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## Sorption of cobalt to bone char: Kinetics, competitive sorption and mechanism

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### ABSTRACT

Swine bone char is the combustion residues of swine bone. Cobalt adsorption to swine bone char was studied. Batch kinetics studies showed that a rapid uptake occurred during the first 5 min and was followed with a very slow intraparticle diffusion process. The sorption kinetics was ideally conformed to pseudo-second equation, indicating several mechanisms involved in the adsorption process. Equilibrium sorption isotherm studies showed that the Freundlich isotherm model satisfactorily described the sorption data. The presence of co-ions had appreciable inhibiting effects on cobalt uptake by bone char because copper and zinc had higher affinity for the bone char surface than cobalt. Calcium concentration in solution and XRD analysis showed that ion exchange was involved in the removal of Co from solution over a certain initial cobalt concentration range.

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### 1. Introduction

Contamination of aquatic environment by heavy metals is a worldwide environmental problem. A variety of methods are used to remove these toxic substances from effluents and industrial wastewater before discharging into a natural water body. The main treatment technologies include precipitation and coagulation, ion exchange, membrane processes and electrolytic technologies. However conventional treatment technologies like precipitation and coagulation become less effective and more expensive when situations involving high volumes and low metal concentrations are encountered [1]. The application of membrane processes and activated carbon are also restricted due to high costs. As a result, an inexpensive yet efficient adsorbent of heavy metals is desired in effluent cleanup. Recently, bone char has aroused much attention from wastewater treatment industry due to its advantages over other adsorbents. One advantage is that bone char is relatively inexpensive since it is made from spent bone. The other advantage is that bone char has been demonstrated as a versatile adsorbent for a wide variety of pollutants, including heavy metals, fluoride, arsenate and dyes [2–8]. Bone char is a product of pyrolysis of ground bone at over 800 °C in a limited supply of oxygen (O<sub>2</sub>). It is

mainly composed of calcium hydroxyapatite (CaHA), carbon and calcium carbonate. The hydroxyapatite has a good ability to remove inorganic cations [9], which has led to the development of its use in removing heavy metals from contaminated water [2].

Cobalt is widely present in various industrial wastewater including petrochemical wastewater, cobalt-bearing mineral mining and smelting wastewater and nuclear wastewater. Acute exposure to cobalt can induce nausea, vomiting and neurotoxicological symptoms such as headaches and changes in reflexes [10]. Chronic exposure to cobalt can induce partial or complete loss of smell, gastrointestinal troubles and dilation of the heart [10]. The objectives of this study were to examine the ability of bone char to remove cobalt (II) from an aqueous solution and the mechanisms of adsorption were also investigated.

### 2. Materials and methods

#### 2.1. Preparation of bone char

Swine bone was boiled for 10 min and the meat attached on the bone was removed. The bone char was produced as the modified method described by Lambert and Graham [11]. The bone was crushed into small fragments and burned by calcination in an electric muffle furnace programmed to reach 800 °C at 2 °C min<sup>-1</sup>, and further calcined at 800 °C for 4 h. The residues were washed with generous deionized water in order to remove soluble inorganic ions. After it was dried at 60 °C for 24 h, bone char was powdered and sieved through a 80 mesh sieve (<180 μm).

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## 2.2. Preparation of solution

Cobalt solution was made from Analar cobalt(II) chloride 6-hydrate ( $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ ). Stock solution ( $4000 \text{ mg L}^{-1}$ ) of cobalt ion was prepared using deionized water and subsequently diluted. The pH of the solutions was not adjusted. Cu (II) and Zn (II) were applied in the forms  $\text{CuCl}_2 \cdot \text{H}_2\text{O}$  and  $\text{Zn}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$  diluted in deionized water, respectively.

## 2.3. Effect of adsorbent concentration

Bone char with various mass was added into 20 ml of  $500 \text{ mg L}^{-1}$  cobalt solution. The suspension was shaken at 150 rpm at  $25^\circ\text{C}$ . After shaking, the solution was immediately filtered through  $0.22 \mu\text{m}$  filter paper. Calcium and cobalt concentrations in filtrate were measured by flame atomic absorption spectroscopy (Varian 6 AAS).

## 2.4. Effect of initial solution pH

The effect of pH on cobalt sorption to bone char was evaluated by adding 0.2 g of adsorbent into flasks containing 50 ml of  $25 \text{ mg L}^{-1}$  cobalt-bearing solutions at different initial pH (2–9). pH of the solutions was adjusted using 0.1 M HCl/NaOH. Flasks were shaken at 150 rpm at  $25^\circ\text{C}$  for 120 min. Initial and equilibrium pH of solutions and residual cobalt concentrations were measured.

## 2.5. Effect of competitive cations

The effect of competitive cations on cobalt sorption to bone char was investigated. The initial solution cobalt concentration was constant ( $200 \text{ mg L}^{-1}$ ) for all experiments. Concentrations of 50, 100, 150 and  $250 \text{ mg L}^{-1}$  of Cu (II) or Zn (II) were tested for competitive uptake with cobalt by bone char. A 200 mg sample of bone char was shaken with 20 mL of binary metal solution at 150 rpm and  $25^\circ\text{C}$  for 120 min. After shaking, the solution was immediately filtered through  $0.22 \mu\text{m}$  filter paper. Cobalt concentrations in filtrate were measured by flame atomic absorption spectroscopy (Varian 6 AAS).

## 2.6. Sorption kinetics studies

The kinetic sorption experiment was carried out as follows: 2 g of bone char were added to flasks containing 100 mL of  $500 \text{ mg L}^{-1}$  cobalt-bearing solution. Flasks were shaken at 150 rpm at  $25^\circ\text{C}$ . Aliquot amounts (2 mL) of solution were collected periodically. The samples were filtered and cobalt concentrations in filtrate were determined by flame atomic absorption spectroscopy on a Varian 6 AAS.

## 2.7. Isothermal sorption studies

The isothermal sorption experiment was carried out as follows: A 200 mg sample of bone char was shaken with 20 mL of metal solution of varying concentration ( $100\text{--}1000 \text{ mg L}^{-1}$  Co) at 150 rpm at  $25^\circ\text{C}$  for 120 min. After shaking, the solution was immediately filtered through  $0.22 \mu\text{m}$  filter paper. Calcium and Cobalt concentrations in filtrate were measured by flame atomic absorption spectroscopy (Varian 6 AAS).

All the sorption tests were triplicated and the standard error values ranged from 1.5% to 4%. The mean values were used.

## 2.8. XRD analysis of bone char

Bone char powder before and after sorption of cobalt was analyzed by X-ray diffractometry (XRD) using a D/Max III D diffractometer with  $\text{Cu K}\alpha$  a radiation. Measurements were made using a step-scanning

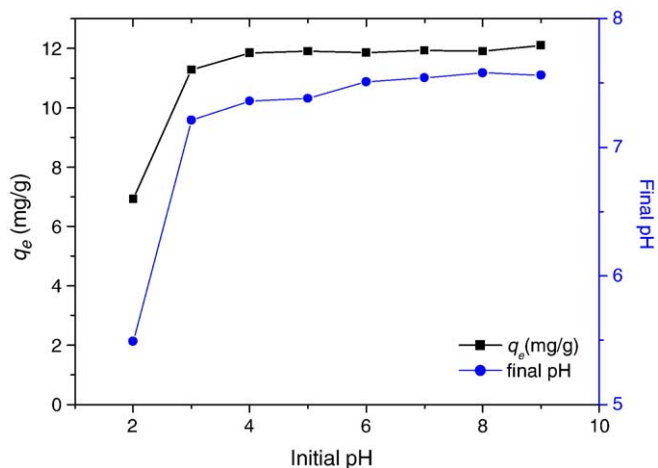


Fig. 1. Effect of pH on cobalt sorption and final pH.

technique with the diffraction angle,  $2\theta$ , step interval of 0.05 from  $5^\circ < 2\theta < 80^\circ$  and an acquisition time of 1 s per step.

## 3. Results and discussion

### 3.1. Effect of pH

Fig. 1 shows cobalt sorption capacity at different pH and the final pH of the solution. The lowest cobalt sorption capacity ( $6.93 \text{ mg g}^{-1}$ ) was found at an initial solution pH of 2. As the initial pH increased to 4, cobalt sorption capacity increased to  $11.28 \text{ mg g}^{-1}$ . Cobalt adsorption capacity varied little and the sorption capacity was kept constant (about  $11.9 \text{ mg g}^{-1}$ ) in the initial pH range 4–8. When the initial pH was 9, the sorption capacity was increased to  $12.1 \text{ mg g}^{-1}$ , which could be attributed to the precipitation of  $\text{Co}(\text{OH})_2$ . A study of the final pH showed that bone char exhibits excellent buffering properties. For the initial pH range 4–8, final pH values are almost kept the same value (7.2–7.6) and the sorption of cobalt is constant in this pH range. The buffering capacity of bone char could be attributed to the properties of its main component, CaHA. It was reported that acidic as well as basic solutions (in pH range 4–10) are buffered after reaction with the reactive surface sites of CaHA to its  $\text{pH}_{\text{pzc}}$  value [12,13]:



At an initial pH below  $\text{pH}_{\text{pzc}}$ , final pH increased due to consumption of protons from the solution by the protonation of surface  $\equiv\text{PO}^-$  and  $\equiv\text{CaOH}^0$  groups. In acidic solution, the surface charge of the CaHA was predominated by positively charged  $\equiv\text{CaOH}_2^+$  and neutral  $\equiv\text{POH}^0$  sites, making surface charge of HAP in this pH region positive. On the other hand, the higher initial pH (above  $\text{pH}_{\text{pzc}}$ ) resulted in a decrease in final pH due to  $\text{OH}^-$  consumption via deprotonation of surface  $\equiv\text{CaOH}_2^+$  and  $\equiv\text{POH}^0$  sites. Consequently, neutral  $\equiv\text{CaOH}^0$  and negatively charged  $\text{RPO}^-$  species prevailed on the surface of CaHA and CaHA surface became negatively charged [12,13].

### 3.2. Influence of concentration of adsorbent

As shown in Fig. 2, an increase of adsorbent concentration resulted in an increase of cobalt uptake by bone char. It was found that when the initial cobalt concentration was  $500 \text{ mg L}^{-1}$ , the cobalt removal percentage by bone char increased from 88.34% to 99.32% as bone char concentration increased from  $100 \text{ mg L}^{-1}$  to  $1000 \text{ mg L}^{-1}$ .

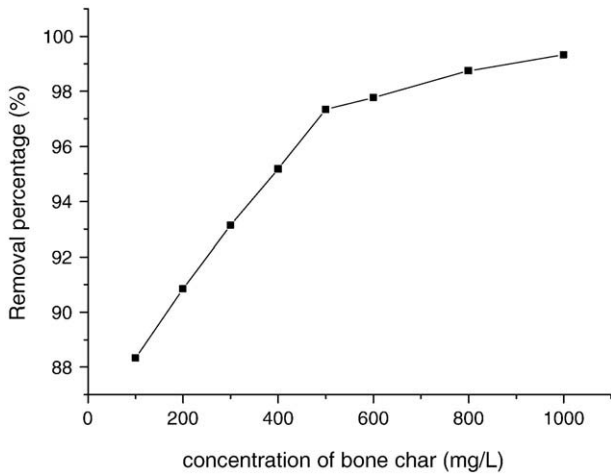


Fig. 2. Influence of dosage of adsorbent on cobalt removal percentage.

3.3. Kinetics studies

Pseudo-first order equal and pseudo-second order were employed to model the sorption data over the entire time range. The pseudo-first order equation of Lagergren [14] is generally expressed as follows:

$$dq / dt = k_1(q_e - q) \tag{3}$$

where  $q_e$  and  $q$  are the amount of metal sorbed per unit weight of sorbent at equilibrium and at time  $t$ , respectively ( $\text{mg g}^{-1}$  dry adsorbent) and  $k_1$  the rate constant of pseudo-first order sorption ( $\text{min}^{-1}$ ). Given the boundary conditions for  $t=0, q=0$ , the Eq. (3) can be integrated to give [15]

$$\log(q_e - q) = \log q_e - (k_1 / 2.303)t. \tag{4}$$

If the sorption process can be described by pseudo-first order equation, there should be good linear relationship between  $\log(q_e - q)$  and  $t$ . The pseudo-second order equation assumes that the sorption process involves chemisorption mechanism and the rate of site occupation is proportional to the square of the number of unoccupied sites. If the rate of sorption is a second order mechanism, the pseudo-second order chemisorption kinetic rate equation is expressed as [15]

$$dq / dt = k_2(q_e - q)^2 \tag{5}$$

where  $k_2$  is pseudo-second order rate constant ( $\text{g mg}^{-1} \text{min}^{-1}$ ). After integrating and applying boundary conditions for  $t=0, q=0$ , Eq. (5) becomes

$$t / q = 1 / (k_2 q_e^2) + t / q_e. \tag{6}$$

The rate constant  $k_2$  can be obtained from the intercept of the linearized pseudo-second order rate equation. If the pseudo-second order equation can fit the sorption data, there should be good linearity between  $t/q$  and  $t$ .

When  $t \rightarrow 0$ , the initial sorption rate  $u$  can be defined as

$$u = k_2 q_e^2. \tag{7}$$

Half-adsorption time ( $t_{1/2}$ ) is the time required for the adsorption to take up half as much cobalt as its equilibrium value. This time is an indicator for the adsorption rate. It was calculated from the following equation:

$$t_{1/2} = 1 / k_2 q_e. \tag{8}$$

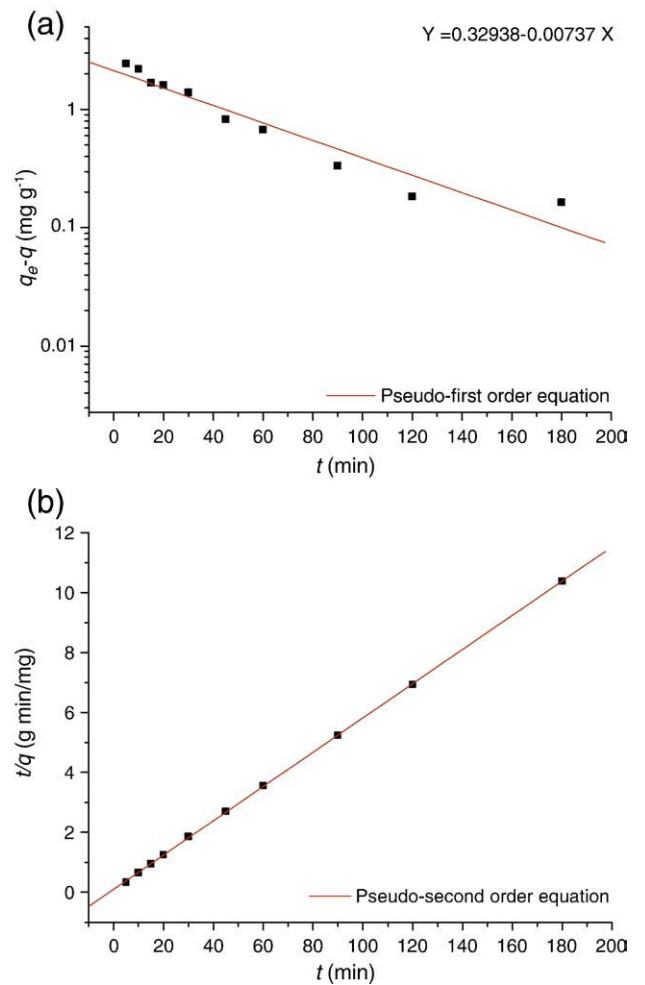


Fig. 3. (a) linear fit of experimental data obtained using pseudo-first order kinetic model ( $\log(q_e - q)$  versus  $t$ ); (b) linear fit of experimental data obtained using pseudo-second order kinetic model ( $t/q$  versus  $t$ ).

The relationship between  $\ln(q_e - q)$  versus time  $t$  in this work was not linear over the entire time range (Fig. 3(a),  $R^2 = 0.926$ ), indicating that more than one mechanism is involved in adsorption. However, Fig. 3(b) showed that the pseudo-second order equation was ideally applicable to all the sorption data ( $R^2 = 0.999, p < 0.0001$ ).  $q_e$  and  $k_2$  obtained by linear regression of  $t/q$  against  $t$  were  $17.50 \text{ mg g}^{-1}$  adsorbent and  $0.032 \text{ g mg}^{-1} \text{ min}^{-1}$ , respectively. The initial sorption rate  $u$  was  $9.8 \text{ mg kg}^{-1} \text{ min}^{-1}$  and half-adsorption time was  $1.79 \text{ min}$ .

3.4. Intraparticle diffusion studies

If the movement of the metal ion from the bulk liquid film surrounding the particle is ignored, the adsorption process can be divided into boundary layer diffusion, sorption of ions to sites and intraparticle diffusion. It is generally accepted that sorption of ions to sites is quite rapid and does not represent the rate determining step. Boundary layer diffusion is characterized by the initial rate of metal ion adsorption. This can be represented by the initial slope of  $C_t/C_0 - t$  ( $C_t$ , ratio of residual concentration in solution at time  $t$ ,  $C_0$ , the initial concentration) curves assuming that the relationship over the first 5–10 min is linear [16]. The initial rate of Co(II) ion adsorption to the bone char was  $0.235$ .

Intraparticle diffusion will be the rate limiting step in many cases and can be determined by using following equation [17]:

$$k_p = q / t^{1/2} \tag{9}$$

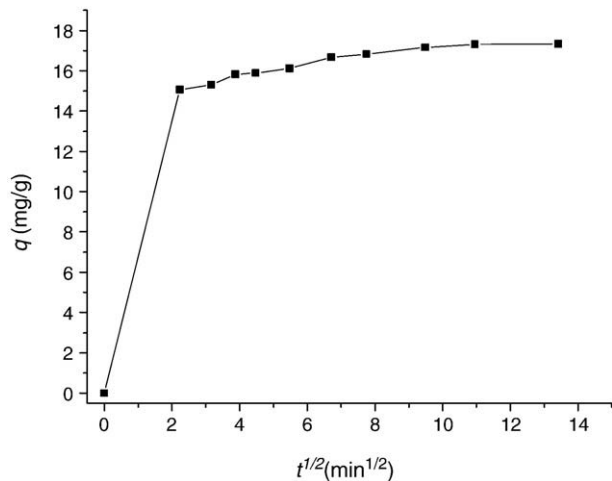


Fig. 4. The amount of  $\text{Co}^{2+}$  adsorbed ( $q$ ) versus square root of time ( $t^{1/2}$ ).

where  $q$  is the amount of metal adsorbed at time  $t$ , ( $\text{mg g}^{-1}$ ),  $k_p$  the intraparticle rate constant ( $\text{mg g}^{-1} \text{min}^{1/2}$ ).

The relationship between  $q$  and  $t^{1/2}$  was not linear over the entire time range (Fig. 4) and the multi-linear plots indicated that two or more steps influence the sorption process. Some researchers [16,18] also reported this non-linear relationship. They considered that there were both boundary diffusion and intraparticle diffusion. Boundary diffusion usually could be represented by the initial curved portion and intraparticle diffusion by the final curved portion. In the present study, cobalt sorption equilibrium was approached at 120 min and little cobalt was adsorbed to bone char from 120 min to 180 min. Intraparticle diffusion seems to be the rate determining step from 45 min to 120 min because there was good linearity over this time range ( $R^2 = 0.986$ ). The rate constant of intraparticle diffusion ( $k_p$ ), which was calculated from the slope of the final linear portion (from 45 min to 120 min), was  $0.157(\text{mg g}^{-1} \text{min}^{1/2})$ .

Theoretically, if the intraparticle diffusion was the only rate determining step, the initial rate parameter ( $k_i$ ) derived by the slope of linear regression between  $t = 0$  and  $t_{\text{lim}}$  (the first breakpoint of the curve) should be directly related to  $C_0^{1/2}$  [15]. In this study, the  $k_i$  was 6.74 and it was far less than  $C_0^{1/2}$  (14.14). This confirmed that intraparticle diffusion was not the only rate determining step for Co(II) adsorption by bone char over the entire sorption time range.

### 3.5. Equilibrium sorption isotherms

The equilibrium of the process was described by Langmuir and Freundlich isotherm models, respectively. The Langmuir isotherm model is a theoretical model for monolayer adsorption:

$$q = q_{\text{max}} b C_e / (1 + b C_e) \quad (10)$$

where  $q$  is the amount of metal adsorbed,  $\text{mg g}^{-1}$  (dry mass);  $q_{\text{max}}$  is the maximum metal uptake value corresponding to sites saturation,  $\text{mg g}^{-1}$  (dry mass);  $C_e$  is the equilibrium metal concentration in solution,  $\text{mg L}^{-1}$ ; and  $b$  is the ratio of adsorption/desorption rates.

The Freundlich isotherm model is an experimental model and it is usually expressed as follows:

$$q = k C_e^{1/n} \quad (11)$$

where  $k$  and  $n$  are constants related to sorption capacity and sorption intensity, other symbols are as previously described.

The sorption data over a concentration range 100–1000  $\text{mg L}^{-1}$  were well represented by the Freundlich isotherm model (Fig. 5(a),  $R^2 = 0.9962$ ). Most of the sorption data, however, did not follow the

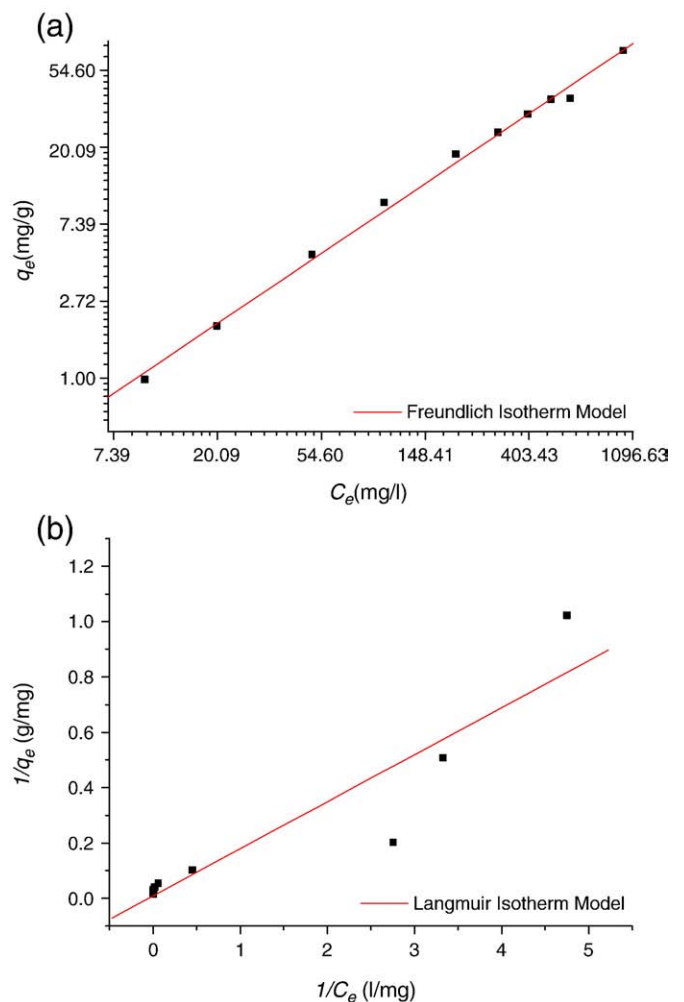


Fig. 5. (a) Freundlich adsorption isotherm; (b) Langmuir adsorption isotherm.

Langmuir isotherm model (Fig. 5(b),  $R^2 = 0.8668$ ). Constants of both isotherm models are listed in Table 1. Application of Freundlich model to the equilibrium data of Co(II) indicates the monolayer coverage of bone char by the ion of Co(II) but this was to non-distinct, or multiple, sites of adsorption, unlike the Langmuir model which is to distinct localized adsorption sites [19].

### 3.6. Influence of competitive cations

In order to study the effect of Cu (II) or Zn (II) on Co (II) adsorption to bone char, Co(II) concentration was kept at a constant value of  $200 \text{ mg L}^{-1}$ , while the concentrations of Cu (II) or Zn (II) varied from  $50 \text{ mg L}^{-1}$  to  $250 \text{ mg L}^{-1}$ . As shown in Fig. 6, both Cu (II) and Zn (II) ions had an appreciable effect on the cobalt uptake capacity by bone char. When Cu (II) and Co(II) were simultaneously present in the solution, 100% of copper was removed from the solution at an initial Cu (II) concentration from  $50 \text{ mg L}^{-1}$  to  $250 \text{ mg L}^{-1}$  whereas Co(II) removal percentage

Table 1

Constants for cobalt sorption by bone char with initial cobalt concentration ranged from  $100 \text{ mg L}^{-1}$  to  $1000 \text{ mg L}^{-1}$ .

Model	Constants	$R^2$	SD	$P$
Freundlich	$k = 0.1332, 1/n = 0.9088$	0.9962	0.09135	<0.0001
Langmuir	$q_m = 108.70, b = 0.0542$	0.8668	0.1257	<0.0001

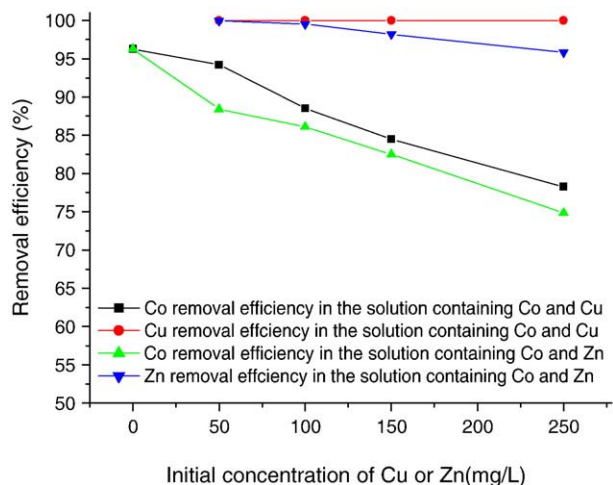


Fig. 6. Influence of competitive cations ( $\text{Cu}^{2+}$  or  $\text{Zn}^{2+}$ ) on the amount of  $\text{Co}^{2+}$  adsorbed by bone char.

decreased from 94.20% to 78.26% as the initial Cu (II) concentration increased from  $50 \text{ mg L}^{-1}$  to  $250 \text{ mg L}^{-1}$ . This result indicates that bone char has higher affinity for Cu (II) than Co(II). Similarly, it was also found that bone char had higher affinity for Zn (II) than Co(II). In the binary metal solution including Zn (II) than Co(II), Co(II) removal percentage decreased from 88.42% at an initial Zn(II) concentration of  $50 \text{ mg L}^{-1}$  to 74.86% at an initial Zn(II) concentration of  $250 \text{ mg L}^{-1}$ , whereas 99.95% to 95.85% of Zn (II) in the binary metal solution was adsorbed to bone char as the initial Zn (II) concentration increased from  $50 \text{ mg L}^{-1}$  to  $250 \text{ mg L}^{-1}$ . This study showed that the presence of Cu(II) or Zn (II) ions had inhibited cobalt sorption to bone char.

### 3.7. Mechanisms

The bone char is mainly composed of calcium hydroxyapatite (CaHA), carbon and  $\text{CaCO}_3$ . Some researchers noted that CaHA is not just a source for adsorption but also enables ion exchange to occur [20,21]. Calcium concentration in solution and XRD analysis showed that ion exchange was involved in removal of Co from solution over a certain initial cobalt concentration range. There was good linear relationship ( $R^2 = 0.9887$ ) between release of calcium into solution and cobalt adsorbed to bone char over a cobalt concentration range from  $10 \text{ mg L}^{-1}$  to  $1000 \text{ mg L}^{-1}$  (Fig. 7). However, the calcium released into solution was apparently influenced by the ratio of cobalt

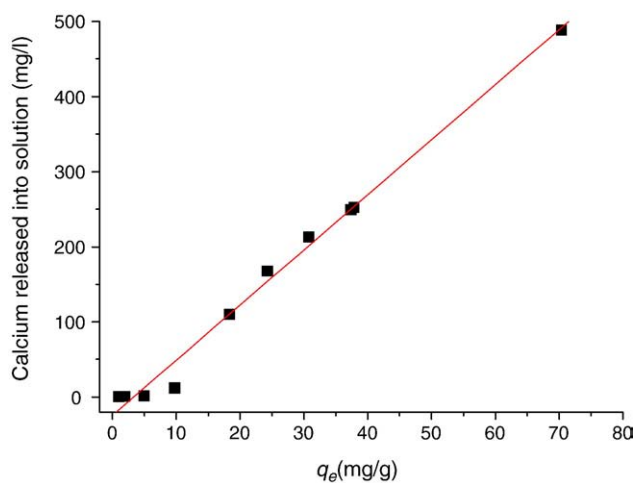


Fig. 7. Calcium released into solution versus the amount of cobalt adsorbed.

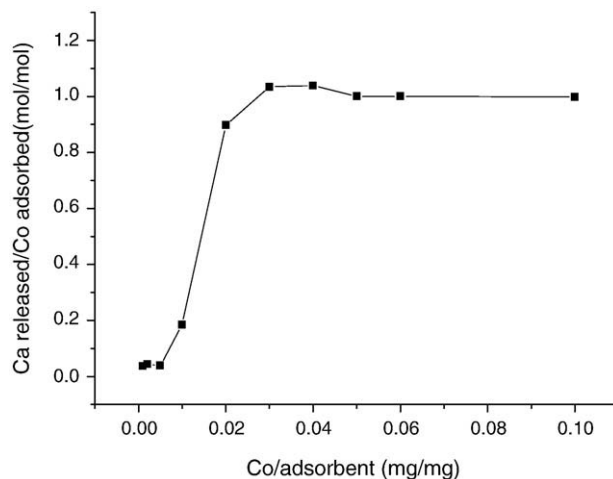
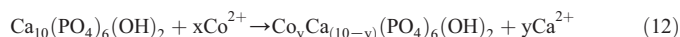
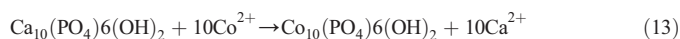


Fig. 8. The mole ratio of  $\text{Ca}^{2+}$  released to  $\text{Co}^{2+}$  adsorbed versus the mass ratio of cobalt to adsorbent.

to adsorbent (Fig. 8). When the ratio of cobalt to adsorbent was less than 0.03, only part of the cobalt substituted for calcium (Eq. (12)):



In this work, as the ratio of cobalt to adsorbent increased from 0.001 to 0.02, the ratio of mole calcium released to the mole of cobalt adsorbed increased from 0.037 to 0.8969. When the ratio of cobalt to bone char was greater than 0.3, nearly 1 mol of calcium was released as 1 mol of cobalt was adsorbed, indicating ion exchange was the most predominant mechanism.



Wilson et al. [22] reported that 0.72 mol or 0.2 mol calcium was exchanged for every one mol copper or zinc was adsorbed. The reasons for the differences between different metal sorption are still not clear.

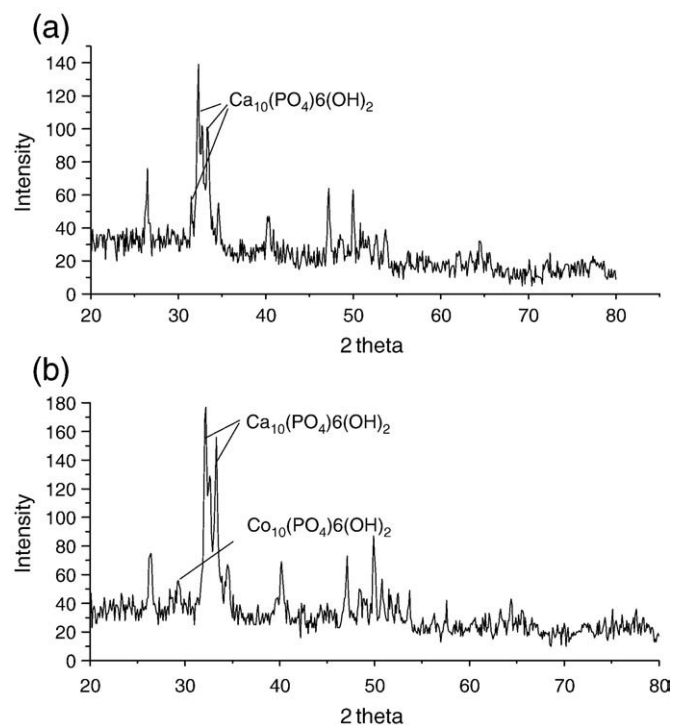


Fig. 9. XRD patterns of bone char before (a) and after (b) incubation with cobalt solutions.

Electronegativity, speciation, ion-size and amount of space in the d-orbitals are considered to have an influence [21,23]. XRD analysis showed that the small peak belonging to CaHA at the left shoulder of the big peaks disappeared after the bone char was incubated in cobalt solution for 3 h and the peak belonging to  $\text{Co}_{10}(\text{PO}_4)_6(\text{OH})_2$  appeared (Fig. 9).

The first portion of sorption kinetics indicated that a rapid uptake occurred during the first 5 min. Then, the metal uptake slowly reaches equilibrium. With initial cobalt concentration of  $200 \text{ mg L}^{-1}$  the metal removal percentage reaches 75.31%. The cobalt uptake capacity at 5 min was  $15.06 \text{ mg g}^{-1}$  and the cobalt uptake capacity at 24 h reached  $18.37 \text{ mg g}^{-1}$ , indicating that cobalt uptake reaction continued to go on with a very slow rate. Valsami-Jones et al. [24] and Deydier et al. [25] observed similar sorption step in lead sorption to apatite or bone char. On the basis of their explanation, the adsorbent particle was coated with insoluble  $\text{Co}_{10}(\text{PO}_4)_6(\text{OH})_2$  layer that was adsorbed at the earlier stage and it would act as a shield, dramatically decreasing phosphate dissolution rate and consequently  $\text{Co}^{2+}$  ions uptake. The cobalt uptake step could be explained by slow diffusion of cobalt in the solid, thus making cobalt phosphate an effective barrier.

To sum up, cobalt uptake was very rapid during the first 5 min, substantive calcium in CaHA was exchanged out by cobalt and the cobalt apatite coating was formed. Then slow diffusion of cobalt in the solid went on very slowly during the following long period.

#### 4. Conclusions

Swine bone char is effective in removing cobalt from solution. Batch kinetics studies showed that a rapid uptake occurred within the first 5 min and the metal uptake slowly reaches equilibrium. The kinetics of cobalt sorption by bone char was ideally conformed to pseudo-second equation, indicating several mechanisms are involved in the adsorption process. Equilibrium sorption isotherm studies showed that the Freundlich isotherm model satisfactorily described the sorption data. The presence of co-ions such as copper and zinc had appreciable inhibiting effects on cobalt uptake by bone char because copper and zinc had higher affinity for bone char surface than cobalt. Calcium concentration in solution and XRD analysis showed that ion exchange was involved in the sorption process over a certain initial cobalt concentration range. When the ratio of cobalt to bone char was greater than 0.3, nearly 1 mol of calcium was released as 1 mol of cobalt was adsorbed.

#### List of symbols

$q_e$	the amount of metal sorbed per unit weight of sorbent at equilibrium, $\text{mg g}^{-1}$ adsorbent;
$q$	the amount of metal sorbed per unit weight of sorbent at time $t$ , $\text{mg g}^{-1}$ adsorbent;
$k_1$	the rate constant of pseudo-first order sorption, $1/\text{min}$ ;
$k_2$	pseudo-second order rate constant, $\text{g mg}^{-1} \text{ min}^{-1}$ ;
$C_t$	ratio of residual concentration in solution at time $t$ , $\text{mg L}^{-1}$ ;
$C_0$	the initial concentration, $\text{mg L}^{-1}$ ;
$k_p$	the intraparticle rate constant, $\text{mg g}^{-1} \text{ min}^{1/2}$ ;
$k_i$	the initial rate parameter;
$u$	the initial sorption rate;
$t_{\text{lim}}$	the first breakpoint of the diffusion curve, min;
$q_{\text{max}}$	the maximum metal uptake value corresponding to sites saturation, $\text{mg g}^{-1}$ dry adsorbent;
$C_e$	the equilibrium metal concentration in solution, $\text{mg L}^{-1}$ ;
$b$	the ratio of adsorption/desorption rates in Langmuir model;
$k$	rate constants of Freundlich model related to sorption intensity of a sorbent;
$n$	rate constants of Freundlich model related to sorption intensity of a sorbent.
$\text{pH}_{\text{pzc}}$	the pH of the point of zero charge

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