Predictive Analysis of Removed Phosphorus Concentration Based on Reaction Time and Grain Size of Iron Oxide Ore during Its Biotreatment

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ABSTRACT

Predictive analysis of removed phosphorus concentration was carried out based on the reaction time and grain size of iron oxide ore during its biotreatment with Acidithiobacillus Ferrooxidans. Following evaluation of experimental results, a model expressed as;

$$\xi = 0.1673\,\vartheta^2 - 0.4704\,\vartheta + 0.0001\,\gamma + 0.43$$

was derived and used as tool for the analysis. The validity of the empirical model was rooted on the expression $\xi - 0.0001\gamma + 0.4704\vartheta = 0.1673\vartheta^2 + 0.43$ where both sides of the expression are correspondingly approximately equal. Statistical analysis of removed phosphorus concentration for each value of the ore grain size as obtained from experiment and derived model-predicted results show standard errors of 0.0436 and 0.0368% respectively. Furthermore, removed phosphorus concentration per unit grain size as obtained from experiment and derived model-predicted results were 0.1406 and 0.1484 %/ mm respectively. Analysis of results of deviations of model-predicted removed phosphorus concentrations (from experimental result) shows that the most suitable size the ore grain should be formed to is between 0.63 and 0.75 mm. These correspond to deviation values 4.48 and 6.98 % respectively, and invariably translate into derived model confidence level of between 93 and 95% as well as between 0.93 and 0.95 response coefficients for the dependence of removed phosphorus on ore grain size and reaction time.

Keywords: Analysis, Phosphorus Removal, Reaction time, Ore Grain Size, Agbaja Iron Oxide Ore.

INTRODUCTION

Abrupt catastrophic failure of iron and steel materials in service has raised the need for intensive research and development aimed at drastic reduction of the concentration of phosphorus present in iron ore.

Research [1] has shown that alkali-leaching and acid-leaching could be used for the dephosphorization of Changde iron ore, which contains an average of 1.12% phosphorus. Results of the study indicate that phosphorus occurring as apatite phase could be removed by alkali-leaching, but those occurring in the iron phase could not. The research shows that after leaching for 20 min at room temperature, 91.61% phosphorus was removed with 1% sulfuric acid, during which iron loss was less than 0.25%. During this leaching process [1], acid was not exhausted and could be recycled, following the pH value of the leaching solution (0.86) after leaching with 1% sulfuric acid. The recycle of sulfuric acid solution is expected to make the dephosphorization process more economical.

Similar study [2] has shown that dephosphorization of iron ore could be carried out using an integrated process which involves leaching and further processing of the leach solution. In this research, phosphoric acid is extracted by isoamyl alcohol (iAmOH) and stripped by nitric acid solution. The phosphoric acid is concentrated by evaporation where most of the nitric acid is removed. The remaining nitric acid is extracted by methyl isobutyl ketone. The raffinate from the phosphoric acid extraction is treated by sulfuric acid for the regeneration of the spent nitric acid, which is extracted by iAmOH and concentrated by distillation before re-used in further leaching [2]. The technical feasibility of the process was established and the economy analyzed and found to be viable.

The potentials of nitric acid for hydrometallurgical removal of phosphorus from iron ore has been evaluated [3]. The apatite content (1%) of a Swedish ore is removed (> 95%) by leaching the ore with nitric acid. The iron loss is less than 0.05% while the alkali metal content is greatly reduced (> 60%).

Report [4] has shown evaluation of some biological processes for phosphorus removal based on the use of several types of microbes, some being oxalic acid producing. The research particularly presented results on the use of Aspergillus niger and their cultural filtrates for removing phosphorus from Agbaja (Nigeria) iron oxide ore. Results of the investigation show that phosphorus removal efficiencies at the end of the 49 days of the leaching process are 81, 63 and 68% for 5, 100 and 250 mesh grain sizes respectively.

Empirical models [5-9] have been derived to analyze, evaluate, quantify and predict the concentration of phosphorus removed (using hydrometallurgy) in relation to certain important input and output process parameters.

The aim of this work is to take a predictive analysis of the removed phosphorus concentration based on the reaction time and grain size of iron oxide ore during biotreatment of the ore using acidithiobacillus ferrooxidans.

MATERIALS AND METHODS

Agbaja (Nigeria) iron ore concentrate used for this work was obtained from Nigeria Metallurgical Development Centre (NMDC) Jos. The concentrate was dried in air (under atmospheric condition) and used in the as-received condition. Five samples of constant weight quantity of the dried iron ore concentrate of particle size 0.32 mesh size were each added to a culture of ATF in a conical flask and the mixtures (each with pH 1.0) allowed to react for 8 weeks at a temperature of 25^0C after which the mixtures were filtered and the concentration of removed phosphorus determined using atomic absorption spectrometer (AAS). The average of the removed phosphorus concentration determined in each experiment set was taken as the precise result. The experiment was repeated with different iron ore grain sizes; 0.63, 0.75. 0.83 and 1.6 and the corresponding phosphorus removal also determined using AAS. Details of the experimental procedures and process conditions prevailing during the biotreatment process are as reported in the previous work [10].

Model Formulation

Experimental data obtained from the highlighted research work were used for the model derivation. Computational analysis of these data shown in Table 1, gave rise to Table 3 which indicate that;

$$\xi - K\,\text{ɤ} + \text{ђ}\,\vartheta \approx S\,\vartheta^2 + N \qquad (1)$$

Introducing the values of K, N, S and ђ into equation (1)

$$\xi - 0.0001\text{ɤ} + 0.4704\,\vartheta = 0.1673\,\vartheta^2 + 0.43 \qquad (2)$$

$$\xi = 0.1673\,\vartheta^2 - 0.4704\,\vartheta + 0.0001\,\text{ɤ} + 0.43 \qquad (3)$$

Where

(ξ) = Conc. of removed phosphorus (%)

(γ) = As- beneficiated phosphorus content of the ore (%)
(ɤ) = Reaction time (weeks)
(ϑ) = Ore grain size (mm)
K = 0.0001, N = 0.43, S = 0.1673 and ђ = 0.4704 are equalizing constant
(determined using C-NIKBRAN [11])

Table 1: Variation of removed phosphorus concentration with iron oxide ore grain sizes [10]

(ɤ)	(ϑ)	(ξ) (%)
8	0.32	0.27
8	0.63	0.21
8	0.75	0.16
8	0.83	0.11
8	1.60	0.09

Boundary and Initial Condition

Consider iron ore (in a furnace) mixed with a culture of ATF. The atmosphere was not contaminated i.e (free of unwanted gases and dusts). Initially, atmospheric levels of oxygen are assumed just before the reaction between the ore and the microbes. Mass of iron oxide ore: (50g), reaction time: 8 weeks, constant treatment temperature: 25^{o}C, range of iron ore grain size used; 0.32 – 1.6 mm.

The boundary conditions are: oxygen atmosphere at the top and bottom of the ore particles interacting with the microbes. At the bottom of the particles, a zero gradient for the gas scalar are assumed and also for the gas phase at the top of the particles. The reduced iron is stationary. The sides of the particles are taken to be symmetries.

RESULTS AND DISCUSSIONS

The result of the chemical analysis carried out on the beneficiated iron ore concentrate is presented in Table 2. The table shows that the percentage of phosphorus present in the as-beneficiated ore is 0.9%.

Table 2: Result of chemical analysis of iron ore used [10]

Element/Compound	Fe	P	SiO_2	Al_2O_3
Unit (%)	78.6	0.90	5.30	11.0

Model Validation

The validity of the model is strongly rooted in equation (2) (core model equation) where both sides of the equation are correspondingly approximately equal. Table 3 also agrees with equation (2) following the values of ξ - 0.0001ɤ + 0.4704 ϑ and 0.1673 ϑ^2 + 0.43 evaluated from the experimental results in Table 1.

Table 3: Variation of ξ - 0.0001ɤ + 0.4704 ϑ with 0.1673 ϑ^2 + 0.43

ξ - 0.0001ɤ + 0.4704 ϑ	0.1673 ϑ^2 + 0.43
0.4197	0.4471
0.5056	0.4964
0.5120	0.5241
0.4996	0.5453
0.8418	0.8583

The derived model was further validated by comparing the removed phosphorus concentration predicted by the model and that obtained from the experiment. This was done using various evaluative techniques such as computational, statistical, graphical and deviational analysis.

Computational Analysis

Computational analysis of the experimental and model-predicted removed phosphorus concentration was carried out to evaluate the degree of validity of the derived model. This was done by comparing phosphorus removal per unit ore grain size valuated from model-predicted results with those from actual experimental results

Removed phosphorus concentration per unit ore grain size ξ (%) was calculated from the equation;

$$\xi = \xi / \vartheta \qquad (4)$$

Therefore, a plot of the concentration of phosphorus removed against initial bioleaching solution pH as in Fig. 1 using experimental results in Table 1, gives a slope, S at points (0.32, 0.09) and (1.6, 0.27) following their substitution into the mathematical expression;

$$\xi = \Delta\xi / \Delta\vartheta \qquad (5)$$

Equation (5) is detailed as

$$\xi = \xi_2 - \xi_1 / \vartheta_2 - \vartheta_1 \qquad (6)$$

Where

$\Delta\xi$ = Change in removed phosphorus concentrations of ξ_2, ξ_1 at two values of the ore grain size ϑ_2, ϑ_1. Considering the points (0.32, 0.09) and (1.6, 0.27) for (ϑ_1, ξ_1) and (ϑ_2, ξ_2) respectively, and substituting them into equation (6), gives the slope as 0.1406 % which is the removed phosphorus concentration per unit ore grain size during the actual leaching process.

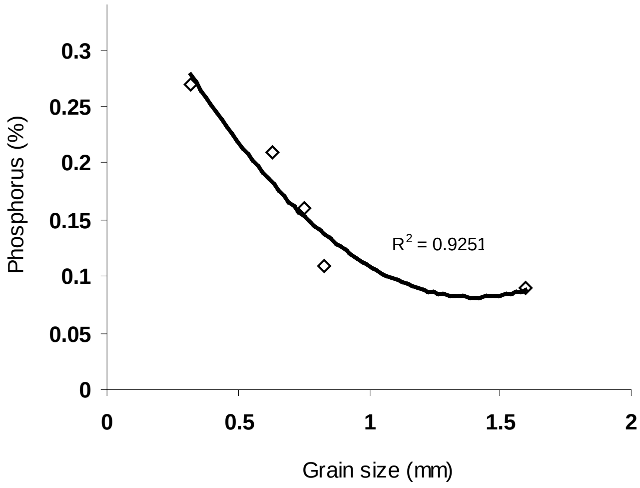

Fig. 1: Coefficient of determination between concentration of removed phosphorus and ore grain size as obtained from the experiment [10]

Similarly, a plot of the concentration of removed phosphorus against ore grain size (as in Fig. 2) using derived model-predicted results gives a slope: 0.1484% on substituting the points (0.32, 0.107) and (1.6, 0.297) for (ϑ_1, ξ_1) and (ϑ_2, ξ_2) respectively into equation (6). This is the model-predicted removed phosphorus concentration per unit ore grain size.

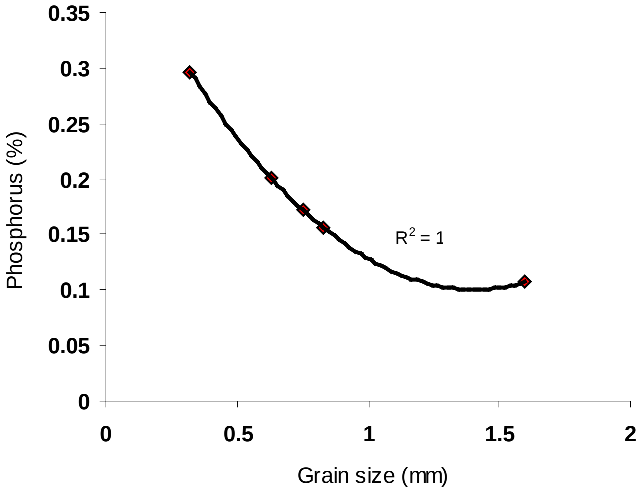

Fig. 2: Coefficient of determination between concentration of removed phosphorus and ore grain size as obtained from derived model

A comparison of this set of values for removed phosphorus concentration (per unit ore grain size) also shows proximate agreement and a high degree of validity of the derived model.

Statistical Analysis

Statistical analysis of generated results shows that the standard errors (STEYX) in predicting the removed phosphorus concentration (using results from experiment and derived model) for each value of the ore grain size are 0.0436 and 0.0368% respectively. The standard error was evaluated using Microsoft Excel version 2003.

Considering the coefficient of determination R^2 from Figs. 1 and 2, the correlations between removed phosphorus concentration and ore grain size as obtained from experiment and derived model predicted results, was calculated using the equation;

$$R = \sqrt{R^2} \qquad (7)$$

The evaluations show correlations 0.9618 and 1.0000 respectively. These evaluated results indicate that the derived model predictions are significantly reliable and hence valid considering its proximate agreement with results from actual experiment.

Graphical Analysis

Graphical analysis of Fig. 3 shows very close alignment of the curves from model-predicted removed phosphorus concentration (MoD) and that of the experiment (ExD). The degree of alignment of these curves is indicative of the proximate agreement between both experimental and model-predicted removed phosphorus concentration.

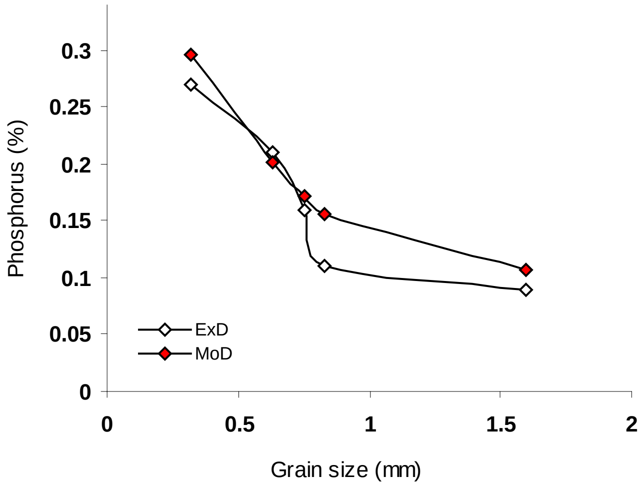

Fig. 3: Comparison of the concentrations of removed phosphorus (relative to ore grain size) as obtained from experiment [10] and derived model

Deviational Analysis

Comparative analysis of removed phosphorus concentrations from the experiment and derived model revealed deviations on the part of the model-predicted values relative to values obtained from the experiment. This is attributed to the fact that the surface properties of the iron ore and the physiochemical interactions between the ore and the bacteria (ATF) which were found to have played vital roles during the process were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted removed phosphorus concentration to those of the corresponding experimental values.

Deviation (Dn) of model-predicted removed phosphorus concentration from that of the experiment is given by

$$Dn = \left(\frac{\xi_{MoD} - \xi_{ex}}{\xi_{ex}} \right) \times 100 \qquad (8)$$

Where

ξ_{MoD} = Removed phosphorus concentration as predicted by derived model
ξ_{ex} = Removed phosphorus concentration as obtained from experiment

Correction factor (Cr) is the negative of the deviation i.e

$$Cr = -Dn \qquad (9)$$

Therefore

$$Cr = -\left(\frac{\xi_{MoD} - \xi_{ex}}{\xi_{ex}} \right) \times 100 \qquad (10)$$

Introduction of the corresponding values of Cr from equation (10) into the derived model gives exactly the removed phosphorus concentration as obtained from experiment.

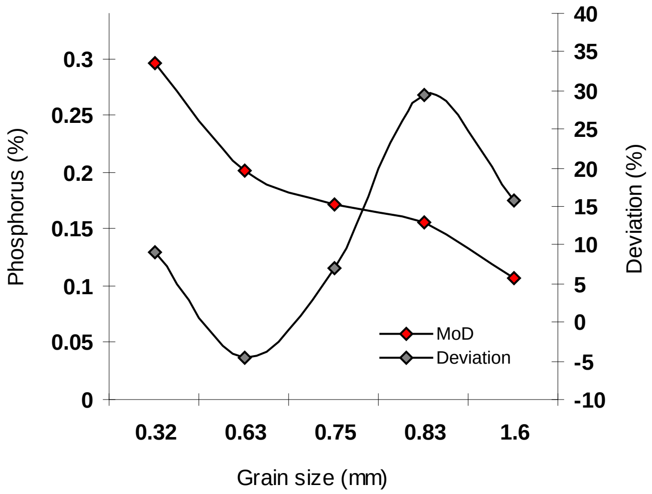

Fig. 4: Variation of model-predicted removed phosphorus concentration with associated deviation from experimental results (relative to ore grain size)

From Fig. 4, analysis of results of deviations of model-predicted removed phosphorus concentrations (from experimental result) (Fig. 4) shows that the most suitable size the ore grain should be formed to is between 0.63 and 0.75 mm. These correspond to deviation values - 4.48 and + 6.98 % respectively, and invariably translate into derived model confidence level of between 93 and 95% as well as between 0.93 and 0.95 response coefficients for the dependence of removed phosphorus on ore grain size and reaction time. The highlighted deviations also correspond to removed phosphorus concentrations: 0.201 and 0.172 %.

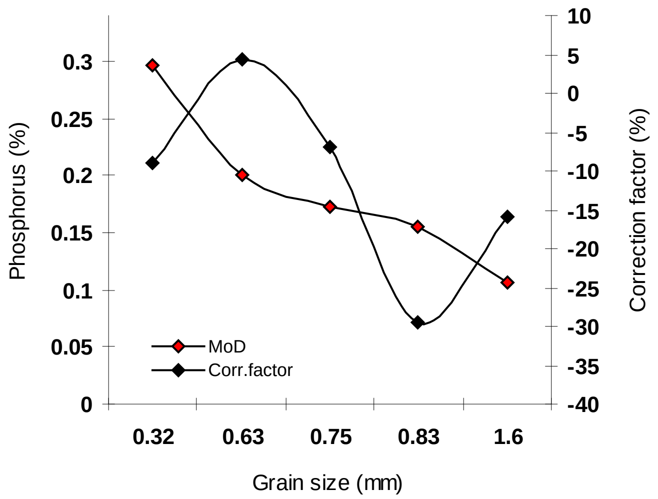

Fig. 5: Variation of model-predicted removed phosphorus concentration with associated correction factor (relative to ore grain size)

Figs. 4 and 5 indicate that the orientation of the curve in Fig. 5 is opposite that of the deviation of model-predicted removed phosphorus concentration (Fig. 4). This is because correction factor is the negative of the deviation as shown in equations (9) and (10). It is believed that the correction factor takes care of the effects of surface properties of the iron ore and the physiochemical interactions between the iron ore and microbes which have played vital roles during the process, but were not considered during the model formulation. Fig. 5 indicates that the deviation values - 4.48 and + 6.98 % corresponds to correction factors + 4.48 and - 6.98 % respectively (equations (9) and (10)). These correction factors correspond to ore grain sizes: 0.63 and 0.75 mm as well as removed phosphorus concentrations: 0.201 and 0.172 % respectively.

It is important to state that the deviation of model predicted results from that of the experiment is just the magnitude of the value. The associated sign preceding the value signifies that the deviation is a deficit (negative sign) or surplus (positive sign).

CONCLUSIONS

Predictive analysis of removed phosphorus concentration was carried out based on the reaction time and grain size of iron oxide ore following its biotreatment with Acidithiobacillus Ferrooxidans. The validity of the empirical model derived for the analysis was rooted on the expression $\xi - 0.0001\text{ɤ} + 0.4704\,\vartheta = 0.1673\,\vartheta^2 + 0.43$ where both sides of the expression are correspondingly approximately equal. Statistical analysis of removed phosphorus concentration for each value of the ore grain size as obtained from experiment and derived model-predicted results show standard errors of 0.0436 and 0.0368% respectively. Furthermore, removed phosphorus concentration per unit grain size as obtained from experiment and derived model-predicted results were 0.1406 and 0.1484 %/ mm respectively. Analysis of results of deviations of model-predicted removed phosphorus concentrations (from experimental result) shows that the most suitable size the ore grain should be formed to is between 0.63 and 0.75 mm. These correspond to deviation values 4.48 and 6.98 % respectively, and invariably translate into derived model confidence level of between 93 and 95% as well as between 0.93 and 0.95 response coefficients for the dependence of removed phosphorus on ore grain size and reaction time.

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