

# Recycling Fe(III)/Cr(III) hydroxide, an industrial solid waste for the removal of phosphate from water

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## Abstract

Industrial solid waste, Fe(III)/Cr(III) hydroxide, was investigated to assess the capacity for the removal of phosphate from aqueous solution. Langmuir and Freundlich isotherms were used to model the adsorption equilibrium data. The system follows both isotherms. Adsorption capacity was found to be 6.5 mg/g. Kinetic studies show that the adsorption obeyed second order kinetics. Thermodynamic parameters were evaluated. Overall adsorption process was endothermic and spontaneous. Optimum pH for phosphate adsorption was found to be 4.0. Effect of coexisting anions has also been examined.

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*Keywords:* Phosphate; Adsorption; Fe(III)/Cr(III) hydroxide; Kinetics; Isotherms; pH effect; Temperature; Foreign ions

## 1. Introduction

Phosphorous is the key nutrient for the growth of algal and other biological organisms, which in excess causes eutrophication of water bodies. Municipal wastewater contains from 4 to 15 mg/L P. In the case of industrial wastewater (such as detergent manufacturing and metal coating process), phosphate level is well in excess of 10 mg/L [1]. Therefore, municipal and industrial wastewater containing phosphate should be treated before discharging. The US discharge limits for phosphate is 0.5–1.0 mg/L P. According to Bureau of Indian Standards, discharge limit for phosphate is 5 mg/L P [2].

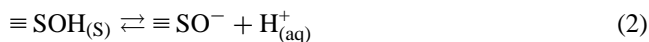
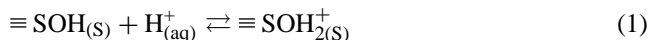
Phosphorous usually occurs in aqueous solution in the form of orthophosphate, polyphosphate and organic phosphate [3]. Many techniques have been proposed for the removal of phosphate from wastewater. Chemical precipitation and advanced biological methods [4] or combination of both are widely accepted methods of phosphate removal at industrial level. Conventional biological methods have limited phosphate removal capacity as microbes utilize

phosphorous during cell synthesis and energy transport. Therefore, some of the soluble phosphates are still present in the effluent [5]. Furthermore, in the case of chemical precipitation, new species such as  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$  are introduced into water. Various physical methods also have been suggested including reverse osmosis, electrodialysis, contact filtration and adsorption [4]. Compared with other techniques, adsorption seems to be cost effective and more work has been focused on novel adsorbents. Active carbon is currently the most widely used adsorbent for wastewater treatment, but recognizing the high cost of activated carbon, many investigators have studied the feasibility of cheap, commercially available materials for replacement. Such materials range from industrial waste to agricultural waste products. Adsorbents such as alumina, iron(III) hydroxide, goethite, aluminium hydroxide, active carbon, fly ash, red mud and kaolinite have been investigated for the adsorption of phosphate [6].

Previous studies [7] showed that oxidic adsorbent, especially iron and aluminium oxides, play an important role for the removal of anions from aqueous solutions. Adsorption of anion onto oxidic surface involves surface complexation phenomenon in the adsorption process. Depending upon the bonding between the anions and the surface active

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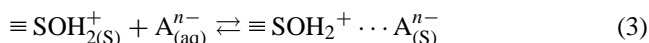
site, the surface complexes formed are classified as inner and outer sphere complexes. In the case of outer sphere complex, there are H<sub>2</sub>O molecules between active site of the adsorbent and anions. Formation of these surface complexes is mostly dependent on the degree of surface protonation and dissociation. The surface reaction [8] could be described as:



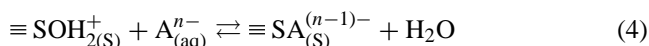
where S is the hydroxylated mineral surface and OH is a reactive surface hydroxyl.

If the number of protonated groups is higher than that of dissociated groups, then the surface is positively charged and becomes suitable for anion adsorption. Thus, the proposed [9] complex formation reactions for anions can be represented as:

In the case of outer-sphere complexes:



In the case of inner-sphere complexes:



where A<sup>n-</sup> represents the anion.

It has been reported that the adsorption of the phosphate anion onto hydroxylated mineral surface occurs by formation of monodentate and bidentate inner-sphere complexes [10]. The aim of the work was to use the industrial solid waste Fe(III)/Cr(III) hydroxide for the removal of phosphate from the aqueous solution without prior treatment. The industrial solid waste Fe(III)/Cr(III) hydroxide has been investigated for the adsorptive removal of dye [11], pesticide [12] and heavy metals [13,14]. Various parameters such as initial concentration of phosphate, effect of temperature, contact time, adsorbent dose and pH were examined. The effects of competitive anions in the aqueous solution such as NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, Cl<sup>-</sup>, VO<sub>3</sub><sup>-</sup>, SeO<sub>3</sub><sup>2-</sup> and MoO<sub>4</sub><sup>2-</sup> have also been investigated.

## 2. Materials and methods

Chemical industries use hexavalent chromium compounds as corrosion inhibitors in the cooling water systems. Periodically fresh Cr(VI) solutions are injected and the spent cooling water is let out. Chromium (VI) in the water is toxic and is reduced to less toxic Cr(III) using ferrous ion produced through an electrolytic process or ferrous sulfate under acidic conditions. The resultant Fe(III)/Cr(III) hydroxide settles as sludge in lagoons and is removed periodically. The Fe(III)/Cr(III) hydroxide sludge is discarded as waste in the industries. In the present work, Fe(III)/Cr(III) hydroxide was obtained from the Southern Petrochemical Industries Corporation Limited (SPIC), Tuticorin, Tamil Nadu, India.

It was ground and washed five times. Then, it was dried at 65 °C for 12 h. The dried adsorbent was sieved to 75–150 μm size. The experimental solutions were made from stock 1000 mg/L phosphate solution, which was prepared using analytical grade potassium dihydrogen phosphate obtained from S.D. Fine Chemicals, Mumbai, India.

### 2.1. Batch mode adsorption studies

Batch mode adsorption studies were carried out by shaking 250 mL polyethylene bottles containing 1 g of Fe(III)/Cr(III) hydroxide and 50 mL of phosphate solution of desired concentration. Then, the suspension was agitated on a mechanical shaker at 160 rpm, 32 °C and at the initial pH 4 except those in which the effect of pH has been investigated. pH of the solution was adjusted with 1 M HCl and 1 M NaOH solutions using a pH meter (Elico, Mode LI-107, Hyderabad, India). At the end of the adsorption period, the supernatant solution was separated by centrifugation at 20,000 rpm for 20 min. Then, the concentration of the residual phosphate was determined by stannous chloride method [15] using UV–vis spectrophotometer (Hitachi, Model U-3210, Tokyo). The amount of phosphate adsorbed was calculated from the concentration in the solution before and after adsorption. Effect of adsorbent dose was studied with different adsorbent doses (200–1600 mg) for the PO<sub>4</sub><sup>3-</sup> concentration 10–40 mg/L. Langmuir and Freundlich isotherms were used to study the adsorption capacity of the adsorbent.

### 2.2. Desorption studies

The adsorbent used for the adsorption of 10 and 20 mg/L of PO<sub>4</sub><sup>3-</sup> solution was separated from the solution by filtration using Whatmann filter paper and washed gently with water to remove unadsorbed PO<sub>4</sub><sup>3-</sup>. Then, the spent adsorbent was agitated with 50 mL of distilled water at different pH values adjusted using 1 M HCl/NaOH solutions. Then the desorbed PO<sub>4</sub><sup>3-</sup> was estimated as before.

### 2.3. Effect of foreign ions

Equimolar concentration (0.78 mM) of PO<sub>4</sub><sup>3-</sup>, SeO<sub>3</sub><sup>2-</sup>, VO<sub>3</sub><sup>-</sup>, MoO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup> and Cl<sup>-</sup> were used to study the competitive effect on the adsorption of PO<sub>4</sub><sup>3-</sup> by Fe(III)/Cr(III) hydroxide. Vanadate [16], selenite [17] and molybdate [18] were estimated by standard spectrophotometric methods. NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup> and Cl<sup>-</sup> were estimated by ion chromatograph.

The adsorbent does not release either Fe<sup>3+</sup> or Cr<sup>3+</sup> into solution in the pH range (3.4–10.0) studied [13]. All the experiments were performed in duplicate and mean values were used for calculations. Maximum deviation was found to be 4%. Preliminary experiments showed that container walls do not adsorb phosphate.

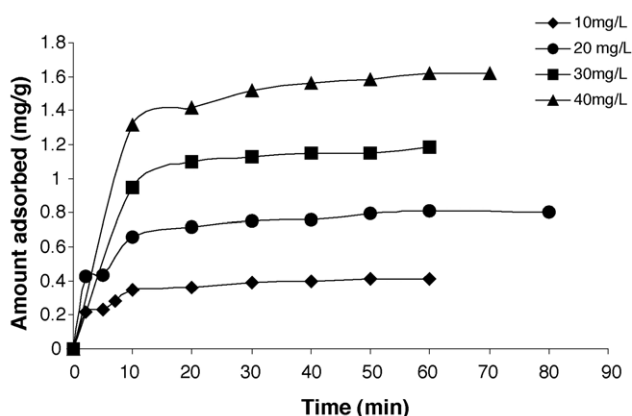


Fig. 1. Effect of agitation time and concentration of  $\text{PO}_4^{3-}$  on removal. Adsorbent dose, 1 g/50 mL; pH, 4.0; temperature, 32 °C.

### 3. Results and discussion

#### 3.1. Effect of initial phosphate concentration

Fig. 1 shows that the uptake of phosphate (mg/g) increased with increase in phosphate concentration and remained nearly constant after equilibrium time. The equilibrium time was found to be 30 min for all concentrations studied. The amount of phosphate adsorbed ( $q_e$ ) increased from 0.38 to 1.47 mg/g as the concentration was increased from 10 to 40 mg/L. It also shows that the adsorption is rapid in the initial stages and gradually decreases with progress of adsorption. The plots are single, smooth and continuous curves leading to saturation, suggesting the possible monolayer coverage of phosphate on the surface of the adsorbent.

#### 3.2. Adsorption kinetics

The adsorption kinetic data of phosphate are analyzed using the Lagergran rate equation [19]:

$$\log(q_e - q) = \log q_e - \frac{k_1 t}{2.303} \quad (5)$$

Table 1

Comparison of first order and second order adsorption rate constants and calculated and experimental  $q_e$  values for different initial phosphate concentrations and temperatures

Parameter	First order kinetic model				Second order kinetic model		
	$q_e$ (exp) (mg/g)	$k_1$ (1/min)	$q_e$ (cal) (mg/g)	$R^2$	$k_2$ (g/mg/min)	$q_e$ (cal) (mg/g)	$R^2$
Initial $\text{PO}_4^{3-}$ concentration (mg/g) <sup>a</sup>							
10	0.387	0.10	0.200	0.9727	0.89	0.417	0.9961
20	0.751	0.12	0.465	0.9627	0.62	0.795	0.999
30	1.118	0.13	0.530	0.9648	0.45	1.190	0.9996
40	1.471	0.15	0.984	0.9477	0.18	1.649	0.9966
Temperature (°C) <sup>b</sup>							
32	0.751	0.12	0.465	0.9627	0.62	0.795	0.999
40	0.754	0.13	0.370	0.9784	0.85	0.811	0.9988
50	0.806	0.28	0.369	0.9508	0.95	0.857	0.9981
60	0.843	0.15	0.983	0.9477	1.23	0.875	0.9964

<sup>a</sup> Conditions: temperature, 32 °C; adsorbent dose, 1 g/50 mL; pH 4.0.

<sup>b</sup> Conditions:  $\text{PO}_4^{3-}$  concentration, 20 mg/L; adsorbent dose, 1 g/50 mL; pH 4.0.

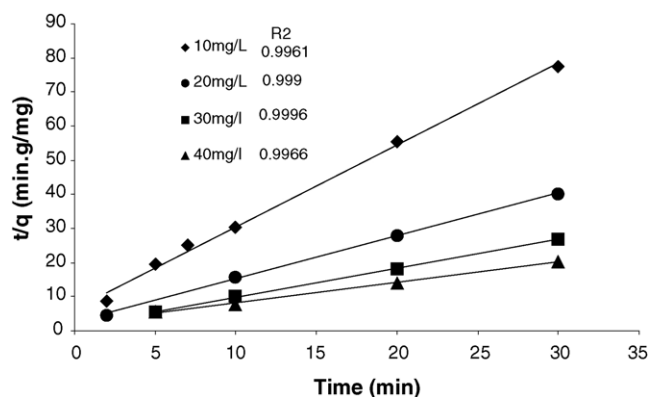


Fig. 2. Plot of the second order model at different initial  $\text{PO}_4^{3-}$  concentrations. Adsorbent dose, 1 g/50 mL; pH, 4.0; temperature, 32 °C.

where  $q_e$  and  $q$  are the amount of phosphate adsorbed (mg/g) at equilibrium and at time  $t$  (min), respectively, and  $k_1$  is the Lagergran rate constant of first order adsorption (1/min). The  $q_e$  and rate constant  $k_1$  were calculated from the slope of the plots of  $\log(q_e - q)$  versus  $t$  (figure not shown). It was found that the calculated  $q_e$  values do not agree with the experimental  $q_e$  values (Table 1). This suggests that the adsorption of phosphate does not follow first order kinetics.

The second order kinetic model [20] can be represented as:

$$\frac{t}{q} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad (6)$$

where  $k_2$  is the equilibrium rate constant of second order adsorption (g/mg/min). Values of  $k_2$  and  $q_e$  were calculated from the plots of  $t/q$  versus  $t$  (Fig. 2). The plot shows that the correlation coefficients for the second order kinetic model obtained at all the studied concentrations were above 0.99 and also the calculated  $q_e$  values agree with the experimental  $q_e$  values. Table 1 depicts the computed results obtained from the second order kinetic model. These results indicate that the adsorption system studied belongs to the second order kinetic model. Similar phenomena have been observed in the

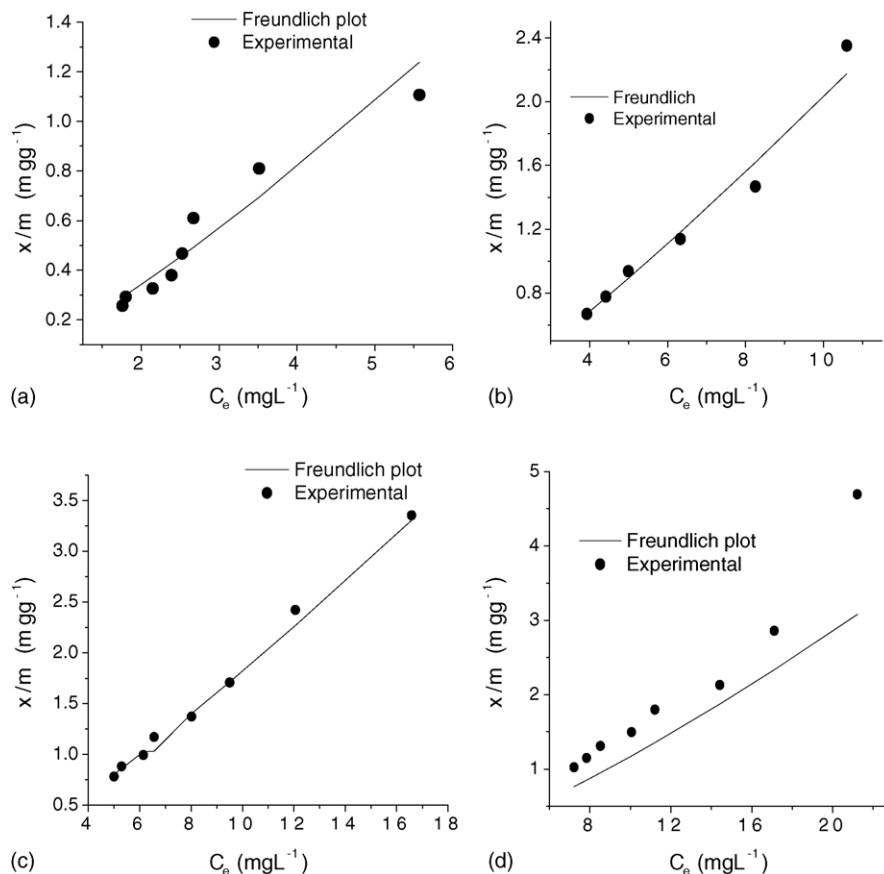


Fig. 3. Plots of  $x/m$  vs.  $C_e$  for adsorption of  $\text{PO}_4^{3-}$ : (a) 10 mg/L  $\text{PO}_4^{3-}$ ; (b) 20 mg/L  $\text{PO}_4^{3-}$ ; (c) 30 mg/L  $\text{PO}_4^{3-}$ ; and (d) 40 mg/L  $\text{PO}_4^{3-}$ .

adsorption of phosphorous on calcined alunite [21] and ion exchange fiber [22].

### 3.3. Adsorption isotherms

The adsorption capacity of the adsorbent has been tested using Langmuir [23] and Freundlich [24] isotherms. To determine the isotherms, the phosphate concentration range 10–40 mg/L was used and the initial pH 4.0. The linear form of the Freundlich isotherm is defined by:

$$\log\left(\frac{x}{m}\right) = \log k_f + n \log C_e \quad (7)$$

where  $k_f$  is the Freundlich constant related to sorption capacity,  $n$  is a constant related to energy or intensity of adsorption and  $C_e$  is the equilibrium concentration of phosphate in mg/L.

Freundlich plots are shown in Fig. 3 along with the experimental data. Freundlich plots do not fit satisfactorily with the experimental data. The Freundlich constants  $k_f$  and  $n$  are shown in Table 2. The Freundlich exponent  $n$  gives information about surface heterogeneity and surface affinity of the solute. Since Freundlich adsorption does not predict any saturation of the adsorbent surface, Langmuir isotherm has been used to study the surface monolayer saturation. Langmuir isotherm is expressed as:

$$\frac{C_e}{Q_e} = \frac{1}{Q_0 b} + \frac{C_e}{Q_0} \quad (8)$$

where  $C_e$  is the concentration of phosphate solution (mg/L) at equilibrium and  $Q_0$  and  $b$  are Langmuir constants related to adsorption capacity (mg/g) and energy of adsorption (L/mg), respectively. Langmuir plot is shown in Fig. 4 along with

Table 2  
Langmuir and Freundlich constants

Langmuir constants				Freundlich constants	
$\text{PO}_4^{3-}$ concentration (mg/L)	$Q_0$ (mg/g)	$b$ (L/mg)	$R_L$	$k_f$ ( $\text{mg}^{1-1/n} \text{L}^{1/n} \text{g}^{-1}$ )	$n$
10	6.53	0.027	0.7874	0.144	0.80
20			0.6493	0.133	0.84
30			0.5524	0.120	0.85
40			0.4807	0.060	0.77

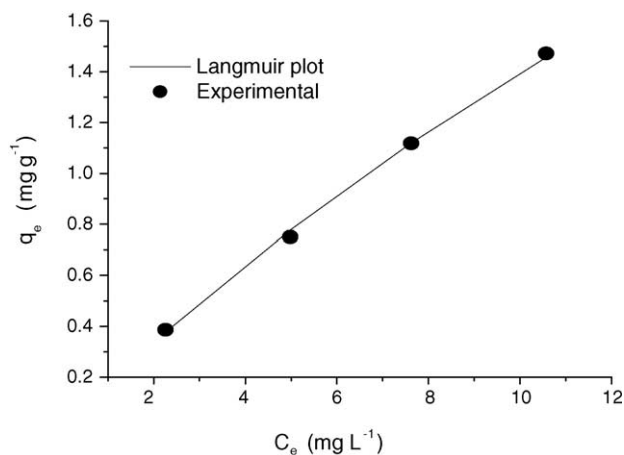


Fig. 4. Plot of  $q_e$  vs.  $C_e$  for adsorption of  $\text{PO}_4^{3-}$ .

the experimental data. Langmuir plot is a better fit with the experimental data compared to Freundlich plots. The value of the Langmuir constant  $Q_0$  was found to be 6.5 mg/g. The adsorption capacity was compared with other adsorbents. It was reported that adsorption capacity of alunite [21], hematite [25], fly ash [26] and furnace slag [27] was 386 (1.3555 mmol/g P), 9 (3 mg/g P), 42 (14 mg/g P) and 1.95 (0.65 mg/g P) mg/g phosphate, respectively. The lower value of the adsorption capacity of the adsorbent is due to the final pH of the solution, which was found to be  $> 8.0$  for all concentrations studied. This condition is not favorable for the adsorption of phosphate (see pH effect). The essential characteristics of the Langmuir isotherm can be expressed by a dimensionless constant called equilibrium parameter  $R_L$  [28]:

$$R_L = \frac{1}{(1 + bC_0)}$$

where  $b$  is the Langmuir constant and  $C_0$  is the initial concentration (mg/g),  $R_L$  values indicate the type of isotherm. The  $R_L$  values between 0 and 1 indicate favorable adsorption. The  $R_L$  values were found to be between 0 and 1 for all the concentrations of phosphate studied (Table 2).

### 3.4. Effect of temperature

The diffusion coefficient  $D$  for intraparticle transport of  $\text{PO}_4^{3-}$  species into the adsorbent particles has been calculated at different temperatures by using the equation [29]:

$$t_{1/2} = \frac{0.03r_0^2}{D} \quad (9)$$

Table 3  
Pore diffusion coefficients

Initial $\text{PO}_4^{3-}$ concentration (mg/g)	Pore diffusion constant $D \times 10^{12}$ ( $\text{cm}^2/\text{s}$ )	Temperature ( $^\circ\text{C}$ )	Pore diffusion constant $D \times 10^{12}$ ( $\text{cm}^2/\text{s}$ )
10	0.1056	32	0.2372
20	0.1056	40	0.2372
30	0.1056	50	0.2372
40	0.1056	60	0.2372

Table 4  
Thermodynamic parameters for the adsorption of  $\text{PO}_4^{3-}$  on Fe(III)/Cr(III) hydroxide

Temperature ( $^\circ\text{C}$ )	$\Delta G^\circ$ (kJ/mol)	$\Delta H^\circ$ (kJ/mol)	$\Delta S^\circ$ (J/K/mol)
32	-2.800	18.37	84.17
40	-2.952		
50	-3.835		
60	-4.660		

where  $t_{1/2}$  is the time for half adsorption (s),  $r_0$  is the radius of the adsorbent particle (cm),  $D$  is the diffusion coefficient ( $\text{cm}^2/\text{s}$ ). If pore diffusion is to be the rate-limiting step,  $D$  should be in the range  $10^{-11}$  to  $10^{-13}$   $\text{cm}^2/\text{s}$ . In the present work,  $D$  was found to be in the range  $10^{-12}$   $\text{cm}^2/\text{s}$ , which shows that the pore diffusion of  $\text{PO}_4^{3-}$  is the rate-limiting step (Table 3). Activation energy [30],  $E_a$ , was calculated using Arrhenius equation and was found to be 23 kJ/mol.

The free energy change is obtained using following relationship:

$$\Delta G^\circ = -RT \ln K_c \quad (10)$$

where  $R$  is the gas constant and  $K_c$  is the equilibrium constant and  $T$  is the temperature in K. The negative values of  $\Delta G$  indicate the spontaneous nature of adsorption (Table 4). Other thermodynamic parameters such as enthalpy change ( $\Delta H^\circ$ ) and entropy change ( $\Delta S^\circ$ ) are evaluated using van't Hoff equation:

$$\log K_c = \Delta S^\circ / (2.303R) - \Delta H^\circ / (2.303RT) \quad (11)$$

Values of  $\Delta H$  and  $\Delta S$  were calculated from the slope and intercept of the van't Hoff linear plot of  $\log K_c$  versus  $1/T$  (Fig. 5). The positive value of  $\Delta H$  confirms the endothermic nature of adsorption. The positive value of  $\Delta S$  shows the increased randomness at the solid/ solution interface during the adsorption  $\text{PO}_4^{3-}$  (Table 4).

Using Lagergran rate equation, first order rate constants ( $k_1$ ) and correlation coefficients were calculated for different temperatures. The calculated  $q_e$  values obtained from the first order kinetics do not agree with the experimental  $q_e$  values (Table 1). This indicates that this system does not follow first order kinetic model. Second order kinetic model shows that the calculated  $q_e$  values agree with the experimental  $q_e$  values (Table 1). This indicates that the adsorption follows second order kinetic model at different temperatures used in this study.

Table 1 shows that the rate constant  $k_2$  increased on increasing the temperature from 32 to 60  $^\circ\text{C}$ . The increase in adsorption may be due to change in pore size, an increase

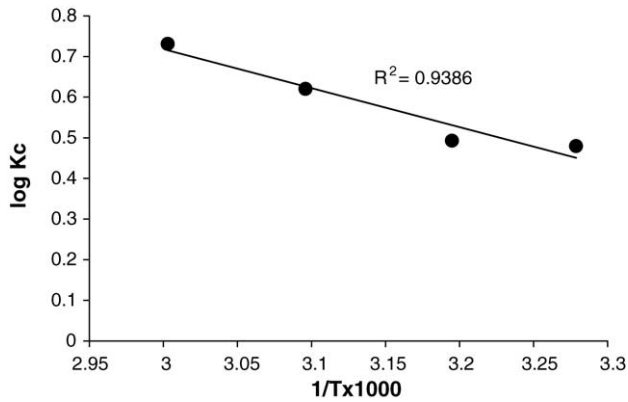
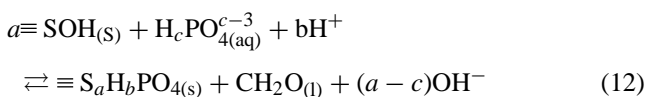


Fig. 5. Van't Hoff plot for  $\text{PO}_4^{3-}$  adsorption.

in kinetic energy of the  $\text{PO}_4^{3-}$  species and the enhanced rate of intraparticle diffusion of adsorbate.

### 3.5. Effect of pH

To study the influence of pH on the adsorption of phosphate on Fe(III)/Cr(III) hydroxide, experiments were performed at various initial solution pH values, from 4 to 10. Initial concentration of 10–40 mg/L of phosphate and 1 g per 50 mL of adsorbent dose were used to examine the pH effect. Fig. 6 shows that removal of phosphate decreased with increase in pH. Similar findings were reported for the adsorption of phosphate on hematite and  $\gamma\text{-Al}_2\text{O}_3$  [31], ion exchange fiber [22], alunite [32] and bauxite [7]. The adsorption of phosphate on to hydroxylated mineral surface can be described by a ligand exchange mechanism [10], which causes an increase in pH due to the hydroxyl ions released from the oxidic adsorbent. The mechanism could be expressed as:



S refers to a metal atom in a hydroxylated mineral, OH to a reactive surface hydroxyl,  $a$ ,  $b$  and  $c$  are stoichiometric coefficients and  $c \leq 3$  is the degree of protonation of the

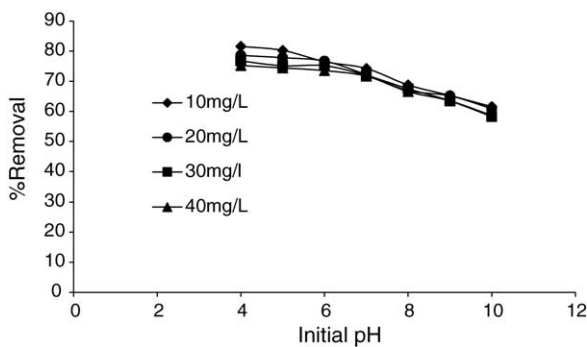


Fig. 6. Effect of pH on removal of  $\text{PO}_4^{3-}$  by Fe(III)/Cr(III) hydroxide adsorbent dose, 1 g/50 ml; agitation time 30 min; temperature, 32 °C.

phosphate ion. The reaction product is referred to as an inner-sphere complex, since it contains no water molecules between the surface Lewis acid site(s) and the adsorbed ion [9]. In the present investigation, final pH was found to be >8.0 at all different initial pH values studied. This also indicates the inner-sphere complex mechanism operating in the adsorption of phosphate on the Fe(III)/Cr(III) hydroxide surface. Depending on the pH, various phosphate species are formed in aqueous solutions. Zero point charge ( $\text{pH}_{\text{zpc}}$ ) of the adsorbent is important parameter for the adsorption of anion onto metal oxides. The  $\text{pH}_{\text{zpc}}$  of the adsorbent was found to be 8.1 [13]. At  $\text{pH} > 8.0$ , phosphates mainly occur as  $\text{HPO}_4^{2-}$  [33]. At  $\text{pH} < 8.1$ , surface of the adsorbent is positively charged. At lower pH, the removal is higher (see figure). In the acidic pH, surface is modified by  $\text{H}^+$ . Due to electrostatic attraction between the anionic phosphate species and the adsorbent surface phosphate removal is maximum at pH 4.0. On increasing the pH, the surface is modified with  $\text{OH}^-$  ions. The repulsion between the hydroxyl ions and the phosphate ions reduces the adsorption of phosphate.

### 3.6. Effect of foreign ions

Partitt [34] investigated the sorption of inorganic anions by soils and soil components and Rajan and Watkinson [35] studied the competitive sorption of several inorganic anions by soils. In the present investigation, the competitive sorption of other inorganic anions by Fe(III)/Cr(III) hydroxide has been studied with a view to understand how such competing ions affect the adsorption of phosphate on Fe(III)/Cr(III) hydroxide. The extend of adsorption of seven inorganic anions by Fe(III)/Cr(III) hydroxide decreased in the order:  $\text{VO}_3^- > \text{PO}_4^{3-} > \text{SeO}_3^{2-} > \text{MoO}_4^{2-} > \text{SO}_4^{2-} = \text{Cl}^- = \text{NO}_3^-$  when these ions are present as sole adsorbates (Table 5) and equimolar quantities. Partitt [34] reported that anion adsorption by soil decreased in the order:  $\text{H}_2\text{PO}_4^- > \text{HAsO}_4^- > \text{HSeO}_3^- = \text{MoO}_4^{2-} > \text{SO}_4^{2-} > \text{Cl}^- > \text{NO}_3^-$ . Similar trend

Table 5  
Effect of foreign anions on the sorption of  $\text{PO}_4^{3-}$

Species	Measured species	Percent removal
$\text{PO}_4^{3-}$	$\text{PO}_4^{3-}$	42
$\text{PO}_4^{3-} + \text{VO}_3^-$	$\text{VO}_3^-$	63
$\text{PO}_4^{3-} + \text{VO}_3^-$	$\text{PO}_4^{3-}$	25
$\text{PO}_4^{3-} + \text{SeO}_3^{2-}$	$\text{PO}_4^{3-}$	36
$\text{PO}_4^{3-} + \text{SeO}_3^{2-}$	$\text{SeO}_3^{2-}$	20
$\text{PO}_4^{3-} + \text{MoO}_4^{2-}$	$\text{PO}_4^{3-}$	40
$\text{PO}_4^{3-} + \text{MoO}_4^{2-}$	$\text{MoO}_4^{2-}$	4
$\text{PO}_4^{3-} + \text{SO}_4^{2-}$	$\text{PO}_4^{3-}$	41
$\text{PO}_4^{3-} + \text{Cl}^-$	$\text{PO}_4^{3-}$	42
$\text{PO}_4^{3-} + \text{NO}_3^-$	$\text{PO}_4^{3-}$	43
$\text{VO}_3^-$	$\text{VO}_3^-$	77
$\text{SeO}_3^{2-}$	$\text{SeO}_3^{2-}$	39
$\text{MoO}_4^{2-}$	$\text{MoO}_4^{2-}$	7
$\text{SO}_4^{2-}$	$\text{SO}_4^{2-}$	Nil
$\text{Cl}^-$	$\text{Cl}^-$	Nil
$\text{NO}_3^-$	$\text{NO}_3^-$	Nil

was also reported for ferric oxide gel [36]. Adsorption of  $\text{MoO}_4^{2-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$  and  $\text{NO}_3^-$  by Fe(III)/Cr(III) hydroxide was very low which agrees with the previous studies. Because of nil or very low adsorption of  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$  and  $\text{MoO}_4^{2-}$  onto Fe(III)/Cr(III) hydroxide, these ions hardly interfered with the adsorption of phosphate, while the other anions  $\text{VO}_3^-$ , and  $\text{SeO}_3^{2-}$  interfered with the adsorption of phosphate. When equimolar quantity of  $\text{VO}_3^-$  or  $\text{SeO}_3^{2-}$  was added to the phosphate,  $\text{VO}_3^-$  and  $\text{SeO}_3^{2-}$  reduced the sorption of phosphate by 17 and 6%, respectively. The results also indicate that sorption of vanadate is higher than phosphate when added equimolar quantities. This agrees with the result proposed by Blackmore et al. [37] in the adsorption of vanadate by iron oxyhydroxide. If there are specific sorption sites as proposed by Hingston et al. [38] available to a particular anion on goethite, we expect that there will be no interference on phosphate adsorption by other ions. On the other hand, phosphate adsorption was reduced by selenite and vanadate. This shows that there is no specific site on the adsorbent for phosphate, vanadate or selenite.

### 3.7. Conclusion

The present study revealed that the industrial solid waste, Fe(III)/Cr(III) hydroxide, can be used as low cost adsorbent for the removal of phosphate. Analysis of kinetic data showed that the uptake of phosphate on Fe(III)/Cr(III) hydroxide follows second order kinetics. Equilibrium adsorption data obey both Langmuir and Freundlich isotherms. Maximum removal occurred at pH 4. Coexisting anions such as  $\text{VO}_3^-$  and  $\text{SeO}_3^{2-}$  interfered with the adsorption of phosphate. Molybdate, sulphates, chloride and nitrate hardly interfered with the adsorption. Thermodynamic studies showed that adsorption was endothermic and spontaneous in nature.

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