Beneficiation of Iron Oxides from Cupola Furnace Slags for Arsenic Removal from Mine Tailings Decant Water*

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Abstract

Large volumes of ferrous metallurgical slags (FMS) are generated annually as waste materials from metal extraction, purification, casting and alloying processes worldwide. Some attempts have been made to use bulk FMS in metal precipitation and concrete works but little success has been achieved because of unstable precipitates and volume expansion of concrete structures. As a result, significant quantities of FMS are still disposed in landfills. This disposal leads to land conflicts and poor environmental practices. The present study focuses on the characterization and separation of iron oxide from selected bulk FMS (Cupola Furnace Slag - CFS) obtained from Ghana into constituent components for use as engineering materials. Quantitative X-ray diffractometry was used to determine the mineralogy of CFS. Iron oxide morphology and spot composition in the CFS were determined using scanning electron microscopy, combined with energy dispersive spectroscopy. The inductively coupled plasma-optical emission spectrometry was used to ascertain the chemical composition of CFS after acid digestion. Wet low intensity magnetic separation technique was employed for beneficiating iron oxides from the CFS. It is shown that the CFS is amorphous and consist of ferrous and non-ferrous material. Results of the investigation confirmed that ferrous materials in the slags can be separated using magnetic separation technique. The study further confirmed that fine grinding (- 75 µm) liberates the magnetic portions of the slag efficiently, and as such, they can be recovered using a low magnetic field. The recovery was 99.04 % and the concentrates obtained from the beneficiation process consist primarily of pigeonite, quartz, magnetite and jacobsite. The beneficiated concentrates have the capacity to adsorb arsenic from mine effluent. This study has demonstrated that, slags can be utilized as secondary resources rather than a waste.

Keywords: Ferrous Metallurgical Slags, Cupola Furnace Slag, Characterisation, Magnetic Separation, Arsenic

1 Introduction

Ferrous metallurgical slags (FMS) are waste products generated in large quantities from pyrometallurgical processes in metal extraction, purification, casting and alloying. They are named from the process of which they are generated: blast furnace (BF) slag, basic oxygen furnace (BOF) slag, electric arc furnace (EAF) slag and ladle furnace (LF) slag (Proctor *et al.*, 2000; Andrews *et al.*, 2012). Rapid growth in industrialization around the globe has resulted in vast land-take for disposal of ferrous metallurgical slags thereby resulting in land-use conflicts, increasing disposal cost and poor environmental practices (Altun and Yılmaz, 2002).
A global quantity of more than 400 million tonnes of iron and steel slags are generated annually (Herbelin *et al.*, 2020). In Ghana the annual slag production stood at 50,000 tonnes in 2012 (Andrews *et al.*, 2012) and this value keeps rising. Most of these slags are currently disposed in un-engineered landfills which require large land-take. Therefore, it is important to develop a sustainable system that can convert all the waste materials into useful products (Reuter *et al.*, 2004). In addition, land-filling with waste has generally been observed to be a potential source of pollution in the geo-environment (Osipov et al. 1990; Reuter et al. 2004; Ghosh et al. 2002). Because of these difficulties, converting metallurgical slags into useful products is a necessary option for ensuring optimal use of natural resources.

Metallurgical slags primarily comprise; CaO, SiO_2, Al_2O_3, MgO, Fe_3O_4, FeO and MnO (Proctor *et al.*, 2000; Semykina, 2010). Over the past decades, metallurgical slags have been utilised for road construction, cement additive, land fill cover material, fertilizers/soil conditioners, neutralization of acidic mine drainage and industrial discharge and for heavy metal adsorption from waste water (Fidancevska et al. 2009; Skuza et al. 2009; Navarro et al. 2010; Sarkar et al. 2010; Chowdhury, et al. 2014). However, some of these applications do not ensure stable constituents/products in the environment. For instance, the use of metallurgical slags containing free CaO and MgO in road construction results in road expansion (about 10 vol %) in humic areas (Andrews *et al.*, 2012). Also, utilisation of metallurgical slags for production of cement is limited due to high FeO content which causes stress in concrete structures as a result of the oxidation of the iron (Semykina, 2010). In addition, the use of metallurgical slags for arsenic remediation (Chowdhury, et al. 2014; Wilkens et al. 2003) results in formation of calcium arsenate which is chemically unstable (Swash and Monhemius, 1996; Mahuli *et al.*, 1997) and can leach into the geo-environment. Thus, bulk metallurgical slag will be unsuitable for such applications; certain unstable components must be removed to enhance the slag's usage. To address these limitations of bulk slag use, separation of the bulk slag into constituent components will ensure acceptable use of the slags.

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Consequently, in this research, magnetic separation was employed to recover the iron oxide portions of the slag. This process exploits the difference in magnetic properties between the ore mineral and gangue to effect separation. The magnetism phenomenon is such that the field around a magnet exerts a force on minerals surrounding it. This field is referred to as the magnetic field and it attracts minerals that are strongly magnetic. The force exerted by the magnet is directly related to the particles mass, m (kg) by equation 1(Dworzanowski, 2010).

$$F \propto \chi m^3 \tag{1}$$

χ (m^3kg^{-1}) is a property of the particle and it known as magnetic susceptibility.

The use of waste minerals, such as, ferrous metallurgical slags for removing other waste, (Wilkens *et al.* 2003; Metz and Benson 2007; Chowdhury *et al.* 2014) is an emerging trend that can help minimise the environmental footprints of most industrial operations and contribute significantly to sustainable development.

Due to the toxic nature and detrimental effects of arsenic on human health and plant growth, the maximum contaminant level (MCL) of arsenic in drinking water is 10 ppb (W.H.O, 2004; Pandey *et al.*, 2009).

Many different types of adsorbents have been exploited in the removal of contaminants from heavy metals. Materials such as carbon (Shooto *et al.*, 2016), metal oxides (Bhaumik *et al.*, 2014; Dave and Chopda, 2014; Malik *et al.*, 2018) and bio-adsorbent (Pandey *et al.*, 2009) to mention a few have been exploited in this field. Amongst these iron oxides is one of the most preferred due to its magnetic property which enables easy separation of adsorbents from the system and hence could be reused for further application (Dave and Chopda, 2014).

Hence, in this work beneficiated iron oxide from cupola furnace was used as an adsorbent for arsenic removal. Ferrous content of different particles sizes was beneficiated prior to being used as an adsorbent.

2 Resources and Methods Used

2.1 Materials

In this research, Cupola furnace slag samples were obtained from Abudia Foundary, Kumasi, Ghana. Slags were used as received.

2.1.1 Sample Preparation

The Cupola Furnace Slag sample was firstly crushed with a jaw crusher (JAQUES laboratory jaw crusher), homogenized and then sieved to obtain a – 2.5 cm particle size range. This was then followed by pulverization. The pulverization was conducted for 5 min using ~ 13000 g solid loading (1000 g FMS and 12 000 g pulveriser disc; LM2-ESSA, Australia). A fine particle size range of 80 % passing 75 µm was obtained. As a precaution to prevent contamination, stainless steel coated pulverising discs were used in this study.

2.2 Methods

2.2.1 Characterisation of FMS

Particle Size Analysis

The particle size analysis of the sample was determined by laser diffraction; Mastersizer 2000 (Malvern Instruments Ltd., U.K.). In this work, all particle size distribution measurements were conducted in de-ionised water and at room temperature. An ultra-sonication of approximately 2 minutes was adhered to in order to ensure good dispersion of particles.

Quantitative X-ray Diffraction (QXRD)

Bulk mineralogy of samples was determined by using quantitative x-ray diffractometry (QXRD; Phillips PW 1050 X-ray generator equipped with Sietronic automated data collection). XRD analysis was performed using the Scintag ARL X’tra diffractometer and CuKα radiation. The data were collected between 5° and 90° 2θ at 0.02° intervals, with an integration time of 1 second per interval. The quantitative (Rietveld) analysis was performed using SIROQUANT V3 software. Prior to taking measurements, the samples were spiked with about 10 wt% of ZnO to allow for calculation of amorphous content of the sample. The sample was then placed into a sample cup insuring that it was well packed, flat and levelled at the top of the cup for analysis.

Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM; FEI Quanta 450 FEG) was used in determining the morphology of samples. Samples for the analysis were prepared by gently pressing unto a double-sided carbon tape placed on a metal stab. Samples were then coated with thin carbon films in a vacuum evaporator, in order to prevent electron build up on the sample surface during analysis. The instrument operates at an accelerating voltage of up to 30 kV.

Acid Digestion

To ascertain the chemical composition of samples used in this work, a known mass of the sample (3 g of - 75 µm) was digested and refluxed with a mixture of acids including hydrofluoric, nitric, perchloric and hydrochloric acid. Selected elements in supernatant solutions were then analysed using inductively coupled plasma optical emission spectrometry (ICP-OES; Perkin Elmer 5300 DV). Loss on ignition (LOI) of the slag samples was determined using the ISO 11536 (2015) procedure.

Magnetic separation

Magnetic separation was conducted in the laboratory with a hand-held magnet obtained from dysfunctional loudspeakers. A hand-held digital TeslaMeter (TD8620) and G-858 MagMapper Magnetometer were used to determine the magnetic strength of the hand-held magnets. Fig. 1 is a schematic diagram of the setup for the magnetic separation process used in this work. The experiment was conducted as follows; 40 g of the various particle sizes (500µm, 425µm, 300µm, 260µm, 150µm and - 75 µm) of the cupola sample was slurried to achieve 10 % solid loading. The hand-held magnet was then used to separate the magnetic fraction in an anti-clockwise panning manner (a gravity concentration method as employed by small scale gold industries in Ghana) by flushing de-ionised water (500 ml) continually on the magnetic material to remove available gangue materials. The panning process was repeated severally to obtain a much cleaner concentrate. Concentrates and tailings from the entire process were then oven dried at 60 °C for metal assay analysis. This was done for both cupola and induction furnace. Results of recoveries were then computed using Equations 2:

$$R = \frac{Cc}{Ff} \times 100\% \qquad (2)$$

where:
R is the % Recovery
C is the weight of concentrate
c is the assay of concentrate
F is the weight of feed
f is the assay of feed

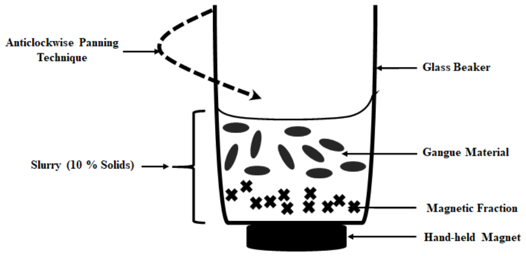

Fig. 1 Schematic Diagram of Set-up for Magnetic Separation Process

Arsenic Adsorption Using Concentrates Beneficiated from FMS

For batch adsorption studies, about 20 mL of laboratory prepared arsenic (5 mg/L) solution at pH 2 and 9 were contacted with the concentrates. The amount of adsorbent used in the experiment was 50 g/L. For mine tailings decant water, experiments were conducted with 25 g/L and 50 g/L adsorbent at a pH of 8.31.

A bench top suspension mixer (Rowe Scientific Pty Ltd; Model: Ratek) was then used to provide a gentle end-over-end tumbling at 180 rpm to enhance the adsorption process for 6 h. The initial pH of the adsorption process was conditioned to 2 and 9 by adding few drops of 1 M HNO_3 or 0.5 M KOH respectively. The experiment was conducted at room temperature (23 ± 1 °C). Measurement of pH was performed using a 211 microprocessor bench pH meter (Hanna instruments).

3 Results and Discussion

3.1 Characterisation of FMS

3.1.1 Physical Characteristics of Slags

Image of cupola furnace slags used in this study is presented in Fig. 2. It can be seen that the colour appears to be black to blue-black. This observation is consistent with work done by (Andrews *et al.*, (2012). The PSD curves of the slags are presented in Fig. 3. The D_{50}, which represents the average particle size of the slags after comminution was found to be 38.24 µm. In choosing an efficient magnetic separator, the influence of particle size cannot be over emphasized (Zong, et al., 2018). Dry High Intensity Magnetic Separators (HIMS) for instance, are limited to ores with particle sizes ≥ 75 µm (Wills and Napier-munn, 2006), hence wet separation was adopted in this work.

Fig. 2 Image of the Cupola Furnace Slag

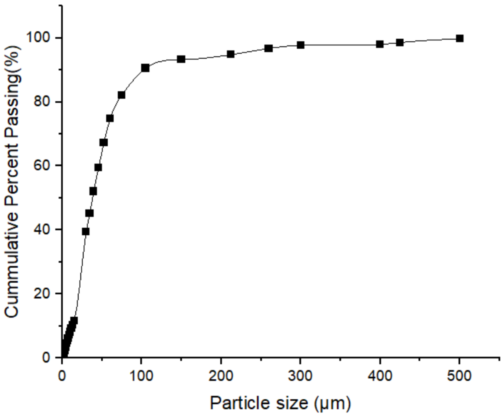

Fig 3 Particle Size Distribution (PSD) Curves of Cupola Furnace Slags

3.1.2 Chemical and Mineralogical Characteristics of Slags

The results of the partial chemical analyses, spot chemical composition and mineralogical composition of the slags are presented in Table 1, Figure 4 and Figure 5 respectively. From the results, it can be observed that the slags consist of ferrous and non-ferrous compounds. The samples contain enough proportion of iron, therefore can be physically separated using magnetic separation.

The slag contains Fe and Si as a major constituent; 19.2 wt% and 22.2 wt% respectively. Constituents such as Al, Ca and Mn were in minor amounts for the slag while Mg, P, Ti and S were in trace amounts. The loss on ignition (LOI) for the slags was negative. This suggests that there was a gain of weight on heating for the two slags rather than LOI, indicating that they contain compounds that can oxidise. For instance, magnetite in these slags can oxidise to maghemite.

Table 1 Partial Chemical Composition of Slag

Element	Composition (wt%)
Al	6.10
Ca	5.07
Fe	19.2
Mg	0 .335
Mn	1.25
Na	4.88
P	0.075
Si	22.2
Ti	0.245
S	0.10
LOI	-3.03

Results of SEM-EDX analysis of the slags are presented in Figs. 4. These results confirmed the presence of iron oxides in the slags. Iron oxide grains examined in the cupola furnace slag was found to be highly crystalline. Spot composition analysis revealed iron and oxygen compositions of ~36.26 and ~30.22 atomic wt.% respectively. Other elements identified in the slag were sodium, calcium, silicon and aluminum.

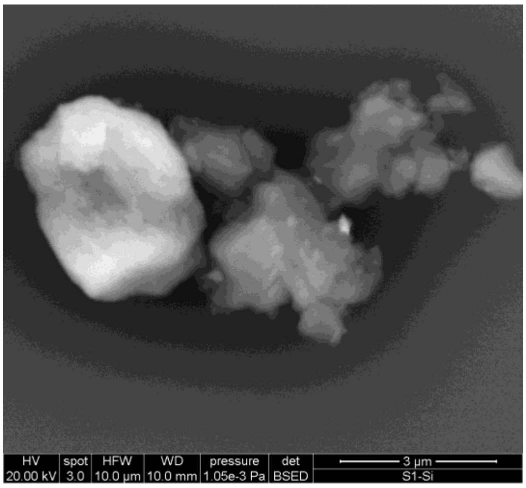

Fig 4 (a) SEM Backscattered Electron Micrograph of CFS showing Iron Oxide Grain surrounded by Gangue Material

The XRD results for the slags are shown in Figure 5. The slag was found to be amorphous in nature. The slag had an amorphous content of 71 wt. %. The results revealed the presence of major phases like Quartz (SiO_2), ilmenite ($FeTiO_3$), Hedenbergite ($Ca(Mg,Fe)[Si_2O_6]$), Fayalite(Fe_2SiO_4), Aluminium silicate(Al_2SiO_3), and magnetite (Fe_3O_4). Other identified phases include Hematite (Fe_2O_3), Calcium silicate (Ca_2SiO_4), Mayenite ($Ca_{12}Al_{14}O_{33}$) and Merwinite [$Ca_3Mg(SiO_4)_2$]. Table 2 shows the phases and composition of the major phase identified. These phases compare well with results achieved by (Tsakiridis *et al.*, 2008; Andrews *et al.*, 2012; Lan *et al.*, 2017). The rate at which a metallurgical slag is cooled has a significant influence on the crystalline and amorphous phases created. The slower the cooling rate, the larger the crystalline phases (Rao, and Nayak 1992). As the amorphous phase is high for both slags, it can be inferred that the slags were rapidly cooled. The ferrous phases present, such as magnetite and Ilmenite have relatively high magnetic susceptibility values of 20 000–110 000 and 46–80 000 × 10^{-8} m^3/kg (De Kimpe *et al.*, 2001) respectively making magnetic separation an appropriate method of beneficiation.

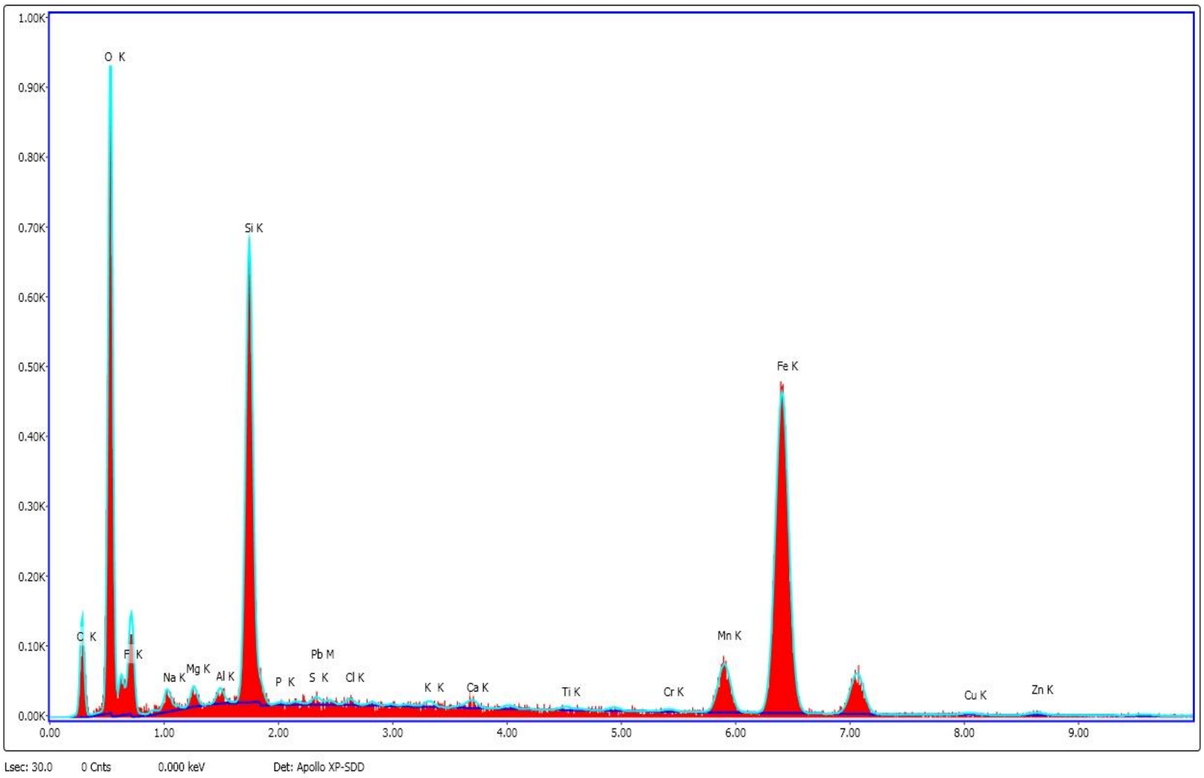

Fig 4 (b) EDX Spectra Showing the Composition of the Grain

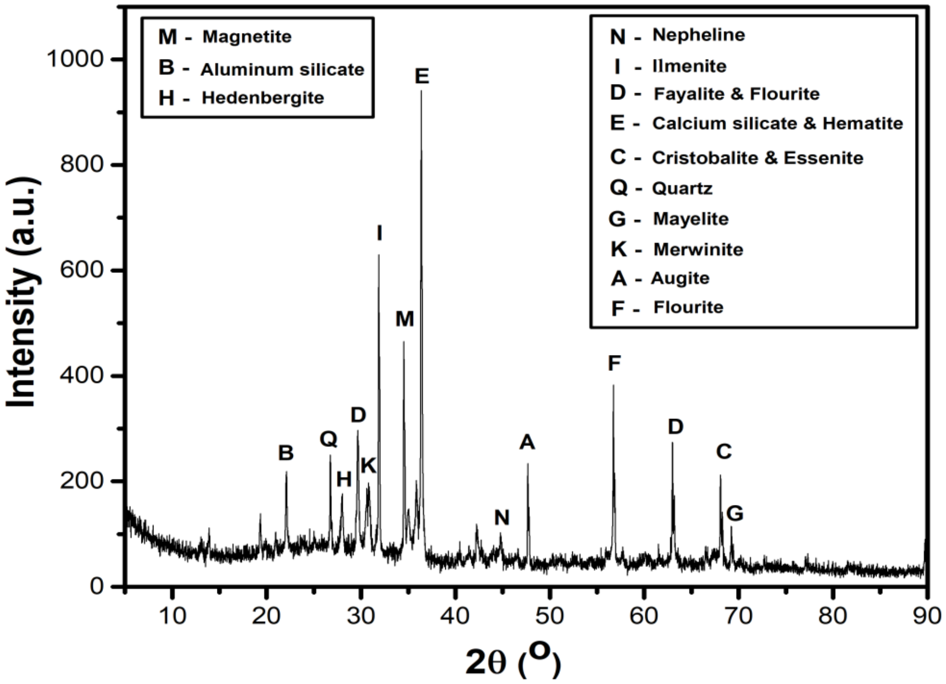

Fig. 5 X-ray Diffractogram of Cupola Furnace Slag

Table 2. Mineralogical Composition of Cupola Furnace Slag

Ferrous Component	**Composition (wt%)**	**Non-ferrous Component**	**Composition (wt%)**
Hedenbergite ($Ca(Mg,Fe)[Si_2O_6]$)	3	Quartz (SiO_2)	4
Augite ($(Ca,Mg,Fe,Al)_2(Si,Al)_2O_6$	5	Cristobalite (SiO_2)	4
Fayalite (Fe_2SiO_4)	5	Nepheline ($Na_3(Na,K)[Al4Si_4O_{16}]$)	5
Magnetite (Fe_3O_4)	<1	Fluorite (CaF_2)	2
Ilmenite ($FeTiO_3$)	<1	Aluminium silicate (Al_2SiO_3)	2
Amorphous Content	69		
Total	~ 100		

3.2 Magnetic Separation

Results from the magnetic separation using a 59.12 ± 0.05 mT magnet is presented in Table 3. From the table, it is observed that for coarser particle sizes, less iron content is recovered. This is due to interferences from gangue materials surrounding the magnetic particles making it less exposed to the magnetic field to be attracted. Finer particle sizes recover more metals of interest due to less interference of the non-magnetic phases and therefore the metal of interest is easily attracted during the magnetic separation (Yu, 2018).

From equation 1, when a constant mass is employed, coarse particles will exhibit a lower net susceptibility due to the presence of minerals with less susceptibility value surrounding the magnetic portions, this leads to low attraction of magnetic portions towards the surface of the magnet. Finer particles however have more magnetic phases liberated, hence high attraction of magnetic portions towards the surface of the magnet and consequently higher recovery values as observed for -75 µm (99.04 %) as compared to – 500 +425 (71.46%). Studies by Herbelin *et al*. (2020) confirms lower susceptibility of slags when magnetic portions are not liberated from non- magnetic portions.

Table 3 Recovery of Iron Oxide at different Particle size range

Particle size (µm)	Percentage recovery (%)
– 500 +425	71.46
– 425 +300	72. 21
– 300 + 260	74.73
– 260 +150	76.16
– 150+75	77.25
– 75	99.04

XRD of Iron Oxide Concentrate

XRD result of beneficiated concentrates is shown in Figure 6. The concentrates consisted predominantly of pigeonite, quartz, magnetite and jacobsite. Additionally, it was noticed that not all iron oxide minerals reported in the concentrates have been fully liberated these are like to be from the coarser particles. The pigeonite and jacobsite were not found in the XRD analysis of the bulk slag. It was however identified in the XRD analysis of the concentrates. This is because, in the bulk slag, their concentrations were low and below detectable limits while in the concentrate they had been upgraded, hence identified. The presence of jacobsite in the concentrate is also as a result of its high magnetic susceptibility. At a density of 4990 kg/m^3, jacobsite can achieve higher susceptibility values of 270×10^{-6} m^3/kg (Herbelin *et al.*, 2020).

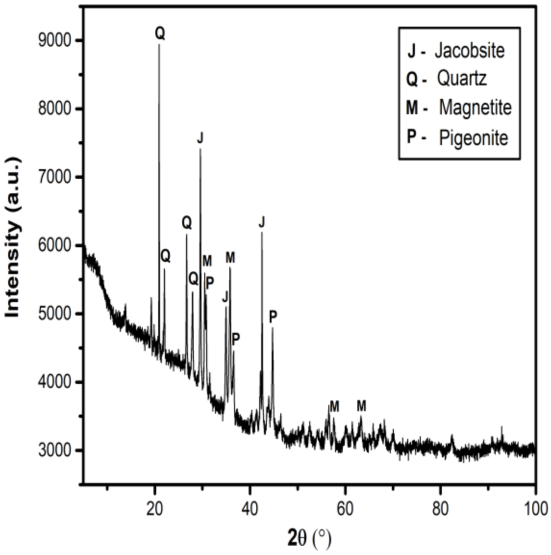

Fig. 6 XRD of Iron Oxide Concentrate

3.3 Arsenic Adsorption Using Iron Concentrates from FMS

3.3.1 Removal of Arsenic from Prepared Arsenic solution Water using Beneficiated Concentrates from FMS

To be able to demonstrate and ascertain the applicability of the ferrous constituent component beneficiated from FMS, the concentrates were applied on arsenic removal from water at initial pH 2 and 9. Results from the experiment are presented in Fig. 7.

The results show that the uptake was in two phases. At initial pH 2, there was a rapid arsenic uptake within the first 15 minutes of the study. The reaction then slowed down and equilibrated after 2 h. Arsenic removal of 99.99 % was achieved. A similar trend was observed for arsenic removal at initial pH 9. Within the first 15 minutes of the adsorption process, arsenic removal of 99.97 % was achieved by the concentrates. The uptake then gradually increased until equilibrium was reached after 4 h. The observed trends may be attributed to the synergistic effects of different iron oxide minerals present in the concentrates. From the XRD results of the concentrates (Fig 6), it is shown that these concentrates primarily consist of magnetite, jacobsite and pigeonite which are different forms of iron oxides. Therefore, during adsorption, each of these iron oxide phases in the concentrates will present individual surface functional groups ($FeOH^{2+}$, FeOH and FeO^-; depending on the pH) (Koomson and Asiam, 2020) to interact with arsenic in solution to complete the adsorption process thereby yielding such results. Also As in solution is usually in the form of $H_2ASO_4^-$, in the acidic region (pH =2) the presence of more positive surface charges on the adsorbent increases the affinity for arsenic. At the basic pH, the surface becomes negatively charged reducing the As adsorption due to the repulsive effect.

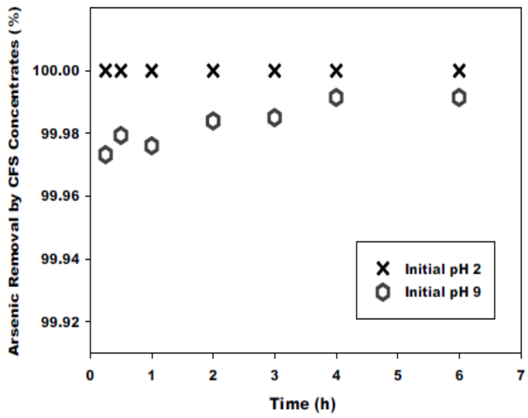

Fig. 7 Arsenic Removal by CFS Concentrates as a Function of Time

3.3.2 Removal of Arsenic from Tailings Decant Water using Beneficiated Concentrates from FMS

Having understood the underlying principles governing arsenic in a solution, mine tailings decant water was contacted with the beneficiated concentrates from FMS. Results of the physical properties and elemental composition of the tailings decant water used in this study are presented in Table 4.

Table 4 Physical Properties (A) and Chemical Composition (B) of Tailings Decant Water

A. Physical Properties	
Parameter	**Value**
pH	8.31
Temperature (°C)	33.09
Dissolved Oxygen (mg/L)	7.03
Total Dissolved Solids (g/L)	1.65
Electrical Conductivity (mS/cm)	2.58
Turbidity (NTU)	617
Colour	Light Brown
B. Chemical Composition	
Element	**Concentration (mg/L)**
As	2.13
Fe	5.66
Cu	0.41
Pb	0.02
Zn	0.02
Ca	20.30
Si	7.85
Cr	0.43
Cd	0.03
Co	0.86

The pH of the decant water was 8.31 indicating that the solution is basic. This is in agreement with report by (Acheampong *et al.*, 2013) and (Acheampong and Nukpezah, 2016) on a typical gold mine tailings decant water from Ghana. The temperature recorded at the time of sampling was 33.09 °C. The dissolved oxygen concentration was also determined as 7.03 mg/L suggesting oxidation of ions can occur: As (III) can be oxidized to As(V). Furthermore, the total dissolved solids (TDS) and electrical conductivity (EC) of the tailings decant water were 1.65 g/L and 2.58 mS/cm. Work done by Shinoda *et al.*(2016) indicates that, the EC is dependent on the quantity of dissolved salts in solution and that it is approximately proportional to the TDS. Therefore, the relatively high EC and TDS content is due to the abundant presence of free ions such as Fe$^{3+,}$ As^{5+}and Ca^{2+} etc., in the decant water.

The results of the chemical composition of the tailings decant water show that the major elements present are calcium, iron, silicon and arsenic. Copper, lead and zinc exist as minor elements. These minor elements can form complex with cyanide. During intensive cyanidation/leaching, calcium oxide/lime is added as a pH modifier, hence its high concentration in the tailings decant water.
The results of the application of the beneficiated FMS concentrates (CFS Concentrates) on arsenic removal from the tailings decant water is presented in Fig. 8.

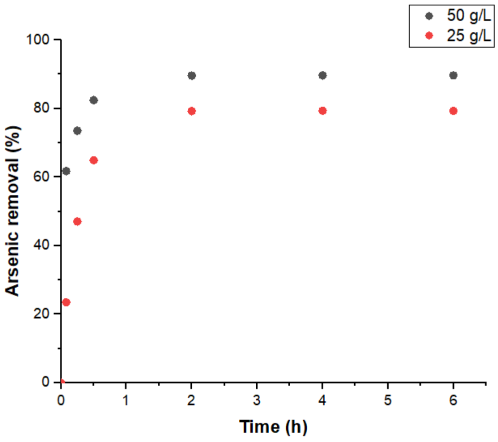

Fig. 8 Arsenic Removal by CFS Concentrates from Tailings Decant Water as a Function of Time

The results indicate that the beneficiated concentrates readily adsorb arsenic from the decant water. At an adsorbent dosage of 25 g/L, there was a gradual arsenic uptake from 5 minutes up to 2 h where the reaction equilibrated. At 5 minutes, 24% of arsenic was removed while a maximum of 79% arsenic removal was achieved in 2 h. A similar trend was observed when the adsorbent dosage was increased to 50 g/L. An arsenic uptake of 62% was obtained within 5 minutes of contact. At 2 h, the reaction equilibrated with a maximum removal of 90%. Comparing the adsorption capacity here with that of the synthesized solutions (Figs. 8 and 7), it is observed that a higher removal was achieved in the latter. This observation can be attributed to the presence of other ions in the tailings decant water competing for adsorption sites on the surface of the beneficiated FMS concentrate during adsorption. As a result, high amount (> 50 g/L) of the beneficiated concentrates will be required for complete removal of arsenic from the tailings.

Adsorption Isotherm

Result of the adsorption experiment was fitted with the Langmuir isotherm model as shown in Figure 9. This was because Arsenic adsorption has been shown to follow Langmuirian model (Koomson and Asiam, 2013; Hao *et al.*, 2018; Bahmani *et al.*, 2019). The results obtained in this work described the isotherm model well. This could be attributed to the fact that the Langmuir model indicates a reversible phenomenon coupled with a monolayer coverage for the reaction (Wibowo et al. 2017). The maximum adsorption capacity (qmax) which corresponds to the surface concentration of adsorbent at monolayer coverage (Jeong, 2005) was determined to be 0.04 mg/g. Furthermore, according to Jeong (2005) the Langmuir constant b is related to the energy of adsorption and tends to increase with increasing adsorption bond strength. Therefore, high "b" value (Tables 5) obtained for arsenic removal using the beneficiated concentrates indicates high adsorption bond strength.

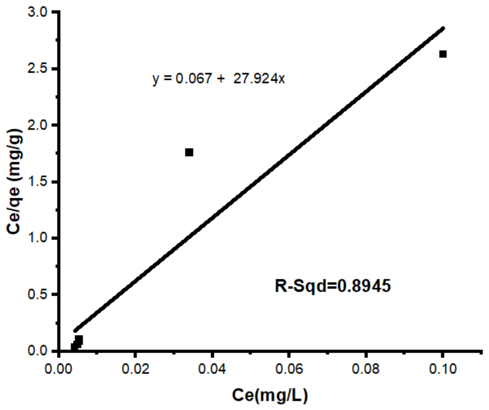

Fig. 9 Langmuir Model for As Adsorption onto CFS Concentrates

Feasibility studies for the Langmuir adsorption process for the experimental analysis was also carried out using the dimensionless constant separation factor "r" (Mckay *et al.*, 1985; Altundoğan *et al.*, 2000) defined in Equation 3:

$$r = 1/(1+bCo) \tag{3}$$

where:

r is the dimensionless separation factor
Co is the initial As concentration (mg/L)
b is the Langmuir constant
The "r" values were calculated using the Langmuir constant "b" obtained from the experimental data for the concentrates for arsenic removal and shown in Tables 4. Initial As concentrations of 1 mg/L and 5 mg/L yielded "r" values of 0.002 and 0.00038

respectively for the that arsenic adsorption from solution by the concentrates is favourable at all concentrations studied.

Gibbs free energy for the adsorption process was also calculated using Equation 4.

$$\ln (1/b) = \Delta G/RT \qquad (4)$$

where:
b is the Langmuir constant (L/mg)
R is the Ideal gas constant (8.314 J/K mol)
T is the temperature in K

Gibbs free energy value of -15.20 kJ/mol was obtained for the Langmuir fit. This indicates that the adsorption of arsenic from solution onto the adsorbent was spontaneous and that the adsorption reaction involving the beneficiated ferrous materials is thermodynamically stable.

Table 5 Summary of Calculated Langmuir Isotherm Constants and other Related Parameters for Arsenic Removal by CFS Concentrates

Langmuir Isotherm Parameter	CFS Value
b (L/mg)	480.77
qmax (mg/g)	0.04
R^2	0.8945
r min	0.002
r max	0.00038
ΔG (KJ/mol)	-15.2

4 Conclusions and Recommendation

The mineralogical analysis confirmed that the slags used in this study are typical CFS. The mineralogical analysis further indicates that the slags consist of ferrous and non-ferrous materials. The ferrous phases of the slag are augite, hedenbergite, fayalite magnetite and ilmenite while the non-ferrous materials are quartz, crystoballite, nepheline, and fluorite.

Also, the study concludes that fine grinding will be required for effective magnetic separation. Furthermore, fine grinding (- 75 µm) liberates the magnetic portions of the slag efficiently, and as such, they can be recovered using a low magnetic field. The ferrous phases recovered in the concentrate are magnetite, jacobsite and pigeonite. The beneficiated ferrous constituents from the slag have the capacity to adsorb arsenic, within 15 minutes up to 99.99% and 99.97 % of arsenic can be adsorbed at pH of 2 and 9 respectively. The adsorption also follows a Langmuirian Model.

The metallurgical slags which are considered as a waste today are potential resources. In this work, it is demonstrated that the slags can be separated and beneficiated using a low intensity magnetic separator if ground fine.

Future research should quantify the amount of the iron oxide phases present in the concentrate and their respective contribution to the adsorption process.

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References

Acheampong, E. A., and Nukpezah, D. (2016), “Assessing the impact of an operating Tailings Storage Facility on Catchment Surface and Groundwater quality in the Ellembele District of the Western region of Ghana”, *Environ Pollut*, Vol.5, No. 2, pp.26-40.

Acheampong, M. A., Adiyiah, J., and Ansa, E. D. O. (2013), “Physico-chemical characteristics of a Gold Mining Tailings Dam Wastewater”, *Journal of Environmental Science and Engineering.* Vol. 2, No. 8A, pp.469.

Altun, I. A., and Yılmaz, İ. (2002), “Study on Steel Furnace Slags with high MgO as Additive in Portland Cement”, *Cement and Concrete Research*, Vol. 32, No. 8, pp.1247-1249.

Altundoğan, H. S., Altundoğan, S., Tümen, F., and Bildik, M. (2000), “Arsenic removal from Aqueous Solutions by Adsorption on Red Mud”, *Waste Management*, Vol. 20, No. 8, pp. 761-767

Andrews, A., Gikunoo, E., Ofosu-Mensah, L., Tofah, H., and Bansah, S. (2012), “Chemical and Mineralogical Characterization of Ghanaian Foundry Slags”, *Journal of Minerals and Materials characterization and Engineering*, Vol. 11, No. 2, pp. 183-192.

Bahmani, P., Maleki, A., Daraei, H., Rezaee, R., Khamforoush, M., Dehestani Athar, and McKay, G. (2019), “Application of Modified Electrospun Nanofiber Membranes with A-Fe2O3 Nanoparticles in Arsenate Removal from Aqueous Media”, *Environmental Science and Pollution Research*, Vol. 26, No. 21, pp. 21993-22009.

Bhaumik, M., Choi, H. J., McCrindle, R. I., and Maity, A. (2014), “Composite Nanofibers Prepared from Metallic Iron Nanoparticles and Polyaniline: High Performance for Water treatment applications", *Journal of colloid and interface science*, 425 pp. 75-82.

Chowdhury, S. R., Yanful, E. K., and Pratt, A. R. (2014), "Recycling of Nickel Smelter Slag for Arsenic Remediation—An Experimental Study", *Environmental Science and Pollution Research*, Vol. 21, No. 17, pp.10096-10107.

Dave, P. N., and Chopda, L. V. (2014), "Application of Iron Oxide Nanomaterials for the Removal of Heavy Metals", *Journal of Nanotechnology*, 2014, pp. 1-14

De Kimpe, C. R., Dejou, J., and Chevalier, Y. (2001), "Magnetic Susceptibility of a Saprolite and a Soil Profile Developed On Pyroxenite at Mont-Saint-Bruno, Quebec, Canada", *Canadian Journal of Soil Science*, Vol. 81, No. 2, pp. 185-192.

Dworzanowski, M. (2010), "Optimizing the Performance of Wet Drum Magnetic Separators", *Journal of the Southern African Institute of Mining and Metallurgy*, Vol. 110, No. 11, pp. 643-653.

Fidancevska, E., Vassilev, V., Hristova-Vasileva, T., and Milosevski, M. (2009), "On a Possibility for Application of Industrial Wastes of Metallurgical Slag and TV-Glass", *Journal of the University of Chemical Technology and Metallurgy*, Vol. 44, No. 2, pp. 189-196.

Ghosh, S., Das, M., Chakrabarti, S., and Ghatak, S. (2002), "Development of Ceramic Tiles from Common Clay and Blast Furnace Slag", *Ceramics International*, Vol. 28, No. 4, pp. 393-400.

Hao, L., Liu, M., Wang, N., and Li, G. (2018), "A Critical Review on Arsenic Removal from Water Using Iron-Based Adsorbents", *RSC advances*, Vol. 8, No. 69, pp. 39545-39560.

Herbelin, M., Bascou, J., Lavastre, V., Guillaume, D., Benbakkar, M., Peuble, S., and Baron, J. P. (2020), "Steel Slag Characterisation—Benefit of Coupling Chemical, Mineralogical and Magnetic Techniques", *Minerals*, Vol. 10, No. 8, pp. 705.

Jeong, Y., (2005), "The Adsorption of Arsenic (V) By Iron (Fe2O3) And Aluminum (Al2O3) Oxides", *PhD Thesis*, IOWA State University, 123 pp.

Koomson, B., and Asiam, E. K. (2020), "Arsenic Adsorption by Some Iron Oxide Minerals: Influence of Interfacial Chemistry", *Ghana Mining Journal*, Vol. 20, No. 2, pp. 43-48.

Koomson, B. and Asiam, E.K., (2013), "Studies on Arsenic Release and its Mitigation from Tailings Dam Using Nanomagnetite Particles", Ghana Mining Journal, 14, pp.66-69.

Lan, Y. P., Liu, Q. C., Meng, F., Niu, D. L., and Zhao, H. (2017), "Optimization of Magnetic Separation Process for Iron Recovery from Steel Slag", *Journal of Iron and Steel Research International*, Vol. 24, No. 2, pp. 165-170

Mahuli, S., Agnihotri, R., Chauk, S., Ghosh-Dastidar, A., and Fan, L. S. (1997), "Mechanism of Arsenic Sorption by Hydrated Lime", *Environmental Science and Technology*, Vol. 31, No. 11, pp. 3226-3231

Malik, H., Qureshi, U. A., Muqeet, M., Mahar, R. B., Ahmed, F., and Khatri, Z. (2018), "Removal of Lead from Aqueous Solution Using Polyacrylonitrile/Magnetitenanofibers", *Environmental Science and Pollution Research*, Vol. 25, No. 4, pp. 3557-3564

Mckay, G., Bino, M. J., and Altamemi, A. R. (1985), "The Adsorption of Various Pollutants from Aqueous Solutions On to Activated Carbon", *Water Research*, Vol. 19, No. 4, pp. 491-495

Metz, S. E., and Benson, C. H. (2007), "Iron Foundry Slags as Permeable Reactive Barrier Materials for Removing Arsenic from Groundwater." *Geoenvironmental Engineering*, pp.1-11.

Navarro, C., Díaz, M., and Villa-García, M. A. (2010), "Physico-Chemical Characterization of Steel Slag. Study of Its Behavior Under Simulated Environmental Conditions", *Environmental science* and *technology*, Vol. 44, No. 14, pp. 5383-5388.

Osipov, V. A., Timofeeva, Z. G., Kurbatskii, M. N., Mironova, P. V., and Ocheretnyuk, F. F. (1990). "Blast Furnace Granulated Slag in The Production of Building Ceramics", *Glass and Ceramics, Vol. 47, No. 6,* pp. 228-230

Pandey, P. K., Choubey, S., Verma, Y., Pandey, M., and Chandrashekhar, K. (2009), "Biosorptive Removal of Arsenic from Drinking Water", *Bioresource technology,* Vol.100, No. 2, pp. 634-637.

Proctor, D. M., Fehling, K. A., Shay, E. C., Wittenborn, J. L., Green, J. J., Avent, C., and Zak, M. A. (2000), "Physical and Chemical Characteristics of Blast Furnace, Basic Oxygen Furnace, And Electric Arc Furnace Steel Industry Slags", *Environmental science* and *technology*, Vol. 34, No. 8, pp. 1576-1582

Rao, G. V., and Nayak, B. D. (1992), "Flotation of Copper from Converter Slags", *Journal of mines, metals and fuels*, Vol. 40, No. 3-4, pp. 131-134

Reuter, M., Xiao, Y., and Boin, U. (2004), "Recycling and Environmental Issues of Metallurgical Slags and Salt Fluxes", In *VII International conference on molten slags fluxes and salts, The South African Institute of Mining and Metallurgy*, Vol. 2004, pp. 349-356.

Sarkar, R., Singh, N., and Das Kumar, S. (2010), "Utilization of Steel Melting Electric Arc Furnace Slag for Development of Vitreous Ceramic Tiles", *Bulletin of Materials Science*, Vol. 33, No. 3, pp. 293-298.

Semykina, A., (2010), "Recovery of Iron and Manganese Values from Metallurgical Slags by the Oxidation Route", *Thesis,* Division of Materials Process Science Department of Materials Science and Engineering, Royal Institute of Technology SE-10044 Stockholm, Sweden, 76 pp.

Shinoda, K., Nakagawa, T., and Tamamushi, B. I. (2016), "Colloidal Surfactants: Some Physicochemical Properties*", Elsevier*, Vol. 12. pp 76

Shooto, N. D., Dikio, C. W., Wankasi, D., Sikhwivhilu, L. M., Mtunzi, F. M., and Dikio, E. D. (2016), "Novel PVA/MOF Nanofibres: Fabrication, Evaluation and Adsorption of Lead Ions from Aqueous Solution", *Nanoscale research letters*, Vol. 11, No. 1, pp. 1-13.

Skuza, Z., Kolmasiak, C., and Prusak, R. (2009), "Possibilities for The Utilization of Metallurgical Slag in The Conditions of the Polish Economy", *Metalurgija*, Vol. 48, No. 2, pp. 125-128.

Swash, P. M., and Monhemius, A. J. (1996), "The Characteristic of Calcium Arsenate Compounds Relevant to The Disposal of Arsenic from Industrial Processes", *Proceedings of Mineral Metals and The Environment II*, pp. 3-6.

Tsakiridis, P. E., Papadimitriou, G. D., Tsivilis, S., and Koroneos, C. (2008), "Utilization of Steel Slag for Portland Cement Clinker Production." *Journal of hazardous materials*, Vol. 152, No. 2, pp. 805-811.

World Health Organization (WHO), (2004), "Guidelines for Drinking-Water Quality: Recommendations", 512 pp.

Wibowo, E., Rokhmat, M. and Abdullah, M. (2017), "Reduction of Seawater Salinity by Natural Zeolite (Clinoptilolite): Adsorption Isotherms, Thermodynamics and Kinetics", *Desalination*, 409, pp. 146 –156.

Wilkens, J., Shoemaker, S., Bazela, W., Egler, A., and Bain, J. (2003), "Arsenic Removal from Groundwater Using A PRB of BOF Slag at The Dupont East Chicago Site", In *Proc. RTDF PRBs Action Team Meeting, Niagara Falls*. 14 pp

Wills, B. A. and Napier-Munn, T. J., (2006), "Wills' Mineral Processing Technology: An Introduction to The Practical Aspects of Ore Treatment and Mineral Recovery", *Elsevier Science & Technology Books,* 7th Edition, pp. 444

Yu, Q. (2018) "Metal Recovery from Steelmaking Slag", *Doctoral dissertation*, University of Toronto, Canada 131 pp.

Zong, Q. X., Fu, L. Z., and Bo, L. (2018), "Variables and Applications On Dry Magnetic Separator", In *E3S Web of Conferences* Vol. 53, p. 02019

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