Application of Microwave Energy for Production of Iron Nuggets from the Pudo Iron Ore using 'Pito' Waste and its Blend with HDPE as Reductant*

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Abstract

The local steel industry is currently facing stiff competition from South East Asia and elsewhere for high grade scrap iron, culminating in a ban by central Government on the export of ferrous scrap. In this work we investigate the potential for producing high grade iron nuggets from the Pudo iron ore in the Upper West Region of Ghana, using carbonaceous materials generated from locally available 'pito' waste and its blend with high density polyethylene (HDPE) as reductant. Composite pellets of the ore containing various blends of uncharred 'pito' and charred 'pito' waste with HDPE were irradiated in a domestic microwave oven and the extent of reduction was determined after 40 min of irradiation. It was observed that highly carburised premium grade iron nuggets can be produced from the Pudo iron ore using 'pito' waste (both charred and uncharred) and its blends with HDPE as reductant. The measured extent of reduction ranged from about 47 % to about 96 %, suggesting that the Pudo iron ore is a potential source of iron from which premium grade metallic iron can be produced commercially to feed the local steel industry. From the point of view of chemical reactivity, it appears the effect of hydrogen is more pronounced than the amount of fixed carbon in the 'pito' waste and this effect was felt in all the HDPE-'pito' waste blends utilised for the investigation. Accordingly dry 'pito' waste may be used directly with HDPE as reductant without the need to char the biomass.

Keywords: Reduction, Pudo Iron Ore, Waste Biomass, Pito Waste, Extent of Reduction

1 Introduction

The reduction behaviour of the Pudo titaniferous-magnetiferous iron ore has not been studied since its discovery by Sir Albert Kittson in April, 1927. The notable research work conducted on this ore was by Kesse and Banson (1975) which pertains to the geology of the ore.

The Pudo iron deposit (Fig. 1) is located in Pudo, near Tumu in the Upper West Region of Ghana and is currently believed to be the richest ore in Ghana, with iron oxide content (Fe_3O_4) up to about 84 wt %.

The iron deposit is known to be a titaniferrous magnetiferrous ore, containing both magnetite and titanium, depending on location. (Kesse and Banson, 1975). Recent work by Aakyiir and Dankwah (2017) reveals a non-magnetic ore of relatively low iron oxide (see Table 1). Chemical analyses by Kesse and Banson revealed the absence of phosphorus and an extremely low sulphur content, making it a promising source of iron oxide for the proposed integrated Iron and Steelmaking Plant for the Country. This work makes use of the non-magnetic iron ore (haematite) whilst work is on-going to ascertain the effect of blending the two ores of iron from the Pudo hills.

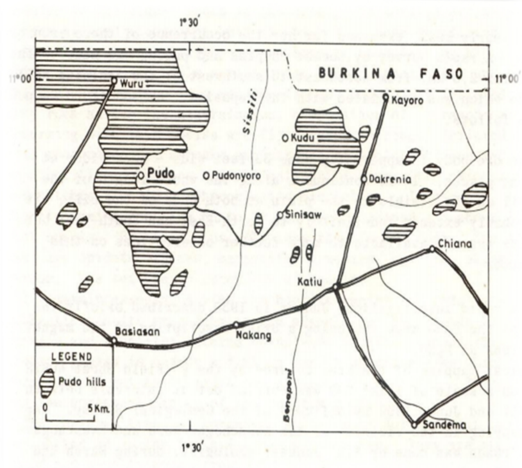

Fig. 1 Location of the Pudo Hills

Pito brewing is one of the major occupations of the women in the Northern sector of Ghana, notably those of the Dagaare tribe. After the processing of pito, a waste product is realised. Pito brewery waste is a by-product of brewed pito usually from fermentation of sorghum or guinea corn. This product is obtained as a residue after filtration of a pulp; the filtrate is further processed into pito. Although this pito waste is sometimes used as feed for fish in local areas, the amount used as fish meal is so meager that a lot is left unused. Limited research has been conducted on the utilisation of

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pito waste. In animal rearing, Kagya-Agyemang *et al.,* (2013) investigated the effect of partial replacement of maize by waste pito mash on the growth performance of weaner rabbits (*Oryctolagus cuniculus)* and concluded that replacement level could exceed no more than 20 wt %. The extent of use of pito waste in this regard could be described to be low. This translates into the ready availability of pito waste as a raw material to be used in iron reduction. Abarike *et al.,* (2012) as part of their investigation measured the ash content of fish meal, pito mash, rice bran, groundnut bran and wheat bran. They observed that pito mash had the lowest ash content of 4.42 wt % compared to those of fish meal (27.93 wt %), rice bran (16.89 wt %), groundnut bran (4.78 wt %) and wheat bran (5.18 wt %). For use as reductant in ironmaking, low ash content is one of the desirable properties. This waste material however until now has not been used in iron reduction processes.

Biomass is considered as renewable and neutral because of the fast growth cycle of 5 -10 years and the fact that this type of cycle can be achieved in tropical forest where CO_2 is converted to C through the process of photosynthesis (Maslejova, 2013). Plants, algae and some bacteria absorb CO_2 from the atmosphere, and in the presence of sunlight and water, they produce glucose ($C_6H_{12}O_6$), which is a simple sugar.

Biomass contains less sulphur than coal, which translates into lower sulphur emissions when higher blending ratios of biomass are used (Maslejova, 2013). Wood fuels generally contain very little ash (1% or less); consequently, increasing the ratio of wood in biomass/coal blends can reduce the amount of ash that needs to be disposed (Maslejova, 2013). A negative aspect of biomass (especially some grasses and straws) is that it can contain more reactive potassium and chlorine than coal. Higher fuel chlorine contents can lead to greater high temperature corrosion in metallic protions of iron making devices such as the electric arc furnace and the like. The use of biomass as a reductant in ironmaking is not new; it is especially common in countries like Brazil, where climatic conditions favour the production of significant amounts of charcoal from fast growing eucalyptus plantation. This explains why Brazil operates a charcoal based pig iron production.

Waste polymer reduction technology is an emerging area in metallurgy where carbonaceous materials generated from waste polymers are used in place of or in combination with other carbonaceous materials as reductants for metal oxides reduction (Dankwah, 2014). Waste polymers (plastics) and biomass offer a readily available alternative to high grade metallurgical coke as reductant for iron making, especially in countries like Ghana where commercial quantities of iron ores are available, but without the relevant source of carbonaceous materials (Dankwah, 2014; Mašlejová, (2013). In the metallurgical field, the use of postconsumer plastics and or biomass as reductants or as a source of energy is currently gaining the attention of various researchers (Matsuda *et al*., 2006; Nishioka *et al*., 2007; Matsuda *et al*., 2008; Ueki *et al*., 2008; Dankwah *et al*., 2011; Kongkarat *et al*., 2011; Murakami *et al.*, 2009; Murakami and Kasai, 2011; Dankwah *et al*., 2012; Dankwah *et al*., 2013; Dankwah and Koshy, 2014; Dankwah *et al*., 2014a; Dankwah *et al.*, 2014b; Dankwah *et al.*, 2015a; Dankwah *et al.*, 2015b; Dankwah *et al.*, 2015c). However, most of the existing research in this area involve the use of thermoplastic polymers and or their blends with metallurgical coke, graphite, or biomass as reductants for the production of metallic iron from reagent grade iron oxides or Electric Arc Furnace (EAF) slags containing iron oxide. Little information exists in literature on the use of these waste polymers as reductants for the production of metallic iron from naturally occurring iron ores. Besides, the use of Pito waste or its blend with waste plastics as reductants for metal production is unknown.

Microwave reduction technology is an emerging phenomenon aimed at addressing part of the environmental issues associated with the conventional production of metals in the blast furnace. The key factor for application of microwaves in the iron industry is its high potential for an essential reduction of carbon dioxide emission (Takayama, 2007). It relies on the ability of either the metal oxide or the carbonaceous reductant or both to absorb microwave energy and to heat rapidly to temperatures sufficient for the reduction of the metal oxide.

The reduction of iron oxides using microwave energy as heating source has been previously investigated. Ishizaki *et al.* (2006) investigated the microwave reduction of magnetite ore–coal composite pellets in a nitrogen gas atmosphere. They observed by means of XRD analysis that the reduction of magnetite started at about 800°C and got to completion (with pig iron formation) at about 1350 °C. They further observed that the heating rate of pellets was independent of their mass but dependent on applied power because of self-heating. Ishizaki and Nagata (2007) investigated the selectivity of microwave consumption in the reduction of Fe_3O_4 with carbon black in mixed powder. Standish and Huang (1991) had earlier observed that the carbothermic reduction of both magnetite concentrates and hematite fines could be satisfactorily and rapidly carried out with microwave heating. Zhong *et al.*, (1996) investigated the reduction of a low-silica taconite concentrate by coke or coal using an industrial microwave generator. Mourao *et al.*,

(2001) investigated the carbothermic reduction of composite pellets containing a hematite iron ore, coke or charcoal as carbonaceous material. Nagata *et al*., (2004) showed that pig iron was obtained from magnetite ore–coal composite pellets by microwave heating. Chen *et al*., (2003) observed that microwave heating with carbothermal reduction can increase the metallization rate of iron ore concentrates containing coal. Morita *et al*., (2001) successfully recovered about 70 % of iron and 25 % of phosphorous from factory steel-making slag by carbothermal reduction using microwave irradiation.

However, little information exists in literature on the use of waste polymers as reductants in the production of metallic iron from naturally occurring iron ores in a microwave.
In this work, the feasibility of utilising Pito waste and its blend with HDPE as reductant for the production of metallic iron from the Pudo iron ore is investigated through the microwave approach.

2 Resources and Methods Used

2.1 Materials

The sampled Pudo iron ore had a particle size between 120 mm and 150 mm. A mallet was therefore used to reduce the different sizes to between 30 mm and 50 mm; 2 kg of the reduced sample was then passed through a jaw crusher to obtain sizes between 5 mm and 15 mm. A secondary crushing technique was employed by using the cone crusher to further reduce the ore to - 5 mm. Tertiary crushing was done with a roll crusher and 1.6 mm to 2.4 mm size range was obtained. The sample was then milled using the ball mill for twenty minutes after which it was sieved with a 250 µm sieve to obtain a -250 µm particle size.

Pito waste was collected from Tumu in the Upper West Region of Ghana. The Pito waste (Fig. 2) was prepared charred and also uncharred and both were used. The virgin (uncharred) Pito waste (2 kg) was dried to remove any moisture and ground directly with a ball mill since it did not require any crushing. It was then screened with a 250 µm sieve to obtain a material below the mentioned sieve size. The other half of the Pito waste was charred and also taken through the grinding and screening process as described above.

Charring was done under controlled temperature conditions (150 - 200°C) using a thermocouple to upgrade the carbon content by expelling the volatile components of the material. The residence time of the charring process was 45 min using a gas fired furnace.

Fig. 2 Raw and Charred Pito Waste

The source of the HDPE was discarded pure water sachets (PWS) collected from UMaT campus. Pulverised carbonaceous reductants were prepared from the PWS using the method described in the work of Dankwah *et al*., (2014b). Samples of the pulverised carbonaceous materials are shown in Fig. 3.

a) b)

Fig. 3 a) Raw PWS b) Carbonaceous Material Prepared from PWS

Blends of carbonaceous materials were prepared by thoroughly mixing the Pito waste with the pulverised HDPE in various proportions (0, 30, 40, 50, 60 and 70 wt %) of HDPE.
Table 1 presents the results of XRF analysis on the Pudo iron deposit.

Table 1 Chemical Composition (XRF) of Pudo Iron Ore

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

For pellet formation (Fig. 4), 21 g (70% of pellet mass) of iron ore and 9 g (30% of pellet mass) of reducing agent was used. A mass of 8 g of the reducing agent consisted of Pito waste-HDPE and 1 g wheat flour which served as a binding agent in all the pellets formation. Weighing was done using an electronic balance. Pellets were prepared into paste for moulding by adding water and stirring with plastic spoon to homogenise the mixtures. Pellets were cured and dried at atmospheric temperature for four days to remove physically held water in the pellets. The dry weights of the pellets were taken after curing using the electronic balance.

Fig 4 Iron Ore-Pito/HDPE Composite Pellet

2.2 Experimental Procedure

The dried pellets were placed into a fire clay crucible and positioned at the central location of the microwave (Fig. 5) to ensure maximum concentration of the radiation emitted.

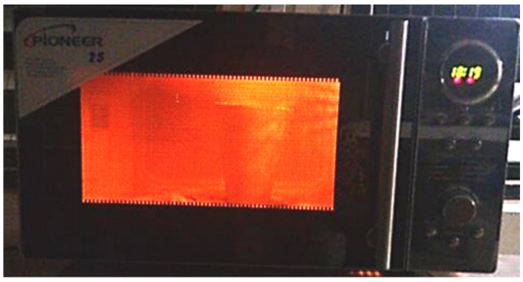

Fig 5 Reduction Process in a Domestic Microwave Oven

After 40 minutes of firing, the crucible was taken out and quenched in air to stop any further reactions. The weights of the reduced iron pellets were recorded. The temperature was measured as described by Aakyiir and Dankwah (2017) and was estimated to be 1197 °C.

3 Results and Discussion

3.1 Reduction of Pudo Iron Ore by Pito Waste-HDPE blends

Fig 6 shows the nature of metal produced from the reduction of the Pudo ore by carbonaceous materials generated from blends of pito waste and HDPE. As shown in Fig. 6, several spherical metals are formed that can easily be separated from the unreduced mass using a simple handheld magnet (Fig. 8). The spherical nature indicates that the metal solidified from the liquid state. This emanates when the molten iron attempts to minimize surface energy, hence the spherical products are formed. Fig. 7 shows the SEM/EDS analysis of a sample metallic sphere. The figure reveal iron peaks with significant amounts of silica and titanium. The maximum temperature recorded in the microwave was about 1197 °C, far below the melting point of metallic iron. The metal formed is therefore highly carburised or contained some other alloying elements.

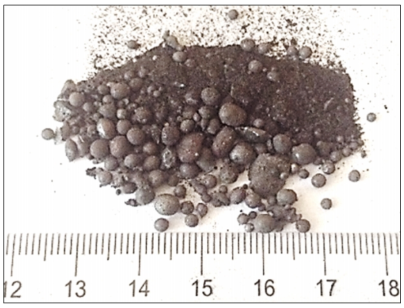

Fig. 6 Spherical Particles of Reduced Pudo Ore

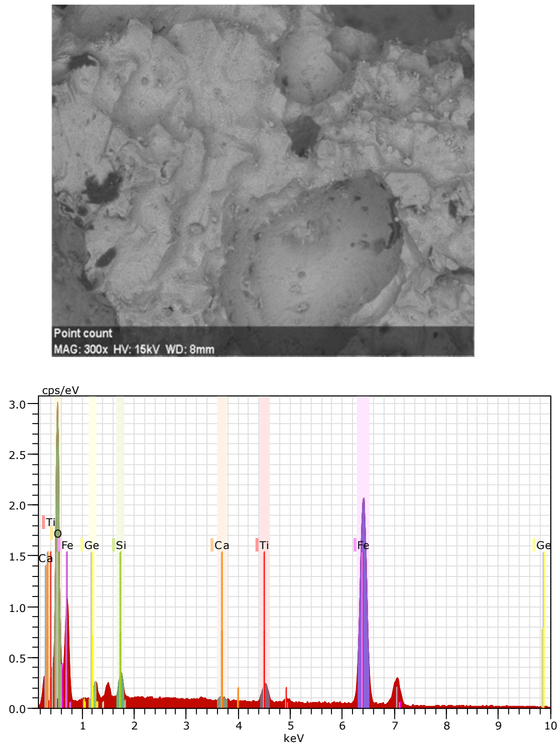

Fig. 7 SEM/EDS of a Sample Metallic Sphere

Fig. 8 Separation of Reduced Metal from Char and Slag

The unreduced mass is shown in Fig. 9 and is likely to be rich in TiO_2 and minor amounts of SiO_2 and Al_2O_3, since these oxides require higher temperatures for reduction (greater than 1600 °C).

Fig. 9 Non-magnetic Portion left over after Removal of Reduced Metal

3.2 Extent of Reduction of Pudo Iron Ore by Various PW-HDPE Blends

The extent of reduction of the ore by Pito waste-HDPE blends was measured for various blends. The results are shown in Figs (10 and 11) for the carbonaceous blends containing charred and raw 'pito' waste, respectively. The conversion of the cellulose in the uncharred pito waste to carbon monoxide increased the amount of reducing agents in the reduction process. The combined effect of this carbon monoxide, hydrogen in both the uncharred pito waste and HDPE as well as carbon in both the HDPE and pito waste accounts for the high reduction in the blends of uncharred pito waste and HDPE. The extent of reduction generally increases with an increase in the amount of HDPE blended with the Pito waste for both raw and charred Pito waste. Comparing Fig 10 to Fig 11, it is apparent that the extent of reduction is higher for blends containing uncharred Pito waste. An increase in the content of HDPE results in an increase in the content of hydrogen in the composite blend. At the same time, charring increases the amount of fixed carbon in the composite pellet but decreases the content of hydrogen. This observation partly agrees with the observation by Dankwah *et al.*, (2011) that reduction of iron oxides is enhanced by the amount of hydrogen in a carbonaceous material. However, we do not see fixed carbon from pito waste playing any positive role in this investigation. It appears the effect of hydrogen is more pronounced as evidenced by all the blends containing the uncharred pito waste. The carbonaceous materials obtained from the pito waste (both charred and uncharred) have not been chemically analysed to ascertain the amount of SiO_2 in the char left behind after charring. Investigation is still ongoing in this respect.

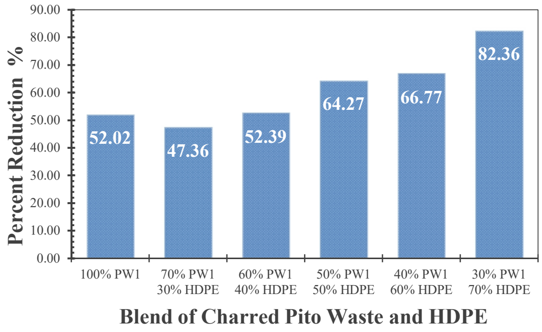

Fig. 10 Graph of Percent Reduction against Blends of Charred Pito Waste and HDPE

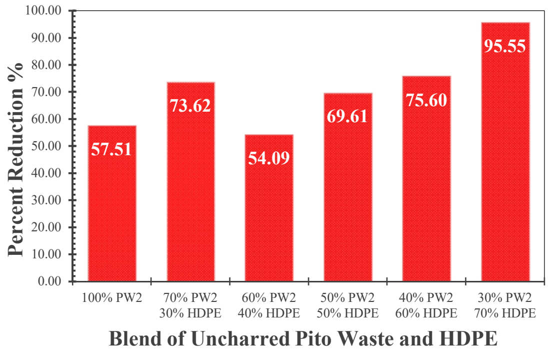

Fig. 11 Graph of Percent Reduction against Blends of Uncharred Pito Waste and HDPE

4 Conclusions

The reduction of the Pudo iron ore has been investigated using carbonaceous material prepared from Pito waste and its blends with HDPE. This resulted to the production of highly carburized iron nuggets which could serve as a potential source of raw material for any steel making industry in Ghana. Major findings of the investigation are:

(i) Pito waste and its blends with waste HDPE proof to be a potential source of carbonaceous material for iron oxide reduction

(ii) The Pudo iron ore can be successfully reduced using carbonaceous materials generated from Pito waste and its blends with waste HDPE

(iii) Extent of reduction increased with an increase in the content of HDPE blended with the Pito waste.

(iv) Blends containing uncharred pito waste generally performed better than those containing charred Pito waste due to the conversion of inherent cellulose in the uncharred Pito waste to carbon monoxide, serving as an additional and efficient reducing agent.

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