Recycling Blends of Waste Groundnut Shells and High Density Polyethylene as Reductants in the Microwave Production of Iron Nuggets from the Pudo Iron Ore*

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Abstract

Different ores of iron have responded differently when subjected to various technologies of iron ore reduction. The Pudo iron ore in the Upper West Region of Ghana is known to exist in two forms; a low grade iron (in the form of Fe_2O_3) which has desirable amounts of CaO and MgO and a high grade titaniferous-magnetiferous ore (Fe_3O_4). In this work, the low grade iron oxide was reduced by using a locally available biomass (Groundnut Shells, GNS) and its blends with High Density Polyethylene (HDPE) as reducing agent. The microwave technology was used for the reduction process. Composite pellets composed of the iron ore, reducing agents of different blends and flour (binder) were formed and subjected to a 2400 MW, 50 Hz microwave for firing. Each pellet was fired for forty minutes. The results of this study indicate that the GNS as reducing agent solely was able to reduce the ore to about 54 % in the reduction process. Blending of the biomass with HDPE led to an improvement in the percent reduction with maximum percent reduction of about 80 %. The reduction process was however accompanied with high undesirable amounts of slag and low amounts of metallic spheres of iron. The iron produced was highly carburised since temperatures below the melting point of iron were recorded during the reduction process (maximum of 1197 ºC). The residue produced in this study is mostly made up of titanium, silicon and other elements in smaller quantities.

Keywords: Reduction, Groundnut Shell, Pudo Iron Ore, Waste Biomass

1 Introduction

The microwave technology has been proven to be a very good technological approach in the reduction of iron ores and in several other areas by several researchers (Aguilar and Gomez, 1997; Dankwah *et al.*, 2015a; Dankwah *et al.*, 2015; Dankwah *et al.*, 2016; Ford and Pei, 1967; Hasanbeigi *et al.*, 2014; Manning and Fruehan, 2001; Standish *et al.*, 1991; Xia and Pickles, 1997). The Pudo iron ore is one of the major deposits of iron in Ghana with iron content of up to 84% (wt %) (Kesse and Banson, 1975). It is a titaniferrous - magnetiferrous ore, containing both magnetite and titanium, depending on location. Chemical analyses by Kesse and Banson (1975) revealed the absence of phosphorus and an extremely low sulphur content (Table 1), making it a promising source of iron oxide for the proposed integrated Iron and Steelmaking Plant for the Country. Very little research has been conducted on the Pudo iron ore aside geological work conducted by Kesse *et al.,* (1975) and work done by Dankwah *et al.*, (2016). In the maiden research pertaining to extractive metallurgy, iron nuggets were produced from the ore by the use of 'pito waste' and its blends with HDPE as reducing agents by the microwave technology (Dankwah *et al.*, 2016). The production of waste plastics (HDPE) has been on the ascendency emanating partly from the production of sachet water, particularly in Ghana and also as a result of packaging among other reasons accounting for the high amounts of waste plastics. Although groundnut shells are sometimes used for stock feed, they are not as popular as cereal straws and legume stovers (Masenda, 2004). Groundnut shells have also been used successfully to produce light weight concrete (Sada *et al.*, 2013). In their research, however, it was realised that increasing percentage of groundnut shell in a blend with the usual fine aggregate resulted in a corresponding decrease in density and compressive strength of the formed concrete cubes. This therefore implies that a relatively small quantity of groundnut shells is required in the above described work. As a result, the use of groundnut shells in the reduction of iron ores as accomplished in this study can be commercialised since there would be no high level of competition from the livestock and the building industries for the raw material.

Only a small fraction of end-of-life 'pure' water sachets (PWS) is currently recycled in Ghana, with the rest being illegally discarded or not landfilled appropriately. Pure water sachets are currently one of the most difficult plastics to deal with by various Metropolitan, Municipal and District assemblies in Ghana. (Dankwah *et al.*, 2016). Attempts have been made in recycling the type of HDPE used in this work (Pure Water Sachet). Dankwah *et al.* (2016) have successfully used this waste plastic in

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a pyrolysis reaction process to produce liquid fuel which is believed would contribute significantly to plastic waste management in Ghana and as well find an alternative means of producing liquid fuels in the sub-region (Dankwah *et al.* 2016). In this work, PWS is used to partially replace groundnut shells due to the presence of significant amounts of carbon and hydrogen (85.5 % and 14.22 %, respectively) in PWS, the major reducing constituents in reduction processes.

Fig. 1 Raw PWS

2 Resources and Methods Used

2.1 Raw Materials

For the purposes of this work, GNS were obtained from groundnut farmers, households and many other sources in the Northern part of Ghana. HDPE was also obtained from the University of Mines and Technology community. These were charred and melted respectively and the products used as carbonaceous materials in this study. Two ores of iron (one magnetic and the other, nonmagnetic) were obtained from Pudo in the Upper West Region of Ghana. The nonmagnetic ore was utilised for this investigation. Its composition by X-ray Fluorescence (XRF) analysis is shown in Table 1. It is an extremely low grade iron ore with a very high silica content and moderately high alumina content. Although the iron oxide content is very low, the ore is self-fluxing as evidenced by the high MgO and CaO contents. Besides, it has no sulphur and its phosphorus content is negligible; these features are ideal for iron and steelmaking technologies.

Fig. 2 shows the blends of carbonaceous materials used in this work.

Table 1 Composition (by XRF) of the Iron Ore used for the Investigation

Component	Composition (wt %)
Na_2O	1.411
MgO	9.057
Al_2O_3	11.844
SiO_2	47.244
P_2O_5	0.010
SO_3	0.000
K_2O	0.107
CaO	12.048
TiO_2	0.947
Mn_3O_4	0.456
Fe_2O_3	14.958
LOI	1.960

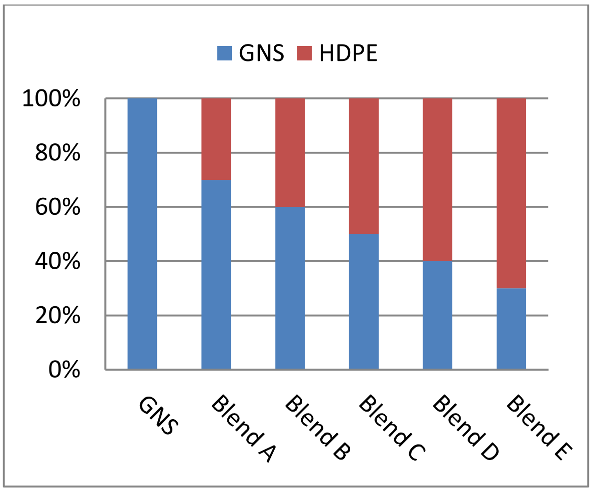

Fig. 2 Blend Compositions of the GNS and HDPE

The above percentages are derived from the 28 % proportion of the pellet composition.

GNS was charred for 30 minutes whereas HDPE was melted and pulverised into granules. The ore was also taken through primary, secondary and tertiary crushing stages after which it was then ground using a ball mill for 15 minutes. -250 µm of each component was used for this work.

Table 2 Elemental Analysis of HDPE

Component	C	H	S	N	O*
HDPE (wt%)	85.5	14.22	0.3	0	0

*By difference

Fig. 3 Groundnut Shells (a) and the Corresponding Waste produced (b)

Fig. 4 Charred Groundnut Shells

Table 3 Proximate and Ultimate Analysis of GNS

Proximate Analysis			
	Units	Dry	DAF*
Moisture Content	wt %	-	-
Ash Content	wt %	3.90	-
Volatile Matter	wt %	41	42.66
Fixed Carbon	wt %	55.1	57.34
Ultimate Analysis			
Carbon	wt %	81.78	85.1
Hydrogen	wt %	2.11	2.20
Nitrogen	wt %	1.15	1.20
Oxygen	wt %	11.05	11.50
Total (with halides)	wt %	100	100
HHV_{Mine}	MJ/kg	29.16	30.34

*Dry Ash Free
Source: Cukierman *et al.*, 1981.

2.2 Pelletising

Iron pellets were formed by mixing the ore and the carbonaceous materials with a composition of 70% and 28% respectively. The remaining 2% was made up of flour which primarily enhanced the binding property of the formed pellets. The carbonaceous material however varied in composition as shown in fig 2 above. The 28 % as mentioned becomes the 100 % equivalent where no blending of the carbonaceous materials was needed and all other percentages were calculated from the equivalent mass of the 28 % which represents the portion of the pellet to be composed of the reducing agent. The process of pelletising was then carried out as described in the book authored by Meyer (1980).

Fig. 5 Formed Pellets allowed to Cure

2.3 Microwave Heating of Pellets

The dry pellets were then subjected to a 2400 MW, 50 Hz microwave oven. Prior to this, a spot was located in the microwave where heating proved to be maximum. This spot was found out to be 8 cm into and 13.5 cm from the left and right sides of the microwave. The diagram below shows the heating process.

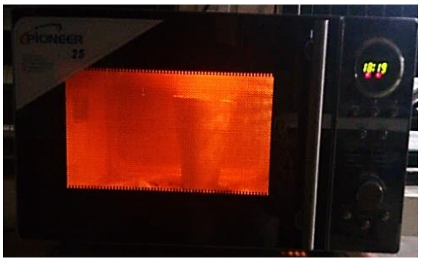

Fig. 6 Microwave in Operation

2.3.1 Temperature Measurement

The estimation of temperature in the microwave was quite a challenge as sophisticated temperature measuring device was not readily available to be used appropriately. However, as a way of estimating the temperature at which reduction was carried out, a thermocouple was used for this purpose. In all cases, the thermocouple was immediately placed in the hot mass after reduction in the microwave and the temperature was recorded. Although it is evident that there would be a slight drop in temperature, an average value was taken out of five measurements in each case. The temperature obtained from this test work was realized to be 1197 °C.

2.4 Reactions Involved in the Reduction Process

The presence of hydrogen in the HDPE, concentrated carbon from the charred GNS and the fixed carbon content in the melted HDPE is expected to result in the following reactions:

2.4.1 Reaction of Fe_2O_3 with H_2 C to produce Fe_3O_4:

$$Fe_2O_3 + \tfrac{1}{3}H_2 = \tfrac{2}{3}Fe_3O_4 + \tfrac{1}{3}H_2O \quad (1)$$
$$Fe_2O_3 + \tfrac{1}{3}C = \tfrac{2}{3}Fe_3O_4 + \tfrac{1}{3}CO \quad (2)$$

The corresponding production of CO gas in reaction (2) above will result in the reduction of the ore. The reaction is shown below:

$$Fe_2O_3 + \tfrac{1}{3}CO = \tfrac{2}{3}Fe_3O_4 + \tfrac{1}{3}CO \quad (3)$$

2.4.2 Reduction of Fe_3O_4 to FeO

Magnetite, as produced in the above reactions then reacts again with H_2, C and CO to produce Wustite as shown below:

$$Fe_3O_4 + H_2 = 3FeO + H_2O \quad (4)$$
$$Fe_3O_4 + C = 3FeO + CO \quad (5)$$
$$Fe_3O_4 + CO = 3FeO + CO_2 \quad (6)$$

2.4.3 Reduction of FeO to Fe

The final reaction is the formation of iron from the reduction of Wustite. This again is as a result of the reaction of the three main reducing agents and FeO as shown below:

$$FeO + H_2 = Fe + H_2O \quad (7)$$
$$FeO + C = Fe + CO \quad (8)$$
$$FeO + CO = Fe + CO_2 \quad (9)$$

The production of CO could also be associated to the gasification of CO_2. This results in the reaction as shown below:

$$CO_2 + C = 2\,CO \quad (10)$$

(Hasanbeigi *et al*., 2014)

3 Results and Discussion

The results obtained from the experimental work as described above are presented. The nature of metal produced, the magnetic property exhibited by the produced metal, the extent of reduction and the corresponding slag formation are presented.

3.1 Nature of Metal Produced

Samples of reduced metal were produced for all the different blends of GNS and HDPE. Metallic spheres were observed in these reduced samples. These spheres were formed immediately the heated mass was poured out of the crucible. Fig. 7 shows the metallic spheres that were realised.

Fig. 7 Spherical Particles of Metallic Iron Produced after Reduction

The spheres produced were mostly naturally liberated in the reduced mass. However, a few of the spheres were locked up in the slag realised after reduction. These were hammered to separate them from the slag and recovered with a magnet. The spherical nature of the metal produced suggests that the metal was formed by solidifying from the molten state. Maximum temperature of about 1197 ºC was recorded during the microwave heating process and once this is below the melting point of iron (about 1538 ºC), it makes the metal produced highly carburised and possibly containing some other alloying elements.

3.1.1 Magnetic Property of the Reduced Metal

All spheres produced from the reduction process appeared to be ferritic iron by showing a high magnetic property along with a metallic lustre. They were readily attracted to a low intensity magnet when it was brought closer to the reduced mass. Fig. 8 shows the attraction of the spheres to a magnet.

Fig. 8 Attraction of Metallic Spheres to a Low Intensity Magnet

3.1.2 Extent of Reduction

The following graph shows the extent of reduction of the different pellets that were formed and microwaved.

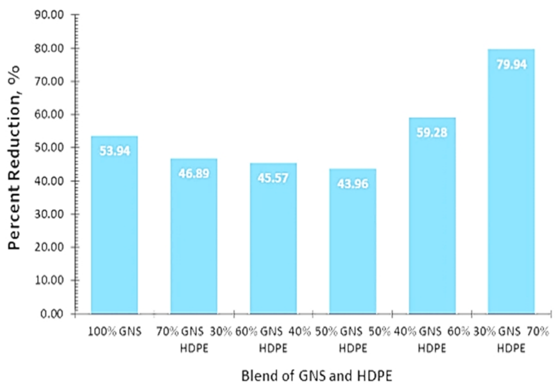

Fig. 9 Extent of Reduction of Composite Pellets.

The percent reduction although reaches a maximum of about 80 %, experienced a gentle dip to as low as about 44 %. This reveals the suppressing effect of ash in the groundnut shell or an undesirable element leading to the initial declining nature of the reduction. The ash content in the groundnut shell char, however, does not completely prevent the microwave reduction process due to its low content as shown in Table 3. Consequently, the increased amount of HDPE sees a positive turnover of the reduction process pronouncing the effective participation of the hydrogen content in the HDPE as shown in Table 2. This assertion agrees with work done by Dankwah *et al.* (2016) where they used 'pito' waste to successfully reduce iron ore to metallic iron. Therefore, hydrogen can be said to be a strong reducing agent of the Pudo iron ore in this respect.

3.1.3 Associated Residue Produced

The product after the reduction process was made up of the reduced metal iron and the associated residue. The residue can be thought of as being comprised significantly of oxides of silicon, aluminium, calcium, magnesium and titanium. The amount of residue produced is not surprising as these constituent oxides require higher reduction temperatures than iron.

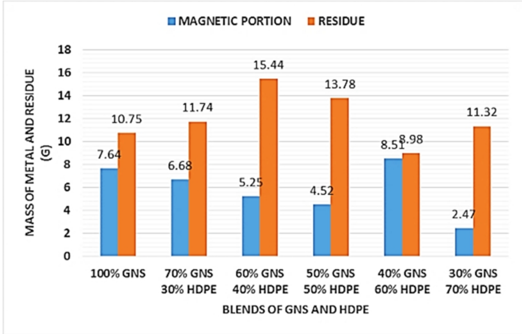

Fig. 10 Metallic Iron and Associated Residue produced

Since temperatures recorded were below the reduction temperatures of these oxides, it suggests that they will report in the residue. Low magnetic metal values are currently being investigated so as to augment the amount of metallic iron produced from the reduction process.

Fig. 11 Residue after Reduction.

4 Conclusions

A laboratory work was carried out to investigate the possibility of reducing the Pudo iron ore using readily available carbonaceous materials and the following could be drawn from the work that has been done:

(i) The Pudo iron ore is amenable to reduction when subjected to microwave irradiation. This is due to the ability of both the ore and the carbonaceous materials to absorb microwave energy and heat up to high temperatures creating an atmosphere for reduction into metallic iron.

(ii) Metallic iron was produced from this study. This proves that the Pudo iron ore can serve as a feed to the proposed iron and steelmaking industry in the country.

(iii) A blend of GNS and HDPE gives a better reduction of the Pudo iron ore. This is evident in the 30:70 ratio of GNS and HDPE in the reduction graph.

(iv) Groundnut shells and HDPE can be recycled into useful products. Hence the intended decision of the country to ban the use of plastics due to its waste menace can be reconsidered due to the above findings.

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