

Full Length Research Paper

Steel making experience in the use of Nigerian Iron Ore at the Delta Steel Company, Nigeria

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The production of steel from the locally available Itakpe Iron Ore in Nigeria was achieved in the Delta Steel Direct Reduction-Electric Arc Furnace Plant. The ore was originally thought to be unsuitable for use in the direct reduction process due to its low total iron content, less than 64% and high gangue content which was in excess of 4% and above the maximum acceptable limit of 3.5%. Pilot and Plant tests were carried out to determine suitable operating parameters and conditions for its use in the iron making pelletizing and direct reduction plants and also the steel making plant. The excessive oversize pellets, +16 mm > 20% coupled with fairly high cold compression strength of the fired pellets yielded only a moderately high direct reduced iron fines content. The high gangue level which is a major issue in steel production did not however pose any major operational problem at the direct reduction plant. The cost of production of 1 tonne of liquid steel from the local ore was about \$61 as against \$80 which was the cost per tonne in the use of the imported ores. This report is an examination of the efforts made in overcoming the challenges associated with production of steel from an ore with excessive gangue materials while still ensuring high grade steel products to meet the needs of the Nigerian steel market.

Key words: Itakpe Iron Ore, Electric Arc Furnace, Steel, Slag.

INTRODUCTION

The impact of iron and steel in any economy is usually tremendous because its production and consumption are measures of the rates and levels of industrialization. Iron and steel are the most widely used engineering materials for production, fabrication, construction and manufacture of most items, including ships, vehicles, military hardware etc. This explains why the per capita consumption of steel is an index for assessing development in the economy of any nation. The availability and development of the iron and steel sector, is essential for industrial

growth, increased engineering capacity and enhancement of technical skills (Raw Materials Research and Development Council, 2010).

In her bid therefore to promote technological growth, the first steel plant (a mini steel plant) was established in Nigeria in 1962. Two similar plants were established in Lagos in 1968 and 1970 through private initiative. These were however far from meeting the steel needs of the country.

In 1967, the Nigerian Government commissioned

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experts from the then Soviet Union (USSR) to carry out feasibility studies aimed at ascertaining the quantity of available raw materials that would warrant the establishment of a major iron and steel plant. Encouraged by the recommendations of the Soviet Experts, the Federal Government promulgated Decree No.19 of 1971 establishing the Nigerian Steel Development Authority (NSDA). The NSDA was given responsibilities and necessary powers to develop the steel sector through exploration, opening up of mines, carrying out research on steel plants worldwide, steel plant design, development of metallurgical processes and raw materials sourcing (Ministry Of Mines and Steel Development, National Minerals and Metals Policy).

The result was the establishment of the Ajaokuta Steel Complex, in September 14, 1979 when the National Steel Council Decree No. 60 of 1979 incorporated it with five other steel companies and construction started in June 1981 (Duru and Agba, 2005).

The National Iron Ore Mining Company (NIOMCO) at Itakpe in Kogi State, Nigeria established in 1979 was to supply 2.1 million tonnes per year of 63/64% Fe grade concentrate to the Ajaokuta Steel Plant when fully operational. This steel plant with an annual production capacity of 1.3 million tonnes of steel, in addition to meeting national steel requirements was aimed at addressing the problem of unemployment, diversifying the economy and helping to generate foreign exchange (Duru and Agba, 2005).

Global recession, poor funding and the installation of massive infrastructural facilities delayed the completion and full commissioning of this plant which at the time was to be Africa's largest steel making Plant. However, convinced by the well advertised advantages of the Direct Reduction – Electric Arc Furnace route to steel production which include:

- a) Efficient use of the abundant natural gas.
- b) Independence from coke imports.
- c) Capacity sized to meet needs rather than economy of scale.
- d) Electric arc furnaces can be rapidly started and stopped, allowing the steel mill to vary production according to demand.
- e) Lower capital cost per ton of product.
- f) Shorter construction time (less than 4 years);

The Federal Government of Nigeria signed an agreement with a consortium of 10 Austro-German companies on 3rd October, 1977, to set up a Direct Reduction – Electric Arc Furnace Integrated steel plant of a capacity of one million tonnes per year of liquid steel at Ovwian-Aladja in Delta State. This plant was commissioned 29 January, 1982.

Three years after commissioning and subsequent commercial production of steel, the Liberian/Guinean Ore Mines the source of the Lamco Iron Ore on the basis of

which the Direct Reduction Plant at Delta Steel was designed, got depleted. This led to the necessity to seek other sources of raw materials. The next alternatives were the Brazilian Companhia Vale do Rio Doce (CVRD) and Feijao Ores which apart from the peculiarity in their operational characteristics were not readily available due to scarce foreign exchange. It therefore became imperative to seek other sources of iron ore. This led to the need to investigate the possibility of utilizing at Delta Steel Company, the locally available iron ore at Itakpe, whose sinter grade had a total iron content of about 63% and a gangue in excess of 4%. This ore was originally conceived for use at the Ajaokuta Blast Furnace Plant (Ola et al., 2009).

The synergetic action of Delta Steel Company (DSC), and National Iron Ore Mining Company (NIOMCO), National Metallurgical Development Centre (NMDC) Jos, which were offshoots from the NSDA (Mohammed, 2002), led to the following:

- i) Beneficiating the Itakpe Iron Ore to a quality acceptable to Midrex direct reduction process;
- ii) Carrying out Pilot tests to ascertain and establish the pelletizability and reducibility of the upgraded iron ore;
- iii) 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:

- i) The beneficiated NIOMCO ore with Fe_{total} of 65.74%.
- ii) The re-beneficiated NIOMCO ore with 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.

PELLETIZING OF IRON ORE

Quality of iron ore or agglomerate is judged by the assessment of several properties. Characterization of iron burden can be classified as given below (Goswami, 2007):

- i) Mineralogical characterization
- ii) Chemical characterization
- iii) Physical characterization and
- iv) Physico-chemical or Metallurgical characterization.

Mineralogical characterization helps in identifying mineral phases and associated gangue materials since these materials greatly influence the bulk chemistry of the process and the quality of hot metal. A clear mineralogical analysis of iron ore samples of any particular deposit helps in selecting suitable reduction modes.

Chemical characterization involves the chemical

analysis of iron ore and agglomerates. The major constituents of iron burden are Fe_2O_3 , FeO , SiO_2 , Al_2O_3 , and trace elements such as Cu, Ni, Co, Pb, Zn and, Mn. The theoretical allowable limits of detrimental elements in iron making and subsequent steel making that may be present in quality ore are listed below:

- i) $\text{Na}_2\text{O} + \text{K}_2\text{O}$: should not exceed 0.8%.
- ii) Zinc: maximum allowable limit is 0.02%.
- iii) Phosphorous: should not exceed 0.04%.
- iv) Cadmium and Sulphur (adversely affects the environment): should be kept below 0.01%.

Physical characterization is carried out through physical tests that are designed for the burden to withstand severe degradation during handling and transportation.

The physico-chemical behaviour is assessed through metallurgical tests that are designed to correlate with actual operations prevailing in the furnace.

Particle size is determined with the help of sieve set and the data is reported as the percentage fraction between the two sieves. The correct size as well as the size distribution of the burden is important in order to ensure uniform flow of the gas through the bed. Permeability influences reducibility as increased percentages of fines (less than 5 mm size) and larger sizes reduce reduction rate considerably.

Iron ore as charge material should be resistant to abrasion. If they break into finer fractions due to impact or abrasion, then there is compression and volume change within the furnace. The smaller particles lead to choking of voids thereby affecting reduction and productivity. Strength is the physical property of the material by virtue of which it withstands degradation during handling and transportation. The extent to which material breaks down during handling has an important bearing on the quality of charge material. It is imperative to evaluate the strength aspect of material by suitable tests such as Tumble test, which is mainly devised to determine the rate of fines generation. The test determines the susceptibility of ferrous material to break due to abrasion during transportation, and handling. Theoretically, for good pellets the tumble and abrasion indices should be between 85 to 95%, and 3 to 7% respectively (Goswami, 2007).

Pelletizing of Itakpe Iron Ore

Froth flotation studies

One of the processes for upgrading ores is by Froth flotation. It is a physico-chemical method of concentrating ground ores. The process involves chemical treatment of an ore pulp to create conditions favourable for the attachment of predetermined mineral particle to air bubbles carrying the selected minerals to the surface of

the pulp, thereby forming a stabilized froth which is skimmed off and from which the pre-determined mineral particles are recovered. Other minerals remain submerged in the pulp

Pilot scale studies were carried out, through froth flotation, to upgrade the Itakpe Iron Ore sinter grade to a super-concentrate grade suitable for use in the direct reduction plant at DSC. This included physical and chemical characterization of Itakpe Iron Ore sinter concentrate (Ola et al., 2009).

The reagents used for the flotation, included Flotigam EDA and Flotanol M both manufactured by CLARIANT and used as collector and frother respectively. 500 g/t Starch, causticized with 25% sodium hydroxide was used as depressant for iron minerals. Another 500 g/t and sodium hydroxide was also used as pH regulator. The following analysis, were carried out:

- i) Particle size distribution analysis with the aid of a sieve shaker,
- ii) Chemical analysis to determine the iron, alumina and silica contents by classical wet analysis methods.

Pilot plant beneficiation

The sinter grade concentrate was fed into the ball mill ($\phi 100 \times 1500$ mm) at 500 kg/h. The pilot plant flotation operation was carried out sequentially in a bank of flotation cells of 0.13 m^3 capacity each. The sinter grade iron ore was treated with 110 g/ton of Flotigam EDA as collector and 10 g/ton of flotanol M frother. The slurry pH was adjusted with sodium hydroxide to be 10.5 and treated with maize starch causticised with 25% NaOH as the depressant for iron oxide. Figures 1 and 2 shows the Pilot plant flow sheet and the material balance of the process respectively (Ola et al., 2009).

Tables 1 to 4 show the physical and chemical characteristics of the various grades of the Itakpe Iron Ore.

As shown in Table 4, the sinter grade of the Nigerian 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% at the roughing stage of the pilot plant froth flotation operation (Ola et al., 2009).

Characterization of Itakpe Iron Ore

Characterization and reducibility tests were carried out on the Itakpe Iron Ore by Adedeji and Sale (1984). Analysis for calcium, magnesium, iron, aluminium and manganese were carried out through atomic absorption spectrometry; silica was determined by a combination of gravimetric and colorimetric methods. X-ray diffraction analysis was performed using Cu-K α radiation in a Siemens

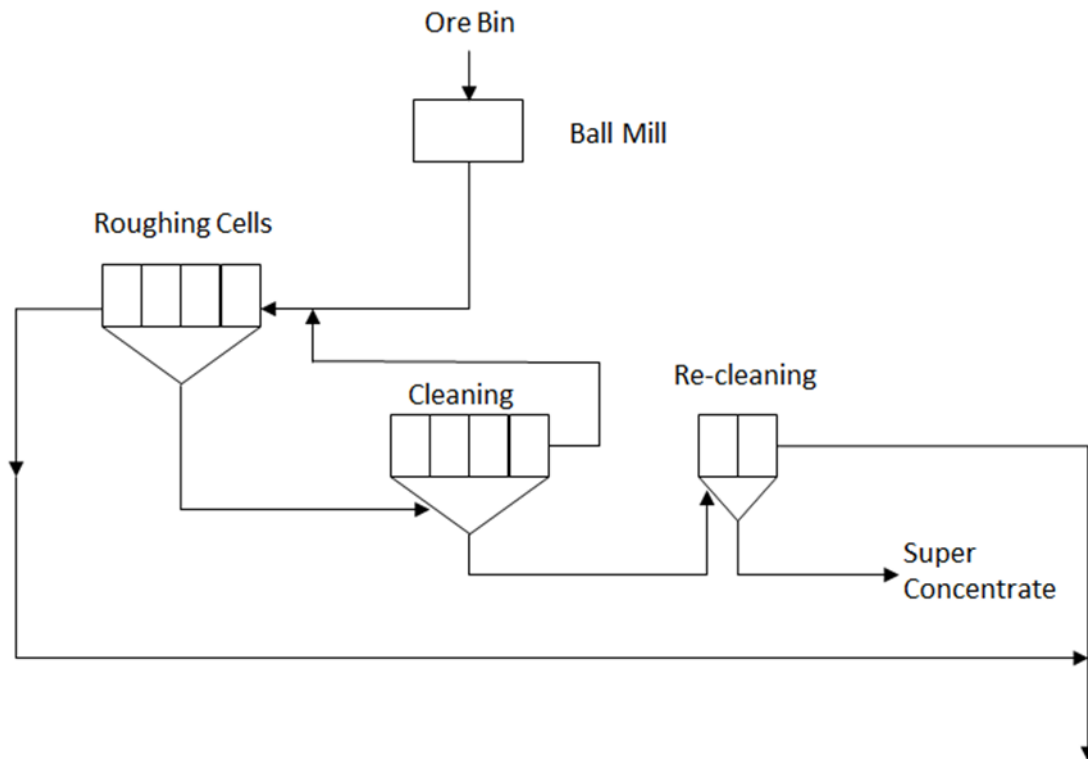


Figure 1. Pilot plant flotation scheme.

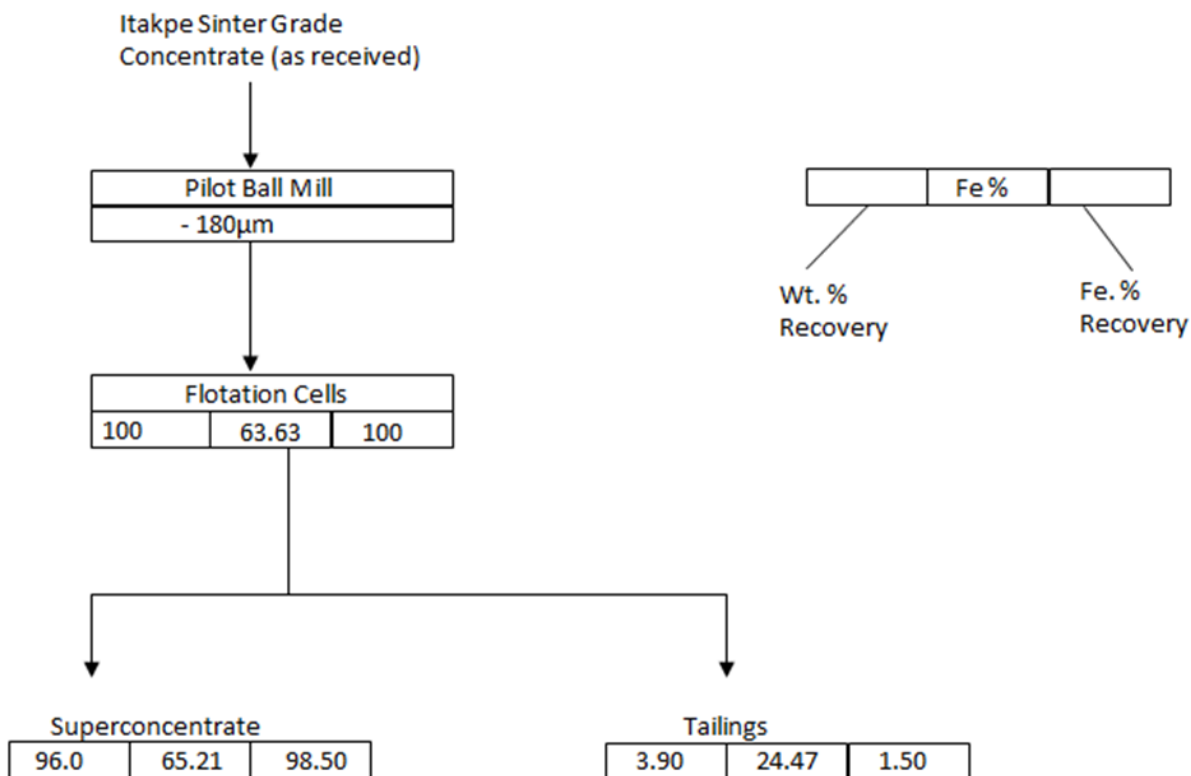


Figure 2. Overall Mass Balance Flowsheet for the Production of Itakpe (perconcentrate by Froth Flotation).

Table 1. Grain size distribution of Itakpe Iron Ore sinter grade concentrate.

S/N	Sieve sizes (μm)	Weight% retained on sieve	Cumulative% undersize	Cumulative% oversize
1	-710	11.13	88.87	11.13
2	-500+355	11.81	77.06	22.94
3	-355+250	14.39	62.67	37.33
4	-250+180	18.50	44.17	55.83
5	-180+125	16.79	27.38	72.62
6	-125+90	13.00	14.38	85.62
7	-90+63	8.04	6.34	93.66
8	-63+45	4.22	2.12	97.88
9	-45	2.00	0.65	99.35

Table 2. Grain size distribution of sinter grade pilot plant flotation feed.

S/N	Sieve sizes (μm)	Flotation feed, cumulative (%) undersize	Flotation feed, cumulative (%) oversize
1	-500	99.83	0.17
2	-355+250	99.20	0.80
3	-250+180	99.58	0.42
4	-180+125	97.58	2.42
5	-125+90	90.33	9.67
6	-90+63	74.37	25.63
7	-63+53	42.94	57.06
8	-53	8.22	91.78

Table 3. Grain size distribution of pilot plant super-concentrate.

S/N	Sieve sizes (μm)	Flotation feed, cumulative (%) undersize	Flotation feed, cumulative (%) oversize
1	-500	99.76	0.24
2	-355+250	99.70	0.30
3	-250+180	9.22	0.78
4	-180+90	97.34	2.66
5	-90+63	81.13	18.87
6	-63+45	55.19	44.81
7	-45	30.57	69.43

Table 4. Chemical analyses of Itakpe sinter concentrate and super-concentrate grades.

Parameters (%)	Itakpe sinter grade	Stages in pilot plant flotation		
		Roughing	Cleaning	Re-cleaning
Fe	63.63	66.66	66.51	65.44
SiO ₂	5.90	3.71	3.88	4.55
Al ₂ O ₃	0.72	0.51	0.51	0.60
SiO ₂ + Al ₂ O ₃	6.62	4.22	4.39	5.15

Kristalloflex 4 diffractometer.

The chemical analysis of the Itakpe Ore as analyzed by them is shown in Table 5.

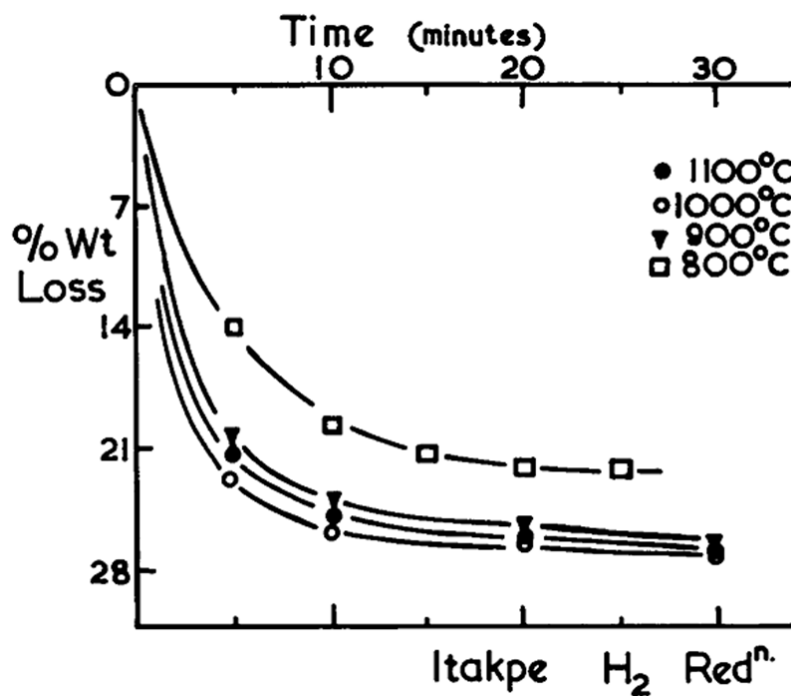
Reducibility experiments

Isothermal mass-change determinations in the range 800

Table 5. Chemical analyses of the iron ores.

Element	Itakpe (As received wt%)	Itakpe (Crushed)	
		Dark particles (wt%)	Light particles (wt%)
Fe	59.10	66.51	5.04
Si	6.80	1.60	40.40
Al	0.38	0.66	nd
Ca	0.36	0.35	nd
Mg	0.028	0.04	0.042
Mn	0.007	nd	nd
P	Nd	nd	nd

nd = not detectable.

**Figure 3.** Isothermal mass-change data for H₂ reduction of Itakpe Ore (Adedeji and Sales, 1984).

to 1100°C were performed on 0.1 to 0.2 g samples using a glass-spring balance and a CI Electronics 2CT5. The electrobalance in both hydrogen and carbon monoxide atmospheres were continuously recorded. Critical gas-flow rate determinations were carried out for both gases. Flow rates of approximately 200 and 150 ml min⁻¹ were used for both gases in the glass spring balance and electrobalance respectively. Fully-reduced and partially-reduced samples were retrieved from the balances for study. Some of the results obtained from their work include:

X-ray diffraction analysis: Itakpe Ore was shown to consist mainly of hematite with a detectable amount of

magnetite, a significant amount of quartz, and a trace of corundum.

Hydrogen reduction: The ore was heat-treated before reduction to remove the volatile components so as to obtain a true reducibility, as determined by mass loss. The isothermal mass-change data obtained at 800, 900, 1000 and 1100°C show that the rate of reduction increased with increase in temperature, except for reduction at 1100°C. The rate of reduction was in the order 1000°C ≥ 1100°C ≥ 900°C ≥ 800°C. This is shown in Figure 3.

Carbon monoxide reduction: The deposition of carbon by the disproportionation of carbon monoxide caused

Table 6. 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 ₂ O ₃ (%)	89.00	93.90	96.31	94-96
SiO ₂ + Al ₂ O 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
SS (cm ² /g)			2056	1850 – 2500

*LOI = Loss on ignition; SS = specific surface.

Table 7. 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 – 19 mm) (%)	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 ₂ O ₃)	0.51	0.75	0.6 min
Firing temperature (max, °C)	1200	1200	1300

Table 8. Reducibility test via shaft furnace basket test using 67.4% Fe^{total} Iron Ore.

Parameter	Itakpe Iron Ore DRI	DSC specification
Fe ^{met} (%)	92	90 min
Degree met (%)	96	80 min
C (%)	1.27	1.1 – 2.0
S (%)	0.003	0.04 max
P (%)	0.04	0.04 max
Reduction temperature (°C)	800	760 – 850

difficulties in interpreting the results at 800 and 900°C. Consequently, most experimental effort was concentrated on reduction at 1000 and 1100°C. Not only was carbon deposition minimized at these temperatures, but the rate of reduction at 1000 and 1100°C increased with increase in temperature.

They concluded as follows: Itakpe Ore is a rich hematite ore in which some hematite forms an intergrowth with magnetite. The main impurity is silica. Following liberation by mechanical crushing and physical separation of the quartz, the Itakpe Ore is suitable as a feedstock to one of the direct reduction methods of iron making (Adedeji and Sale, 1984).

Pilot tests at Delta Steel Company

Two grades of iron ore were produced for pilot tests. These were the beneficiated Itakpe Iron Ore (Fe_{tot} – 65.74%, SiO₂ + Al₂O₃ = 8.10%) and the re-beneficiated iron ore (super concentrate) with Fe_{tot} of 67.40%, SiO₂ + Al₂O₃ of 2.45% derived from the former, using facilities available at National Metallurgical Development Center (NMDC), Jos. The significant aspect of the latter exercise was the reduction of the acid gangue from about 6% to less than 3%. Table 6 shows the results of the beneficiation of the Itakpe Iron Ore, while Tables 7 and 8 show the pelletizability and reducibility of the ore via Pilot

Table 9. Physico-chemical properties of pellets derived from Itakpe Iron Ore.

Parameter	Prime Ore	DSC Specification
Green pellets		
Moisture (%)	8.10	7 – 8.0
Drop No. (D/P)	5.7	4.8 min
CCS (N/P)	11.22	9.0 min
Fired pellets		
Physical properties		
CCS (N/P)	4561	3450
+ 16 mm (%)	21.41	5.0 max
6.3 – 19 m (%)	95.05	92.0 min
Tumble index (%)	94.51	93.0 min
Abrasion index (%)	3.93	5.0 max
Firing temperature (°C)	1300	1300
Chemical properties		
Fe ^{tot} (%)	65.10	66.00 min
Fe ₂ O ₃ (%)	93.21	94.00 min
SiO ₂ + Al ₂ O 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.

Table 10. Typical chemistry of ore delivered to DSC.

Parameter	%
Fe ^{tot}	65.77 (mfs)
Fe ₂ O ₃	94.05
SiO ₂	3.93
Al ₂ O ₃	0.80
CaO	0.13
LOI	0.11
H ₂ O	2.36

*mfs = moisture free state.

plant reducibility and Basket tests in the Direct Reduction shaft furnace in DSC respectively.

Following the results from pilot tests, the Itakpe Iron Ore after beneficiation was successfully pelletized at the Pellet Plant of the Delta Steel Company.

The physical properties of the fired pellets were good except for the high proportion of the oversize pellets (+ 16 mm = 21.41%) as shown in Table 9.

This problem however was an extrinsic rather than an intrinsic property of Itakpe Ore. This is because

Table 11. 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 ₂ O 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 – 16 mm)	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 temperature (°C)	760	760-860

production of oversize pellets had been encountered occasionally when processing imported ores.

The typical chemistry of the ore delivered to DSC for large scale production and the physico-chemical properties of the oxide pellets produced there from after the successful beneficiation of the ore, are shown in Tables 9 and 10 respectively.

DIRECT REDUCTION OF ITAKPE IRON ORE

The DRI produced by the MIDREX process features high metallurgical iron content, but almost no nonferrous metal impurities which are undesired in steel (Kempken et al., 2008). With regard to the DRI obtained from the Itakpe oxide pellets, the silica and alumina contents gave a total acidic oxide content of 5.42% that was above the upper limit of 3.6% for Midrex plants (Midrex Direct Reduction Plant Operating Manual, 1981). The properties of the DRI produced from the Itakpe Ore are shown in Table 11.

STEEL MAKING WITH DRI DERIVED FROM ITAKPE IRON ORE

Electric arc furnace

The electric arc furnace (EAF), shown in Figure 4, used for steelmaking consists of a refractory-lined vessel, usually water-cooled in larger sizes, covered with a

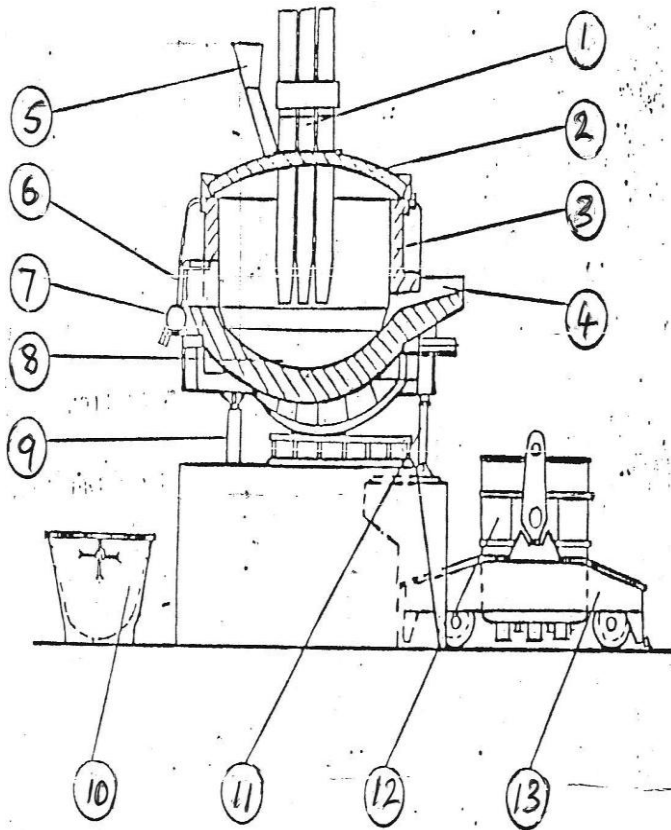


Figure 4. Electric arc furnace. Source: Delta Steel Company training Manual. 1- Electrode, 2- Ladle, 3- Wall of vessel, 4- Tapping sprout, 5- DRI feed chute, 6- Slag door, 7- Electrode weir, 8- Hearth of vessel, 9- Tilting mechanism, 10- Slag pot, 11- Stabilizer, 12- Ladle, 13- Ladle transfer car.

retractable roof, through which one or more graphite electrodes enter the furnace. The furnace is primarily split into three sections (Beaty, 1978) namely:

1. The Shell, which consists of the sidewalls and lower steel "bowl";
2. The Hearth, which consists of the refractory that lines the lower bowl;
3. The Roof, which may be refractory-lined or water-cooled,

The mechanical parts comprise the following (Delta Steel Company training Manual, 1981):

- a) Furnace vessel
- b) Roof
- c) Tilting device
- d) Portal with roof raising and swiveling device
- e) Electrode raising and supporting device with power supply.

The electrical system comprises the following (Delta Steel Company training Manual):

- a) High voltage switch gear
- b) Main circuit breaker on the furnace
- c) Furnace transformer
- d) Electrode control system.

The electrodes are round in section, and typically in segments with threaded couplings, so that as the electrodes wear, new segments can be added. The arc forms between the charged material and the electrode, and the charge is heated both by current passing through it and by the radiant energy evolved by the arc. The electrodes are automatically raised and lowered by a positioning system, which may use either electric winch hoists or hydraulic cylinders.

The electric arc furnace operates as a batch melting process producing batches of molten steel known as "heats". The electric arc furnace operating cycle is called the tap-to-tap cycle and is made up of the following operations:

- i) Furnace charging
- ii) Melting
- iii) Refining
- iv) De-slagging
- v) Tapping
- vi) Furnace turn-around

Arc furnace operation

Scrap is loaded into large buckets called Scrap Buckets. The scrap bucket is then taken to the melt shop, the roof is swung off the furnace, and the furnace is charged with scrap.

After charging, the roof is swung back over the furnace and meltdown commences. The electrodes are lowered onto the scrap, an arc is struck and the electrodes are then set to bore into the layer of shred at the top of the furnace. Lower voltages are selected for this first part of the operation to protect the roof and walls from excessive heat and damage from the arcs. Once the electrodes have reached the heavy melt at the base of the furnace and the arcs are shielded by the scrap, the voltage can be increased and the electrodes lifted slightly, lengthening the arcs and increasing power to the melt.

As the melting operation starts, DRI is continuously fed into the furnace. Chemical energy is supplied via oxygen lances. The oxygen is used for carburization, de-slagging of silicon, manganese, and phosphorous, aluminum etc. Heat is transferred to the scrap by flame radiation and by convection through the hot products of combustion. Heat is also transferred within the scrap by conduction.

All of these reactions are exothermic and supply additional energy to aid in the melting of the scrap. The metallic oxides that are formed end up in the slag. During tapping, some alloy additions are introduced into the metal stream, and more lime is added on top of the ladle to begin building a new slag layer.

Table 12. Some performance indices of DRI from Itakpe Iron Ore in SMS.

Parameter	Itakpe Ore	Imported Ore
Energy to melt 100 t DRI (MWH)	67.46	53.09
Liquid steel yield (%)	78.36	83.10
Slag volume (No. of slag pot)	2	1
Slag basicity	1.30	1.98

Table 13. Typical level of tramp elements in steel derived from Itakpe DRI.

Parameter (%)	C	Si	Mn	S	P	Cr	Ni	Sn	Cu	Ti
Itakpe heat No. 534885	0.09	0.09	0.43	0.002	0.02	0.03	Trace	Trace	0.01	Trace
Imported ore	Depends on steel grade				0.04 Max	0.04 Max	0.10 Max	0.05 Max	0.25 Max	0.1 Max

Often, a few tonnes of liquid steel and slag is left in the furnace to form a "hot heel", which helps preheat the next charge of scrap and accelerate its meltdown. During and after tapping, the furnace is "turned around", the slag door is cleaned of solidified slag, repairs may take place, and electrodes are inspected for damage or lengthened through the addition of new segments.

In the steel plant, a Ladle Furnace (LF) is used to maintain the temperature of liquid steel during processing after tapping from the EAF or to change the alloy composition of the steel.

It consists of a refractory roof, a heating system, and, when applicable, a provision for injecting argon gas into the bottom of the melt for stirring (Jones and Lefrank, 1998).

The Delta Steel Company has four (4 Nos) 110-Tonne capacity Electric Arc Furnaces. The utilization of DRI derived from Itakpe Iron Ore in the steel making shop did not pose any unanticipated problems. Table 12 shows the performance indices of Itakpe DRI during Steel making as compared with the same parameters from the imported ore while Table 13 shows the tramp elements in the steel produced from the DRI obtained from the Itakpe oxide pellets. Significantly, the low level of tramp elements in the steel was attributed to their levels in the parent Itakpe Iron Ore deposit which were low in comparison with the same elements in the imported ore. The implication of this is that the Itakpe Ore, if properly beneficiated would yield an excellent quality of steel.

Molten steel dynamics

Chemistry of molten steel

The worries of users of direct reduced iron for EAF operations are centered on the value of SiO₂ and Al₂O₃ contents of the ore. Slag chemistry and weight affect yield in any EAF.

When melting DRI, a steelmaker should carefully design the slag so that good foaming takes place with the minimum weight of slag at the correct basicity. Regular XRF or wet chemistry testing and quick reporting of EAF slag chemistries is recommended to maintain EAF yields and refractory wear (Gregory, 2010).

A rough assessment of the chemistry of the Itakpe Ore indicated the problems likely to be encountered in its utilization vis-à-vis the slag that would be generated.

High SiO₂ content (above 2.5%) results in high slag volume in steel making process and requires additional power consumption. Although, the alumina content is known not to constitute a problem from the stand point of the reduction process, since it is an acid gangue, additional flux would be required in the steel making process which would lead to high slag volume resulting in concomitant refractory erosion.

The total acid gangue (SiO₂ + Al₂O₃) in the DRI of 5.42% as against the Midrex direct reduction maximum specification of 3.6% was high. As a result, successful utilization of the ore in steel making, of a necessity led to devising steps to accommodate the high level of gangue.

The lime consumption level for Itakpe Iron Ore in the steel making shop varied from 6 to 8 tonnes as shown in Table 14. This was required so as to have minimum refractory damage. The slag basicity for Itakpe Ore was far below the recommended minimum value of 2.0, the highest value recorded being 1.63 showing that the slag generated was acidic with resultant increase in refractory wear. The chemical properties of DRI also naturally demanded an increase in quantity of lime addition.

To achieve a slag basicity of 2.0 and above, a minimum lime dosage of 10 tonnes, was required. This resulted in a slag volume of more than two slag pots, additional energy cost, and invariably pressure on slag moving equipment.

It was therefore necessary to strike a balance between the cost of measures taken to minimize refractory wear and the resultant effect of such measures – higher

Table 14. Typical slag chemistry from Itakpe Iron Ore with and without MgO addition.

Heat No.	FeO (%)	CaO (%)	SiO ₂ (%)	MgO (%)	Al ₂ O ₃ (%)	Slag wt (Tonnes)	Quantity of lime (Tonnes)
543478	10.19	36.92	25.73	9.45	8.47	24.5	6
543479	14.27	34.43	32.02	6.98	9.96	23.7	7
543480	24.50	35.54	25.73	8.15	5.68	25.5	8

Table 15. Dolomite deposits in Nigeria.

State	Location	Estimated tonnage
Kogi	Elebu, Ekinrin Ade	Not available
	Osara	17 million tonnes
FCT	Burum	16,572,000
	Takusara	12,000,000
Niger	Takalafia	4,000,000
	Kwakuti	2,500,000
Katsina	Kankara, Malumfashi	Under investigation
Oyo	Igbetti	Not available

Source: Raw Material Sourcing for Manufacturing in Nigeria.

energy consumption and the additional wear and tear on slag moving equipment.

Use of dolomite

Dolomite also known as 'Dolostone' is a sedimentary carbonate rock, consisting of mainly the mineral dolomite (CaMg(CO₃)₂). Rocks containing only 10 to 50% of the mineral dolomite are a replacement of the pre-existing limestone and this replacement process is known as 'Dolomitisation'. The process is often incomplete and rocks termed dolomite are usually a combination of dolomite, dolomitic limestone and limestone. Dolomite deposits are therefore usually associated with limestones. This, together with the presence of variable amounts of impurities such as silica, sulphur, iron oxides and alumina has an important bearing on the sustainability of dolomite for specific application (US Department of Geological Survey, 2006).

In Nigeria, the dolomite deposits are often associated with the metasediments such as schists, amphibolite complex and metaconglomerates and are used as flux in steel making. Table 15 shows the locations of the marble and dolomite deposits in Nigeria.

Theoretically, dolomite (CaCO₃.MgCO₃) contains CaCO₃ 54.35% and MgCO₃ 45.65% or CaO 30.4%, MgO 21.9% and CO₂ 47.7%. However, in nature, dolomite is not available in this exact proportion. Hence, in commercial parlance, the rock containing 40 to 45%

MgCO₃ is usually called dolomite. It is grouped under flux and construction minerals and is important for Iron and Steel and Ferro-Alloys industries. Limestone (CaCO₃) and dolomite (CaMg(CO₃)₂) are basic raw materials having commercial applications in a number of industries. These carbonates are consumed in the mineral industries (e.g. during the production of cement, lime and glass) and also in metallurgy (e.g. iron and steel), agriculture, construction and environmental pollution control (e.g. flue gas desulphurisation) (Indian Mineral Year Book, 2011).

Raw dolomite and calcined dolomite have a number of different uses in the Iron and Steel industry. However changes in iron and steel making technology during the 20th century have had a marked effect on the demand for dolomite for specific uses and the market continues to evolve. The principal uses of dolomite are those that utilize the mineral in calcined form (Dolomitic lime). The most important of these is a steel making slag flux where the dolomitic lime replaces some of the quicklime (CaO) used in slag production.

The theoretical quality of dolomite for melting purpose (% composition) is as follows (Raw material sourcing for manufacturing in Nigeria):

CaO = 31.02
 Al₂O₃+SiO₂ = 4.33
 MgO = 20.76
 S = -
 P = 0.13
 Fe, total = 0.20

$\text{Fe}_2\text{O}_3 = 0.28$

$\text{MnO} = 0.005$

Humidity = (0.5 max. in dry season) and 2.0 (5 max. in wet season)

L.O.I = 43.575.

In addition to increasing slag fluidity, the presence of magnesia also helps to protect and thus improve the life of the steel vessel's refractory linings which are made of magnesia. The total quantity used has been declining with a fall in iron and steel production. Some 260 000 tonnes of calcined dolomite were used up for this purpose in 2004 (British Geological Survey, 2009). For many of the applications in the Iron and Steel industry, there are strict limits on the chemistry of the dolomite used which mainly needs to be low in silica (often $<0.55\%$ SiO_2) or ($<0.3\%$ for some applications with low iron ($<0.55\%$ Fe_2O_3), sulphur ($<0.1\%$) and phosphorus ($<0.02\%$).

Refractory erosion and possible solution

The initial utilization of DRI derived from Itakpe Iron Ore for steel making operation in DSC gave rise to increase in refractory wear. As already indicated, the acid gangue level was fairly high leading to large volume of slag with low basicity.

To combat the problems, a fair knowledge of the implications of slag volume and chemistry on the wear and tear of the refractories is required. The correlation between the acid gangue level in DRI and the resulting slag weight in EAF is shown in Figure 5.

It is known that the degree of slag attack on refractories is slag-basic dependent. The more basic the slag, defined by the value of CaO/SiO_2 , the less the attack on refractories. It is therefore possible to estimate and quantify the degree of attack by a careful study of both the slag chemistry and the component of charge materials.

Since the refractory linings are MgO – based, the quantity of MgO in the slag obviously reflects the degree of damage done to the refractory walls. About 95% of MgO found in slag is known to result from slag-induced dissolution, the balance, accruing from mechanical damage and input material. It is envisaged that at a given temperature, dissolution will continue until the slag is saturated with MgO. It is therefore intuitive to envisage that MgO dissolution rate will be fastest at the beginning of slag formation (that is, between power on and meltdown) and diminishes with time.

More than 60% damage done to refractory wall via dissolution incidentally occurs within this period; the balance occurring during tap period due to high temperatures (1600 to 1700°C), and longer contact with slag.

It is difficult to determine with precision the MgO

solubility in slag by virtue of so many variables in slag Composition and the quasi-equilibrium conditions prevalent in the furnace.

Remedial measures based on raising CaO/SiO_2 value via excess addition of lime may have its own drawback in the sense that the solubility of CaO, in slag is not indefinite but limited by the saturation of slag with dicalcium silicate, ($\text{CaO}.\text{SiO}_2$). Once saturated with dicalcium silicate, further lime addition remains undissolved and engulfed in dicalcium silicate globules in slag. This undissolved lime in slag does not participate in the inhibition of refractory dissolution but will only give false basicity value for the slag. However, it is known that the addition of MgO in slag can further increase the solubility of the dicalcium silicate by providing extra chemical driving force via shifting of liquidus isotherm to higher concentration of CaO.

Estimates from Figure 6, gave the solubility value for MgO in slag to be 9% at slag basicity of 2 and 12% at basicity of 1.5. Assuming an arbitrary slag weight of 20 tonnes from slag induced refractory attack, and further assuming that all the MgO in slag results from slag induced refractory attack, then quantity of MgO removed from the refractory lining would be 1.8 tonnes per heat at a basicity of 2 and 2.4 tonnes at a basicity of 1.5.

Thus, a mere shift in slag basicity from 2 to 1.5 would be accompanied by an increase in refractory erosion of 600 kg per heat (in terms of MgO). This implies that reduction of slag erosion of basic refractory lining would involve pushing CaO/SiO_2 value beyond 2.

Alternatively, it is possible to satisfy slag affinity for MgO at low basicity either by reverting to the use of dolomitic lime ($\text{CaO}.\text{MgO}$) or introducing ground MgO bricks extraneously into the furnace to a point of saturation to discourage further migration of MgO from refractory lining into the slag.

Also, at basicity higher than 2, MgO solubility diminishes significantly and becomes less dependent on the level of FeO, as shown in Figure 6.

The beneficial effect of FeO may be traced to its foaming propensities causing the submersion of powerful arcs in foam and thus shielding the refractory walls from intense arc radiation.

In heat 543479, 7 tonnes of burnt lime was charged together with 1 tonne of MgO- based flogate (MgO= 80%) while heat No. 543478 had only 8 tonnes of burnt lime charged. Mass balance calculations using data from the characteristics of input material in addition to the appropriate slag chemistry yielded the results in Table 16. The data indicated that in Heat No. 543478 with 8 tonnes of lime charged, a slag weight of 24.5 tonnes resulted in 2.31 tonnes of refractory erosion (measured in tonnes of MgO).

In Heat No. 543479, 7 tonnes of burnt lime was added in addition to 0.80 tonnes of MgO. This resulted in 23.7 tonnes of slag containing 1.65 tonnes of MgO out of which only 0.85 tonnes was derived from refractory walls.

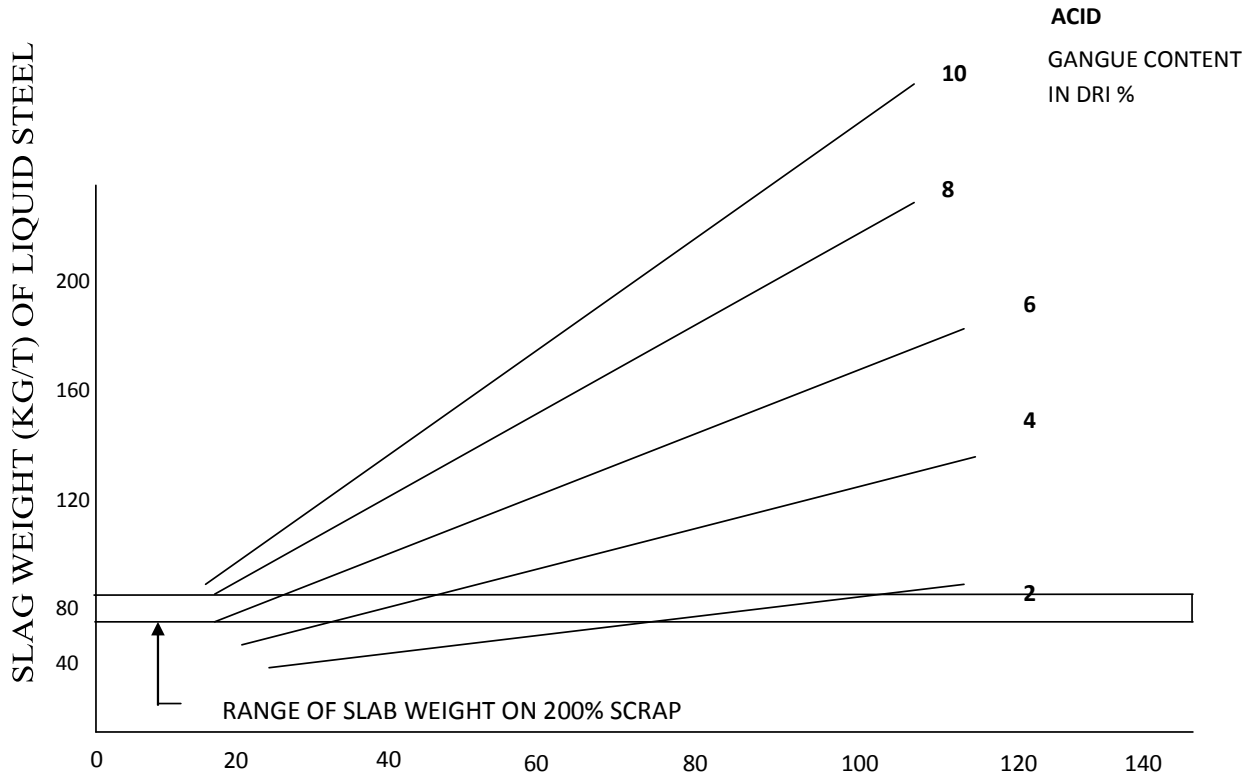


Figure 5. Effect of gangue content in DRI on slag weight. Source: Chatterjee and Pandey (2001).

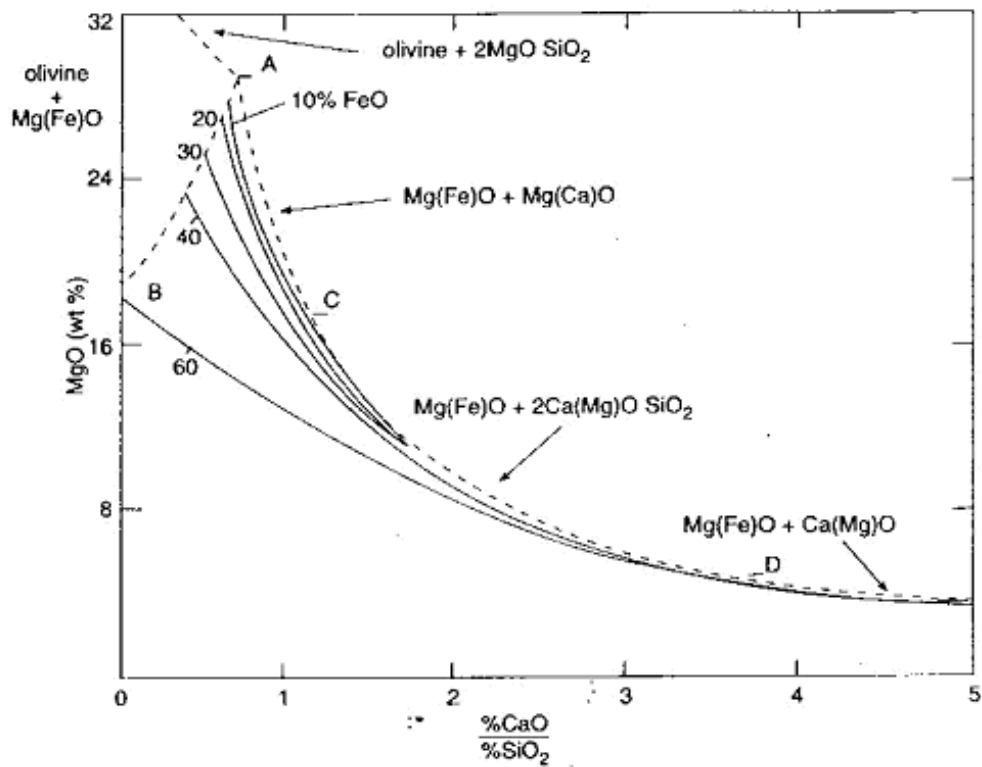


Figure 6. The solubility of MgO in CaO-SiO₂-FeO slags. Source: Making and Shaping and Treating of Steel (1999).

Table 16. Impact of extraneous addition of MgO on refractory wear intensities.

Heat No.	Quantity of CaO charged (Tonnes)	Quantity of MgO charged (Tonnes)	Slag wt (Tonnes)	MgO in Slag (Tonnes)	MgO from refractory (Tonnes)
543478	7.2	None	24.5	2.31	2.31
543479	6.3	0.8	23.7	1.65	0.85
543480	7.2	0.8	25.5	2.08	1.28

Average CaO value in burnt lime = 90%.

Addition of 8 tonnes of burnt lime and 0.80 tonne of MgO, in Heat No. 543480 resulted in 25.5 tonnes of slag with pseudo-refractory erosion of 1.28 tonnes of MgO. This erosion value of 1.28 tonnes for Heat No. 543480 is a distortion emanating from extensive repairs with 3.3 tonnes of MgO slinging mass, some of which must have fallen into the bath and subsequently incorporated into the slag.

The indications from the above data derived from these preliminary trials, showed that migration of MgO from refractory walls to the slag medium can be significantly discouraged by satisfying partially, the affinity of slag for MgO through introducing it extraneously into the furnace.

The marked effect on Heat No. 543479 may be related to smaller slag weight of 23.7 tonnes with refractory erosion of only 0.850 tonnes as against 2.310 tonnes for a similar heat (Heat No. 543478) without MgO addition. The significance of slag volume is related to the surface area effect. However, the beneficial effect of extraneous introduction of MgO in the furnace to combat refractory erosion has long been known and this has guided many steel plants in the use of dolomitic lime with 30 to 35% MgO content. The option of using MgO bricks may be marred by inadequate supply of the desired quality of bricks.

Based on the above, the use of dolomitic lime became plausible. However, its use in DSC had a major constraint arising from the humid environment in which the plant is situated and which led to the problems of blockage in the SMS pneumatic lime conveying system. As a result, the lime had to be introduced through other external means.

Energy consumption

Many factors can lead to increase in energy consumption when melting DRI. With good slag foaming, an EAF melting 100% cold scrap typically will consume between 400 to 435 KWh/tap ton of liquid steel without other energy inputs.

For comparison purposes, a shop melting a charge mix consisting of 98.2% DRI with very good slag foaming has achieved an average energy consumption level of 635 KWh/tap ton steel (Morales et al., 1995). Also, DRI metallization affects energy consumption. The lower the metallization, the higher the FeO level. Chemical

reduction of FeO is an endothermic reaction. Reduction of one ton of FeO to Fe will require around 800 KWh at steelmaking temperatures. Increasing levels of SiO₂ in the DRI raise energy demands and SiO₂ requires the addition of lime (CaO) to maintain the basicity ratio. Melting one ton of slag requires about 530 KWh. Increased amounts of SiO₂ require increasing amounts of CaO in order to maintain the basicity ratio. Both the SiO₂ in the DRI and calcined lime consume energy during the melting process (Gregory, 2010).

In this report, the energy used to melt 100 tonnes of DRI was 67.46 MWh for Itakpe Ore and 53.09 MWh for imported ore. This energy difference was by virtue of acid gangue differential between the ores.

The DRI to liquid melt yield was 78.36% for Itakpe Ore, although the theoretical maximum yield for Itakpe DRI was 81.0% based on DRI chemistry and 83.10% for imported ore. The implication of this data was that the minimum energy required to produce 100 tonnes of liquid Steel was 86.09 MWh for Itakpe, and 63.89 MWh for imported ore. The energy difference for 100 tonnes of liquid steel for the ore was therefore appreciable.

ECONOMIC CONSIDERATIONS

The Iron and Steel industry is often regarded as a dynamic sector of industrialization because of its backward and forward linkages to the economy. By backward linkage, we mean a situation where the establishment of a steel industry will induce attempts to supply, through domestic production, the resources needed in that outfit while forward linkage simply means that the establishment of say Ajaokuta Steel Complex brings with it the establishment of industries like the National Iron Ore Mining Project at Itakpe to supply raw materials needed. In other words, steel development births the establishment of various upstream and downstream industries (Duru and Agba, 2005).

In Direct Reduction (DR) processes, the characteristics and cost of available iron ores play a very important role. The selection of suitable raw materials will optimize productivity, energy consumption and the overall economy of industrial plants.

The raw material specifications for direct reduction processes should be determined primarily by the overall

economics of both the direct reduction plant and the associated steelmaking plant (Morales et al., 1995).

However, the economic aspect of using the local Itakpe Iron Ore to sustain steel production cannot be quantified only in terms of cost of importation of iron ore from other countries, but should be assessed in terms of total impact on the Nigerian Socio-economy. According to the Ministry of Mines and Steel Development, while the Itakpe Iron Ore deposits are being mined as raw material feed for Ajaokuta smelting facilities, opportunities for investment in the iron ore resources of Nigeria exist for the deposits in Northwestern and Southwestern Nigeria (Ministry of Mines and Steel Development, 2010).

Development of the iron and steel sector and particularly the iron sources in Nigeria has great potential for job creation and, possibly, in future, foreign exchange earning via iron ore exportation. Additionally, it will free the steel industries in Nigeria from the usual politics associated with world trade.

According to Bernadette and Richard (2002), the purpose of exploration is to discover new mineral deposits and prove their economic potential. Whether a profit can be gained from a mineral deposit is dependent on a number of physical and economic factors. Using modern exploration techniques, the risks associated with estimating the physical characteristics of ore bodies are considerably reduced and remain relatively fixed in comparison to economic factors such as mineral prices, capital and operating costs, infrastructure, transportation, and taxation rates. In addition, technological developments, local government legislation, and legal and social influences can significantly affect the economic viability of a mineral deposit.

In a study conducted on the economic analysis of the production of iron ore in Nigeria, Adebimpe and Akande (2011) stated that the production of iron ore in Nigeria is economically viable. This is in line with the Federal Government decision to attract direct foreign investment to the solid mineral sector and to further diversify the solid mineral sector. The use of discounted cash flow micro-economic assessment (Iloiu and Iloiu, 2008) is required in order to evaluate large scale iron ore production in Nigeria. The iron ore project had an initial investment cost of USD 73.934m, annual expenditure and benefit of USD 48.128m and USD 270m respectively (Adebimpe and Akande, 2011). The net present value (NPV), internal rate of return (IRR) (Ilori et al., 1997), and payback period of financial analysis at 100% capacity utilizations are USD 833.10m, 444.36% and 6 years respectively. They concluded that the economic assessment also showed a positive NPV at both 75 and 60% capacity utilizations and that the project had good economic potential (Adebimpe and Akande, 2011).

Calculations from Cost and Management Accounts Department of the Delta Steel Company, also indicated that the apparent cost of producing one tonne of billet from Itakpe Iron Ore was N 9,866.00 (about \$61), while

that derived from imported ore cost N12,874.52 (about \$80) per tonne (CMA Report, 1993). Taking the current state of the economy in the country into consideration, the cost of production using imported iron ore will be higher than what is quoted above.

Although the implicit production cost using the local ore will be higher than the quoted figure due to the additional slag handling facilities, increased stresses on these facilities and a slight increase in the refractory requirement, it will still be less than the result from the use of the imported ore.

Additionally, the cost of production, using Itakpe Ore will be further reduced with the completion and utilization of the Itakpe – Aladja rail project, which will reduce cost of transportation of the super concentrate from the NIOMCO Plant.

CONCLUSION

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 but was successfully beneficiated for use at the Delta Steel Direct Reduction – Electric Arc Furnace plant. The production cost per tonne of liquid steel was found to be lower than same in the use of the imported ores. Therefore, its successful utilization ensures ready availability of raw material for the only major operating steel plant steel in Nigeria. This will lead to higher capacity utilization, and further reduce cost of production. Finished products will readily be available in the markets at cheaper prices leading to a boost particularly in the building sector with associated positive band-wagon effects on other aspects of the economy.

Conflict of Interest

The authors have not declared any conflict of interest.

REFERENCES

- Adebimpe RA, Akande JM (2011). Engineering Economic Analysis on the Production of Iron Ore in Nigeria. *Geomat.*1:14-20.
- Adedeji FA, Sale FR (1984). Characterization and Reducibility of Itakpe and Agbaja (Nigerian) iron ores. *Clay. Min.* 19:843-856.
- Beatty HW (1978). *Standard Handbook for Electrical Engineers*. 11th Ed., McGraw Hill, NY: 2:171-176.
- Bernadette O'R, Richard M (2002). Investment Decisions of International Mining Firms: Policy Approaches, *SIMULATION*. 78(6):362-379.
- British Geological Survey (2009).
- Chatterjee A, Ramesh S, Pandey B (2001). *Metallics For Steel*

- Making-Production and use, iSponge Iron Production by Direct Reduction of Iron Oxide, Allied Pub. P. 586.
- Cost and Management Report (1993).
- Delta Steel Company Training Manual (1981).
- Duru EJC, Agba MS (2005). Industrialization And Economic Development In Nigeria: A Study Of The Role Of The Iron And Steel Sector, Eur. J. Sci. Res. 7(3):68-84.
- Goswami MC (2007). Physical And Physico - Chemical characterization of iron ore and agglomerates. 1:27-38.
- Gregory LD (2010). Use of DRI in EAF's. Pt. IV. Direct Reduced Iron Process Effects and Applications. Pawleys Is. SC. USA.
- Iloiu S, Iloiu M (2008). Ore Reserve Estimation and Project Profitability, Annals Univ. Petroşani. Mech. Eng. 10:85-88.
- Ilori MO, Irefin IA, Adeniyi AA (1997). Engineering Economic Studies on the production of non-alcoholic beverages from some tropical crops, Technovation, 17 (11/12):715-721.
- Indian Mineral Year Book (2011).
- Jones JAT, Lefrank BA (1998). Electric Furnace Steelmaking in the Making, Shaping and Treating of Steel. AISE St. Foun. pp. 525-660.
- Kempken JG, Kleinschmidt K, Schmale U, Thiedemann HP, Gaines JT, Kopfle (2008). Short Route – Long-Term success: Integrated Mini-Mill solutions by Midrex and SmsDemag, Archives. Met. Mat. 53:2.
- Midrex Direct Reduction Plant Operating Manual (1981).
- Ministry of Mines and Steel Development (2010). Iron Ore Exploration opportunities in Nigeria.
- Mohammed S (2002). Nigerian Steel Industry – Historical Development. African Iron and Steel Association.
- Morales RD, Lule GR, Francisco L, Jorge C, Romero JA (1995). The Slag Foaming Practice in EAF and Its Influence on the Steelmaking Shop Productivity. ISIJ Int. 35(9):1054-1062.
- Ola SA, Usman GA, Odunaike AA, Kollere SM, Ajiboye PO, Adeleke AO (2009). Pilot Scale Froth Flotation Studies to Upgrade Nigerian Itakpe Sinter Grade: J. Min. Mat. Cha. Eng. 8(5):405-416.
- Raw Materials Research and Development Council (2010) 'Steel raw materials in Nigeria'.
- US Department of Geological Survey (2006).