Reducibility Tests on Itakpe Iron Ore

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***Abstract-* The successful upgrading of the sinter grade of the Nigerian Itakpe iron ore which was originally earmarked as blast furnace feed, to a super-concentrate with a higher Fe content to meet the requirement of the Midrex Direct Reduction based Plant at the Delta Steel Company, for large scale manufacture of iron and steel led to the need to carry out pilot scale reduction experiments for the purpose of setting up suitable process and operating parameters.**

The parameters examined in the experiments include the effect of change in reduction temperature on the percentage of oxygen removal or reduction degree, effect of reducing gas flow rate, product discharge rate, oxide pellet size, H_2/CO ratio on the percentage of oxygen removed or reduction degree. It was observed that the patterns noticed were similar to those obtained in the reduction of most imported oxide feed for the direct reduction process. A reduction temperature of $760^{O}C$, a pellet size of 1.2mm diameter and an H_2/CO ratio of 1.5 were found to be suitable for a successful reduction of the Itakpe iron ore. A reduction temperature increase beyond this value would be accompanied by a corresponding increase in the product discharge rate.*

***Indexed Terms-* Direct reduced iron, Itakpe iron ore, Oxide pellets, Reducibility**

I. INTRODUCTION

The enshrinement of iron and steel industries in an economy will subsequently result in the following industrial activities:

The effective development and utilization of locally available natural resources through extraction and conversion of the raw materials;

The development of the upstream and downstream sub-sector leading to the production of raw materials, intermediate products, machinery, spare parts, support services etc;

The development of related industries, such as mining, chemicals, agriculture, transport, construction, communication, etc, through the supply of steel and steel products.

The generation of employment and the development of skilled manpower;

- Increase in foreign exchange earnings.

According to the Raw Materials Research and Development Council, Nigeria as a developing country required the development of iron and steel in order to avoid the overbearing dependence on importation for industrialization, with attendant effect on real manufacturing. Considering the large tonnage of iron and steel products used annually and the need to harness the available iron and steel mineral raw material resources of the country, the Federal Government since 1970s embarked on the establishment of iron and steel industries, and mineral raw materials sourcing and development agencies. The whole idea, as envisaged by the Government, was to reduce the large foreign exchange expenditure on iron and steel products. (Raw Materials Research and Development Council, 2010)

The National Steel Development Authority (NSDA) was established in 1971 to plan, operate and maintain iron and steel plants in the country and was also charged with the responsibility of carrying out steel raw materials surveys and mining operations to ensure adequate supply of raw materials to the Nigerian Steel industry.

Under the auspices of the NSDA, Nigerian and Soviet geologists and technologists were able to determine the resources and suitable local raw materials required to set up an integrated iron and steel plant at Ajaokuta in Kogi State.

Global recession, poor funding and the installation of massive infrastructural facilities stood in the way of the completion and full commissioning of this plant which at the time, was Africa's largest steel making Plant.

Due to this delay, and convinced by its well-advertised advantages, The Federal Government signed a contract, on a turn-key basis, with a consortium of 10 Austro-German Companies for the establishment in the Delta region of the country, of an integrated Iron and Steel plant with a capacity of 1 million tonnes per annum of liquid steel, utilizing the modern Direct Reduction/Electric Arc Furnace route to steel production.

This led to the commissioning of the Delta Steel Company (DSC) in 1982 to fill in this gap. This Plant was to operate on imported high grade iron ore based on the Direct Reduction Process (DRP) and Electric Arc Furnace Route of Steel making. (Raw Materials Research and Development Council, 2010)

During the production period, iron ore which constitutes about 80% of the raw material input for steel production was imported from Liberia (1982 – 1989) and Brazil (1989 – 1993).

The low draft of the Warri River through which the imported iron ore was delivered to DSC, coupled with the petroleum pipeline on the river bed made it impossible for ships of more than 15,000 tonnes net weight to berth at the Delta steel quays thereby leading to very high cost in the production of steel. In addition, the downturn in the Nigerian economy resulted in difficulty in obtaining foreign exchange for purchase of this raw material.

This led to the need to investigate the possibility of utilizing at Delta Steel Company, the locally available iron ore at Itakpe in Kogi state of Nigeria, whose sinter grade had a total iron content of about 63% and a gangue in excess of 4% and which was originally conceived for use at the Ajaokuta Blast furnace plant. (Ola et. al., 2009)

The synergetic action of Delta Steel Company (DSC), National Iron Ore Mining Company (NIOMCO), National Metallurgical Development Centre (NMDC) Jos, offshoots from the NSDA (Mohammed Sanusi, 2002), in 1990 as mandated by the then Ministry of Mines and Steel, led to the following:

Beneficiating the Itakpe iron ore to a quality acceptable to Midrex Direct Reduction Process, carrying out Pilot tests to ascertain and establish the pelletizability and reducibility of the upgraded iron ore,

Running a full-scale plant test based on the success of the above two programmes.
Two grades of iron ore came out of this venture:
The beneficiated NIOMCO ore of Fe_{total} of 65.74%,
The re-beneficiated NIOMCO ore of Fe_{total} of 67.40%.
These formed part of the initial efforts and success in the production of steel from the locally available iron ore at Itakpe in the middle belt region of Nigeria.

II. IRON MAKING WITH ITAKPE ORE

2.1 Itakpe Iron Ore.

Itakpe is a rural area situated in Okene local Government area of Kogi state in central Nigeria, lying within the latitudes 7^{O}36'N to 7^{O}39'N and longitudes 6^{O}17'E to 6^{O}22' as shown in Figure 1.

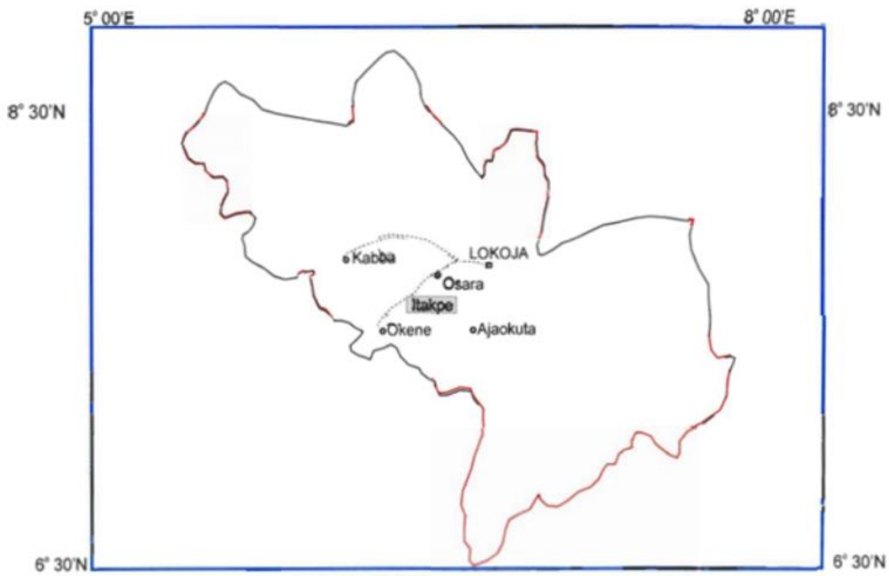

Figure 1: Map showing location of Itakpe in Kogi State (Source: Akpah, 2008)

The Itakpe iron ore deposit is located about 16 km northeast of Okene town in Kogi state and is reported to form a series of iron-bearing quartzites ridge in that area. This ridge is approximately 1 km wide and 5 km in length and reaching a maximum elevation of about 500 m above the surrounding low land with the deposit consisting of eastern and western mines (Ameh, 2014). The Itakpe iron-ore deposit is localized within the gneiss-migmatite quartzite unit (Akinrisola and Adekeye, 1993). Figure 2 shows the Geological map of the Itakpe iron ore deposit. Figure 3 shows a sample of Itakpe iron ore.

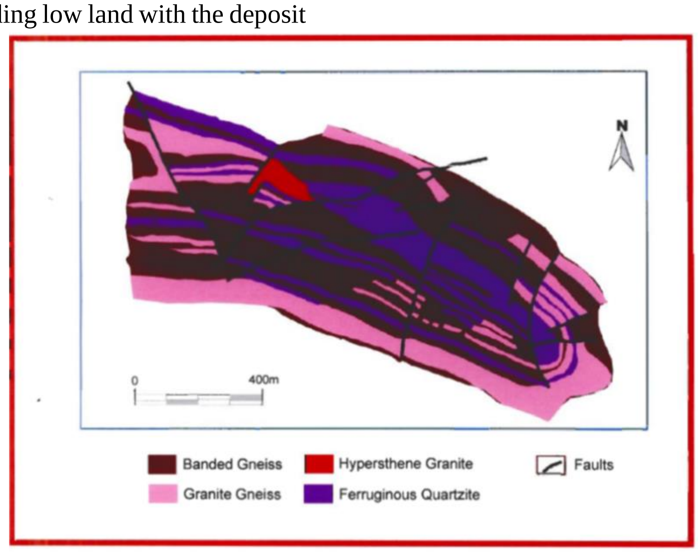

Figure 2: Geological Map of Itakpe Iron ore deposit. Source: Akpah (2008)

Figure 3: Itakpe Iron Ore sample

The data on Itakpe ore was collected from Ore mining Corporation, Itakpe, Nigeria. Figures 4 and 5 show the stock yard of the Corporation.

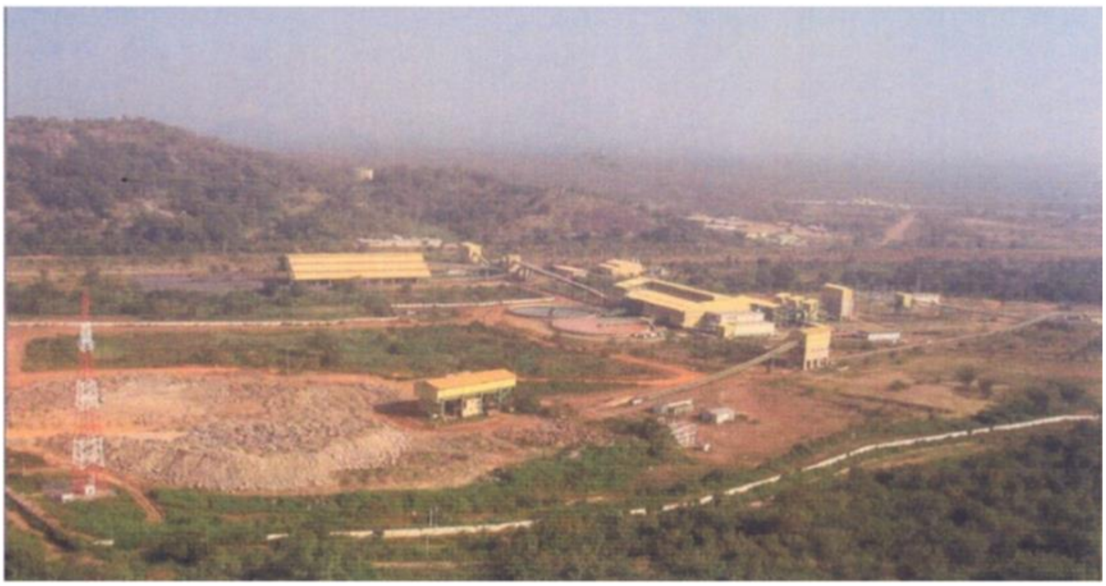

Figure 4**:** Iron ore mines at Itakpe (Ministry of Mines and Steel Development, 2010)

The stock yard of the National Iron Ore Mining Corporation, Itakpe, Nigeria showing beneficiated and stacked iron ore pellets is shown in Figure 3.2. The National Iron Ore Mining Corporation operates a beneficiation plant for upgrading the Run-Off mine ore which has a total iron content of about 36% to a concentrate of 64% and a super concentrate of about 67% Fe content.

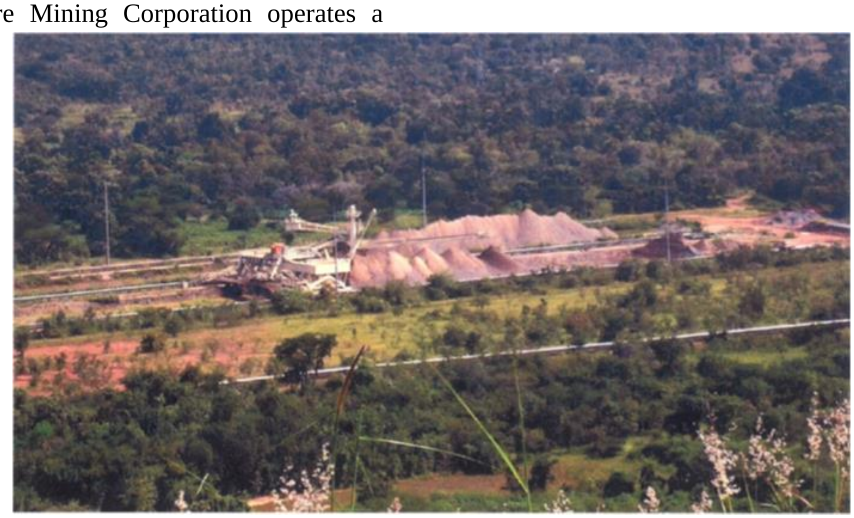

Figure 5: Stock yard for Itakpe beneficiated ore (Ministry of Mines and Steel Development, 2010)

Itakpe iron ore deposit, with an estimated reserve of about 200 million tons was found in 1977. The deposit is embedded in the Itakpe hill, near Okene, in the north central Kogi state of Nigeria. The deposit extends approximately 3,000m in length and includes about 25 layers of ferruginous quartzite. From a tectonic point of view, the Itakpe deposit is confined to the southern limb of a large Itakpe-Ajabanoko anticline with enclosing rocks and conformable ore layers striking sub- latitudinally slightly bending to the North and dipping southwards at angles ranging from 40° to 80° with local complications like minor folds.

The deposit contains a mixture of magnetite and hematite whose ratio varies throughout the deposit. The ore consists of coarse, medium and fine grained particles. The fine ores are mainly in the eastern part of the deposit and in the thin layers, while the coarse and medium ores are relatively mixed. However, the coarse ore particles predominate in the north and west of the central layers and the medium sizes in the centre of the central layers. The average content of iron in the ore is approximately 35%. (Raw Materials Research and Development Council (2010)

The Nigerian National Iron Mining Company Ltd. (NIOMCO), Itakpe, was established to upgrade this ore to sinter grade of 63% to 64% Fe for the blast furnace based Ajaokuta integrated steel plant, Ajaokuta, Kogi state. The sinter grade of the Itakpe iron ore that assayed 63.63% Fe and total acid gangue of 6.62% was successfully upgraded to a super-concentrate with a higher Fe content of 66.66% and lower acid gangue of 4.22% to meet the requirement for a Midrex-grade super concentrate, though the acid gangue content exceeded the upper limit of 3.5%. (Ola et. al., 2009)

2.2 Direct Reduction of Itakpe Oxide Pellet

In a work by Adedeji & Sales (1984), the reducibility of Itakpe ore was carried out and the Hydrogen and Carbon monoxide reduction were examined. The ore was heat-treated before reduction to remove the volatile components and reducibility determined by mass loss.

The isothermal mass change data obtained at 800, 900, 1000 and 1100^{O}C showed that rate of Hydrogen reduction increased with temperature increase except at 1100^{O}C as shown in Figure 6.

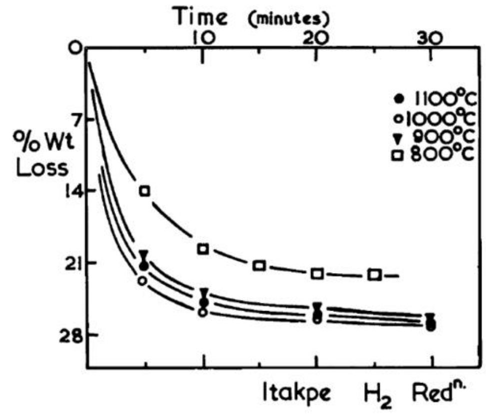

Figure 6: Isothermal mass- change data for H_2 reduction of Itakpe ore

Also, for CO reduction, it was discovered that rate of reduction increased with increasing temperature and in addition, carbon deposition was minimized at the higher temperatures.

Processing of the pellets, from the prime ore showed that oxide pellets are easily reducible at comfortable reduction temperature of 760^{0}C with moderate fines level. Table 6 shows the average physico-chemical properties of the derived DRI.

The Fe^{met} which gives the level of metallic iron was below the DSC specification by virtue of the chemistry of the ore, which is characterized by high silica level. The gangue level was however accommodated in Steel Making Shop by careful choice of production strategy. This paper reports on the pilot tests on the use of Itakpe iron ore in a direct reduction process.

III. MATERIALS AND METHODS

Two grades of Iron ore were produced for pilot tests. These are the beneficiated Itakpe Iron ore (Fe^{tot} – 65.74%, $SiO_2 + Al_2O_3$ = 8.10%) and the re-beneficiated Iron ore (super concentrate) with Fe^{tot} of 67.4%, $SiO_2 + Al_2O_3$ of 2.45% derived from the former using facilities available at National Metallurgical Development Center, Jos.(NMDC). The significant aspect of the latter exercise was the reduction of the acid gangue from about 8% to less than 3%. Table 1 shows the results of the beneficiation of the Itakpe Iron ore, while Table 2 shows the properties of the oxide pellets obtained from the Itakpe ore.

Table 1: Properties of Itakpe Ore used for Pilot Tests

PARAMETERS	AS-RECEIVED ORE (CONCENTRATE)	BENEFICIATED ORE	RE-BENEFICIATED ORE (SUPER CONCENTRATE)	DSC SPECIFICATION
Fe^{total} (%)	62.28	65.74	67.40	66-67
Fe_2O_3 (%)	89.00	93.90	96.31	94-96
$SiO_2 + Al_2O_3$	11.10	8.10	2.45	3.5 max
CaO (%)	0.17	0.001	0.17	0.1
MgO (%)	-	Trace	0.03	0.1
S	-	0.004 max	0.001	0.04 max
P	0.011	0.06 max	0.04	0.05
LOI	0.21	0.18	0.24	1.2 max
SSA	-	-	2056	1850 – 2500

*LOI = Loss on Ignition
SSA = Specific Surface Area

Table 2: Properties of Oxide Pellets derived from Itakpe Ore

PARAMETER	BENEFICIATED ORE	RE-BENEFICIATED ORE	DSC SPECIFICATION
Compression Strength (N/P)	4955	5000	3450
Pellet Size (6.3 – 19mm) (%)	98.47	97.00	92-97
Tumble Index (%)	96.92	95.00	93.00 min
Abrasion Index	2.31	3.50	5.0 max
Basicity (CaO + MgO / $SiO_2 + Al_2O_3$)	0.51	0.75	0.6 min
Firing Temp (max) ^{0}C	1200	1200	1300

The average physical properties of the green pellets in addition to the physico-chemical properties of the fired pellets are shown in Table 3.

Table 3: Physico-Chemical Properties of Pellets derived from Itakpe Iron Ore

PARAMETER	PRIME ORE	DSC SPECIFICATION
GREEN PELLETS MOISTURE (%) DROP NO (D/P) CCS (N/P)	 8.10 5.7 11.22	 7 – 8.0 4.8 min 9.0 min
FIRED PELLETS PHYSICAL PROPERTIES		

CCS (N/P)	4561	3450
+ 16mm (%)	21.41	5.0 max
6.3 – 19m (%)	95.05	92.0 min
Tumble Index (%)	94.51	93.0 min
Abrasion Index (%)	3.93	5.0 max
Firing Temp (^{0}C)	1300	1300
CHEMICAL PROPERTIES		
Fe^{tot} (%)	65.10	66.00 min
Fe_2O_3 (%)	93.21	94.00 min
$SiO_2 + Al_2O_3$ (%)	4.57	3.50 max
CaO (%)	2.13	1.50 – 01.70
MgO	Trace	2.00 max
S	0.001	0.001 max
P.	N.D	0.03 max
Basicity	0.51	0.60 min

*CCS = Cold Compression Strength

With regard to DRI obtained from the Itakpe oxide pellets, the silica and alumina contents of 5.90% and 0.72%, respectively, gave a total acidic oxide content of 6.62% that was far above the upper limit of 3.6%. (Midrex Direct Reduction Plant operating manual Vol. 1, 1981)

The properties of the Direct Reduced Iron (DRI) produced from the Itakpe ore are shown in the table 4.

Table 4: Physico – Chemical Properties of Dri Derived from Itakpe Iron Ore

PARAMETER	DRI	DSC SPECIFICATION
CHEMICAL PROPERTIES		
Fe^{total}	88.30	90 min
Fe^{met}	81.20	82 min
Deg. Met	92.00	88 min
FeO	09.10	2.0 – 9.4
CaO	01.22	2.5 max
$SiO_2 + Al_2O_3$	05.42	3.6 max
C	02.08	1.1 – 2.0
MgO	Trace	0.04 max
P	N.D	0.03 max
S	0.006	0.03 max
PHYSICAL PROPERTIES		
CCS (N/DRI)	970	700
Grain Size (%) (9.5 – 16mm)	89.50	90 min
Tumble Index (%)	83.33	80 min
Abrasion Index (%)	6.67	6.0 max
Fines Level (%)	6.27	6.0 max
Reduction Temp (^{0}C)	760	760-860

3.1 Experimental Shaft Furnace

The aim of the experiment, was to determine the appropriate reduction temperature and examine the operational behavior of the Itakpe pellets under various operating conditions and determine the optimum operating parameters. The equipment that was used for the experiment was similar to that used by Takenaka et. al., (1986) shown in Figure 7. The specifications of the experimental apparatus are shown in the Table 5.

Table 5: Specifications of the experimental apparatus

Effective height	2m
Internal Diameter	0.13m
Maximum	1,173^{O}C
Maximum Gas	1.5bar

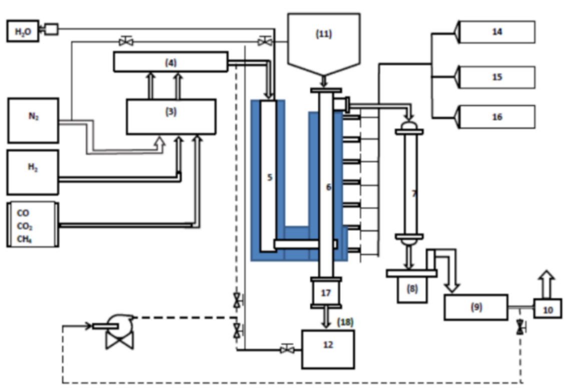

Figure 7: Schematic diagram of the experimental apparatus.

1) Gas container
2) Pump
3) Gas flow controller
4) Gas mixer
5) Heat exchanger
6) Reaction tube
7) Gas cooler
8) Drain and dust remover
9) Pressure controller
10) Flare stack
11) Vessel for raw materials
12) Vessel for products
13) Blower
14) Temperature recorder
15) Pressure recorder
16) Gas analyzer
17) Solid cooler
18) Table feeder

3.2 Experimental Procedure

The pellets were fed in from the raw material vessel of the experimental furnace. Different runs of the experiment were carried out to determine the effect of various parameters on the reduction process. These included the effect of change in temperature, change in size of the oxide pellet feed, changes in the flow and composition of the reducing gas, the effect of change in the height of the bed, variations in the pressure of the furnace and the feed composition.

After each run, the furnace was cooled down by nitrogen gas at the end of the measurements.

The physical and chemical properties of the beneficiated Itakpe Iron oxide pellets utilized for the experiment and the reducing gas compositions are shown in Tables 6 - 8.

Table 6: Physical Analysis of oxide pellet feed.

Parameter	Itakpe Pellets	DSC Specification
Cold Compression Strength	4000 N/p	3450 N/p
Tumble Index (%)	96	93 min
Average pellet size (6.3 – 19mm) (%)	97	92 - 97

Table 7: Chemical Analysis of Oxide pellet feed used for the experiments

Parameter	Value (%)
Fe_{tot}	64.43
Fe_2O_3	92.50
FeO	0.26
SiO_2	2.53
Al_2O_3	0.48
CaO	2.62
MgO	0.06
Mn	Trace
S	0.007
P	0.004

Table 8: Composition of reducing gases (%)

No.	H_2 (%)	CO (%)
1	48	47
2	52	44
3	57	38
4	62	34
5	65	32

IV. RESULTS AND DISCUSSIONS

4.1 Effect of Reduction Temperature

The degree of reduction of the pellets measured by the degree of removal of the oxide content of the iron oxide pellets was measured at different reduction temperatures. The data for the different reducing temperatures are presented in Table 9.

Table 9: Reduction Degree versus Time for various Reduction Temperatures

Time (mins)	T = 720 C	T = 740 C	T = 760 C	T = 780 C	T = 800 C
0	0	0	0	0	0
25	0	0	2	10	28
50	0	1	12	30	60
75	1	2	23	50	80
100	2	5	35	70	86
125	4	8	48	78	88
150	6	12	60	84	90
175	9	18	70	87	92
200	12	25	77	90	12
250	18	40	86	93	18
300	25	55	90	95	25
350	32	68	92	96	32
400	40	74	94	97	40
450	47	75	95	97	47
500	50	75	96	97	50

The graph showing this relationship is shown in Figure 8 (a) and (b)

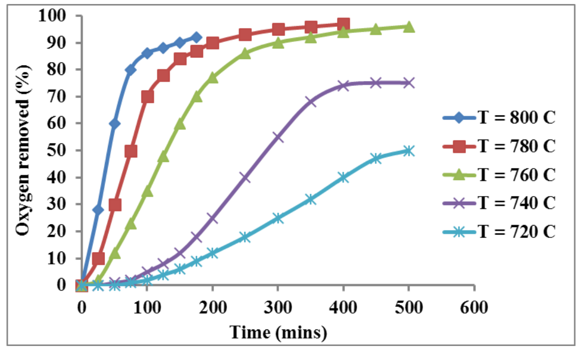

Figure 8: Oxygen removed versus Time at different reducing Temperatures

The amount of oxygen removed as should be expected increases with increasing temperature. This is depicted in Figure 8. In the experiments, the highest reduction for this ore was achieved at 760^{O}C though there was a slight drop after this temperature. Excessive burden temperature can result in clustering of the pellet and create channeling in the furnace which would eventually result in lower quality direct reduced iron. The optimum reduction temperature for the Itakpe ore is 760^{O}C. Any increase beyond this temperature would attract an increase in the rate of production for the maintenance of good product quality. The increase in the temperature of the inlet reduction gas led to an acceleration of the reaction flow rate which tended to intensify the reduction process. The same observations were made by Almasari et. al., (2011) and Zhang and Ostrovski (2002). Wagner et. al. (2006) in their experiments in the use of hydrogen for iron oxide reduction had similar profiles for reduction at temperatures between 550 and 900^{O}C. Other Authors who made the same observations in the reduction of pellets from different regions include Towhidi and Szekely (1981), (1983) and Bonalde et. al. (2005).

4.2 Effect of Size of Pellets

The data on the effect of the changes in the size of the pellets is shown in Table 10.

Table 10: Effect of Pellet size on removal of Oxygen

Effect of pellet size on Oxygen removal			
Time (mins)	r = 0.005m	r = 0.006m	r = 0.007m
0	0	0	0
1	0.12	0.11	0.04

2	0.17	0.15	0.08
3	0.23	0.22	0.13
4	0.28	0.25	0.17
5	0.35	0.30	0.21
6	0.38	0.36	0.25
7	0.42	0.41	0.29
8	0.47	0.45	0.33
9	0.50	0.49	0.37
10	0.53	0.52	0.40
12	0.54	0.53	0.46
15	0.54	0.54	0.48
16	0.55	0.55	0.48
17	0.57	0.56	0.49
18	0.58	0.57	0.50
20	0.59	0.57	0.50
22	0.59	0.57	0.50
23	0.59	0.57	0.50
25	0.59	0.57	0.50

The data from the above table are plotted in Figure 9.

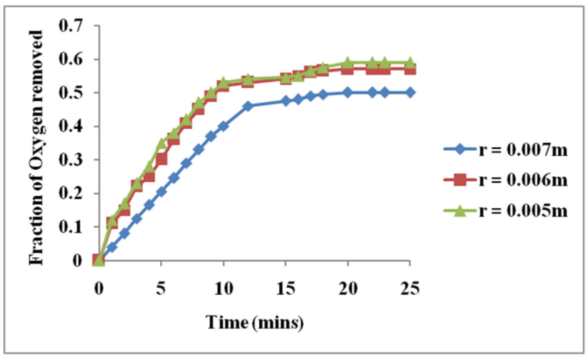

Figure 9: Fraction of Oxygen removed versus Time for different Pellet sizes

From the graphs, larger sized were slower than smaller sized pellets in attaining complete reduction. This was as a result of the longer diffusion path associated with the larger sized pellets.

The optimum radius would be those that have an average diameter of 12cm (6cm radius).

4.3 Effect of Reducing gas flow

Experiments were conducted varying the flow of the reducing gas in the reduction of the oxide pellet of 1.2cm sized diameter.

Table 11: Effect of Reducing Gas Flow rate on Oxygen removal

Effect of Reducing Gas Flow rate on Oxygen removal				
Time (mins)	50 Nm^3/s	100 Nm^3/s	150 Nm^3/s	200 Nm^3/s
0	0	0	0	0
1	0.04	0.08	0.08	0.12
2	0.07	0.14	0.19	0.18
3	0.10	0.20	0.23	0.24
4	0.13	0.24	0.29	0.28
5	0.17	0.28	0.36	0.35
6	0.20	0.31	0.40	0.39
7	0.23	0.34	0.45	0.43
8	0.26	0.36	0.49	0.48
10	0.29	0.40	0.53	0.51
12	0.33	0.42	0.55	0.54
14	0.37	0.45	0.57	0.55
16	0.40	0.47	0.57	0.56
18	0.43	0.48	0.57	0.58
20	0.44	0.50	0.59	0.59
22	0.45	0.51	0.61	0.60
24	0.47	0.51	0.61	0.60
26	0.48	0.51	0.60	0.60

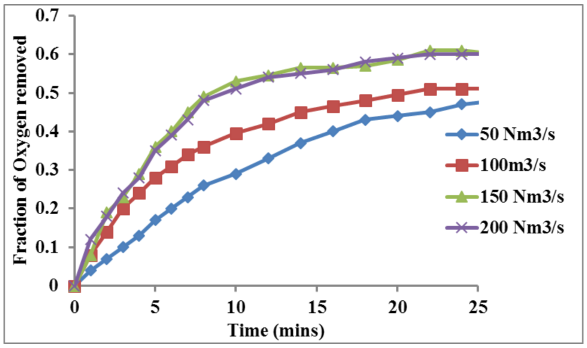

Figure 10: Fraction of Oxygen removed at different Reducing gas Flow rates

A desirable increase in the conversion, would require an increase in the residence time of pellets inside the furnace which would subsequently lead to a reduction in production.

The higher the flow rates of the reducing gas, the greater the removal of the oxygen content hence the higher the reduction degree. This is because more reductants were available for reaction. Hence, the rates of reaction for the lower flow rates were reduced because of the reduced concentration of the reducing gas. The higher flow rates led to higher concentrations at the lower portion of the experimental apparatus due to higher turbulence in this zone and sudden impact on pellets. These observations were in line with the findings of Masood (2012).

4.4 Effect of Length of Bed

An increase in the length of the bed resulting from an increase in the reduction zone length was studied. The data are shown in Table 12 and the data are plotted in Figure 11.

Table 12: Effect of variation in Bed length on Oxygen removal

Effect of Bed Length			
Time (mins)	L = 0.5m	L = 0.75m	L = 1.5m
0	0	0	0
1	0.10	0.12	0.09
2	0.17	0.18	0.14
3	0.23	0.23	0.19
4	0.30	0.28	0.23
5	0.38	0.35	0.27
6	0.42	0.39	0.32
7	0.45	0.43	0.35
8	0.47	0.47	0.40
9	0.48	0.51	0.44
10	0.49	0.53	0.47
12	0.50	0.55	0.54
14	0.51	0.56	0.56
16	0.52	0.58	0.58
18	0.52	0.59	0.59
20	0.52	0.59	0.61
22	0.52	0.59	0.62
24	0.52	0.59	0.63
25	0.52	0.59	0.63

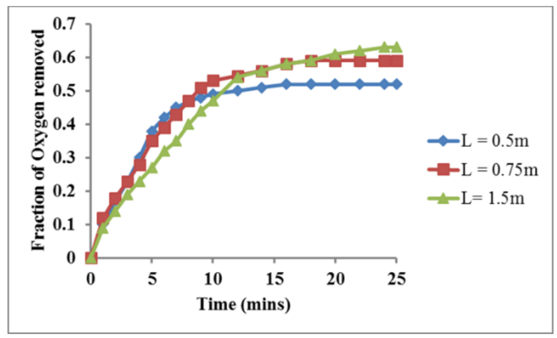

Figure 11: Effect of variation of Bed length on Oxygen removal

An increase in the reactor length results in improved conversion of solid at the outlet when other parameters are held constant. This is in line with the findings of Arabi and Rafsanjani (2008) who in their experiment observed that when the furnace length is increased, resulting in a bed length increase of 15.5%, there is a corresponding 6% increase in the conversion.

4.5 Effect of variation of H_2/C0 ratio

The H_2/CO ratio is a very important factor in iron oxide reduction. The effect of the variation of this ratio on the reduction process are shown in Table 13 and Figure 12.

Table 13: Effect of change in H_2/CO ratio on reduction degree

	Oxygen removed (%)		
Time (mins)	H_2/CO = 1.2	H_2/CO = 1.5	H_2/CO = 2.0
0	0	0	0
25	8	15	28
50	15	35	60

75	25	50	80
100	36	70	86
125	45	75	88
150	58	84	90
175	70	87	92
200	75	90	92
250	86	93	93
300	90	95	94
350	92	96	95
400	94	97	96
450	95	98	97
500	96	98	98

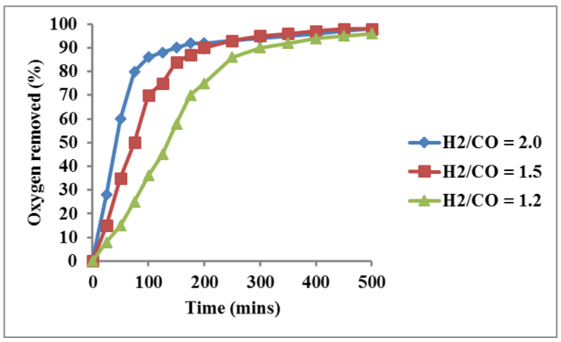

Figure 12: Effect of change in H_2/CO ration on oxygen removal

An increase in the H_2 content as against the reduction in the CO content led to higher removal of oxygen as seen in Figure 12 implying higher metallization degree. These observations were also made by El-Geassy & Rajakumar (1985), Bonalde et al. (2005), and Pineau et al. (2006). As also seen in the graph, Tsay et. al., (1976) observed that the higher the hydrogen content in the reducing gas, leading to faster overall rate of reaction the higher was the conversion which they however noted was largely not linear.

4.6 Effect of change in Product discharge rate

Generally, the need to increase productivity can be done by reducing the residence time of the pellets in the furnace. This can be achieved by reducing the product discharge rate. Experiments were carried out with this in view and keeping the reduction temperature and reducing gas flow rate constant at 760^{O}C and 300cc/sec respectively.

The discharge rate of the product was varied as shown in Table 14 and Figure 13.

Table 14: Effect of change in Product Discharge rate on Reduction Degree

	Effect of change in Discharge Rate on Oxygen removal				
Time (mins)	2.0Kg/s	3.0Kg/s	4.0Kg/s	5Kg/s	6Kg/s
20	0.47	0.31	0.09	0.05	0.03
25	0.56	0.39	0.15	0.08	0.05
30	0.60	0.45	0.19	0.10	0.06
35	0.65	0.51	0.23	0.13	0.09
40	0.71	0.60	0.30	0.17	0.10
45	0.74	0.64	0.34	0.19	0.12
50	0.80	0.69	0.38	0.22	0.16

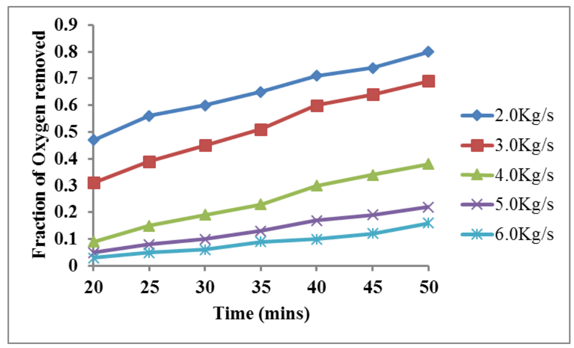

Figure 13: Effect of change in Product discharge rate on reduction degree

The removal of oxygen which is a reflection of the rate of reduction was found to increase with reduction in pellet discharge rate in line with the findings of Takenaka et. al. (1986).

At the beginning of reduction zone inlet, the ore is majorly hematite (Fe_2O_3). As the reaction proceeds, the iron oxide is gradually reduced by reduction gas and oxygen is removed. In experiments conducted by Takahashi et. al. (1986), they observed a similar profile and attained a fractional reduction of 0.81 at a reduction temperature of 870^{O}C using a reducing gas with H_2/CO ratio of 1.8. The oxide pellets used in their experiments had a total iron content of 64.6 % and a silica content of 3.71%. A similar result was obtained by Almasari et. al., (2011).

Mousa & Ghali (2015), noticed a similar trend but at reduction temperatures between 800 - 980^{O}C and at shorter reduction times. Ranzani da Costa et. al. (2008) made a similar observation at 900^{O}C over a reduction period of 300 minutes but with the use of hydrogen gas only as reductant. A similar trend was observed by Valipour (2009) in the reduction with Syngas at an H_2/CO ratio of 1.64 and also Beheshti et. al. (2014) at a reduction temperature of $850^{O}C$ over a reduction time period of 25 minutes. The latter carried out their experiments at an H_2/CO ratio of 1.6.

CONCLUSION

Generally, temperature, pressure and concentration are responsible for the changes which occur in the operating parameters. Overall plant performance is maximized when the furnace is operating at optimum efficiency.

The parameters examined in the experiments include the effect of change in reduction temperature on the percentage of oxygen removal or reduction degree, effect of reducing gas flow rate, product discharge rate, oxide pellet size, H_2/CO ratio on the percentage of oxygen removed or reduction degree. It was noticed that the patterns observed were similar to those obtained in the reduction of most oxide feed for the direct reduction process. A reduction temperature of $760^{O}C$, a pellet size of 1.2mm diameter and an H_2/CO ratio of 1.5 were found to be suitable for a successful reduction of the Itakpe iron ore. A reduction temperature increase beyond this value would be accompanied by a corresponding increase in the product discharge rate

The successful upgrading of the sinter grade of the Nigerian Itakpe iron ore to a super-concentrate with a higher Fe content to meet the requirement of the Midrex Direct Reduction based Plant at the Delta Steel Company, marked a major milestone in the production of steel from iron ore in Nigeria. The ore was originally earmarked for use in Blast Furnace based Plant at Ajaokuta, due to its low quality; therefore, its successful utilization is an innovation. The utilization of the local ore ensures ready availability of raw material for the steel industries leading to higher capacity utilizations, and further reduction in production cost. The finished products will readily be available in the markets at cheaper prices resulting in a boost particularly in the building sector with associated positive band-wagon effects on other aspects of the economy.

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