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Comprehensive Investigation of Important Factors Governing Metal-Ion Adsorption by an H-Type Granular Activated Carbon

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ABSTRACT

A comprehensive experimental investigation of metal ion adsorption by Filtrasorb 200, an H-type activated carbon, was carried out. Potentiometric titration of the carbon showed that surface charge was increased with a decrease in pH. Its absolute value increased with an increase in ionic strength. Higher pH and ionic strength and lower initial concentration increased the metal-ion removal percentage. The removal capacity for a single metal ion was in the following descending order: Cu $>$ Zn $\approx$ Co. Experiments with competitive metal ions showed that adsorption of zinc and cobalt ions was reduced dramatically with the addition of copper, while adding zinc or cobalt was less important for copper removal.

Kinetic study showed that most copper removal occurred in the first hour and was completed within 4 h. Mass transfer was an important controlling factor in the metal uptake rate. The effect of pH on the removal kinetics seemed to be insignificant; however, higher ionic strength and initial metal concentration can result in faster adsorption. Adsorption kinetics was much faster for copper than for zinc. The addition of competitive metal ions did not affect other metal-ion adsorption kinetics.

Key Words. Adsorption; Metal ions; Equilibrium; Kinetics; Multi-component; Competitive effect

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INTRODUCTION

Heavy metals such as Cu^{2+}, Pb^{2+}, Zn^{2+}, and Co^{2+}, released into watery environments are toxic to human beings if their concentrations exceed tolerance levels. Toxicity of heavy metals has triggered a number of studies aimed at removal of the metal ions from aqueous solutions. In treatment of wastewater streams containing heavy metals, precipitation is a commonly used treatment approach. However, the effectiveness of precipitation depends strongly on the composition of the wastewater. In addition, precipitation produces sludge that requires further treatment. Ion exchange and adsorption have been alternative methods for removing metals.

One effective treatment, adsorption by various types of activated carbon, has been used for removing toxic metal pollutants from aqueous solutions (1–15). H-type and L-type activated carbons are commercially available (16–18).

H-type carbons are activated at high temperatures and adsorb hydrogen ions. The raw carbons are first heated to 1200°C in a vacuum or carbon dioxide atmosphere, then exposed to air at room temperature. Examples of H-type activated carbons are coconut-shell-based activated carbons and coal-dust activated carbons such as Filtrasorb 400 and 200. The predominant oxides on the surface of an H-type carbon are lactones, quinones, phenols, and carboxylates (17).

L-type carbons are low-temperature oxidized carbons that primarily adsorb OH^- ions. The raw materials are heated at about 200–400°C in air. Wood-based activated carbons, such as WAC5, are L-type carbons. The predominant functional groups on the surface of L-type carbons include carboxyl, phenolic hydroxyl, carbonyl, carboxylic acid, anhydrides, lactone, and cyclic peroxide (18).

Numerous studies on metal adsorption have been conducted by using H-type activated carbons. H-type adsorption is strongly pH dependent. Corapcioglu and Huang used 14 brands of activated carbons from Nuchar, Filtrasorb, and Darco (4); adsorption of copper ions by activated carbon increased dramatically from pH 3 to 5. Reed and Matsumoto (5, 6) showed that the adsorption edge for cadmium ranged from pH 3.5 to 9 when Darco HDB or Nuchar SN was used. Adsorption-equilibrium experiments with initial pH ranging from 2 to 3.5, three initial concentrations ($c_o = 7 \times 10^{-5}$ M, 3×10^{-4} M, and 8×10^{-4} M) and Filtrasorb 400 were carried out by Chen et al. (11). The removal efficiency increased from 10% to 95% and the adsorption edge ranged from pH 2.3 to 7.

Experiments researching metal ion adsorption kinetics show that adsorption follows two phases. Rapid sorption occurs initially, followed by a much slower phase, from a few hours to several weeks. Huang and Smith (14) investigated cadmium adsorption kinetics by using activated carbon Nuchar SN and Nuchar SA at various values of pH and concentration of sorbents, and in the presence of CN^- and BF_4. They found that maximum adsorption was reached in the first two minutes. Thirty minutes was enough for the complete adsorption of lead and copper (initial concentrations of 9.5 and 9.8 mg/L, respectively) by Barney Cheney NL 1266 (carbon amounts of 0.2 g/L and 0.5 g/L for lead and copper, respectively) as reported by Netzer and Hughes (12). However, the equilibrium time was increased to 120 min when 3 g/L activated carbon was used to treat cobalt with an initial concentration of 9.3 mg/L. Reed and Matsumoto (5, 6) used Darco HDB and Nuchar SN to remove cadmium and found that the adsorption of cadmium was completed in 6 h.

Metal-ion adsorption with granular activated carbon was slower than adsorption with powdered activated carbons (5). Rubin and Mercer (15) reported that the equilibrium time for the 8–10 mesh activated carbons was 95 h, whereas cadmium sorption achieved equilibrium in 6 h with 50–200 mesh carbons. Mass transfer is important in metal-ion-removal kinetics according to these experimental findings. Moreover, Chen et al. (11) used a kinetic model to describe the copper removal rate with good agreement between the modeling and experimental results. The equilibrium relationship in their stimulation was based on the surface complex formation model.

Most studies have considered pH, concentration, and types of activated carbons. The effect of ionic strength seldom appears in the literature, even though it is intensively studied in metal-ion adsorption onto hydrous oxides. Comparison of adsorption capacities for various metal ions is rarely considered. Moreover, most studies focus on single-component metal-ion adsorption. However, multi-component metal-ion adsorption is normally involved in treatment systems, as well as natural surface and subsurface systems. Although activated carbon provides important mitigation against heavy metals, little is known about competitive metal-adsorption behavior in complicated aqueous environments. Compared to single-component metal-ion adsorption, relatively few data are available on multicomponent metal-ion adsorption.

The main objective of this study was to investigate the adsorption equilibrium and kinetics of single- and multicomponent metal ions onto Filtrasorb 200, a major brand of granular activated carbon. Copper, zinc, and cobalt were chosen because of their high toxicity across a wide pH range in wastewater. The experiments were first conducted to obtain an understanding of characteristics of single-component metal adsorption. Effects of pH, ionic strength, and initial concentration on metal-ion adsorption were investigated. To compare the adsorption capacities for various metal ions, single-component metal adsorption of copper, zinc, and cobalt was studied. Further studies of multicomponent metal-ion adsorption (Cu-Zn, Zn-Co, and Cu-Zn-Co) in batch reactors were carried out to determine the competitive effects on individual metal-ion removal. Finally a series of kinetic experiments was conducted to study the effects of particle size, solution pH, initial concentration, and competitive metal ions on the uptake of the metal ions. Experimental data obtained from this study are being used to develop models for adsorption equilibrium and kinetics. Furthermore, the results obtained here will be helpful in the design of adsorption units for metal removal.

MATERIALS AND METHODS

Materials

Filtrasorb 200 from Calgon (Pittsburgh, PA) with size 20–32 mesh was used in this study. The specific surface area (S) was found to be 1008.8 m^2/g by a BET test, much higher than the value of 482 m^2/g reported in the literature (4, 13). Cupric chloride from J. T. Baker (Phillipsburg, NJ), and sodium chloride, zinc chloride, hydrochloric acid, and sodium hydroxide from Merck (Germany), and cobalt chloride hexahydrate from Aldrich (Milwaukee, WI) were used in this work. All chemicals were of reagent grade. A shaking water bath (GFL 1083, Germany) was used in this study. Laboratory film (parafilm) from American National Can (Chicago, IL) was used to cover the flasks to prevent the dissolution of carbon dioxide.

Analytic Methods

Concentration of metal ions was measured by an Inductively Couple Plasma Emission Spectroscopy (ICP) (Perkin Elmer Optima 3000, USA). The solution pH was measured by an Orion model 525A pH meter (Boston, MA). All samples were acidified and filtered (Whatman Autovial syringeless 0.45 PTFE from Clifton, NJ) before analysis. Titration experiments were carried out using an automatic titrator (Metrohm 716 DMS Titrino, Switzerland). The specific surface area of granular activated carbon was obtained using a BET test by AutoSorb-1-C (Quantachrome).

Potentiometric Titration

Activated carbon (2.5 g) was added to conical flasks containing 250 mL of 0.05 M sodium chloride solution. The activated carbon was kept in solution in a shaker for 24 h. Titration was then carried out by using 0.1 M hydrochloride acid or 0.01 M sodium hydroxide solution. The equilibrium time needed to establish surface charge was assumed to be 2 h. The titration was conducted at ionic strength of 0.005 and 0.05 M.

Equilibrium Experiments

Metal-ion solutions at different concentrations were prepared. The solution pH was adjusted by adding hydrochloride acid, and the ionic strength was kept at 0.05 M by adding sodium chloride. A 100 mL volume of solution was added to a 125 mL conical flask. One gram of GAC was then added to each flask. The flasks were placed in a shaking water bath with temperature controlled at 25° C for 48 h, which was determined by several kinetic experiments. The final samples were acidified, filtered, and analyzed by the ICP. The final pH of the solution was also measured. The same experiments were conducted at ionic strength of 0.005 M. In competitive adsorption experiments, all the metal ions with the same concentration were added to the solution simultaneously. Other procedures were the same as the adsorption experiments with the single metal ions.

Kinetic Experiments

Two series of kinetic experiments, with and without pH control, were carried out. In the experiments without pH control two 250 mL solutions were prepared. Ionic strength of the solutions was kept at 0.05 M by adding sodium chloride. Initial concentrations of metal ion were 1×10^{-4} M and 0.5×10^{-4} M. Activated carbon (2.5 g) was then added to the solution. The solution pH was monitored and at a certain time interval a sample was taken, acidified, filtered, and analyzed by the ICP. The experiments were than conducted the ionic strength of 0.005 M.

The adsorption kinetic experiments with pH control were slightly different from those without pH control. The pH values of the solutions were kept at a constant value of 3 and 6, which was accomplished by using the automatic titrator. Other procedures were the same as those for the kinetic experiments without pH control.

RESULTS AND DISCUSSION

Potentiometric Titration

Titration results of activated carbon at different ionic strengths are shown in Fig. 1. The intersection of the titration curves gives the point of zero charge (pH_{PZC}) as 7.2. This value is lower than the values of 8.2 for Filtrasorb 200 (4, 10, 13) and 9.5 for Filtrasorb 400 (11). The surface-charge density defined by uptake of protons by the surface is determined by the potentiometric titration as (19),

$$\sigma_o = \frac{(c_A - c_B + [\mathrm{OH}^-] - [\mathrm{H}^+])F}{Sa} \tag{1}$$

where c_A and c_B are the concentrations of acid and base needed to reach a point on the titration curve, in mol/L, $[\mathrm{H}^+]$ and $[\mathrm{OH}^-]$ are the concentrations of H^+ and OH^-, in mol/L, F is the Faraday constant (96,490 C/mol), S is the spe-

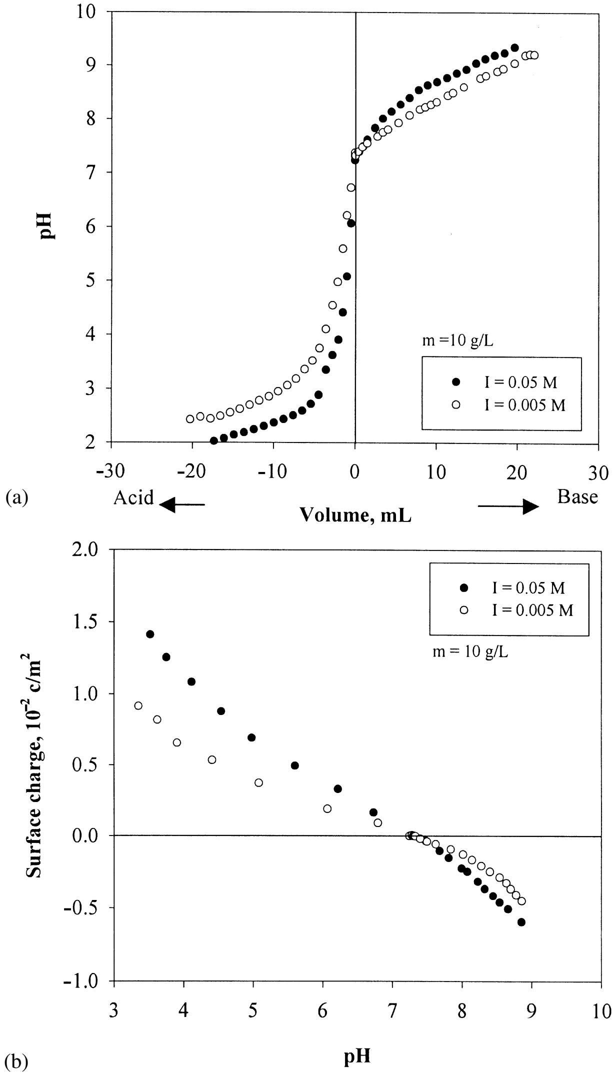

FIG. 1 Potentiometric titration of activated carbon with various amounts of acid or base at various ionic strength values: (a) pH curves, (b) surface charge-curves.

cific surface area, in m^2/kg, and a is the concentration of activated carbon, in kg/L.

The surface charge as a function of solution pH is shown in Fig. 1(b). As the pH increases, the surface charge decreases. The surface charge is negative when the solution pH is above pH_{PZC} and positive when pH is below pH_{PZC}. This behavior implies that adsorption of metal ions could be higher at higher pH. It was also observed that the absolute values of the surface charge increase with an increase in ionic strength.

The surface charges are the result of adsorption reactions on the activated-carbon surface (4, 9, 13, 20, 21). The surface contains ionizable functional groups, which can be represented as SOH. The surface charges of activated carbon become dependent on the degree of ionization and consequently on the solution pH, according to the following reactions

$$\mathrm{SOH} + \mathrm{H}^+ = \mathrm{SOH}_2^+ \tag{2}$$

$$\mathrm{SOH} = \mathrm{SO}^- + \mathrm{H}^+ \tag{3}$$

At low pH (i.e., high concentration of hydrogen ions), a positively charged surface prevails, whereas a negatively charged surface is formed when pH is high. Furthermore, as ionic strength is increased, compression of the electrostatic double layer (EDL) takes place, which results in an increase in the absolute values of surface charge.

Adsorption Equilibrium of Single-Component Metal Ions

Equilibrium experiments of copper-ion adsorption were conducted under various pH values. The experimental results show that the adsorption of metal ions on activated carbon is strongly pH-dependent, as illustrated in Fig. 2(a). The metal-ion removal efficiency increases from 5% to 99% from pH 2.0 to 5.5. Corapcioglu and Huang (4) reported that the adsorption edge for copper ion ranges from pH 2.5 to 5.0, while Reed and Matsumoto (5, 6) showed that the adsorption edge for cadmium ranges from pH 3.0 to 9.0. Chen et al. (11) showed that the removal efficiency increases from as low as 10% to 95% in pH 2.3 to 7. Comparison of our findings with those in the literature show that the adsorption edge here is slightly narrow. This indicates that Filtrasorb 200 is a better activated carbon, because narrow adsorption edge means that more metal ions can be removed.

The increase in removal could be related to surface charges that are strongly dependent on the pH of the solution. As pH increases, more negatively charged sites are available, which results in higher metal-ion removal efficiency. In addition to the availability of negative surface charges, adsorption reactions play an important role. The mechanisms for metal-ion adsorption can be proposed as (4, 9, 13, 20, 21)

$$\mathrm{SOH} + \mathrm{Cu}^{2+} = \mathrm{SO}^-\,\mathrm{Cu}^{2+} + \mathrm{H}^+ \tag{4}$$

As pH is increased, concentration of hydrogen ions is decreased, which causes the equilibrium of the reaction to shift from left to right. More copper ions, therefore, are adsorbed onto the activated carbon.

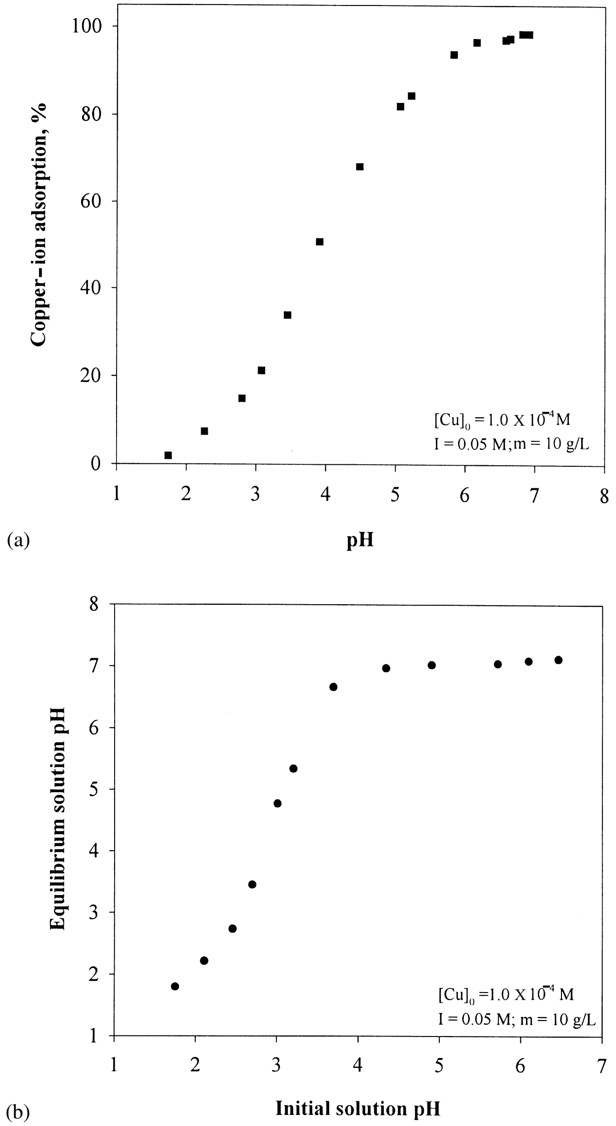

FIG. 2 Equilibrium of copper-ion adsorption: (a) effect of pH, (b) variation of pH.

In this study, initial copper-ion concentration was 1×10^{-4} M, and pH ranged from 2 to 8. At high pH, copper ions can precipitate in the form of tenorite (CuO) (19)

$$Cu^{2+} + H_2O = CuO + 2H^+ \qquad pK = 7.56 \tag{5}$$

As stated under Material and Methods, all samples were acidified before analysis to prevent any precipitation. The concentration measured was the total concentration instead of the nonprecipitated copper-ion concentration. Copper-ion removal by the activated carbon was due to adsorption of soluble metal ions instead of precipitation. Because copper ions can be precipitated at a pH level higher than 5.8, adsorption of tenorite on the surface of activated carbon could lead to some metal-ion removal.

Equilibrium experiments of copper-ion adsorption show that the equilibrium pH is a function of initial solution pH as demonstrated in Fig. 2(b). The solution pH at equilibrium was increased dramatically from 1.5 to 7 when the initial pH was adjusted from 1.5 to 4.5. When the initial pH is higher than 4.5, the pH of the solution at equilibrium stays close to pH 7.3. The emission of gas was also observed when the activated carbon was added into the metal solutions. Because Filtrasorb 200 (H-type activated carbon) can adsorb hydrogen ions from the solution, the solution pH increases. Because of the subsequent increase in the solution pH, the surface of activated carbon becomes negatively charged and more functional groups are available, resulting in higher removal of metal ions.

The effect of ionic strength on copper-ion adsorption is shown in Fig. 3. Higher metal-ion removal takes place when the ionic strength of a solution is higher. The EDL of activated carbon is compressed when the ionic strength of the solution is increased. Therefore, this can cause more adsorption of metal

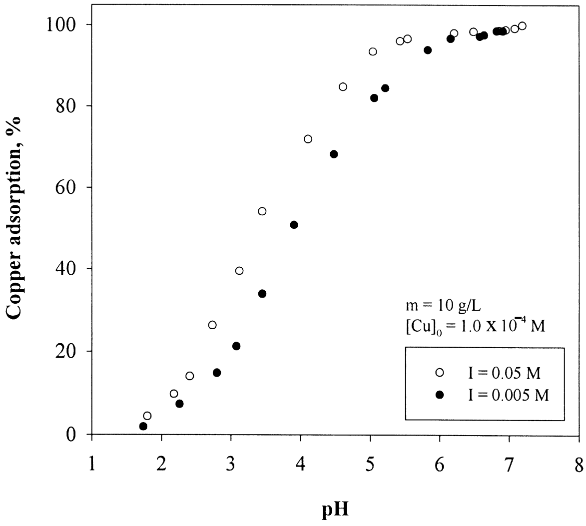

FIG. 3 Effect of ionic strength on copper-ion adsorption.

ions from aqueous solutions. The effect differs from that caused by biosorbents, as reported by Chen et al. (22), wherein less metal ions are adsorbed by calcium alginate (one of the biosorbents) because of the competition between metal ions and cations for the functional groups.

When the initial concentration of copper ion is increased, metal removal is decreased, as shown in Fig. 4. As adsorption capacity (or concentration of adsorption sites) of the activated carbon is limited, the total amount of metal ions adsorbed is limited. Therefore, the relative adsorption amount, i.e., copper-removal percentage, is lower for the higher initial concentration. In addition, the higher surface coverage resulting from the increase of metal-ion concentration raises the activation energy for reaction, thereby making it more difficult for the surface to bind metal ions (23).

Equilibrium experiments with zinc and cobalt were also performed, with the results demonstrated in Fig. 5, together with the results for copper adsorption. Only one kind of metal ion was added to each solution. Adsorption of zinc and cobalt ions on activated carbon is also strongly dependent on solution pH. Higher solution pH results in higher metal-ion removal. The adsorption curves of zinc and cobalt ions are almost identical and significantly differ from the copper adsorption curve. The adsorption of zinc and cobalt starts at pH 4, whereas adsorption of copper begins at pH 2. The amount of metal ions adsorbed on the activated carbon is in the descending order $Cu^{2+} > Zn^{2+} \approx Co^{2+}$. For example, at pH 5, the metal-ion-removal percentages for copper, zinc, and cobalt are 94%, 30%, and 28%, respectively.

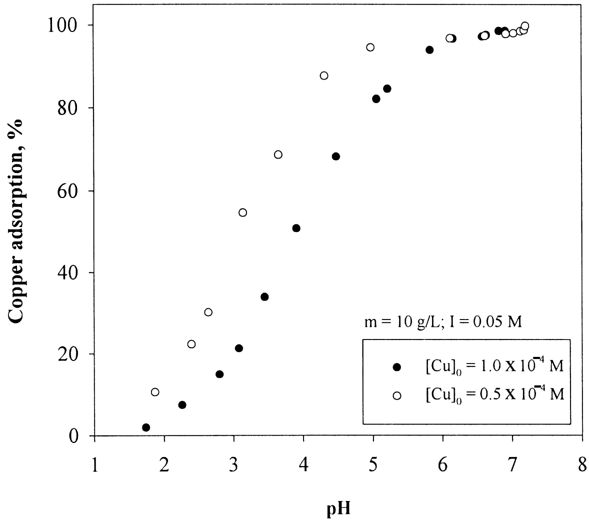

FIG. 4 Effect of initial copper concentrations on its adsorption.

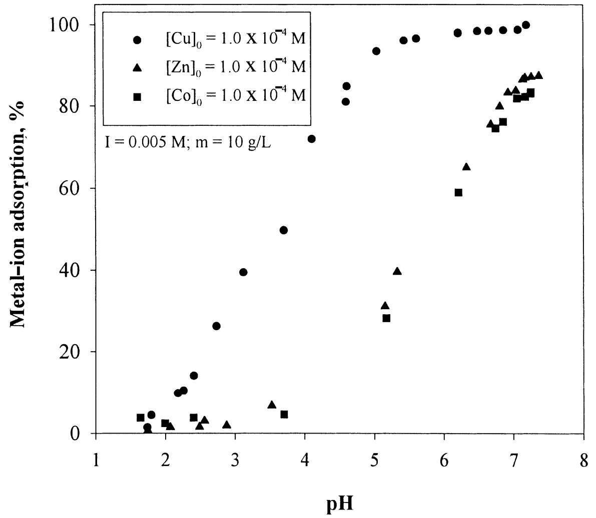

FIG. 5 Comparison of metal-ion adsorption among copper, zinc, and cobalt.

At a fixed pH, the surface-charge density is always independent of the types of metal ions in the solutions. The role of electrostatic repulsion or attraction is therefore the same for metal ions. Difference in adsorption capacities for copper, zinc, and cobalt must be caused by other physical properties and chemical reactions.

Pauline ionic radii of these metal ions are as follows: Cu^{2+} − 0.069 nm, Zn^{2+} − 0.074 nm, Co^{2+} − 0.074 nm (24). Because copper ions have the smallest radius, they can easily penetrate into smaller pores in activated carbon and thus have greatest access to the interior carbon surfaces. In addition to physical properties, adsorption reactions can contribute to the difference in the adsorption capacity for various kinds of metal ions.

Surface-complex formation between the metal ions and functional groups can play an important role. On the basis of the observations here, the functional groups had higher affinity for copper than for zinc and cobalt.

Normally the constants of reactions between organic compounds and metal ions were also in the order $Cu^{2+} > Zn^{2+} \approx Co^{2+}$ (25). For example, constants of reaction between L-2-aminopropanoic acid (alanine) and copper, cobalt, and zinc are $10^{8.11}$ M^{-1}, $10^{4.31}$ M^{-1}, and $10^{4.58}$ M^{-1}, respectively (25). The metal-ion adsorption order observed in this study is in agreement with this order. As activated carbon and organics (such as alanine) have similar functional groups, such as carboxyle and hydroxyl groups (26, 27), the trends of the removal of copper, zinc, and cobalt are similar to those of reaction constants between organics and metal ions.

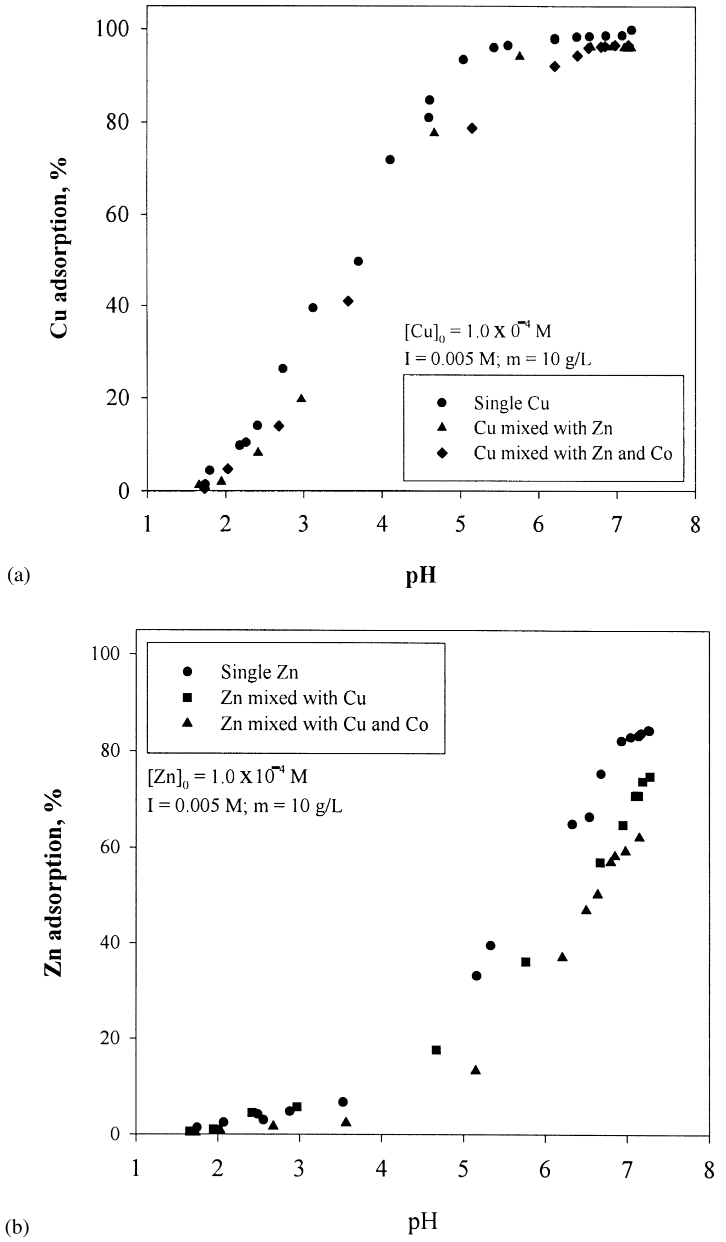

FIG. 6 Effect of competitive metal ions on adsorption: (a) copper, (b) zinc, and (c) cobalt.

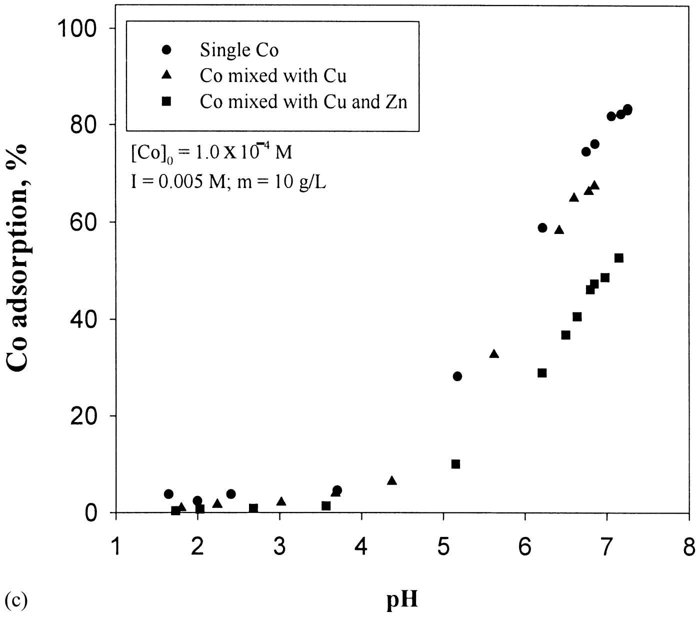

FIG. 6 Continued

Adsorption Equilibrium of Multi-Component Metal Ions

To find out the competitive effect in a solution containing two or three different metal ions, equilibrium experiments at various pH values were carried out, with the results presented in Fig. 6. Initial concentrations of various metal ions in these experiments were 1×10^{-4} M. The adsorption of copper, zinc, and cobalt ions was increased dramatically by increasing pH from 1.5 to 7.5. The adsorption removal of copper ions is slightly hindered by the presence of the other metal ions, as illustrated in Fig. 6(a). Because copper affinity for activated carbon is the highest among these metal ions, the inhibitory effect of added cations (zinc or cobalt) is not significant, which was also observed by Netzer and Hughes (12). On the other hand, Figs. 6(b) and 6(c) demonstrate that zinc and cobalt ion adsorption are reduced significantly by the presence of copper or other metal ions. As the strongly binding metal (Cu) is added, it occupies more adsorption sites, which in return decreases the sites for zinc and cobalt adsorption.

Adsorption Kinetics of Single Metal Ions

Adsorption kinetic experiments using two sizes of activated carbon were carried out to determine the adsorption equilibrium time and controlling step of this process. Most copper-ion adsorption takes place in the first hour, followed by a slower process (Fig. 7). The adsorption equilibrium is established in 3 h. The equilibrium time is shorter than that for metal-ion adsorption by other kinds of activated carbon (6, 11), hydrous oxide (28), and biosorbents (21, 22).

Reed and Matsumoto (6) reported that the equilibrium time for the adsorption of Cd^{2+} by the activated carbon was 6 h, while Lo and Leckie (28) showed that the adsorption of Cd^{2+} on amorphous aluminum oxide reached equilibrium in 60 h. Chen et al. (11) used Filtrasorb 400 to treat copper wastewater of 7×10^{-5}, 3×10^{-4}, and 8×10^{-4} M. Most of the adsorption was observed in the first hour, followed by a slower adsorption that lasted for approximately 4 h. Wilczak and Keinath (29) reported that initial adsorption of copper and lead onto Nuchar SA and Filtrasorb 400 occured rapidly, followed by a slow adsorption step that took about 35 d, which was probably due to slower shaker speed. Chen and co-workers (21, 22) reported that copper-ion removal by calcium alginate beads reached equilibrium in 15 h.

Comparison of the adsorption kinetic curves in Fig. 7 indicates that adsorption by 32–65 mesh activated carbon is faster than adsorption by 20–32 mesh activated carbon in the initial phase of adsorption. Adsorption equilibrium experiments with the same amounts of these two kinds of activated carbon pellets demonstrated identical levels of metal-ion removal. The BET test found that these two activated carbons have approximately the same specific surface area. The size of the activated carbon has no influence on the adsorption ca-

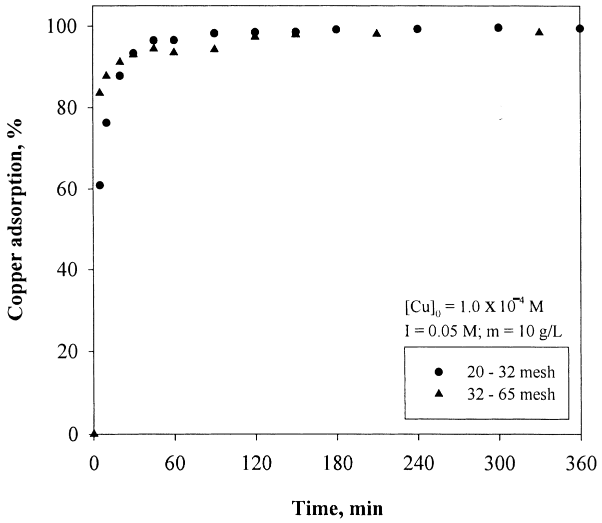

FIG. 7 Comparison of copper adsorption kinetics by activated carbon with different sizes.

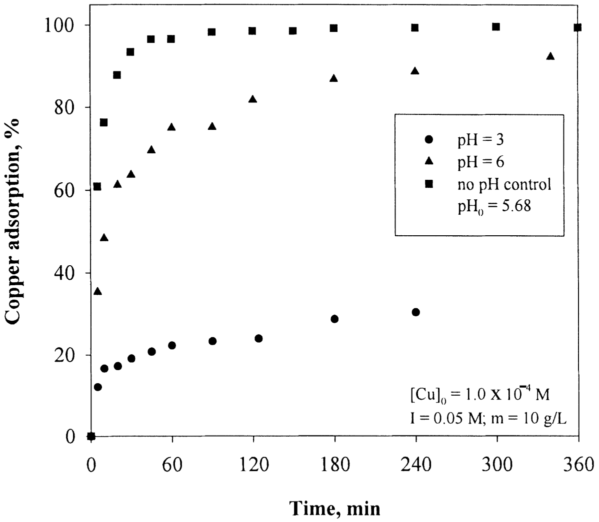

FIG. 8 Effect of pH on copper adsorption kinetics.

pacity (final removal) according to our experiments (not shown here). This clearly shows that the effect of mass transfer on adsorption kinetics is an important factor.

The results of three kinetic experiments, two at pH 3 and 6 controlled by using the titrator, and one at initial pH 5.68 (without pH control), are presented in Fig. 8. A higher percentage of removal occurs at higher pH levels, similar to the adsorption equilibrium experiments shown previously. Most of the adsorption is observed in the first hour, and the equilibrium is established within approximately 3 h. The effect of pH on removal kinetics seems to be insignificant. Experiments without pH control show higher removal than those with pH control. As discussed before, the solution pH is increased as soon as the activated carbon is added. As a result, the increase in pH causes higher removal of copper ions.

The effects of initial concentration and ionic strength were investigated; the results are illustrated in Fig. 9. The solution pH was not controlled in these experiments. As was observed in the previous kinetic experiments, the removal increased rapidly in the first hour. Adsorption reached equilibration in 3 and 4 h for initial concentrations of 1×10^{-4} M and 0.5×10^{-4} M, respectively. The kinetics increased as the initial concentration is increased, in agreement with Chen et al. (11). Because of the control of adsorption kinetics by mass transfer, as discussed previously, the metal uptake rate is proportional to the difference between concentration in the solution and that on the surface of activated carbon (11, 20, 21). When the initial concentration is increased, the kinetic rate therefore increases.

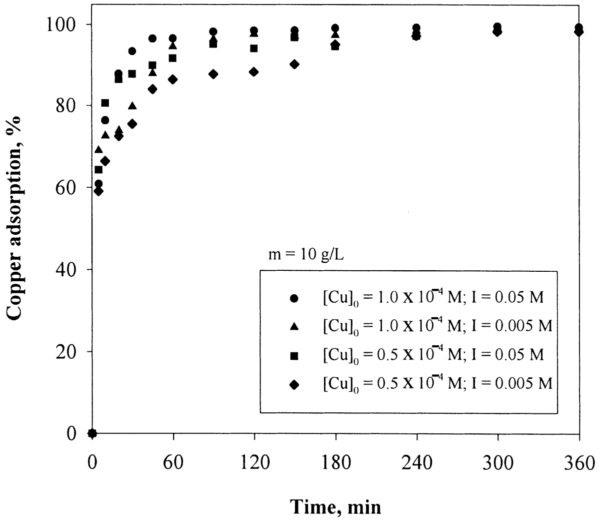

FIG. 9 Effect of ionic strength and initial copper concentration on its adsorption kinetics.

Higher ionic strength leads to higher metal-removal kinetics. As the EDL is compressed when ionic strength is increased, adsorption of copper ions from the aqueous solution is enhanced. During the experiments, the solution pH was increased until it reached 7.5. As shown in Fig. 3, the effect of ionic strength can be negligible when pH reaches 7. As a result, there is no significant difference in copper removal at equilibrium.

Adsorption Kinetics of Multicomponent Metal Ions

Kinetic experiments of multicomponent metal-ion adsorption were conducted to investigate the effect of competitive metal ions on adsorption kinetics. In the experiment with a solution containing copper and zinc ions, initial concentrations of both metal ions were 1×10^{-4} M. Figure 10 shows that adsorption kinetics of copper is faster than that of zinc in mono- as well as bimetal ion solutions. Complete adsorption of copper ions takes place in 3 h, while adsorption of zinc ions occurs in about 30 h. This is because mass transfer of copper ions is faster than that of zinc ions.

The presence of zinc in solution slightly affects the adsorption kinetics of the initial copper ion adsorption kinetics. However, adsorption of zinc ions (at equilibration) is reduced significantly in the presence of copper ions, which is in agreement with the equilibrium studies. Comparison of copper or zinc adsorption kinetics in mono-metal and bimetal solutions illustrates that competitive metal ions do not change the adsorption kinetics. This could be because

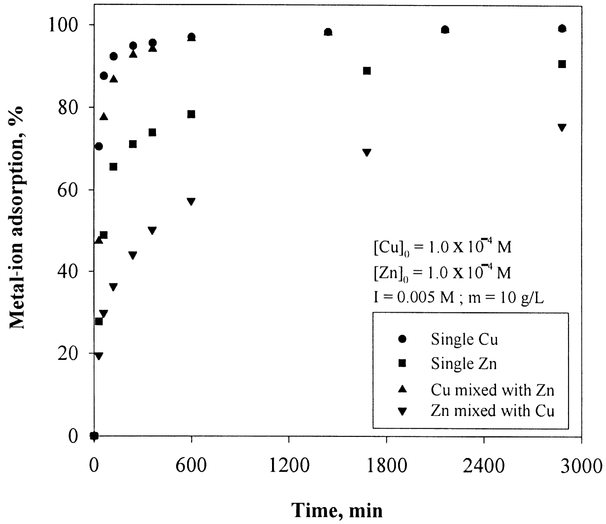

FIG. 10 Effect of competitive metal ions on copper and zinc adsorption kinetics.

metal-ion adsorption is controlled by mass transfer instead of chemical adsorption reactions.

CONCLUSIONS

Potentiometric titration experiments showed that the surface charge of Filtrasorb 200 increased with a decrease in pH. The absolute value of the surface charge increased with an increase in ionic strength. An increasing pH and ionic strength and a decreasing initial concentration enhanced metal-ion-adsorption percentage. Adsorption experiments with single metal ions showed that the metal-ion-removal capacity was in the descending order Cu $>$ Zn $\approx$ Co. Competitive effect played an important role in zinc and cobalt ion adsorption in a solution containing multicomponent ions of Cu-Zn, Cu-Co, and Cu-Zn-Co. Adsorption of zinc and cobalt ions was reduced dramatically with the addition of copper ions, whereas adding zinc or cobalt was insignificant for copper-ion removal.

Kinetic study showed that most of the adsorption occurred in the first hour and removal was complete within 3 h. Mass transfer was an important controlling factor in metal-ion uptake rate. Effect of pH on removal kinetics seemed to be insignificant; however, higher ionic strength can result in slightly faster adsorption. It is also illustrated that the kinetics increased as the initial concentration increased. Adsorption kinetics for copper was much faster than that for zinc. The addition of competitive metal ions did not affect the other metal-ion adsorption kinetics. The effect of adding zinc on the copper uptake was less important. Presence of copper did not affect the zinc removal rate, but lowered its final removal.

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