practice during melting in the electric arc furnace. During a first stage, iron ores are directly converted to metallic iron in the solid phase, and in a second stage this solid material is converted into liquid steel in the electric arc furnace.

Table 1.3 How steel is made in India

Route	2003-04	2004-05	2005-06	2006-07
BF-BOF	19.8	19.8	21.7	22.2
EAFs	8.2	10.2	11.3	13.3
IFs	6.0	8.2	13.5	15.4
Total crude steel	34.3	38.5	46.5	50.9
Share of EAF/IF,%	41.6	48.0	53.3	56.4
Source steel world.com				

Table 1.4 Share of various processes for crude steel production

Crude steel production by process route	Percentage share(%)		
	2004-2005	2008-2009	2009-2010 (Apr-Dec*)
BOF	52	45	47
EAF	18	24	26
IF	30	31	27
Total	100	100	100
Source: JPC; *=Provisional			

Advantage of DRI over scrap used in EAF

- Scrap contain elements like Cu, Ni, Sn, Mo,W that cannot be removed by oxidation during refining gives rise to undesirable residuals in the final steel. This is where DRI scores over scrap –it is totally free from all the above undesirable elements[2].

In comparison with the "Classical Route, this technology has the following main advantages:

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

1.4 Aims & objectives of the project

- **Study of effect of sugarcane juice as binder on the strength and reducibility of iron ore pellets.**

- **Study of the effect of temperature on the degree of reduction of iron ore pellets .**

- **Study of the effect of time on the degree of reduction of iron ore pellets.**

- **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.**

- **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.**

- **The use of sugarcane juice as a binder is to see whether it is helpful in providing good binding properties so that we can blend the wasted +100# fines along with -100# fines to form pellets.**

CHAPTER-2 LITERATURE SURVEY

2. Literature survey

The quality of raw materials is most significant variable that affects the productivity and energy consumption of blast furnace. All over the world, substantial improvement in the blast furnace performance is have been brought about by using superior quality of raw materials. Consistent in quality is another key requirement for ensuring efficient blast furnace operation.

The most widely used materials are coke, lump iron ore, sinter, pellets and fluxes like limestone and dolomite. Sinter and pellets are together referred to as agglomerates.

2.1 Details of iron ore reserves in India

India has sixth largest reserves of iron ore in the world, and these are of high grade. The reserves of good quality iron ore in India are around 12 billion tones. Out of total reserves, high grade ore(min. 65% Fe) is 13%, medium grade ore(62-65%) is 47% and the rest is low grade ore [2].

The iron ore deposits in India are located mainly in eastern India(especially in Odisha and Jharkhand)or in central India(Chattisgarh and Madhya Pradesh). High grade lumpy ore in these ore constitutes about 6-7% of total[1]. Blast furnace operation based on lump ore cannot be a long term option for India. Apart from this major reserves of Magnetite around 11 billion tonnes are found in western India. The problem with these ores is less iron content i.e. 40% and occurs in very fine form. Thus, these ores require beneficiation and agglomeration processes [2].

Most of the iron ore deposits in India occur in the form of hillocks that project above the ground. Control blasting is carried out of these hillocks to obtain the iron ore. The run-of-mine(ROM) thus excavated is crushed using crushers, followed by screening to obtain these basic products.

- 10-30mm or 10-40mm size fraction, which is used as lump ore in blast furnace iron[2].
- All intermediate fraction(below 10mm mostly 8-6mm and above 100#)for sinter making[2].
- Fines below 100#. The fines are first beneficiated to increase the iron content to over 65%, since the gangue in iron ore gets concentrated in the 'fines' fraction. These fines are either rejected or used to make pellets [2].

Lump ore, sinter and pellets thus becomes feed stock for liquid iron production in blast furnace. In most deposits, hard lump ore constitute around 10% and around 15-20% of the ROM are after processing is in a size that is used for sinter making [2].

2.2 Definition of pellets

Pellets are approximately spherical lumps formed by agglomeration of the crushed iron ore fines in presence of moisture and binder, on subsequent induration at 1300°C.

2.3 Mechanism of pellet formation

- **Ball Formation**– Surface tension of water & gravitational force creates pressure on particles, so they coalesce together & form nuclei which grow in size into ball.
- **Induration (Heat Hardening)** – Solid state diffusion at particle surfaces at higher temperature cause recrystallisation & growth giving strength.

2.4 Advantages of pellets

- Very good reducibility due to high micro porosity(porosity 25-35%)[3].
- Small uniform size (10-20mm)gives very good bed permeability[3].
- More accessible surface per unit weight and more iron per unit of furnace volume because of high bulk density, 3-3.5 tonnes/m^3. Large surface and increased time of residence per unit weight of iron gives better and longer gas/solid contact time and improved heat exchange[3].
- High iron content and more uniform chemical composition. Lower flux requirement which leads to lower slag volume so less fuel requirements[3].
- High softening temperature, 1200-1350^oC with narrow range[3].
- High strength- average compression strength about 150-250kg[3].
- Heat consumption much less than for sintering[3].
- Ideal for direct reduction process[3].

Sinter usage has increased to at least 50% in most blast furnaces, and pellets, now constitute upto 30% of charge. The global pellet production has crossed 300Mt(India around 15Mt). Pellets are made in large quantities(3-6Mt) in one central location and then transported by sea or rail. Since sinter cannot be transported easily over long distances after it is made, sinter plants are normally located inside almost all integrated steel plants.

Table 2.1 Typical properties of pellets suitable for use in blast furnace

Parameter	Target
SiO_2, %	2.8±0.1
CaO/SiO_2	1.42±0.05
MgO, %	2.1±0.1
(Na_2O+K_2O),%	<0.075
Mean diameter, mm	11.2±1
Below 4mm %	<0.5
Porosity, %	26.5±0.3
Compressive strength, kg/pellet	>260
Above 210kg/pellet, %	>80
Reduction degradation index(-3mm), %	<5.5
Swelling index, %	<12
Contraction, %	<9
LTBT	Min. 80%, +6.3mm Min. 7.5%, -0.5mm

2.5 Swelling of iron-ore pellets

Some pellets show an abnormal or catastrophic swelling with volume increase upto 400 percent. Such enlarged volume leads to

- Softening of pellets.
- Increase in porosity.
- Decrease in mechanical strength.

2.6 Industrial significance

In the blast furnace, the compaction of such a material under load reduces bed voidageand causes serious impedance to gas throughflow. However, swelling increases the rate of iron oxide reduction because of the formation of highly porous reduction products. Maximum swelling occurs during reduction at temperatures 900-1000°C [2]. Ores and sinter seldom swells to such a degree as compared to iron-rich pellets which are prone to swelling.

2.7 Mechanism of swelling

The phenomenon of swelling is intimately associated with the mode of nucleation and growth during reduction of wustite. According to Biswas and many other authors, whisker formation occurs during the reduction stage wustite/iron from pellets impregnated with oxides of sodium, potassium and calcium. In extreme cases of preferential nucleation, caused by a pronounced lattice distortion when a large foreign cation is introduced, the diffusion of iron ions will be greatly enhanced and they will stream towards the preferred sites and the iron will grow as needles or whiskers. The growth of whiskers may be deemed to be an extreme case of preferential nucleation which occurs when the relative rates of iron ion diffusion and oxygen removal are comparatively high, i.e., when the reduction potential of the gas is low and the iron ore diffusion high. Pronounced lattice disturbances occurring due to diffusion of ions larger than Fe^{2+} into the wustite lattice and consequent expansion of the wustite unit cell gives rise to preferential sites of nucleation of iron on the wustite surface. Freshly reduced iron ions tend to diffuse towards these rather than form new nuclei, resulting in further elongation and growth of whisker. The swelling is predominant at 900-1000^oC is probably due to about 100 times more mobility of ferrous ions at 900^oC than 600^oC.

Swelling of pellets depends upon many factors

- Composition, nature and quantity of impurities [3].
- Time and temperature of induration [3].
- Degree of oxidation [3].
- Time, Temperature and degree of reduction [3].
- Gas composition [3].
- Porosity, before and during reduction [3].

Swelling can be avoided by following measures

- Prolonged enduration of pellets at high temperature [3].
- Addition of pre-reduced ore or return fines or certain ores from different sources [3].
- Avoidance or minimization of alkali metals input through ore [3].

2.8 Thermodynamics and kinetics of iron ore reduction

On heating

Coal → char + tar + gases (CO, CO_2, H_2, C_nH_m and N_2)

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

Reduction of hematite :

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

Reduction of magnetite:

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

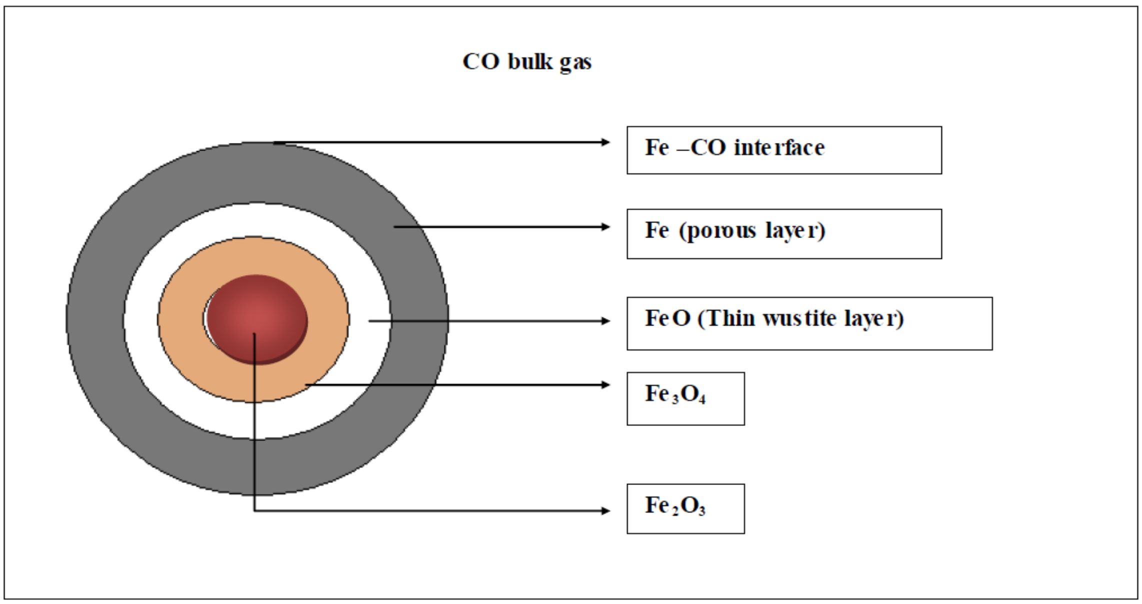
Reduction of wustite:

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

Besides the above mentioned reactions, the next three possible reactions are :

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

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



A schematic diagram in modes of reduction of iron oxide

Before the formation of Metallic Layer

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

- Transport of CO/H_2 gas from bulk gas phase to Fe_2O_3-CO/H_2interface.
- Adsorption of CO/H_2 gas at the Fe_2O_3- CO/H_2interface.
- Chemical reaction between $Fe_2O_3$and CO/H_2gas at the Fe_2O_3- CO/H_2interface and desorption of the product gas CO_2/H_2O from this interface.

• Transport of product gas from Fe_2O_3- CO/H_2interface to the bulk gas phase.

After the Formation of Metallic layer

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

• Adsorption of CO/H_2 gas at the Fe- CO/H_2 interface.

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

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

• Desorption of the product gas CO2/H_2O from this interface.

• Transport of CO_2/H_2O gas from Fe_2O_3 - Fe interface to Fe-CO/H_2interface.

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

CHAPTER-3

EXPERIMENTAL

3. Experimental

3.1 Material selection: Two types of ores DR Pattnaik iron ore and B.P.J iron ore were used. Their composition is indicated in table 3.1.

Table 3.1 Material selection:

Ore	Fe%	Fe_2O_3%	Al_2O_3%	SiO_2%	TiO_2%	MnO%
D.R Pattnaik	>64(65.22)	93.26	1.6-3	0.9-2.6	0.07	0.06
B.P.J	61-63	88-90	4-5	3-5	0.11	0.01

Two types of ores Pattnaik iron ore and B.P.J iron ore were used. Fines were generated by means of crushing in a pestel and mortar. The generated fines are screened in 100# sieve. +100# fines and -100# fines were separated. Minimum 800 gm of -100# fines were collected. The -100# fines are further subjected to sieve analysis. The results of sieve analysis is shown in table 3.2. After sieve analysis all -100# fines are mixed together and kept in the dessicator. +100# fines are also kept in another dessicator.

Table 3.2 Sieve analysis:

Sieve No.	-100+200# (weight %)	-200+240# (weight %)	-240+300# (weight %)	-300# (weight %)
Pattnaik ore	52.9	38.4	6.6	1.2
B.P.J ore	52.38	33.66	12.43	0.87

Table 3.3 proximate analysis of Basundhara non-coking coal(dry basis)

Volatile matter	27.26%
Ash	32.63%
Fixed carbon	40.11%

3.2 Experimental procedure:

- Ironore fines of two types of ores were generated by means of crushing in a pestel and mortar.
- The generated fines are screened in 100# sieve.
- Minimum 800 gm of -100# fines were collected.

- The -100# fines are further subjected to sieve analysis. The results of sieve analysis is shown in table 3.2.
- **Binder:** The sugarcane juice was heated at about 110^{o}C inside oven to concentrate it to get better binding properties.
- **Preparation of pellets:** Pellets of appropriate size were prepared by mixing -100# fines with binder (3%, 6% and 10% binder) and appropriate amount of moisture by gently and prolonged rolling between the palms of hand. The pellets were kept inside the oven at 110^{o}C for drying and removal of moisture for 2 h. After 2 h the pellets were taken out and kept in separate plastic pouches, with each pouch was marked properly regarding the percentage of binder.
- **Firing:** The pellets were then fired at three different temperatures (1000, 1100 and 1300^{o}C for 1 h, respectively). After 1 h the furnace was switched off and the pellets were allowed to cool in the furnace itself. The pellets were taken out and kept in the separately marked pouches regarding the percentage binder and firing temperature.
- **Crushing strength:** The crushing strength of fired pellets (approx. size 15mm) have been determined by employing a cold uniaxial hydraulic press (capacity 20 tons).
- **Degree of reduction:** Reduction studies of fired pellets were carried out in a stainless steel container (80mm height × 40 mm diameter).
- The reactor was made full with the non coking coal with size analysis(25.81% (-4+6#), 59.52%(-6+16#), 3.39%(-16+18#), 11.26%(-18+25#))

- Diameter (mm) of the fired pellet of the required grade was taken and weight(g) measurement was done and then it was placed centrally on this coal bed and the remaining portion of the stainless steel container was filled with coal so as to cover the fired pellet completely. The stainless steel container had a hole centrally for the escape of gas.

- The stainless steel container having coal and pellet was then introduced into the muffle furnace and heated from room temperature to the required temperature of 850ºC, 900ºC soaked there for 0, 15, 30, 60, 75, 90 minutes respectively and for 950^{o}C, 1000^{o}C soaked for 0,5,10,15,20,25 minutes respectively.

- The containers were then taken out and cooled in air. The weight losses in pellets were recorded by an electronic balance and final diameter measurements were done with the help of vernier calliper .

- Calculation for degree of reductions and percentage swelling were made.

- Drop no. test was carried out for different type of pellets.

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

$$\sigma_c = W/A$$

Where, σ_c 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

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

Apparent porosity = [W – D/ W- (S-s) ×100]

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

'W' is the weight of kerosene oil saturated piece;

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

And 's' is the weight of thread only while immersed in kerosene oil

3.5 Determination of degree of reduction: The degree of reduction was calculated by using the following formula:

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

3.6 Determination of percentage swelling: Swelling is a volumetric expansion of the agglomerate during reduction of iron oxide. The diameters of pellets before and after the reduction were measured with the help of vernier caliper and the percentage swelling was calculated by using the following formula:

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

Where, V_f= final volume of the reduced pellet; V_i= initial volume of the fired pellet

Swelling up to 20% has generally been accepted as “normal‘‘ whereas higher values are called “abnormal swelling‘‘ or even “catastrophic swelling‘‘.

3.7 Drop Number test: This number was determined by dropping pellets, ranging in diameter between 14.5 and 18 mm, one by one from a height of 45 cm on a cast iron plate and counting the number of drops upto breakage.

CHAPTER-4

RESULTS & DISCUSSIONS

4. Results and Discussions

4.1 Effects of firing condition on the crushing strength and porosity of the pellets.

In the present project work, pellets were fired at various temperatures (1000, 1100 and 1300^oC respectively). As shown in fig 5.12, 5.13 and 5.14, the Crushing Strength of fired pellets increased with increase in firing temperature. This appears to be due to increase in the extent of slag bond in the pellets[4]. The effect of firing temperature on the crushing Strength is more pronounced at firing temperature of 1300^oC. Fig 5.10 also clearly indicate that the porosity of the fired pellets decrease with increase in firing temperature. The decrease was found to be more pronounced at firing temperature of 1300^oC. This appears to be due to slag formation and filling of the pores at a firing temperature of 1300^oC.

4.2 Effects of firing temperature on the extent of reduction and swelling of fired haematite iron ore pellets.

As shown in fig 4.9, a decrease in degree of reduction was observed with increase in firing temperature. This appears to be due to lower porosity in the pellets fired at higher temperature.

4.3 Effect of reduction temperature on the degree of reduction and extent of swelling of fired haematite iron ore pellets.

As shown in fig 4.1 to 4.7, that degree of reduction increases with increase of reduction temperature. An increase in the degree of reduction with reduction temperature appears to be more and more participation of gaseous reducing agents (CO and H2) released from the devolatilization of coal and C + O2 →2CO reaction. The high rates of diffusion of gases through the metallic layer also contribute to this.

As shown in fig 4.19, 4.20 and 4.23 the extent of swelling first increase a little bit with increase of reduction temperature after that it decreases with increase in reduction temperature. The initial increase may be due to high temperature, high degree of reduction and high rate of diffusion of gases. The decrease in the swelling after that with increase in reduction temperature is more likely to be due to sintering of iron whiskers at higher temperature.

4.4 Effect of reduction time on degree of reduction and extent of swelling of fired haematite iron ore pellets.

As shown in fig 4.1-4.7, the degree of reduction increases with increase of time at a particular reduction temperature. This increase in degree is due to the exposure of pellets with the reducing agents (C, CO, and H2) for a longer period of time .The higher reduction rate in initial conditions may be attributed to the combined effect of less resistance offered to the flow of reducing glass into the pellet and significance contribution of volatile matter release initially.

As shown in fig 4.18, the extent of swelling increases with increase in reduction time at a particular reduction temperature and particular firing temperature. This is believed due to fibrous growth of iron whiskers in the pellet matrix without any restriction in the growth, however the pellets fired at higher temperature showed a decrease in the extent of swelling with increase in reduction time. This appears due to decrease in porosity due to better densification which restricts the fibrous growth of whiskers and prevents volume expansion.

4.5 Effect of firing temperature on drop number, of fired haematite iron ore pellets.

As shown in fig 4.15, 4.16 and 4.17 the drop number increases with increase in firing temperature. This increase in the drop number values is due to more densification whilefiring at higher temperatures and resultant decrease in porosity.

4.6 Scanning electron micrographic study of the reduced pellets.

As shown in fig 4.30 to 4.33 cracks are developed in the iron ore pellets due to swelling, the cracks are more pronounced at 900^{o}C as compared to 850^{o}C. Cracks at 950^{o}C and 1000^{o}C are finer cracks because of densification due to reduction at high temperatures.

As shown in fig 4.34 to 4.37, densification of the iron ore particles has occurred. Densification is much more in case of reduction at 1000^{o}C as compared to other lower reduction temperatures.

As shown in fig 4.26 to 4.29, the excessive swelling of the iron ore pellet is due to fibrous growth of iron whiskers in the pellet matrix[3].

Table4.1Apparent porosity values of BPJ and DR Pattnaik haematite ironore pellets

Sl no.	Pellet specification Size:100%(-100#)	D*(g)	S**(g)	s^(g)	W^^(g)	%porosity= 100(W-D)/W-(S-s)
1.	D.R Pattnaik without binder(fired-1300^{o}C)	5.57	4.64	0.15	5.77	15.62
2.	D.R Pattnaik 3% binder(fired-1300^{o}C)	7.70	6.425	0.146	7.90	12.33
3.	D.R Pattnaik 6% binder(fired-1300^{o}C)	9.75	7.95	0.130	9.57	9.3
4.	D.R Pattnaik 10% binder(fired-1300^{o}C)	8.80	7.521	0.129	9.10	17.56
5.	B.P.J 3% binder (fired-1300^{o}C)	8.35	6.91	0.132	8.67	16.91
6.	B.P.J 6% binder (fired-1300^{o}C)	6.92	5.832	0.257	7.27	20.64
7.	B.P.J 10% binder (fired-1300^{o}C)	6.90	5.697	0.838	7.06	7.27
8.	D.R Pattnaik without binder(fired-1100^{o}C)	5.57	4.64	0.15	5.77	15.6
9.	D.RPattnaik3% binder (fired-1100^{o}C)	-	-	-	-	-
10.	D.RPattnaik6% binder (fired-1100^{o}C)	5.78	4.88	0.112	5.93	13.02
11.	D.RPattnaik10% binder (fired-1100^{o}C)	5.55	4.593	0.101	5.70	12.4
12.	B.P.J without binder (fired-1100^{o}C)	6.34	5.25	0.098	6.78	27
13.	B.P.J 3% binder (fired-1100^{o}C)	6.04	5.022	0.0932	6.46	27.45
14.	B.P.J 6% binder (fired-1100^{o}C)	6.36	5.232	0.101	6.84	28.08
15.	B.P.J 10% binder (fired-1100^{o}C)	5.85	4.735	0.121	6.34	28.38

*'D' is the weight of dried piece;

**'W' is the weight of oil saturated piece;

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

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

Table 4.2

Physical properties of fired BPJ iron ore pellets							
Pellet description					**Pellet properties**		
-100# (%)	**-25+36# (%)**	**Firing temperature (^{o}C)**	**Firing time (hr)**	**Binder (sugarcane juice)(%)**	**Crushing strength (kg/pellet)**	**Apparent porosity**	**Drop. No.**
100	**0**	**1100**	**1**	**Nil**	**45**	**27**	**19**
100	**0**	**1100**	**1**	**3**	**95**	**27.45**	**144**
100	**0**	**1100**	**1**	**6**	**75**	**28**	**157**
100	**0**	**1100**	**1**	**10**	**100**	**28.38**	**295**
100	**0**	**1000**	**1**	**3**	**75**	**41.54**	**23**
100	**0**	**1000**	**1**	**6**	**70**	**38.59**	**33**
100	**0**	**1000**	**1**	**10**	**60**	**39.33**	**114**
100	**0**	**1300**	**1**	**3**	**560**	**16.91**	**212**
100	**0**	**1300**	**1**	**6**	**335**	**20.64**	**500**
100	**0**	**1300**	**1**	**10**	**280**	**7.3**	**730**
90	**10**	**1300**	**1**	**3**	**480**	**11.8**	**1050**

Table 4.3

Physical properties of fired D.R Pattnaik Iron ore pellets							
Pellet description					**Pellet properties**		
-100# (%)	**-25+36# (%)**	**Firing temperature (°C)**	**Firing time (hr)**	**Binder (sugarcane juice)(%)**	**Crushing strength (kg/pellet)**	**Apparent porosity**	**Drop. No.**
100	0	1100	1	Nil	155	15.6	222
100	0	1100	1	3	160	-	400
100	0	1100	1	6	175	13	258
100	0	1100	1	10	165	12.4	405
100	0	1000	1	3	155	29.68	340
100	0	1000	1	6	105	33.69	68
100	0	1000	1	10	160	32.75	320
100	0	1300	1	3	1460	12.33	2500
100	0	1300	1	6	600	9.30	1320
100	0	1300	1	10	580	17.56	1400
90	10	1300	1	3	820	7.59	>1500
80	20	1300	1	3	580	8.9	1400

Table 4.4

Degree of reduction and swelling values of fired BPJ haematite iron ore pellets reduced in Basundhara non-coking coal								
-100# (%)	-25+36# (%)	Binder (wt%)	Firing Temperature (^oC)	Firing time (min)	Reduction temperature (^oC)	Reduction Time (min)	Degree of reduction (%)	Swelling (%)
80	20	3	1300	60	850	0	35.14	17.45
						15	53.53	10.03
						30	64.13	15.13
						45	72.10	21.07
						60	71.19	12.21
80	20	3	1300	60	900	0	56.96	20.14
						15	73.05	19.64
						30	82.35	11.74
						60	93.81	18.11
						75	89.66	19.58
						90	100	28.84
80	20	3	1300	60	950	0	76.21	6.18
						5	80.83	5.18
						10	82.98	1.61
						15	89.01	10.02
						20	85.16	8.2
						25	83.89	10.44
80	20	3	1300	60	1000	0	85.33	3.4
						5	87.98	3.8
						10	99.35	9.46
						15	99.20	18.29
						20	93.58	8.43
						25	93.33	8.81

Table4.5

Degree of reduction and swelling values of fired BPJ haematite iron ore pellets reduced in Basundhara non-coking coal								
-100# (%)	-25+36# (%)	Binder (wt%)	Firing Temperature (°C)	Firing time (min)	Reduction temperature (°C)	Reduction Time (min)	Degree of reduction (%)	Swelling (%)
90	10	3	1300	60	900	0	57.38	14.64
						15	68.60	8.84
						30	78.86	8.81
						60	77.84	13.24
						90	87.14	16.19
90	10	3	1300	60	950	0	75.76	5.4
						5	78.19	5.2
						10	90.39	9.86
						15	84.73	9.37
						20	80.55	6.28
						25	72.29	14.66
90	10	3	1300	60	1000	0	76.40	4.74
						5	93.10	3.54
						10	86.7	6.17
						15	92.68	2.13
						20	96.55	9.32
						25	92.38	3.7

Table 4.6

Degree of reduction and swelling values of fired DR Pattnaik haematite iron ore pellets reduced in Basundhara non-coking coal								
-100# (%)	-25+36# (%)	Binder (wt%)	Firing Temperature (^oC)	Firing time (min)	Reduction temperature (^oC)	Reduction Time (min)	Degree of reduction (%)	Swelling (%)
80	20	3	1300	60	850	0	43.18	7.04
						15	58.18	4.61
						30	62.37	2.78
						60	66.18	5.23
						90	70.85	4.25
80	20	3	1300	60	900	0	64.44	1.66
						15	72.87	2.60
						30	76.95	3.85
						60	91.74	1.36
						75	96.68	excessive
						90	98.28	3.89
80	20	3	1300	60	950	0	70.29	1.3
						5	77.6	0.55
						10	83.33	1.7
						15	97.22	1
						20	86.95	1.82
						25	91.81	1.6
80	20	3	1300	60	1000	0	87.06	1.21
						5	91.26	1.16
						10	96	3.05
						15	100	0.57
						20	89.87	2.5
						25	95.81	1.15

Table 4.7

Degree of reduction and swelling values of fired DR pattnaik haematite iron ore pellets reduced in Basundhara non-coking coal								
-100# (%)	-25+36# (%)	Binder (wt%)	Firing Temperature (^oC)	Firing time (min)	Reduction temperature (^oC)	Reduction Time (min)	Degree of reduction (%)	Swelling (%)
90	10	3	1300	60	900	0	100	0.21
						15	97.5	0.83
						30	100	0
						60	100	1.18
						90	100	0.21
90	10	3	1300	60	950	0	69.86	12.01
						5	73.71	1.6
						10	94.61	1.24
						15	85.35	1.99
						20	91	0.99
						25	96	1.97
90	10	3	1300	60	1000	0	78.61	3.86
						5	90.10	2.78
						10	96.29	4.16
						15	95.16	-1.5
						20	98.4	-8.05
						25	100	-6.6

Table 4.8

Degree of reduction and swelling values of fired BPJ haematite iron ore pellets reduced in Basundhara non-coking coal: A comparison for the effect of firing temperature								
-100# (%)	**-25+36# (%)**	**Binder (wt%)**	**Firing Temperature (^oC)**	**Firing time (min)**	**Reduction temperature (^oC)**	**Reduction Time (min)**	**Degree of reduction (%)**	**Swelling (%)**
100	**0**	**3**	**1000**	**60**	**950**	**0**	**77.36**	**-1.26**
						5	**90.76**	**-20.96**
						10	**93.42**	**-16.86**
						15	**97.61**	**-13.86**
						20	**93.10**	**0.71**
						25	**94.55**	**4.05**
100	**0**	**3**	**1100**	**60**	**950**	**0**	**81.88**	**20.14**
						5	**96.21**	**19.64**
						10	**95.77**	**11.74**
						15	**96.35**	**18.11**
						20	**94.47**	**19.58**
						25	**94.44**	**28.84**
90	**10**	**3**	**1300**	**60**	**950**	**0**	**75.76**	**4.74**
						5	**78.19**	**3.54**
						10	**90.39**	**6.17**
						15	**84.73**	**2.13**
						20	**80.55**	**9.32**
						25	**72.29**	**3.7**

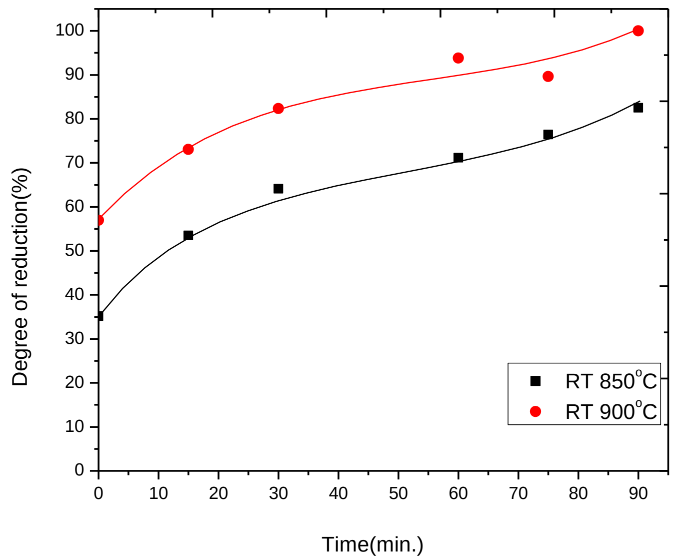


Fig4.1: Degree of reduction vs time plots for fired BPJ haematite iron ore pellets [3% binder, firing temperature-1300°C, firing time-1hour, {-100#(80%),-25+36#(20%) }]

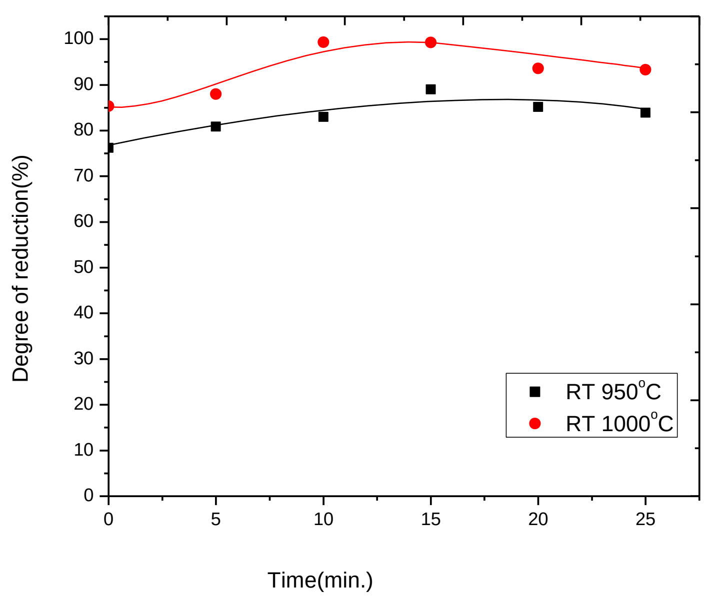


Fig4.2: Degree of reduction vs time plots for fired BPJ haematite iron ore pellets, [3% binder, firing temperature-1300°C, firing time-1hour, {-100#(80%),-25+36#(20%) }]

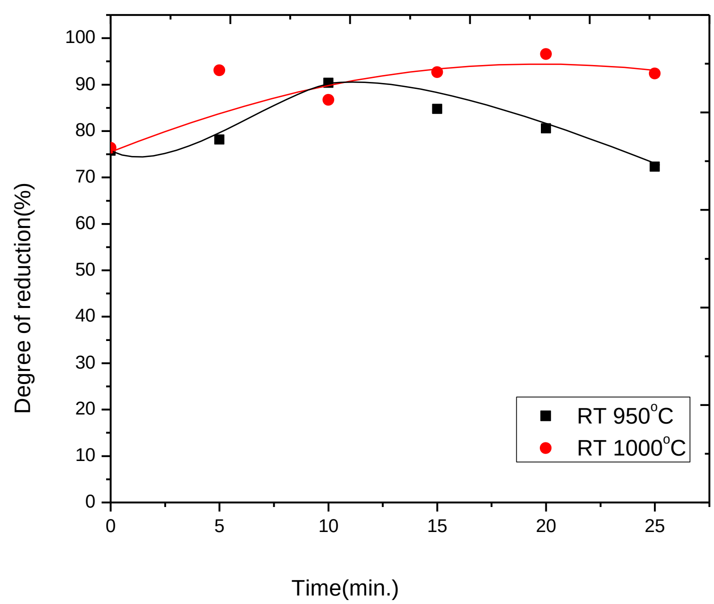


Fig4.3: Degree of reduction vs time plots for fired BPJ haematite iron ore pellet, [3% binder, firing temperature-1300°C, firing time-1hour, {-100#(90%),-25+36#(10%) }]

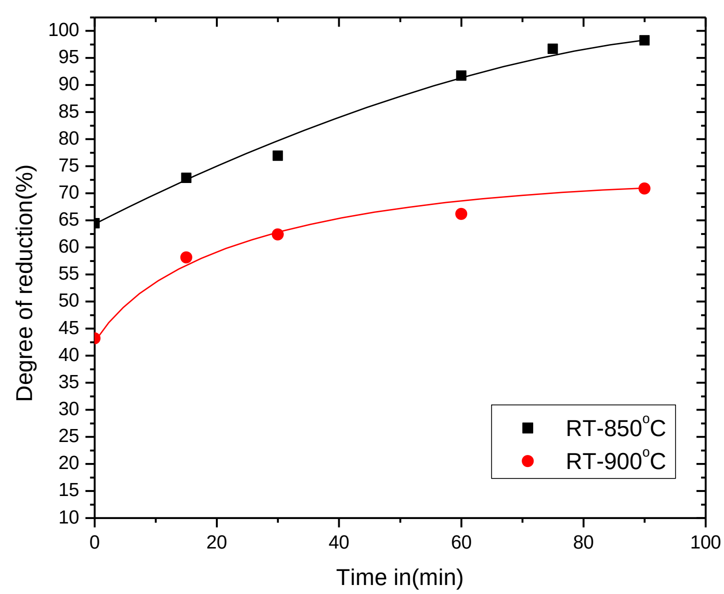


Fig4.5: Degree of reduction vs time plots for fired DR Pattnaik haematite iron ore pellets [3% binder, firing temperature-1300°C, firing time-1hour, {-100#(80%),-25+36#(20%) }]

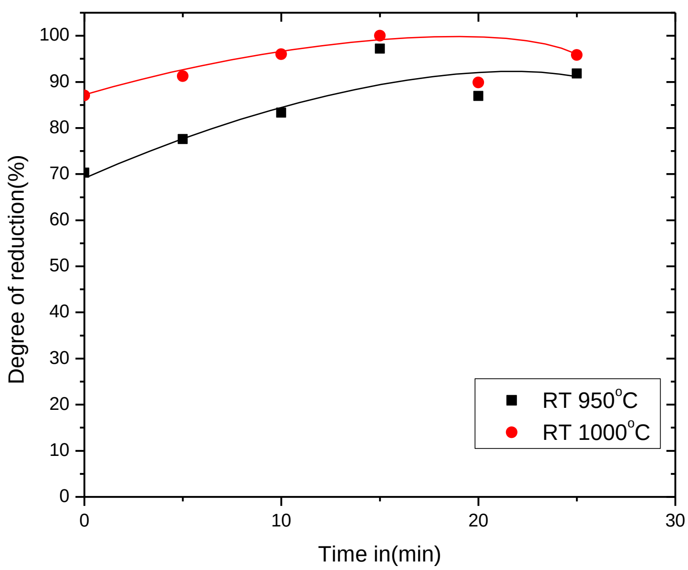


Fig4.6: Degree of reduction vs time plots for fired DR Pattnaik haematite iron ore pellet [3% binder, firing temperature-1300^{o}C, firing time-1hour, {-100#(80%),-25+36#(20%) }]

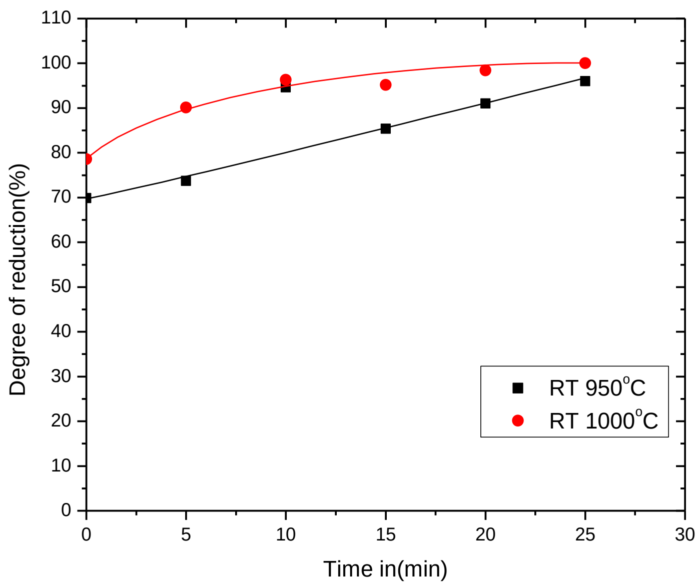


Fig4.7: Degree of reduction vs time plots for fired DR Pattnaik haematite ironore pellets [3% binder, firing temperature-1300^{o}C, firing time-1hour,{-100#(90%),-25+36#(10%) }]

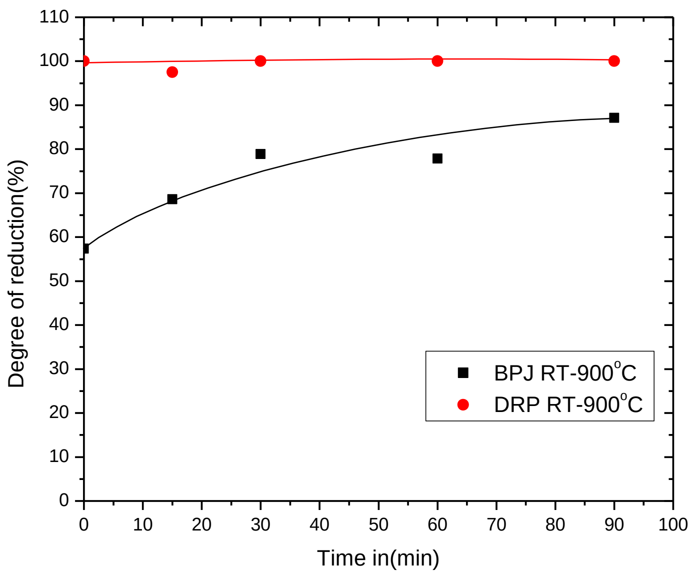


Fig4.8: Degree of reduction vs time plots for fired BPJ and DR Pattnaik haematite ironore pellets [3% binder, firing temperature-1300^{o}C, firing time-1hour,{-100#(90%),-25+36#(10%) }]

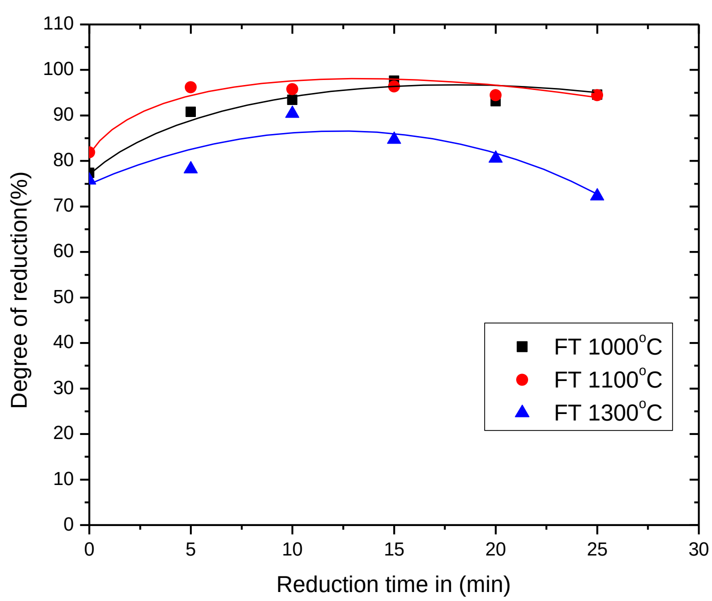


Fig4.9: Degree of reduction vs time plots for fired BPJ haematite ironore pellets [3%binder, effect of firing temperature, reduction temperature-950^{o}C firing time-1hour, {-100#(90%),-25+36#(10%) }]

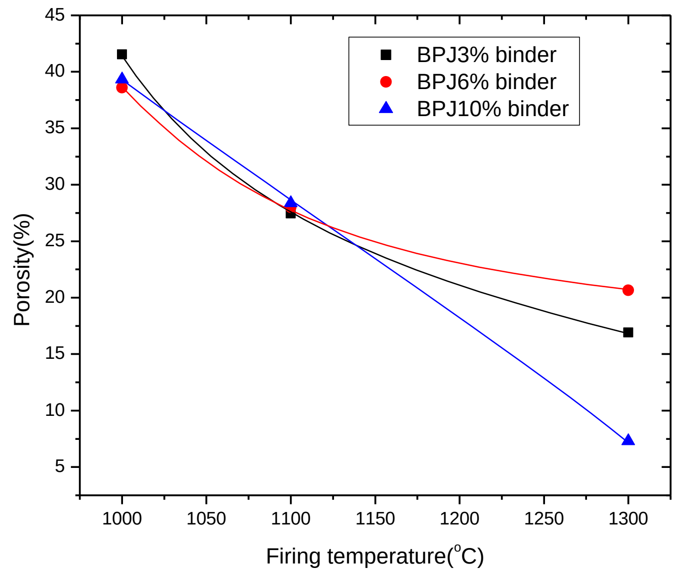


Fig 4.10: Porosity vs firing temperature plots for fired BPJ haematite ironore pellets [firing time-1 hour,{-100#(100%)}]

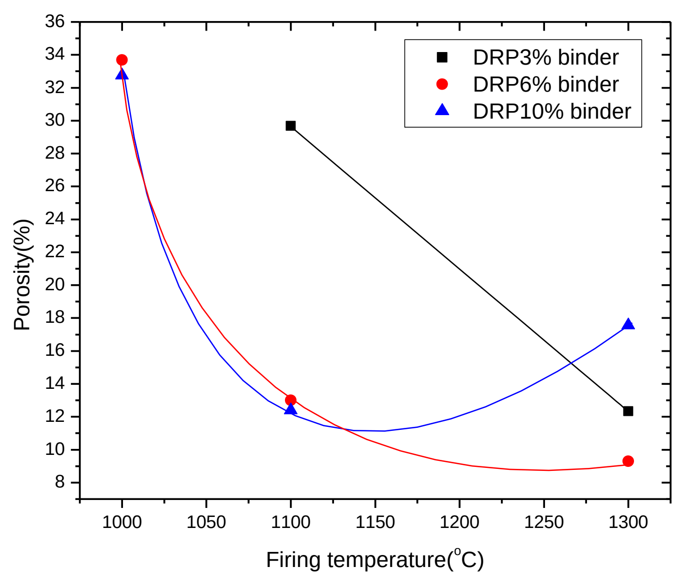


Fig 4.11:Porosity vs firing temperature plots for fired DR Pattnaik haematite ironore pellets [firing time-1 hour,{-100#(100%)}]

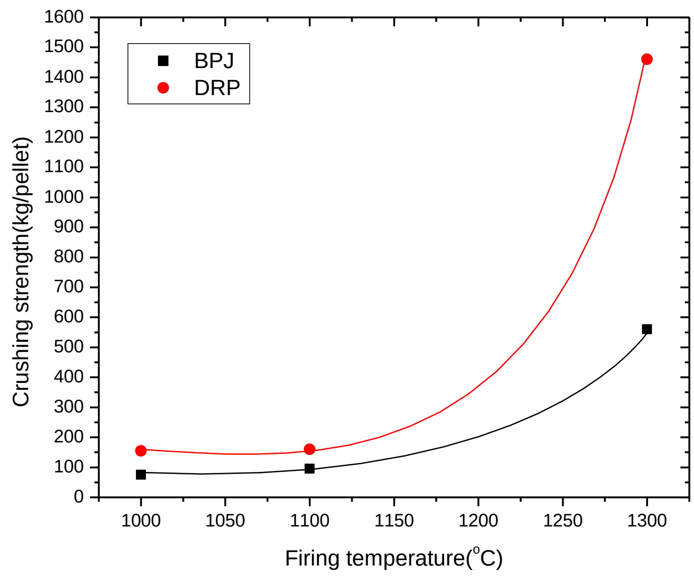


Fig 4.12 :Crushing strength vs firing temperature plots for fired BPJ and DR Pattnaik haematite ironore pellets [3% binder, firing temperature-1300°C, firing time -1hour,{-100#(100%)}]

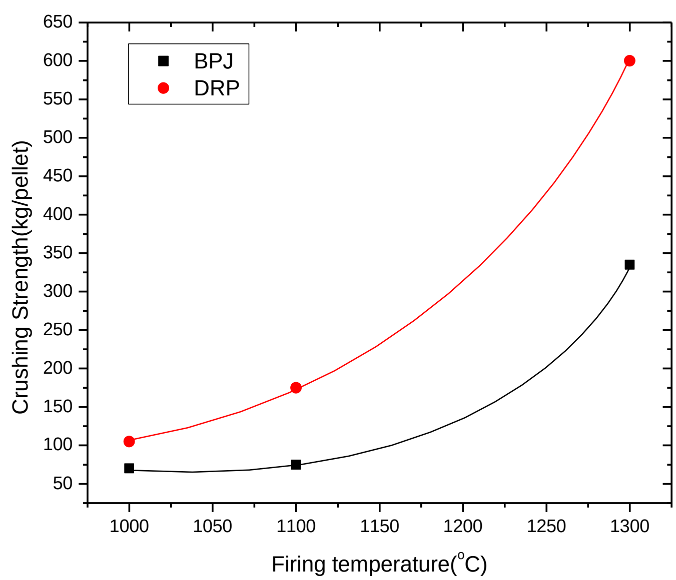


Fig 4.13 : Crushing strength vs firing temperature plots for fired BPJ and DR Pattnaik haematite ironore pellets [6% binder, firing temperature-1300°C, firing time -1hour,{-100#(100%)}]

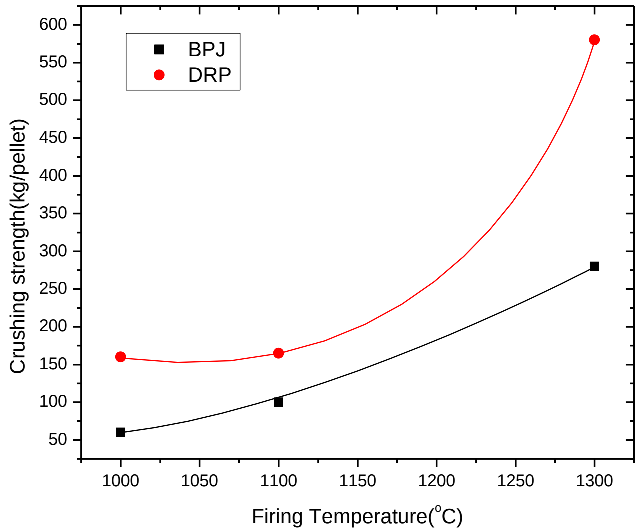


Fig 4.14 : Crushing strength vs firing temperature plots for fired BPJ and DR Pattnaik haematite ironore pellets [10% binder, firing temperature-1300°C, firing time -1hour,{-100#(100%)}

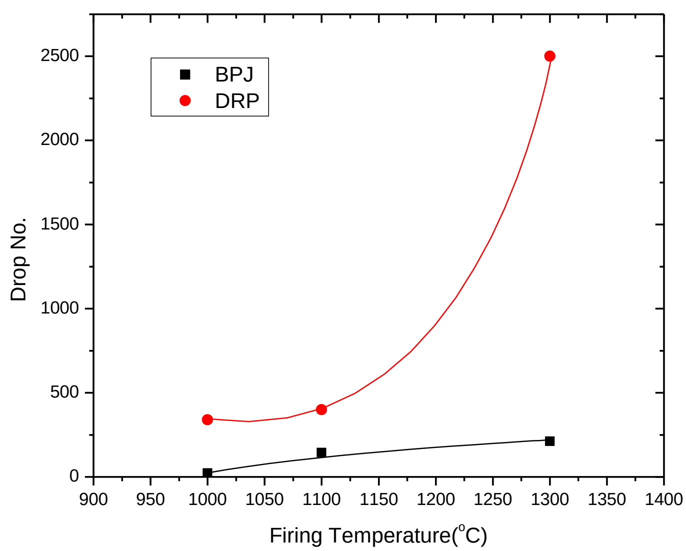


Fig 4.15: Drop No. vs firing temperature plots for fired BPJ and DR Pattnaik haematite ironore pellets [3% binder, firing time -1hour, {-100#(100%)}]

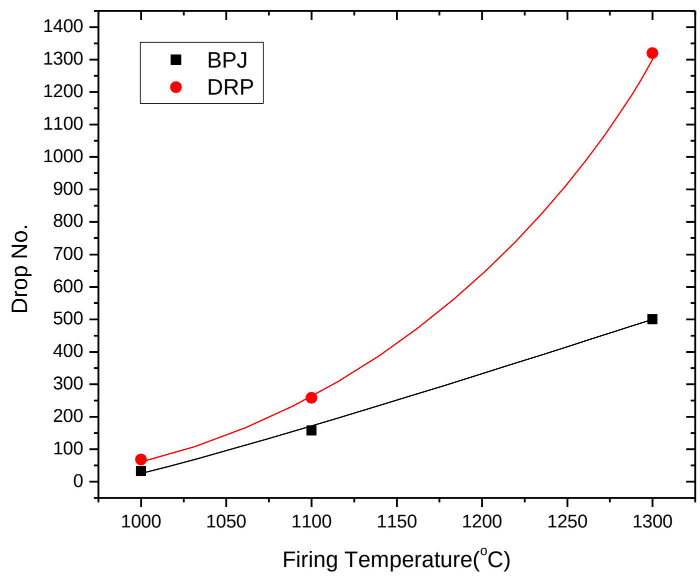


Fig 4.16: Drop No. vs firing temperature plots for fired BPJ and DR Pattnaik haematite ironore pellets [6% binder, firing time -1hour, {-100#(100%)}]

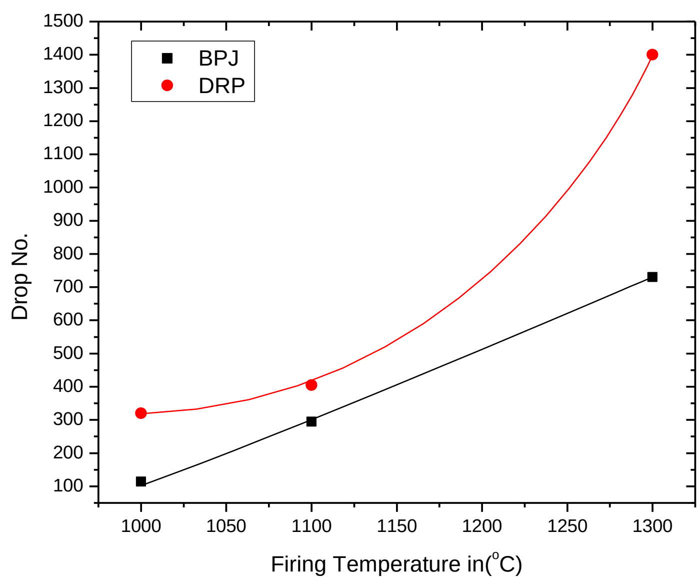


Fig 4.17: Drop No. vs firing temperature plots for fired BPJ and DR Pattnaik haematite ironore pellets [10% binder, firing time -1hour, {-100#(100%)}]

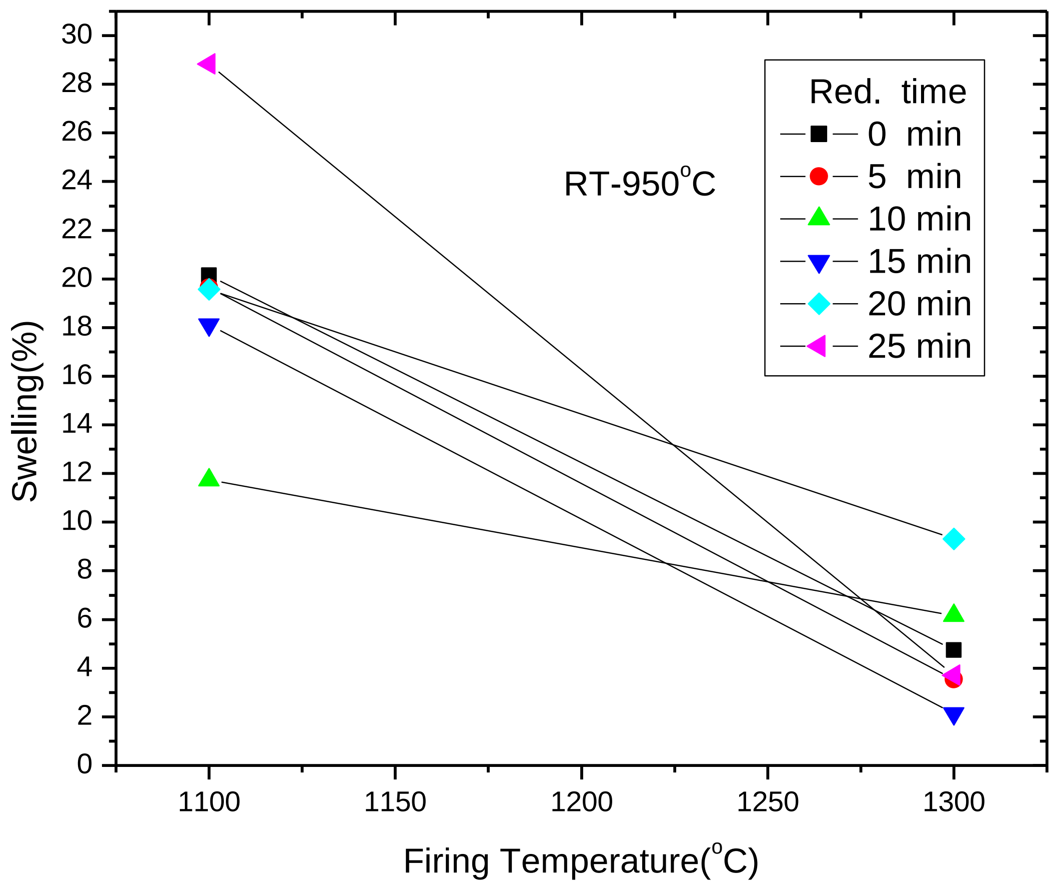


Fig 4.18: Percentage swelling vs firing temperature plots for fired BPJ haematite ironore pellets [3% binder, firing time -1hour, {-100#(100%), reduction temperature-950°C}]

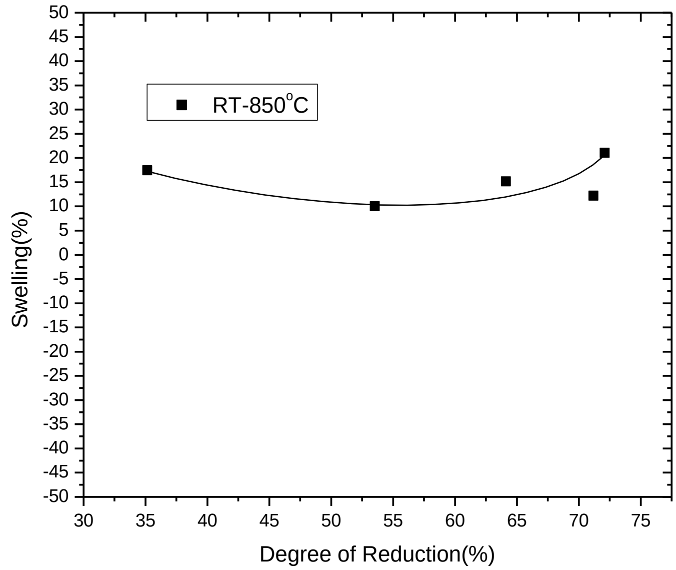


Fig 4.19: Percentage swelling vs degree of reduction plots for fired BPJ haematite ironore pellets [3%binder, firing temperature-1300°Cfor 1hour, {-100#(80%), -25+36#(20%)}]

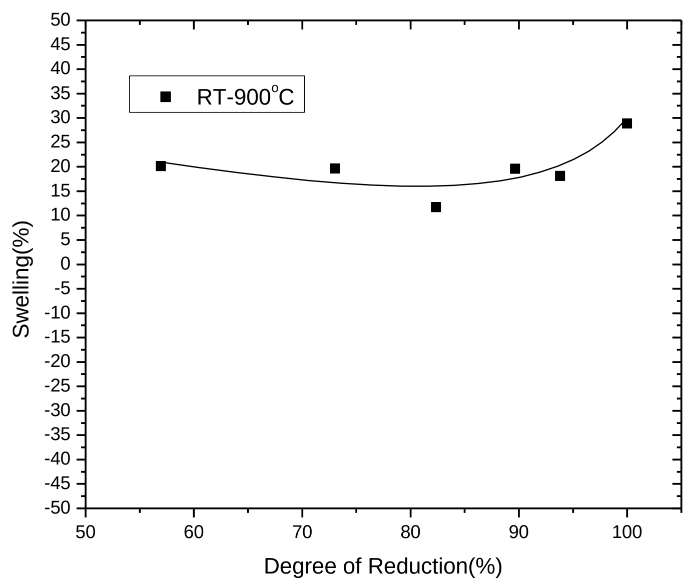


Fig 4.20: Percentage swelling vs degree of reduction plots for fired BPJ haematite ironore pellets [3%binder, firing temperature-1300°Cfor 1hour, {-100#(80%), -25+36#(20%)}]

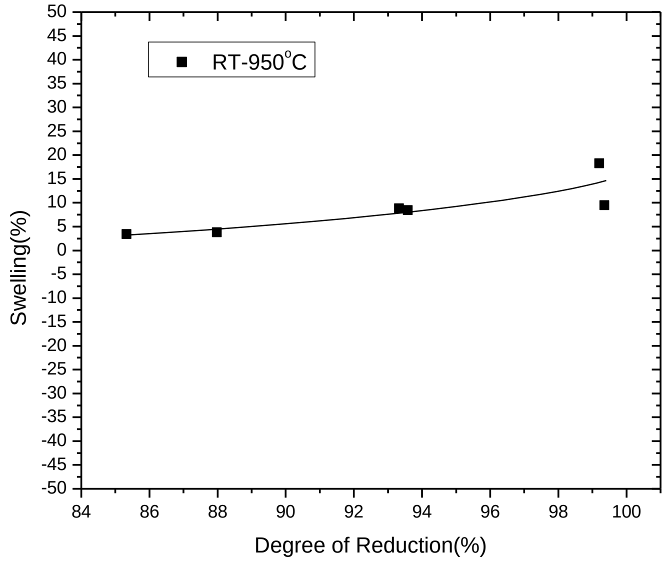


Fig 4.21: Percentage swelling vs degree of reduction plots for fired BPJ haematite ironore pellets [3%binder, firing temperature-1300^{o}C for 1hour, {-100#(80%), -25+36#(20%) }]

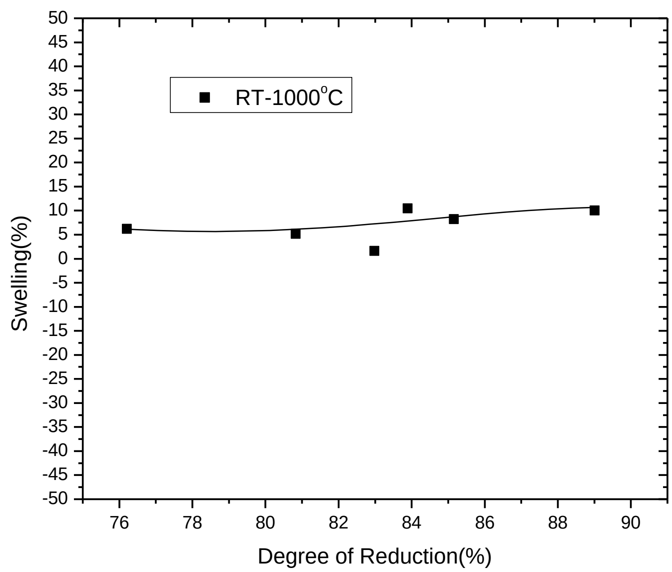


Fig 4.22: Percentage swelling vs degree of reduction plots for fired BPJ haematite ironore pellets [3%binder, firing temperature-1300^{o}C for 1hour, {-100#(80%), -25+36#(20%) }]

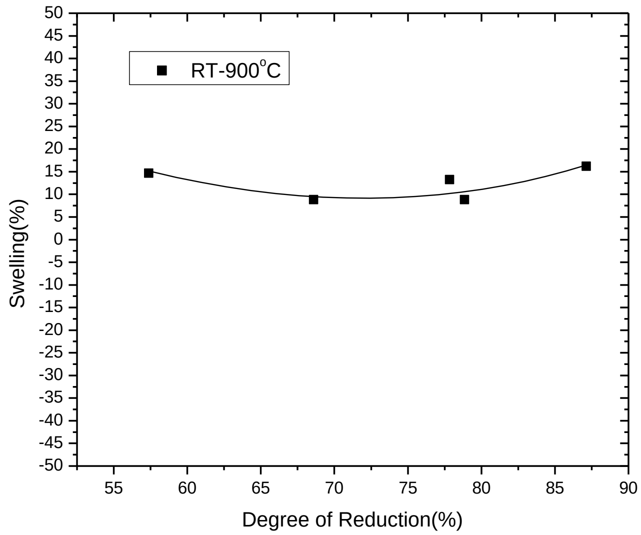


Fig 4.23: Percentage swelling vs degree of reduction plots for fired BPJ haematite ironore pellets [3%binder, firing temperature-1300^{o}C for 1hour, {-100#(90%), -25+36#(10%) }]

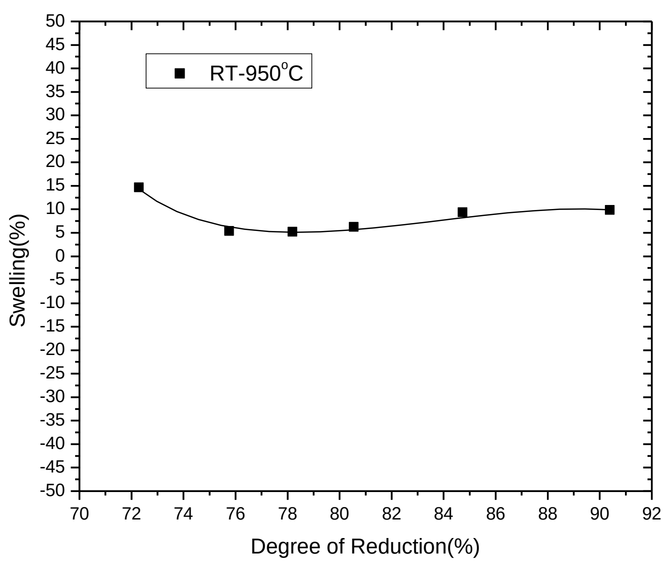


Fig 4.24: Percentage swelling vs degree of reduction plots for fired BPJ haematite ironore pellets [3%binder, firing temperature-1300^{o}C for 1hour,{-100#(90%),-25+36#(10%) }]

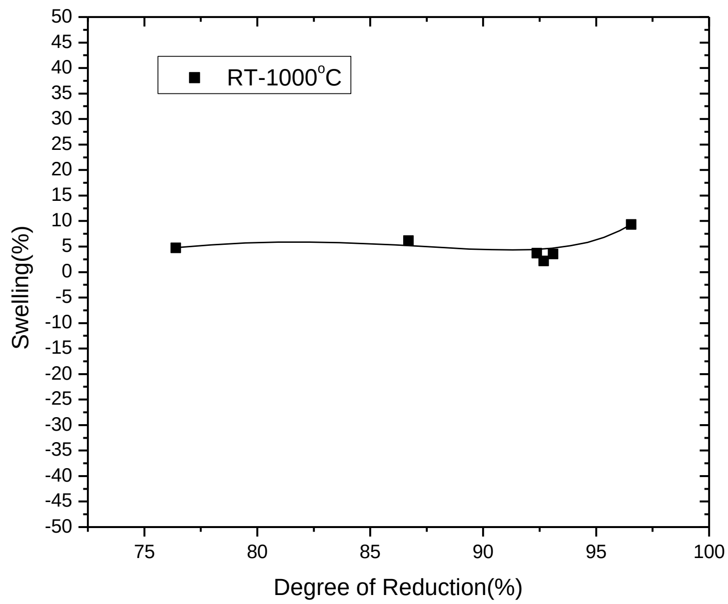


Fig 4.25: Percentage swelling vs degree of reduction plots for fired BPJ haematite ironore pellets [3%binder, firing temperature-1300°C for 1hour, {-100#(90%), -25+36#(10%) }]

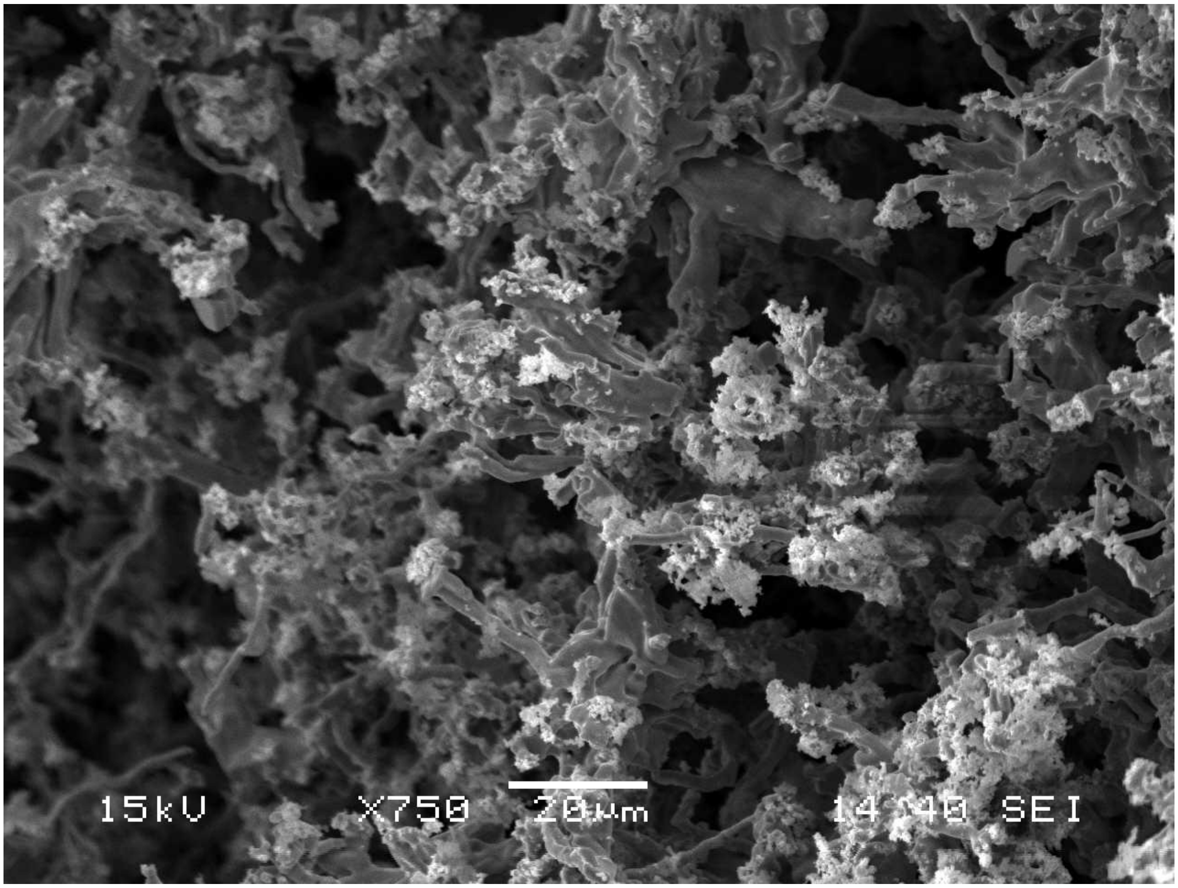


Fig 4.26: SEM photograph of reduced DR Pattnaik haematite iron ore pellet fired at 1300^{o}C for 1 hour [reduction temperature-900^{o}C, 3% binder, reduction time-75 min,{-100#(80%),-25+36#(20%)}]

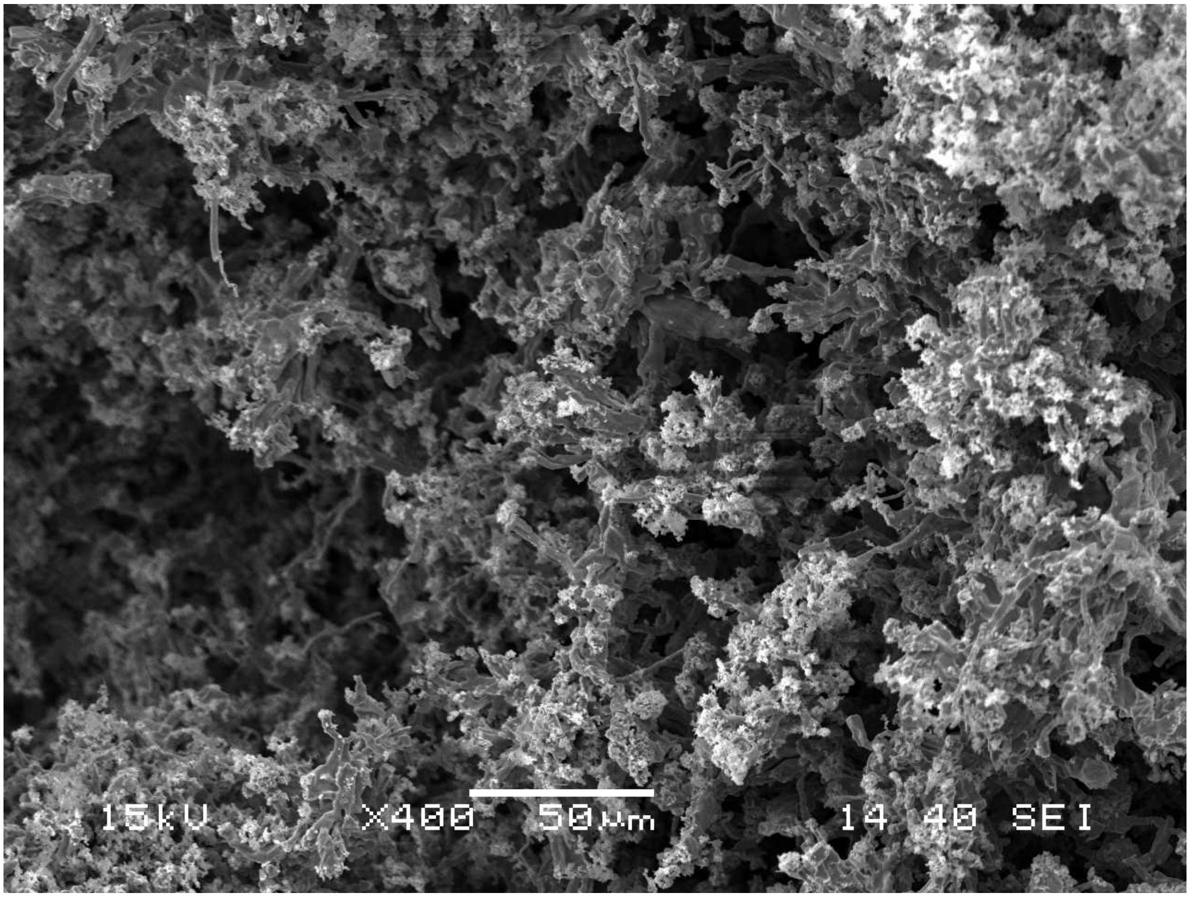


Fig 4.27: SEM photograph of reduced DR Pattnaik haematite iron ore pellet fired at 1300^{o}C for 1 hour [reduction temperature-900^{o}C, 3% binder, reduction time-75 min,{-100#(80%),-25+36#(20%)}]

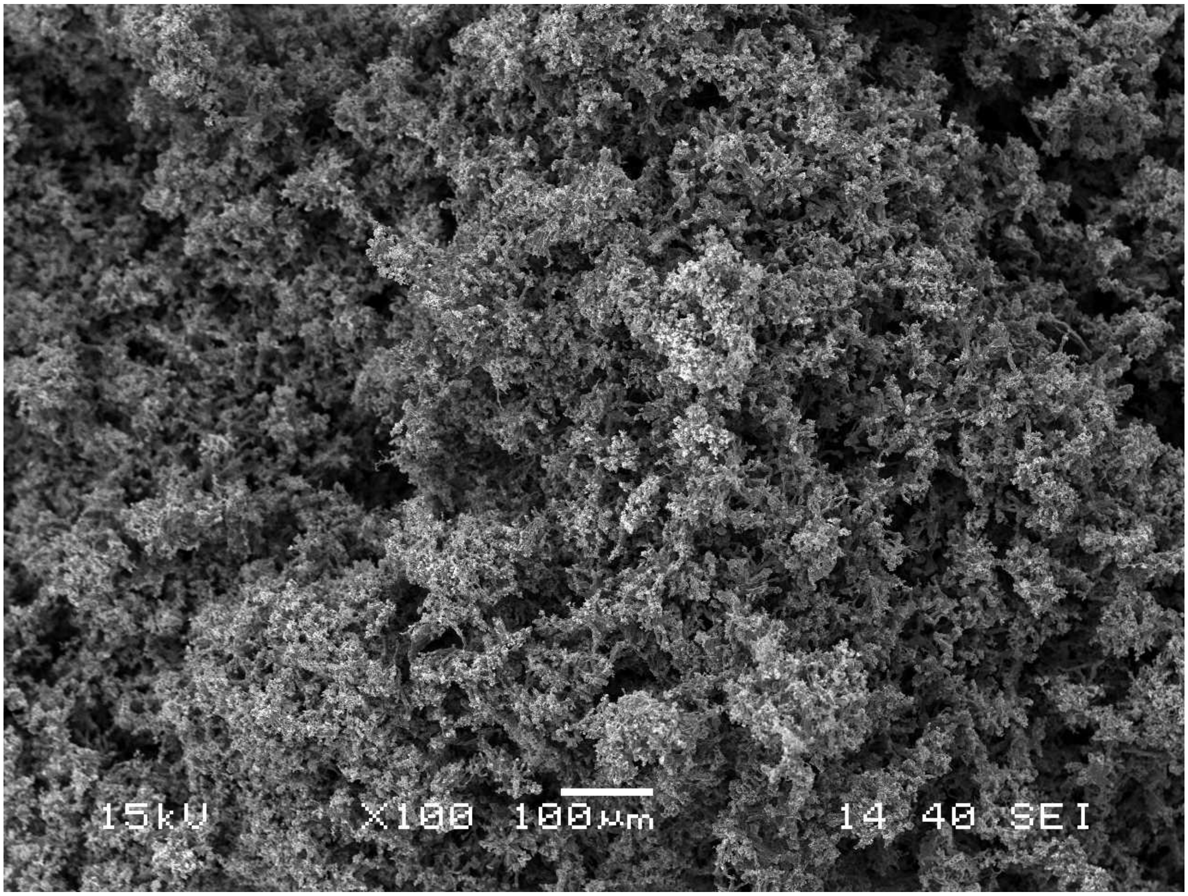


Fig 4.28: SEM photograph of reduced DR Pattnaik haematite iron ore pellet fired at 1300^oC for 1 hour [reduction temperature-900^oC, 3% binder, reduction time-75 min,{-100#(80%),-25+36#(20%)}]

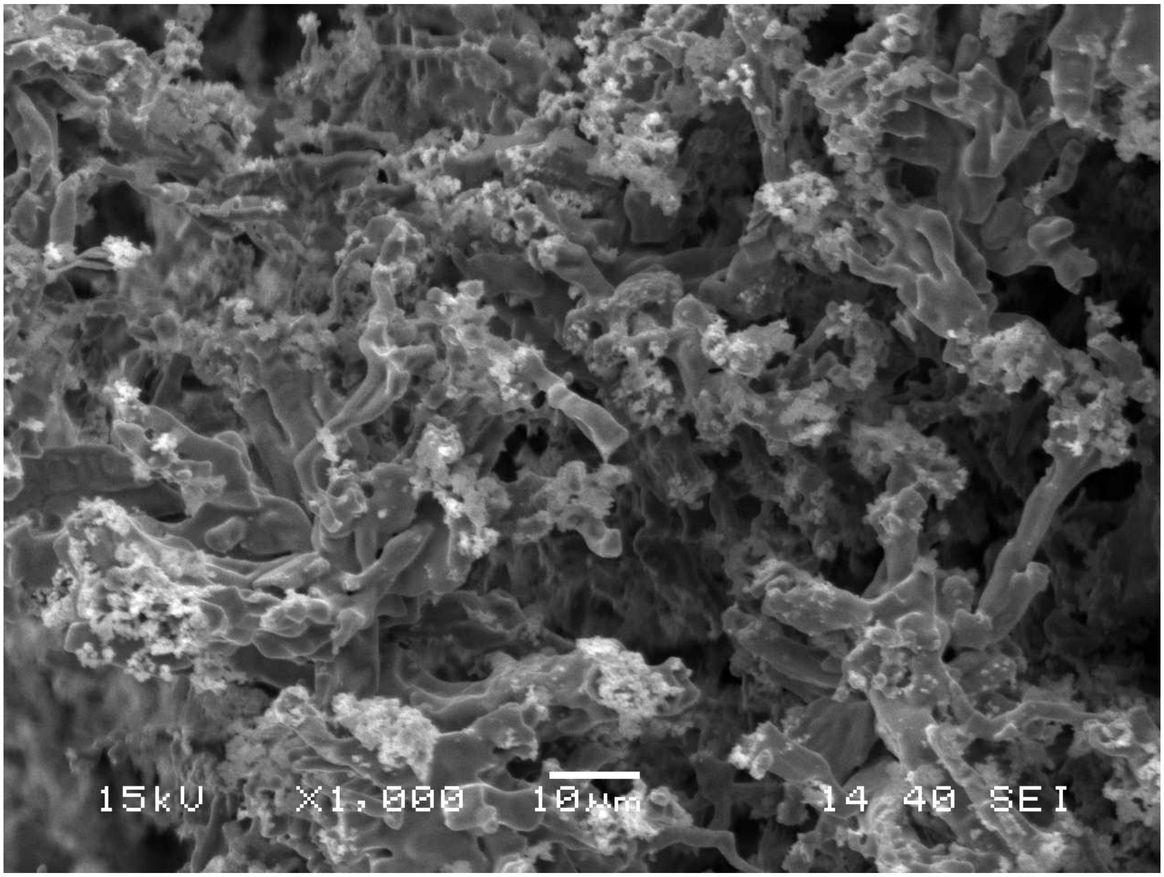


Fig 4.29: SEM photograph of reduced DR Pattnaik haematite iron ore pellet fired at 1300°C for 1 hour [reduction temperature-900°C, 3% binder, reduction time-75 min,{-100#(80%),-25+36#(20%)}]

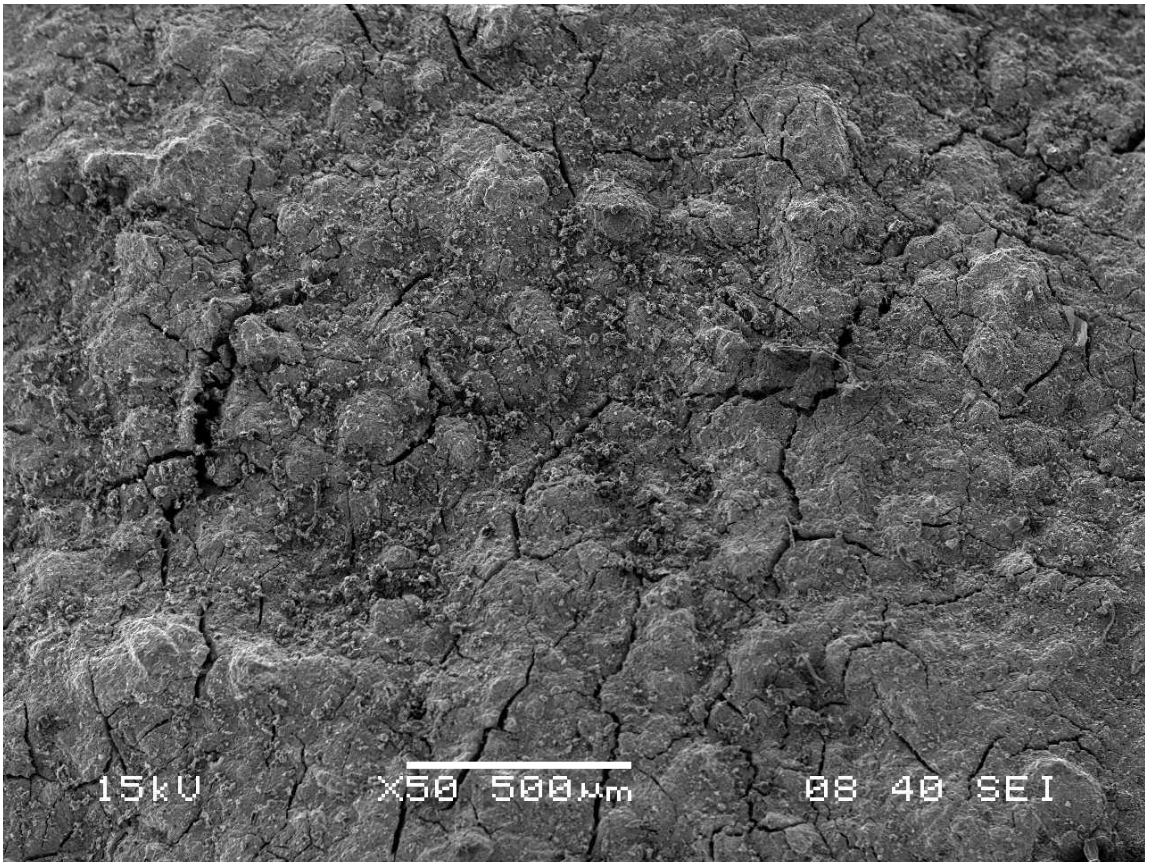


Fig 4.30: SEM photograph of reduced DR Pattnaik haematite iron ore pellet fired at 1300°C for 1 hour [reduction temperature-850°C, 3% binder, reduction time-90 min, {-100#(80%),-25+36#(20%)}]

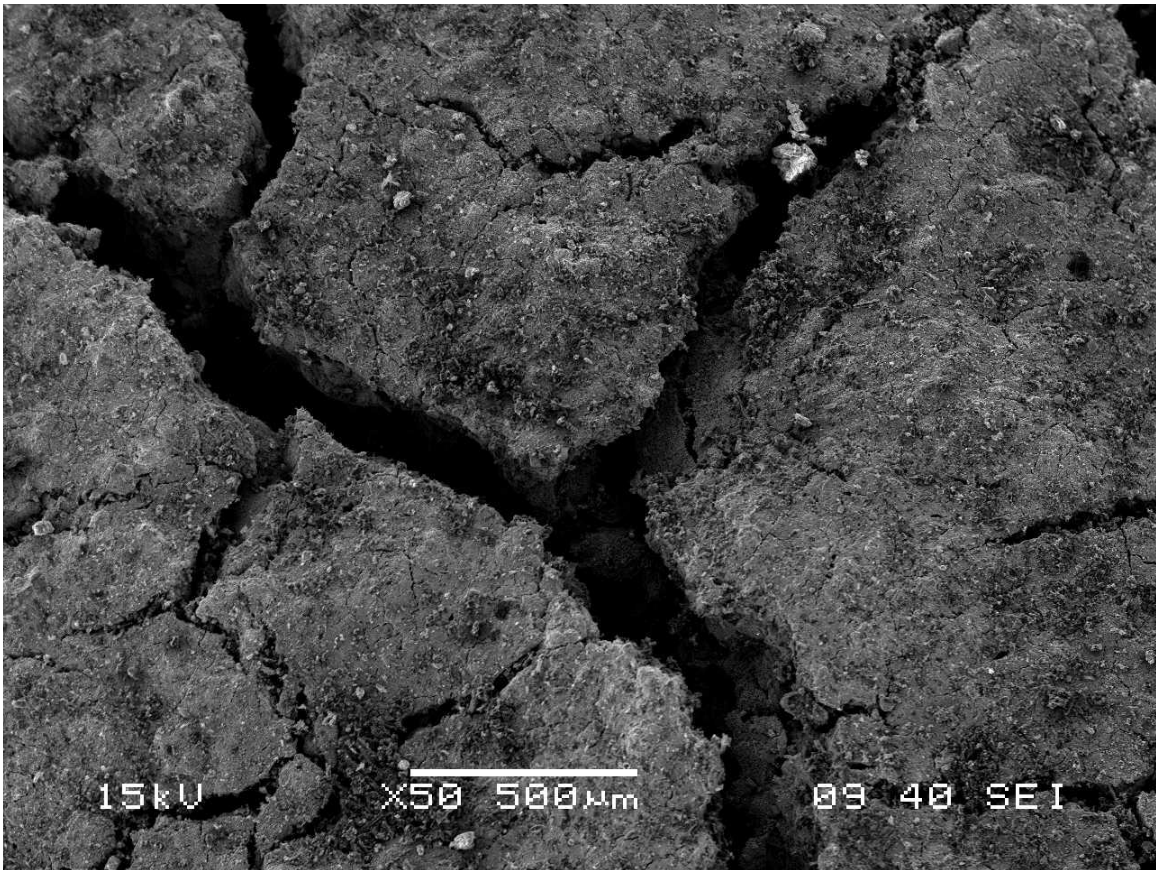


Fig 4.31: SEM photograph of reduced DR Pattnaik haematite iron ore pellet fired at 1300°C for 1 hour [reduction temperature-900°C, 3% binder, reduction time-30 min, {-100#(80%),-25+36#(20%)}]

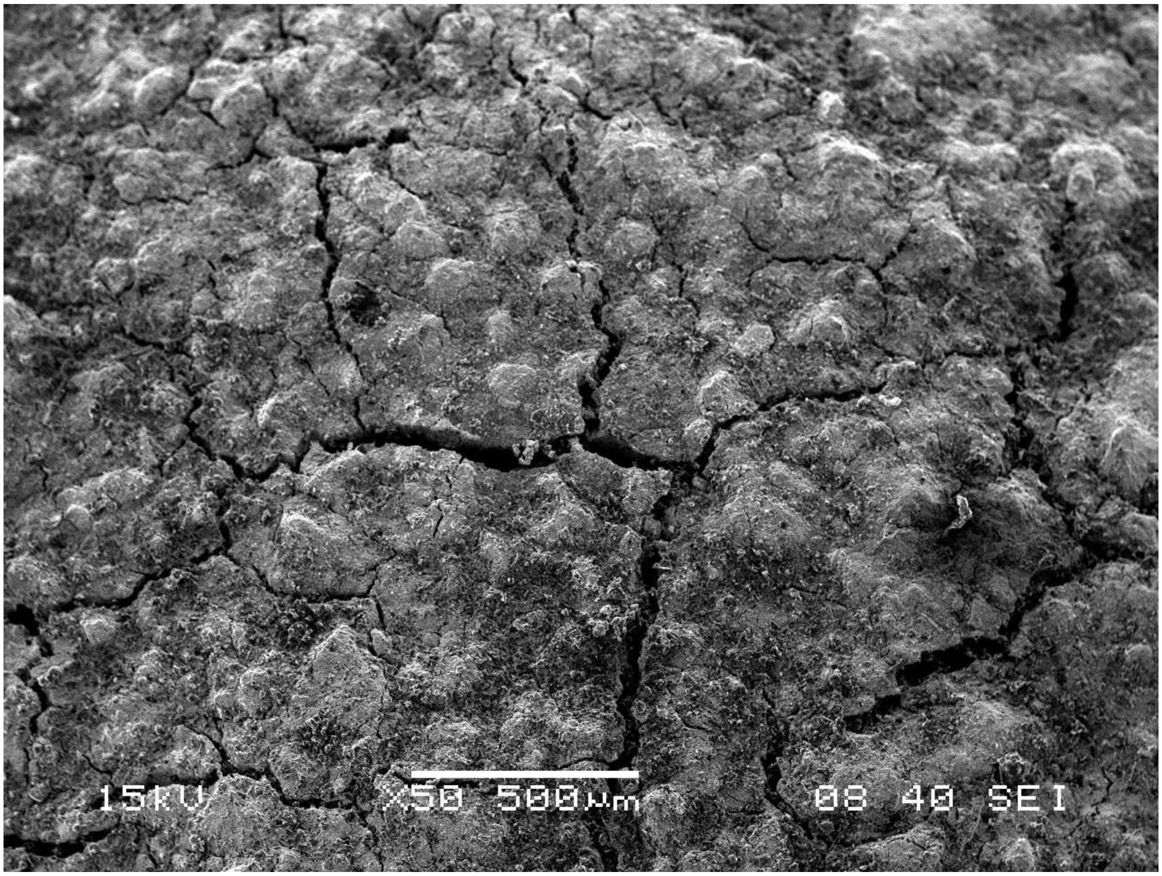


Fig 4.32: SEM photograph of reduced DR Pattnaik haematite iron ore pellet fired at 1300^{o}C for 1 hour[reduction temperature-950^{o}C, 3% binder, reduction time-25 min,{-100#(80%),-25+36#(20%)}]

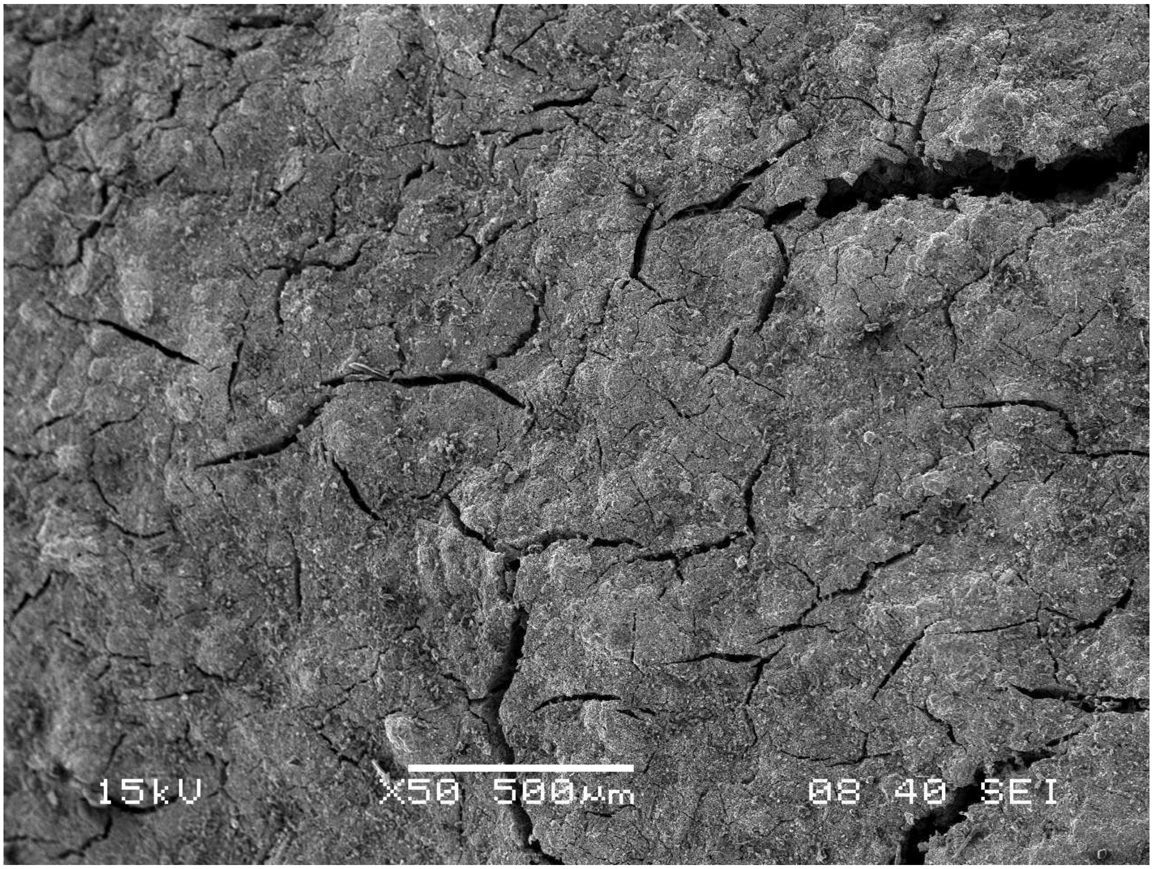


Fig 4.33: SEM photograph of reduced DR Pattnaik haematite iron ore pellet fired at 1300°C for 1 hour [reduction temperature-1000°C, 3% binder, reduction time-25 min,{-100#(80%),-25+36#(20%)}]

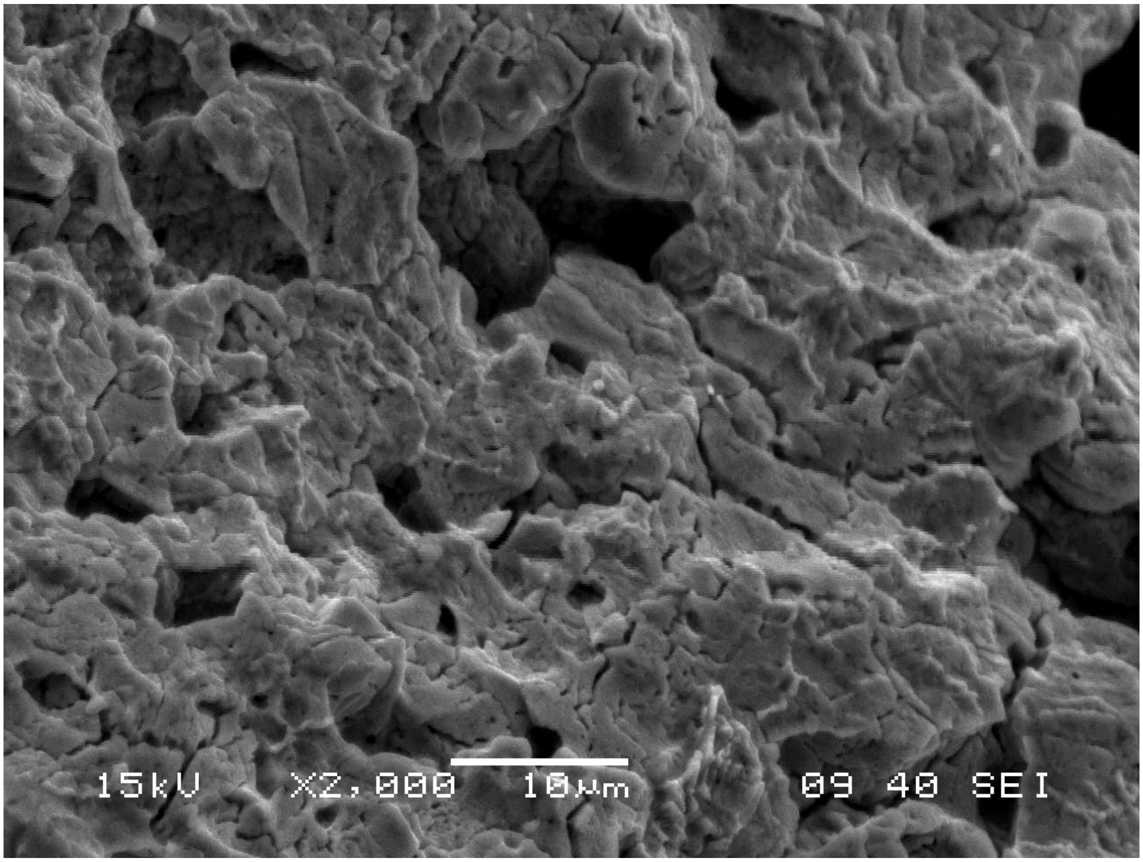


Fig 4.34: SEM photograph of reduced DR Pattnaik haematite iron ore pellet fired at 1300^{o}C for 1 hour [reduction temperature-850^{o}C, 3% binder, reduction time-90 min,{-100#(80%),-25+36#(20%)}]

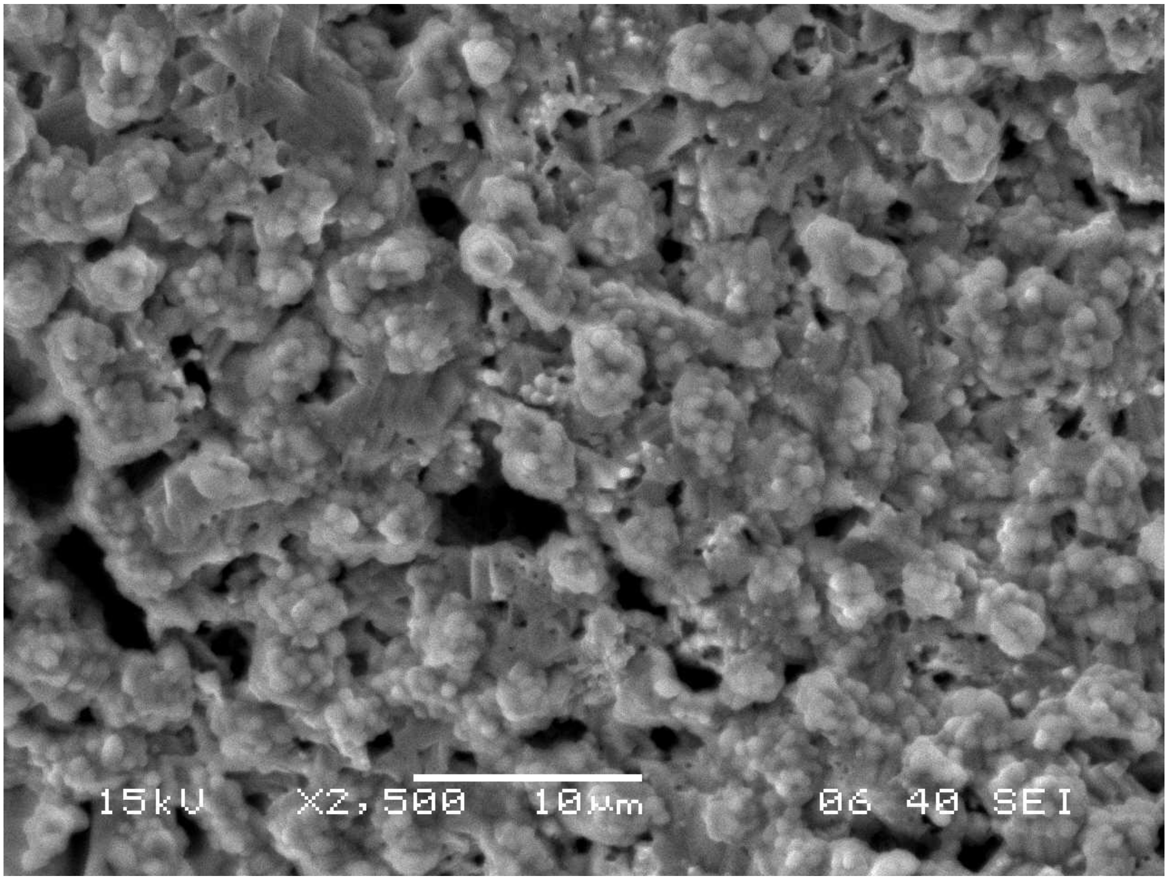


Fig 4.35: SEM photograph of reduced DR Pattnaik haematite iron ore pellet fired at 1300^{o}C for 1 hour [reduction temperature-900^{o}C, 3% binder, reduction time-90 min,{-100#(80%),-25+36#(20%)}]

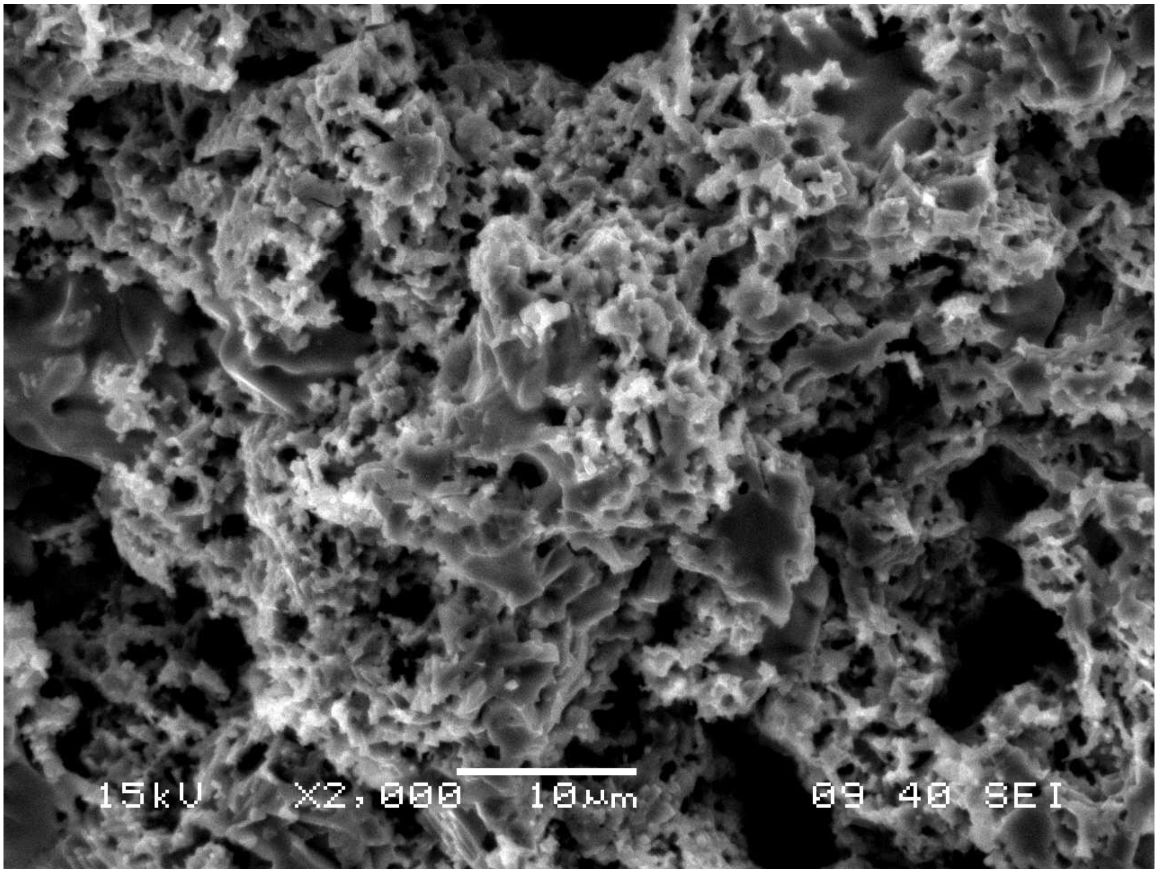


Fig 4.36: SEM photographs of reduced DR Pattnaik haematite iron ore pellet fired at 1300°C for 1 hour [reduction temperature-950°C, 3% binder, reduction time-25 min,{-100#(80%),-25+36#(20%)}]

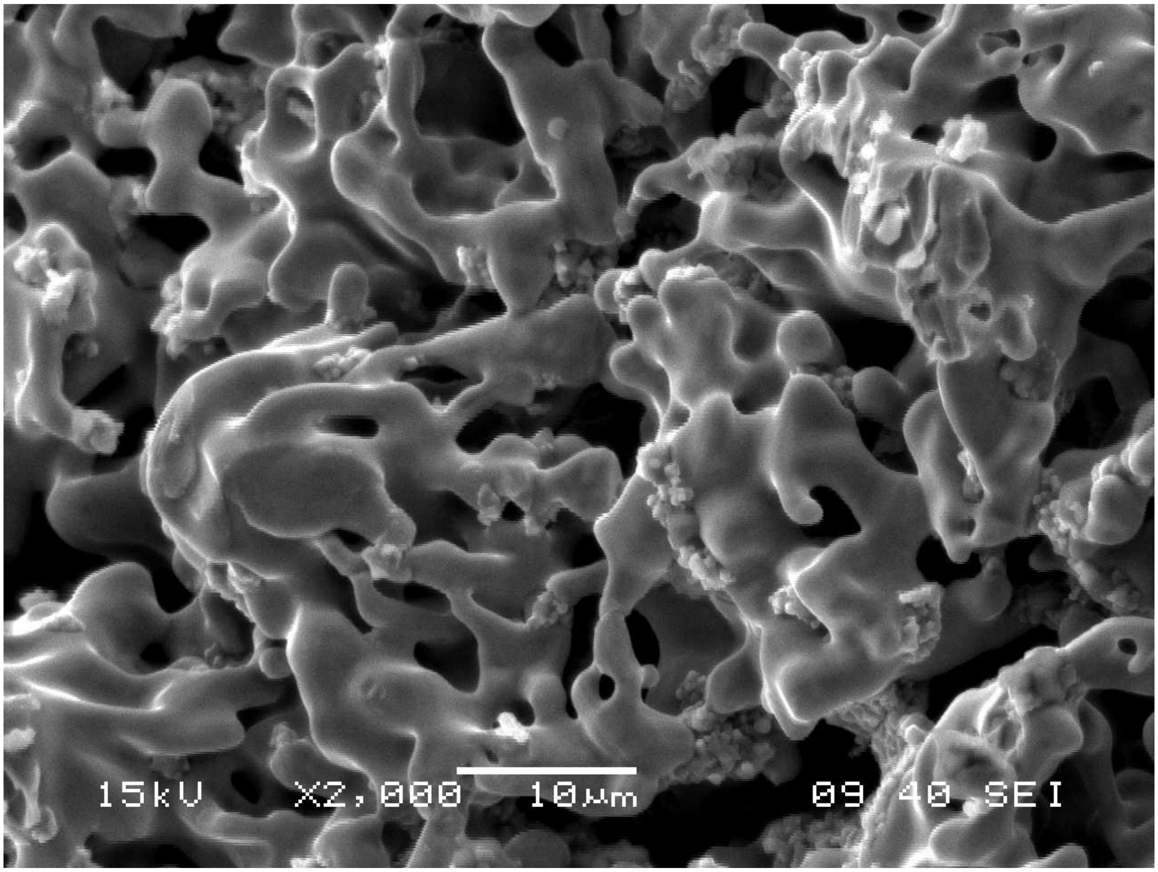


Fig 4.37: SEM photographs of reduced DR Pattnaik haematite iron ore pellet fired at 1300^{o}C for 1 hour [reduction temperature-1000^{o}C, 3% binder, reduction time-25 min,{-100#(80%),-25+36#(20%)}]

CHAPTER-5

CONCLUSIONS

5. Conclusions

- The Crushing Strength of fired pellets increased with increase in firing temperature. The effect of firing temperature on the Crushing Strength is more pronounced at firing temperature of 1300^oC.
- Porosity of the fired pellets decrease with increase in firing temperature. The decrease was found to be more pronounced at firing temperature of 1300^oC.
- A decrease in degree of reduction was observed with increase in firing temperature.
- Degree of reduction increases with increase of reduction temperature.
- The extent of swelling first increases and then decreases with increase in reduction temperature.
- The degree of reduction increases with increase of time at a particular reduction temperature.
- The extent of swelling increases with increase in reduction time at a particular reduction temperature and particular firing temperature. However the pellets fired at higher temperature showed a decrease in the extent of swelling with increase in reduction time.
- The drop number increases with increase in firing temperature.
- Use of concentrated sugarcane juice as binder is helpful in providing good binding properties so that we can blend the wasted +100# fines(-25+36#) along with -100# fines to form pellets. The reduction behaviour of these mixed pellets was found similar to pellets made from -100# fines only. Thus use of concentrated sugarcane juice as binder gives a way to utilize the waste fines thus avoiding problem of disposal and saving of enormous amount of energy.

CHAPTER-6
FUTURE WORK

6. Suggestions for future work

1. This work may be extended for other iron ore pellets existing in this region.

2. Similar studies may be carried out with other non-coking coal of Orissa, Jharkhand, Chattisgarh and nearby areas.

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

4. Detailed studies on the carbon pickup in the reduced products, under different parameters, may be carried out.

5. The addition of other possible binders on the chemical and physical properties of iron ore pellets may also be carried out.

CHAPTER-7

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7.References

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